

## **TELESCIENCE OPERATIONS WITH THE SOLAR ARRAY MODULE PLASMA INTERACTION EXPERIMENT**

Lawrence W. Wald and Irene K. Bibyk

NASA Lewis Research Center

### **ABSTRACT**

The Solar Array Module Plasma Interactions Experiment (SAMPIE) is a flight experiment that flew on the Space Shuttle Columbia (STS-62) in March 1994, as part of the OAST-2 mission. The overall objective of SAMPIE was to determine the adverse environmental interactions within the space plasma of low earth orbit (LEO) on modern solar cells and space power system materials which were artificially biased to high positive and negative direct current (DC) voltages. The two environmental interactions of interest included high voltage arcing from the samples to the space plasma and parasitic current losses. High voltage arcing can cause physical damage to power system materials and shorten expected hardware life. Parasitic current losses can reduce power system efficiency because electric currents generated in a power system drain into the surrounding plasma via parasitic resistance.

The flight electronics included two programmable high voltage DC power supplies to bias the experiment samples, instruments to measure the surrounding plasma environment in the STS cargo bay, and the on-board data acquisition system (DAS). The DAS provided in-flight experiment control, data storage, and communications through the Goddard Space Flight Center (GSFC) Hitchhiker flight avionics to the GSFC Payload Operations Control Center (POCC). The DAS and the SAMPIE POCC computer systems were designed for telescience operations; this paper will focus on the experiences of the SAMPIE team regarding telescience development and operations from the GSFC POCC during STS-62.

The SAMPIE conceptual development, hardware design, and system verification testing were accomplished at the NASA Lewis Research Center (LeRC). SAMPIE was developed under the In-Space Technology Experiment Program (IN-STEP), which sponsors NASA, industry, and university flight experiments designed to enable and enhance space flight technology. The IN-STEP Program is sponsored by the Office of Space Access and Technology (OSAT).

## **INTRODUCTION**

Contemporary satellites and spacecraft have evolved in size, weight and sophistication to the point that they now require space power systems which operate at higher operating voltages than current spacecraft. This demand creates a new challenge for spacecraft designers to contend with the interaction of space plasma with materials and systems.

The Solar Array Module Plasma Interactions Experiment (SAMPIE) is a Space Shuttle experiment designed by NASA LeRC to investigate and quantify high voltage plasma interactions. The objective of SAMPIE was to determine the environmental effects of the low earth orbit (LEO) space plasma environment on modern solar cells and space power system materials artificially biased to high plus and minus DC voltages. The two environmental effects of interest included high voltage arcing from the samples to the space plasma, which can cause physical damage to power system materials, and parasitic current losses, in which electric currents generated in a power system drain into the surrounding plasma via parasitic resistance. These parasitic losses reduce power system efficiency. SAMPIE results will play a key role in the design and construction of high voltage space power systems.

The Principal Investigators (PI's) of the SAMPIE experiment were Dr. Dale Ferguson and Dr. G. Barry Hillard, both of the LeRC Space Power Technology Division. The Project Manager (PM) for the experiment was Lawrence W. Wald. Irene K. Bibyk was Deputy to Mr. Wald. Task work was accomplished by an in-house project team consisting of LeRC and NYMA Technology, Inc., engineers and technicians. The project was supported by the NASA Headquarters Office of Space Access and Technology.

## **BACKGROUND**

Numerous ground and flight experiments have shown that there are two basic interactions with the space plasma when spacecraft surfaces are biased at high potentials relative to it.

First, conducting surfaces whose electrical potential is highly negative with respect to the plasma undergo arcing - damaging the material and resulting in current disruptions, significant Electromagnetic Interference (EMI), and large discontinuous changes in potential.

Second, solar arrays or other surfaces whose potential is positive with respect to the plasma collect electrons from the plasma, resulting in a parasitic loss of power to the power system and a change in the floating potential of the system.

## **PROJECT OBJECTIVE**

The overall objective of SAMPIE is to minimize adverse environmental interactions by investigating the arcing and current collection behavior of materials and geometries likely to be exposed to the Low Earth Orbit (LEO) plasma on high voltage space power systems [Ref. 1]. There are seven specific objectives of the experiment:

1. For selected solar cell technologies, determine the arcing threshold, arc rates, and magnitude of arc current.
2. For these sample arrays, measure plasma current collection versus applied bias.
3. Design and test an arc mitigation strategy; i.e., modifications to standard design which may significantly improve the arcing threshold.
4. Design and test simple metal/insulator mock-ups to allow the dependence of current collection on exposed areas to be studied with all other relevant parameters controlled.
5. Design and fly an experiment to determine the dependence of arcing threshold, arc rates, and arc strengths on the choice of metal with all other relevant parameters controlled.
6. Design and fly controlled experiments to study arcing from anodized aluminum using alloys and anodization processes typical of ones being considered for use on large space structures.
7. Measure a basic set of plasma parameters to permit data reduction and analysis.

## **EXPERIMENT APPROACH**

The SAMPIE flight experiment is shown in Fig. 1. Mounted to the top side of the experiment is the Experiment Plate, which contains the experimental samples. The samples include modern solar cells, samples used to verify program elements of the Space Station program, sample items of modern power system materials, and samples used to collect data to verify numerical simulation computer codes. A diagram of the Experiment Plate is shown in Fig. 2; a short description of each sample is listed below.

### ***SPACE STATION CELLS***

A four-cell coupon of 8-cm by 8-cm space station cells having copper interconnects on the reverse side will allow a test of this technology. Arcing is expected to occur from the cell edges and there is considerable interest in arc rate versus bias curves as well as in the arcing threshold for these cells. Current collection from these cells will perhaps be even more interesting, as it can dramatically affect the floating potential of spacecraft.

### ***APSA***

A twelve-cell coupon of 2-cm by 4-cm Advanced Photovoltaic Solar Array (APSA) cells will test the behavior of this relatively new, very thin (60  $\mu\text{m}$ ) technology. For use in LEO, the sample blanket will use germanium-coated Kapton for protection from atomic oxygen attack. Ground tests have shown that the use of such material, which is a weak conductor, leads to increased plasma current collection under some conditions.

### ***STANDARD SILICON***

By including a coupon of traditional 2-cm by 2-cm silicon solar cells, a baseline for comparison is provided by including the technology that has been used exclusively in the U. S. space program to date. Second, computer codes that predict the results of plasma interactions are now mature though largely unvalidated. A key feature of such codes is the ability to predict current collection for solar arrays. Unfortunately, plasma sheath effects make scaling the current collection to large arrays highly nonlinear and very difficult to predict. We have devised an experiment to study this effect. Data is taken from a four-cell coupon of 2-cm by 2-cm silicon solar cells wired as a series string. A second independent series string of 12 cells surrounds the inner four. a third series string of 20 cells, also independent, surrounds the entire assembly. By biasing these strings independently in various combinations, these scaling effects will be studied.

### ***MULTIPLE BREAKDOWN TEST***

The samples tested on this plate will explore the hypothesis that negative potential arcing is a special case of the classical vacuum arc. With geometry and test conditions controlled, only the composition of the metal will be varied. Two different types of measurements of five different pure metals - gold, silver, copper, aluminum, and tungsten - will be made.

## ***SNAPOVER***

To study current collection and snapover (a condition where an entire surrounding surface, normally an insulator, behaves like a conductor), we include six 1 cm diameter copper disks covered with 3-mil-thick Kapton. Each has a pinhole in the center with hole sizes tentatively chosen as 1 mil, 5 mil, 10 mil, 15 mil, 20 mil, and 30 mil. the use of such simple geometry will enable computer modeling of the essential physics without the complications introduced by geometrical complexities inherent in solar cells. The resulting family of current versus applied bias curves will be compared with computer predictions and other theoretical treatments.

## ***MODIFIED SPACE STATION***

On the bottom of the experiment plate are three coupons of four cells. These are space station cells reduced from the normal 8-cm by 8-cm size to 4-cm by 4-cm. This size reduction is necessary to increase the number of experiments that can be done in the limited area provided by the experiment plate. The data returned from the selected experiments will not be impacted by the scaling. Several factors in the cell design are now known to significantly affect plasma interactions. The three coupons to fly are designed to study several of these factors.

## ***SINGLE BREAKDOWN TEST***

The single breakdown test consists of a sample of anodized aluminum. There is considerable concern that this material undergoes dielectric breakdown and arcing when biased to high voltages. The particular alloy and sulfuric acid anodization process are chosen to be identical with that currently baselined for the space station main truss structure.

## ***FLIGHT HARDWARE***

The SAMPIE main electronics unit (MEU), is shown in an exploded view in Fig. 3. The package consists of a 2.54 cm baseplate to which a card cage for printed circuit boards (PCB's) and various instrument boxes are attached. Most of the instruments and electrical subsystems are on PCB's mounted within the card cage. The enclosure cover is a one piece case which provides a mounting surface for the experiment plate. Two electrical probes - a Langmuir probe to monitor plasma density and temperature and a V-body probe to monitor Shuttle potential with respect to the ionosphere - are part of the package. Since SAMPIE will significantly disturb the ionosphere within an area estimated to be about 1 m. in all directions, these probes are positioned on a side mount on the Hitchhiker-M carrier, about 2 m. away, from the SAMPIE MEU, as shown in Fig. 4.

A microprocessor is used to control the experiment and record the data. Data is stored on board in flash memory cards and will be transferred to PC as soon as possible after flight. A minimum subset of experiment data and housekeeping information will be downlinked in real time. Data analysis will be performed in-house at LeRC.

The Data Acquisition System (DAS) consists of a 25 MHz 68030 based single board computer (DMV-141), a custom made I/O Board, two Flash Memory Boards (DMV-540), and two A/D Boards (DMV-666). In general, the DAS provides the following: 1) Executes instructions in firmware to operate each experiment contained within SAMPIE's timeline; 2) Collects data from and controls the operation of other electronic boards/modules within SAMPIE's electrical system; 3) Interface to the outside world (GSE) via an RS422 interface. Specifications of each board that makes up the DAS are discussed below:

**CPU Board:** 68030 based board, 512 Kbytes of static ram (SRAM), 512 Kbytes of flash memory, two RS-232 ports (only one is required on SAMPIE), two 8-bit timers, and VMEBus interface circuitry. Located in VME Backplane slot one.

**Memory Boards:** Each card contains 4 MBytes of Flash Memory, write protection, VME interface, and Built-In-Test (BIT). Located in VME Backplane slots two and three.

**A/D Board:** Analog to Digital Converter, 12-bit resolution and 20  $\mu$ S conversion time, 16-single ended inputs or 8 differential inputs, Inputs configurable to  $\pm$ 40 VDC,  $\pm$ 10 VDC, 0-20 mA with programmable gain control. Located in VME Backplane slots five and six.

## **FLIGHT OPERATIONS**

In a simplified description of the experiment, one sample is biased to a particular voltage for a preset time while all remaining samples are held at ground potential. The power supply will bias the solar cell samples and other experiments to dc voltages as high as +300 V and -600 V with respect to shuttle ground. When biased negative, suitable instruments will detect the occurrence of arcing and measure the arc rate as a function of bias voltage. For both polarities of applied bias, measurements will be made of current collection versus voltage. A set of plasma diagnostics measurements is then taken and the procedure repeated at the other bias voltages. Diagnostic measurements consist of background pressure, plasma density and pressure, and the potential of the Shuttle with respect to the plasma.

The flight electronics included two programmable, high voltage DC power supplies to provide voltages from -600 VDC to +300 VDC to the samples. A transient current detector detected arcs and measured arc-rates as a function of negative DC

voltages for each sample. An electrometer, a precision DC current measuring device, measured parasitic current collection versus voltage for both positive and negative DC voltages. A plasma diagnostic instrument suite collected data on the plasma environment during operation of the experiment. The on-board data acquisition system (DAS) recorded the flight data, stored the information on nonvolatile memory, controlled the flight experiment, and provided communications capability to SAMPIE team members located in the Payload Operations Control Center at the Goddard Space Flight Center during the mission.

Vehicle orientation with respect to its velocity vector is critical since ram and wake effects are known to be significant. SAMPIE's operations plan will request control of Shuttle orientation such that one entire set of measurements is made with the payload bay held in the ram direction and a second set with the bay in the wake. The experiment timeline is expected to require approximately 25 hours of bay-to-ram and about 15 hours of bay-to-wake.

A team of LeRC and NYMA engineers and scientists were to be at the GSFC POCC for on-orbit operations during the mission. The total on-orbit time would be around 40 hours, which would require several shifts of support staff. POCC personnel would control the experiment operation by sending commands from the POCC to SAMPIE via uplink telemetry. Command acknowledgment, experiment data, and health & welfare data for the experiment would, in turn, be sent to the POCC from the experiment. The data received in the POCC was to be a subset of the on-orbit data; it would allow the engineers and scientists to monitor the environmental effects and if necessary, certain experiments could be repeated by sending the appropriate commands to the experiment.

After the OAST-2 mission is completed, the SAMPIE payload will be removed from the Hitchhiker-M carrier and returned to the Lewis Research Center. The data stored on-board the experiment will be copied to floppy disk media for the Principal Investigator and Project Scientist to study and analyze. The SAMPIE experiment will then be inspected, re-furbished as necessary, and safely stored in preparation for future flight opportunities.

## **FLIGHT DATA AND RESULTS**

The SAMPIE flight experiment was flown on STS-62 from March 4-19, as part of the OAST-2 payload. During the mission, project personnel located at the GSFC POCC participated in the on-orbit operations of the experiment, sending commands to and receiving downlinked data from the payload. From the data received in the POCC, the SAMPIE experiment provided a number of "firsts" to the investigation of modern solar arrays and power system materials. These include the first data ever taken on actual Space Station flight solar cells and Advanced Photovoltaic Solar Array (APSA) cells. SAMPIE is also the first high voltage plasma interaction

experiment ever retrieved after its in-space operations were completed. Along with the data collected for each experiment sample a set of plasma diagnostic data was collected, providing information on the payload bay environment.

SAMPIE completed its mission objectives in a comprehensive manner. The minimum success criteria and all planned plasma current collection measurements were completed in the bay-to-ram and bay-to-Earth orientations. The bay-to-Earth measurements were obtained in the wake of the Extended Investigation of Spacecraft Glow (EISG) experiment, and were representative of bay-to-wake measurements. All planned low voltage (to -300 VDC) arcing measurements were completed in the bay-to-ram orientation. Approximately three quarters of all desired high voltage (-400 V and higher) arcing measurements were also completed in a bay-to-ram orientation.

During bay-to-ram orientation, high voltage arcing on the APSA array, a large arc at -600 VDC caused one of SAMPIE's two high voltage power supply circuits to eventually cease operation. This limited subsequent arcing measurements to the arc mitigation samples, the metal samples, and the space station anodized aluminum samples and precluded any further current collection data. By that time, however, good high voltage arcing data had already been obtained for the APSA, space station, standard silicon, and Z-93 samples. Because all current collection and arcing measurements on all samples had already been completed under worst case (bay-to-ram) conditions throughout their anticipated useful voltage range, no essential engineering data were lost.

Subsequent to the power supply anomaly, several sets of true bay-to-wake high voltage arcing data were obtained for approximately half of the SAMPIE samples.

Throughout SAMPIE operation data was obtained on the payload bay neutral pressure, plasma density and temperature, Shuttle potential, and temperatures within the SAMPIE enclosure. This data will enable full analysis of the current collection and arcing data, so they can be used directly to confirm or require modification of analytical models used for spacecraft power system and charging analysis.

LeRC personnel received the downlink data in real time at Lewis, in Cleveland, Ohio, in the User Operation Facility (UOF). This enabled a larger group of scientists to view the flight results first hand.

SAMPIE also took pressure data in support of and in conjunction with the EISG experiment. SAMPIE measured high voltage arcing characteristics and payload bay pressures in a bay-to-ram orientation, low altitude (140 nm) circular orbit and later in an extremely elliptical orbit with a perigee of 105 nm.



## **TELESCIENCE LESSONS LEARNED**

A written mission plan should be completed prior to departure from LeRC to the mission POCC. The mission plan for the experiment details the following: the success criteria for the experiment, the on-orbit experiment milestones and their nominal time of occurrence, and the nominal command plan for the experiment. The plan should be written by the PM and/or the PI. An electronic copy should be in the POCC for reference and mission time updates. POCC personnel must be familiar with the mission plan prior to on-orbit operations. POCC personnel should be familiar with the expected on orbit thermal performance and electrical requirements of the experiment in order to determine nominal operation

8 hour fixed shifts are recommended and staff each shift with at least 2 people. Allow experiment personnel to pick their shifts (if possible). The day shift is very important for public affairs reasons and either the PI or the PM should be assigned to this shift.

POCC personnel must be prepared to answer a variety of questions from mission management personnel in the areas of experiment function, success criteria, environmental limits, etc..

During the 18 day mission of STS-62, SAMPIE collected data on environmental interactions during several periods. Our observations regarding telescience operations are as follows:

- Real time changes in the experiment timeline can be accommodated as necessitated by any of the following reasons:
  - 1) Significant experiments may be repeated a number of times in order to collect as much flight data as possible.
  - 2) Accommodation of unforeseen changes in the shuttle operation during flight may be made. An experimenter may choose not to operate during water dumps, shuttle maneuvers, or the loss of on-orbit communication capability.
- Project personnel provided real time data on the density of the space plasma to another experiment on OAST-2 which enhanced their science return during their primary on-orbit operations.
- Scientists and engineers in the UOF POCC were able to see the downlinked data in real time and make recommendations to the primary POCC team at the GSFC

## **CONCLUSIONS**

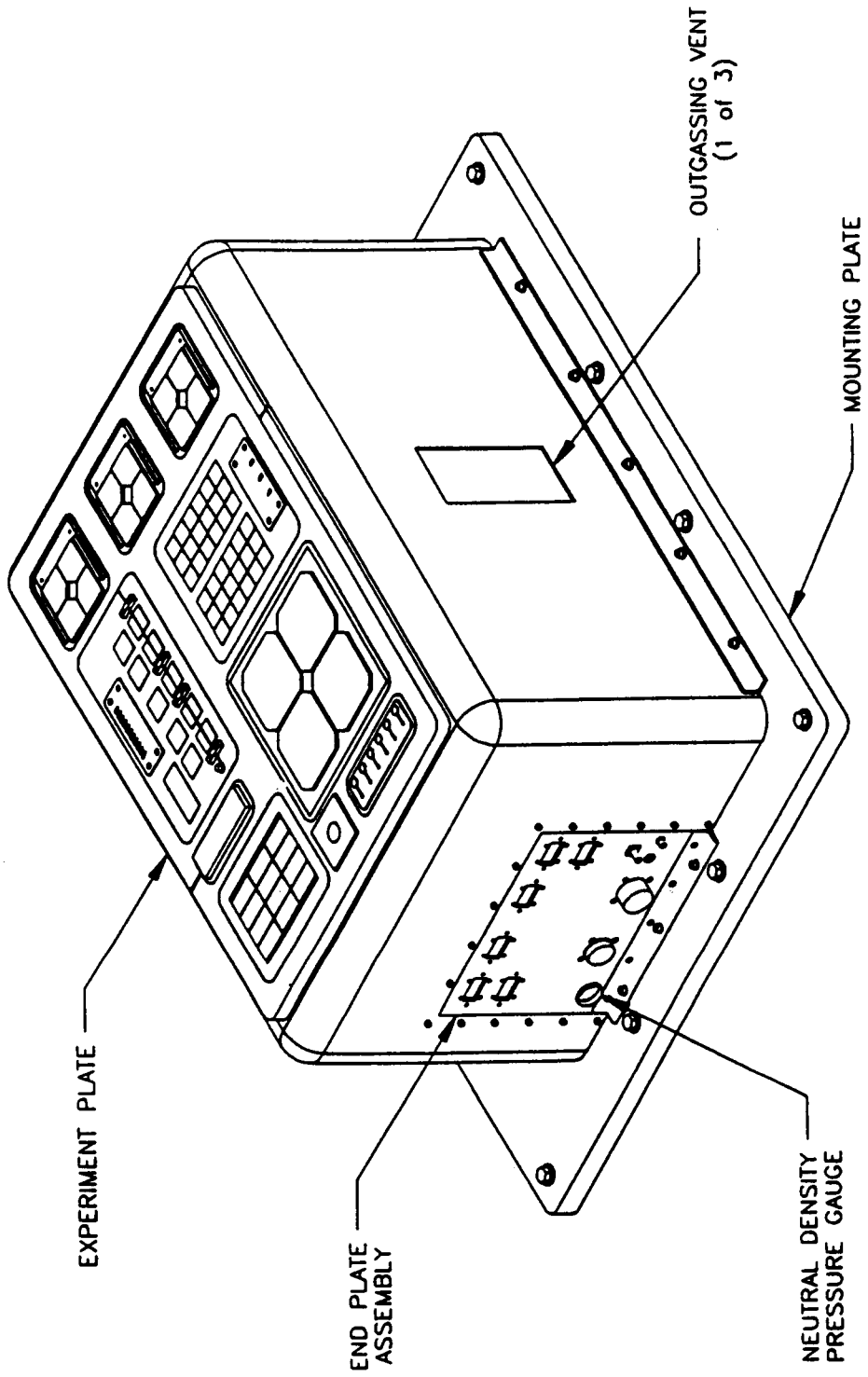
The Columbia was launched on March 4, 1994 and landed at KSC on March 19, 1994. During the 16 day mission SAMPIE operated over 70 hours in space. The primary set of required measurements were taken with the Columbia payload bay oriented in the "ram" direction (coincident with the velocity vector). In this orientation all planned current collection data at DC voltages to +300 VDC was collected, all low voltage arcing data (at voltages down to - 300 VDC) were collected, and 90% of the high voltage DC data (at voltages down to -600 V) was collected.

In the other required attitude orientation, known as the "wake" direction (with the payload bay oriented 180 away from the velocity vector) the planned low voltage (to +300 VDC) current collection measurements were not taken due to on-orbit problems with the high voltage bias line of one of the power supplies. The other high voltage power supply was used to collect high voltage arcing data in the wake. This was not in the original plan due to the pre-flight assumption that there would be no arcing in the wake due to the low plasma density. In fact, arcing was seen on several samples in the wake, providing unexpected information to the SAMPIE team. During both shuttle attitudes the plasma diagnostic instruments collected high fidelity data on plasma temperature, plasma turbulence, and shuttle vehicle potential. This data will be used to "normalize" the arcing and current collection data, removing variations due only to plasma variations.

Currently the flight data is being analyzed by the SAMPIE PI, Dr. Dale Ferguson. The PI has already used the flight data to validate the design of the ISSA plasma contactor program. The flight data will also be used to help validate computer modeling codes that have been developed at Lewis in support of space power system design. The SAMPIE flight hardware is currently in bonded storage at the LeRC awaiting another flight opportunity.

## **References**

1. G. Barry Hillard and Dale C. Ferguson: "The SAMPIE Flight Experiment Final Technical Requirements Document", NASA TM 106224, June 1993.



**Fig. 1 SAMPLE Payload**

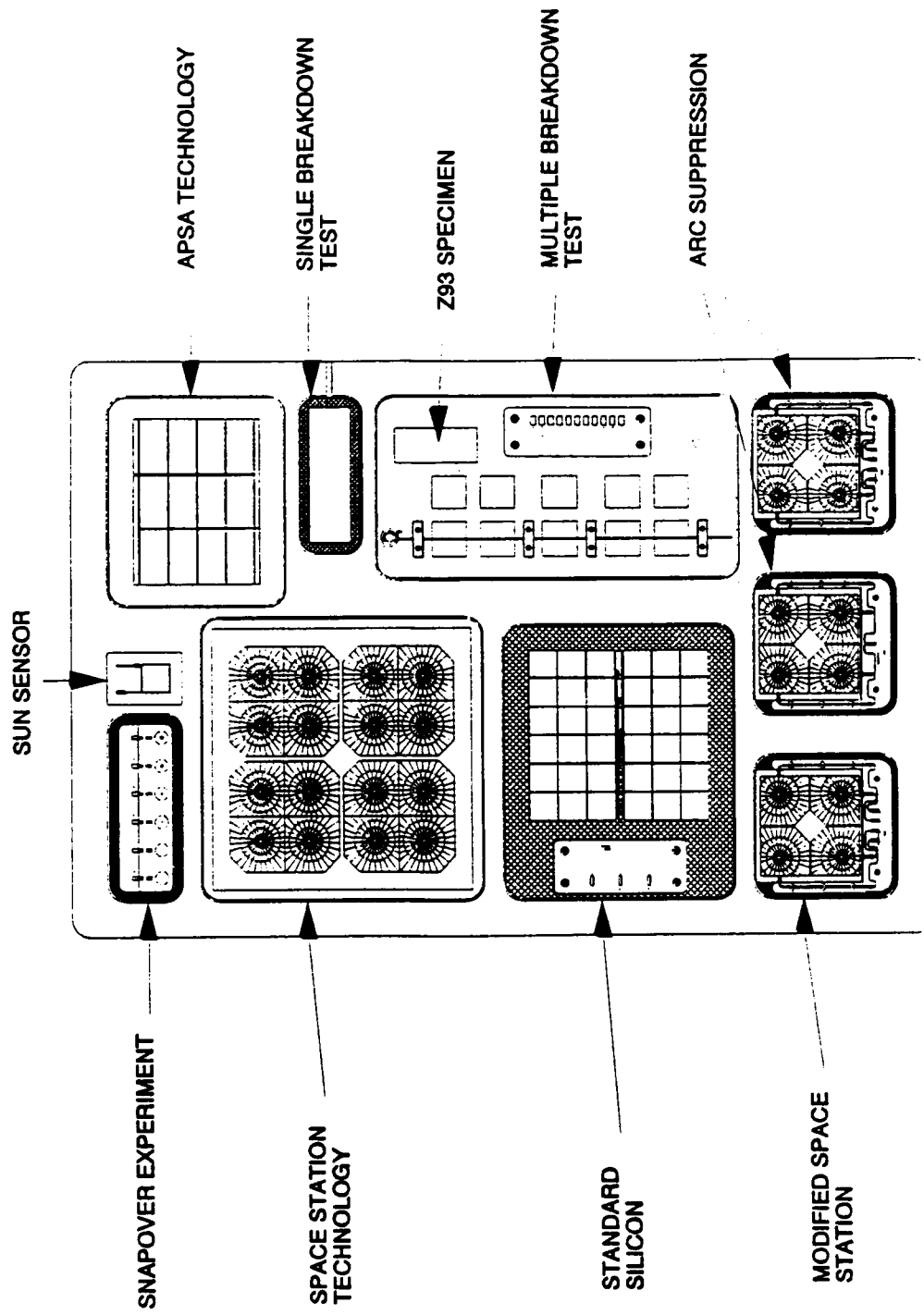
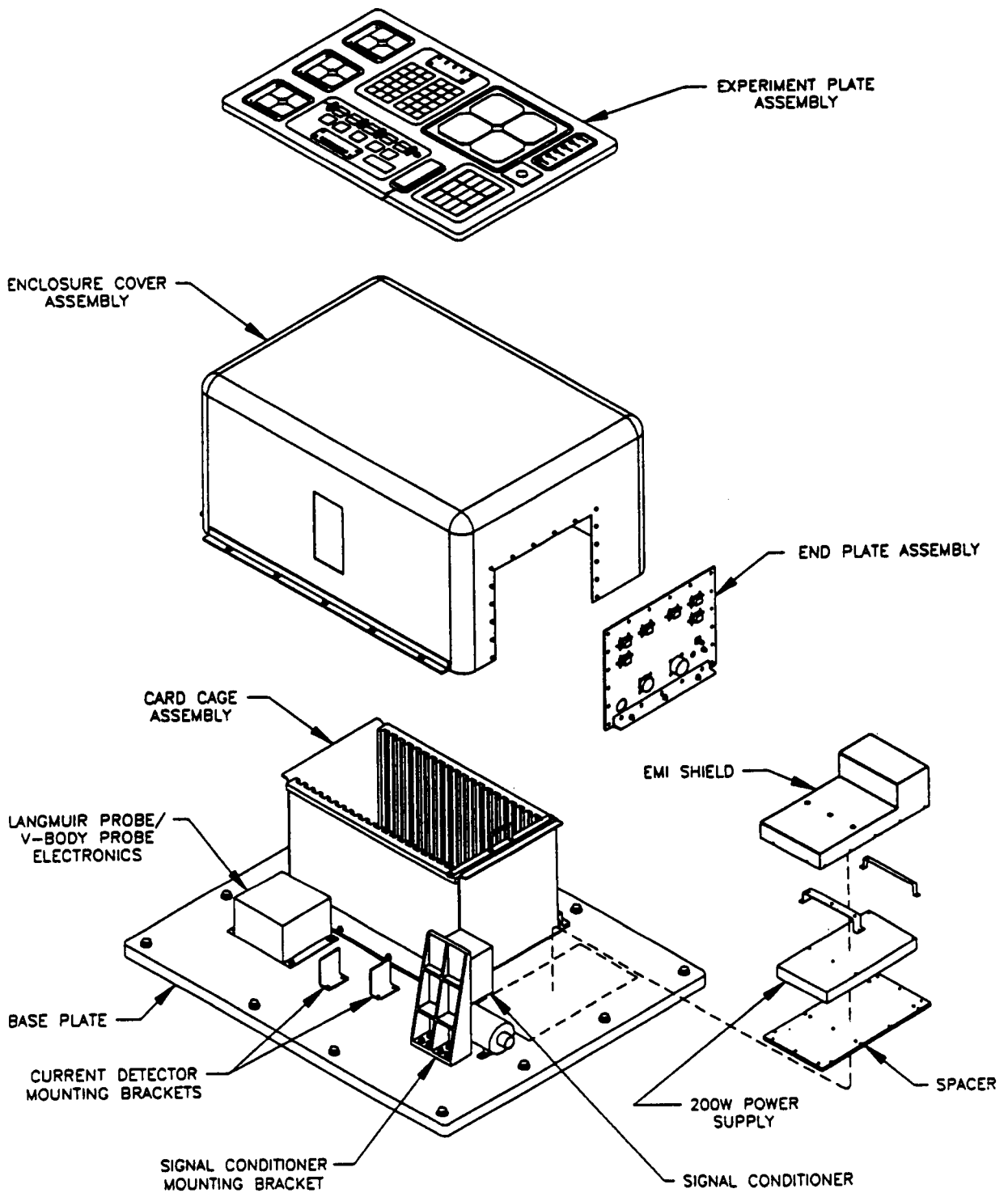
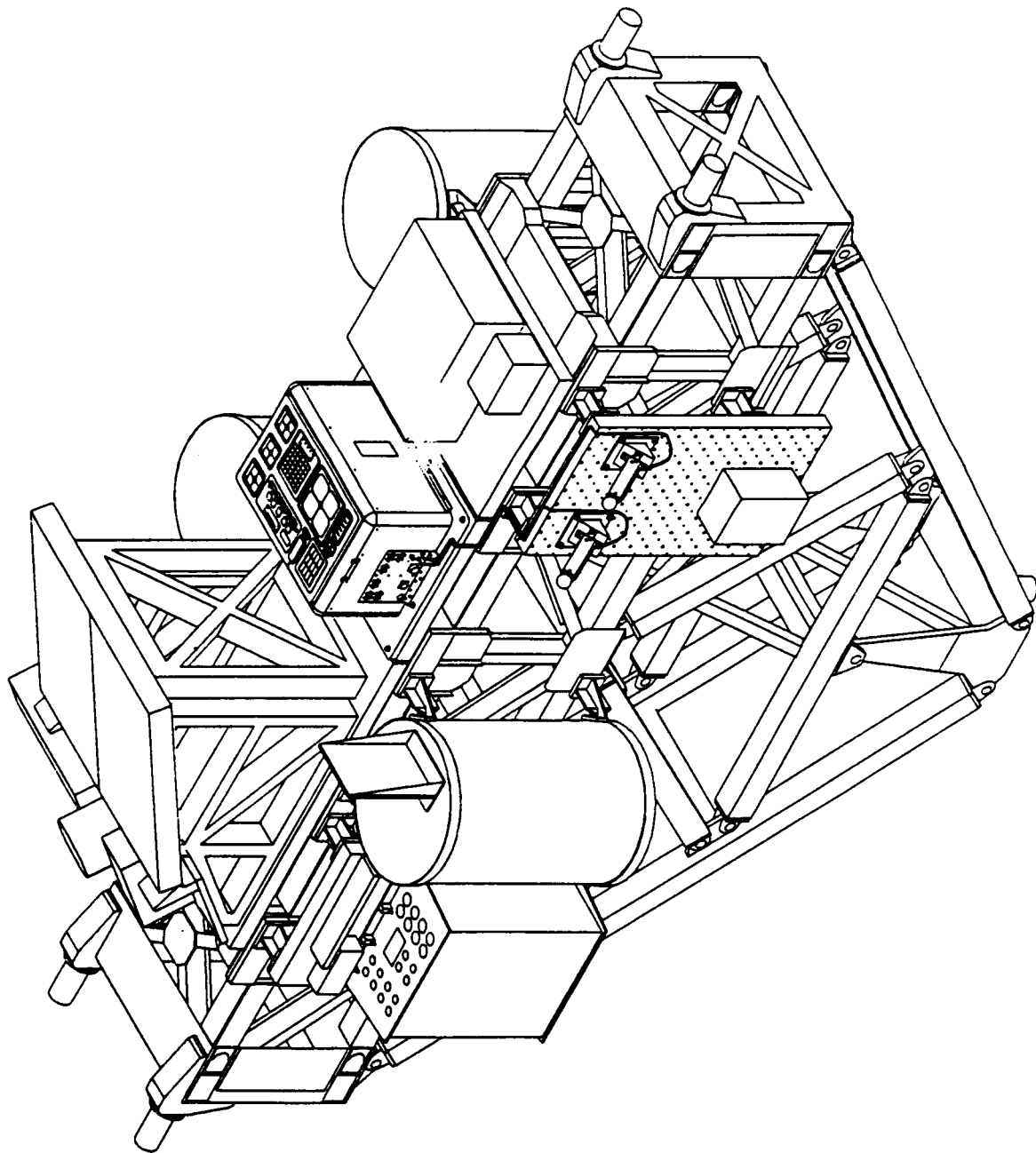


Fig. 2 SAMPIE Experiment Plate



**Fig. 3 SAMPIE Payload (Exploded View)**



**Fig. 4 SAMPIE Mounted on the Hitchhiker-M Carrier (OAST-2)**