FLIGHT QUALIFICATION OF A 1.8 KW HYDRAZINE ARCJET SYSTEM

R. D. Smith*, S. E. Yano**, K. Armbruster†, and C. R. Roberts‡
Rocket Research Company, Redmond, WA, USA,

D. A. Lichtin§, and J. W. Beck§ §
Martin Marietta Astro Space, Princeton, NJ, USA

Abstract

The MR-508 hydrazine arcjet system has completed flight qualification at Rocket Research Company under sponsorship of Martin Marietta Astro Space (Astro Space), for use on Astro Space Series 7000 communication spacecraft. All specification requirements have been met or surpassed. Results of the complete qualification test sequence are summarized, with emphasis on the system-level performance and life tests. Two system-level, duty-cycle life tests (with >50% qualification margin) were successfully completed. The first, using ambient temperature propellant and a flight-type, engineering development model PCU, was voluntarily terminated after accumulating 703,424 N-sec (158,144 lbf-sec) total impulse and demonstrating a life test average Isp of 538 sec. The second life test used worst-case (43°C) propellant, and demonstrated 744,217 N-sec (167,315 lbf-sec) and 545 sec Isp in the process of successfully completing the PCU qualification. The two life tests demonstrated 898 hrs and 989 hrs of duty-cycle thruster operation, equivalent to approximately 16 and 17 years of on-orbit operation of a Series 7000 class spacecraft. Component-level tests included vibration, thermal vacuum testing, EMI/EMC evaluation, and cable corona testing. Protoflight spacecraft-level integration testing of the AJS, performed on the first Series 7000 flight spacecraft, has also been successfully completed, with the AJS meeting or exceeding all performance requirements. Also summarized are the results of spacecraft impact evaluation testing carried out using development hardware. These evaluation tests, conducted outside of the formal qualification test program, successfully retired concerns about potential effects of arcjets on spacecraft surfaces (including solar arrays), discharging, and payload operation.

Introduction

In 1988, Martin Marietta Astro Space (Astro Space), then General Electric Astro Space Division, and Rocket Research Company (RRC) initiated a program to bring hydrazine arcjet technology to flight readiness for North-South station keeping applications on geosynchronous communications satellites. This effort is now complete. The MR-508 arcjet system is fully flight qualified, with all specification requirements having been met or exceeded. Flight arcjet systems have successfully completed protoflight integration testing on the first Astro Space Series 7000 spacecraft, and the first launch is scheduled for late 1993.

The qualification and spacecraft integration programs which the MR-508 Arcjet System (AJS) has undergone to demonstrate its flight readiness are depicted in Fig. 1. The formal AJS qualification test program carried out at RRC included both component and system-level tests, with the end result being the successful completion of two duty-cycle life tests to greater than 150% of the mission throughput requirement. Another important series of tests was carried out at NASA LeRC, using a development arcjet system, to assess the potential impacts of arcjet operation on spacecraft and solar array surfaces, spacecraft discharging, and payload operation. While not part of the formal qualification test program, these tests were important confidence builders in that they evaluated potential interactions between the arcjet and the spacecraft and found them to be benign or even beneficial. The arcjet system described herein is in fact a subsystem at the spacecraft level, and first article spacecraft integration testing is an important step in the verification of flight readiness for the MR-508 design. Spacecraft-level integration and protoflight testing of the first Series 7000 spacecraft is now complete, and the AJS met or exceeded all performance requirements.

This paper summarizes the qualification test program depicted in Fig. 1, with emphasis on the system-level performance and life test results. The combined performance and life requirements of 502 sec mission average specific impulse (Isp) and 653,855 N-sec represent the most challenging aspect of this qualification program. The successful
The elongated shape of the thruster body results from thermal management considerations: heat conduction from the anode region back to the gas generator and to the power cable must be minimized. The primary thruster heat rejection mode is radiation from the anode. Radiation from the hot anode is enhanced by a high emissivity coating which plasma sprayed onto the anode and downstream portion of the barrier tube. Most of the energy is radiated away from the spacecraft. Extensive thermal analysis of hot bias conditions has shown that thermal interaction with the spacecraft is a significant achievement of the MR-508 design/qualification program. The two life tests demonstrated total impulses equivalent to approximately 16 and 17 years of on-orbit operation of a Series 7000 class spacecraft, while demonstrating mission average Isps of 538 sec and 545 sec, respectively. Moreover, the second life test was run at a worst case, constant propellant inlet temperature of 43°C, thereby demonstrating the robustness of the MR-508 design.

While this paper provides an overview of the program elements depicted in Fig. 1, space does not permit a complete reporting of all of the qualification test results. Elements of the overall qualification sequence have been reported elsewhere. At various points within the paper, particularly regarding component-level test results, the reader is referred to the appropriate references for further details.

**Description of The Arcjet System**

The Arcjet system (AJS) is comprised of an Arcjet Thruster (AJT), a Power Conditioning Unit (PCU) and a power cable assembly (Fig. 2). The system mass of approximately 5.5 kg is broken down as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arcjet Thruster</td>
<td>0.9</td>
</tr>
<tr>
<td>PCU</td>
<td>4.1</td>
</tr>
<tr>
<td>Cable/Connectors</td>
<td>0.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5.5</td>
</tr>
</tbody>
</table>

The Series 7000 spacecraft design includes four AJS, with two thrusters firing simultaneously for N-S station keeping maneuvers, and a redundant pair as backup. A typical duty cycle would require steady-state firings of approximately one hour duration, approximately once per week. Each pair of thrusters is capable of completing the entire mission with substantial (>50%) margin, thus complete redundancy is obtained.

**Arcjet Thruster**

The flight arcjet thruster design (Fig. 3) is a derivative of a design developed prior to 1989 in several RRC and NASA/RRC programs. The arcjet configuration was made similar to RRC’s flight qualified Electrothermal Hydrazine Thrusters (EHTs) in order to simplify spacecraft integration, utilize existing flight qualified components where possible, and provide the most compact envelope. The location of the propellant valve and gas generator to the side of the arcjet body also provides maximum compactness and direct access to the electrical pass through for power cable installation.

Propellant is supplied to the thruster through a fluid restrictor which regulates propellant flow rate and thruster operating pressure by creating a large pressure drop between the spacecraft propellant feed system and the thruster. The thruster control valve is a solenoid actuated dual redundant seat valve which controls propellant flow to the gas generator in an on/off mode. The gas generator is an improved version of a design originally flight qualified on previous EHT programs. Thermal design modifications were made to both the gas generator and the system configuration to enhance gas generator life capability.

Hydrazine decomposition gases flow from the gas generator to the arcjet body through a delivery tube. Once inside the body these gases flow through annular passages, regeneratively cooling the barrier tube that supports the anode. Near the nozzle end of the body the gases pass through a vortex injector that creates a strong swirling flow field around the cathode. Energy is added to the gas stream principally by ohmic heating in an arc column which originates from the cathode tip and is swept through the anode constrictor by the swirling flow to attach to the diverging portion of the nozzle.

Current provided from the PCU by the power cable passes down the cathode which is concentrically located within the body, crosses to the anode through the arc column and returns to the cable by way of the body wall. Electrical isolation between the cathode and anode is provided by ceramic insulators which also support the cathode. A titanium mounting structure couples the thruster components together and provides a high degree of thermal isolation from the spacecraft. While typical heat rejection to the spacecraft is less than 10 W, the thruster is designed and tested for steady state operation when thermally isolated from the spacecraft.

The elongated shape of the thruster body results from thermal management considerations: heat conduction from the anode region back to the gas generator and to the power cable must be minimized.
manageable, and thermal integration with the spacecraft is therefore straightforward.

Power Conditioning Unit

The PCU is designed and built by Pacific Electro Dynamics (PED), which is co-located with RRC in Redmond, WA, and along with RRC, a part of Olin Aerospace Division. The PCU is a pulse-width modulated, switch-mode power converter which provides regulated DC power at 1620 W to the negative-impedance arc during steady-state operation, over an input voltage letdown of 96-65V, and over a thruster (arc) voltage range of 90-140V. Measured efficiencies range between 91 and 94.5% over this combination of input and output voltage ranges. The unit will therefore reject less than 160 W of thermal energy to the spacecraft, and will draw less than the maximum 1800 W of power from the spacecraft, under all operating conditions. The PCU also delivers a short high voltage pulse to initiate arch break down on thruster startup. The PCU is designed for high efficiency, low mass, high reliability, and radiation tolerance. The unit's EMI performance meets MIL-STD-461 tailored for this spacecraft application. The input filter is designed to reject spacecraft noise and prevent internal switching noise from reaching the spacecraft battery bus.

The power converter is an advanced design based on a push-pull buck regulator with transformer isolation between the input and output. Constant power is achieved through pulse-width modulation based on a fast, internal constant-current loop, and a slower, outer constant-power loop. Voltage and current sensors provide feedback signals to the control circuitry to ensure proper power regulation. The control circuitry also processes command and telemetry signals. An output inductor is used both to smooth the output current waveform and for generation of the start pulse. S-level active components are used throughout the PCU. The MTBF for the unit is predicted to be greater than 1,000,000 hours. The PCU design is described in more detail in Reference 3.

Switching is achieved by two identical custom, power hybrid microcircuits that consist of multiple, large-area MOSFET power transistor die to reduce on-resistance. The hybrid microcircuits are housed in hermetic packages which are mounted directly to the PCU base plate in order to provide a good thermal sink for heat generated by switch losses. Lot acceptance testing at both the component (MOSFET) and hybrid levels for these S-level (now K-level) devices is tantamount to qualification testing of every lot of power hybrids.

Power Cable Assembly

The power cable assembly, designed and manufactured for RRC by Reynolds Industries, consists of a specially manufactured triaxial cable and two end connectors which mate to receptacles on the PCU and arcjet thruster. The center conductor of the cable, which is connected to the arcjet cathode, carries the current output of the PCU to the arcjet. Current is returned through the inner EMI shield which is tied to the anode. The anode is grounded to the spacecraft body as is the PCU chassis. An outer metallic braid provides additional EMI shielding. The flexible cable is approximately 0.64 cm in diameter.

The triaxial cable assembly design is 275 cm in length, and uses radiation cross linked ETFE as the outer and inner jacket material for radiation resistance and light weight. The cable assembly is designed to withstand a total radiation exposure of 2 x 107 Rads minimum over mission life. The connectors and cable assemblies are designed to promote rapid venting on orbit.

Arcjet System Test Program

The AJS qualification test program is depicted in Fig. 4. The formal qualification test program consisted of component level qualification of the AJT, PCU, and Power Cable followed by system level qualification of the AJS through performance and life testing. The original intent of the qualification program was to complete component-level testing of the qualification AJT, PCU, and cable, then join these three components for one system-level performance and life test. However, delays in receipt of S-level components for the qualification PCU necessitated use of a flight-type Engineering Development Model (EDM) PCU for the first (AJT) qualification life test. This EDM PCU is identical in all design and performance respects to the qualification PCU, with the exception that certain non-S components were substituted for schedule compliance. This approach enabled timely completion of the AJT qualification testing (using AJT S/N 001), but also resulted in the need for a second (PCU) life test using the qualification PCU. For this test, a second qualification AJT (S/N 002), identical in all respects to S/N 001, was fabricated. With successful completion of the PCU life test, the end result was effectively a successful two-engine qualification of the AJT. These two tests were identical with the significant exception of different propellant temperatures, discussed below. The first life test is depicted within the AJT test sequence in Fig. 4.
while the second life test is shown at the end of the PCU test sequence.

The cable assembly component-level testing is depicted in the lower sequence of Fig. 4. This testing was carried out by Reynolds Industries, the manufacturer of the hardware, and used a qualification cable assembly, a PCU receptacle, and the electrical hermetic pass through. The latter parts are built into the PCU and arcjet thruster, respectively. Certain environmental tests, however, are best conducted with all three parts mated together into a single, stand-alone test assembly. No PCU or thruster was used in these tests.

The system-level qualification testing of the power cable assembly, PCU receptacle and hermetic pass through were carried out as part of the AJT and PCU qualification tests, as depicted in the first three sequences of Fig. 4. These tests were carried out using qualification cable assembly hardware separate from that used in the environmental tests. This hardware underwent acceptance testing at Reynolds Industries prior to installation into qualification test hardware at RRC.

The component-level arcjet, cable assembly, and PCU testing are described elsewhere. System-level cable qualification is described in this section, and the remainder of the paper will focus on the two system-level performance and life tests, spacecraft integration tests and spacecraft impact tests.

As indicated in Fig. 4, the qualification cable assembly was used for portions of both the AJT and PCU life tests. For the balance of each test, a test cable assembly with a "break-out box" was substituted for diagnostic purposes. This test cable assembly allowed collection of PCU output voltage and current data, such as high speed oscilloscope traces, independent of PCU telemetry.

The hours of life and number of starts accumulated by the qualification cable assembly on each life test are therefore less than the AJT's or PCU's with which they were tested. However, the combined life and starts accumulated by the cable assembly during the two tests are well in excess of the specification requirements. In particular, the qualification cable assembly accumulated approximately 1.8 times the qualification life requirement (1,463 hours) and 1.7 times the number of arcjet starts required for qualification (1,523), with no degradation in performance or appearance.

**AJT Test Apparatus Description**

Qualification test firings were conducted in Cell 10 of the RRC Electric Propulsion Test Facility. Vacuum levels below 4 Pa were maintained with a Stokes 1729 vacuum pump and blower system. Thrust was measured on a swinging arm, null balance thrust stand. This equipment was designed and built at RRC specifically for testing electric propulsion thrusters. A horizontal swing arm which supports the test hardware is fixed to a stationary pylon by torsional flexures at the axis of rotation of the arm. The flexures are used to carry power, propellant, cooling water, and instrumentation signals between the pylon and swing arm. For qualification testing, the thrust stand was calibrated for measurement up to 0.3 N. When installed, the AJT was optically aligned to verify less than 0.5 degree angular displacement of the nozzle axis with respect to the thrust measurement axis. In the range of interest between 0.18 and 0.30 N, measurement uncertainty of better than ±1.5% was maintained.

Propellant flow rate was measured using a Micromotion flowmeter. Water conditioned jackets were installed on the propellant line to maintain inlet temperatures within specification. Hydrazine meeting MIL-P-26536D, Amendment 2, High Purity Grade and high purity helium pressurant were used for all testing. All arcjet system components were mounted on a thermally conditioned plate as shown in Fig. 5. Ceramic standoffs of appropriate thermal conductance were used at the mounting interface to isolate the AJT.

Test control and data acquisition were made via a micro-computer based system which was programmed to remotely control external functions and record data. Long-term unattended operation is permitted by constant monitoring of these test parameters and comparison to set limits. In addition to thrust and mass flow rate, the complete data set included 20 thermocouple inputs, 3 pressure inputs (propellant feed pressure, GG chamber pressure, and vacuum cell pressure), and PCU input and output voltages and currents. Six PCU telemetry outputs were also monitored. In the event of out-of-limit conditions on one or more of the test parameters (for example, due to power grid fluctuations) the test controller can initiate a controlled, orderly shutdown of the test with no damage to the test article or test equipment.

**AJT/AJS Test Results**

**Description of AJT Qualification Tests**

The AJT qualification sequence (Fig. 6) was initiated by first performing the full acceptance test procedure (ATP) required for production hardware. Acceptance level vibration consisted of 3 axes random vibration at 0.10 G2/Hz over a frequency interval of 20 to 2000 Hz (overall level = 14.1 g rms). Standard functional tests were performed following vibration and firing of the AJT. A steady-
state performance map matrix consisting of three propellant feed pressures and two input voltage letdown curves for a total of six firings was then completed and the standard functional tests repeated. Following successful acceptance testing, qualification level vibration was performed. The test levels\(^{(1)}\) were later shown by spacecraft-level vibration testing to be conservative.

Qualification test firings consisted of beginning-of-life performance measurements, duty cycle life, and in the case of AJT S/N 001, end-of-life demonstration of tolerance to several modes of propellant flow interruption as well as propellant feed pressure upper/lower margins.

The life test parameters were established to simulate on-orbit firing requirements. The total AJT firing duration was established by evaluating measured thrust levels at beginning-of-life and predicting required firing time to meet the total impulse specification (653,855 N-sec). A minimum firing time of 830 hours was thus established. Additionally, demonstration of 900 minimum starts was required.

A duty cycle of 60 minutes on/30 minutes off was used. This firing duration approximates an average burn requirement. Specific firing times over the duration of a mission are determined by maneuver \(\Delta V\) requirements and spacecraft power availability. The 30 minute off time ensured adequate temperature cycling while allowing completion of the test within a reasonable period of time. Since the test was conducted on a thrust stand, steady state performance levels were recorded at the end of each burn.

The propellant feed pressure blowdown curve simulated a typical dual-mode profile. The AJT firings were grouped in feed pressure blocks at average pressures for 25% propellant consumption increments.

Following completion of the S/N 001 life test, steady state firings were performed to specifically demonstrate stable AJT operation or safe shutdown under the following conditions: feed pressure margins beyond nominal beginning and end of life pressures, flow interruption due to helium bubble ingestion, and flow interruption due to thruster propellant valve closure. In the cases of both types of flow interruption, the arc was extinguished and the PCU initiated an automated shutdown as planned, with no damage to AJT, PCU, or power cable.

**Life Test Results**

Table 1 summarizes the key performance and life test results for each of the AJT components, and compares them to the specification requirement where applicable. Note that the life-related requirements shown include a 50% qualification margin over the 10 year mission requirement. Clearly the MR-508 arcjet system can fulfill, with ample margin, the required total impulse requirement, while delivering excellent performance, well in excess of the minimum required Isp. Results of the two life tests are described in more detail below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Qual Arcjet Thruster (S/N 001)</th>
<th>Qual PCU</th>
<th>Qual Cable (System)</th>
<th>Arcjet Thruster (S/N 002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Impulse</td>
<td>653,855 N-sec</td>
<td>703,424 N-sec</td>
<td>N/A</td>
<td>N/A</td>
<td>744,217 N-sec</td>
</tr>
<tr>
<td>Mission Average Specific Impulse</td>
<td>502 sec</td>
<td>522 sec</td>
<td>N/A</td>
<td>N/A</td>
<td>536 sec</td>
</tr>
<tr>
<td>Beginning of Life ATP</td>
<td>N/A</td>
<td>538 sec</td>
<td>N/A</td>
<td>N/A</td>
<td>545 sec</td>
</tr>
<tr>
<td>Life Test Average</td>
<td>N/A</td>
<td>838 hrs</td>
<td>1463 hrs</td>
<td>17 yrs.</td>
<td>1463 hrs</td>
</tr>
<tr>
<td>Total Firing Time</td>
<td>830 hrs (aprx)</td>
<td>15 yrs.</td>
<td>15 yrs.</td>
<td>26 yrs.</td>
<td>17 yrs.</td>
</tr>
<tr>
<td>Minimum Thrust (BOL ATP)</td>
<td>0.209-0.184 N</td>
<td>0.227-0.213 N</td>
<td>N/A</td>
<td>N/A</td>
<td>0.227-0213 N</td>
</tr>
<tr>
<td>Starts</td>
<td>N/A</td>
<td>918</td>
<td>907</td>
<td>1523</td>
<td>1169</td>
</tr>
<tr>
<td>Fuel Throughput</td>
<td>134 kg</td>
<td>N/A</td>
<td>N/A</td>
<td>140 kg</td>
<td></td>
</tr>
<tr>
<td>Fuel Temperature</td>
<td>20°C</td>
<td>N/A</td>
<td>N/A</td>
<td>43°C</td>
<td></td>
</tr>
<tr>
<td>PCU Efficiency</td>
<td>&gt;90%</td>
<td>N/A</td>
<td>&gt;91.5%</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
S/N 001 Life Test

The results of the first life test were described in Reference 2. In summary, the first life test exceeded the life requirements, and the test was terminated voluntarily after a total of 898 hours of operation, including ATP firings and life test performance mappings. The post-test Disassembly and Inspection (D & I), also reported in Reference 2, indicated a healthy engine, with the electrodes and gas-generator having several hundred hours of additional life capability remaining.

Figures 7, 8, and 9 reproduce from Reference 1 the voltage, thrust, and Isp profiles over life for the S/N 001 life test. While these results will not be discussed in detail here, the slow increase in Isp during each feed pressure block deserves comment. This effect is due to a slow decrease in anode constrictor diameter with life, and a resulting decrease in mass flow rate. This constrictor closure, discussed further below, was confirmed by post-test D & I results.

S/N 002 Life Test

The second life test, while principally a PCU qualification life test, also served as a second qualification life test for the AJT design. The test conditions were identical to those of the first life test with one notable exception: propellant temperature. The first life test was run with ambient temperature (20°C) propellant, as measured at the inlet to the fluid restrictor. The second life test was run with propellant conditioned to a worst case temperature of 43°C. The actual propellant temperature over life will of course vary with the spacecraft thermal environment, and the choice of a constant 43°C propellant temperature resulted in a conservative test of the life capability of the MR-508 design.

For a given feed pressure, mass flow rate through the fluid restrictor is inversely proportional to propellant temperature. The increased propellant temperature of the second life test therefore resulted in lower flow rates through AJT S/N 002 throughout the test relative to those of the first life test. The lower flow rates had two significant effects on AJT operation. First, NVR deposition in the gas generator (GG) inlet was accelerated. NVR deposition due to propellant boiling in the inlet is known to be the primary life-limiting mechanism for the GG in this application. Second, the lower flow rates caused the anode temperatures to increase significantly. The constrictor closure mechanism noted above is caused by a complex creep mechanism, the rate of which is a strong function of temperature. The higher anode temperatures in the second life test therefore accelerated the constrictor closure. This in turn served to further reduce flow rates over life.

As expected, cathode burn-in occurred at about the same rate in the second life test as in the first, as indicated by the PCU output voltage profile (Fig. 10). In both tests, the initial burn-in had stabilized within the first 200 hours, with cathode recession occurring at a slower, relatively constant rate for the remainder of the tests. The increased arc voltage resulting from cathode recession has a beneficial effect on PCU efficiency (output power/input power) over life (Fig. 11). In order to show the effect of cathode burn-in on PCU efficiency, Fig. 11 includes data taken both before and after the PCU life test restart. Throughout the life test, the PCU efficiency, as averaged over each one hour burn with simulated battery voltage letdown, was 92.5 % or higher.

Figures 12 and 13 present thrust and Isp vs. time, respectively, for the second life test. While BOL thrust was similar to that of S/N 001, the thrust decreased more rapidly over life due to the higher rate of constrictor closure. S/N 002's BOL Isp was greater than S/N 001's due to the lower BOL mass flow rate, and Isp increased more rapidly over life due to the higher constrictor closure rate. As a result, the mission average Isp demonstrated in the second life test was 545 sec, significantly higher than the 538 sec of the first test, and once again, an indicator of the very conservative nature of the second life test.

It should be noted that there is a 151 hour difference between the demonstrated life values for the qualification PCU and AJT S/N 002 called out in Table 1. At 134 hours into the PCU life test, a vacuum related overheating condition on one of the PCU circuit cards caused a test shutdown. After identification of the problem (inadequate thermal sinking of a snubber resistor), a design change was implemented, and PCU testing was restarted. Due to the nature of the problem, the cumulative life on the PCU was reset to zero, while the life on the AJT, which had remained undisturbed, was continued at the original count. The life test was then restarted and run until the PCU had satisfied its full qualification requirement. Additional performance mapping account for the remaining 17 hours of the difference. This qualification PCU is currently being used in a duty-cycle life test on a subsequent flight arcjet program, and at this writing has delivered upwards of 850 hours of additional, nominal service.

As a result of the PCU test restart described above, the S/N 002 AJT was required to demonstrate approximately 150 hours of life over and above the
qualification life requirement. Moreover, this extended life test was carried out at a worst case elevated propellant temperature of 43°C, with the resulting lower mass flow rates noted above. However, the decision was made to run the life test until the AJT failed in order to determine the life limit of the MR-508 configuration under these conditions. At approximately 950 hours of total life on the AJT, the thruster began to show signs of GG plugging. At 989 hours the test was terminated.

Subsequent D & I of the S/N 002 AJT confirmed the failure mechanism to be GG injector plugging. All other parts of the thruster, including the electrode assembly, appeared to have substantial life capability remaining. The anode constrictor diameter decrease of approximately 10% was consistent with the observed decrease in mass flow rate.

At test conclusion, the S/N 002 AJT had exceeded its life requirement by approximately 90,000 N-sec (20,000 lbf-sec), with the total impulse demonstrated corresponding to an equivalent life of approximately 17 years on orbit. Moreover, the results of this test-to-failure approach were instructive, and RRC and Astro Space have used them to improve the arcjet design for subsequent, longer-life applications. While the arcjet body and GG designs have remained essentially unchanged, thermal management improvements in the mounting structure have substantially reduced the GG injector temperature, and the fluid restrictor design has been modified to more closely match the propellant temperature to the desired mass flow rates. In addition, thermal management improvements at the spacecraft level have substantially reduced propellant inlet temperatures. With these relatively minor improvements, this same basic arcjet design is currently being qualified to 865,000 N-sec (195,000 lbf-sec), and the same 502 sec BOL mission average Isp.

**Spacecraft-Level Integration Tests**

Figure 14 presents a summary of protoflight (first article) spacecraft-level testing of the AJS at Astro Space. The sequence shown is identical to the flight testing which all subsequent spacecraft undergo, but includes in addition sine vibration, thermal vacuum balance testing and 3 dB higher levels for acoustic testing. The PCUs and surrounding heat pipe panels were instrumented with thermocouples for the thermal-vacuum test and the arcjet thruster brackets were instrumented with three-axis accelerometers for the sine vibration and acoustic exposures. The spacecraft level environmental test results confirmed that the qualification testing performed at the component and AJS levels at RRC enveloped the spacecraft protoflight level environments with ample margins.

The pre- and post-environmental health of the arcjet thrusters was verified by flow, leak and electrical functional testing. The thermal control, temperature sensing and propellant valve control circuitry were also exercised and performed nominally during thermal vacuum cycle/thermal balance testing.

The compatibility of the PCUs and power cables with all spacecraft subsystems was confirmed at bus, payload and spacecraft levels. Load simulators were used throughout the flow to verify acceptable PCU electrical performance. The resistive load simulators, designed and built by PED, verify the presence of the high voltage start pulse, and simulate steady-state arcjet operation, providing in-situ a high-fidelity checkout of PCU and power cable operation.

All testing depicted in Fig. 14 has been successfully completed except for final end-to-end polarity tests, post environmental Reaction Control Subsystem (RCS) leak check and Launch Site System Electrical Performance Evaluation Testing (SEPET). AJS spacecraft installation and integration has proceeded smoothly as planned, while arcjet system testing at the spacecraft level has met or exceeded all performance requirements.

**Spacecraft IMPACT Tests**

In addition to the formal AJS qualification program carried out at RRC, a set of spacecraft impact studies were performed at the NASA Lewis Research Center (LeRC). These studies, described in more detail in Reference 4, exposed the MR-508 AJS to much of the same system-level (thruster plus PCU) EMI/EMC tests as the 1.4 kW NASA/RRC arcjet (MR-507) experienced during the NASA funded Arcjet System Integration Demonstration at TRW(6). However, the MR-508 tests at LeRC also addressed start-up transient emissions, potential surface degradation effects, electrostatic discharge phenomena, and relay/fusing design.

During 1991 a Joint Arcjet Test program was initiated between Astro Space, NASA LeRC, and RRC, to investigate potential spacecraft surface material contamination, electrostatic discharge (ESD) phenomena, and electromagnetic interference from a complete arcjet system. This program was enabled by a Space-Act Agreement between Astro Space and LeRC, was carried out in the LeRC Electric Propulsion Laboratory Tank 5, a large chamber capable of maintaining high vacuum (<0.013 Pa) even under the load of a continuously operating thruster.
The test employed a NASA-owned/RRC-manufactured AJT essentially identical to the MR-508 AJT, except that it was configured to run on a nitrogen/hydrogen gas mixture simulating hydrazine decomposition products. PED provided the EDM PCU which had been used to carry out the S/N 001 AJT qualification life test. Astro Space supplied sample material coupons, some antennae, specialized ESD test equipment, and a breadboard version of the arcjet relay/fuse assembly.

Detailed descriptions of the material contamination and ESD elements of this program have been presented in Reference 6, while steady-state and transient EMI signature information, as well as material contamination and ESD elements are described in detail in Reference 4. The tests and their results are summarized below.

Surface Interactions

The potential contamination of spacecraft surfaces was evaluated by positioning well characterized spacecraft material samples in appropriate positions relative to the arcjet, and exposing them to unaugmented (no arc) and augmented (w/arc) plumes for periods of 40 hours. Samples included several paints, ITO coated OSR's, thermal blanket material, Carbon-loaded Kevlar, and a 4x4 silicon solar cell array.

Only one sample exhibited a significant change in absorbance or emittance (possibly due to a test artifact), and that material is not used on Series 7000 spacecraft. Changes in surface resistive properties were well within acceptable levels when extrapolated to nominal mission exposure periods. Solar array current/voltage characteristics were also found to be unaffected.

Electrostatic Discharge Phenomena

The effects of arcjet operation on charged spacecraft were investigated by carefully charging relevant material samples and monitoring their discharge upon exposure to ambient and plume conditions. It was found for all three types of surfaces tested (solar cell array, OSR, and painted) that a nearly complete grounding was achieved within one second of exposure to an augmented arcjet plume (vs. little change in potential with no plume or an unaugmented thruster plume) without the triggering of a potentially damaging ESD event.

Steady State and Transient EMI/EMC Testing

A full range of steady state emission measurements was taken, with particular attention being given to communication bands. In addition, a transient digitizing oscilloscope was used to detect start-up emissions. In agreement with the results presented in Reference 6, the AJS appears to be compatible with UHF, S, C, Ku and Ka band communications spacecraft. While some transient emissions were detected, they are short lived (1-2 microseconds), and at a relatively low level.

Conclusions

At the outset of the joint RRC/Astro Space MR-508 Arcjet Flight Program, a systematic sequence of design, development, analysis, qualification tests, and spacecraft-level impact and integration tests was defined to bring this state-of-the-art propulsion technology to flight readiness. This program is now complete. The MR-508 hydrazine arcjet system has successfully completed a rigorous flight qualification test program at RRC, and flight arcjet systems have successfully completed integration testing on the first Series 7000 spacecraft at Astro Space.

To ensure the viability of those aspects of the MR-508 Arcjet System which are difficult to test rigorously, extensive analyses of the design were carried out, including a reliability analysis, FMECA, worst case analysis, and of course detailed thermal and structural analyses.

To address spacecraft/arcjet interactions for which testing with a flight spacecraft is not feasible, a series of "impact" tests have been carried out in a joint Astro Space/NASA LeRC program. These tests successfully retired concerns about potential effects of arcjets on spacecraft surfaces (including solar arrays), discharging, and payload operation. While not part of the formal qualification test program, these tests were important confidence builders in that they evaluated potential interactions between the arcjet and the spacecraft and found them to be benign or even beneficial.

In component and system-level testing at RRC, the MR-508 AJS met or exceeded all mechanical, thermal, structural, performance, and life requirements specified by Astro Space. The key requirements for performance (502 sec) and life (653,855 N-sec) were in fact substantially exceeded. The two life tests demonstrated total impulses equivalent to approximately 16 and 17 years of on-orbit operation of a Series 7000 class spacecraft, while demonstrating mission average Isp's of 538 sec and 545 sec, respectively. Moreover, the successful completion of a second life test, run at a worst case, constant propellant inlet temperature of 43°C, provides added assurance of the soundness and reproducibility of the design.
A significant result of the worst-case, test-to-failure approach of the second life test was the identification of straightforward design changes to substantially enhance the life capability and propellant temperature tolerance of hydrazine arcjet thrusters for future applications. The MR-509 AJS, an improved derivative of the MR-508 design, is currently being qualification tested to 865,000 N-sec (195,000 lbf-sec), over 30% greater than the MR-508 specification requirement, with identical specific impulse. Ongoing research and development programs at RRC promise significantly enhanced performance within the same basic arcjet configuration\(^8\). Subsequent qualification programs based on this research will significantly increase the performance capability of this class of arcjet system.

Through a coordinated program of test and analysis, the flight readiness of the MR-508 Arcjet System in particular, and of hydrazine arcjet technology in general, has been demonstrated. All that remains is successful operation on orbit. Launch of the first Astro Space Series 7000 spacecraft is scheduled for late 1993. Shortly thereafter, the first arcjet firing in space should take place, and it will represent a significant step forward for electric propulsion. The era of commercial application of arcjet technology in space, long a dream, will have become a reality.

References


---

**Fig. 1. MR-508 Arcjet System Qualification and Spacecraft Integration Tests**
Fig. 2. MR-508 Arcjet System

Fig. 3. Arcjet Thruster Assembly
Fig. 4. MR-508 Arcjet System Qualification Test Sequence

- ATP FUNCTIONAL
- PROOF PRESSURE LEAKAGE ELECTRICAL
- EDM PCU BURN-IN REF. PERFORMANCE
- EDM PCU BREAK-OUT BOX CABLE ASSY
- 830 HOURS DUTY CYCLE BLOWDOWN EDM PCU
- 480 HR WINDING CABLE

SYSTEM QUAL CABLE ASSY

△ DENOTES FULL FUNCTIONAL ELECTRICAL PERFORMANCE TEST

POWER CONDITIONING UNIT

CORONA BURN-IN ATPQUAL VIB

- 250 HRS DUTY CYCLE 1 ATM LOAD BOX

ATP

ATP VIB

ATP QUAL VIB

STEADY-STATE PERFORMANCE MAP
- FLOW INTERRUPTION TEST
- PRESSURE MARQUIS
- STEADY-STATE PERFORMANCE MAP

THERMAL BOAK

- 6 HRS AT 84°C
- 6 HRS AT 100°C
- 1 ATM

THERMAL BENCH

- DWELL 18°C LOAD BOX VACUUM
- 10 CYCLES -20 TO +72°C 1 ATM LOAD BOX
- 3 CYCLES -20 TO +72°C VACUUM LOAD BOX

THERMAL VAC

- 1 ATM LOAD BOX

COMPONENT QUAL CABLE ASSY

ATP HUMIDITY PRE-THERMAL CYCLE TESTS
- LOOP RESISTANCE
- INSULATION RESISTANCE
- DIELECTRIC WITHSTAND CORONA

THERMAL CYCLE
- 360 CYCLES -40 TO +100°C
- 1 ATM N₂

THERMAL CYCLE TESTS
- REPEAT

HERMETICITY
- 1 bar LEAK CENTER CONTACT 1.4, 2.3 rd

CONDUCTOR LOAD TESTS
- 200 pcls

PROOF PRESSURE
- 400 pcls

BURST PRESSURE
- 1 bar LEAK

HERMETICITY

CABLE ASSY/PASS THRU PCU RECEPTACLE MATED TOGETHER THROUGHOUT TEST

HERMETIC PASS-THRU ONLY

1 atm
Fig. 5. Arcjet System Test Setup

Fig. 6. MR-508 Arcjet Thruster Qualification Test Sequence
Fig. 7. S/N 001 Arcjet Thruster Qualification Life Test PCU Output Voltage

Fig. 8. S/N 001 Arcjet Thruster Qualification Life Test Thrust

Fig. 9. S/N 001 Arcjet Thruster Qualification Life Test Isp
Fig. 10. S/N 002 Arcjet Thruster Qualification Life Test PCU Output Voltage

Fig. 11. Qualification PCU Efficiency

Fig. 12. S/N 002 Arcjet Thruster Qualification Life Test Thrust
Fig. 13. S/N 002 Arcjet Thruster Qualification Life Test lsp

Fig. 14. Arcjet Subsystem Spacecraft Integration Test Flow