TECH LIBRARY KAFB, NM
0062382

NASA - Funded Paper.

NAS5-9274

SOLAR SATELLITE PROJECT

NAS4-184



N70-20748
(ACCESSION NUMBER)
37
(PAGES)
CR 109435
(NASA CR OR TMX OR AD NUMBER)
1
(THRU)
1
(CODE)
14
(CATEGORY)
FACILITY FORM 602

HARVARD COLLEGE
OBSERVATORY

60 GARDEN STREET
CAMBRIDGE, MASS

RECEIVED
MAR 1970
CFSTI

HIGH VOLTAGE BREAKDOWN
IN AN
OSO-IV POINTED EXPERIMENT

Technical Report #11

By N. L. Hazen
M. C. E. Huber
E. M. Reeves

HARVARD COLLEGE OBSERVATORY

March, 1969

Presented to, and to be published in the proceedings of the Voltage Breakdown in Electronic Equipment at Low Air Pressures Workshop, Jet Propulsion Laboratory, March 5-7, 1969.

PASADENA

ABSTRACT

A high voltage failure occurred in the Harvard Solar Spectrometer-Spectroheliometer experiment aboard the OSO-IV spacecraft five weeks after launch. This failure is analyzed and traced to a sequential process comprising two modes which took place within the high voltage power supply. The primary failure was within the transformer. The test history of this and previous instruments is discussed, including pertinent work on sub-assemblies and modules. This testing included extensive thermal-vacuum work and corona and plasma exposure. Preventive measures that are being taken on a later experiment to fly in August 1969 are discussed, including pertinent recommendations in manufacturing technique, qualification and acceptance tests, and an overload switch that automatically turns off the high voltage power supply.

CONTENTS

	Page
(Abstract)	i
(Table of Contents)	ii
(List of Illustrations)	iii
Introduction	1
Instrument Description	2
Development and Test Background	5
Failure Analysis	9
Recommendations	15
Conclusion	19
(Acknowledgements)	20
(References)	21

(Parenthetical sections were not presented orally.)

LIST OF ILLUSTRATIONS

1. OSO-IV Instrument Outside Appearance
2. Instrument Optical Layout
3. Electronics Block Diagram
4. Instrument Interior
5. Basic Data Summary
6. Plasma Test Arrangement
7. Orbital Geography at Failure
8. Data Summary - Orbit #637
9. Schematic - High Voltage Power Supply
10. Exploded View - High Voltage Power Supply
11. Photomicrograph - High Voltage Transformer Section
12. Overload Protection Circuit Block Diagram

INTRODUCTION

The second of a series of experiments prepared by the Harvard Observatory for the Orbiting Solar Observatory program was launched aboard OSO-IV on October 18, 1967. After five weeks of highly successful scientific operation[1], a failure occurred in the high voltage subsystem associated with the primary detector and permanently disabled the instrument.

Our experience on a previous OSO and the early stages of development of this particular instrument were reported at the last workshop on high voltage breakdown at JPL[2], so that it seemed pertinent to make this follow-on report about the effectiveness of the measures described at that time for avoiding high voltage problems. This paper will describe the instrument, its test background, and the nature of the failure that occurred in orbit. Also, certain recommendations will be drawn based on the experience that is described.

It should be noted that although the technology invested in the equipment described is several years old, this will always be the case with recent flight experiments, because they require designs and developments over a period of several years. Similarly, the developments reported at this workshop and the recommendations made in this paper will not be fully exploited until some time in the future.

INSTRUMENT DESCRIPTION

The Harvard instrument consists basically of a scanning spectrometer placed at the focus of a single-element reflecting telescope.

The exterior of the instrument is shown in Figure 1. It is approximately 4 inches by 8 inches by 42 inches in size, weighs approximately 40 lbs., and is housed in polished gold covers for proper radiative thermal properties.

The wavelength region covered by the instrument (300 to 1400Å) explains the simplicity of the optics shown in Figure 2. Optical efficiencies are so poor as to prevent the use of anything except the simplest of reflective optics. There are no optically transmitting materials for these wavelengths and hence no windows or protective envelopes can be used around sensitive elements.

Radiation from the sun (see Figure 2) enters an aperture and falls on a spherical telescope mirror which focuses an image of the solar disc into the plane of the spectrometer entrance slit. The small dimensions of the entrance slit (approximately 150 microns square) act as a field stop and admit the radiation from one arc minute of the solar disc. This radiation passes into the spectrometer and is diffracted by an original concave grating ruled in gold. The emission line spectrum typical of this wavelength region is scanned

by rotation of the grating, bringing successive parts of the spectrum to the exit slit. The combined slits produce a resolution or band pass of approximately 3Å. The photon flux through the exit slit is sensed by a windowless photomultiplier operating with grounded cathode. In addition, a white light sensor behind a third slit serves as an angular reference during wavelength scan by detecting the zero order radiation reflected from the grating.

The electronic system is shown in Figure 3 and can be separated into three main subsystems. Shown at the top is the command and digital control subsystem. A digital control network (wavelength selector) receives commands and basic spacecraft timing pulses and in turn produces the remaining timing signals required by the instrument. It also controls the wavelength scanning system consisting of a pulse shaper, stepping motor and mechanical drive. The power distribution and housekeeping data subsystems are shown at the bottom of the illustration and consist of two low-voltage power supplies, the matrix or junction box, and various sensors.

The ultraviolet (UV) detection and primary data subsystems are shown in the center of Figure 3 and consist of a high voltage power supply (HVPS), temperature compensated voltage divider, photomultiplier, pulse pre-amplifier and amplifier, and finally the 16-bit binary counter/shift register. The photomultiplier is a crossed-field magnetic electron

multiplier[3,4] produced by the Bendix Corporation. It has a tungsten photo-cathode (insensitive to near UV and visible light), continuous resistive dynode and field strips, and external magnetic field structure. It requires a high voltage of 1750 volts for proper operation and has no protective envelope.

The actual instrument configuration, with the external covers removed, is shown in Figure 4. Note particularly the HVPS, the UV detector assembly, and the connectors and cable which join them.

The instrument acquires ultraviolet data in two fundamental forms as shown in Figure 5. At the bottom is a typical wavelength scan of a small central region of the solar disc from 300 to 1400Å with approximately 3Å resolution. By commanding the wavelength scan system to place the band pass on any emission line, and by activating the spatial (i.e., azimuth and elevation) raster system of the spacecraft, one can acquire spectroheliograms (images in particular wavelengths) of the sun which when reconstructed by suitable data reduction techniques take the pictorial form shown on the upper part of the illustration.

DEVELOPMENT AND TEST BACKGROUND

As a result of the OSO-II experience, which was reported previously[2], effort was devoted to developing and testing the OSO-IV instrument in order to avoid the high voltage breakdown problems suffered before.

The instrument was designed at the Harvard Observatory, but was constructed in hybrid fashion. Some of the modules were developed and built by subcontractors, others were developed at Harvard and fabricated by vendors, and still other parts were fabricated at Harvard. Instrument final assembly, integration, and test were done at Harvard. Critical subassembly and all final assembly were done in Federal Class 100 clean facilities. Extraordinary precautions were taken in design with materials selection and electronics piece-part usage. Elaborate qualification and ageing procedures were used on electronic parts, and instrument handling was carefully controlled to prevent contamination. The instrument design was reviewed critically by several independent groups to ensure that design defects had been substantially eliminated.

After completion of the various model instruments, all normal qualification and acceptance tests required by GSFC were performed, including exposure to temperature extremes, thermal-vacuum, vibration, acceleration, and others. In addition, however, as a result of our OSO-II experience a number of special tests were

performed on the prototype and flight models. These explored two general areas: (i) the immunity of the system to external influence such as extreme temperature, vacuum and plasma environments, and (ii) the ability of the system to withstand (at least for many hours) conditions of high voltage breakdown without disabling damage.

Insensitivity to combined temperature-vacuum conditions was tested on a number of occasions. In addition to the normal thermal vacuum qualification and acceptance tests (approximately 15 days and 9 days respectively in temperatures ranging between -10°C and +40°C, and vacuums between 10^{-5} to 10^{-9} torr) the UV detector subassembly and the entire instrument were subjected to hundreds of hours of vacuum and thermal vacuum exposure in the course of normal calibration activities. After delivery, the instrument also underwent thermal vacuum exposure as part of the normal spacecraft acceptance tests. These tests were thought to be more than adequate to demonstrate immunity to vacuum conditions.

The prototype instrument was also tested to investigate how orbital plasma affected the performance of the instrument[5]. These tests were made at GSFC in a facility generally like that illustrated in Figure 6. This testing facility is described more completely in another paper[6] presented at this Workshop.

Simulated plasma densities were varied between 10^4 and 10^6 particles/cm^2. The instrument was subjected to these conditions while operating fully and observing an ultraviolet source. The conclusions from the tests were that simulated orbital plasma did not induce any high voltage discharge during the operation of the experiment nor did it produce any undue interaction with the detection system. Additional exploratory tests performed in more sensitive (non-flight) configurations produced only moderate interactions.

Two principal types of tests were performed to establish the degree of immunity to high voltage breakdown conditions in the vicinity of the experiment. The first was a series of "corona" tests performed on the complete fully operating instrument and separately on the HVPS. With the operating instrument within a vacuum test chamber, the pressure would be systematically varied between .01 and .20 torr. This would invariably induce spontaneous corona within various parts of the high voltage detection system because of the open construction mentioned earlier. It was our goal to make the instrument immune to damage even though these conditions were not expected to be encountered in orbit. After the correction of several design deficiencies, this immunity appeared to be achieved, as demonstrated by many hours of continuous exposure in the laboratory.

The second type of test involved establishing the degree of immunity of the instrument to transients received from external sources along the various input-output lines. This was accomplished by introducing 1/2 millijoule transients of 100V initial amplitude, produced by a capacitor discharge, on each of the input and output lines of the instrument. Again such testing produced no apparent damage.

As a result of these tests, we were confident at the time of launch that the instrument was immune to the hostile factors of the immediate environment and also to any possible brief high voltage breakdowns within itself.

FAILURE ANALYSIS

The instrument failure occurred after approximately five weeks of useful service. The topography of the spacecraft orbits associated with the failure analysis is shown in Figure 7. A "Quick-Look" hard-line data link had been established between the Fort Myers STADAN (Satellite Tracking and Data Acquisition Net) station and Goddard Space Flight Center (GSFC), and also between GSFC and the Harvard Observatory, to allow near-real time data coverage from those orbits that passed over the Fort Myers station. Only Fort Myers had this capability. As illustrated, the failure occurred during orbit #637 on November 29th, shortly after the last daily pass within range of the Fort Myers station. The failure was therefore not observed for corrective action until 16 hours later during orbit #646, the first pass the following day at Fort Myers. The play-back data for the critical orbits around the point of failure were subsequently obtained from the Johannesburg and Santiago stations, and showed a clear record of the events preceding and following the failure. Data analyses and laboratory studies were performed in considerable detail and the results are available in a Harvard Observatory technical report[7]. For the purposes of this paper we will, therefore, present enough data to depict what most probably occurred, without the considerable substantiating evidence that is available.

The principal data characteristics of this failure were a) unusually high primary current readings from the HVPS, b) noise in the main digital system, and c) interaction with the mechanical reference (MR) circuitry which activates a status bit in the Pulse Code Modulation (PCM) data word and serves as a wavelength scan reference.

The data for the 50 minutes contiguous to the time of failure are presented in summary form in Figure 8. The basic time interval is 30.72 seconds, which represents one cycle of the analog housekeeping data subcommutator and hence one sample at the HV primary current. This is also the equivalent of 192 Harvard data words in the PCM system. The characteristics of normal operation of the instrument can be observed at the left of the illustration. At the top, the high voltage current is between 9 and 11 milliamperes with modest fluctuations. A second plot shows the MR status bit recurring at regular infrequent intervals in an expected manner. The remaining two somewhat complementary presentations of the main data output reflect normal data and the fluctuations expected from the geometry of raster picture operation. (Time to complete one raster picture equals 5.12 minutes.)

An abrupt change can be seen at the time of failure. The high voltage primary current immediately achieves the current-limited value and is interpreted as resulting from an excessive load on the power supply.

The primary data can be shown to have no statistical correlation with the previous ultraviolet data, and this is interpreted as a loss of high voltage to the detector. The third characteristic is the frequent and random triggering of the mechanical reference circuitry. The combined presence of these three characteristics has been designated as Mode I.

At the far right of the illustration a different set of characteristics can be observed. The high voltage primary current is still high but apparently fluctuating randomly. The primary data system is uniformly quiet, and there is no unusual interaction remaining with the mechanical reference circuitry. These characteristics have been designated collectively as Mode II. One can observe in the first 35 minutes after failure several occasions of transition between Mode I and Mode II. The existence of these transitions is further demonstrated by a careful analysis of the complete data.

Fortunately for the analysis, both a prototype and a spare flight instrument were available for test and they allowed very accurate simulation of the various presumed mechanisms of failure.

Careful system and data analysis determined that the counter and pulse amplifying system were operating satisfactorily and therefore were not the source of the noise in the main data system or of the mechanical reference interactions.

Laboratory tests were continued and showed that although high voltage breakdown to a variety of places could produce the data noise and high current, only high voltage breakdown to the primary ground return could additionally produce the spurious mechanical reference indications and therefore the Mode I condition. This was shown to result from the close physical proximity of the primary return wire and the mechanical reference circuit input line within the matrix or junction box. (See Figure 9)

The identification of Mode II is a bit more difficult. When the presumed breakdown path was reduced to a short circuit to the primary, the noise and mechanical reference interaction disappeared, but the current remained high and stable. Further testing demonstrated that the additional Mode II characteristic (i.e., oscillation of the supply primary) was present only when the capacitor C1 was open circuited and the effective resistance on the secondary was low or zero. When the effective resistance was high, Mode I characteristics were still present even though capacitor C1 was open.

Capacitor C1 is a 35-volt tantalum capacitor which has been shown in the laboratory to become open-circuited at very modest voltages, especially in the inverted polarity.

The high voltage is close to the primary ground return in two principal places, both within the high

voltage power supply, which is illustrated in Figure 10. One of these places is within the transformer module and the other is a point where a pin servicing the high voltage enable plug and a copper printed-circuit conductor are closely adjacent. This second potential breakdown path is impeded by a physical separation and a conformal epoxy coating on the printed circuit board, and is thought to be improbable.

The remaining potential breakdown area is the transformer illustrated in Figure 11. It consists of an aluminum core box which is wrapped in Teflon tape overlayed with the primary winding. This is again wrapped with Teflon and the secondary applied. The finished transformer is finally wrapped in Teflon tape and then conformally coated with General Electric RTV-11 silicon rubber at atmospheric pressure. As reported by the manufacturer, the transformer is assembled into a module and the entire module is encapsulated with Armstrong C-7 epoxy after having been degassed at a pressure of approximately 20 torr. The module is released to atmospheric pressure prior to curing. From elementary pressure-volume relationships, one can show that the gas (namely air) trapped within the transformer by virtue of the RTV seal is at a pressure of 20 torr if no penetration of the encapsulant occurred, or at some higher pressure if penetration did occur.

With the information available we can reconstruct the probable failure mechanisms of orbit #637.

Following the launch of the instrument, the air trapped within the transformer by the manufacturing process gradually leaked or diffused out of the module until its pressure reached a value favorable to high voltage breakdown between the leads or windings of the primary and secondary.

Such breakdown then occurred, producing the Mode I condition and producing large transients on the primary return line. These transients, aggravated by the presence of the inductor and series resistor in that leg, caused the capacitor C1 to open. As the breakdown condition continued, interaction developed with the materials of the transformer, which reduced the resistance paths first intermittently and then more permanently, and eventually produced the Mode II condition.

A number of other possible related factors were brought into the analysis and considered. These included unusual variations in the instrument temperature, the observed passages through the South Atlantic Anomaly which resulted in data system noise, the occurrence of solar flares in the period before failure, and the observation of a variety of anomalies in spacecraft performance. All of these have been studied and none have been shown to have any bearing on the observed failure.

RECOMMENDATIONS

In view of the specific experience with our OSO-IV experiment we have formulated recommendations for our future flight experiments. Our OSO-G1 program, the next instrument to fly, will use the spare flight instrument from OSO-IV with a few modifications to improve its scientific capabilities. Obviously, the problems in the high voltage section have to be prevented from recurring and that they have been prevented has to be proved by meaningful testing. Our recommendations now are:

First, the manufacturing techniques used in the transformer section must be improved. This has been done in cooperation with Transformer Electronics Company (TEC) of Boulder, Colorado. The goal was to avoid high electric fields by proper winding, and to encapsulate the transformer thoroughly. Mr. Byers of TEC has discussed the methods employed in these areas in a paper presented at this Workshop[8].

In addition, for further confidence we ordered supplies of similar capability from Electro-Mechanical Research of Princeton, New Jersey, whose units stem from a well developed design. Ideally, the power supply with the best pre-launch performance record would be flown but it appears now that only one will be available in time.

Second, we recommend qualification and accept-

ance tests which go beyond even the extra testing requirements imposed on our OSO-IV instrument, such as plasma, corona, and spike tests. Besides these and the conventional vibration and thermal-vacuum tests, there appears to be a definite need for extended vacuum exposure of high voltage equipment. By this we mean tests at orbital pressures for full desired life times. Preferably, the entire instrument should successfully pass a vacuum exposure test for the period of the mission. This, however, is prohibitive in most missions for several reasons, including the resulting delay of the launch and the financial aspects of lengthening the schedule. The increased obsolescence of an experiment due to the time required to perform such tests is also significant Nevertheless, high-vacuum life tests for qualification of high voltage equipment, performed on a statistically meaningful sample, should be required. Flight units should be tested for unit acceptance by an operational vacuum exposure for the minimum desired life time.

Third, we recommend the use of an overload-sensitive circuit which protects the instrument by turning off the high voltage power supply immediately in case of overload. This will probably prevent irreversible damage to the electronics that would occur during prolonged operation under faulty conditions. As shown in Figure 12 the load (i.e., the input current) is sensed across a 10Ω resistance in the +19V input line. The nominal voltage drop across this resistor is approximately .17V and therefore insignificant.

The trip point is specified as an rms load 50% above nominal for a time exceeding 100 ms. This load level is, of course, below the level corresponding to the current limited operation of the power supply. Also, short transients which may be induced from outside the experiment will not turn off the high voltage supply, because they are excluded by the time delay. The status of the overload protection is transmitted by telemetry. A most important aspect is the capability to override the sensing circuit and thus keep the instrument from being disabled by a malfunction in a safety device.

Lastly, we recommend a carefully developed progressive turn-on plan in orbit. Time should be taken to follow a systematic approach, starting with a check-out of low voltage systems and, after an appropriate outgassing period, short periods of high voltage turn-on. The periods of high voltage exercise are lengthened until acceptable permanent operation has been established. A Quick-Look capability is indispensable for this work. On OSO-IV high voltage was turned on the first time for 5 seconds after approximately 140 hours in orbit (i.e., after nearly 6 days). By synchronizing this five-second period so that it included a telemetry reading of the HVPS input current, we obtained enough data to establish the perfect performance of the entire detection system. Since the data were received in real time, we could evaluate them immediately and

progress more rapidly through. The overload protection in OSO-G1 should take care of some of the problems we were concerned about in OSO-IV, namely irreversible damage in case of a breakdown. Nonetheless, we will follow a similar turn-on schedule again as a matter of sound practice.

CONCLUSION

As long as instruments such as ours continue to require open high voltage systems for detection, there will continue to be a critical concern about high voltage breakdown. We have described our most recent experiences and the additional precautions to be exercised on the next flight. Eventually, through such experience, and through exchange of information in Workshops such as this, the handling of high voltage exposed to vacuum may become a routine matter.

ACKNOWLEDGEMENTS

The work described in this paper was performed under NASA Contracts NAS4-184 and NAS5-9274 from the Goddard Space Flight Center. We would also like to acknowledge the contributions of the Observatory engineering group, notably Messrs. Chevrier, Diamond, Dower, Gramer and Rechavi.

REFERENCES

1. Ultraviolet Solar Images from Space, by L. Goldberg, R. W. Noyes, W. H. Parkinson, E. M. Reeves, G. L. Withbroe, Science, 162, 95, (1968).

2. High Voltage Effects in Satellite-Borne Spectrometers, E. M. Reeves, Technical Memorandum 33-280, JPL Proceedings of the Workshop on Voltage Breakdcwn, December, 1966.

3. Photoelectron Counting in the Extreme Ultraviolet, by L. Heroux, Applied Optics, 7, 2351, (1968).

4. Solar Blind Photoelectric Detection Systems for Satellite Applications, P. J. Macar, J. Rechavi, M. C. E. Huber, E. M. Reeves, HCO Solar Satellite Project Technical Report #9 (to be published July, 1969).

5. A Simulated Orbital Plasma Test of the HCO OSO-IV UV Spectrometer, by S. Diamond, HCO Solar Satellite Project Technical Report #8 (to be published May , 1969).

6. Testing of High Voltage Spacecraft Systems in a Simulated Ionosphere Plasma, by D. R. Burrowbridge, Workshop on Voltage Breakdown, JPL, 1969 (to be published).

7. Harvard College OSO-IV Pointed Experiment - An Analysis of the Malfunction during Orbit #637, by R. Dower, N. Hazen, J. Rechavi, HCO Solar Satellite Project Technical Report #7, February, 1969.

8. Design Considerations for Corona-Free High Voltage Transformers, by H. C. Byers. Workshop on Voltage Breakdown, JPL, 1969 (to be published).

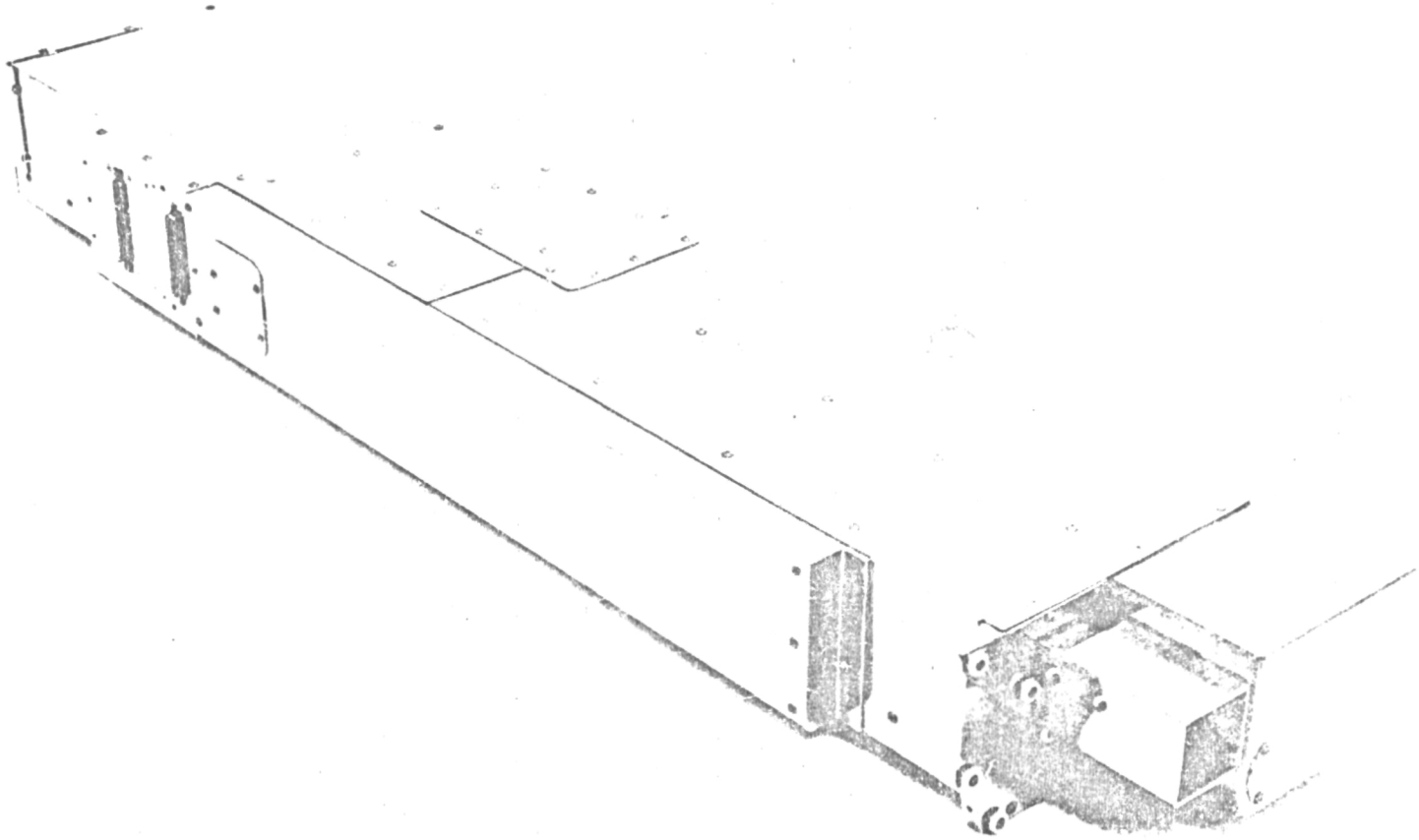


FIGURE 1

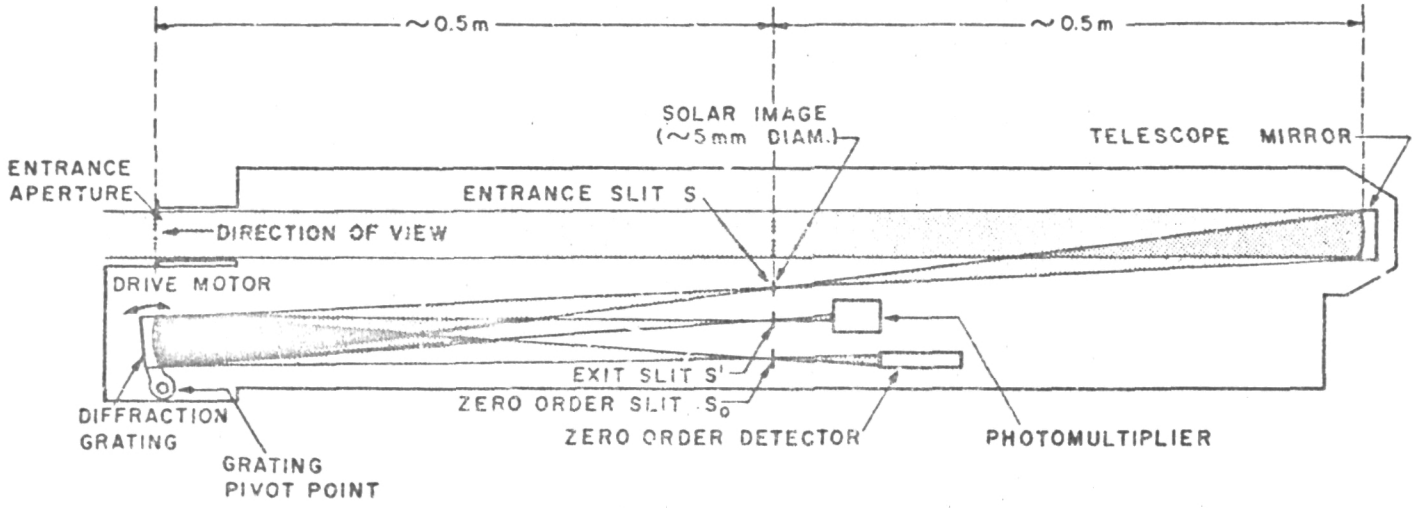
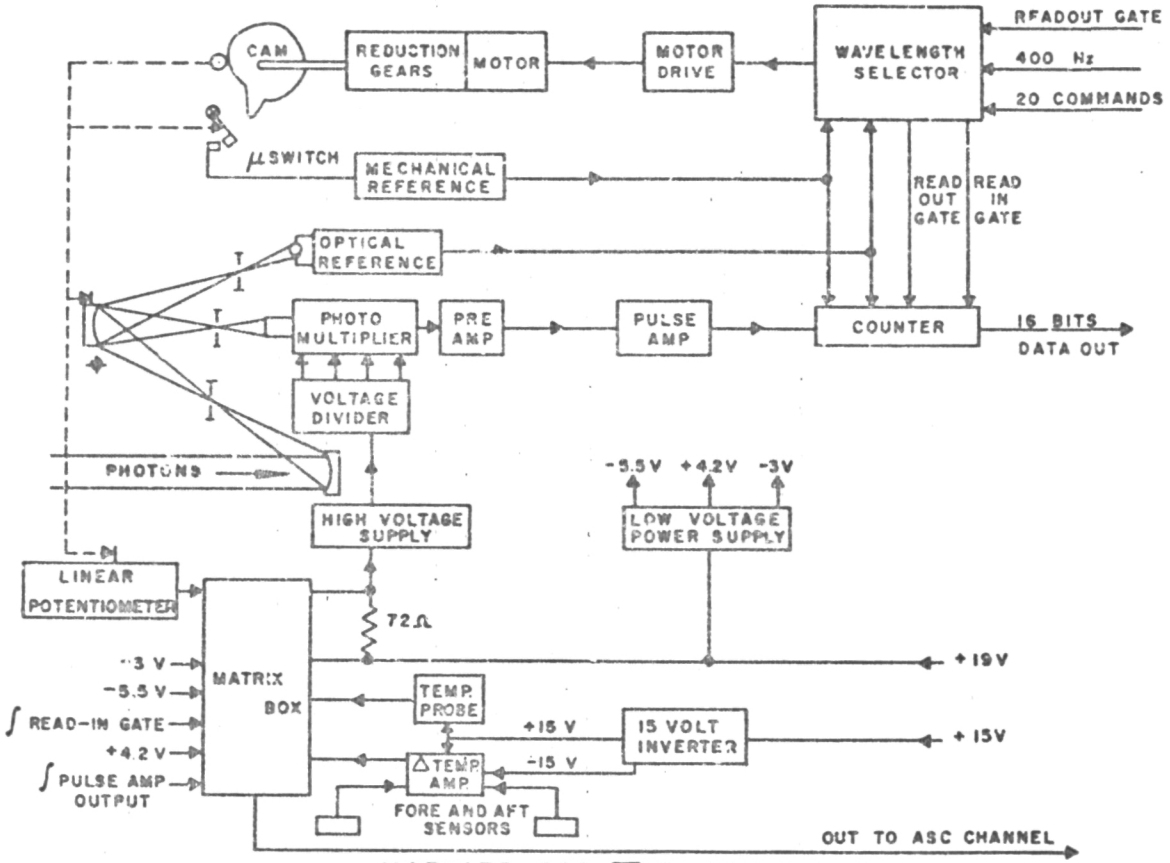
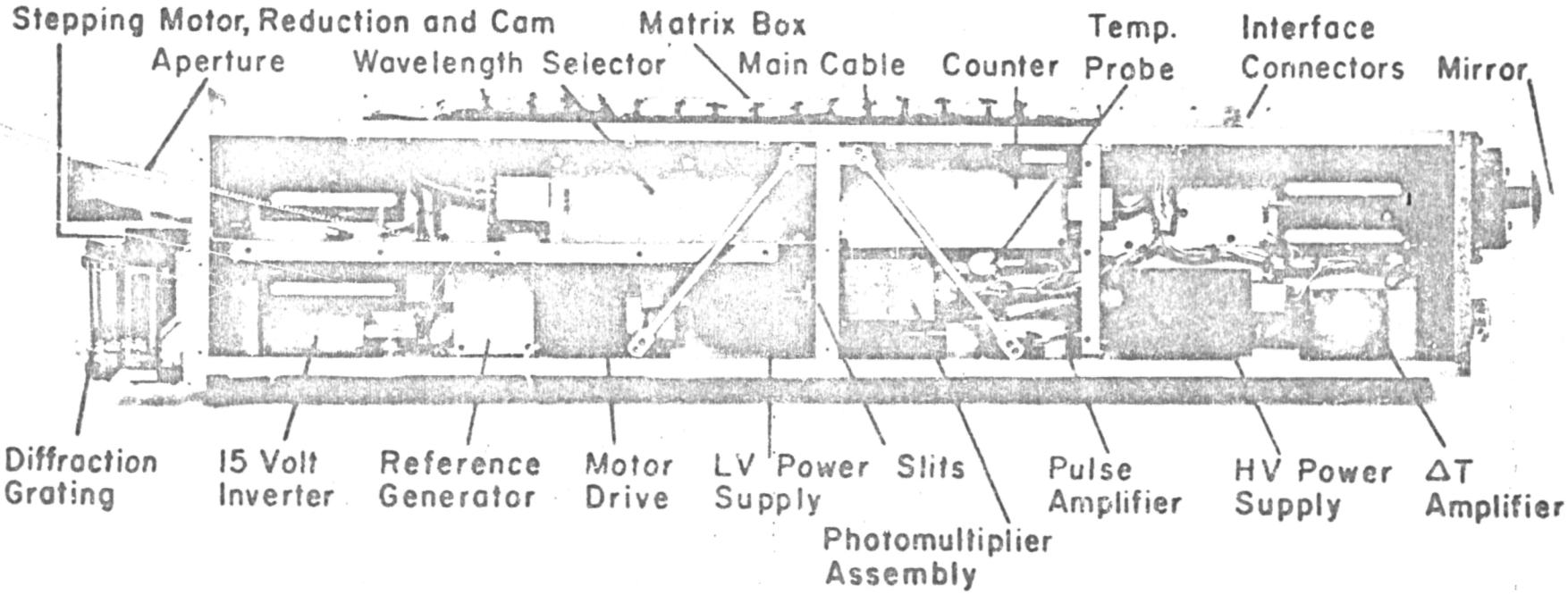

~0.5m
~0.5m
SOLAR IMAGE
(~5mm DIAM.)
TELESCOPE MIRROR
ENTRANCE
APERTURE
ENTRANCE SLIT S
DIRECTION OF VIEW
DRIVE MOTOR
EXIT SLIT S'
ZERO ORDER SLIT S_o
DIFFRACTION
GRATING
GRATING
PIVOT POINT
ZERO ORDER DETECTOR
PHOTOMULTIPLIER

FIGURE 2



HARVARD OSO-IV BLOCK DIAGRAM


Stepping Motor, Reduction and Cam
Aperture
Wavelength Selector
Matrix Box
Main Cable
Counter
Temp. Probe
Interface Connectors
Mirror
Diffraction Grating
15 Volt Inverter
Reference Generator
Motor Drive
LV Power Supply
Slits
Photomultiplier Assembly
Pulse Amplifier
HV Power Supply
ΔT Amplifier

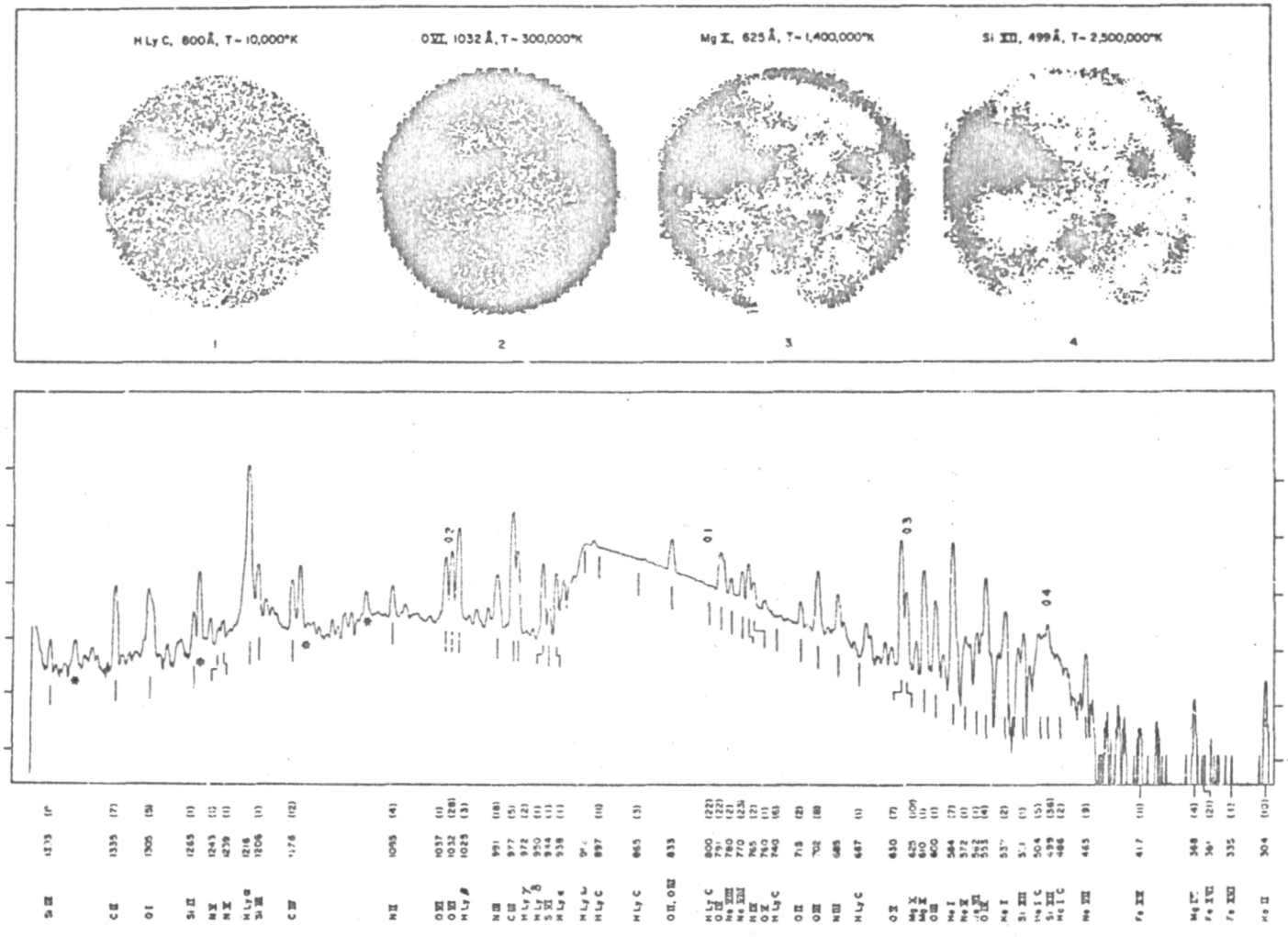
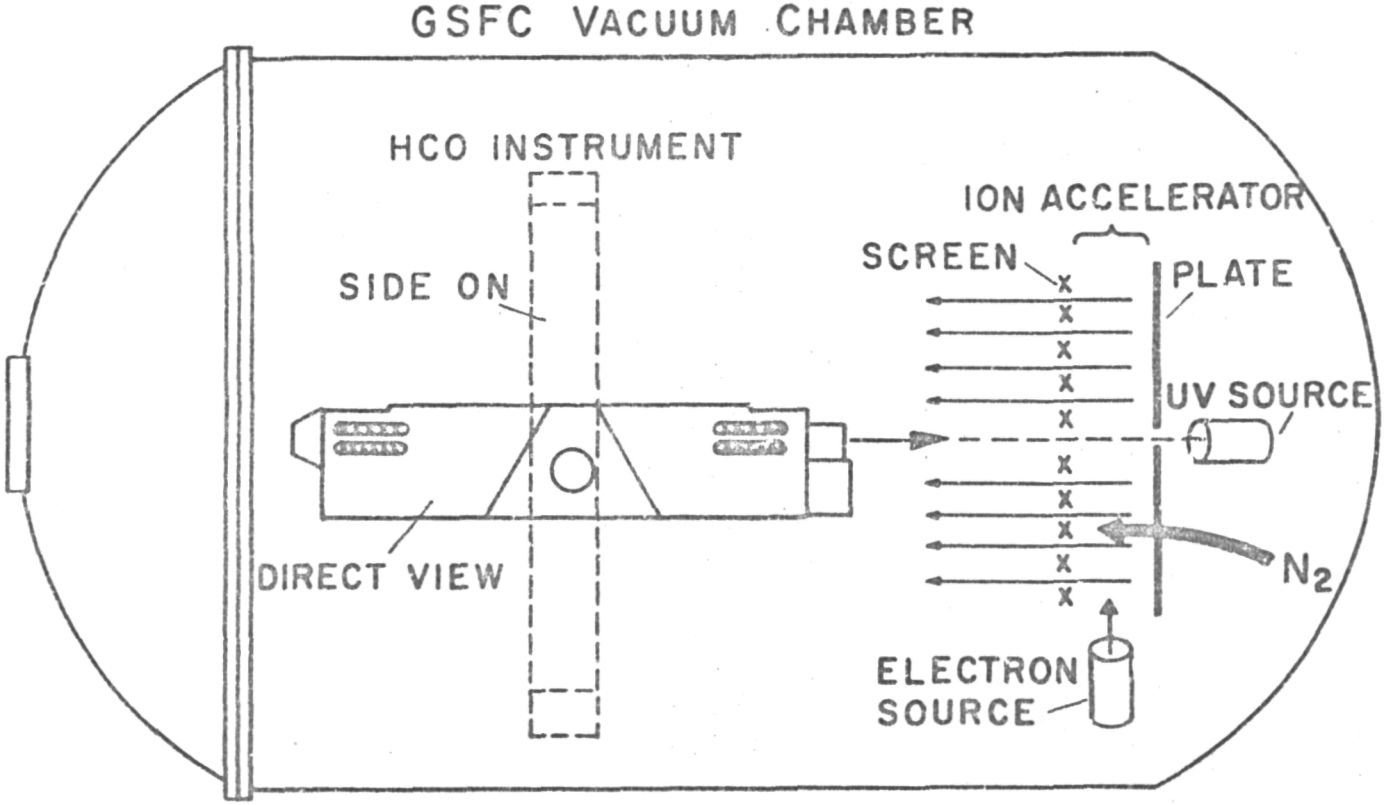
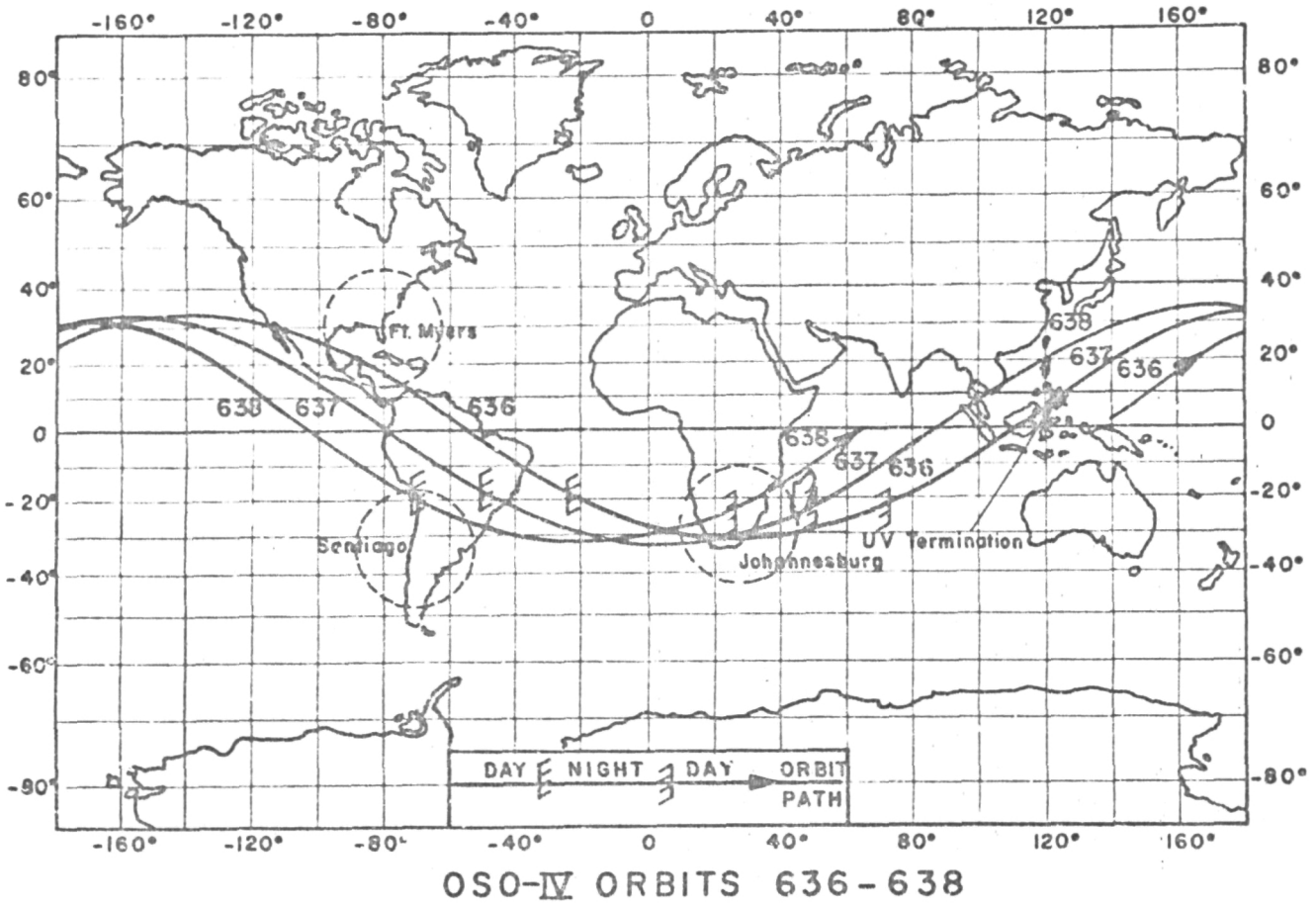

H Ly C, 800Å, T ~ 10,000°K
OVI, 1032 Å, T ~ 300,000°K
Mg X, 625 Å, T ~ 1,400,000°K
Si XII, 499Å, T ~ 2,500,000°K
1
2
3
4
log (COUNTS / 080 SEC)
0 1
0 2
0 3
0 4

FIGURE 5



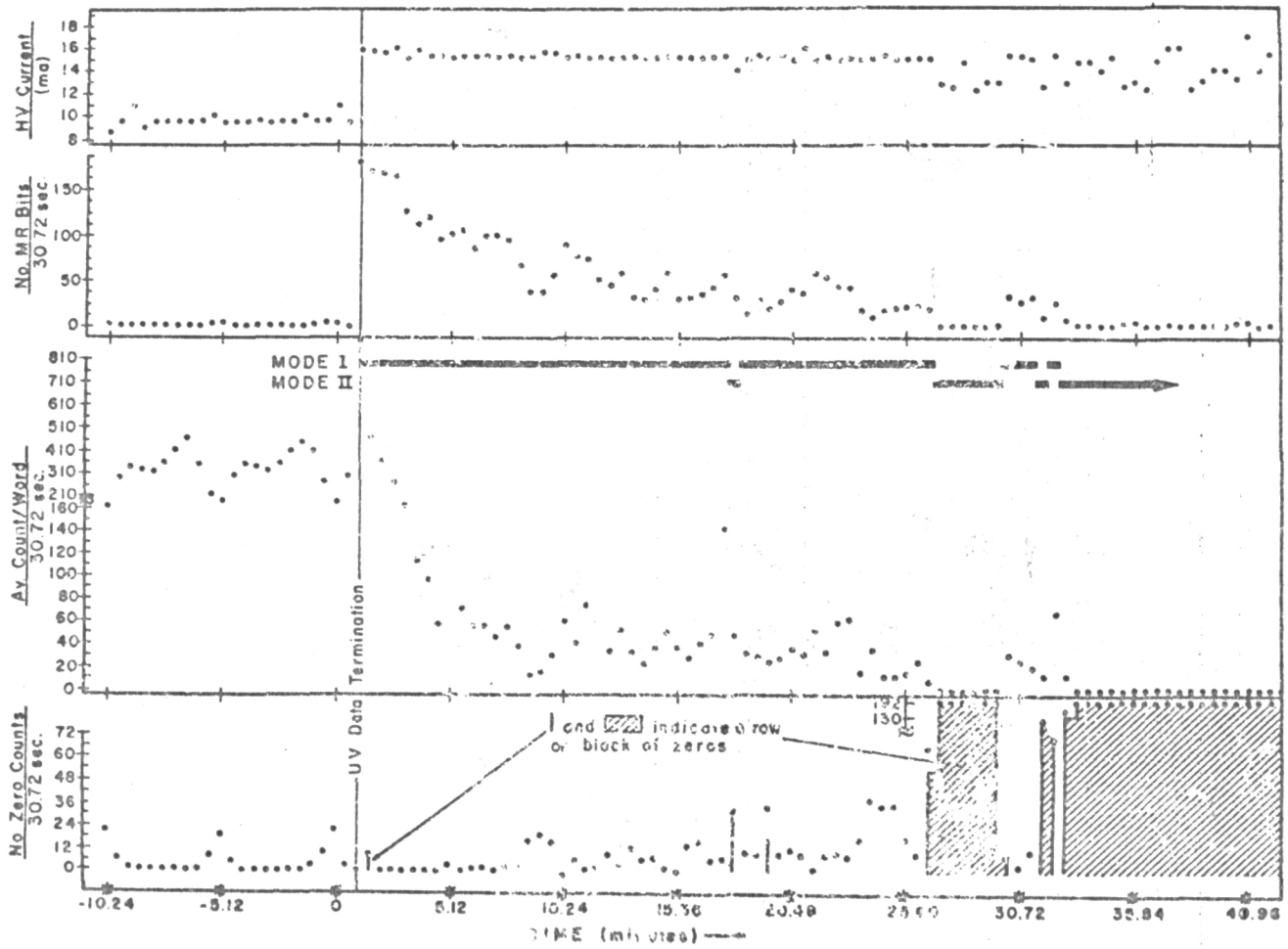
PLASMA TEST ARRANGEMENT

Fig 6



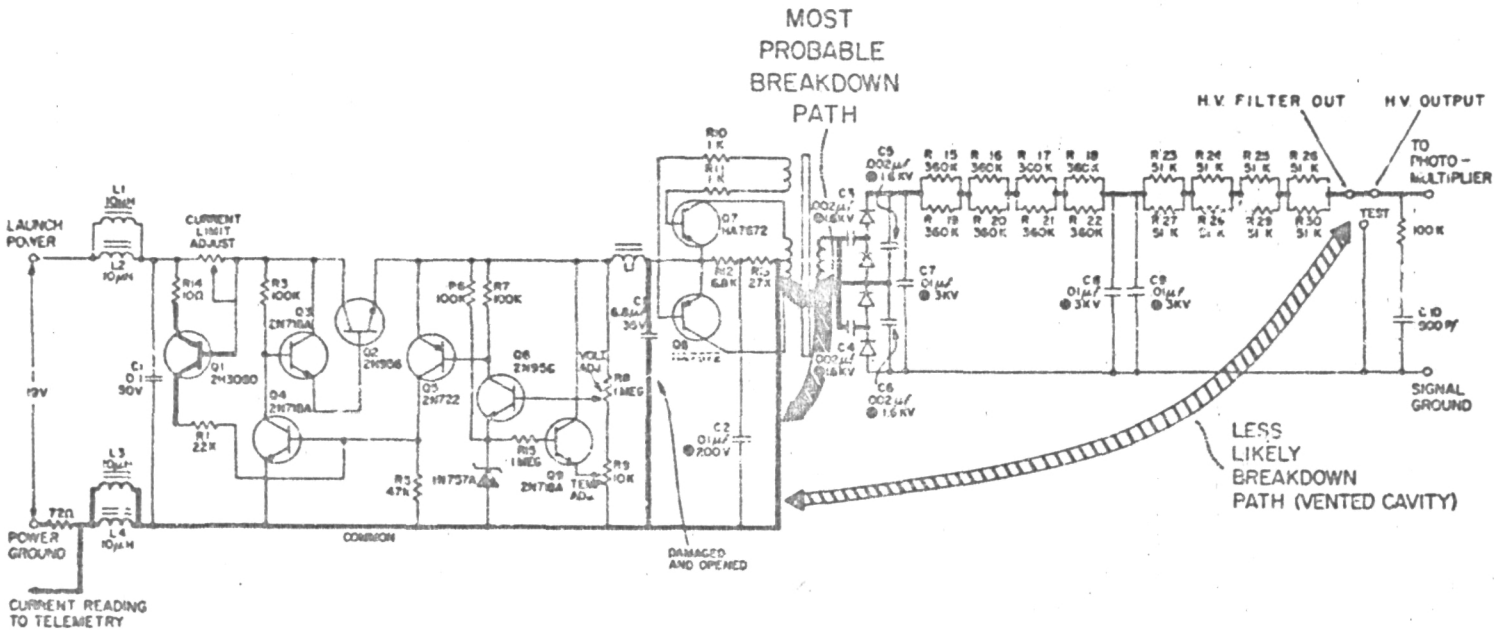
OSO-IV ORBITS 636-638

FIGURE 7



OSO - IV HARVARD DATA — ORBIT 637

Fig 8



OSO-IV HCO HIGH VOLTAGE SUPPLY

Fig. 7

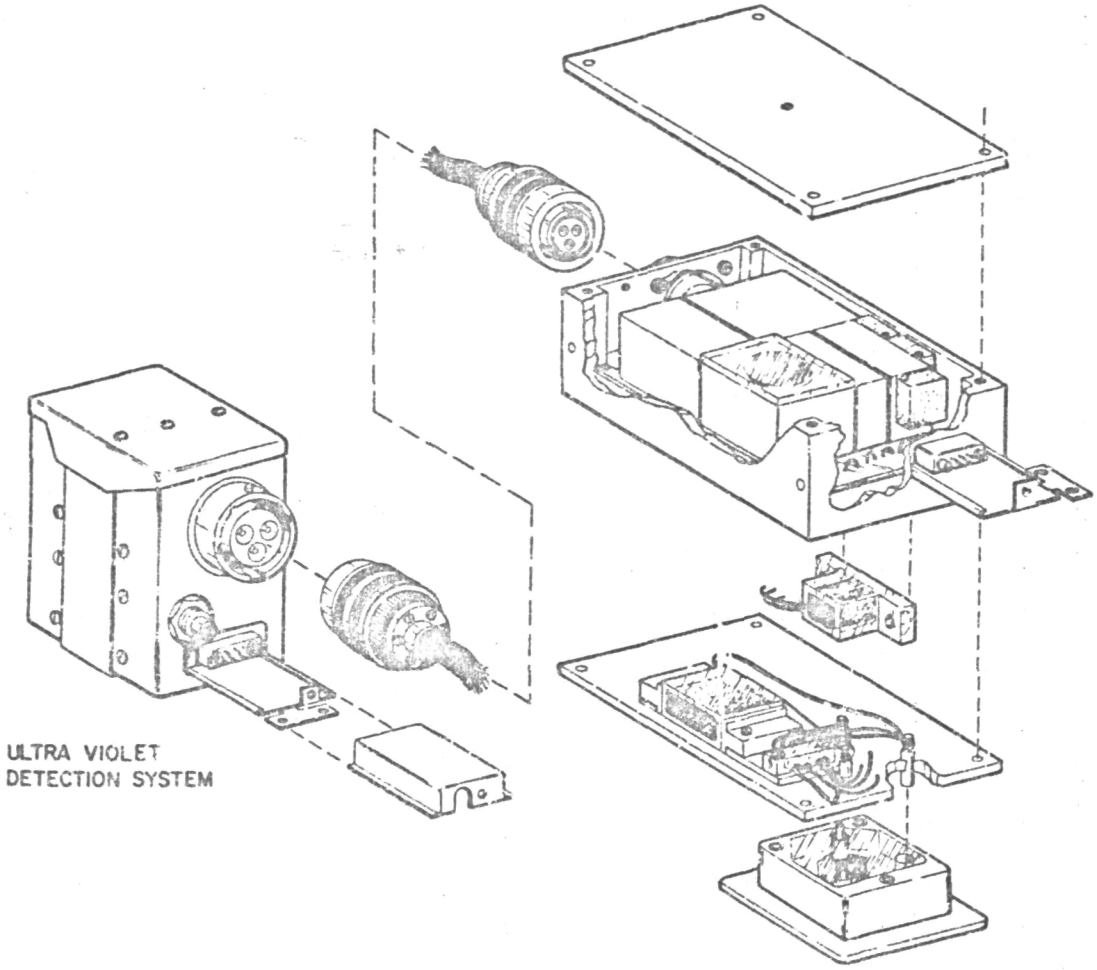
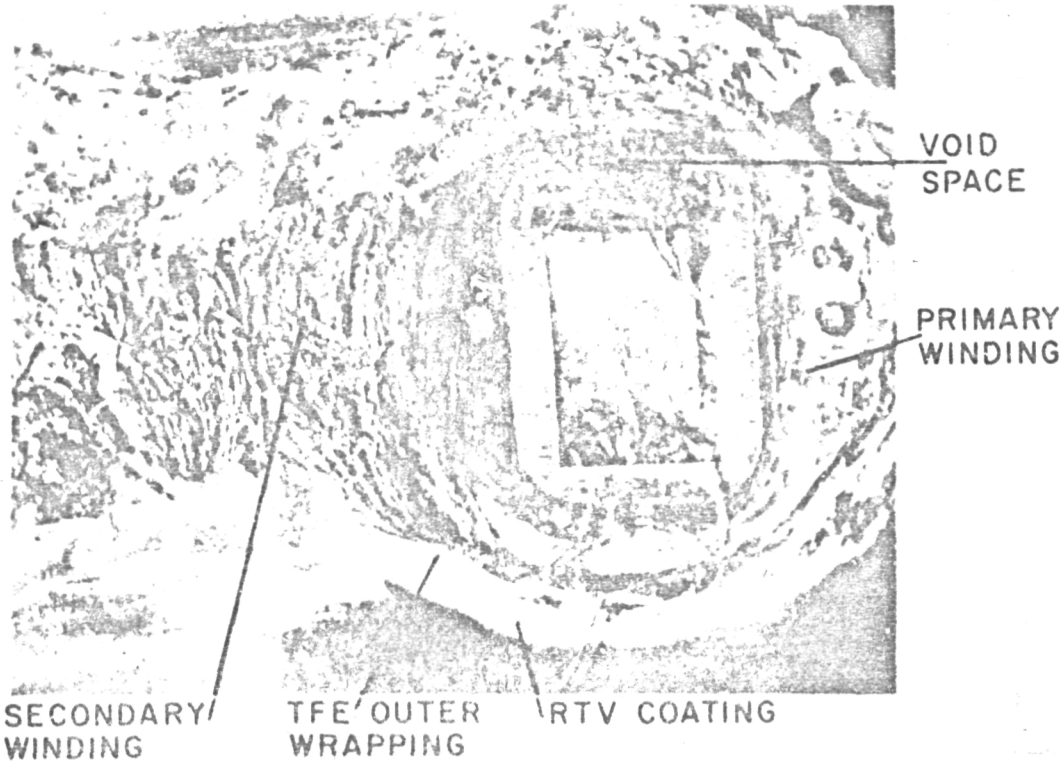


FIGURE 10



HV TRANSFORMER CORE MODULE

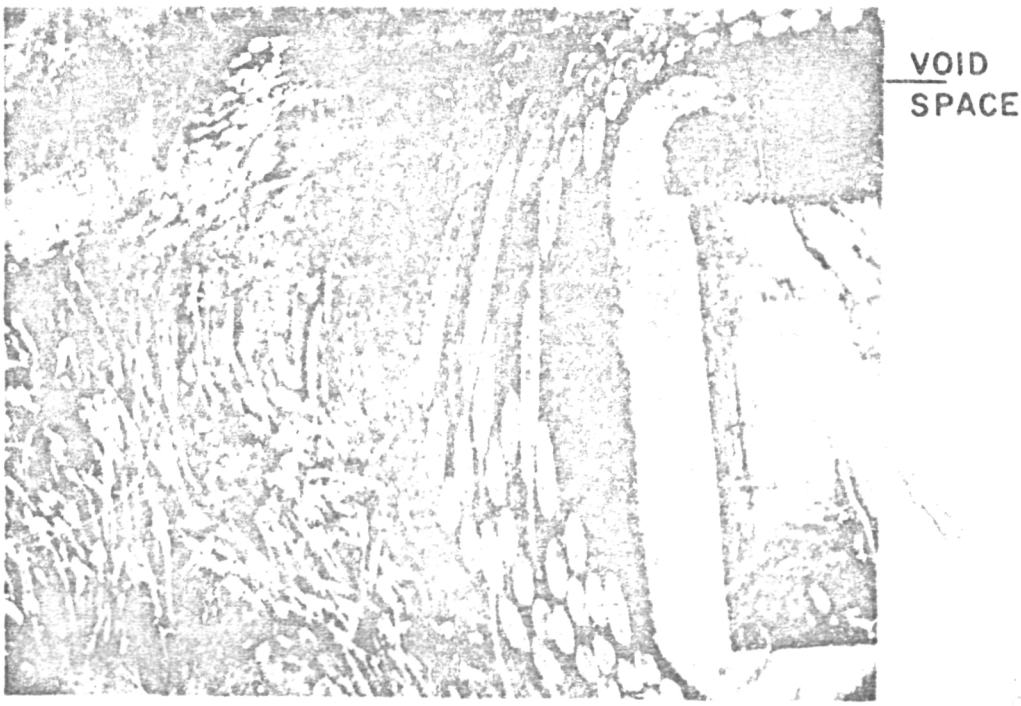


FIGURE 1