# Design and Development of High Voltage Direct Current (DC) Sources for the Solar Array Module Plasma Interaction Experiment

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## ABSTRACT

Two programmable, high voltage DC power supplies were developed as part of the flight electronics for the Solar Array Module Plasma Interaction Experiment (SAMPIE). SAMPIE's primary objectives were to study and characterize the high voltage arcing and parasitic current losses of various solar cells and metal samples within the space plasma of low earth orbit (LEO). High voltage arcing can cause large discontinuous changes in spacecraft potential which lead to damage of the power system materials and significant Electromagnetic Interference (EMI). Parasitic currents cause a change in floating potential which lead to reduced power efficiency.

These primary SAMPIE objectives were accomplished by applying artificial biases across test samples over a voltage range from -600 VDC to +300 VDC. This paper chronicles the design, final development, and test of the two programmable high voltage sources for SAMPIE. The technical challenges to the design for these power supplies included vacuum, space plasma effects, thermal protection, Shuttle vibrations and accelerations.

## INTRODUCTION

The Solar Array Module Plasma Interaction Experiment (SAMPIE) was a flight experiment that flew on the Space Shuttle Columbia (STS-62) in March 1994, as part of the OAST-2 mission. SAMPIE and OAST-2 were sponsored by the Office of Space Access and Technology (OSAT) as part of the In-Space Technology Experiments Program (IN-STEP). The SAMPIE conceptual development, hardware design, and system verification for Shuttle flight were accomplished at the Lewis Research Center (LeRC) in Cleveland, Ohio, with support from NYMA engineers. The technology requirements and experiment definition were developed by Principal Investigator (PI), Dr. Dale Ferguson, and the Project Scientist (PS), Dr. G. Barry Hillard, of the LeRC Space Power Technology Division. The experiment required two high voltage power supplies which were developed by American High Voltage (AHV), to meet SAMPIE performance specifications.

The two programmable, high voltage DC power supplies provide voltages from -600 VDC to +300 VDC with respect to Shuttle ground. These biases were applied to experiment samples, such as solar cells and metal/insulator materials. High Voltage Power Supply #1 (HVPS #1) was a complex and unique design that could bias test samples from -600 VDC to +300 VDC. In addition, HVPS #1 provided electrical isolation, output overcurrent protection, and isolated logic voltages to the precision current measurement circuitry on the SAMPIE Electrometer Board. High Voltage Power Supply #2 (HVPS #2) was a 0 to -500 VDC programmable voltage source that was a commercial off-the-shelf (COTS) item.

SAMPIE Technology Background

A detailed description of the experiment may be found in Ref. 1 and will not be discussed in this paper, but a general overview of the hardware and science may be helpful to understand the function of the two high voltage power supplies. The main objective of SAMPIE was to collect data to quantify and investigate high voltage interactions on solar cells and power system materials. The results will be vital to the design and construction of future high voltage space power systems. Flying SAMPIE in space was needed in order to subject the various components to the space plasma environment and thereby to understand the space plasma interaction effects as a function of spacecraft orientation in the ram and wake. The ram orientation is achieved when the Shuttle velocity vector is coincident with the line normal to and out of the shuttle payload bay. The wake orientation is 180 degrees away from ram. The flight results will also validate analytical codes used for spacecraft charging analysis and prediction.

SAMPIE Hardware Overview

SAMPIE consisted of an aluminum box that contained the Main Electrical Unit (MEU) with an experiment plate fixed on the top surface. Solar cell and material samples were mounted on the outside of the experiment plate, as shown in Fig. 1. The MEU was mounted to a 2.54 cm thick aluminum base plate for structural support and thermal capacitance. Inside the aluminum box and bolted to the base plate was a card cage that contained printed circuit boards and instrument boxes. To measure the plasma environment, SAMPIE had a Langmuir probe to monitor plasma density and temperature and a V-body probe to monitor Orbiter potential with respect to the ionosphere.

A simple description of the experiment is that each test sample is biased to a series of voltages ranging from +300 VDC to - 600 VDC. Some electrical functions are as follows:

0 When samples are negatively biased, the circuitry will detect and measure the sample arc rates as a function of bias voltage.

0 For both negative and positive bias voltages, plasma current collection versus bias voltage measurements are made. Current collection from the samples is measured by the Electrometer Board with a sensitivity of +/- 1 nA.

0 One relay board is located between each high voltage power supply output and the test samples. Relay Board #1 is connected to HVPS #1 and contains eighteen reed relays with high isolation resistance and low contact resistance. These characteristics are vital so that the

Electrometer Board can measure currents down to the nanoamp level. Relay Board #2 is connected to HVPS #2 and contains fourteen reed relays.

The Data Acquisition System (DAS) controls the sequence of sample selection, voltage selection, data collection and storage, and uplink/downlink communications.

High Voltage Power Supply #1

A custom high voltage power supply made by American High Voltage provided a programmable bias voltage to one sample set. Controlled by the DAS, the HVPS #1 generated an output voltage that varied from -600 VDC to +300 VDC. In addition to the programmable bias voltage, the supply features included:

1) Electrical isolation between high voltage output and experiment ground.

2) Output overcurrent protection, whereby the supply shuts down if output current exceeds 50 mA.

3) Switching frequency of 50 kHz, common with the other switching power supplies used in SAMPIE. A common frequency was used to minimize EMI.

4) Electrical isolation of the +5 VDC and the +\-15 VDC logic power supplies provided to the Electrometer Board.

HVPS #1 is mounted on a circuit card (Fig. 2) that includes the Electrometer Board and other housekeeping electronics. The critical areas for space flight development will be described in the next section.

High Voltage Power Supply #2

High Voltage Power Supply #2 provided programmable voltages to a second set of samples connected to a second relay board. For the experiment, the output voltage varied from 0 to -500 VDC and was also controlled by the DAS. HVPS #2 was made by American High Voltage (AHV), the same company that made the custom HVPS #1. One major difference in the two supplies is that HVPS #1 was a unique design, specifically made for SAMPIE and HVPS #2 was a COTS item, space-qualified by LeRC for this application. HVPS #2 was also mounted on a circuit card as shown in Fig. 3.

Development For Space-Flight Environment

Thermal Control for HVPS #1

Since HVPS #1 was required to operate in a vacuum, convection heat transfer could not be accomplished and conduction was the primary heat transfer mechanism. Complicating this issue is the fact that electrical insulation must be maintained, thus preventing the metal to metal contact which is ideal for conductive heat transfer. Therefore, thermal issues for components were resolved with a combination of solutions. Heat sinks were attached to high power components and the heat sinks were attached to the power supply case. Thermal conduction, without electrical conduction, was achieved by using a material called Co-therm, applied between the heat sinks and case. Co-therm is an electrical insulation material that has good thermal transfer characteristics. Active components, such as the Field Effect Transistors (FETs), were attached to the power supply case, and the case acted as a heat sink.

HVPS #1 was potted to provide resistance to vibration and to maintain an acceptable thermal profile during operation. Potting the units with the standard material used by AHV was not adequate for the thermal profile of HVPS #1, because the material had a low thermal conductivity. SAMPIE engineering personnel found a material from Nusil (CV2946), which had a higher thermal conductivity, for use in HVPS #1.

To evaluate the effectiveness of these thermal design accommodations, a test unit was constructed with thermocouples attached to several critical areas in the unit. The unit was subjected to 8 hours of high voltage, full load operation in a vacuum chamber. Temperatures stayed within their specified limits during the test.

To provide a thermal path from the power supplies to the SAMPIE base plate the supplies were mounted on printed circuit cards (PC) which used thermal planes, also known as heat ladders (see Fig. 2 & 3). Between each power supply case and the thermal plane, 30 mil silver foil was used to enhance the thermal conductivity. Other foils were considered but were not chosen because of their expense. On the PC card edges, wedge-lock card guides were used to conduct the heat from the thermal plane to the aluminum card cage. The card cage was bolted to the base plate; the base plate provided the thermal mass needed for conducting the heat from the electronics. One risk with thermal planes in a vacuum environment is the possibility of high voltage arcing or dielectric breakdown; therefore, conformal coating was applied after the power supplies were mounted to their respective PC cards.

The use of potting material and conformal coating is a trade-off. The benefits for space use are thermal conductivity for improved thermal control, structural stability for improved vibration resilience and electrical isolation for improved control with high voltage applications in a vacuum. The disadvantages for space use are additional weight, cost and the difficulty with component re-work, if necessary.

HVPS #1 Transformer Integration/Packaging

Transformer encapsulation is necessary to withstand the vibration and maintain an acceptable thermal profile during operation. Five transformers are used in HVPS #1. The standard encapsulation techniques used by AHV were inadequate for HVPS #1 because of packaging constraints. AHV used several hybrid techniques to encapsulate the transformers to provide the required structural stability to meet vibration and thermal requirements. The major concern with the transformer packaging was that the wires used in the transformers not break from stress due to vibration and/or thermal mismatch at the wire connection points. Thermal shrink tubing over the wire at the interface between the hybrid encapsulation and the wire was used to relieve the stress at that point.

HVPS #1 EMI Control

For Shuttle experiments, electromagnetic interference (EMI) is always a concern, especially radiated emissions from high frequency power components. Standard practices were used to decrease the radiated emissions from the two power supplies. For HVPS #1, input filters were used and a "snubber-resistor" was placed across a switching circuit to absorb power spikes as FETs switched at 50 kHz. Preliminary EMI testing at Lewis Research Center showed that the power supply operated within the limits that were necessary for shuttle applications. At the Goddard Space Flight Center (GSFC), the SAMPIE payload was tested for EMI compliance to the General Environmental Verification Specification (GEVS) document for STS payloads. Among the suite of tests performed by the GSFC personnel were the narrow band conducted emissions tests (CE01/CE03), from 30 hz to 50 MHz, broadband conducted emissions (CE03), from 20 kHz to 50 MHz, and the radiated emissions tests (RE02 and RE04), from 30 hz up to 18 GHz. SAMPIE passed these tests with no problems or necessary re-work.

FLIGHT OPERATIONS

SAMPIE's primary mission objectives were to collect arcing measurements as a function of negative voltages and current measurements as a function of both positive and negative voltages. The SAMPIE measurements were taken on test samples that were identified by the PI and PS to support Space Station and other future high voltage power systems for space applications. In addition, one set of measurements were needed in the bay-to-ram orientation, the worst-case condition for plasma effects, and another set was planned for the bay-to-wake orientation. The essential engineering data was not the entire planned mission timeline, but a subset which contained current collection and arcing measurements on all samples in a bay-to-ram orientation, with voltage ranges of particular interest for space applications. Therefore, the minimum success criteria for SAMPIE was defined as this essential engineering data and these experiments were performed at the start of the planned mission timeline.

Both high voltage power supplies operated as designed throughout the entire flight, with SAMPIE collecting the data needed to meet its minimum success criteria and collecting nearly all of its planned flight data. All SAMPIE mission objectives, in both orientations, were met except for approximately 10% of the high voltage timeline (voltages ranging from -400 VDC to -600 VDC) in the bay-to-ram orientation. Therefore, data in the bay-to-ram orientation that was collected included all current and arcing measurements on all samples with bias voltages ranging from -300 VDC to +300 VDC. During the bay-to-ram orientation and high voltage arcing at -600 VDC, a voltage breakdown occurred between the case of a component on the Electrometer Board and the thermal plane on the Electrometer Board. This resulted in an overcurrent condition seen by HVPS #1, which caused HVPS #1's high voltage output to shut down. The breakdown on the Electrometer Board caused a component to fail, which precluded any further collection current measurements.

HVPS #2 operated as designed throughout SAMPIE's entire flight. In addition, HVPS #2 continued to operate after HVPS #1 shut down due to an overcurrent condition. Therefore, all test samples that were connected to HVPS #2 were not affected by the anomaly and SAMPIE continued to collect useful arcing measurements, with bias voltage ranging from 0 VDC to -500 VDC.

RECOMMENDATIONS

The high voltage power supplies were a challenge for space flight development and most engineering efforts were spent on thermal, high voltage and packaging developments. The following high voltage engineering recommendations, based on our SAMPIE experience, are listed as follows:

1. Conformal coating and potting material must be applied following manufacturer's procedures to preclude the formation of any voids or bubbles in the material, especially for high voltage operations. These voids may be the site of partial outgassing, which, due to Paschen's Breakdown Effects, may allow inadvertent arcing to occur in a circuit. These recommended procedures usually include the following:

a) Cleaning the surface of circuit boards and parts prior to application of the coating.

b) Heating the circuit boards and components for a period of time to drive off any surface moisture.

c) Degassing the coating material in a vacuum bell jar prior to its application. After the application curing the coated boards/components in a vacuum, if possible at elevated temperatures.

2. Thermal planes on circuit cards are highly effective for thermal conduction on components which are located on the cards. Heat is conducted to the sides of the circuit cards, where wedge-lock card guides (illustrated in Figs. 2 and 3) are mounted to ensure good thermal contact to the card cage.

3. Conformal coating and potting materials provide enhanced thermal conduction, but choose a material that can easily be removed in case of the need for rework.

4. Before operating high voltages in a vacuum, the electronic unit should be given time to outgas by sitting for a predetermined time in the vacuum environment. The outgassing time is dependent on the package volume, temperature, moisture content, and mean free path length for any trapped gas molecules.

**REFERENCES**

1. Lawrence Wald and Dr. G. Barry Hillard: "The Solar Array Module Plasma Interaction Experiment". Presented at the 26th IECEC Conference, in Boston, Massachusetts, August, 1991.

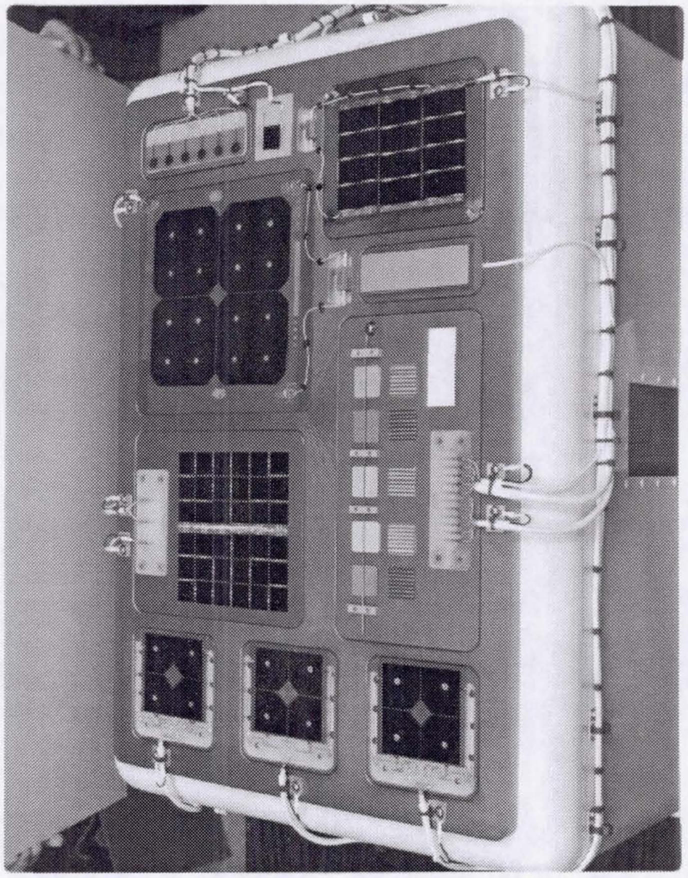

Figure 1.—SAMPIE experiment samples.

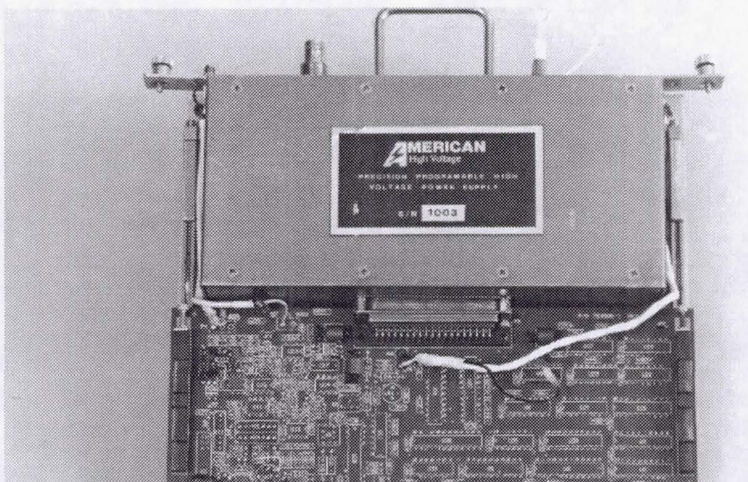


Figure 2.—High voltage power supply No. 1.

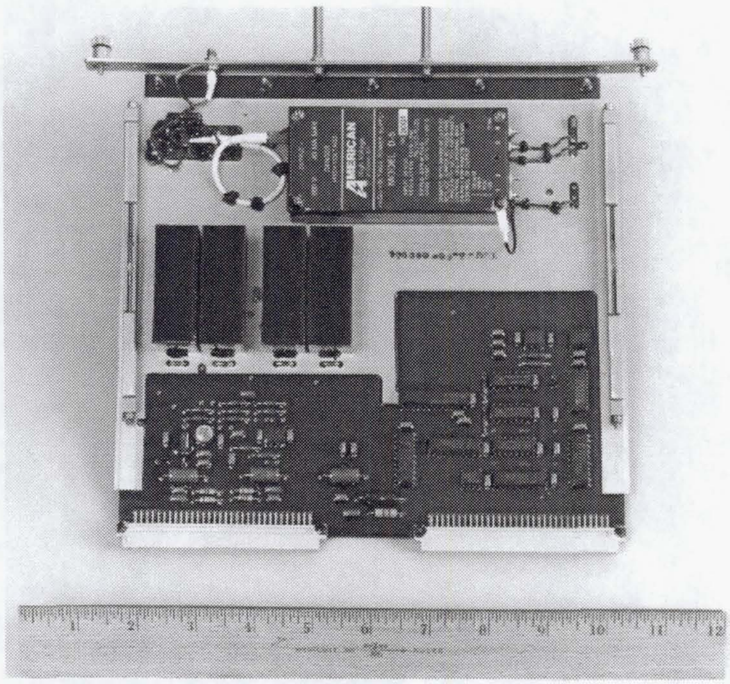

Figure 3.—High voltage power supply No. 2.