Endurance Test of an Ammonia Arcjet at 10 kWe

J. E. Polk* and K. D. Goodfellow*
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract

An ongoing endurance test of a 30 kWe-class ammonia arcjet operated at 10 kWe has demonstrated 1136 hours of operation at the time of publication and the engine shows no signs of damage that could jeopardize the goal of 1500 hours. The propellant flow rate is 0.170 g/s, and the measured performance has increased from approximately 650 s specific impulse at 36 percent efficiency at the beginning of the test to a current value of 675 s at 39 percent. The voltage increased and the current dropped slightly over the first 400 hours of the test, but the electrical characteristics have remained essentially unchanged since then. Although a depression has formed on the tip of the thoriated tungsten cathode, no whisker growth is evident.

Introduction

Electric Orbit Transfer Vehicles (EOTV's) propelled by hydrogen or ammonia arcjets have the potential to provide greater launch vehicle flexibility, increase payload capability and prolong on-orbit time for commercial and military satellites. The Air Force in cooperation with TRW is now defining the Electric Insertion Transfer Experiment (ELITE), a flight test designed to demonstrate critical technologies required for an operational EOTV, including the arcjet propulsion subsystem, large solar arrays and autonomous guidance, navigation and control in an integrated system. The 1800 kg spacecraft, currently scheduled for launch in September 1995 or later, will be boosted into an initial orbit at 370 km. An ammonia arcjet will then raise the spacecraft to a final altitude of 3900 km, where system degradation in the Van Allen radiation belts will be studied. The electric power for the propulsion subsystem will be provided by solar arrays with an initial output of 10 kWe; however, solar array degradation in the Van Allen environment could result in an end-of-life power of 3-4 kWe. This mission will require an engine lifetime on the order of 1500 hours.

A candidate engine for this flight test is the 30 kWe-class arcjet that has been tested extensively at JPL [1] and is being further developed by the Air Force [2]. Throttling capability of the baseline engine design [3] to power levels at and below 10 kWe was demonstrated in an earlier program at JPL [4], and a modified design offering higher performance was developed recently at the Rocket Research Corporation (RRC) [2]. The endurance of this design at 10 kWe has not yet been explored, however. The longest operation achieved with the baseline design at 30 kWe was 573 hours [1], well below the desired engine lifetime.

The endurance test currently being conducted at JPL is designed to build confidence in the capability of the current engine design. Failure of the arcjet before the targeted 1500 hours of operation will serve to expose failure modes to be corrected in subsequent design modifications. In addition, changes in thruster performance due to component wear are being studied. In this paper the engine design and test facility will be outlined and the behavior of the arcjet over the course of the test discussed.

* Member of the Technical Staff, Member AIAA
Experimental Apparatus

Arcjet Engine

The engine used in this endurance test is a modified version of the D-1E 30 kWe-class design [3], with a constrictor and nozzle geometry developed in testing at RRC [2]. A schematic of the thruster is shown in Fig. (1). The constrictor is 0.381 cm in diameter and has a length-to-diameter ratio of unity. The conical nozzle has a 19° half-angle and an expansion ratio of 40. The cathode axial position was set by first inserting the cathode into the thruster until the conical tip contacted the constrictor inlet, then retracting it 0.610 cm upstream. A 7° lapped joint seals between the pure tungsten nozzle piece and the molybdenum body piece. All other seals in the rear of the engine are accomplished by compressing grafoil gaskets. The nozzle and body are plasma spray-coated with ZrB2, which increases the surface emittance to provide better radiative cooling.

Vacuum Facility

The arcjet is hung from a hollow stainless steel beam mounted in a flange at the top of a stainless steel vacuum facility with an internal diameter of 1.2 m and a centerline length of 2.1 m. The arcjet exhaust is collected by a water-cooled diffuser 16 cm in diameter and pumped by a 6320 l/s Roots blower backed by a 610 l/s Roots blower and a 140 l/s Stokes mechanical pump. The system is capable of achieving a vacuum of approximately two mTorr with no propellant flow, and a pressure of 35 to 38 mTorr for the test flow rate of 0.170 g/s. The exhaust is discharged to atmosphere through a dilution stack.

Power Supplies

The arcjet is powered by a Linde PHC-401 arc-welding power supply, which can provide 400 A at a load voltage of 215 V continuously or 500 A at 180 V with a 50 percent duty cycle. The initial gas breakdown is achieved by application of high voltage from a Quality Transformer Model E202 1500 V power supply. A ballast resistance of 1.875 Ω is used during start-up to suppress current surges. After the engine starts, the ballast resistance is reduced to 0.3 Ω. The power supply current ripple with this ballast resistance is approximately 31 percent at 10 kWe. The current is conducted to the arcjet through coaxial water-cooled mercury pools located under the thruster.

Propellant Feed System

A diagram of the propellant feed system is shown in Fig. (2). The ammonia is stored in a tank located outside the building and delivered to the thruster through stainless steel lines. The ammonia flow may be switched from the large tank to a bottle mounted on a digital scale, which allows gravimetric calibration of the mass flow rate during the endurance test. Two pressure regulators maintain a constant pressure upstream of a micrometer valve which is used to regulate the flow rate. The flow rate can be regulated within ±0.001 g/s of the desired value by the system and is monitored with a Sierra Instruments Side-Trak Model 830 flow meter located upstream of the metering valve. A bypass circuit allows the Sierra meter to be isolated to check for zero drifts during the test. The propellant gas passes through a plenum bottle on top of the tank before entering the chamber through a flange at the top. The propellant flows through a stainless steel tube in the hollow beam from which the arcjet is suspended and enters the engine through the cathode feedthrough at the rear. A parallel system, used in starting the arcjet, supplies argon from a cylinder located near the vacuum tank. The argon mass flow rate is measured and regulated using a Sierra Model 830 automatic flow controller.

Diagnostic Equipment and Data Acquisition System

The thruster voltage, current, thrust, propellant mass flow rate, tank pressure, plenum pressure, feed system pressures, arcjet temperature, and various facility temperatures are continuously monitored with a Hewlett-Packard 3421A Data Acquisition/Control Unit and an HP9836 computer. The system allows unattended operation, shutting down the facility when specified engine or facility parameters exceed upper or lower bounds or when a computer failure occurs.

The arcjet voltage is measured differentially with
Figure 1: 30 kWe-class arcjet design used in the endurance test at 10 kWe.

Figure 2: Arcjet propellant feed system.
leads mounted near the cathode and the anode. When corrected for the 2.5 mΩ resistance between the measurement point and the engine, the measured values are accurate within ±0.2 percent. The current is determined by measuring the voltage drop across a 505.6 µΩ coaxial shunt with an accuracy of ±0.10 percent. A variable-capacitance type transducer mounted in a flange on the top of the tank is used to determine the tank pressure. This gauge has a range of 0–10 Torr and is capable of measuring the pressure to within ±0.5 percent. The pressure upstream and downstream of the metering valve and at the inlet to the vacuum chamber are monitored with Teledyne-Taber pressure transducers. The pressure measured at the tank inlet is referred to as the "plenum pressure" and is approximately equal to the pressure in the arcjet discharge chamber.

Relative measurements of the engine nozzle temperature were made continuously with a Raytek optical pyrometer to monitor engine health. In addition, quantitative measurements at the six locations along the nozzle and body indicated in Fig. (3) were taken periodically with a Leeds and Northrop disappearing filament-type pyrometer. In the temperature range of these measurements the uncertainty is ±6-8°C.

The thrust is determined by measuring the deflection of the cantilevered beam from which the arcjet is hung with a linear variable differential transducer (LVDT). The assembly housing the LVDT and the cantilevered beam is enclosed in a water-cooled jacket to minimize thermal shifts. The mercury pools used to transfer power to the arcjet mechanically isolate it from the power leads. A set of known weights is used to calibrate the thrust stand, and periodic tests of the calibration consistently indicated that the standard error of the measurement is approximately ±2 g. This uncertainty arises primarily because of hysteresis in the thrust stand motion. However, the largest source of error in the thrust measurements performed during the endurance test is due to thermal drift. Previous tests [4] indicated that the thermal drift is 5±5 g. In this test the engine was voluntarily shut down to check the zero drift once, and subsequent shutdowns that occurred because of facility problems provided further opportunities to estimate the magnitude of the thermal shifts.

The Sierra brand thermal mass flow meter has been calibrated by Dick Munns Company in Los Alamitos, California using rotameters traceable to NBS standards and independently at JPL under the conditions of operation. The JPL calibration tests were performed at a given flow rate set point by measuring the mass loss from an ammonia cylinder over a period of time. The testing time varied from two to four hours depending on the flow rate considered; the weight removed from the cylinder was typically about 1.5 kg for each test. The weight versus time was then curve-fit to determine the average flow rate. The measurements are subject to zero drifts, apparently due to cooling by the expansion of ammonia in the meter or controller [4], but when corrected for the measured shifts all calibrations agree well. All calibrations performed during the last year are shown in Fig. (4). The results of two gravimetric calibrations performed during the endurance test are also included.

Later in the test, a Questar telescope was set up to view the engine nozzle and constrictor along the centerline through windows in the back of the vacuum chamber and the diffuser. A Nikon camera was used periodically to record still images of the end view and the dynamic behavior of the arc was periodically recorded on video tape with a Cohu video camera. An HP 54111D digitizing oscilloscope was also added later in the test to monitor the current and voltage waveforms. The current and voltage were measured differentially near the vacuum chamber feedthroughs. A Tektronix A6902B Isolator was required to reject the common mode signal from the voltage.
The Endurance Test

A power level of 10 kW was chosen for the endurance test because it represents the most demanding condition encountered in the ELITE mission. An ammonia mass flow rate of 0.170 g/s was chosen to yield a specific impulse exceeding 600 s on the basis of preliminary performance measurements made by RRC at 10 kW with this nozzle and constrictor design [2]. The operating procedures that are being used in this test will be described in this section following a discussion of initial difficulties with external arcing that helped define the subsequent start procedure. The history of test interruptions and the behavior of the engine over the first 1136 hours of operation will then be presented.

Initial Problems With External Arcing

The endurance test was initially plagued by external arcs to the propellant feed line, as shown in the summary of the test starts and interruptions given in Table (1). The first ten test interruptions were associated either with discharges in the rear of the engine or with operation on argon to preheat the engine before starting on ammonia. The propellant feed line exits from the thrust beam near the engine and forms a U-shaped segment before entering the engine at the cathode feedthrough. In the initial configuration, a ceramic tube located in the upper leg of the U-shaped section electrically isolated most of the feed line. However, most of the U-shaped segment was at cathode potential. The discharges often resulted in the destruction of a swagelock fitting near the propellant line inlet. The thruster component serving as anode for these arcs could not be identified, however.

The engine seemed particularly susceptible to these external discharges when started directly on ammonia without initially preheating the engine for several minutes on argon. External arcs could be avoided during engine starting by preheating, but continued to occur after only a short period of operation on ammonia. The higher breakdown voltages required for direct ammonia starts with a cold engine and small leaks in the fitting that appeared as the engine temperature increased may explain this behavior. Various attempts to insulate the fitting with cylindrical
boron nitride enclosures were unsuccessful. The feed line was ultimately modified so that the ceramic isolator appeared in the lower leg of the U-shaped piece, leaving only a short segment of the line at cathode potential. This section and the ceramic tube were then enclosed in a boron nitride cylinder vented on the side furthest from the engine. This modification allowed operation without external discharges.

Operational Procedures

Preheating the engine with an argon discharge became a part of the standard start procedure followed throughout the remainder of the experiment because of the susceptibility to external arcing with direct ammonia starts. In addition, very reliable starts with argon had been demonstrated in previous testing with a similar engine. The start procedure involves establishing an argon flow rate of 0.351 g/s and then engaging the Linde power supply at a controller setting of 300 (arbitrary units) with a ballast resistance of 1.875 Ω. When this is insufficient to achieve breakdown, the voltage from the high-voltage start supply is ramped up until an arc is initiated. Under these conditions the discharge current is typically about 55 A and the voltage is about 25 V. After the start, the ballast resistance is reduced to 0.3 Ω in two stages. First a 0.450 Ω resistor and two 0.225 Ω resistors are switched out of the circuit and the current allowed to stabilize, then the final three 0.225 Ω resistors are removed. The engine current is then increased to 150–160 A.

When the engine glows bright orange, typically after 5–9 minutes of operation, it is shut off. The ballast resistance is then increased to its full value, an ammonia flow rate of 0.200 g/s established and the Linde power supply set at 350. Application of high voltage from the start supply results in an arc at about 41 A and 117 V. The ballast resistance is then decreased to 0.3 Ω, the current increased and the mass flow rate set at 0.170 g/s. During the start on argon, the plume flickers for approximately 10–15 s until the cathode is warm. Rotation of the plume sometimes occurs during the ammonia starts, but the plume quickly stabilizes as the power is increased. No signs of constrictor or anode damage during startup on either argon or ammonia have been observed.

A complete facility check is performed four times daily to correct potential facility problems, monitor engine health and adjust the engine power or mass flow rate, if necessary. Pump operation; cooling water temperatures, pressures, flow rates and chemistry; power supply voltage and current; and propellant feed system pressures are recorded to detect any changes that might signal potential problems. The arc position in the constrictor and the condition of the nozzle and constrictor exit are monitored with the telescope. The external engine temperatures are also measured daily, and in the latter part of the test the engine current and voltage waveforms have been checked daily. For the first few hundred hours of the test, the engine power was adjusted often in an attempt to maintain 10 kWe. As in previous long duration tests with the Linde power supply, the power fluctuates with a period of 24 hours, perhaps due to a day-night cycle in the grid voltage [1]. Because this results in excursions of only about ±0.25 kWe, attempts to correct for the fluctuations were abandoned and subsequent adjustments made only to maintain an average of 10 kWe. The mass flow rate tends to drift by no more than about ±0.001–0.002 g/s, and is typically adjusted when not at the nominal value.

The specific impulse and efficiency are particularly sensitive to the measured thrust and mass flow rate. The thrust stand and mass flow meter responses to the engine thrust and flow rate are linear, and both the slope and the zero of the calibration can potentially drift during long-duration tests. In frequent tests conducted by isolating the Sierra mass flow meter, the output at zero flow rate has been found to vary between −0.002 and −0.003 g/s. The calibrations shown in Fig. (4) demonstrate that the slope of the meter response is also stable over long periods of time. Several gravimetric calibrations have been conducted during the endurance test to verify the indicated mass flow rate. These tests, performed at cumulative operating times of 321 and 392 hours yielded values of 0.170±0.0002 g/s and 0.169±0.0003 g/s. The slope of the thrust stand calibration line has also been checked periodically, and the results are displayed in Table (2). One voluntary test interruption was performed after 26 hours 50 minutes of operating time to measure the thrust stand offset due to thermal drift. Several involuntary shutdowns provided additional opportunities to measure the zero shift, yielding the values shown in Table (2).
Table 1: Engine Start and Shutdown History

<table>
<thead>
<tr>
<th>Start Date</th>
<th>Start Time</th>
<th>Propellant</th>
<th>Duration of Run (h:m)</th>
<th>Cumulative Operating Time at Shutdown (h:m)</th>
<th>Cause of Shutdown</th>
<th>Duration of Shutdown (h:m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/24/91</td>
<td>16:13</td>
<td>NH₃</td>
<td>-</td>
<td>-</td>
<td>External Arc</td>
<td>0:02</td>
</tr>
<tr>
<td>7/24/91</td>
<td>16:15</td>
<td>NH₃</td>
<td>0:02</td>
<td>0:02</td>
<td>Voluntary</td>
<td>0:05</td>
</tr>
<tr>
<td>7/24/91</td>
<td>16:22</td>
<td>NH₃</td>
<td>0:14</td>
<td>0:16</td>
<td>External Arc</td>
<td>39:58</td>
</tr>
<tr>
<td>7/26/91</td>
<td>8:34</td>
<td>NH₃</td>
<td>-</td>
<td>0:16</td>
<td>Voluntary</td>
<td>0:07</td>
</tr>
<tr>
<td>7/26/91</td>
<td>8:41</td>
<td>NH₃</td>
<td>0:02</td>
<td>0:18</td>
<td>External Arc</td>
<td>0:05</td>
</tr>
<tr>
<td>7/26/91</td>
<td>8:48</td>
<td>Ar</td>
<td>0:02</td>
<td>0:20</td>
<td>Voluntary</td>
<td>0:01</td>
</tr>
<tr>
<td>7/26/91</td>
<td>8:51</td>
<td>NH₃</td>
<td>0:29</td>
<td>0:49</td>
<td>External Arc</td>
<td>25:46</td>
</tr>
<tr>
<td>7/27/91</td>
<td>11:06</td>
<td>Ar</td>
<td>0:09</td>
<td>0:58</td>
<td>Voluntary</td>
<td>0:02</td>
</tr>
<tr>
<td>7/27/91</td>
<td>11:17</td>
<td>NH₃</td>
<td>0:17</td>
<td>1:15</td>
<td>External Arc</td>
<td>0:03</td>
</tr>
<tr>
<td>7/27/91</td>
<td>11:37</td>
<td>NH₃</td>
<td>1:13</td>
<td>2:28</td>
<td>External Arc</td>
<td>68:26</td>
</tr>
<tr>
<td>7/30/91</td>
<td>9:16</td>
<td>Ar</td>
<td>0:07</td>
<td>2:35</td>
<td>Voluntary</td>
<td>0:02</td>
</tr>
<tr>
<td>7/30/91</td>
<td>9:25</td>
<td>NH₃</td>
<td>24:15</td>
<td>26:50</td>
<td>Voluntary</td>
<td>0:03</td>
</tr>
<tr>
<td>7/31/91</td>
<td>9:43</td>
<td>NH₃</td>
<td>401:12</td>
<td>428:02</td>
<td>Pump Failure</td>
<td>151:56</td>
</tr>
<tr>
<td>8/22/91</td>
<td>10:51</td>
<td>Ar</td>
<td>0:06</td>
<td>428:08</td>
<td>Pump Failure</td>
<td>203:07</td>
</tr>
<tr>
<td>8/22/91</td>
<td>10:58</td>
<td>NH₃</td>
<td>81:51</td>
<td>509:59</td>
<td>Voluntary</td>
<td>0:01</td>
</tr>
<tr>
<td>9/03/91</td>
<td>7:57</td>
<td>Ar</td>
<td>0:09</td>
<td>510:08</td>
<td>Brown-out</td>
<td>17:51</td>
</tr>
<tr>
<td>9/03/91</td>
<td>8:09</td>
<td>NH₃</td>
<td>392:57</td>
<td>903:05</td>
<td>Voluntary</td>
<td>0:01</td>
</tr>
<tr>
<td>9/20/91</td>
<td>10:58</td>
<td>Ar</td>
<td>0:08</td>
<td>903:13</td>
<td>Unknown</td>
<td>0:07</td>
</tr>
<tr>
<td>9/20/91</td>
<td>11:07</td>
<td>NH₃</td>
<td>101:23</td>
<td>1004:36</td>
<td>Voluntary</td>
<td>0:02</td>
</tr>
<tr>
<td>9/24/91</td>
<td>16:38</td>
<td>Ar</td>
<td>0:05</td>
<td>1004:41</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>9/24/91</td>
<td>16:45</td>
<td>NH₃</td>
<td>131:19</td>
<td>1136:00</td>
<td>Pump Failure</td>
<td>-</td>
</tr>
</tbody>
</table>

Test Shutdown History

All of the brief argon runs listed in Table (1) were voluntarily terminated after completion of engine preheating. The ammonia test interruptions tabulated in the first half of the list occurred as a result of the problems encountered with external arcs, as described above. During the three longest interruptions that occurred at the beginning of the test the vacuum chamber was opened to repair the propellant feed line. The engine had to be completely disassembled after the external arc occurring at 49 minutes of cumulative operating time. The only voluntary interruption of an ammonia run was performed after 26 hours 50 minutes to measure the thrust stand zero shift.

Shortly after 428 hours of operating time the 610 l/s Roots blower failed, and an automatic experiment shutdown occurred when the tank pressure exceeded 50 mTorr. Examination of the blower interior revealed a thick brown coating with the consistency of molasses. This fluid was also found in the large blower. After exposure to air for several days the coating dried to form a cracked yellow-brown film. Analysis indicated that the substance was an amine that was probably produced in a reaction between ammonia or ammonia dissociation products and pump oil. Oil appears to be leaking from the gear box into the pumping chamber of the large Roots blower through the bearing seal. The viscous liquid is apparently formed in the large blower and flung into the smaller. The small Roots blower was replaced and the test resumed after about four days. The tank was opened during this shutdown to realign the thrust stand calibration mechanism.

After an additional 81 hours of operation the replacement blower seized, again because of contamination by the viscous fluid. During this shutdown the thick liquid was cleaned from both blowers, which
Cumulative Operating Time | Calibration Slope | Zero Shift (g) | Corrected Thrust (g)
--- | --- | --- | ---
0:49 | - | -4.1 | 111.1
26:50 | - | 5.5 | 109.4
206:00 | 0.959 | - | -
296:00 | 0.964 | - | -
428:00 | 0.998 | - | -
453:00 | 0.972 | - | -
509:59 | - | 5.5 | 109.5
636:00 | 1.000 | - | -
684:00 | 0.899 | - | -
766:00 | 1.008 | - | -
854:00 | 1.008 | - | -
903:05 | - | 6.0 | 116.3
955:00 | 1.000 | - | -
1004:36 | - | 3.0 | 114.7
1059:30 | 0.991 | - | -
1136:00 | - | -2.1 | 115.2

Table 2: Thrust stand calibration checks. The calibration slope is the ratio of applied weight to indicated thrust.

required that the tank be vented.

A momentary power dip occurring 903 hours into the test caused an automatic shutdown. The vacuum chamber was not vented during this interruption, and the engine was restarted the next morning. After 1004 hours an automatic shutdown occurring because several parameters simultaneously went out of the set tolerances. Apparently the arc was extinguished, but the cause is unknown. The engine was restarted immediately after the shutdown with no problem.

After a total run time of 1136 hours the small Roots blower once again failed. Both blowers are contaminated with the thick liquid and are currently being cleaned. The test will be resumed as soon as the fluid has been removed, and a major overhaul to repair the seals will be undertaken at the end of this experiment.

Engine Behavior

The record of engine power consumption is plotted in Fig. (5). The day-night cycles produce a power fluctuation about 10 kWe with a peak-to-peak amplitude of about 0.5 kWe. This cycle is reflected in the current and voltage histories, shown in Figures (6) and (7). The day-night cycle results in fluctuations with an amplitude of about 5–6 A in the discharge current, but only about 2 V in the voltage. The mean current dropped from an initial value of about 98 A to 94 A in the first 400 hours of operation. However, since the 400 hour point the mean current has remained within approximately 1 A of 94 A. The voltage, related to the current by a negative characteristic, increased during the first 400 hours from about 101 V to 107 V. Since then it has remained within 1–2 V of 107 V.

In contrast, the plenum pressure has increased steadily from an initial value of 618 Torr to about 646 Torr over the 1136 hours of operation achieved so far, as shown in Fig. (8). The rise is approximately linear, with a slope of 0.025 Torr/h.

The brightness temperatures measured along the body and nozzle are plotted in Fig. (9). The temperature at each station is approximately constant except for a general dip of about 50°C occurring between 350 and 500 hours. Because there are no visual references to identify stations 2 and 5 on the engine the position at which these measurements are actually made varies more than the other stations, leading to more scatter in the data. The measurements at these two stations serve primarily to demonstrate that the temperature decreases monotonically toward the back of the engine. The temperature decreases slowly along the nozzle, as indicated by the measurements at stations 1 and 2, and drops significantly only near the joint with the cooler body.

The measured thrust is displayed in Fig. (10). The points at which the zero and slope of the thrust stand calibration were checked are indicated by "Z" and "S," respectively. The values measured at these points are recorded in Table (2). The low thrust values shown at the beginning of the history, 428 hours, 510 hours and 903 hours were all measured after restarts when the engine and thrust stand had not reached thermal equilibrium. Several hours after each startup the indicated thrust reached a value of 115–120 g. The calibration slope checks performed at 206 and 296 hours indicate that the increase in indicated thrust at 150–200 hours is the result of a shift in the thrust stand calibration, rather than a real increase in performance. The next step increase at 350 hours
Figure 5: Time history of engine power consumption.

Figure 6: Current vs cumulative operating time.
Figure 7: Voltage vs cumulative operating time.
Figure 8: Plenum pressure time history.
Figure 9: Engine nozzle and body brightness temperature vs cumulative operating time.

Figure 10: Indicated thrust vs cumulative operating time.
may have a similar explanation, but there is no data to confirm this conjecture.

Subsequent slope checks indicate that the calibration slope has remained constant since the thrust stand calibrator was adjusted at the 428 hour point. The increase in indicated thrust at 670 hours appears to reflect a true increase in the thrust, because the thrust stand zero drift measured at 903 hours is not substantially different from that at 510 hours. The subsequent drops in indicated thrust at 903 hours and 1130 hours are primarily due to decreases in the thrust stand zero offset. The thrust measured at the zero check points, corrected for the zero drift and calibration slope change, is shown in the last column of Table (2). The thrust appears to have risen from about 110 g initially to about 115 g, perhaps in the discontinuity noted at 670 hours. The uncertainty in these measurements is on the order of ±5 g. These values imply a specific impulse of about 650 s with an efficiency of 36 percent at the beginning of the test, and 675 s at 39 percent currently. The uncertainty in the calculated quantities is approximately ±35 s for the specific impulse and ±4 percent for the efficiency. This performance is slightly higher than the 622 s specific impulse and 31 percent efficiency measured at the Rocket Research Corporation under similar conditions [2], and will be verified in more controlled performance measurements to be conducted after the endurance test.

There has been no significant visual evidence of engine degradation in the first 1136 hours of operation. After approximately 300 hours of operation the plume was observed to flicker occasionally when viewed from the side. In the view from the end of the tank a bright spot could be distinguished inside the constrictor. The luminosity in this region can be identified with the arc column and the cathode attachment point. At approximately 360 hours this spot was first observed off-center in the constrictor. The spot was also occasionally seen rotating around the engine axis inside the constrictor, although the equilibrium point seemed to be slightly off-center at the 10 o'clock position. The rotational motion is probably correlated with the flickering of the plume. This behavior has continued throughout the test, but does not seem to affect engine operation or performance.

During the shutdown at 428 hours the engine was examined in the tank. The nozzle walls had recrystallized, but were otherwise undamaged. The constrictor also showed no signs of deterioration. A crater approximately 2.5 mm in diameter was visible on the cathode tip. A smaller depression approximately 1 mm in diameter was found on the rim of the larger crater at about the 11 o'clock position. Both craters had rough rims, but the large scale whisker growth found in endurance tests at 30 kW e after several hundred hours [1] was not present. In Fig. (11) the exterior of the nozzle and body are shown on the right, and the nozzle, constrictor and cathode tip are visible in the reflection on the left. The high-emissivity coat-
but there were no distinct crystalline whiskers. Since this interruption the arc behavior has not changed significantly. The bright spot in the constrictor is often observed off-axis, and is occasionally unstable or rotates around the axis. At 831 hours a bright yellow spot was noted at the 12 o'clock position in the nozzle just outside the constrictor exit. After 900 hours another spot appeared near the first, and after the shutdown at 903 hours 3 or 4 small yellow spots were visible. The intensity of the bright points occasionally fluctuates and is often correlated with the arc column motion. This behavior indicates that they are simply reflections of the arc column.

The vacuum chamber has been opened to examine the engine after the shutdown at 1136 hours, and the nozzle and constrictor still appear undamaged. There are tiny crystalline deposits near the constrictor exit that are probably responsible for the bright yellow spots observed during operation. The cathode tip has a large flat or slightly depressed area approximately 3 mm in diameter. A small crater about 1.5 mm in diameter appears at the 5 o'clock position, shifted off-axis by about half of its diameter. Both of the craters are visible in the photograph shown in Fig. (12). There are still no signs of whisker growth from the crater rims.

Figure 12: Photograph of the engine exterior, nozzle, constrictor and cathode tip taken after 1136 hours of operation.

Discussion

In several respects the arcjet behavior in this endurance test is distinctly different from that observed in long tests at 30 kWe [1]. The most significant difference is the increased longevity demonstrated in this experiment. Previous attempts to achieve long-duration operation were thwarted by the development of whiskers on the edge of the cathode emission site that apparently contacted the anode and shorted the engine. Although there have been several opportunities to examine the engine during this test, no signs of whisker growth have been noted. The voltage in this test has also not increased as dramatically as in tests at 30 kWe, where increases of up to 15 V in the first 400 hours were not uncommon. The electrical characteristics of this lifetest engine changed only slightly in the first 400 hours and have since remained essentially constant. The voltage increase has been attributed to an increase in arc column length due to cathode tip erosion, so the voltage plateau in this test suggests that the cathode has achieved a stable geometry.

The increased lifetime demonstrated thus far in this test may be attributable to several changes in operation and geometry. First, operation at lower power decreases the thermal loads on the engine components. The anode in these tests shows a peak brightness temperature just over 1300°C, compared to approximately 2000°C in the baseline engine design operated at 30 kWe. The current demand on the cathode is also reduced from about 300 A to under 100 A. This could result in lower current densities and reduced operating temperatures on the cathode tip, although this cannot yet be experimentally verified.

In addition, the 31 percent current ripple in this test is much higher than in previous endurance runs conducted with a current ripple of 0.2-3.0 percent. Previous experiments at JPL showed no systematic variation in erosion rate or whisker growth over this range of current ripple [1], but recent results from Texas Tech suggest that higher values of current ripple may reduce the cathode erosion rate [5]. However, the authors found evidence of enhanced whisker growth on thoriated-tungsten cathodes with higher ripple. They suggest that the erosion reduction is due to an increase in the cathode emitting area, but the effect of current ripple on the phenomena respon-
sible for whisker growth is unknown.

Finally, the electrode gap in this engine configuration is approximately 3 times longer than in the baseline 30 kWe engine design, so the upstream half of the arc column is not contained inside the constriction. This may allow the arc root to move more freely on the cathode surface. The photographic evidence indicates that the arc often attaches off-center and periodically rotates around the axis, probably on the rim of the central crater. The small crater on the rim of the central depression observed at 428 hours and 1136 hours demonstrates that the off-axis attachment can cause mass loss on the rim. The absence of large whiskers may be a result of the less constricted arc's ability to attach in these regions. In any case, the longer gap delays engine failure due to whisker formation because the filaments must span a larger distance to short the electrodes.

The endurance already demonstrated in this ongoing test provides hope that medium power ammonia arcjets can satisfy the lifetime requirements for orbit transfer missions. The engine shows no signs of deterioration that could prevent reaching the 1500 hour goal. The next step is to demonstrate the required lifetime with realistic stop-start cycles and engine throttling.

Acknowledgements

The research described in this paper was conducted at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Air Force Phillips Laboratory through an agreement with the National Aeronautics and Space Administration.

The authors would like to thank W.R. Thogmartin, R.L. Toomath and A.G. Owens for their technical assistance and rapid, effective response to facility problems. The authors would also like to acknowledge the assistance of C.E. Garner, T.J. Pivirotto, R.L. Toomath and S.D. Leifer in performing the after-hours facility checks. Joe Cassady at Rocket Research also provided welcome advice in properly starting the new arcjet design.

References


