International Electric Propulsion Conference, October 2017, Atlanta, Georgia
IEPC 2017-305

Development of a Hydrazine Arcjet System Operating at 100 Volts Input Voltage

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Abstract

Since 1996, Aerojet Rocketdyne MR-510 hydrazine arcjet systems have provided North-South station keeping for more than 44 geostationary spacecraft. A typical system consists of four 2 kW arcjets, two of which can be operated simultaneously from a Power Conversion Unit (PCU) that includes three power converters in a three for two redundant arrangement. Over the last two years, the flexibility of the system was expanded by developing and qualifying a modern state of the art PCU for a 100 VDC spacecraft power bus.

To set the stage, the paper summarizes the development and deployment history of hydrazine arcjet systems beginning in 1993. It discusses the changes and repeated system life tests which significantly expanded the flexibility and robustness of the arcjet system. The paper then describes the changes necessary to accommodate the new PCU with an input voltage of 100 VDC and a new communication protocol. While there were only a limited number of changes required for the thruster and its subcomponents, the PCU underwent a complete redesign. Aerojet Rocketdyne incorporated advances in design philosophy, electronic components, and materials to avoid component obsolescence while improving overall system reliability.

1. Hydrazine Arcjet System History

Electric propulsion (EP) systems are usually grouped by their primary acceleration mechanism (electrothermal, electrostatic, and electromagnetic), and there are six classical EP thruster types: resistojets, arcjets, ion thrusters, Hall current thrusters, Pulsed Plasma Thrusters (PPT), and Magneto Plasma Dynamic thrusters (MPD) [1]. To date (mid 2017), all of these have flown on a variety of missions, although some only on experimental or technology demonstration platforms.

After some early studies of arcjet systems in the 1950s and 1960s, the development of arcjet propulsion systems was dormant until a development effort initiated by NASA and industry in the early 1990s put hydrazine arcjets on the GE-Astro (now Lockheed Martin) Series 7000 spacecraft bus in the form of the Aerojet Rocketdyne MR-508/509 hydrazine arcjet system.

This system consisted of four arcjets, each of which had its own dedicated Power Conversion Unit (PCU), providing a total of about 1.75 kW input power to each PCU-thruster combination.

Between 1993 and 1996, a total of 11 spacecraft with MR-508/509 single string arcjet systems

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(one PCU for each arcjet thruster) reached orbit. Two examples of the MR-512, a later modification for a different bus voltage, were launched in 2002 and 2008, respectively [2] under the auspices of the Japanese Space Agency JAXA through their prime contractors Mitsubishi Electric Company (MELCO) and NEC – Toshiba Space (NTS).

This 1.7 kW system was quickly followed by the more advanced MR-510 hydrazine arcjet system, which increased the thruster performance to a mission average specific impulse of 600 s and 2.2 kW of input power to the PCU per arcjet.

For a detailed history of the MR-508/509 – MR-510 hydrazine arcjet family and other arcjet flight experiments, please refer to reference [3] that was published in 2014 in conjunction with the 20th anniversary of the first in-space operation of an arcjet thruster.

When the first arcjet system was launched in late 1993, its operation was marred by unexpected interruptions to the arcjet firing. These were quickly explained by gas bubbles entrained in the flow of liquid hydrazine propellant into the arcjet gas generator, where the gas bubbles briefly reduced the mass flow and thus, lead to unstable arc operation [3, 4]. These have been overcome nearly completely through a PCU internal "Bubble Protection Mode" [5, 6] and a mechanical filter or "Gas Arrestor" [7, 8].

2. System Architecture of the MR-510 Arcjet System

While the MR-508/509 arcjet system was still in its final stages of ground testing and qualification during the mid 1990s, mission trades and upgrades to the spacecraft bus already called for an arcjet system with improved performance. The Lockheed Martin A2100™ GEO satellite bus was designed to make 4.5 kW of electric power available to the arcjet system, and a NASA funded development effort [8] pioneered a 2 kW arcjet with a mission average specific impulse of 600 seconds.

The resulting MR-510 also introduced a change to the arcjet system architecture. While the previous system had a dedicated PCU for each arcjet, the new MR-510 system employs a single PCU box which houses three redundant power converters, two of which can be operated in parallel at any given time to power two out of four arcjets connected to the PCU (Fig. 1 and 2). In addition to improved reliability and flexibility, this architecture reduces the total system mass. The all-in-one PCU of the MR-510 system weighs less than 75 percent of the total mass of four single-string-style 2 kW PCUs.

For the arcjet thruster, the increase in input power from 1630 W to 2000 W manifested itself primarily in material challenges. The increased heat load on the anode uncovered limitations in the material used in the MR-509. A significant development effort [9, 10] was necessary to overcome this problem.

Shortly after the completion of the basic one PCU / four arcjet MR-510 system, the development of a "relay box" allowed six arcjets to be powered by a single PCU [10] (Fig. 3). In its initial application, the two additional arcjet thrusters were utilized for East-West station keeping on a larger version of the A2100™ bus. After its initial development in 1997, the relay box has recently undergone an upgrade to overcome component obsolescence. Nevertheless, the vast majority of MR-510 arcjet systems have been of the one PCU / four arcjets version.

3. Upgrades to the MR-510A Arcjet System

The concern over bubble induced shutdowns of an arcjet thruster during a maneuver was already significantly reduced by the introduction of the PCU bubble protection mode in 1994. Nevertheless, a “mechanical gas arrestor” [7] was introduced and qualified in 1999/2000 to cope with the few remaining cases of bubble shutdowns. This miniaturized propellant management device (PMD) downstream of the arcjet propellant control valve (see Fig. 1), together with the PCU bubble protection mode, have virtually eliminated maneuver shut downs due to gas bubbles. Arcjets equipped with the gas arrestor received the MR-510A designation and have now become the standard thruster configuration.

To further increase arcjet system performance and to compensate for power losses in the power cables that connect the arcjet to the PCU, the total power output of the PCU was increased by two percent when it was recognized that the design had additional thermal margin available. This improvement was realized without major changes in design and circuit board layout, leading to the current “MR-510 EPCU” (Enhanced PCU).

The combination of the MR-510A gas arrestor equipped arcjet and the 2040 W MR-510 EPCU has been the current state of the art since 2002, and more than 44 spacecraft have been launched with the MR-510 / MR-510A system for geosynchronous station keeping.

4. Recent Improvements from the MR-510A Baseline

After 12 years of production without any significant changes to the original MR-510 arcjet system since 2002, a major upgrade of all system components was recently completed at Aerojet Rocketdyne These changes affect both the arcjet thruster and the PCU.

4.1 Description of Design Changes and Upgrades

4.1.1 Arcjet Thruster

Throughout the years, a series of lifetests provided the necessary confidence that the thrusters built today still meet the performance expectations of the original design [3, 11]. Only minor design changes to individual piece-parts to improve the manufacturability and to replace obsolete manufacturing processes have been made.

4.1.2 Power Conditioning Unit (PCU)

The PCU is the principal system component for the control and management of arcjet thruster power. For use on a new spacecraft with a 100 VDC bus voltage, a new PCU has recently been qualified. The 100V PCU (Figure 4) uses the architecture of the flight 70V EPCU architecture. On the piece part level, the replacement of obsolete or soon to be obsolete parts provides for continuous availability of this design. The design philosophy of its Printed Wiring Boards also considered modern high-voltage isolation and manufacturing standards.

The main PCU subassemblies consist of three integrated Power Convertors with three power control and gate drive cards, an input filter circuit card assembly (CCA), an output select CCA, four power output connectors, and a Master Control board for Telemetry and Command (T&C). The latter is currently configured for a customer specific serial spacecraft interface, but could readily be modified to support the MIL-STD-1553 protocol. The three power convertors use the same heritage MR-510 design of a push-pull converter.

To align the design with more recent design standards, the new PCU implemented plasma shields internal to the PCU enclosure. These prevent failure propagation between modules and improve overall system reliability and design robustness.

Heat conduction to the spacecraft through the mounting surface is the primary PCU thermal control mechanism. Heat paths are provided to the baseplate heat sink by tailoring wall thickness to maintain component temperature below de-rated limits.

As can be seen by comparing Figures 2 and 4 and Table 1, the new PCU maintained nearly the same footprint and input and output connector locations. All circuit boards of the new PCU were optimized to improve manufacturability while implementing increased robustness to prevent failure propagation.

4.2 Arcjet Life Tests

Over the years, the MR-510 arcjet system has been subjected to a series of lifetests to establish and expand its capabilities, and to verify that an arcjet built today is still capable of the same lifetime and propellant throughput that was demonstrated in 1996. The important performance parameters of these tests are listed in Table 2.

Specifically, the following thruster life tests were conducted over the years:

1996/97: Initial MR-510 arcjet lifetest

1999 & 2001: MR-510A arcjet gas arrestor qualification test. This test was conducted in two parts.

2000: MR-510B pressure regulated test [7]. This test intended to demonstrate arcjet operation in a constant feed pressure system (all other applications have used a pressure blow down feed system). While the test demonstrated the capability of the pressure regulated system, it has not yet been implemented on a flight application.

2004: Lifetest to demonstrate previously unverified short duty cycles

2008: Lifetest to demonstrate extended operation at lower power levels

2011: Lifetest to confirm the suitability of S-405 as a hydrazine catalyst for arcjet applications. This test also confirmed that no production creep or the replacement of obsolete manufacturing processes have diminished the capabilities of the arcjets after 15 years since the original lifetest in 1996 [10, 11].

As can be seen from this list, extending the overall capabilities of the arcjet system was always validated by a corresponding lifetest, and was not done by extrapolating previous performance capabilities. This rather conservative approach is used because development testing before the first flight system had shown some design thresholds. Nevertheless, these tests provided the justification to stepwise open the operating range of the arcjet system.

5. Spacecraft Integration and Operation

The most critical task when integrating an arcjet system on a satellite is to manage the thermal environment for both the PCU and the arcjet thruster.

The spacecraft must provide the ability to conduct excess heat away from a PCU. While arcjet PCUs have a conversion efficiency of ninety percent or better, this still means that in the case of the MR-510 system, a total of 450 W need to be dissipated when two arcjets are operating simultaneously.

Command of the PCU is accomplished by a digital serial control interface; telemetry is available in the form of conditioned analog signals. To date, all PCU telemetry and command (T&C) interfaces have been customer specific, but a MIL-STD-1553 bus could readily be implemented.

Typical telemetry available from an arcjet maneuver include arc voltage, arc current, and gas generator temperature. All commands (e.g. heater control, valve opening and closing, PCU configuration and arc start) are sent directly from the spacecraft's housekeeping computers, making an arcjet maneuver a chain of timed events that require no immediate operator interaction.

6. Spacecraft Interactions

One advantage arcjets have vs. ion or Hall thrusters is the absence of ion sputtering. Studies have found that the ionization fraction in an arcjet plume is less than 5 % at the exit plane, rapidly decreasing downstream from the thruster. Plume temperatures at the exit plane are below 3500 K [12]. Except for the higher temperature, plume constituents are the same as those from chemical hydrazine thrusters, namely hydrogen, nitrogen, and ammonia. These characteristics have all been demonstrated to be benign to normal spacecraft structural materials [13].

One of the major concerns about the use of electrical spacecraft propulsion, especially on communication satellites, has been the possibility of detrimental interactions between the EP system and the telecommunication payload and telemetry and command (T&C) systems. To date, no such negative interactions have been documented for any EP system, and the arcjet systems flown are no exception.

Specifically for the arcjet system, in 1990 an early compatibility ground test [14] confirmed the lack of adverse interactions. Since then, the ESEX arcjet system with its 30 kW ammonia arcjet on a U.S. Air Force spacecraft was able to document that even a 30 kW arcjet system does not impact communications with the spacecraft [15].

In another more recent, more sophisticated ground test [13], Lockheed Martin was able to quantifiably measure that no significant interference is created. In addition, there have been no reports of interference with orbiting spacecraft, either. This information at least qualitatively confirms the ground test results [8].

10. Conclusion

Hydrazine arcjets developed and built by Aerojet Rocketdyne have demonstrated their maturity for North-South station keeping on geostationary communication satellites since 1993, when the first arcjet system was launched on the Telstar 401 satellite. Since then, the hydrazine arcjet product line has expanded its performance, culminating in the 2 kW MR-510 family. 57 hydrazine arcjets systems have been successfully launched on geostationary spacecraft and have been in use since 1994. In recent years, an upgrade program has ensured the availability and flexibility of the system by upgrading the PCU to a wider range of input voltages and by eliminating obsolete components and materials for both the PCU and the arcjet thruster.

This new system has been successfully integrated onto a new spacecraft bus with a 100 VDC power bus for which the arcjets facilitate North-South-station keeping. The new arcjet system has by now been proven in on-orbit operation and has demonstrated the flexibility of the original design.

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Table 1: Comparison of Hydrazine Arcjet Flight Systems Discussed in this Paper

	MR-508 / -509	MR-512	MR-510	MR-510A	MR-510E
Mission	N-S-station keeping	N-S-station keeping	N-S-station keeping	N-S-station keeping	N-S-station keeping
Systems flown to date (Spring 2017)	11	2	14	>28	1
Arcjet & PCU arrangement[1]	4 & 4	4 & 4	4 & 1[3]	4 & 1[3]	6 & 1 & 1 relay box
PCU input voltage, VDC	65 - 96	31 – 51.5	70	70	100
PCU mass, kg	4.1	6.2	15.8	15.8	19.1
PCU size, mm[3]	236 x 185 x 83	310 x 220 x 95	631 x 359 x 108	631 x 359 x 108	629 x 375 x 131
Typical PCU efficiency	> 90%	> 90%	> 91%	> 91%	> 90%
PCU output power, W	1630	1630	2000	2040	2040
Arcjet feed pressure, MPa / psi	1.79 – 1.38 / 260 - 200	1.79 – 1.38 / 260 - 200	1.79 – 1.38 / 260 - 200	1.79 – 1.38 / 260 – 200	1.79 – 1.38 / 260 - 200
Arcjet specific impulse	> 502	> 502 / > 470[2]	> 585 s	> 585 s	> 585 s
Arcjet thrust, mN	254 – 213	254 – 213 / 286 – 262[2]	258 – 222	258 – 222	258 - 222
Demonstrated life					
Starts	> 1170		See Table 2		
Arc on time, h	> 1050				
Propellant throughput, kg	175				

Notes:

- All parameter list nominal values. Mission specific numbers may differ slightly.
1. Number of arcjets and PCUs for a satellite (a "shipset"), the MR-510 PCU incorporates three redundant converters
2. The first number denotes the standard MR-512A arcjet, the second number the MR-512B arcjet
3. All MR-510 arcjet systems can be expanded with a relay box to a 6 thruster & 1 PCU & 1 relay box configuration

Table 2: Life Tests Conducted with the MR-510 Aerojet Rocketdyne Arcjet Thruster

	MR-510	MR-510A	MR-510B	Short duration	Low power	MR-510A requalification
Year	1996	1999 & 2001	2000	2002	2008	2011
Purpose	Original qualification	Gas arrestor qualification	Demonstrating the mechanical pressure regulator	Expand demonstrated duty cycles	Demonstrate extended operation at 1500 W	Demonstrate suitability of S-405 catalyst
Propellant throughput, kg	250	182	203	30.7	138	261
Number of starts	1962	1892	1611	2067	1362	1686
Total arc on time, h	1730	1164	1558	162	928	1622
Total impulse, Ns	1,450,900	997,245	1,230,000	130,500	700,000	1,347,400

Note: All parameter list nominal values. Mission specific numbers may differ slightly.

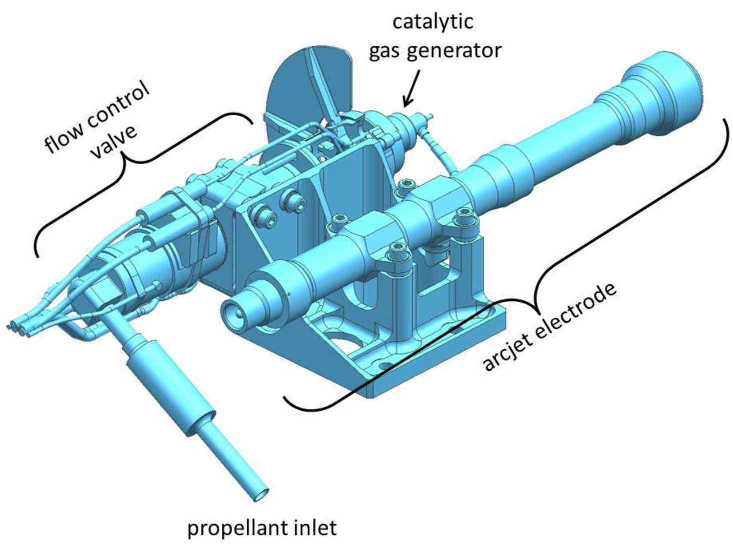

Fig. 1: Isometric view of an MR-510A arcjet thruster. The arcjet electrode assembly is approximately 200 mm long.

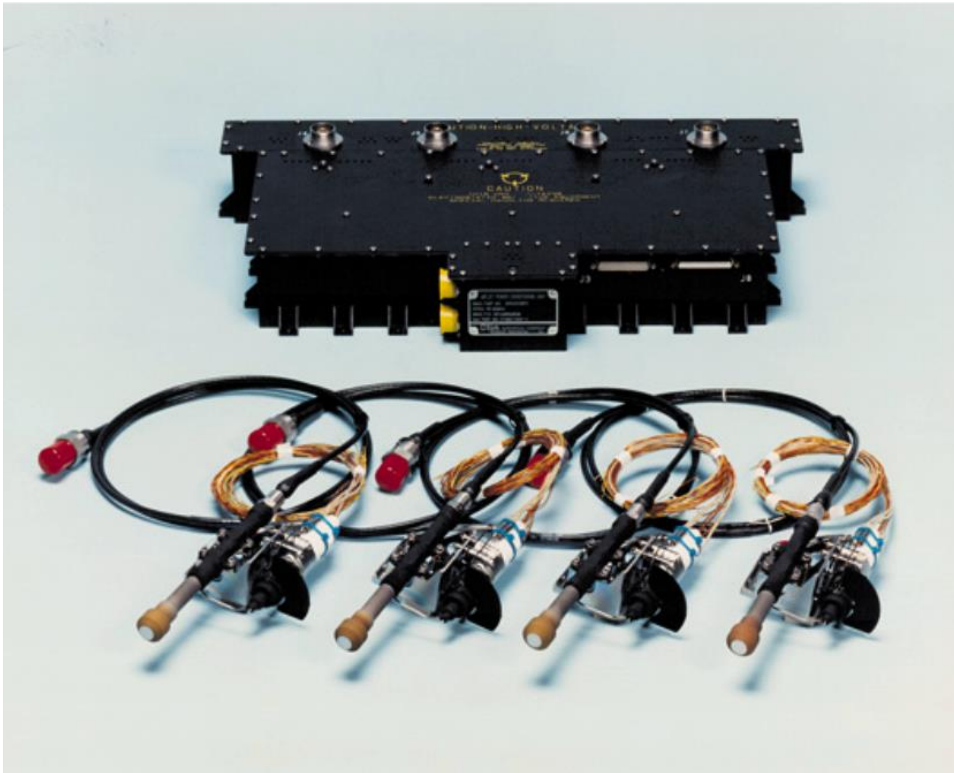

Fig. 2: A typical MR-510 arcjet shipset consists of one PCU, four power cable assemblies, and four arcjet thrusters

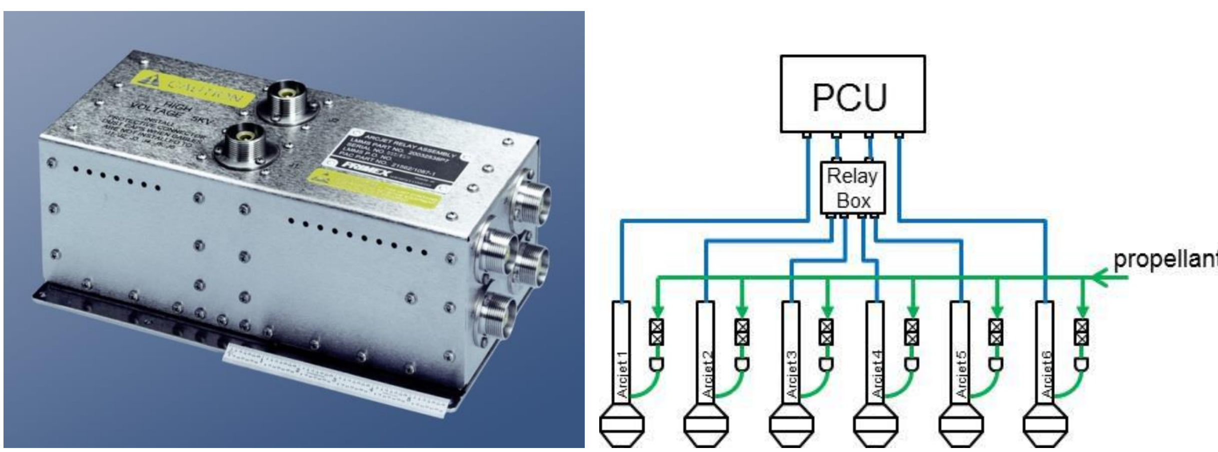

Fig. 3: The MR-510 arcjet system relay box allows to add two additional arcjets for a total of six per system by switching two power inputs (top of the box) to four power outputs (right side of the box).

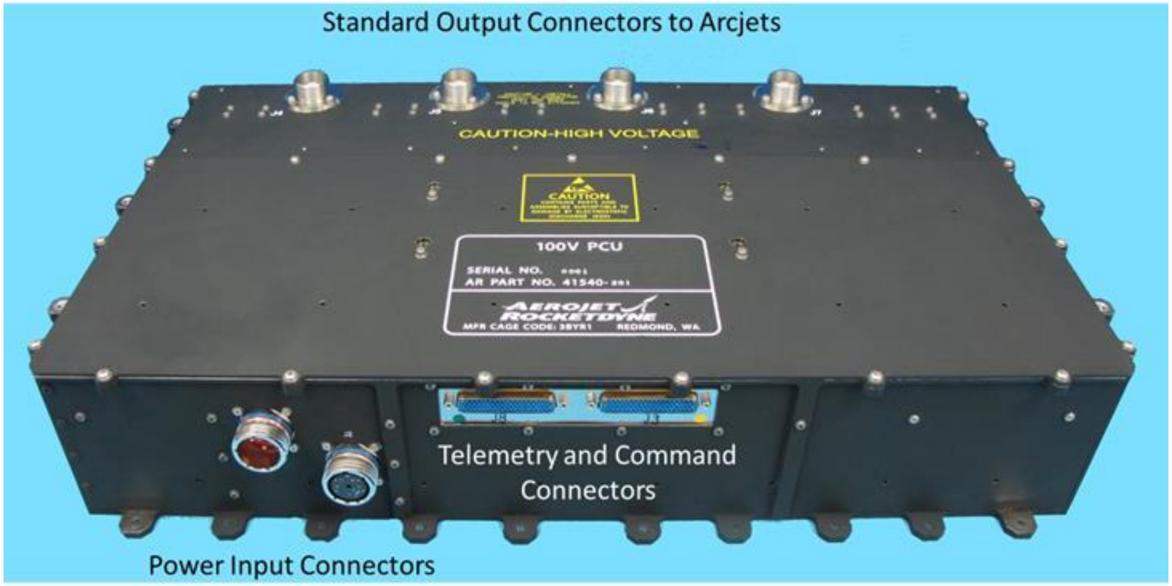

Fig 4: The MR-510 100V PCU design addresses parts obsolescence while maintaining overall architecture.