OPERATION OF A BRASSBOARD PCU WITH A LOW POWER ARCJET

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ABSTRACT

Characterization testing of a brassboard PCU was conducted using a 1 kW arcjet to examine PCU/engine behavior and validate the overall PCU architecture. The PCU was characterized by a switching frequency of 33 kHz and can operate in either constant power or constant current mode. The MOD-B arcjet was used for the tests and had a constrictor with a diameter of 1.02 mm and a length of 0.59 mm while the electrode gap was set at 0.4 mm. A gas mixture used to simulate hydrazine was fed to the engine at mass flow rates of 50 and 60 mg/s while the thruster was supplied by the PCU with currents between 8 and 14 A. The PCU was able to start and run the arcjet in all cases and showed the generally expected behavior.

NOMENCLATURE

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
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<td>Beginning-of-Life</td>
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<tr>
<td>BPD</td>
<td>BPD Difesa e Spazio (Company)</td>
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<tr>
<td>DAS</td>
<td>Data Acquisition System</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>IPA</td>
<td>Isopropyl Alcohol</td>
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<td>LVDT</td>
<td>Linear Voltage Displacement Transducer</td>
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<td>MOD-B</td>
<td>Low Power Arcjet Used For Testing Described in This Paper</td>
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<tr>
<td>MOS</td>
<td>Metal Oxide Semiconductor</td>
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<tr>
<td>PCU</td>
<td>Power Conditioning Unit</td>
</tr>
<tr>
<td>PFS</td>
<td>Propellant Feed System</td>
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<tr>
<td>PWM</td>
<td>Pulsed-Width Modulated</td>
</tr>
<tr>
<td>SEPA</td>
<td>FIAT CIEI Divisione SEPA</td>
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<tr>
<td>SPT</td>
<td>Stationary Plasma Thruster</td>
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<tr>
<td>SSPA</td>
<td>Studio di Sistema Propulsione ad Arcetto</td>
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<tr>
<td>S1</td>
<td>Start-Up Unit Capacitor Charging Switch</td>
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<td>S2</td>
<td>Start-Up Unit Start Switch</td>
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<td>S3</td>
<td>Start-Up Unit Diode/Inductor By Pass Switch</td>
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<td>Molybdenum Alloy</td>
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<tr>
<td>VP-2</td>
<td>Vacuum Facility No. 2 at BPD</td>
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<td>2%ThW</td>
<td>2% Thoriated Tungsten Metal</td>
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INTRODUCTION

Several electric propulsion subsystem technologies are presently under development in Europe for orbit maintenance of geostationary satellites; arcjets, ion engines and SPT thrusters. Low power arcjets (1 kW-class) can offer substantial propellant mass savings with respect to currently used chemical propulsion systems due to their higher specific impulse. Arcjet systems also have a lower dry mass and are less complex than ion engine and SPT systems while, based on specific impulse considerations alone, ion engine and SPT systems typically provide a larger propellant mass reduction. Arcjet thrusters also minimize spacecraft integration difficulties with monopropellant or bipropellant chemical systems which include hydrazine while ion engine and SPT systems require a separate propellant feed system. Arcjets also have a much smaller beam divergence angle than either ion or SPT engines easing satellite integration geometric constraints. In addition, SPT thrusters suffer from significantly higher material erosion rates than arcjets (or ion engines). In fact, insulator material is eroded from SPT engines which, if deposited on the communication satellites antennas, could significantly inhibit communication systems effectiveness. Therefore, electric propulsion systems based on arcjet thrusters are of particular interest and are presently being developed world-wide with laboratory and advanced development work on arcjet technology is ongoing in Italy, Germany, Japan, and the USA with system qualification complete in the USA.

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+ Member of the Technical Staff.
In a flight configuration, each arcjet satellite propulsion subsystem will include an arcjet assembly, power conditioning unit and interconnecting power cable. The PCU is required to start-up and operate the arcjet once a flow of propellant has been established. The PCU will generally require feedback control since the arc exhibits a non-linear, negative resistance load. Therefore the PCU is generally composed of a high voltage start-up unit, a power converter, input and output filters, a feedback control system and internal diagnostics. Much development work has occurred on arcjet PCUs and is based on PWM, DC-DC converter topologies with switching frequencies in the range of 15 - 20 kHz. Recent work has shown that higher switching frequencies do not impact engine operation and therefore hold promise to reduce the mass of the PCU.

This paper describes initial low power arcjet/PCU characterization test activities conducted as part of an ASI-funded system study activity being conducted by BPD Difesa e Spazio (BPD) in support of low power arcjet system implementation in Europe. The overall systems study covers the definition of a Reference Mission; detailed arcjet propulsion subsystem specifications and requirements definition; and layout of the overall propulsion subsystem including design of its primary components along with identification of critical areas and delineation of a development plan to achieve subsystem ground qualification by the mid-nineties. The arcjet PCU development activity has been carried out as part of this system study contract by FIAT CIEI - Divisione SEPA (SEPA) in support of BPD and has also included the development of an arcjet electrical simulator and definition of diagnostics package options. Ansaldo Ricerche has supported SEPA by developing the PCU inverter unit. These activities were conducted to provide an appropriate background for definition of a flight-type PCU. The MOD-B low power arcjet was used for these tests. Following a description of the apparatus and facilities, the test procedures are reviewed. Then the results of MOD-B arcjet/brassboard PCU characterization testing are discussed. The PCU start-up transient and initial steady-state performance are presented along with the PCU response to changes in the load and commanded output current.

APPARATUS AND FACILITIES

The MOD-B arcjet design, brassboard PCU architecture and test facilities are reviewed below.

MOD-B ENGINE DESCRIPTION

PCU/Low power arcjet characterization testing was conducted using the MOD-B engine which is shown in Fig. 1. This engine was designed for low cost flexibility in engine geometry changes while trying to better mimic the thermal characteristics of flight-oriented engines than other laboratory model arcjets. The MOD-B configuration used for these tests included a 2% thoriated tungsten (2%ThW) nozzle insert with a 1.02 mm-diameter and 0.59 mm-long constriction. The conical nozzle had a 20° half-angle and an area ratio of 100. The propellant was tangentially injected into the plenum chamber through four, 0.5 mm diameter injectors with a semicircular cross-section. The injectors were milled into a molybdenum insert. The cathode was a 3 mm-diameter, 2%ThW rod with a 15 mm-long, 2 mm-diameter front section. The cathode ended with a conical tip which had an included angle of 60° and a tip radius of 0.3 mm. The cathode was inserted through the rear of the engine and held by a Swagelok connector. The electrode gap was set at 0.4 mm. To eliminate potential problems from the unequal thermal expansion of different materials within the engine, a stainless steel spacer ring was placed within the rear assembly nut to maintain the sealing pressure at the graphite gasket. The compression spring compensated for the different thermal expansions between the boron nitride insulator and the TZM outer engine body and insured continuous contact between the insulator, gas injection insert and anode piece. Hydrazine was injected near the rear of the engine to provide some regenerative cooling of the engine and pre-heating of the propellant.

BRASSBOARD PCU ARCHITECTURE

The Power Conditioning Unit is a special power supply designed to convert the satellite bus power (solar arrays or batteries) to a usable form to start the arc and to precisely control the electrical current or power supplied to the arcjet. The characteristic parameters are inferred from the preliminary specifications of the arcjet and are summarized in Table 1 while a block diagram of the unit is shown in Fig. 2. During testing, a Farnell DC power supply Model H 60/50 was used to supply power to the PCU simulating the satellite bus.

The PCU is shown schematically in Fig. and is composed of two main functional units: the Control Unit and Inverter Unit. The Control Unit controls PCU operation to force the Inverter Unit to deliver a constant current or a constant power to the
arc. Additional functions within the Control Unit for provide monitoring of the basic operational parameters (Signal Conditioning and Monitoring Block), safety override (Safety Block), start-up sequencing (Start-Up Block) and general supervision of the PCU operation (Supervisory Block). The controller unit provides both constant current control and constant power control.

The Inverter Unit is a PWM step-up power supply delivering constant current or constant power to the arcjet and also provides the start-up pulse to the arcjet. The inverter unit includes the PWM modulator, driver and MOS bridge, main transformer, rectifier, output filter/start-up circuitry and the DC/DC converter. The PWM block supplies the driving pulses to the MOS-bridge switches via the driver circuitry. The pulse width is proportional to the voltage of the control signal A1. The switching frequency is 33 kHz. The main transformer is used as a step-up element to provide the relatively high-voltage required to sustain the arc discharge. In addition, it provides electrical isolation between the power bus and the arc electrodes. Given the high switching frequency of the PWM controller, a ferrite core has been selected for the main transformer. The rectifier block rectifies the AC output current from the main transformer using a high-speed silicon half-bridge or full-bridge configuration depending on whether the main transformer has a center-tapped or normal secondary. The first solution is the most appealing because the power losses of the rectifiers are half of the other configuration but it requires a larger volume. The output filter and start-up circuitry block implements the output filter using only an inductor. The same inductor is used to provide the high voltage pulses to initiate the electrical discharge between the electrodes. The DC/DC converter is a resonant power supply and derives its power from the power bus (in this case the Farnell power supply). It provides three isolated outputs which are used to supply the MOS-drivers, the start-up circuitry and the logic circuitry.

FACILITIES AND INSTRUMENTATION

The MOD-B arcjet/PCU tests were performed in Facility VP-2 of BPD’s Electric Propulsion Laboratory. This facility is described in detail elsewhere and summarized below. The facility is based on a 1.6 m-long, 0.8 m-diameter steel vacuum chamber connected to a vacuum plant composed of a four-stage, Roots blower-based pumping group. The vacuum system provided a pumping speed of 19,000 m³/hr at an inlet pressure of 2 x 10⁻³ mbar. Bellows were used to damp vibrations through the connecting pipes. A capacitance manometer with an accuracy of ±0.15% of the reading was used to measure the vacuum chamber pressure.

Prior to arcjet operation using the brassboard PCU, the engine behavior was characterized using a laboratory power supply system. The laboratory power supply system, Fig. 4, was composed of a main power supply and a start up circuit connected in parallel. The start-up system was composed of a high voltage/flow current power supply unit, a 5 μF capacitor bank, a diode block and a 1.4 μH inductor. The matching of the electrical characteristic of the main power supply and the engine was accomplished by a 0 to 11 ohm ballast resistor in series with the thruster. The variable ballast resistor was also used to reduce the current spike during the capacitor bank discharge and to compensate for the main power supply ramp-up time. The inductor was connected to increase the capacitor bank discharge time and to cut current oscillations during the ignition transient. A by-pass switch was also installed to avoid diode and inductor overheating. Referring to Fig. 4, the capacitor bank was charged by closing switch S1 while switches S2 and S3 were open. Then, the arc was ignited by opening switch S1 and closing switch S2. As soon as the arc was stable, switch S3 was closed to by-pass the diodes and inductor. The start up and run voltages were measured by voltage probes with attenuation factors of 1000 and 100, respectively. The probes had an accuracy of ±3%. A calibrated shunt, in series with the anode current feedline, was used to measured the arcjet current. The current was measured with an accuracy of ±0.5%.

The propellant feed system (PFS) provided a controlled flow of a gas mixture simulating hydrazine (N₂ + 2H₂) to the arcjet. The nitrogen and hydrogen mass flow rates were controlled by dedicated thermal-type mass flow controllers with a listed accuracy of ±1% and then injected into a mixing manifold. Downstream of the mixing manifold, the total mass flow rate of the gas mixture was measured by a Coriolis force-type mass flow meter with an accuracy of ± 2%. Pressure transducers were placed at the mixing manifold and vacuum chamber door. The latter served as the feedline pressure measurement transducer. The pressure transducers had listed accuracies of ±0.5% and ±0.3%, respectively. Two bottles for each gas were available in the storage area of the PFS. The bottles were connected in parallel to allow empty
bottle removal and replacement without interruption of a test cycle.

The thrust balance was a parallelogram, swing arm-type device. The thrust balance is illustrated in Fig. 5 with the MOD-B arcjet mounted along the support beam by means of a thermally isolated clamp interface. The thrust was calculated by measuring the support beam displacement using a linear variable displacement transducer (LVDT). The thrust balance calibration was performed by correlating the LVDT output to the displacements caused by sequential application of four known weights. The weights simulated a thrust range of 0.068 to 0.282 N. The sensitivity of the thrust balance was 0.14 N/V. The least squares linear fits indicated that the standard error of the measurement was about ±2 mN corresponding to approximately 1% of the reading. The thrust measurement was affected by a thermal drift of the zero point. Tests indicated that thermal drift was mainly caused by the thermal elongation of the thruster support beam. A comparison of the calibration curves before and after a test indicated that the thermal drift affected the calibration zero offset only. Therefore, the thrust measurements were performed by turning off the engine after each cycle and recording the zero drift. Then the thrust was corrected by subtracting the zero-drift from the measured values.

Temperatures on the body of the engine and on various components of the thrust stand were measured by means of K-type thermocouples. The anode temperature was measured by means of an optical pyrometer with a wavelength range from 0.8 to 1.1 μm and a listed accuracy of ± 1 ºC. The pyrometer had a spot size of 5 mm at a distance of 1 m.

RESULTS AND DISCUSSION

The test procedures are described below followed by a description of the MOD-B/PCU test results.

TESTING PROCEDURES

The procedures included preparing the engine for the test cycle; installing the PCU in the VP-2 facility; test stand integration; leak testing the system; calibration of the thrust stand; execution of the test and; engine component and PCU check. These steps are described in more detail below.

Engine Preparation All of the metallic parts were cleaned with alcohol (IPA) and dried with nitrogen. The engine piece parts were then assembled. Prior to positioning the cathode in the engine body, a preliminary leak check was conducted to verify proper engine assembly. The electrode gap was set by inserting the cathode rod into the engine until the cathode tip touched the converging cone of the anode, then pulling back the cathode by the desired gap setting. The gap was measured by means of a micrometer with a resolution of 5 x 10⁻³ mm. A leak check of the assembled engine was made by pressurizing the engine to 4 bar with compressed air. Leaks were detected using a liquid leak detector. The resistance between the cathode and anode was checked for infinite impedance. The engine was then attached to the thrust stand interface.

PCU Installation A schematic of the connections between the PCU, DC power supply and the data acquisition system (DAS) is shown in Fig 6. This architecture enabled all of the measurements (current, voltage, specific impulse, efficiency, gas mixture flow rate...) to be monitored and controlled using a personnel computer-based DAS. The transients of the voltage and current were recorded with a digital oscilloscope.

Test Stand Integration The MOD-B engine was then mounted within the test stand of Facility VP-2 as was shown in Fig. 5. This included mounting the engine on the thrust balance support and making all of the mechanical, electrical and fluid connections. The engine was mounted along the main axis of the thrust stand support bar and aligned horizontally with the point of load application on the calibration weight loading bar. Following engine alignment, the cathode and anode current feed cables were connected. To prevent unexpected arc discharges, the exposed cathode current feed connections were covered with a high temperature resistant insulator. The propellant feed connection was then made.

Engine Leak Test The propellant feed line was pressurized to 20 bar with filtered nitrogen to check for leaks in the line connections. No visible leakage was allowed. The pressure was then slowly vented to atmospheric pressure.

Thrust Balance Calibration Prior to sealing the vacuum chamber and activating the vacuum plant, the thrust measurement balance was aligned to insure accurate and reliable thrust measurements. The alignment controls included:

* Command the DAS to remove the thrust balance locking mechanism and lift the calibration weights from the loading bar.
* Control the alignment of the loading bar in the horizontal direction and within the vertical plane of the engine support bar.

* Control the loading and unloading of the weights on the loading bar. Repeat this activity several times to guarantee proper weight application on the bar and seating within the retainer.

* Control the alignment of the LVDT transducer bore within the transducer core with weights applied and removed. The bore must be situated near to the center of the core for best performance.

* Lock thrust balance in place and close the vacuum chamber.

After the final pressure was reached in the vacuum chamber, the thrust balance was calibrated. A least squares linear fit was used to determine the thrust balance force versus LVDT voltage correlation. The calibration was repeated until a correlation coefficient of better than 0.9998 was obtained.

**Test Execution**
A gas mixture simulating hydrazine (N₂ + 2H₂) was used for the PCU characterization tests. The test sequence was started by activating the PCU with the mass flow rate at either 50 or 60 mg/s and the PCU current set point selected. Data were recorded by the DAS using a sampling rate of 2 s during the start up and 10 s during the test. Data were printed every 60 s. The thrust values were corrected by subtracting the zero-shift measured at the end of each cycle.

**Component Check**
The engine and PCU were examined at the end of the test. The component conditions and critical dimensions were controlled and documented.

**CHARACTERIZATION TEST RESULTS**
The following functional tests were conducted at BPD with the PCU using the MOD-B 1 kW arcjet as a load:

- **START-UP CIRCUIT VERIFICATION**
- **SETTLING TIME MEASUREMENT**
- **OPERATION AT NOMINAL POINT**
  - **PCU Response To A Change In Load**
  - **PCU Operation In Constant-Power Mode**

These tests are discussed below.

**START-UP CIRCUIT VERIFICATION**
This test was conducted to verify the nominal parameters of the high voltage pulses required to initiate the arc discharge between the anode and cathode of the arcjet thruster. The PCU was operated in its current-controlled mode with an input voltage of 60 V and an output current of 14 A. The test was conducted using two different mass-flow rates: 50 mg/s and 60 mg/s. Figures 7 and 8 show the start-up pulses for 50 mg/s and 60 mg/s respectively. The pulses show peak values of 2580 V and 2500 V respectively. The pulse shapes are nominally the same. The recorded values are lower than the values of the pulse measured on 900 ohm resistive load (Fig.9).²⁹ because at the ignition of the arc in the arcjet it's equivalent resistance drops to a low value (7 ohm).

**SETTLING TIME MEASUREMENT**
The settling time of the output current from the PCU, at the ignition of the arcjet, was measured. The PCU was operated in current-controlled mode with an input voltage of 60 V and a 15 A output current. Again, two values of the mass-flow rate were used: 50 mg/s and 60 mg/s. Figures 10 and 11 show the profiles of the output current for 50 mg/s and 60 mg/s, respectively. The settling time is about the same for two mass flow-rates (400 μs).

**OPERATION AT NOMINAL POINT**
The tests were intended to demonstrate the capability of the PCU to control the parameters (current and power) around the nominal point. Prior to the start of the PCU characterization tests, the laboratory power supply system was used to establish baseline engine operating characteristics. Figure 12 shows the baseline voltage-current characteristics for MOD-B arcjet operation with the laboratory DC Power Supply (SORENSEN type DCR 300-35A) at arcjet mass-flow rates of 50 and 60 mg/s. These characteristics were also measured using the PCU powered with a FARNELL DC Power Supply type H 60-50. These data points are also shown on Fig. 12. The characteristics at 60 mg/s are in good agreement.

**PCU Response to a Change in Load**
The PCU was operated in current-controlled mode with a 12 A output current. The engine mass-flow rate was set at 60 mg/s. After the engine was turned on and reached steady-state operation, the voltage was 82.5 V (Fig. 13, channel 1) according to the electrical characteristic shown in Fig. 12. Then the mass-flow...
rate was reduced to 50 mg/s with the same output current (Fig. 13, channel 2). The new current and voltage were: 12 A and 76.2 V, respectively (Fig. 14). These are close to the expected values of 12 A, 72.5 V (Fig 12).

Figure 15 shows the current and voltage vs. time during one hour of operation at a mixture mass-flow rate of 50 mg/s with the output current set at 12 A and the PCU in current-controlled mode. Operation was quite steady. The measured thrust was 0.201 N over this time period.

**PCU Response to a Current Change** The PCU was operated in current-controlled mode with a 12 A output current. The mass-flow rate was set at 60 mg/s. The voltage and current are shown in Fig. 13. The PCU output current was then changed to 8 A. The corresponding measured current and voltage were: 8.25 A and 91.2 V (Fig 16). These values are in reasonable agreement with the expected values (Fig. 12).

**PCU Operation in Constant-Power Mode** The PCU was then operated in power-controlled mode at 1000 W with the propellant (simulated hydrazine) mass-flow rate set at 60 mg/s. The voltage 84.1 V (channel 1) and current 11.67 A (channel 2) measured during the test are shown in Fig. 17. The actual power output to the engine was 976 W. The difference between the set power and the actual power is due to the resolution of the setting potentiometer. Then the mass-flow rate was changed to 50 mg/s. The voltage and current values changed to 77 V and 12.7 A for a power of 978 W according to the expected values (Fig 18).

**SUMMARY AND CONCLUSIONS**

A brassboard power conditioning unit has been developed and undergone initial testing at BPD. The PCU was developed for BPD by SEPA with support from Ansaldo Ricerche. The tests showed that the PCU was able to start and operate a low power arcjet under all conditions tested. Start-up voltages of 2500 V were measured for the particular MOD-B low power arcjet geometry used during the tests. A settling time of 400 μs was found. The PCU voltage-current characteristics were in reasonable agreement with engine operation using a laboratory power supply system. The PCU demonstrated excellent response in both current- and power-controlled modes.

**ACKNOWLEDGMENTS**

The authors would also like to thank M. Magnanini and D. Monaco for operating the facilities and assistance in conducting the tests.

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**REFERENCES**

Table 1. PCU Specifications.

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<td>Maximum Current Pulse in 2 μs (A)</td>
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<td>Efficiency (at BOL)</td>
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Figure 1. Schematic of MOD-B Low Power Arcjet.
Figure 2. Block Diagram of PCU.\textsuperscript{15}

Figure 3. Electrical Schematic of PCU.\textsuperscript{15}
Figure 4. Schematic of Laboratory Power Supply System.

Figure 5. MOD-B Arcjet Integrated Onto The Thrust Balance.
Figure 6. Schematic of PCU Integration Within Test Stand.

Figure 7. MOD-B Start-Up Pulse at 50 mg/s Using PCU.
Figure 8. MOD-B Start-Up Pulse at 60 mg/s Using PCU.

CH1 2V A 1 us 3.4 V VERT

Figure 9. Start-Up Pulse Delivered By The PCU To A 900 Ohm Resistive Load.

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Figure 10. PCU Output Current Transient at Start-Up; Shows Settling Time at a Mass Flow of 50 mg/s.

Figure 11. PCU Output Current Transient at Start-Up; Shows Settling Time at a Mass Flow of 60 mg/s.
Figure 12. MOD-B V-I Characteristics at 50 and 60 mg/s; Using Laboratory Power Supplies and PCU.

Figure 13. PCU Voltage and Current Output at 60 mg/s.
Figure 14. PCU Voltage and Current Output at 50 mg/s.

Figure 15. PCU Voltage and Current Output Over 1 hr of Operation.
Figure 16. PCU Voltage and Current Output at 60 mg/s In Current-Controlled Mode at 8.25 A.

Figure 17. PCU Voltage and Current Output at 60 mg/s In Power-Controlled Mode at 976 W.
Figure 18. PCU Voltage and Current Output at 50 mg/s In Power-Controlled Mode at 978 W.