TESTING OF 30 kW ARCJET PCU WITH ARCJET THRUSTERS

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Abstract

Space Power, Inc. (SPI) has been developing 30 kW class arcjet Power Conditioning Units (PCU's) for space propulsion[1]. The objective is to design a high power, space qualified, flight-type PCU for orbit transfer applications. The design is a simple buck regulator with a built-in flyback starter circuit. The PCU's are capable of delivering 30 kW output power to the thrusters with efficiency exceeding 95%. These PCU's have recently been tested with arcjet thrusters in NASA LeRC[2], JPL[3] and RRC[4]. Both JPL and RRC used ammonia as propellant and NASA LeRC used hydrogen as propellant. All three facilities were able to operate the arcjet PCU with their thrusters. Therefore, these tests were very helpful in identifying the strengths and weaknesses of the PCUs. During these tests, we operated the arcjet PCU for hundreds of hours and generated thousands of start pulses. No sign of degradation in the PCU was observed after these tests.

Background

A 30 kW class arcjet system is a key candidate technology for Electric Orbit Transfer Vehicles (EOTV). Research activities have been funded by U.S. government agencies including SDIO, NASA LeRC and Air Force. SPI has designed and built three full scale breadboard PCUs under the support and guidance of these agencies. Over the past several years, all these units have been tested with 30 kW class arcjet thrusters in various facilities. The tests were performed on a co-operative basis. The technical objectives of these tests were not limited to PCU performance. As the PCU developer, our main objective was to demonstrate the stable operation of the PCU with an arcjet thruster, the capability of initiating the arcjet with its build-in starter, and the long-term endurance of the PCU.

1. The Arcjet PCU development was supported by Air Force and SDIO-SBIR funding and monitored by AFAL, AFWAL and NASA LeRC.

2. This test was a joint effort of NASA LeRC and SPI. SPI's effort was part of the SDIO-SBIR Phase II.

3. This test was supported by SDIO and operated by JPL. SPI was responsible for the preparation of the PCU.

4. This test was supported by a subcontract from Rocket Research Company.

The Three Breadboard Units

Even though these units were designed and built over a period of two to three years, they all have similar electronic configurations.

A buck regulator was selected as the baseline design for all of the high power arcjet PCU's. The decision was based on its superior efficiency, reliability and compactness. Although the buck regulator has many virtues, it is necessary that the input voltage of the main power bus be greater than the arc maintenance voltage. However, any space power system capable of 30 kW will probably distribute its power at ~200V, which is higher than the voltage of typical arcjets. Therefore, we selected a simple buck regulator approach despite this limitation.

To minimize the arcjet current ripple and to allow a redundant design, three buck regulators were operated in parallel (i.e., three-phase operation). The corresponding circuit is shown in Figure 1. The switch symbols in this circuit are parallel groups of high-current, metal oxide semiconductor field effect transistors (MOSFETS). Redundancy has been designed in so that if one phase fails, the other two have sufficient capacity to continue full power operation.

The switches for the arcjet PCU operate at approximately 20 kHz per pulse. The switches are fired 120° out of phase to provide smooth regulation (effective ripple is 60 kHz, as shown in Figure 2. The current in each of the three phases is interrupted in a staggered sequence to complete one cycle. The current in one phase rises while its switch is closed and the current in the interrupted phase decreases.

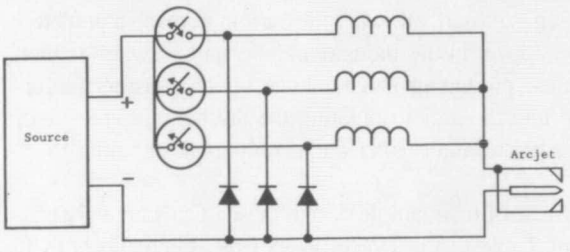


Figure 1. Simplified Conceptual Schematic of 3-Phase Regulator for Arcjet Current Control.

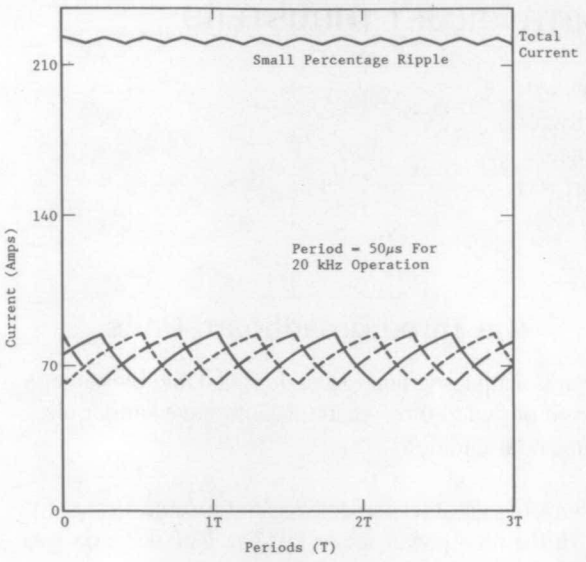


Figure 2. Three Phase Buck Regulator Output.

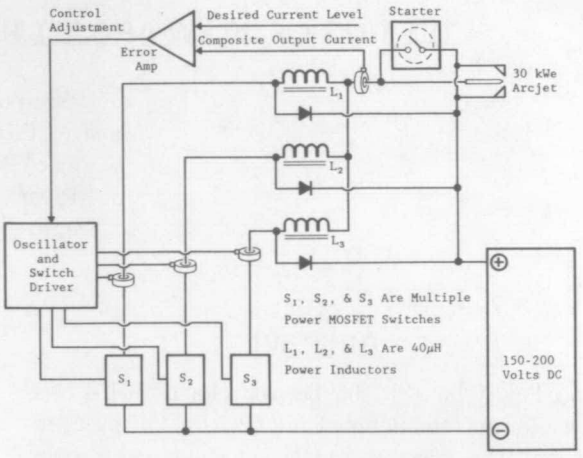


Figure 3. Three Phase Buck Regulator.

The PCU's operate the arcjet at a continuously selectable level of arcjet current. The conditioner must accommodate the arcjet I-V characteristics, which include negative dynamic resistance. The characteristics are complex and vary with time over a broad frequency spectrum. This requires monitoring the arcjet operating current for feedback to control the drive timing. With this approach, the arcjet current remains at the desired operating value despite the changing arcjet I-V characteristics and/or varying power source voltage.

A more complete description of the feedback control circuit is shown in Figure 3. A current measuring device generates a signal proportional to the output current. This voltage is compared with a voltage corresponding to a desired current level to produce an error voltage. The time integral of this error voltage is used to set the peak current of each of the three phases. The desired current may either be operator selected or remote computer controlled.

Another high voltage semiconductor switch is connected across the arcjet, as shown in Figure 3, to shunt current for trigger firing at start-up. In the start-up sequence, this starter switch is closed, allowing the current to reach a predetermined level in the inductors. The starter switch is then opened, producing a high voltage, which transfers the current into the arcjet, initiating the discharge. The starter switch is normally open and is only used for starting.

Because of their simple design these PCU's are very efficient. Table 1 shows the efficiency measurements of PCU No.3 with a dummy load. These PCU's are also designed to withstand output short-circuits. Figure 4 shows the current waveform when the output was abruptly short circuited.

The following is a brief description of each individual PCU model:

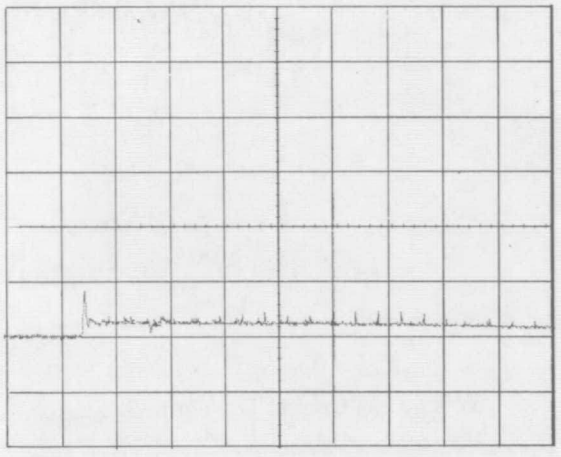
PCU No.1 (also referred as PCU I.1)

This is the first 30 kW class arcjet PCU developed and built under an Air Force contract. The top view of this PCU is a circular design. A photograph is shown in Figure 5. The structure of the chassis is made of copper plates and cooling pipes for liquid cooling. The control electronics of this PCU were originally built and tested with a wire-wrap board. This was later replaced by a printed circuit board for increased reliability. An arcjet starter was added to the PCU at this time.

Table 1. Power Supply Efficiency Data

V_{in} / V_{out}	I_{in} / I_{out}	P_{in} / P_{out}	Efficiency
150.0	47	7,050	94%
49.7	134	6,659	
150.0	68	10,200	95%
60.1	162	9,736	
150.0	90	13,500	96%
69.9	187	13,071	
150.0	118	17,700	96%
80.2	213	17,082	
150.0	148	22,200	96%
90.1	238	21,443	
150.0	179	26,850	97%
100.0	262	26,200	

Device Under Test: 30kWe Arcjet



110 A/Div 2ms/DIV

Figure 4. Short Circuit Response (After Improvement).

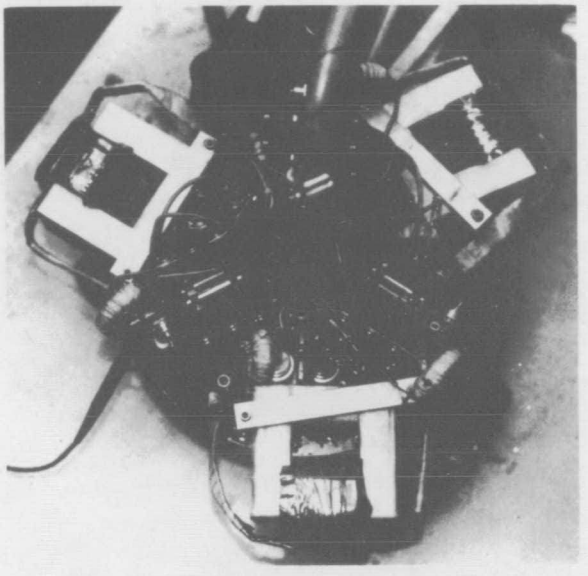


Figure 5. Buck Regulator Design.

PCU No.2 (also referred as PCU I.2)

This PCU was built under an SDIO-SBIR Phase I program. The design has a rectangular foot print. Two photographs of the PCU are shown in Figures 6 and 7. It was first built to operate with only one phase, and circuitry for the other two phases was added later. The main structure was also made with a copper base plate and copper cooling pipes.

PCU No.3 (also referred as PCU II)

This was designed and built under an SDIO-SBIR Phase II program. This is the most sophisticated unit and it was later selected as the baseline design for the flight-qualified unit of an Air Force Arcjet program.

This unit used an aluminum base plate to minimize the weight. In this unit, we also eliminated the requirement for liquid cooling by carefully mounting all heat generating components onto the base plate directly. A photograph is shown in Figure 8. Although all units have similar efficiency, this is the most efficient; it measured about 97% under certain conditions.

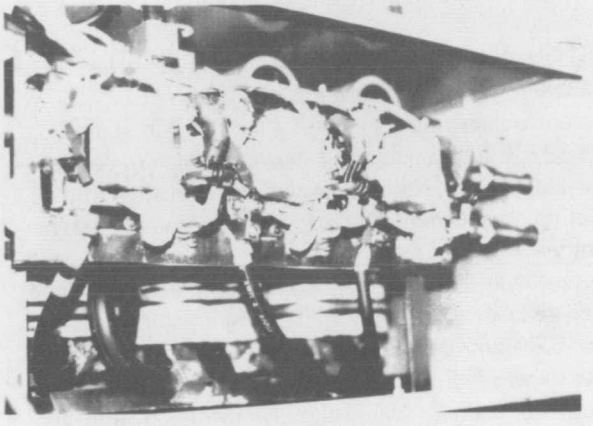


Figure 6. 30kWe Arcjet PCU 1.2 (B).

Four Arcjet Integration Tests

With cooperation and/or support from SDIO, Air Force, NASA LeRC and Rocket Research Company (RRC), we have performed four arcjet integration tests over the last three to four years.

RRC TEST-A

This test was the first time that a 30 kW class arcjet PCU was used to operate a real arcjet thruster. PCU No.1 was used (the only existing PCU). The test was performed with an ammonia arcjet. At that time, the control elec-

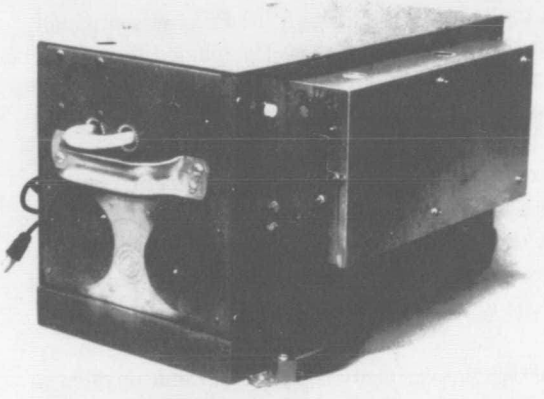


Figure 7. 30 kWe Arcject PCU 1.2 (A).

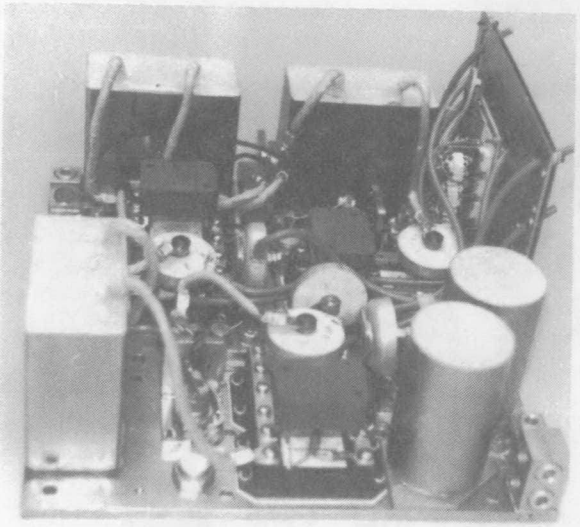


Figure 8. PCU No. 3.

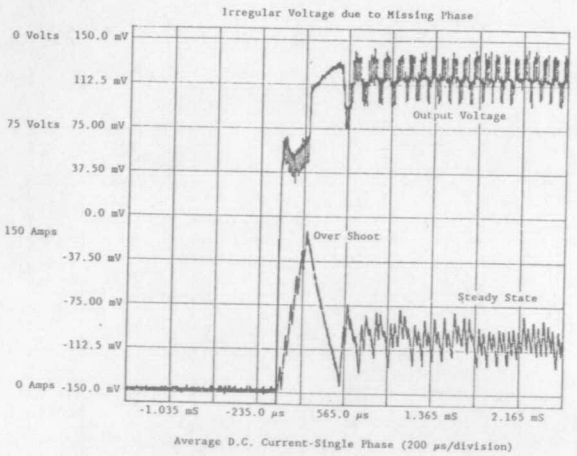


Figure 9. Voltage and Current Waveform At Startup.

tronics was in a wire-wrap board. The arcjet starter was not finished yet. The arcjet was started by an external high voltage source and a rectifier was used to de-couple the high voltage source from the arcjet PCU.

The test was successful in demonstrating the steady state operation without a ballast resistor. It also demonstrated the power handling capability of the PCU. It operated at full 30 kW for 25 hours and showed no sign of degradation after the test. However, we were not satisfied with the start-up surge current. Figure 9 shows the voltage and current waveform at arcjet start-up. Even though the surge current with this PCU was lower than that of a general purpose laboratory supply with ballast resistor, it was still over 100% above the steady state current. Because the surge current was believed to be responsible for a significant portion of cathode degradation, we identified surge current suppression as the key area for arcjet PCU design improvement.

NASA LeRC TEST

This test was conducted in July 1990 at NASA Lewis Research Center with the PCU No. 3. This test used hydrogen as the propellant, although the PCU was originally designed for an ammonia arcjet. The major difference between ammonia and hydrogen arcjets, from the PCU point of view, is operating and starting voltages. Fortunately, the PCU had enough design margin to cover operating ranges of a hydrogen arcjet[5]. The PCU was also equipped with its built-in starter circuit and improved start-up surge current suppression. The thruster was a NASA LeRC 30 kW class arcjet thruster which was a scaled up model of the NASA LeRC low power arcjet thruster.

The test was successful after some initial start-up difficulties were overcome. The initial difficulty was related to a soft-start circuit that we put in as part of the surge current suppression improvement (it was somewhat overdone). The soft-start circuit was designed to pull down the reference signal for the arcjet current control momentarily to generate a soft start-up. However, the arcjet extinguished when the current dropped below a threshold value that would demand a voltage higher than the PCU could support. This action terminated the arc shortly after start-up.

We effectively bypassed the soft-start circuit by shortening its time constant from 40 msec to 400 µsec. This led to several successful starts of the hydrogen arcjet. Even though we could not start the arcjet in every attempt (high voltage start pulse) the circuit topology for starter and start-up transition was demonstrated.

The tests began at about 10 kW and the output power was slowly increased. The maximum operating power was at 24 kW when the test was terminated for facility reasons. The total operating time was about 30 minutes. Figure 10 shows the arc from the side viewing port. Figure 11 shows the plume from the top viewing port.

NASA LeRC personnel tried to operate the same PCU later and reported more start-up difficulties. This indicated that the voltage and/or the pulse width of the start pulse was probably not high enough to guarantee consistent arcjet breakdown.

JPL TEST

This test was conducted in August 1990 at Jet Propulsion Laboratory used PCU No. 2. Unlike the test in NASA LeRC, the PCU test in JPL was performed with an ammonia arcjet. The objective of JPL in this testing was to characterize the performance of an ammonia arcjet at

5. Under certain conditions and thruster design, hydrogen arcjets can operate outside the voltage range of existing PCU designs.

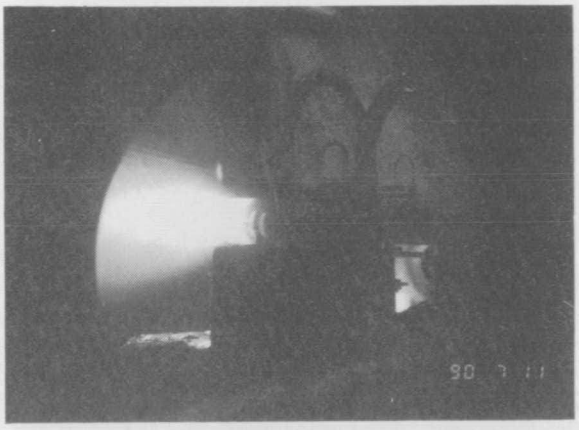


Figure 10. Arc From The Side Viewing Port.

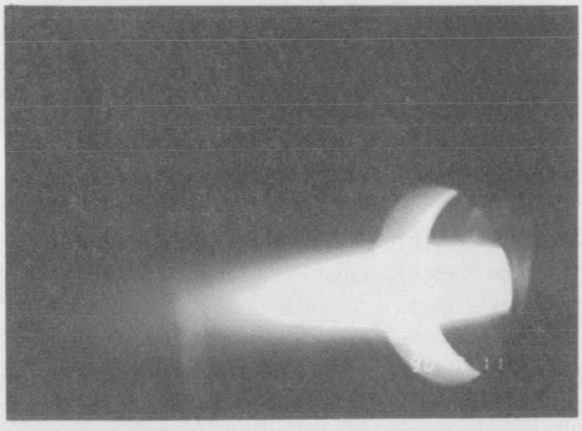


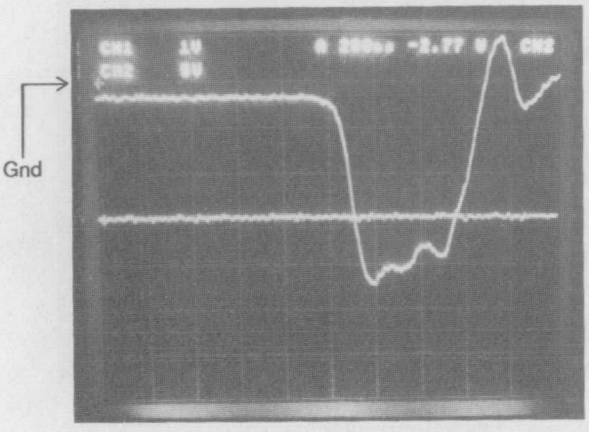
Figure 11. Arc From The Top Viewing Port.

different power levels with different propellant flow rates. We had two objectives: The first was to test the capability of our build-in starter circuit with an ammonia arcjet; the second was to operate the arcjet PCU uninterrupted for a long period of time.

Even though this arcjet PCU was built almost two years before the test, it had been updated with all the latest circuit improvements that were developed later. Therefore, the test results reflected the performance of the other two PCU's. The key difference between PCU No. 2 and PCU No. 1 and No. 3 was the number of MOSFET modules. Both PCU No. 1 and No. 3 used two MOSFET modules per phase while PCU No. 2 used only one module per phase. Therefore, we expected PCU No.2 to be somewhat less efficient and less reliable. Fortunately, this difference did not affect the input/output characteristic and functionality of the PCU.

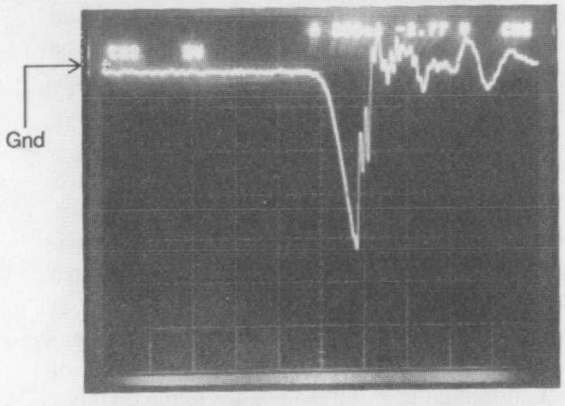
Since both operating and breakdown voltages of an ammonia arcjet are lower then those of a hydrogen arcjet, it was not surprising that the start-up in this test was easier than the hydrogen arcjet tests conducted in NASA LeRC. However, the start-up was still not consistent. Sometimes it started on every attempt and, occasionally, it would not start even with the exact setup that had been successful a few hours before. Figure 12 shows a waveform of the start pulse without breakdown and Figure 13 shows a waveform of the start pulse at breakdown. The start-up surge current was satisfactory. The overshoot varied on every start due to a variation in the arc impedance. Figure 14 shows a typical start-up current waveform taken during this test.

The arcjet system operated at 20 kW continuously for 200 hours. The system was then operated at 30 kW for another 8 hours at which time it was shut down by the PCU safety circuit because the arcjet voltage was higher than 135 V (which was the output voltage limit for 165 V input). The arcjet was restarted and operated at 25 kW for another 160 hours until the arcjet voltage dropped to 70 V due to the cathode degradation. The test was then terminated voluntarily by JPL personnel. Figure 15 is a photo of the operating ammonia arcjet.



500V/div 200 nsec/div

Figure 12. Start Pulse (No Breakdown).



500V/div 200 nsec/div

Figure 13. Start Pulse (Breakdown).

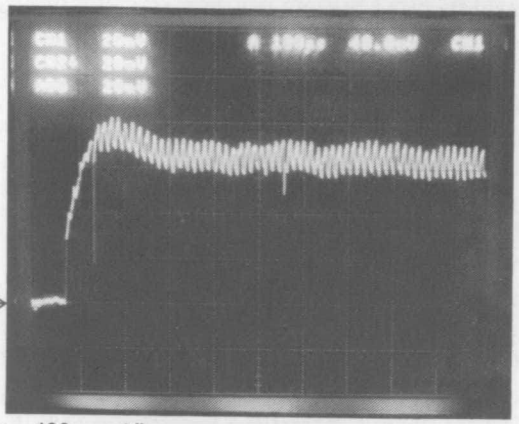


Figure 14. Arcjet Current Waveform At Startup.

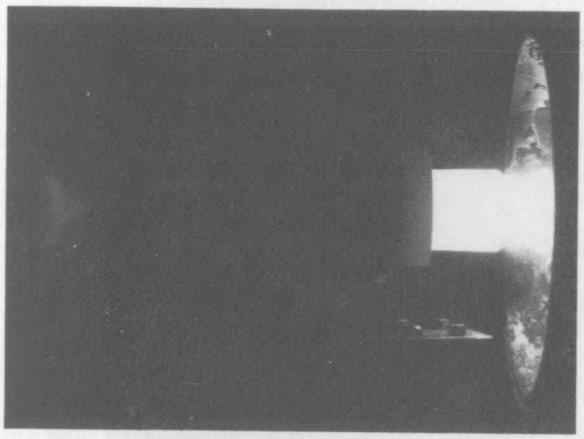


Figure 15. Operating Ammonia Arcjet.

Although we tested our arcjet PCU in-house at or near full power for tens of hours, we have never operated the PCU overnight. The JPL facility provided many long-hour endurance tests with an automatic monitoring and safety system to allow unattended operation. This was a good opportunity for us to demonstrate the reliability and the durability of the arcjet PCU.

During this test, we had intentionally avoided 2/3 duty cycle operation (output voltage = 2/3 input voltage). Operation at 2/3 duty cycle had higher random fluctuation in current ripple due to interference between the three phase power switches turning off one phase — while, at the same moment, turning on another phase. The random fluctuation slightly increased the ripple content of the arcjet current and caused annoyance to the operator when watching the oscilloscope current waveform. However, it did not seem to be significant enough to affect the arcjet operation. In fact, we had already noticed the higher than normal interference before the PCU was shipped to JPL for this test. Because of the benign nature of this problem, we decided to proceed with the test but to avoid the 2/3 duty cycle operation.

RRC TEST - B

This test was conducted at Rocket Research Company in January, 1991 with an ammonia arcjet and PCU No. 3.

Based on the previous start-up experience from the previous integration tests, we felt the starter design was marginal. Therefore, we modified the starter circuit to increase the energy stored in the start pulse before this test. The modification to the starter produced a higher current level before the shorting switch was opened. The starter circuit was a shorting switch across the output terminals. A high voltage pulse was generated when this switch was opened after being closed momentarily to let current in the output inductors build up. Figure 16 shows the schematic of the original starter and Figure 17 shows the schematic of the modified starter.

Even with the modification we expected the open circuit voltage of the starter to remain unchanged because the voltage should be held down by the protective zener diodes. Incidentally, the zener diodes were opened by the high pulse energy shortly after the test began. The opening of the zener diodes had no significant effect on the circuit except the output voltage was allowed to increase from about 2000 V to about 3000 V. Therefore, the modified starter turned out to be more powerful than we originally planned.

Based on this, one would expect the start-up to be quite easy and consistent with the new starter. However, it didn't start the arcjet at the beginning of the test. We

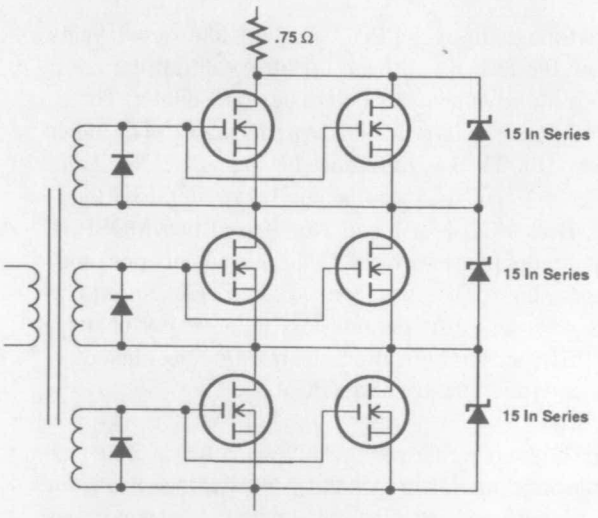


Figure 16. Original Starter.

were rather surprised because the original starter had performed successfully in many instances and this starter generated even significantly higher voltage pulses.

The arcjet was eventually started with an external starter that could generate over 4000 V pulses. Once the thruster was warmed up (seasoned), the built-in starter had no trouble starting the arcjet consistently. At this point, it was obvious that the breakdown criteria depended on many parameters including thruster condition. The particular thruster used in this test had not been used for a long period of time and might had been subjected to many thermal cycles due to shipping. Oxidation or other contamination were suspected to be responsible for the initial start-up difficulty.

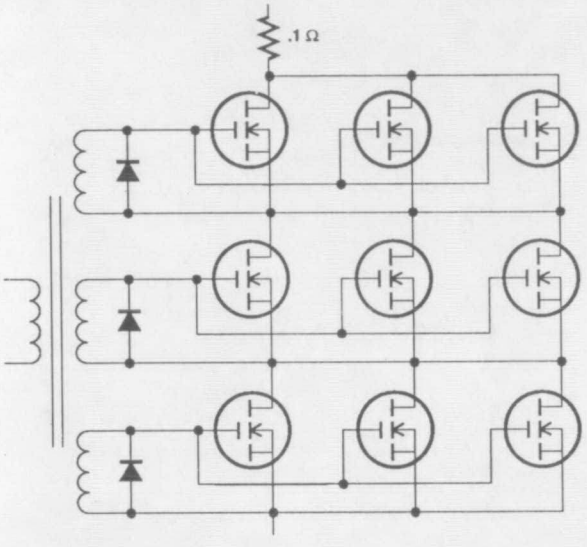


Figure 17. Modified Starter.

Other than the above mentioned problem, the starter circuit seemed to initiate arcjet breakdown very consistently at any practical flow rate even after the arcjet had been completely cooled down. The breakdown voltage was about 2000 to 2500 V. If we considered the initial breakdown difficulty to be a cathode contamination problem and the starter design did not need to cover contaminated thrusters, the starter had performed well for its intended purposes.

During this test, the arcjet initiated gas breakdown consistency for over a thousand trials. The reliability of the starter circuit has been demonstrated. Under certain conditions, the arcjet fail to sustain after the gas breakdown. The possible cause of the failure are inadequate propellant flow, low input bus voltage, and misfiring of the starter shorting switch, but not the high voltage start pulse.

The maximum power for this test was 26 kW, which was the specified arcjet power for the program.

Acknowledgment

Thanks to the support and coordination from NASA LeRC, JPL and RRC; SPI and the corresponding organization were able to operate the arcjet PCU's in these facilities and to obtain valuable test data.