FLIGHT QUALIFICATION OF THE 1.8 KW MR-509 HYDRAZINE ARCJET SYSTEM

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Abstract

PRIMEX Aerospace Company's MR-509 arcjet system has been flight qualified for use on Lockheed Martin's Series 7000 communications satellite bus. Substantially greater total impulse capability for NSSK has been demonstrated over that of its predecessor, the MR-508, in a full flight qualification program which included two complete thruster qualification test sequences. These test sequences, which included automated, duty-cycle life tests of 198,558 and 201,169 lb-ft, respectively, at mission-average specific impulses of 521 and 531 lb/sec, respectively, qualified the MR-509 for a 13 year mission, including a 50% margin over a worst-case scenario which includes a half system failure on day one of the mission. Details of these test sequences are presented. The second of the two planned life tests included continual injection of helium bubbles into the propellant feed, thus verifying by worst-case test a simple modification to the PCU circuitry which makes the MR-509 tolerant to entrained bubbles. The virtual elimination of uncommanded shutdowns on the five Series 7000 satellites currently on orbit verifies the efficacy of this modification as well as changes to spacecraft propulsion subsystem propellant loading procedures designed to reduce bubble entrainment.

Introduction

After the qualification of the PRIMEX Aerospace Company's (PAC) MR-508 hydrazine arcjet system for use on the three inaugural satellites (10 yr. nominal mission) of the Lockheed Martin Company's (LMC) Series 7000 satellite bus, LMC and PAC initiated design and qualification of an upgraded arcjet system, denoted the MR-509, to meet the more demanding (13 yr.) mission life requirements of subsequent Series 7000 orders. This qualification was successfully completed in March 1995, and is the subject of this paper.

Modifications to create the MR-509 arcjet design were extensive, while modifications to the PCU and cable were minor. The arcjet thruster qualification program was therefore planned from the outset to involve two arcjet thrusters and two complete qualification test sequences. This paper describes performance and life tests which were conducted on two arcjet thrusters, S/N's 001 and 002. Arcjet Thruster (AJT) S/N 001 testing was conducted during the period of June, 1993 through September, 1993. AJT S/N 002 testing was conducted during the period September, 1994 through February, 1995.

As events unfolded, the on-orbit data from the first space application of arcjets (S7000 Flt 1) became available after the first of the arcjet life tests was complete, but before the second had commenced. The MR-508 arcjets on S7000 Flt 1 were designed and tested to shut down automatically in the event low flow rate caused the arc voltage to fall below a pre-set level. Unfortunately, the S7000 Flt 1 propellant feed system contained an unexpectedly large number of gas bubbles, probably helium, which caused the MR-508 PCU to automatically shut down more frequently than desired during stationkeeping burns. Compounding the diagnosis and cure for this problem was the difficulty in reproducing the effect of small bubbles on arcjet operation in a 1-G environment. A joint PAC/LMC team determined that while a major portion of the problem could probably be eliminated by modifying propellant loading, a modification to the PCU to make the arcjet system more bubble tolerant was required as added assurance that the problem would not occur on subsequent satellites.

An intense, cooperative effort involving PAC and LMC produced a modification to the PCU circuitry which allowed the arcjet system to continue operating during the passage of most bubbles, with minimal damage to the electrodes. This rather simple modification was incorporated into the remaining MR-508 PCU's, all MR-509 PCU's, and has been incorporated into PAC's more recent, higher performance MR-510 hydrazine arcjet system.

The proprietary design modification incorporated into the PCU causes the unit to sense the incipient passage of a bubble. During bubble passage the PCU maintains the arc in a stable operating mode which minimizes thermal stresses to the anode at low flow rates. After the PCU senses completion of bubble
passage, it returns the AIT to normal, steady-state operation in a controlled fashion. The PCU also senses the infrequent case of very large bubble ingestion, and will automatically extinguish the arc according to a controlled procedure. The spacecraft will then automatically restart the arc with little or no delay. Bubble-related shutdowns on the six spacecraft launched after this modification was introduced have been very rare.

In conjunction with the PCU modifications, LMC implemented several spacecraft-level modifications to minimize gas entrapment in the propellant feed system. Propellant loading procedures were modified to avoid bubble ingestion. The propulsion subsystem design was modified slightly to eliminate bubble entrapment during loading. And, thermal management devices were incorporated to minimize peak temperatures in zones of hydrazine contact with ferrous metals.

Since incorporation of the above changes, arcjet on-orbit performance on five Series 7000 satellites has been essentially nominal, with a very significant reduction in bubble frequency, and almost no uncommanded shutdowns. When bubble passage does occur, telemetry indicates that the arcjet systems are bubble-tolerant, with the bubble modification working as designed and tested.

The second lifetest described herein was purposely delayed until the bubble-tolerant modification described above was fully developed and could be incorporated into the PCU used in the test. Bubbles were then injected regularly into the propellant stream during the test to verify the bubble tolerance of the design. The size and frequency of the bubbles were based on careful analysis of on-orbit data from S7000 Flt 1 and other satellites. The total number of bubbles injected into the second life test arcjet was commensurate with the total expected for the S7000 Flt 1 spacecraft over it’s projected life. The test did not incorporate the beneficial effects of any propulsion subsystem improvements, and was therefore conservative with respect to projections for post-S7000 Flt 1 spacecraft. Moreover, the size of the bubbles was chosen to be larger than expected on orbit to maximize the potential specific heat loading of the electrodes during bubble passage, thus verifying that the system could tolerate large bubble passage without damage to the electrodes.

In summary, the second life test represented not only the originally intended second verification of the MR-509 extended life capability, but also a worst case test of the arcjet system’s bubble tolerance. The successful completion of this two-thruster qualification program therefore confirmed that the MR-509 arcjet system could meet all Series 7000 mission requirements.

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**Arcjet System Description**

The MR-509 Arcjet System (AJS) is comprised of an Arcjet Thruster (AIT), a Power Conditioning Unit (PCU) and a power cable connecting the AIT and PCU.

The four MR-509 arcjet systems in a Series 7000 shipset (Figure 1) comprise two redundant pairs. In normal operation, two AJS's are fired simultaneously for about an hour, once a week (except during eclipse season) to perform north-south stationkeeping maneuvers.

![Figure 1. PAC AJS-509 Arcjet System (1 Shipset)](image)

Key characteristics of the MR-509 arcjet system include:

- **Power**: 1830 W (max input to PCU)
  1630 W (min input to thruster)
- **Specific Impulse**: > 500 lbr/see/lb
- **Total Impulse**: > 195,000 lbr-sec
- **Life**: ~1000 hrs
- **Thrust**: 47 - 52 mblb
- **Feed Pressure**: 255 - 205 psia (blowdown)

Because the MR-509 PCU and power cable designs are very nearly identical to their MR-508 predecessors, the PCU qualification program was planned for only one PCU and one qualification test sequence. The qualification PCU passed a component-level qualification test sequence similar to that of the MR-508 PCU. The unit, which included the bubble-tolerant design modification, then underwent full qualification life testing (1049 hours of vacuum operation with 1102 starts) on a combination of AIT and resistive loads.

With the successful completion of the post-life functional tests, the PCU (including the bubble design modification) was deemed fully qualified. The remainder of this paper will focus on the AIT qualification.
Arcjet Thruster Description

The configuration and operation of the MR-509 AJS is similar to that of the MR-508 AJS, which has been described elsewhere\(^{(1,3,5)}\). The MR-509 AJT, shown in Figure 2, is an updated design based on the previously qualified MR-508 AJT. Increased life capability and higher fuel inlet temperatures made the upgraded design and qualification efforts necessary. The total impulse requirement for the MR-509 AJS was increased by 33% over that of the MR-508, from 147,000 lbf-sec to 195,000 lbf-sec, and the fuel inlet temperature was increased from 20°C to a range of 20-43°C (30°C average). The mass of the MR-509 AJS, at 5.5 kg, is essentially unchanged from the MR-508 AJS. The MR-509 AJS was designed to operate over a blowdown feed pressure range of 2.5 psia to 205 psia. Modification for operation over a different blowdown pressure range is possible by changing the fluid impedance rating of the fluid resistor.

The major changes incorporated into the MR-509 AJT were designed to meet the increased total impulse and propellant temperature requirements, and to improve the manufacturability by incorporating lessons learned from the MR-508 program. The pressure drop rating of the fluid resistor located at the AJT inlet was lowered to maintain flow rates similar to the MR-508 at the increased propellant inlet temperatures. The AJT mounting structure was extensively revised for better thermal management, primarily to increase the gas generator life capability. The gas generator assembly is similar to the MR-508. The only changes to the electrode assembly were a larger nozzle expansion ratio\(^{(1)}\) for increased performance, and a simplified insulator design for improved manufacturability. The valve, heaters, manifold, barrier tube, cathode, vortex injection geometry, and electrical pass-through were left unchanged to maximize MR-508 design heritage.

The MR-509 AJT power cable is the same as the flight qualified MR-508. Both the S/N 001 and S/N 002 life tests incorporated new, flight pedigree cables.

Both qualification AJT's were identical to production flight units with the following exceptions: 1) A gas generator chamber pressure (Pc) tap, normally cut off with the opening welded shut following ATP, was retained throughout life testing, 2) Additional test thermocouples were installed to monitor critical thruster temperatures, and 3) The second AJT, (S/N 002) used a propellant valve configuration modified to allow bubble injection into the AJT.

Arcjet Thruster Test Program

The qualification test sequences used for both qualification AJT's were similar to that for the MR-508. They included qualification-level sine and random vibration testing, followed by performance mapping, duty cycle life testing, post-life performance mapping, and a thorough disassembly and inspection (D&I). Initial, post-vibration, and post-life functional test sequences confirmed that the AJT had passed each test sequence without damage or unexpected operational changes.

Performance and life testing were conducted in PAC's Altitude Cell 10\(^{(1,3,5)}\). The nominal vacuum pressure during firings was less than 5 \(\times 10^{-2}\) Torr. Thrust was measured on a null balance, swing-arm thrust stand\(^{(6)}\). The AJT was optically aligned on installation to verify less than 0.5 degree of angular displacement of the nozzle axis with respect to the thrust measurement axis. In the range of interest here, thrust measurement uncertainty of better than +/- 1.5% was maintained. End-of-run thrust measurements were made throughout the S/N 001 life test, as well as for the pre- and post-life performance maps. For S/N 002 testing, thrust measurements were made only during pre- and post-life performance mapping. During the S/N 002 life test, accurate thrust measurements were not possible due to installation of the helium lines needed for bubble injection which imposed uncontrolled tares on the thrust stand.

The propellant temperature conditioning and delivery systems were similar to those described previously\(^{(6)}\). Hydrazine meeting MIL-P-26536D, Amendment 2, High Purity grade (Olin Ultra Pure) and high purity helium pressurant were used in all testing. For the S/N 002 life test, helium was bubbled through the hydrazine feed tank to insure the hydrazine sent to the AJT was saturated. No specific determination of propellant saturation was made for the S/N 001 test. A separate helium feed system was required for S/N 002 testing to perform bubble injection.

To insure reproducible bubble injection, the AJT propellant valve and gas generator were rotated 10 degrees upward to allow bubbles to pass through the valve. A separate valve and orifice were attached to the propellant valve to control gas volume injection.

Test data acquisition and control were carried out by a micro-computer based system which was programmed to remotely control external functions and record data\(^{(2,4)}\). Both life tests ran unattended under computer control, 24-hour/day with a duty cycle of 60 minutes on/30 minutes off. During the S/N 002 testing, several bubble feed system pressures were also monitored to insure reproducible bubble injection was occurring. Software was modified to accommodate specific MR-509 test requirements, including limit checking for automated operation and controlled shutdown in the event of an anomaly. A mass flow meter made by Micro Motion was used to measure steady state
propellant flow rate. The meter is calibrated on a flow
bench with water to an uncertainty range of +/- 1.1%.
End-of-run performance measurements were obtained
with minimal thermal drift error.

Discussion of Results

Table 1 summarizes the key MR-509 performance
and life capabilities demonstrated by the S/N 001 and
002 qualification test programs.

Table 1.
MR-509 Arcjet Thruster Qualification Test Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AJT S/N 001 Demonstrated</th>
<th>AJT S/N 002 Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Impulse (lb-sec)</td>
<td>198,558</td>
<td>201,169*</td>
</tr>
<tr>
<td>Calculated Mission Average</td>
<td>511</td>
<td>514</td>
</tr>
<tr>
<td>1&lt;sub&gt;a&lt;/sub&gt; from BOL Data (lb-sec)</td>
<td>521</td>
<td>531</td>
</tr>
<tr>
<td>Life Test Avg. 1&lt;sub&gt;a&lt;/sub&gt; (lb-sec)</td>
<td>1064</td>
<td>1085</td>
</tr>
<tr>
<td>Total Firing Time (hr)</td>
<td>1199</td>
<td>1252</td>
</tr>
<tr>
<td>Fuel Throughput (lb.)</td>
<td>384</td>
<td>381</td>
</tr>
<tr>
<td>He Bubbles Ingested</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Denotes values calculated from BOL thrust vs.
flow data because thrust data unavailable during life test.

S/N 001 Life Test

In addition to the life firings, feed pressure margin,
flow interruption, and eclipse battery voltage letdown
demonstration runs were successfully completed either
before or after life testing. The life requirement is based
on the assumption of a half-system failure on day one of
the mission, so that one of the redundant pair of arcjets
must demonstrate the capability to carry out the entire
mission (~130,000 lb-sec). Over and above this mission
requirement, a 50% qualification margin must be
demonstrated, resulting in the total qualification life
requirement of 195,000 lb-sec.

The thrust stand remained operational during the
entire life test enabling performance measurements to be
acquired on a continual basis. Using the same data
acquisition methods implemented for performance map
testing, steady state measurements were made at the end
of each cycle firing and reduced using post-shutdown
zeroes. Life plots of mass rate, arc voltage, thrust, and
specific impulse are presented in Figures 7-9, which
include S/N 001 and S/N 002 data (discussed below) for
comparison. Propellant feed pressure and temperature
were varied over the life test to approximate projected
on-orbit conditions. As shown in the life plots, the initial
2/3 of the life test contained four feed pressure blocks,
while the final 1/3 (qualification margin) contained four
similar blocks. The Series 7000 bus has the capability for
a mid-life repressurization, which would normally occur
within the mission demonstration (initial 2/3) of the life.
Running the entire mission demonstration portion on a
single blowdown thus represents a conservative test
design since the most stressful thruster operation occurs
at low flow rates associated with EOL feed pressures.

Performance curves for augmented operation are
shown in Figures 3 and 4. Beginning-of-life (BOL) and
end-of-life (EOL) measurements are included in the plots
for comparison. BOL flow rates (not shown due to space
limitations) were lower, as expected, due to normal area
reduction of the nozzle throat over life. For the
augmented runs, a slight increase in overall efficiency
was also realized, due to higher operating pressure
associated with the throat reduction, higher operating
voltages, and potentially lower thermal losses associated
with degraded emissivity of the AJT body surfaces.

S/N 001 Performance Map

Prior to the start of the duty cycle life test, each
AJT underwent an unaugmented (arc power-off)
performance map, a 3 hour augmented steady-state burn-
in, an Acceptance Test Procedure (ATP) performance
map, and a life test reference performance map. The
unaugmented performance map consisted of one 15
minute firing each at 255 psia and 205 psia. The ATP
and life-test referencefirings lasted 45 minutes each and
were conducted at the feed pressure end points and
everal intermediate pressures. All performance firings
were carried out at 30 +/- 5 C. PCU input voltage was
varied during each firing according to projected on-orbit
battery performance.

The AJT flow rate trend is consistent with changing
feed pressure over the two simulated blowdowns and
slight closure of the AJT nozzle throat which is a normal
aging effect. The arc voltage measurement provides an
indication of both the AJT flow characteristics and
condition of the electrodes. The comparatively higher
rate of voltage change over the first 100 hours of firing
was anticipated and consistent with prior life tests.
Following this burn-in period the rate of voltage change
is reduced considerably and partially offset by the
reduction in flow rate due to progressively lowering feed pressures.

Consistent performance over life is evident in the thrust and Isp plots. Since the flow rate at constant feed pressure decreased slightly with lifetime, thrust decreased and Isp increased correspondingly. The average Isp over the duration of life testing was 521 seconds compared to a calculated mission average Isp over the same blowdown range of 511 seconds using BOL data.

Following successful completion of the life test and post-life performance mapping, a disassembly and inspection of the S/N 001 AJT was carried out. All AJT piece parts were found to be in excellent post-test condition.

S/N 002 Test Results

Prior to performance mapping tests, AJT S/N 002 passed functional and qualification vibration tests identical to those of S/N 001. S/N 002 underwent unaugmented performance firings and a three-hour burn-in firing prior to augmented performance testing according to test conditions and procedures identical to those of S/N 001.

S/N 002 Performance Map

Performance curves for augmented operation pre- and post-life are shown in Figures 5 and 6. EOL performance was higher, as expected, due to normal area reduction of the nozzle throat over life. As with S/N 001, higher overall efficiencies were apparent at EOL.

Using the same calculation method as required for flight AJT ATP, BOL mission average Isp from the performance data was 524 seconds as shown in Table 1, significantly higher than the nominal design points of 511 seconds. This occurred for two reasons; a) the fluid resistor used was at the low end of its flow tolerance range and could not be substituted since it was welded to the valve which had been modified specifically for bubble injection, and b) the AJT S/N 002 electrode delta P was at the high end of its normal scatter range. Normally, these components are matched appropriately to minimize the overall impact of the two effects. The resulting flow rate for this combination, however, was approximately 2.5% below the average of 24 MR-509 flight AJT's which had been tested up to that point. It was agreed that a feed pressure adjustment of 10 psid above the nominal blowdown levels would be implemented for life testing so that AJT S/N 002 would be run at nominal rather than minimum flow rates. The corresponding average Isp level of AJT S/N 002 at these flow rates is approximately 514 seconds.

Following completion of performance map runs, the thrust stand arm was locked in place and the gas injection helium system connected to the AJT propellant valve to enable bubble ingestion characterization runs to be made.

Bubble Characterization

Bubble characterization tests were performed prior to starting the life test to ensure consistent injection parameters would be reliably achieved in a one-G environment. Small gas increments were injected into the propellant valve until a critical gas volume was reached, at which point the larger accumulated bubble in the valve would pass through the AJT electrode causing a sudden drop in flow rate. The transient profiles of bubble passage, as measured by electrical and gas dynamic characteristics, were very similar to profiles from on-orbit telemetry.

S/N 002 Life Test

The life test was conducted using feed pressure and temperature blocks similar to the S/N 001 test. The number of bubbles ingested was varied according to bubble frequency projections based on S7000 Flt 1 on-orbit data. Bubble events were equally spaced within a firing.

Throughout the life test, steady state and minimum chamber pressure for each bubble event were measured to ensure bubbles were consistently meeting minimum size criteria established for accurate simulation of on-orbit behavior. Of the bubbles ingested, approximately 3% were substantially larger than the minimum criteria and activated the automatic PCU shutdown mode. An automatic re-start procedure consistent with anticipated on-orbit capability was initiated in these cases.

Life plots of flowrate, arc voltage, thrust, and specific impulse are presented in Figures 7-9. Thrust and specific impulse values in these plots were estimated from the measured flowrate, using BOL performance data. Engine performance throughout the life test was smooth and uneventful, with all performance requirements being met. Feed pressure margin, flow interruption, and eclipse letdown demonstration runs were also successful.

The S/N 001 and S/N 002 data sets provide a good comparison of how bubble ingestion impacted the AJT operating characteristics over life. S/N 002 EOL flow rates were about 10% lower (not shown) than those of S/N 001 due to a higher rate of nozzle throat closure caused by repeated bubble passage. These lower flow rates also caused the difference between the BOL and EOL performance of S/N 002 to be greater than that for S/N 001 (Figure 5).
EOL performance of S/N 002 to be greater than that for S/N 001 (Figure 5).

A post-test disassembly and inspection of AJT S/N 002 found all components and key features to be in good condition. The gas generator was found to be near its usable life capability.

Power Conditioning Unit

The qualification PCU underwent a component-level qualification test sequence similar to that of the MR-508 PCU[2], including qualification vibration testing, thermal vacuum testing, and EMI testing. Due to PCU fabrication delays, the qualification PCU was not available until approximately 500 hours into the second AJT qualification life test. Therefore, the first 545 hours (597 starts) of the PCU life test were conducted with the PCU firing the S/N 002 AJT. The final 504 hours of operation and 505 starts were conducted with the PCU connected to a resistive load fixture. The first AJT qualification life test, and the first half of the second, were conducted using a flight-type, engineering development PCU, which was modified prior to the S/N 002 life test to incorporate the enhanced bubble tolerance circuitry. With the successful completion of the post-life functional tests, the PCU (including the bubble design modification) was deemed fully qualified.

Conclusions

Primex Aerospace's MR-509 arcjet system has been qualified for use on a longer life version of Lockheed Martin's Series 7000 communications satellite bus. The discovery of a problem with bubbles in the propellant feed of the S7000 Flt 1 satellite allowed the second of two life tests to qualify a design modification which significantly enhanced the MR-509 system bubble tolerance. This second life test, which included injection of potentially damaging bubbles over the entire test, represents a worst-case with respect to bubble size and total bubble quantity. Concurrent to the development and test of the bubble-tolerant arcjet system design modification, LMC incorporated several changes to propellant loading designed to greatly reduce the quantity of gas entrained in propellant as loaded, and entrapped within the satellite propellant feed system. Subsequent to completion of the MR-509 qualification, five long-life Series 7000 satellites have been launched, and in all cases the MR-509 arcjet systems have operated flawlessly. On-orbit telemetry confirms that the steps taken at the satellite level have reduced the number of bubbles entrained in the propellant feed to the arcjet system, and that the arcjet systems are tolerant to the passage of the vast majority of the remaining bubbles. Uncommanded arcjet shutdowns are very rare and certainly within acceptable limits.

The qualification of the MR-509 arcjet system for a 13 yr. mission with a 50% qualification margin represents a substantial improvement over the MR-508 arcjet system. A total of nine Series 7000 satellites with MR-509 arcjet systems will be, or have already been, launched. The bubble-tolerant features of the MR-509 AJS, as well as many of the production-related design improvements are incorporated into PAC's hydrazine arcjet product line, including the advanced performance, 2.2 kW MR-510 arcjet system.

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References

Figure 2. MR-509 Flight Arcjet Thruster

Figure 3. MR-509 Qual AJT S/N 001 Performance Maps
Thrust vs Feed Pressure

Figure 4. MR-509 Qual AJT S/N 001 Performance Maps
Specific Impulse vs Feed Pressure

Figure 5. MR-509 Qual AJT S/N 002 Performance Maps
Thrust vs Feed Pressure

Figure 6. MR-509 Qual AJT S/N 002 Performance Maps
Specific Impulse vs Feed Pressure
Figure 7. S/N 001 and S/N 002 Life Test. Flowrate vs Life

Figure 8. S/N 001 and S/N 002 Life Test PCU Output Voltage vs Life

Figure 9. S/N 001 and S/N 002 Life Test Thrust & Isp vs Life

*SN 002 Thrust & Isp calculated from performance maps and measured flowrates.