# THE DESIGN, FABRICATION, AND TEST OF A 26 KW ARCJET AND POWER CONDITIONING UNIT

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## Abstract

The Arcjet Advanced Technology Transition Demonstration (Arcjet ATTD) Program has completed design fabrication and test of a very high power electric propulsion system, comprising a 26 kW arcjet and Power Conditioning Unit (PCU). Rocket Research Company and Pacific Electro Dynamics under the sponsorship of TRW and the Air Force Phillips Laboratory are completing preparations to conduct a flight experiment of this high power arcjet propulsion system as a part of the Electric Propulsion Space Experiment (ESEX) on the Air Force P91-1 Atmospheric Research and Global Observation Satellite (ARGOS).

The arcjet is a 30 kilowatt (kW) class ammonia electrothermal thruster. The arcjet, when operated in space, will provide for the measurement of exhaust plume contamination, electromagnetic interference, radiative heating effects, and arcjet performance. The power cable/connector is an unique solid conductor triaxial design. The arcjet will be operated in steady-state mode and will produce 1.88 newtons of thrust with an Isp of 7850 ± 250 N-sec/kg (800 ± 25 lbf-sec/lbm).

The PCU converts unregulated direct current (DC) input power to a regulated DC output suitable for running a high-power arcjet thruster. The PCU monitors and responds to input commands, monitors arcjet-related transducer signals, outputs conditioned signal and status data, controls the arcjet propellant feed valve, and provides a high-voltage pulse to activate the arcjet during a start sequence.

The flight experiment utilizing this arcjet propulsion system will validate the space operation of intermediate to high power arcjets and become the precursor of subsequent flight demonstrations with subsequent electric orbit transfer vehicle application.

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## Nomenclature

| | |
|---|---|
| ATTD | Advanced Technology Transition Demonstration |
| CCU | Command Control Unit |
| CID | Charge Injection Device |
| ESEX | Electric Propulsion Space Experiment |
| EMI | Electro Magnetic Interference |
| IMS | Integrated Mission Simulation |
| Isp | Specific Impulse |
| LeRC | NASA Lewis Research Center |
| PCU | Power Conditioning Unit |
| PFS | Preopellant Feed Subsystem |
| PIU | Power Integration Unit |
| ST/T | Space Test & Transportation Program Office |

## Background

The objective of the Arcjet ATTD Program is to develop, demonstrate and qualify, on the ground, a flight-ready arcjet propulsion flight unit suitable for flight demonstration. The flight unit will consist of a 26 kW arcjet, PCU, propellant feed subsystem (PFS), command/control subsystem, diagnostic package, power source, thermal management subsystem and structure previously described(1). Once the flight unit has completed its ground qualification test, it will be given to the Space Test and Transportation Program Office of the Air Force's Space Systems Division (ST/T) for launch vehicle integration and space test. The flight unit's space test is known as the ESEX. ST/T has contracted with Rockwell International to integrate the ESEX flight unit with seven other experiments onto the launch vehicle. The launch is planned for 1995. ESEX's mission scenario is to perform ten firings of 15 minutes each with a maximum of 100 hours between each firing to allow its energy storage batteries to recharge. The objectives of the ESEX flight are to measure plume deposition, electromagnetic interference, thermal radiation, and acceleration in space. Plume deposition, electromagnetic interference, and thermal radiation are operational issues addressing the concerns of potential users.

The Arcjet ATTD flight unit will depend on its host vehicle for attitude control, battery recharge, housekeeping power and ground communications on orbit. To power the arcjet propulsion system, the flight unit includes a silver-zinc battery capable of providing 6,780 W-hr per arcjet firing and requiring less that 100 hours for recharging. Figure 1 shows the relationship of the subsystem elements directly related to the arcjet propulsion system including the arcjet, PCU and PFS. The PFS has been previously described elsewhere(2), the arcjet and PCU are described below.

## Component Descriptions

### Arcjet

The 26 kW arcjet is similar, but much larger than, the NASA LeRC 1.4 kW arcjet and its closely related derivative the Telstar 4 arcjet(3, 4). Figure 2 shows the internal configuration of the 26 kW arcjet. The design incorporates an elongated thermal barrier tube intended to reduce the heat flux from the thruster electrodes into the spacecraft. To improve the radiative heat dissipation from the arcjet anode a high emissivity titanium carbide coating is applied to the outer surfaces. The cathode and anode are electrically isolated using ceramic insulators. A key to the design is the hermetic pass-through that allows the cathode to pass from the interior of the arcjet body to the cable assembly. A unique metal to ceramic braze joints allow this transition to be implemented. The cable assembly uses a coaxial copper bus bar with spiral machined slots for strain relief. Figure 3 shows the Engineering Model cable and connectors that conduct power from the PCU to the arcjet. Figure 4 is a photograph of the completed engineering model arcjet prior to test firing with the cable/connector assembly attached.

### PCU

The Arcjet ATTD requires the design and operation of a 30 kW class PCU to take the battery power and condition it to the start-up, ramp-up, and steady-state voltages and currents required by the arcjet. The PCU development work has been performed by the team of Pacific Electro Dynamics and Space Power Incorporated under subcontract to the Arcjet ATTD Program team of TRW, Rocket Research, and DSI.

The PCU uses a buck regulator topology to maximize efficiency and reliability(5). The unit was designed with 3 buck phases to minimize current ripple. The PCU converts electrical power input power, at 160 to 240 Vdc, provided by the silver-zinc rechargeable battery into a conditioned, constant power output that is applied between the anode and cathode of the arcjet thruster. To initiate the electrical arc in the thruster, the PCU outputs a short duration, >5,000 Vdc pulse. After arc initiation, the PCU maintains a constant thruster warm-up current of about 85 amperes for approximately 10 seconds and then ramps up the output current at a nominal 10 kW per minute rate until a 26 kW output power level is achieved. The gradual increase in output power during the start-up sequence minimizes the temperature gradients in the arcjet thruster. After warm-up, the 26 kW output power level is maintained for a 15 minute firing duration.

The PCU receives power and command inputs from the TRW designed and built Power Integration Unit (PIU) and Command and Control Unit (CCU) and provides PCU status and conditioned transducer signals (pressure and temperature, voltage and current) to the CCU. The PCU controls the operation of the propellant valve to provide propellant to the arcjet thruster during firing periods.

The principal performance characteristics of the PCU are summarized in Table 1. The PCU is illustrated in Fig. 5. A block diagram illustrating the implementation of the buck regulator topology is presented in Fig. 6. The physical layout of the PCU assembly is illustrated in Fig. 7. Important features of the design implementation include bonding of the hybrid FET switches to the baseplate for optimum thermal dissipation and the use of parallel plane bus bars to minimize EMI effects within the enclosure. The auxilliary card cages are isolated from the power converter by bulkheads. Vent holes in the enclosure (0.28 $cm^2$ per liter) are provided to limit pressure build-up during outgassing of volatiles under vacuum.

At the expected efficiency of 95% a total of 1368 watts of power are dissipated through the base plate. A large aluminum heat sink will limit the baseplate temperature to less than 55° C following a 15 minute firing. The overall weight of the unit is approximately 48.5 kg yielding a specific mass 1.62 kg/kW at the full rated power of 30 kW.

## Test Description

### Engineering Model Arcjet Performance Test

The objective of this test was to demonstrate that the arcjet, PCU and PFS successfully operated together as a "subsystem". The performance of the engineering model arcjet was evaluated at steady-state conditions. Start-up and steady-state operation of the PCU and arcjet system were evaluated as follows.

| Table 1. PCU Requirements Summary | |
|---|---|
| Input Power | 160 – 240 Vdc (main power)<br>+28 Vdc (auxiliary power) |
| Output to arcjet thruster | 90 – 130 Vdc<br>26,000 ± 370 watts steady state |
| Output ripple current | 15% peak-to-peak |
| Arcjet thruster start voltage | 5000 ± 1000 Vdc (1.5 μ second duration) |
| Efficiency | 95% |
| Dynamic regulation | 10 amps output current change for step load change of 0.05 ohms |
| Envelope | 46.74 cm x 60.96 cm x 15.24 cm (18.4" x 24.0" x 6.0") |
| Mass | 48.4 Kg (107 lbm) |
| Reliability | 15,000 hours MTBF (per MIL-HDBK-217E) |
| Mounting surface temperature | -29°C to +55°C (on-orbit) |
| Pressure | $10^{-6}$ torr (operating)<br>$10^{-3}$ torr, 40 Torr (test) |
| Acceleration | 10 g's (X, Y, Z axes) |
| Vibration | 9.3 g rms (X, Y, Z axes) |
| Launch shock | 1500 g's |
| Radiation | 10 Rad (200 nautical mile orbit altitude) |
| EMI | MIL-STD-461C, Category A2a (tailored) |

Testing was conducted to determine that the PCU, when attached to the EM arcjet as a load:

- Met the peak voltage and start energy level requirements to achieve reliable arc breakdowns between the arcjet electrodes at the nominal mass flow rate of 240 ± 5 mg/s
- Met the plateau current level and duration requirements
- Met the power ramp requirements
- Met the constant power and efficiency requirements
- Met the steady-state thrust and Isp performance of the EM arcjet.

All electrical interface connections were made to simulate actual spacecraft interface requirements. The Micro-DACS combined with the Test Control Fixture provided command control and instrumentation measurement capability to partially serve as a surrogate for the PIU. For thrust measurement the PCU was located outside the vacuum chamber due to load limitations of the null balance thrust stand. Facility power cables were routed from the PCU output power receptacle through the test control fixture and up to the vacuum chamber wall. An additional cable delivered power from the chamber wall, across the thrust stand flexures, and terminated at a simulated PCU output power receptacle (shown in Fig 4). The flight-type engineering model power cable connected directly to the receptacle and to the arcjet electrical pass-through. The arcjet installation including the thermal radiation shield in the vacuum chamber is shown in Fig. 8.

Electrical power to the PCU was provided by a Rapid Electric Model SCR-A4-300-250 DC power supply operating in voltage control. The PCU input power was routed through the test control fixture. An inductor and a capacitor bank were installed across the output of the Rapid Electric Power Supply to help compensate for voltage drop experienced during the start-up transient.

## Arcjet Breakdown

Arcjet Breakdown tests were performed to evaluate the high voltage pulse characteristics of the start circuit and its effectiveness in achieving reliable arc breakdowns at the nominal propellant mass flow rate. Arcjet breakdown voltage levels were typically in the 6 kV range with voltage rise times in the range of 0.5 to 1.5 microseconds. The high voltage transients were measured with a Tektronix P6015 Broad Bandwidth High Voltage Probe combined with a digital oscilloscope. Breakdown tests were conducted at both the high (240 Vdc) and low (150 Vdc) PCU input voltage levels.

## Arcjet Start

Tests were conducted to evaluate the PCU current control during the start-up transients. The transition to constant current was measured with a digital oscilloscope during the initial 200 microseconds to determine the extent, if any, of current over-shoot. PCU output current and output voltage during arc transition from "low mode", (normally within several hundred milliseconds following arc break-

down), were measured with a digital oscilloscope. PCU output current and input voltage during the first 500 milliseconds after breakdown were also measured to evaluate output current control during input voltage transients due to the input power supply. During all of these start-up measurements the arcjet was operated for 3 to 5 seconds to demonstrate a successful "start" and then shut down by issuing a "stop" command to the PCU. Start-up tests were conducted at both the high (240 Vdc) and low (150 Vdc) PCU input voltage levels. Power ramps to full power at the nominal mass flow rate were performed to verify proper PCU current control.

Arcjet Steady State

Five steady-state firings of 15 minutes duration were performed. The steady-state performance of the arcjet was evaluated by directly measuring thrust from the null balance thrust stand. PCU efficiency was determined by measuring both the input (both Logic & Bus) and output power of the PCU at equilibrium conditions in terms of voltage and current levels. Tests were performed to verify constant power control tolerance at 26 kW nominal. Output power current ripple and ground currents on logic, telemetry and command were measured with a Tektronix Model 6302 Hall Effect current probe routed to a digital oscilloscope.

Integrated Test

The objective of this test was to demonstrate that the components of the propulsion system perform properly in an integrated configuration. System compatibility between the arcjet and PCU was evaluated on issues such as reliable start transients, power control, thermal distribution and noise interference.

The arcjet, power cable and power conditioning unit were mounted in the vacuum chamber. Electrical interface connections were made to simulate actual spacecraft interface requirements. The Micro-DACS combined with the Test Control Fixture provided command control and instrumentation measurement capability to partially serve as a surrogate PIU.

With the nominal arcjet ammonia mass flow rate, the vacuum level within Chamber 11 was approximately 100 to 150 milli-torr. At this pressure level the PCU would experience arc breakdowns within the high voltage sections of the unit. To prevent this from occurring, the PCU was installed within an independently pumped Lexan sealed enclosure to maintain a vacuum environment of less than 50 milli-torr. The PCU was mounted directly to a water cooled thermal base plate for heat rejection. Five 15 minute firings were conducted to simulate the flight experiment. The installation of the PCU into the vacuum chamber is shown in Fig. 9.

## Results

All of the planned arcjet/PCU tests were successfully completed These tests demonstrated:

- There are no adverse interactions between the arcjet and PCU
- Full flow rate starts of the arcjet can be reliably obtained at a PCU start circuit output voltage of approximately 6 kV
- The arcjet performance was within the expected range (799 vs 900 lbf-sec/lbm)
- The arcjet thermal design successfully isolated the heat flux from the elastomeric materials in the cable/connector
- The PCU thermal design successfully dissipated the heat flux from the power converters and inductors
- The PCU and arcjet met all requirements for the mission duty cycle duration.

PCU/Development Arcjet Tests

The PCU was successfully vibrated in three axes to the Arcjet ATTD flight levels plus margin. Hot fire tests of the PCU with an early version development arcjet were also successfully completed. The start circuit demonstrated the capability to reliably start the arcjet at the full design mass flow rate and to transition from the start power (i.e., 5 to 10 kW) to full power (i.e., 26 kW) within one minute. Stand-alone testing of the PFS was completed and the subsystem is now ready for combined PFS/PCU/arcjet testing.

Engineering Model Arcjet

The engineering model arcjet and cable assembly was successfully vibrated to the Arcjet ATTD flight levels. There has been a change to the flight anode design so the performance data will be collected with a second version of the engineering model arcjet. The thermal data collected on the hot firing indicates confirmation of the thermal model. The PCU start sequence functions properly with the engineering model arcjet.

Engineering Model Arcjet/PCU Performance Tests

All of the Engineering Model arcjet and PCU tests have been successfully completed. The only remaining test is the full integrated mission simulation test. The primary remaining interaction to be demonstrated is the effect of the flight battery on the PCU performance.

Start and transition testing confirmed that the new 6 kV start circuit would reliably and repeatably start the arcjet. For two of the early test the flow was reduced to 75% of full flow, however, the parasitic inductance and capacitance of the facility cables was affecting the pulse amplitude and duration adversely. All of the starts with the flight configuration cable between the PCU and arcjet were accomplished with a single pulse at full mass flow rate. Figure 10 is an oscilloscope generated plot of a typical start pulse; in the specific case shown arc breakdown occurred at 5.5 kV. Figure 11 extends the time scale of Fig. 10 to show the transition from start circuit to power converter operation. The transition occurs approximately 80 μsec after the start pulse and is marked by a change in the voltage and current frequency content. Smooth transitions to full power operation have been consistently obtained with the engineering model PCU.

The ten mission duty cycle firings were successfully completed. Figure 12 is a photograph of the arcjet during one of the firings. The temperature of the incandescent portion of the anode was measured by pyrometer and CID camera and determined to be 2000 to 2150 K. Typically about one firing per hour could be accomplished once the test sequence was started. Figure 13 is a plot of the peak thermocouple temperature of the anode which was located at an electron beam Mo/41Re weld. The temperature is stable following approximately 500 seconds of run time. This confirms that the measurements taken during the flight experiment in a 15 minute firing will be a good representation of thermal equilibrium. The plot shows that the anode had not completely cooled in the interval between firings. Figure 14 is a plot of the thrust measurement taken during the same firing (run no. 4). Thrust is stable shortly after the PCU power completes ramp-up. During the firings the Isp was measured to be 7,835 N-sec/kg (799 lbf-sec/lbm) at a thrust efficiency of 27.2%. The peak connector temperature was about 340 K.

Summary and Conclusions

Progress has been made toward the completion of a limited end-to-end chamber verification of the 26 kW arcjet propulsion system to be flown on the Air Force P91-1 spacecraft. Each of the system elements tested thus far successfully met all performance requirements and desired engineering criteria. Final preparation for the integrated mission simulation firings including the engineering model propellant feed subsystem, flight battery, EMI measurements, and a demonstration of the flight camera are in progress and the test will be conducted in the last quarter of 1993. At the time of this writing, the flight hardware fabrication is in progress, specifically:

- Assembly of the flight arcjet is in progress.
- Assembly of the flight PCU is in progress.
- The engineering model PFS has been assembled and tested and is now awaiting the completion of other system elements.
- Fabrication of the flight PFS is in progress.
- Final assembly of engineering model battery is in progress.
- Fabrication of test support equipment is complete.

Acknowledgment

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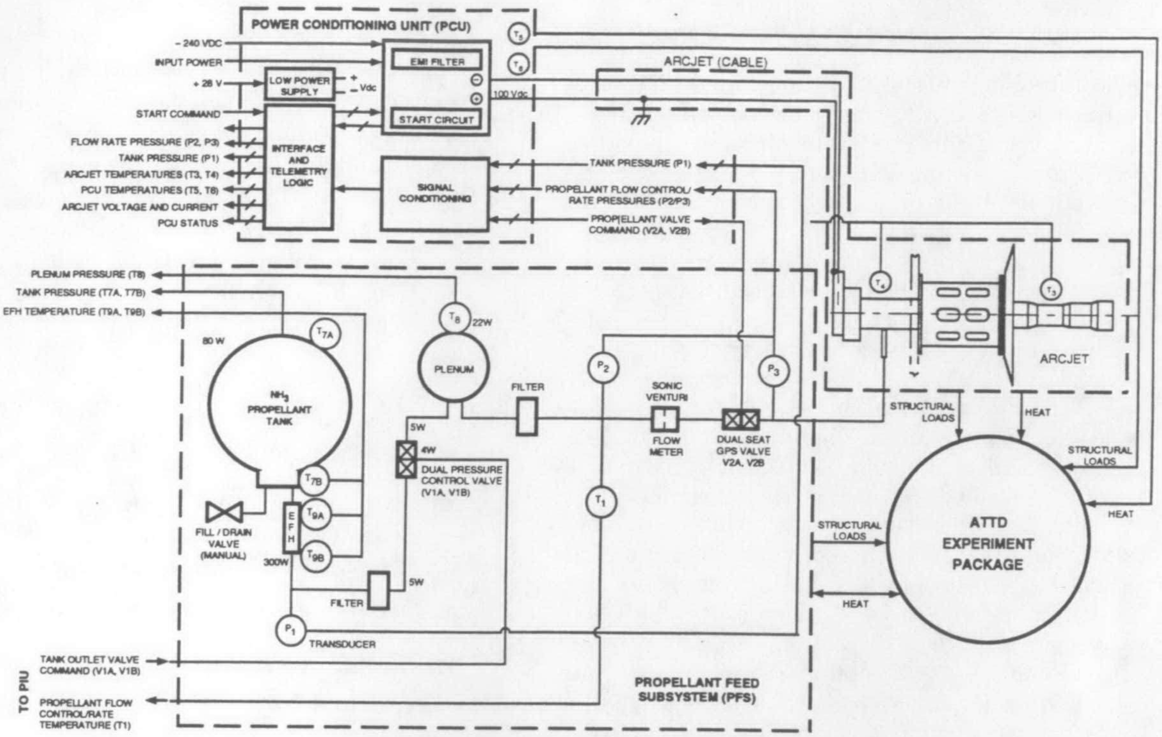


**Fig. 1. ATTD Arcjet Propulsion Subsystem Interfaces.**

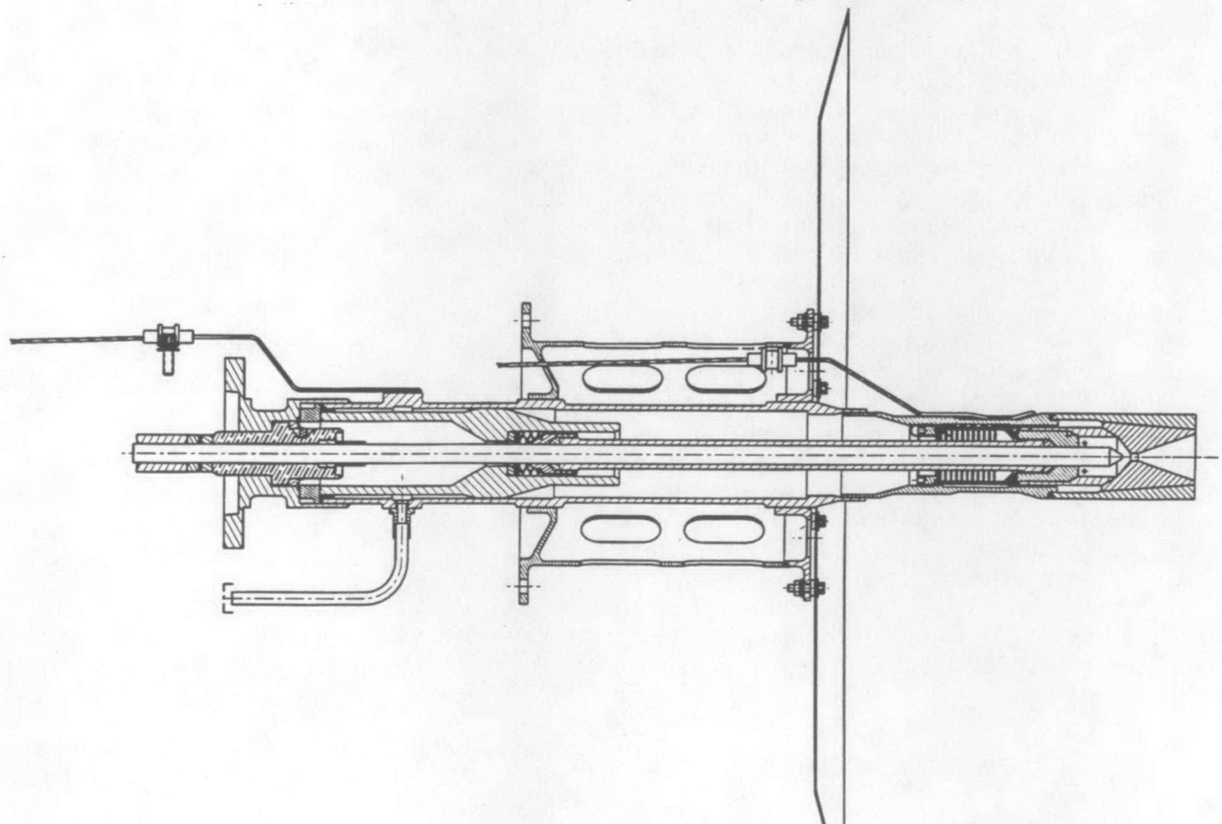

**Fig. 2. Cross-Section of the ATTD 26kW Arcjet with TheTungsten Insert Anode Configuration.**

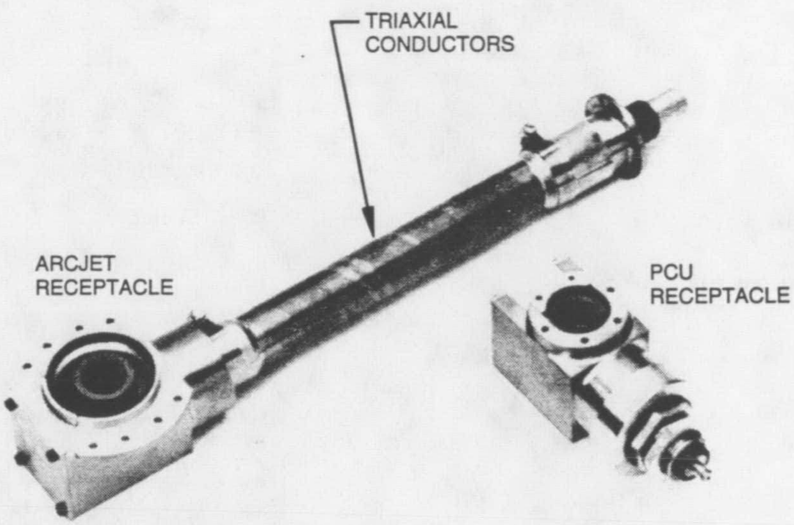


**Fig. 3. Engineering Model Cable and Connector.**

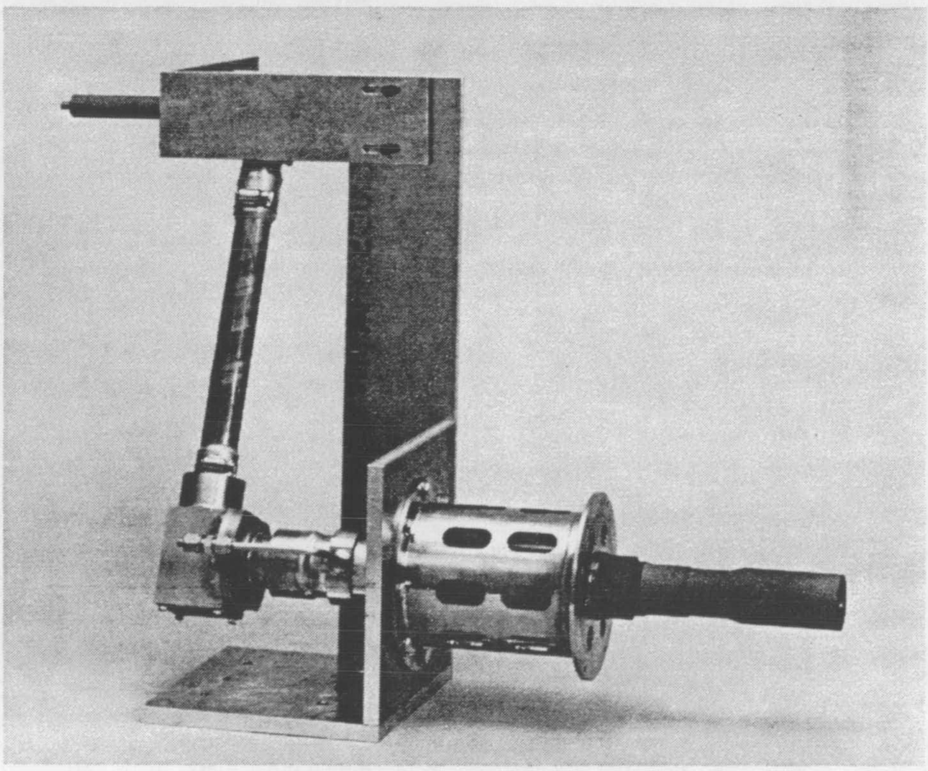

**Fig. 4. ATTD Arcjet with Power Cable Installed Assembled in The Test Configuration.**

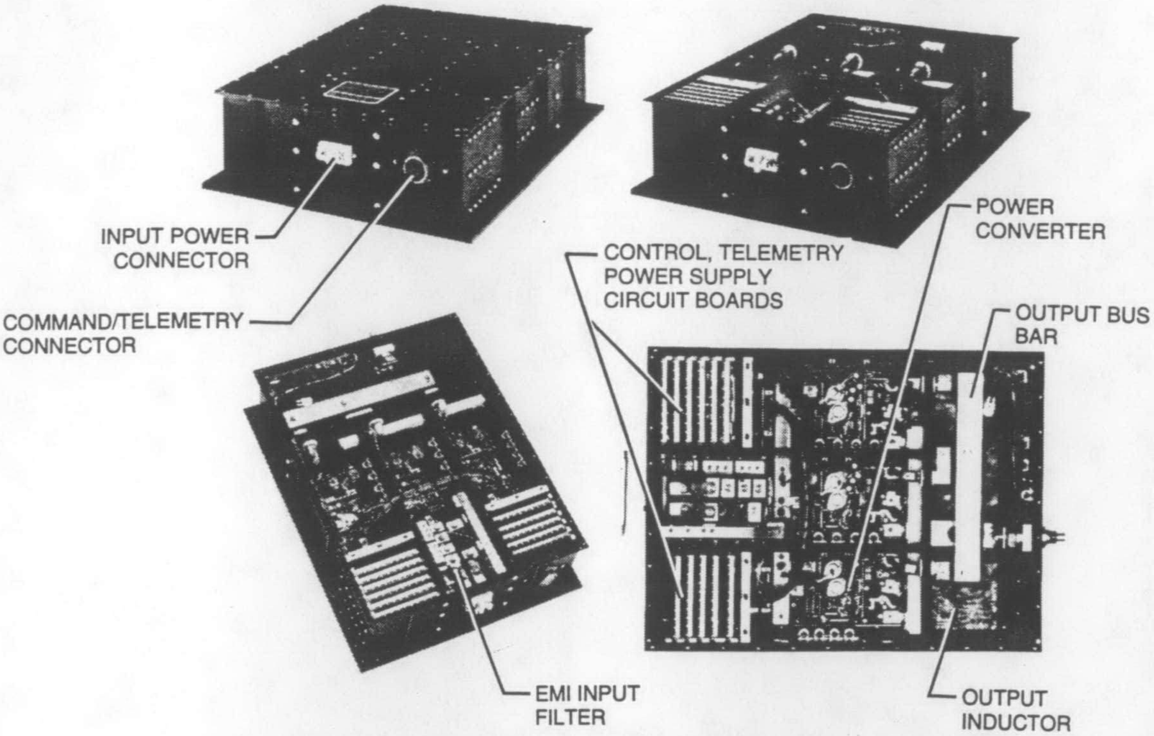


**Fig. 5. Engineering Model PCU.**

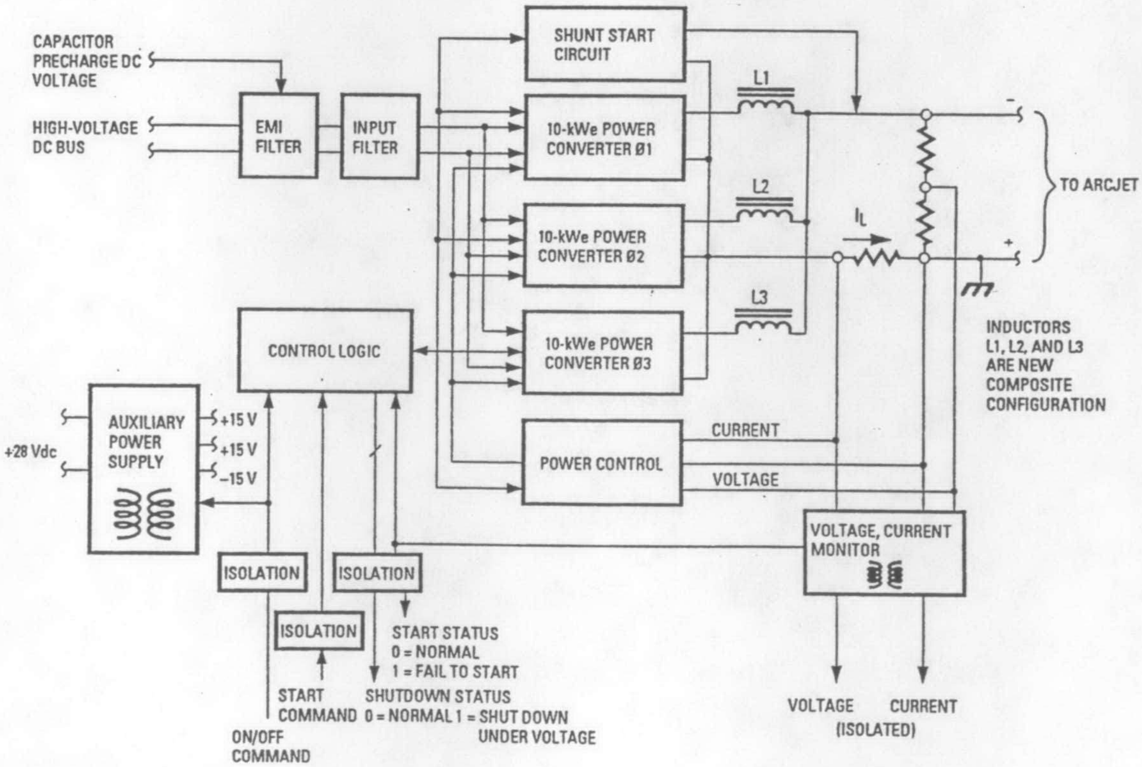


**Fig. 6. PCU Power Converter 26-kWe Block Diagram.**

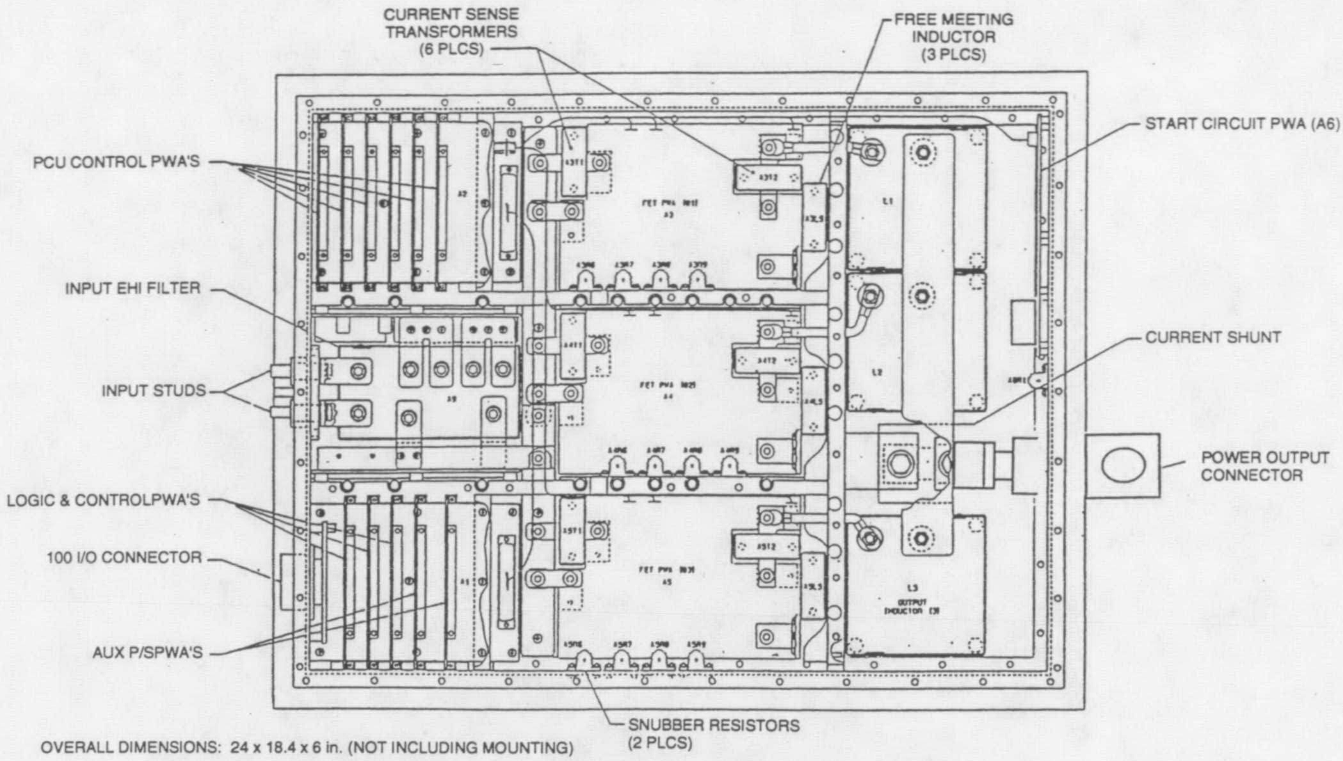


**Fig. 7. Plan View of The ATTD Flight PCU Configuration.**

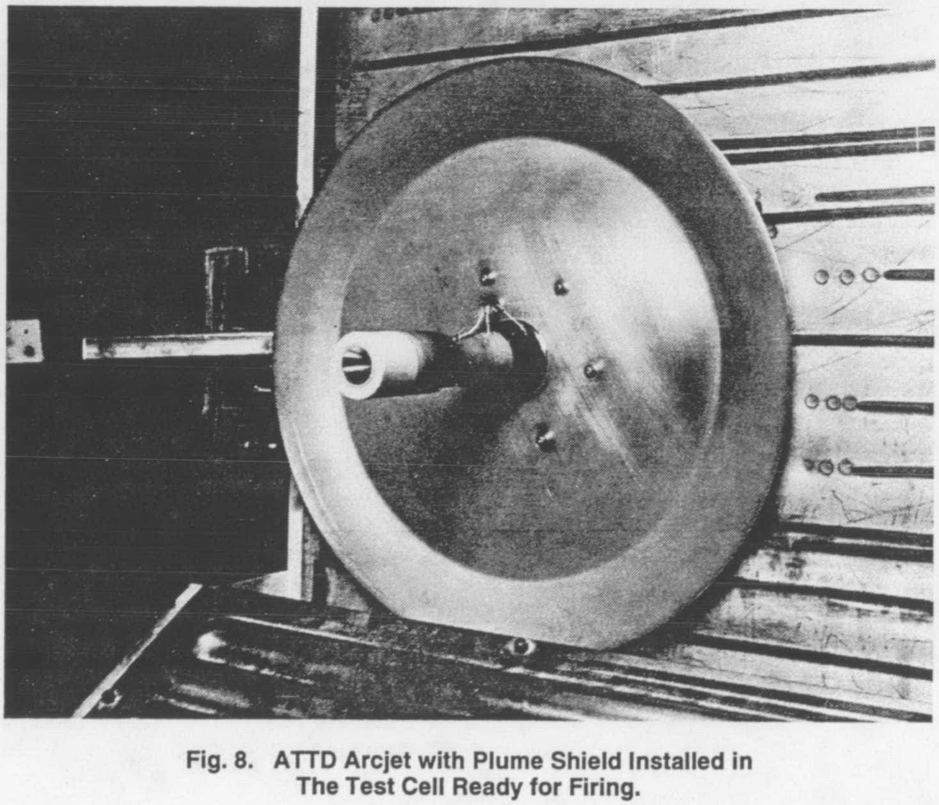

**Fig. 8. ATTD Arcjet with Plume Shield Installed in The Test Cell Ready for Firing.**

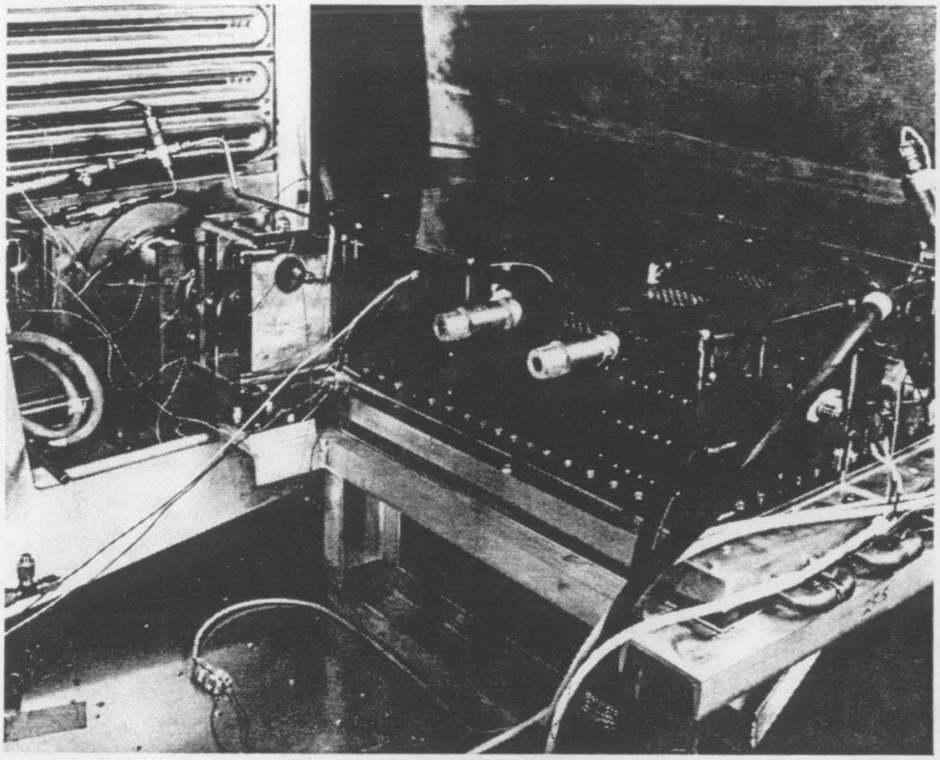

**Fig. 9. ATTD PCU with Secondary Vacuum Enclosure Installed in The Test Cell.**

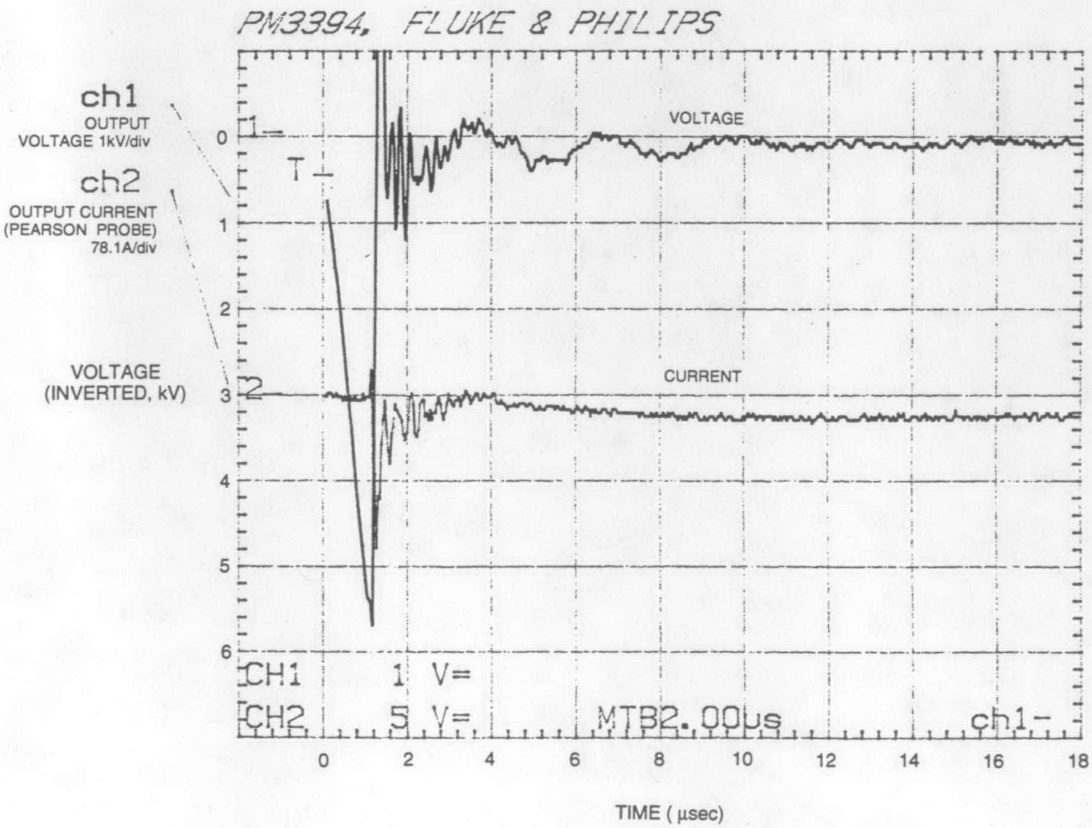


**Fig. 10. ATTD Breakdown and Transition Data.**

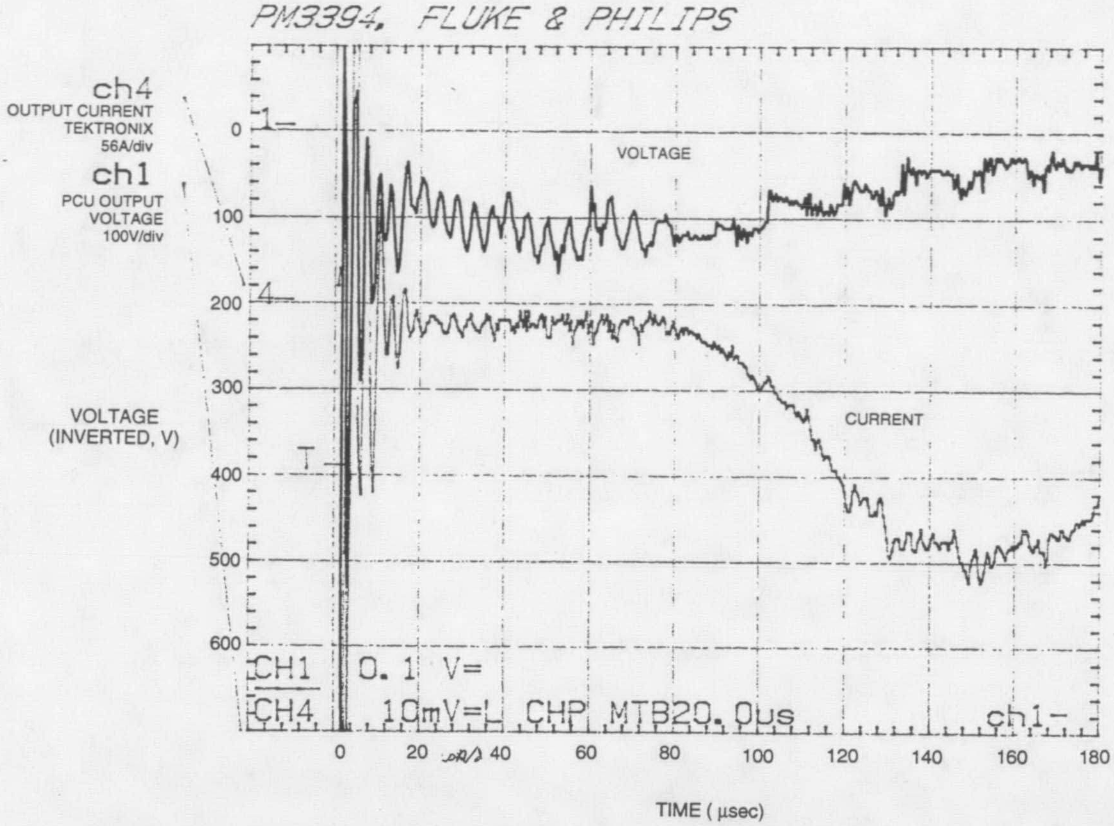


**Fig. 11. ATTD Transition Data**

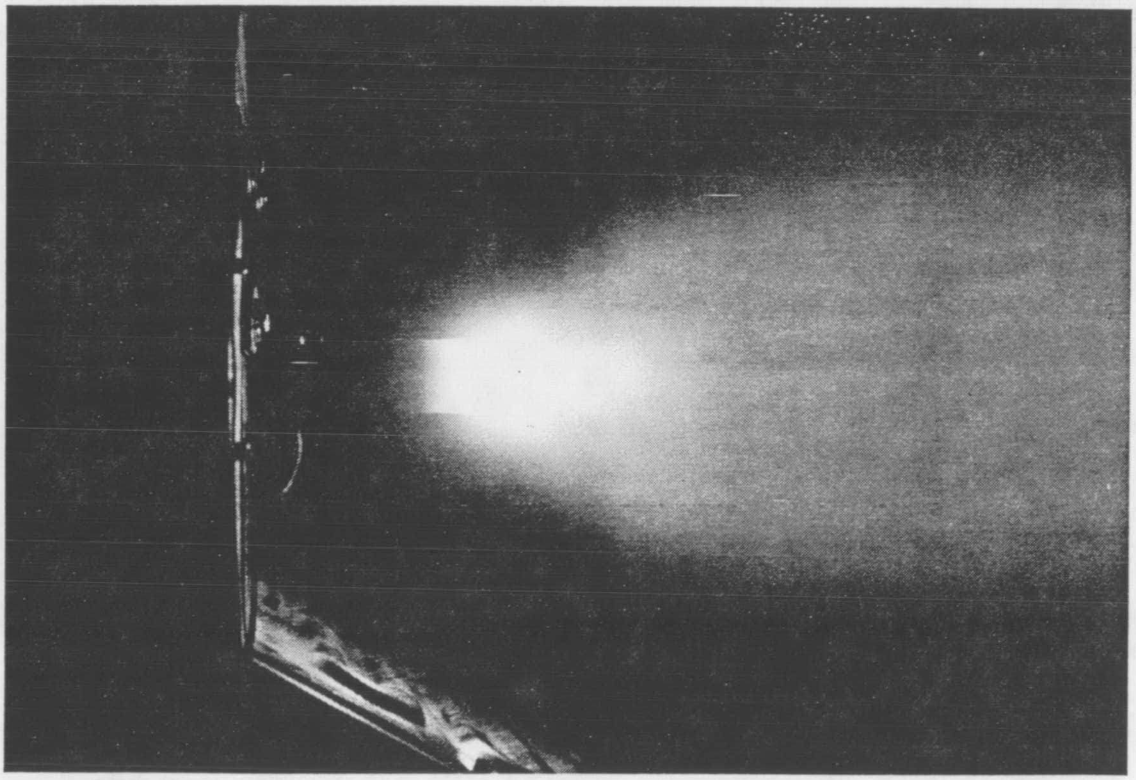

**Fig. 12. ATTD EM" Arcjet During Hot-Fire Testing.**

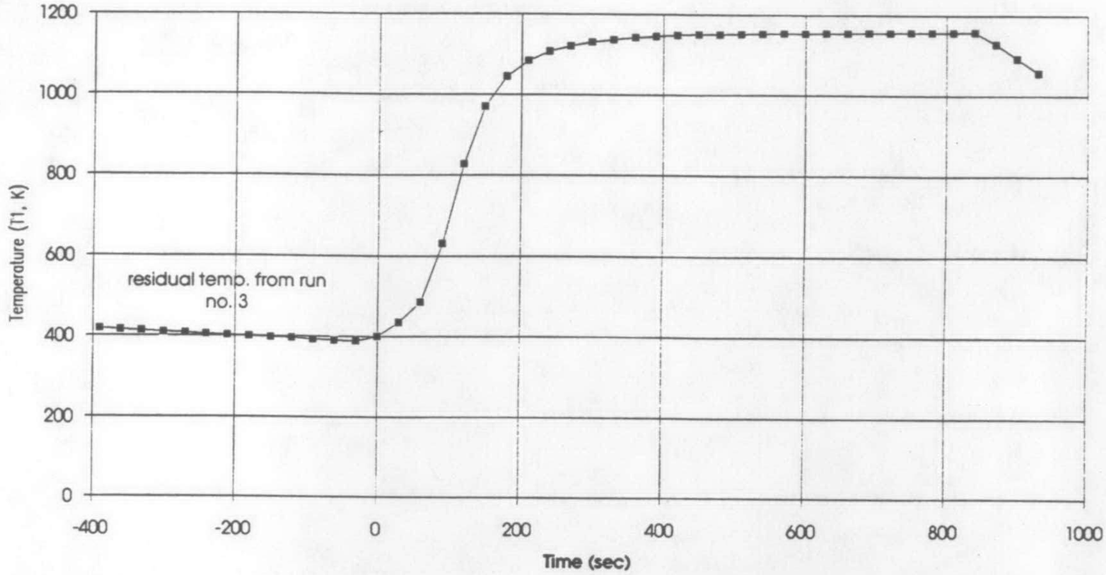


**Fig. 13. ATTD EM" Arcjet Anode Weld Temp. (run no. 4).**

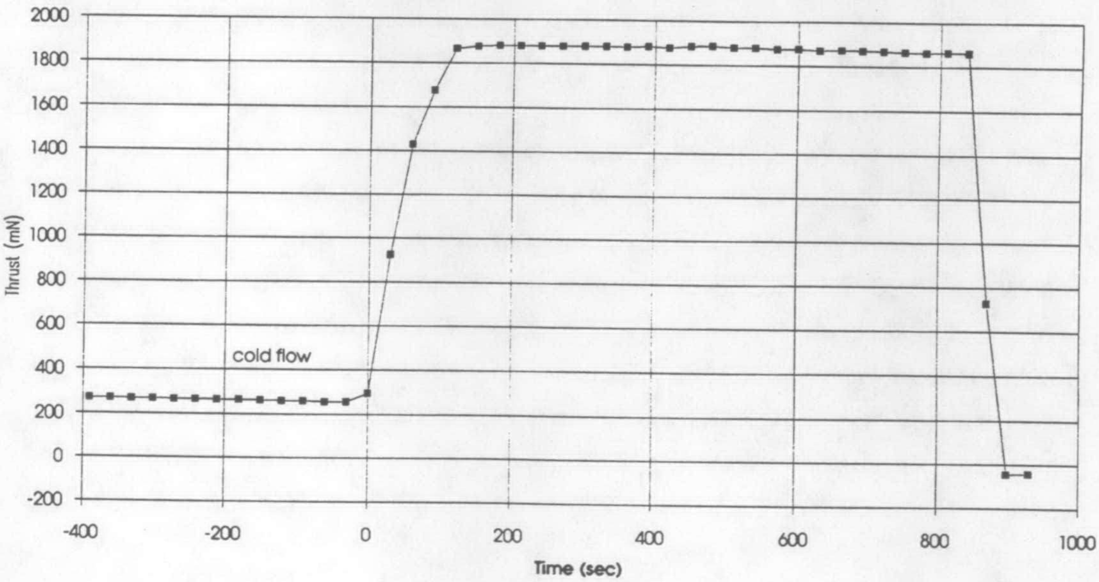


**Fig. 14. ATTD EM" Arcjet Thrust Profile (run no. 4).**