ACOUSTICAL RESONANT BEHAVIOR AND V-I CURVES
FOR A 30 kWe NITROGEN ARCJET

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Abstract

The arcjet facility at Texas Tech University has many features that are unique. In particular, the WPS-1 power supply was designed and built specifically as a laboratory instrument to power an arcjet load. The WPS-1 is a phase-controlled, triple-regulated power supply whose output can be varied continuously from 0 to 100%. This unique feature allowed for the recording of continuous arcjet characteristic V-I curves. Previous investigators obtained V-I curves by curve fitting several discrete points.

The curves presented in this paper were recorded by keeping all other factors constant and varying only the power supply current at a fixed propellant flow rate. V-I curves were recorded for flow rates of nitrogen at 0.15, 0.2, 0.25, 0.3, 0.35, and 0.4 g/s with currents ranging from the minimum stable operating point to a maximum of 375 A.

Results show that, for most current settings, the arcjet operates in a nearly constant-voltage manner. However, there were two well defined mode changes which were observed to affect arcjet operation. Primary mode changes were characterized by a relatively large change in arc voltage between flow rates of 0.15 and 0.2 g/s. Primary mode changes are believed to be due to a change in the arc attachment point. Secondary mode changes are believed to be a previously undiscovered arcjet anomaly. The secondary mode changes are characterized by a well defined change in the slope of the V-I curve. The effect of flow rate was to increase the current at which the mode changes occurred. The V-I curves, with the mode changes, could be reproduced, even after the arcjet was operated for more than 2 hours.

One of the most unusual characteristics that accompanied a secondary mode change was a change in pitch of the background arcjet noise that could be heard outside of the vacuum chamber. Acoustical data measured during arcjet operation suggest that an acoustical resonant condition exists that is responsible for the anomalous behavior.

Experimental Setup

The water cooled arcjet built for this experiment operates with nitrogen propellant, and is rated for 30 kWe operation. Figure 1 shows a cross-sectional diagram of the arcjet assembly. To facilitate the use of various experimental electrode materials, both the anode and cathode electrodes were mechanically designed to be easily and quickly replaced. The shape and size of the electrodes are simple and small enough so that the cost of materials and machining are minimized.
Propellant is fed radially into the engine in the vicinity of the cathode tip. Provisions were made for the use of several propellant types including nitrogen, ammonia, and hydrogen.

The engine is mounted on a fixed chassis inside of a 0.81 meter diameter vacuum chamber. The vacuum tank is fitted with six diagnostic ports that are aligned with the center line of the arcjet exhaust plume. Power is brought out of the vacuum enclosure by a vacuum feedthrough that is rated for both high voltage and high current operation.

The arcjet plasma plume is cooled by a stainless-steel water-cooled ducting system. The tank is isolated from the vacuum pumps by a bellows and a gate valve. Additional exhaust gas cooling is provided by a water-cooled heat exchanger.

Arcjet starting is provided by a high-frequency starter designed for welding applications. For high-current operation, the starter unit is bypassed by an electrically controlled pneumatic switch.

Power for the arcjet experiment is provided by the WPS-1 regulated power supply. The WPS-1 can provide an open-circuit voltage of 320 V and a sustained current of 450 A. The output of the WPS-1 can be continuously varied during operation from 0 A to its full operational rating.

Prime power for the WPS-1 comes from a 480-VAC 3-phase 3-wire service rated at 600 A. Voltage is stepped down by a 480 to 208 VAC 3-phase transformer rated at 225 KVA with a gross weight of 817 kg.

Power supply adjustability is accomplished by phase control on the primary of the power transformer. Two thyristors (SCRs) are connected on each of the three input lines as shown in Figure 2. The SCRs are controlled by a commercially available control board. The input for the SCR control board is a 4-20 mA control signal.

The WPS-1 has the unique capability of regulation in three selectable modes: constant voltage, constant current, and constant power. Voltage regulation is accomplished by negative feedback from a voltage sampling resistive divider network. Current regulation is similarly provided by negative feedback from a current sample provided by a Hall-effect type current monitor. Power regulation is accomplished by taking the analog product of the voltage and current samples for negative feedback.

Amplitude levels for each of the three negative feedback signals are independently adjustable.
Control for the feedback electronics is provided by an adjustable, highly-stable voltage reference connected to the positive input of the difference amplifier. The output of the difference amplifier is converted to a 4-20 mA signal that controls the SCR control board.

All internal electronics of the WPS-1 are cooled by two high-flow blowers. Operation of the cooling system is controlled by the power-up interlock contactors.

Filtering for the WPS-1 comes from an adjustable R-C network. Unfiltered, the power supply ripple can be as high as 28%, but with filtering as low as 0.8%.

Power conditioning comes from a water-cooled ballast resistor whose resistance is selectable at values of 2.0, 1.0 and 0.5 Ω. Water cooling gives the ballast resistor a sustained power dissipation rating of 85 kWe and a peak power rating of 120 kWe. A block diagram of the overall electrical system is shown in Figure 3.

![Figure 3: System Block Diagram](image)

**Experimental Data**

**Characteristic V-I Curves**

The arcjet V-I characteristic curves were recorded by continuously varying the arcjet operating current at several fixed flow rates. The measurement procedure involved slowly ramping the power supply output current back and forth from the minimum stable arcjet operating point to a maximum current of about 375 A. In an effort to maintain arcjet thermal equilibrium, a minimum of ten minutes was allotted to complete one ramp up and ramp down cycle.

The resultant V-I characteristic curves are given in Figure 4. Data curves were taken at flow rates of 0.15, 0.2, 0.25, 0.3, 0.35, and 0.4 g/s.

**Spectral Measurements**

The acoustical data in Figures 5, 7, 9, 11, 13, and 15 were measured with an audio spectrum analyzer across a piezo transducer with the arcjet operating at a fixed flow rate of 0.3 g/s and at cathode currents of 150, 200, 225, 250, 275, and 300 A. These currents were chosen since they bound either side of the secondary mode change points as shown in Figure 4.

The cathode current spectrum plots (Figures 6, 8, 10, 12, 14, and 16) were measured across a cathode current shunt with the arcjet operating at the same flow rates and at the same currents as measured for the acoustical data.

**Data Analysis**

**Primary Mode Changes**

The most prominent feature of the V-I characteristic curves is the relatively large differential voltage between the curves measured at 0.15 g/s and 0.2 g/s. This voltage shift is defined as a "primary" mode change from low voltage to high voltage operation. Inspection of the arcjet exhaust for flow rates in both low and high voltage operation revealed a visually different exhaust plume. Observations of the exhaust plume while operating in the low voltage mode include: less relative light intensity and a less defined plasma column center. For high-voltage mode operation, the plasma column was much bright-
er and much more clearly defined, particularly along the axis of the plume, at the exit of the nozzle, where shock diamonds were observed to develop.

Observations of the arcjet plume behavior in the low voltage mode implies that the arc anode attachment point was in the vicinity of the cathode tip. This conclusion was backed up by observations of accelerated anode erosion in the cathode tip region for arcjet operation exclusively in the low voltage mode.

Evidence strongly suggests that once the arcjet jumps from low voltage to high voltage operation, arc attachment moves from the vicinity of the cathode tip, through the constrictor region, to attach in the nozzle expansion region. Observations made by viewing directly into the arcjet nozzle confirm the outside arc attachment when operating in the high voltage mode.

It is believed that the arc attachment point is related to a pressure minimum. Pressure data taken by Harris et al.\(^2\), clearly correlate pressure minima points to regions where the most electrode erosion was observed.

**Secondary Mode Changes**

Secondary mode changes are defined as sharp variations in the slope of the V-I curves, which take place as the current is varied at a fixed propellant flow rate. The occurrence of secondary mode changes are identified in Figure 4 by two dashed lines drawn through the centers of the mode change break points.

The secondary mode changes are much less prominent than the primary mode change. The slope of each characteristic V-I curve is relatively constant, except in the region near the secondary mode change break points.

**Spectral Analysis**

Another characteristic of a secondary mode change was an audible change in pitch of the background arcjet operating noise. It was believed that the cause for these pitch changes was arcjet acoustical resonances being mechanically transmitted to the outside air through mechanical couplings in the vacuum chamber tank.

In an effort to confirm the presence of resonances, the frequency content of the background audio was measured using an audio spectrum analyzer connected to a piezo transducer which was mounted to the arcjet cathode assembly. The spectral content of the cathode current was also measured with the spectrum analyzer connected across a series shunt.

The acoustical and current spectral plots, measured at a current of 150 A (Figures 5 and 6 respectively) show no significant frequency components above 8 kHz. The series of decaying spectral components shown in Figure 6 was determined to be the power supply primary ripple frequency and its harmonics. At 150 A, the arcjet was operating below the first secondary mode change, which occurred at approximately 175 A for a flow rate of 0.3 g/s (refer to Figure 4).

The current spectral plot measured at 200 A (Figure 8) shows a broad spectrum of noise beginning to appear at frequencies ranging from 10 to 17 kHz. The acoustical plot at 200 A (Figure 7) does not show this high-frequency noise. This is due partly to the low sensitivity of the acoustical transducer at these frequencies.

By 225 A, the arcjet had begun to operate in a region between the two secondary mode shifts. Figures 9 and 10 show the spectral plots for vibration and current respectively. Figure 10 indicates that the amplitude of current noise had increased greatly and had begun to separate into two distinct frequency
groups centered at approximately 10.5 and 13 kHz. The amplitude of the acoustical noise (Figure 9) had increased enough at 225 A that these two frequency groups could be detected.

Figures 11 and 12 show the vibration and current plots at 250 A. Arcjet operation at 250 A corresponded approximately to the occurrence of the second secondary mode shift (Figure 4). The current data in Figure 12 show that the amplitude of the two frequency groups had increased further. There was also a slight increase in the vibrational amplitude at these two frequency groups, as shown in Figure 11.

As current was increased to 275 A, the arcjet was operating well into a constant slope region of the V-I operating curve (Figure 4). The current shunt spectral plot (Figure 14) indicates that the two frequency groups were beginning to merge into one large group centered at about 11.25 kHz. This trend was confirmed by the acoustical plot (Figure 13) which also shows only one frequency group centered at about 11 kHz.

The final spectral plots were measured with the arcjet operating at 300 A. The current shunt plot (Figure 16) indicates that the two frequency groups, measured at 250 and 275 A, had converged completely into a single group. In addition, the single spectral group had shifted higher in frequency to center at approximately 13.5 kHz. The acoustical plot (Figure 15) confirms both the upward shift in frequency and the decrease in the amplitude of the noise.

**Conclusions**

The primary mode change, observed in this experiment, is believed to be due to a change in the arc attachment point. However, secondary mode changes are not as well understood. Changes in the pitch of the arcjet background operating noise suggests that an anomalous resonance condition exists that affects arcjet operation.

Resonances were observed by measuring the spectrum of both the cathode current and the vibrations of the cathode. At currents below the first secondary mode shift, no resonances were observed. At currents between the two secondary mode shifts, pronounced resonances were observed at two separate frequency groups. At currents above the second secondary mode shift, only one resonance group was observed, which was lower in amplitude and higher frequency than the two previous spectral groups.

The presence of resonances implies that arcjet performance parameters, such as thrust, efficiency, or cathode erosion might be affected. Experiments by Harris and Grimes et al., suggests that electrode erosion was profoundly affected by power supply ripple. If cathode vibration, caused by power supply ripple, was a contributing factor to electrode erosion, then the resonances associated with secondary mode changes could also affect electrode erosion.

**References**


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Arcjet V-I Characteristic Curves
Propellant: Nitrogen

Figure 4: Characteristic V-I Curves
Figure 5: Acoustical Transducer Spectral Plot for $I = 150$ A.

Figure 6: Current Shunt Spectral Plot for $I = 150$ A.
Figure 7: Acoustical Transducer Spectral Plot for $I = 200 \text{ A}$.

Figure 8: Current Shunt Spectral Plot for $I = 200 \text{ A}$.
Figure 9: Acoustical Transducer Spectral Plot for I = 225 A.

Figure 10: Current Shunt Spectral Plot for I = 225 A.
Figure 11: Acoustical Transducer Spectral Plot for I = 250 A.

Figure 12: Current Shunt Spectral Plot for I = 250 A.
Figure 13: Acoustical Transducer Spectral Plot for I = 275 A.

Figure 14: Current Shunt Spectral Plot for I = 275 A.
Figure 15: Acoustical Transducer Spectral Plot for I = 300 A.

Figure 16: Current Shunt Spectral Plot for I = 300 A.