FLIGHT QUALIFICATION OF THE 2.2 kW MR-510 HYDRAZINE ARCJET SYSTEM

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Abstract

PRIMEX Aerospace Company's MR-510 hydrazine arcjet system has been flight qualified for use on Lockheed Martin Corp.'s A2100™ communication satellite bus. All specification requirements have been met or surpassed. The MR-510 arcjet system includes four, 2 kW arcjet thrusters (two redundant pairs), four power cables, and one power conditioning unit which draws a maximum of 2.2 kW per arcjet thruster (>90.7% efficiency, worst case). Results of the completed arcjet thruster qualification test sequence are described, with emphasis on performance and life tests. The mission simulation duty-cycle life test demonstrated 325,776 lb_f-sec total impulse (1730 hours), with a mission average specific impulse of 592 sec, qualifying the MR-510 for a 15 year mission on the A2100™ AX-class bus, including margin significantly greater than 50% over a worst case scenario which includes a half-system failure on day one of the mission. On-orbit performance to date on the first two A2100™ satellites has been nominal, with all indicators pointing to operation of the MR-510 arcjet system as designed and tested.

Introduction

At the outset of the design of Lockheed Martin Corporation's (LMC) A2100™ satellite bus[1], LMC (then GE Astro Space) determined that a higher performance, higher power hydrazine arcjet system was needed. Under the sponsorship of NASA's Lewis Research Center (LeRC), PRIMEX Aerospace Company (PAC), then Olin Aerospace Company, had been developing advanced hydrazine arcjet technology[2,3] which extended the existing capability[4,5] to higher power and specific impulse. Based on the promise demonstrated by this NASA LeRC development program, PAC and LMC undertook to bring this technology from the development phase to flight qualification. With the successful qualification of the resulting MR-510 arcjet system, described herein, this effort is now complete.

The inaugural launch of the A2100 satellite bus occurred in September, 1996, with first operation of the MR-510 AJS shortly thereafter. Two A2100™ communications satellites have been launched to date, and the MR-510 arcjet systems onboard have operated flawlessly. The MR-510 AJS is currently in production to meet A2100 production requirements.

Arcjet System

The MR-510 Arcjet System (AJS) is comprised of four MR-510 Arcjet Thrusters (AJT), four power cables, and one Power Conditioning Unit (PCU). One MR-510 AJS shipset, Figure 1, is integrated into each A2100 satellite, and is used for north-south stationkeeping (NSSK). Typically, one of the two redundant pairs of AJT's would be fired for about 1 hour, once per week for NSSK. Specific firing times over the duration of a mission are determined by maneuver delta-V requirements and spacecraft mass. A mass breakdown of the MR-510 AJT is presented in Table 1. System reliability is projected to be 0.998.

Table 1. MR-510 Mass Summary.

Component	Mass (kg)
Arcjet Thruster (4 ea)	3.96
Cable Assy (4 ea, 86 in.)	1.45
PCU (1 ea)	14.94
Total	20.35

The PCU design is a major departure from the MR-508/9 designs which used one PCU per AJT. The single MR-510 PCU is designed to be single-fault tolerant, and is capable of driving two AJT's simultaneously, as selected by command from the spacecraft. The AJT's are typically driven at a constant power of 2 kW, so the PCU is capable of 4kW output while drawing a maximum of 4.4 kW from the spacecraft bus. The PCU average efficiency is 90.7% under worst case conditions, with more typical operating conditions allowing average efficiencies approaching 92% over a firing. Worst case heat rejection to the spacecraft is less than 410 W. The PCU may be commanded to drive the AJT's at any of four output power settings from 1500 to 2000 W. The command/telemetry interface to the

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spacecraft is over a redundant serial data bus with telemetry multiplexing. The PCU contains a unique, proprietary start circuit capable of starting each arcjet through a wide range of cable lengths. The triaxial power cable design is identical to those of the MR-508 and MR-509 arcjet systems, but available in different cable lengths.

The A2100 bus design and the MR-510 AJS design incorporate the same bubble avoidance/ tolerance features successfully demonstrated on the Series 7000 bus and MR-509 designs[5]. The PCU incorporates the bubble tolerance circuitry developed for the MR-509 arcjet system. In addition, the A2100 is designed to minimize bubble entrapment volumes, propellant loading procedures avoid bubble ingestion, and thermal management devices were incorporated to minimize peak temperatures in zones of hydrazine contact with stainless steel. Finally, the A2100™ bus employs a 100% titanium propellant management device. Telemetry indicates MR-510 on-orbit performance on the two satellites launched to date has been essentially nominal, with a bubble frequency at or below the improved Series 7000 design levels and no reported uncommanded shutdowns.

The MR-510 AJS was designed to leverage MR-508/9 flight heritage while delivering higher performance. The system is designed to deliver 585 ± 15 sec mission average specific impulse, as calculated from BOL performance over the mission blowdown pressure range of 270 psia to 200 psia. To maximize flight heritage, many of the key components, such as the AJT valve, fluid resistor, valve and gas generator heaters, and the hybrid power FET switches used in the PCU are either identical to those used in the MR-509 AJS or are close derivatives. Detailed descriptions of the design and operation of the MR-508 and MR-509 arcjet systems have been discussed in prior publications[4-7].

The PCU underwent a full qualification test sequence including qualification level vibration testing, thermal benchmarking, thermal vacuum testing, EMI testing, and finally, a full, duty-cycle, vacuum life test. This test program has been successfully completed, and will be described in a future paper. As noted above, the power cable was qualified by similarity at the component level. For this program, a new, qualification power cable underwent vibration testing connected to the PCU and AJT during each of those component tests, respectively, then underwent the full qualification life test with the qualification AJT. The remainder of this paper will focus on the qualification testing of the arcjet thruster, with emphasis on the performance and life test results.

Arcjet Thruster Description

The MR-510 AJT, Figure 2, was designed to build on the MR-508/509 heritage while achieving higher performance (585 sec nominal), extended hydrazine throughput capability at lower flow rates, and a lower manufacturing cost. As the arcjet is an electrothermal device, the higher performance was achieved through higher specific power levels, which produced higher bulk gas temperatures. The higher specific power levels were achieved with a 23% increase in power (2 kW into the AJT vs. 1.63 kW into the MR-509) and slightly lower flow rates. The resulting higher anode temperatures, which had the potential to cause unacceptably high constrictor closure rates, were managed with an improved anode design incorporating the W/4Re/HfC anode material which was identified and tested under a NASA LeRC sponsored development program at PAC[2,3].

The extended throughput requirement challenged the capability of the MR-509 gas generator design. An advanced gas generator design developed at PAC was therefore brought to thermal and structural flight readiness and incorporated into the MR-510 AJT. By incorporating a mid-life repressurization, EOL flow rates were kept above minimum acceptable levels.

The principles of integrated product development were used throughout the MR-510 AJS program. A key goal of the program was increased manufacturability. Lessons learned from the MR-508 and 509 programs were used to reduce the number of piece parts and simplify the assembly. Specialized fabrication and assembly processes are similar or identical to those for the MR-509.

Arcjet & Cable Test Program

Performance and life testing were conducted in PAC's Altitude Cell 11[6,7]. The cell is 2.44 m in diameter and 2.44 m long, and is fully water jacketed to maintain constant ambient temperature levels. Vacuum is achieved by use of a Stokes multi-stage pumping system rated at 13,950 ft^3/min. 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[8]. 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 life test, as well as for the pre- and post-life performance maps.

The propellant temperature conditioning and delivery systems were similar to those described previously[7]. Hydrazine meeting MIL-P-26536D, Amendment 2, High Purity grade (Olin Ultra Pure) and high purity helium pressurant were used in all testing.

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. Long-term, unattended operation was permitted by constant monitoring of these test parameters and comparison to set limits. The complete data set included thrust and mass flow rate, 25 thermocouple inputs, propellant feed pressure, gas generator chamber pressure, vacuum cell pressure, PCU input and output voltages and currents, and six PCU telemetry outputs. Software was modified to accommodate specific MR-510 test requirements, including limit checking for automated operation and controlled shutdown in the event of an anomaly. The life test ran automated 24 hours per day with a duty cycle of 60 minutes on/30 minutes off. Longer off periods were required periodically during refueling or unplanned shutdowns (e.g., test cell maintenance). Mass flow measurements and the use of end-of-run zeroes to avoid thermal drift error were similar to the MR-509 AJT life testing[5].

Discussion of Results

The qualification test sequence for the MR-510 AJT was very similar to that of previous tests[4,5] and will not be described in detail here. It 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.

The design of the MR-510 power cables differs from the MR-508/9 designs only in the availability of multiple cable lengths. Component-level qualification was therefore by similarity. A new flight cable, 86" long, accompanied the AJT through it's qualification test sequence. Prior to performance and life testing, the PCU-end of the cable passed qualification-level vibration testing using a production vibration tool.

Performance Map

Prior to the start of the life test, the 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 260 psia and 205 psia. The ATP firings (45 minutes each) and the life-test reference firings (30 minutes each) were conducted at the feed pressure end points and several intermediate pressures. All performance firings were carried out with a propellant inlet temperature of 35 ± 2.5 C. PCU input voltage was maintained at minimum bus voltage.

Performance curves for augmented operation are shown in Figures 3 and 4. The beginning-of-life (BOL) performance of this AJT is within the family of performance maps for the flight AJT's delivered to date, currently numbering greater than 30. After BOL performance mapping was complete, the AJT passed an upper feed pressure margin test at a feed pressure of 330 psia.

End-of-life (EOL) measurements are included in Figures 3 and 4 for comparison. EOL flow rates (not shown) were lower, as expected, due to normal area reduction of the nozzle throat over life. For the post-life augmented runs, a slight increase in post-life augmented efficiency was apparent, probably due to higher operating pressure associated with throat area reduction, higher operating voltages, and, possibly, lower thermal losses associated with degraded emissivity of the AJT body surfaces. EOL performance data also included a successful low pressure margin test (not shown), conducted at 185 psia. While there is more scatter in measured Isp at EOL, the EOL performance map on the whole indicates stable, predictable operation after a conservative life test, and is consistent with similarly stable operation throughout the life test described below.

Life Test Results

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 (121,700 lb_f-sec for the original A2100™ A-class satellite). Over and above this mission requirement, a 50% qualification margin must be demonstrated. The original life test plan was focused on the A2100 A-class satellite, so that the total impulse requirement was 182,600 lb_f-sec. After the original satellite life requirements were determined, market forces created the need for an A2100 AX-class satellite with an increased NSSK life requirement. Upon completion of the original life test PAC and LMC elected to extend the life test in two increments of 100 lb_m (N_2H_4) each. The cumulative total impulse over the original life test plus extensions represents a demonstration of the largest planned AX-class mission life requirement (assuming half-system failure on day one) plus well in excess of a 50% qualification margin.

The A2100 bus has the capability for a mid-life propellant feed system repressurization, with the point within the mission life at which this occurs to be variable and commanded by the satellite operator. The feed pressure profiles for the life test were chosen to simulate a repressurization within the initial A-class mission life portion, another within the A-class margin demonstration, and additional repressurizations within each of the two extensions to meet the AX-class requirement. The blowdown pressure profile for the initial pressurization and each repressurization was simulated as four feed pressure blocks (depicted at the bottom of each life plot). Propellant feed temperature was varied from block to block as well. While these blocks did not maintain the actual pressure blowdown and propellant temperature profiles expected on orbit, especially during the two life test extensions, they did maintain the averages and expected distributions of throughput over the ranges of these parameters.

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 life cycle firing and reduced using post-shutdown zeroes. Life plots of flow rate, thrust, specific impulse, voltage, and throat area ratio are presented in Figures 5-9.

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. Figure 9 contains a plot of the calculated throat area ratio over life, inferred from pressure and flow rate measurements. This gradual closure (confirmed by D&I results) is normal and is due to complex cyclical stresses within the anode resulting from transient thermal gradients which accompany each firing/ cooldown cycle. The higher performance and life capability of the MR-510 AJT is due to the fact that the W/Re/HfC anode material used in this design is more resistant to such closure than the pure tungsten anodes of the MR-508 and 509 designs.

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 (Figure 8) is due to cathode burn-in and is consistent with prior life tests. Following this burn-in period the rate of voltage change is reduced considerably, also consistent with previous tests.

Consistent performance over life is evident in the thrust and Isp plots. Within each pressure block a steady decrease in thrust, and corresponding increase in specific impulse, is evident. These trends were expected and are due to the throat area reduction and corresponding flow rate decreases discussed above. Due to the effect of the throat closure, the average Isp over the duration of life testing (592 seconds) was higher than the mission average Isp of 582 sec calculated from BOL performance data over the same blowdown range.

At the conclusion of the original life test segment an additional 183 AJT starts were accomplished on an accelerated basis (run 2.5 minutes after start, off 12 minutes, start again, etc.) to satisfy a start pulse margin requirement. At the conclusion of all life testing, the AJT also successfully completed a 20 hr continuous firing, during which operation was smooth and uneventful. This demonstration is consistent with prior development test experience at PAC which indicates that steady-state operation over multiple hour firings is significantly less stressful than the duty cycle mode used for the life test. Table 2 summarizes the key thruster performance and life test results.

Table 2. MR-510 Arcjet Qualification Life Test Summary

Parameter	Demonstrated
Total Impulse	325,763 lb_f-sec
Average. Specific Impulse	
BOL "ATP" Mission Average	582 sec
Life Test Average	592 sec
Firing Time: Total	1730 hrs
Max. Continuous	20 hrs
Min.	2 min.
Minimum Thrust (BOL ATP)	51 - 58 mlb_f
Total Starts	1900
Fuel Throughput	550 lb_m
Fuel Temperature (average)	33°C

Following successful completion of the life test and post-life performance mapping, a D&I of the qualification AJT was carried out. All AJT piece parts were found to be in excellent post-test condition, for a thruster that had gone through such an arduous test.

Conclusions

Primex Aerospace's MR-510 hydrazine arcjet system has been flight qualified for use on Lockheed Martin Corp.'s A2100 communication satellite bus. All specification requirements have been met or surpassed. The mission simulation duty-cycle life test, carried out as a baseline, A2100™ A-class life test plus two extensions, demonstrated 325,776 lb_f-sec total impulse (1730 hours), with a mission average specific impulse of 592 sec. This total impulse demonstration qualifies the MR-510 for a 15 year mission on the A2100 AX-class bus, including margin significantly greater than

50% over a worst case scenario which includes a half-system failure on day one of the mission.

The inaugural launch of the A2100 satellite bus occurred in September, 1996, with first operation of the MR-510 AJS shortly thereafter. Two A2100 communications satellites have been launched to date; on-orbit performance has been nominal, with all indicators pointing to operation of the MR-510 arcjet systems as designed and tested. The MR-510 AJS is currently in production to meet A2100 production requirements.

Acknowledgments

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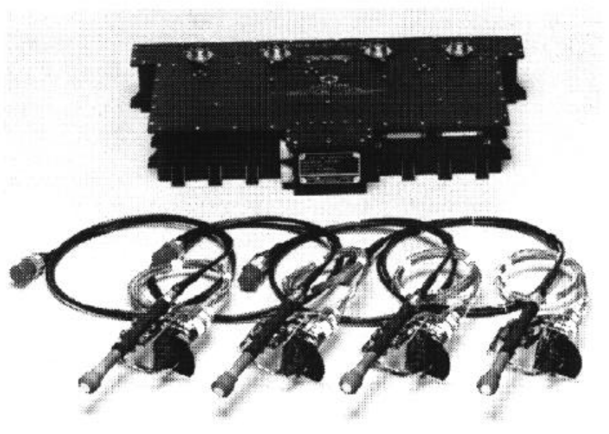


Figure 1. MR-510 Arcjet System
(1 Shipset)

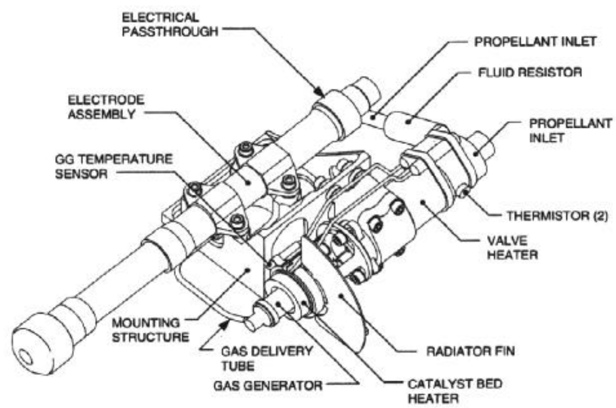


Figure 2. MR-510 Hydrazine Arcjet Assembly

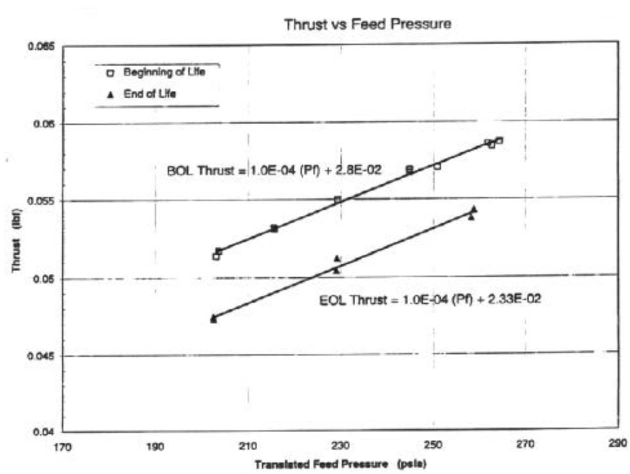


Figure 3. MR-510 Qual AJT S/N 003Q
Performance Maps

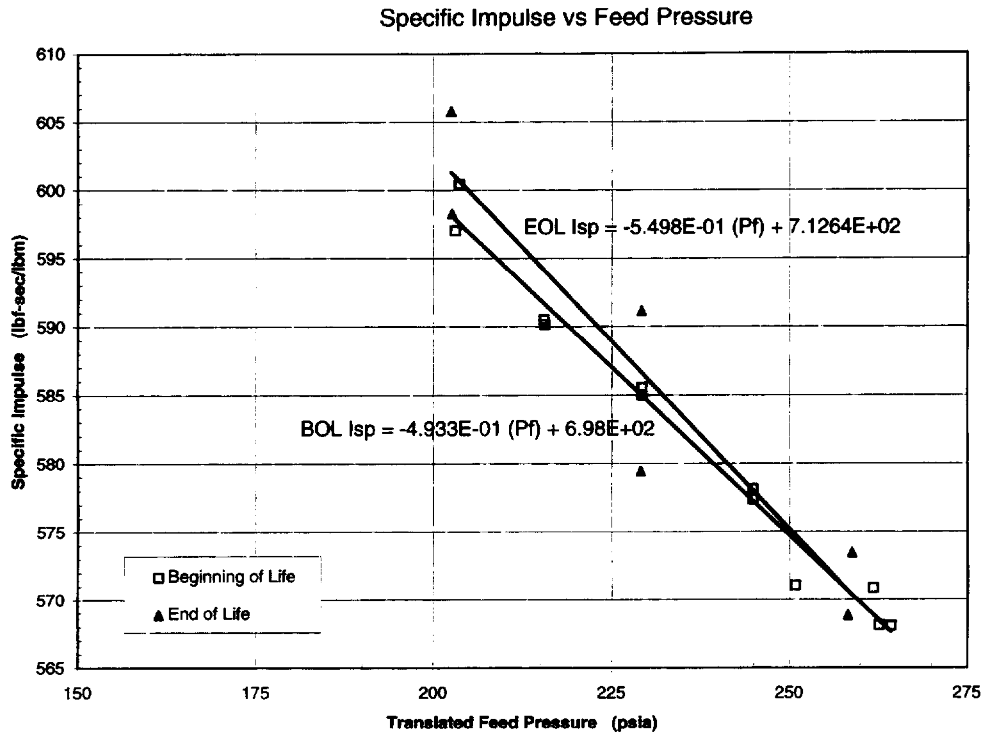


Figure 4. MR-510 Qual AJT S/N 003Q Performance Maps

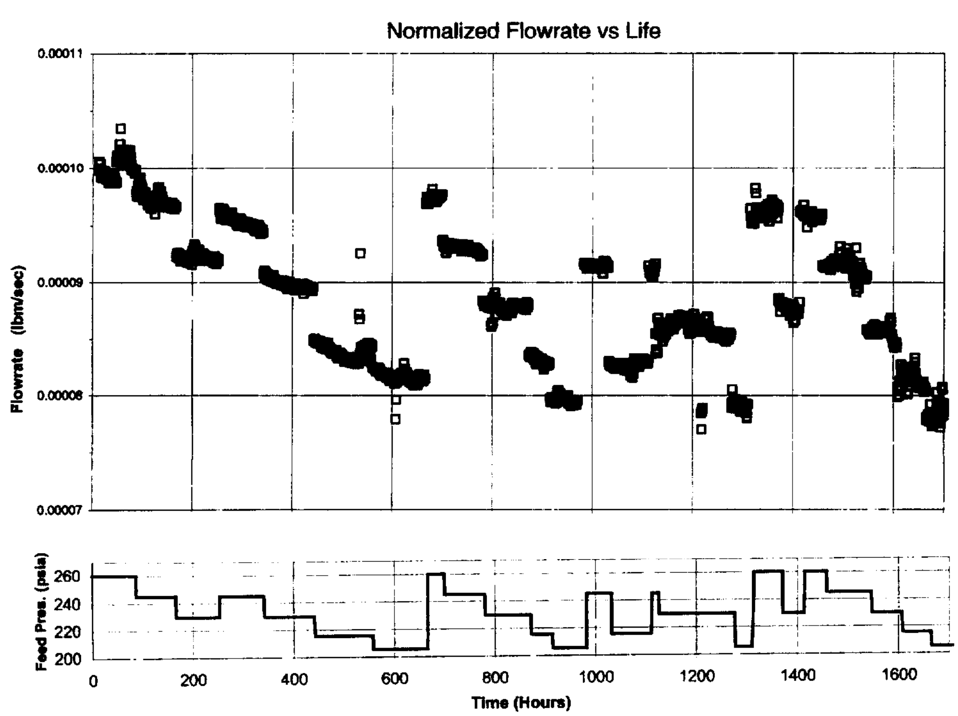


Figure 5. MR-510 S/N 003Q Life Test

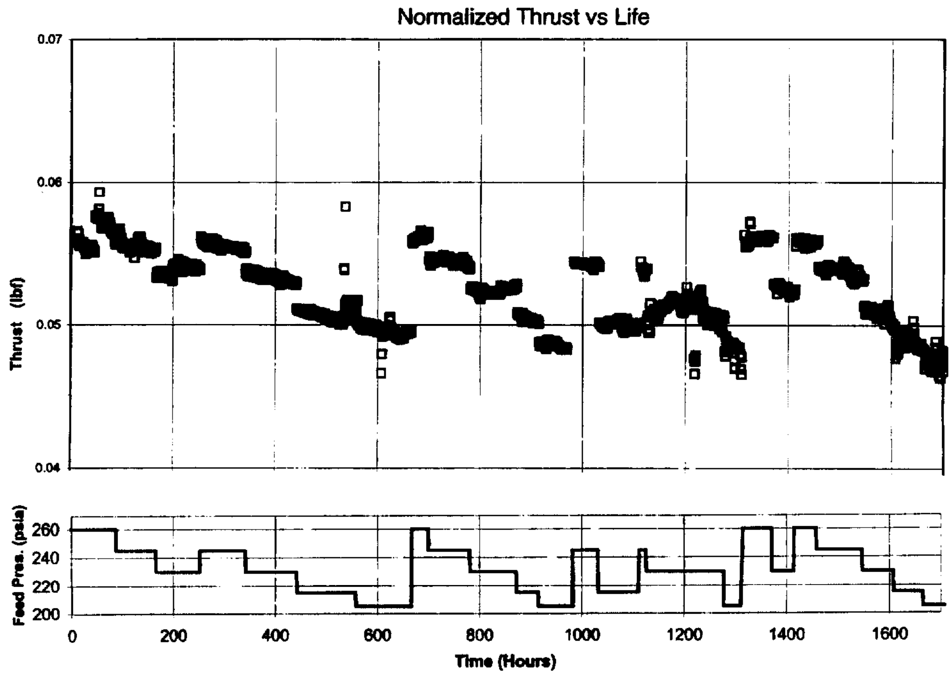
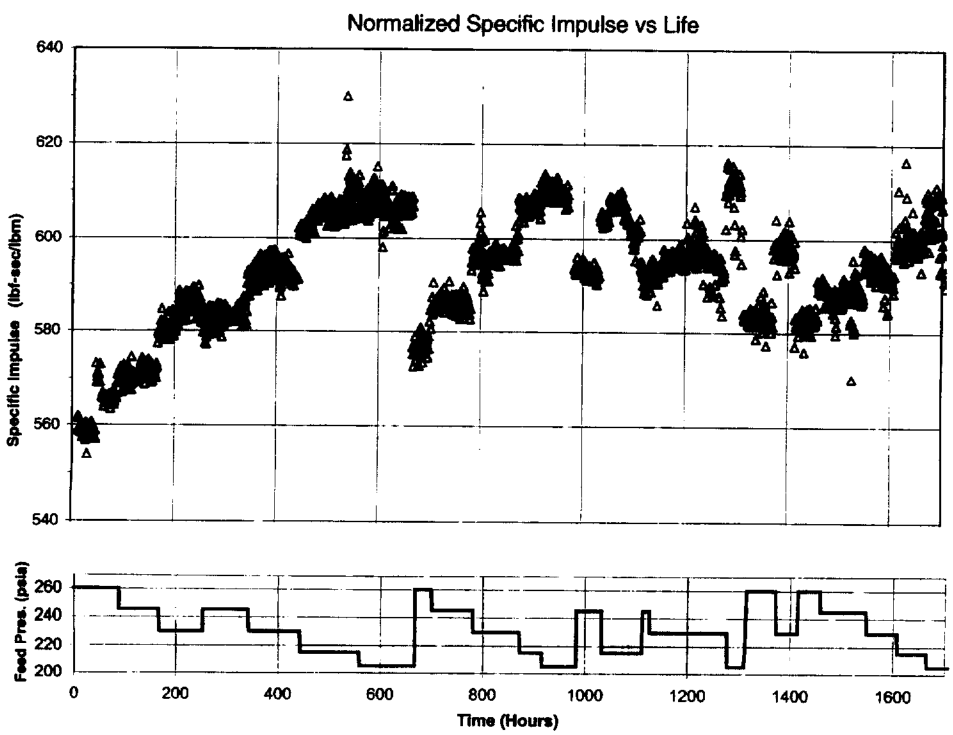


Figure 6. MR-510 S/N 003Q Life Test



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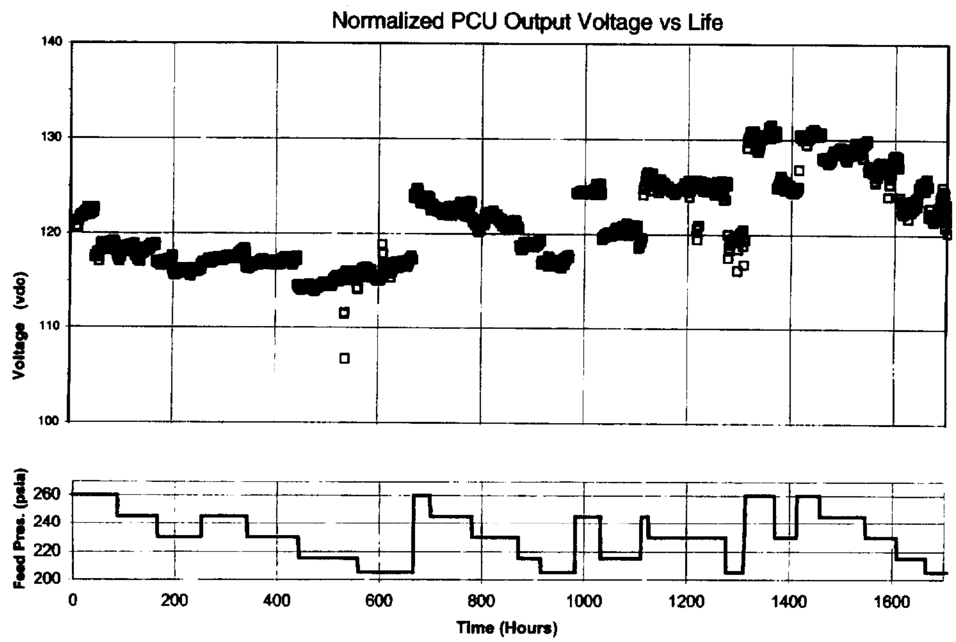

Figure 8. MR-510 S/N 003Q Life Test

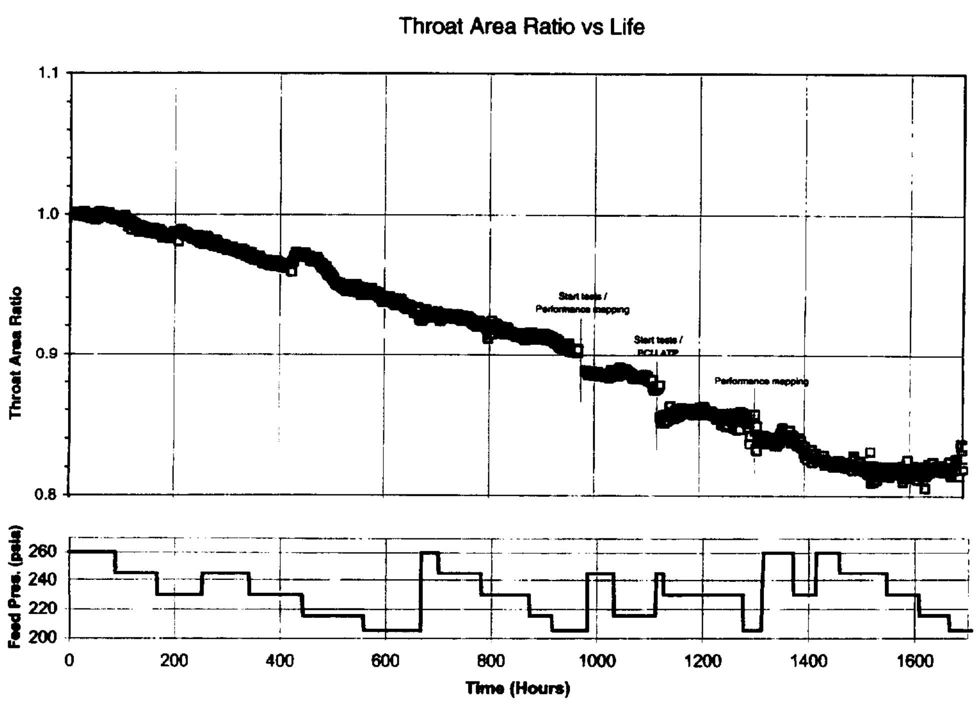

Figure 9. MR-510 Qual AJT S/N 003Q