DESIGN, QUALIFICATION, AND ON-ORBIT PERFORMANCE OF THE
ATLAS PLASMA CONTACTOR*

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ABSTRACT

In this paper, we describe the Plasma Contactor Neutralizer System that was part of the ATLAS-1 (Atmospheric Laboratory for Applications and Science) experiment conducted on the Shuttle Atlantis during March of 1992. ATLAS-1 included a reflight of the SEPAC (Space Experiments with Particle Accelerators) experiment that was flown in 1983 on Spacelab 1. SEPAC uses a 1.6-A, 7.5-kV electron-beam accelerator (EBA) firing from the Shuttle bay to study a variety of phenomena related to vehicle charging and charge neutralization, atmospheric interactions, and virtual-antenna operation. The ATLAS Plasma Contactor Neutralizer System consists of a 25-cm-diam xenon plasma source, a xenon neutral-gas source, a xenon storage and control unit, and a power processor. In ground testing, the plasma source provided 1.5 A of xenon ion current with an input power of about 210 W and a xenon gas flow of about 2.2 standard liters/h. The neutral-gas source was designed to release about $10^{23}$ atoms of xenon in 100-ms pulses. During the week-long mission of STS-45, the ATLAS Plasma Contactor Neutralizer System was restarted for 27 experiments involving SEPAC and operated flawlessly for a total of 7.3 h. Performance of the plasma source was inferred from electrical data to be the same as that documented during pre-flight ground testing.

NOMENCLATURE

\[
\begin{align*}
J_i & = \text{ion emission current, A} \\
J_{ck} & = \text{cathode keeper current, A} \\
J_D & = \text{anode current, A}
\end{align*}
\]

\[
V_{ck} = \text{cathode keeper voltage, V} \\
V_D = \text{anode (discharge) voltage, V} \\
J_{EBA} = \text{EBA current, A} \\
V_{EBA} = \text{EBA voltage, V}
\]

INTRODUCTION

The first flight of the Atmospheric Laboratory for Applications and Science (ATLAS-1) was conducted in March of 1992. The ATLAS-1 experiment package included a reflight of the Space Experiments with Particle Accelerators (SEPAC) experiment that was flown in 1983 on Spacelab 1. SEPAC involved the firing of an electron-beam accelerator (EBA) from the Shuttle bay to investigate a variety of phenomena related to vehicle charging and charge neutralization, atmospheric interactions, and virtual-antenna operation. The EBA can provide electron currents up to 1.6 A at energies up to about 7.5 kV.

Experience with firing an energetic electron beam (E-beam) from the Shuttle during the earlier flight of SEPAC confirmed that the Orbiter's electrical potential could be maintained near that of the ambient space plasma during 1-ms firings of an onboard magnetoplasmadynamic (MPD) thruster. When the SEPAC electron gun was operated without the MPD thruster to provide a source of argon plasma, the Orbiter charged to the EBA potential (as high as 5 kV), and return currents provided by the ambient space plasma caused the entire payload bay to glow as a result of atomic excitation produced by high-energy electron bombardment.

The MPD plasma plume was very successful in achieving short-term stabilization of the Orbiter's potential during the EBA firings on Spacelab 1. However, the inability of the MPD thruster to operate continuously or in long pulses prevented steady-state or long-pulse operation of the EBA without the Orbiter charging up. This limitation was overcome in the ATLAS-1 experiments with SEPAC by replacing the MPD thruster with a plasma contactor to provide a continuous source of neutralizing plasma during the EBA firings. This paper describes the Plasma Contactor Neutralizer System that stabilized the Orbiter's potential during the ATLAS-1 flight of SEPAC. This system maintained the Orbiter's potential near that of the surrounding space plasma during
EBA firings through a combination of ion emission from the xenon plasma source and electron collection from the ambient space plasma; Fig. 1 illustrates the envisioned current flow. As a result of stabilizing the Orbiter's potential, the full energy of the EBA was realized for the first time, enabling an unprecedented science return by SEPAC.¹

![Fig. 1. Current flow during the firing of an electron-beam accelerator from the Orbiter.](image)

**PLASMA CONTACTOR SYSTEM**

Figure 2 presents a photograph of the plasma contac- tor neutralizer system, which consists of a 25-cm-diam plasma source, a neutral-gas source, a xenon storage and control unit, and a power processor. The plasma source is capable of producing steady-state xenon ion currents of up to about 2.5 A, while the neutral-gas source can release up to \(10^{23}\) atoms (22 g) of xenon gas during 100-ms openings of a fast-acting solenoid valve. (The neutral-gas system, which is intended to support a study of critical-ionization phenomena, is logically unrelated to the plasma-contactor function but is physically combined with it because of the commonality of gas-feed components.) The power processor operates under the command of the SEPAC computer to provide conditioned inputs to the plasma and neutral-gas sources. Details of the various components of the system are presented in the remainder of this section.

**Plasma Source**

The plasma source is derived from the 25-cm-diam ion thruster that is part of the Xenon Ion Propulsion Subsystem (XIPS) that Hughes has developed for satellite stationkeeping.²-⁷ Figure 3 is a schematic of the XIPS thruster after having been reconfigured for use as a plasma contactor by removing its ion-extraction electrodes and its ion-beam-neutralizer assembly.

![Fig. 2. Photograph of the Plasma Contactor Neutralizer System for ATLAS.](image)

![Fig. 3. Schematic of XIPS thruster reconfigured as a plasma contactor.](image)
Xenon plasma is generated in the 25-cm-diam ring-cusp source by electron bombardment in a Penning discharge driven by electrons emitted by a thermionic hollow cathode. The cathode is heated by a coaxial heater for startup, and then operates in a low-power (≤55 W) "IDLE" mode after a discharge is established between the cathode and its keeper electrode. In the "ON" mode of operation, sufficient current is conducted between the anode and cathode to ionize about 10% of the xenon provided to the plasma source.

Because of the Bohm-presheath effect, the ions escape much faster than the gas atoms, and the fluxes of these particles exiting the plasma source are approximately equal. Although a small amount of xenon is introduced through the cathode, the bulk of the xenon flow is through the plenum, which serves to distribute the gas in a uniform manner. Electrical isolators in the xenon feed lines permit the ion emission from the plasma source to be measured by connecting its cathode to Orbiter ground through an ammeter.

Under typical steady-state operating conditions, a xenon gas flow equivalent to an ion current of about 2.5 A is introduced into the plasma source, and about 4.5 A of electron current is provided by the hollow cathode. For these conditions, the ion-production rate is sufficiently high to enable ion currents of 1.5 A to be driven out of the plasma source by the approximately 30-V difference between the anode (plasma) and cathode (spacecraft) potential. A photograph of the flight plasma source is presented as Fig. 4.

**Power Processor**

A block diagram of the power processor is presented in Fig. 5. The unit operates from the 28±4 V SEPAC power bus and contains the power and signal electronics necessary for operating the plasma and neutral-gas sources, controlling the feed-system valves, and conditioning the analog-telemetry signals. The housekeeping inverter is a pulsewidth-modulated design that provides ±12-Vdc regulated power. The anode, keeper, and heater supplies produce current-regulated outputs by pulsewidth modulation. The anode supply is a push-pull design, while the keeper and heater are flyback designs. The keeper supply produces an open-circuit voltage of 300 V for igniting the keeper discharge, whereupon it goes into current regulation at its design operating point.

**Xenon Storage and Control Unit**

A schematic of the xenon-storage and control unit is presented in Fig. 6. Approximately 2700 standard liters of xenon are stored as a high-pressure gas at an initial on-orbit pressure of about 6.9 MPa (1000 psia) at 20°C. The flow of gas into the plasma source is controlled by the regulated pressure of 68.9 kPa (10 psia) on the upstream side of commercial flow restrictors. The flow restrictors are located in the gas manifold, which distributes the flow to the hollow cathode and plenum chamber of the plasma source.

A normally closed squib valve isolates the xenon from the rest of the system until after launch. Once on orbit, the squib is fired using one of its dual initiators. A 2-μm filter is located downstream of the squib valve to protect the remainder of the system from contaminant particles. ON/OFF control of the xenon gas flow into the plasma source is achieved using a solenoid valve. Parallel arrangements of vent valves prevent over-pressurizing the plasma source and neutral-gas source in case of an unlikely failure of the 1.6 MPa (245-psia) pressure regulator.

**Neutral Gas Source**

Operation of the neutral-gas source consists of opening the solenoid valve between the xenon-storage tank and the neutral-gas plenum, allowing the plenum to fill to the output of the high-pressure regulator (1.6 MPa or
PLASMA SOURCE PERFORMANCE

Performance testing of a flight and laboratory model plasma source established the steady-state and transient performance characteristics described in the remainder of this section.

Steady-State Performance

Following an initial on-orbit activation of its hollow cathode, the plasma source operates in one of two modes. In the IDLE mode, the cathode heater and the cathode-keeper discharge operate, consuming about 55 W of power. In the ON mode, the cathode-anode discharge operates (in addition to the heater and keeper) at one of three current setpoints selected by the SEPAC computer.

Figure 7 presents the performance characteristics of the flight plasma source with the cathode biased 50 V positive of the vacuum-chamber ground (enabling the saturated ion-emission current to be measured). The power is the total consumed by the heater, keeper, and the anode discharges. With about 210 W of input power, the plasma source produces 1.5 A of ion-emission current with a xenon flow rate of about 2.2 standard liters/h.

This gives a gas-utilization efficiency of about 60%, consistent with the high level of performance characteristic of the XIPS ion thruster.

Transient Performance

During the SEPAC experiments the plasma source operates in the IDLE mode, responding quickly to commands from the SEPAC computer to place it in the ON mode (at one of three discharge-current setpoints) during 1-s firings of the EBA. Figure 8 presents a time history of the currents and voltages of a laboratory-model plasma source in response to the ON command to the setpoint corresponding to a discharge current of 6 A. The plasma source is shown initially to be operating in the IDLE mode, consuming about 55 W of power. The ON command increases the anode open-circuit voltage to 75 V, and within 8 ms the plasma source is emitting 1.5 A of xenon ion current. Similar transient-performance characteristics were documented for the flight-model plasma source.

SYSTEM QUALIFICATION TESTS

The complete Plasma Contactor Neutralizer System was subjected to vibration and thermal-vacuum testing in accordance with the requirements for Shuttle flight experiments. These tests are described in the remainder of this section.

Thermal Vacuum

Thermal-vacuum tests of the flight system were performed at the conditions indicated in Table 1. The plasma source was operated once every three hours during the cold- and hot-soak tests to verify its ability to provide an ion-emission current of 1.5 A ±0.15 A. These tests demonstrated the ability of the plasma source to provide the required ion-emission current at ambient temperature
Table 1. Thermal-Vacuum Test Conditions.

<table>
<thead>
<tr>
<th>Soak Condition</th>
<th>Temperature (°C)</th>
<th>Ion-Current Tests</th>
<th>Interval (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>40</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Cold</td>
<td>0</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

and at the hot- and cold-soak temperature extremes. In these system-performance tests, the flight unit provided a xenon ion current of 1.5 A with a total input (bus) power of about 337 W.

**Vibration**

The flight Plasma Contactor Neutralizer System was subjected to a sinusoidal resonance survey (frequency of 5 to 2000 Hz and peak amplitude of 0.5 g) as part of its verification testing. In addition, a random vibration test was conducted for each of three orthogonal axes. The random vibration test conditions are indicated in Fig. 9. Both the resonance survey and random vibration tests were passed without incident.

**ON-ORBIT PERFORMANCE**

The Shuttle Atlantis was launched on March 24, 1992 (STS-45), carrying the ATLAS-1 experiment package shown in Figs. 10 and 11. The Plasma Contactor Neutralizer System operated without incident over a period of a week until it eventually used up its supply of xenon. Following an initial on-orbit thermal conditioning to activate its hollow-cathode insert, the plasma source of the Plasma Contactor Neutralizer System was started and operated on 27 separate occasions, accumulating a total operational time of 7.3 h. On-orbit performance was essentially identical to that observed in ground testing. Both the cathode keeper and anode currents and voltages were observed to be very stable.

Figure 12 presents typical flight data, showing the response of the plasma source due to 1-s firings of the EBA. At the highest EBA current of 850 mA, the ion-emission current from the plasma source is about 650 mA. The 200-mA difference is believed to be electron current collected by the exposed conducting surfaces of the Orbiter. We have no way of distinguishing just how much of the 650-mA current was ion flow from the plasma contactor and how much was electron current collected from the ambient plasma.
current with a total input power of about 337 W, and with a gas-utilization efficiency of about 60%. The flight-model Plasma Contactor Neutralizer System passed the performance, vibration, and thermal-vacuum tests required for Shuttle flight experiments, and the system was delivered to Kennedy Space Center for integration with the ATLAS-1 payload.

The ATLAS-1 was launched on the Orbiter Atlantis on March 24, 1992. The Plasma Contactor Neutralizer System operated flawlessly until its xenon supply was depleted approximately one week later. During this time, the plasma source was started on 27 separate occasions and accumulated 7.3 h of operation.

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REFERENCES


