500-WATT ARCJET SYSTEM DEVELOPMENT AND DEMONSTRATION

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ABSTRACT

Due to its high specific impulse (>425 sec) a low power arcjet system is greatly beneficial to power-limited satellites for missions such as LEO orbit raising and North-South stationkeeping in GEO. This paper summarizes the progress in the development and demonstration of a 500 W hydrazine arcjet system under the NASA-sponsored Low Power Arcjet Thruster System (LPATS) development program. The program objective is to develop a flight qualifiable arcjet system (including the arcjet, power conditioning unit, and propellant feed system) with a mission-averaged specific impulse greater than 425 sec at a power level of 500 W. The feed system regulator, developed by Moog Inc., has been tested at PRIMEX Aerospace Company (PAC) under vacuum conditions through a wide range of flow rates and upstream pressures. Output pressure regulation of +/- 3% of the setpoint was demonstrated. Arcjet performance testing and a limited life test (255 hours) have demonstrated fabrication and assembly techniques, stable operation, and an average specific impulse of 445 seconds. LPATS design modifications, incorporating the results of the 255-hour test, have been made and demonstrated. An engineering model power conditioning unit (PCU), based on MR-509 PCU technology, has also been fabricated and demonstrated to operate the 500 W arcjet. LPATS is now ready for flight qualification.

INTRODUCTION

In the mid-1980's, the NASA Lewis Research Center (LeRC) and the Primex Aerospace Company (PAC) identified the need for advanced propulsion for north-south stationkeeping (NSSK) of large geosynchronous communication satellites (GEO Comsats). Both organizations proposed the use of the arcjet thruster for this application. The increased specific impulse (I_{sp}) of the arcjet thruster could reduce on-board propellant requirements, increase satellite life, and/or increase revenue generating payload compared to satellites using hydrazine thrusters. In 1984, NASA began supporting both an in-house and a contracted effort to develop an arcjet thruster system. The technical goal of the contracted effort was to develop a flight qualifiable arcjet thruster system capable of 450 seconds (s) I_{sp} at a power level of 1.4 kW.

The program was successfully completed in 1989 with a 811 hour (h)/811 cycle performance demonstration of an engineering design model (EDM) thruster system including an arcjet thruster, power processor, and a gas generator.[1] This technology became the baseline design for the successful transfer to a commercial satellite application. Lockheed/Martin Corporation (LMC), formerly known as Martin Marietta Corp., contracted PAC to develop a 1.8 kW, 502 s minimum nominal mission average (NMA) I_{sp} arcjet. First generation arcjets built by PAC have logged nearly two years of NSSK operation on the first LMC Series 7000 satellite.

In 1991 NASA began a second Arcjet Thruster Development (ATD) Program with the goal to advance the performance threshold of arcjet technology to greater than 600 s NMA I_{sp} at 2200 watts (W). This effort, conducted by PAC under contract to NASA, identified and resolved key life limiting factors of a thruster operating at extremely high performance levels.[2] Unique design approaches were required to resolve low flow start and steady state stability issues.[3] A particular life limiting phenomenon, constrictor closure, required the redevelopment of a high temperature /high strength tungsten alloy and the associated manufacturing and machining processes.[2,3] The ATD program was successfully completed with the demonstration of an EDM thruster for over 1000 h/1000 cycle at a NMA performance level of 607s I_{sp} at 2000 W input power. The flight qualified version of this arcjet (MR-510) is currently flying on three LMC-manufactured GEO satellites.

In 1994, the trend to smaller spacecraft led NASA to initiate the Low Power Arcjet Thruster System (LPATS) Technology Program. The program was awarded to PAC in early 1995. The specific program objective was to maximize performance in the sub-kilowatt power range. The approach is consistent with a spacecraft industry trend towards life extension of existing bus designs as well as size and cost reduction goals for future spacecraft designs.[4]

The LPATS program has been divided into three phases. The objective of Phase I was to assess the satellite user market to determine the arcjet thruster system power level and performance range appropriate for the broadest set of applications. Results of this effort showed broad support for low power arcjet use for the following applications: GEO North-South stationkeeping of small, power limited satellites; LEO constellation orbit transfer; and for small satellite low earth orbit drag make-up. The second objective of Phase I was to demonstrate the key arcjet system components required to meet the above specifications.

The objective of Phase II was to demonstrate sufficient performance and life to provide confidence in a baseline flight design. A 250 hour life demonstration, with a NMA Isp of >445 sec, has provided confidence in the arcjet design. The power conditioning unit has demonstrated arcjet starting and efficient operation (88-90%). Testing of the liquid pressure regulator demonstrated regulation to +/- 3% of the desired pressure setpoint over a wide range of input pressures and flow rates. The focus of this paper is the review of phase II activities including a development status of the arcjet, power conditioning unit, and liquid pressure regulator.

The objective of the Phase III effort is to complete the flight design and qualification of a low power arcjet system. Completion of the three phase program will result in the availability of sub-kilowatt arcjet technology for application to the next generation satellite systems.

ARCJET

ARCJET ASSEMBLY

The primary elements of the arcjet assembly (shown in Figure 1) include the arcjet thruster, hydrazine gas generator, propellant valves and fluid resistor. The arcjet was a radiation-cooled laboratory type thruster based on a flight arcjet design. The thruster had modular features to provide easy and reliable exchange of electrodes and internal components. The anode retaining nut secured the anode assembly to the thruster body with sealing provided by a grafoil ring. The internal thruster features such as electrode isolation, flow passages and vortex injection techniques were based on previously successful designs. The laboratory thruster also had a sealed electrical pass-through fabricated from commercially available components.

The cathode is a 2% thoriated tungsten rod. The sub-kilowatt arcjet thruster anode (Figure 2) was fabricated in two parts. A W-4Re-HfC alloy insert was used because of its superior strength characteristics at extremely high temperatures.[2] Pure tungsten was shown to have unacceptable constrictor closure characteristics at a specific impulse of greater than 430 seconds at 500 W. The test configuration also included a vortex injector modifications to insure short duration low mode starts. The internal insulator materials and configurations were similar to those planned for the flight configuration.

ELECTRODE DESIGN APPROACHES

Sub-kilowatt development work conducted at NASA[6-11] and at PAC[12] over the past 5 years has provided substantial amounts of data and a number of design approaches to meet the above LPATS goals. NASA has investigated both conventional thruster design approaches as well as unconventional approaches such as subsonic arc attachment anodes. NASA has also recently investigated the effects of variable nozzle expansion ratios on the performance of sub-kilowatt arcjets.[13] The results indicated a diminishing return with increasing expansion ratio over approximately 500:1.

PAC has also investigated the conventional designs and an unconventional bi-angle approach.[12] Because of the broad performance goals and power range targeted for the LPATS program, PAC chose to baseline the conventional anode design with an expansion ratio of approximately 250:1. This approach was felt to have the greatest flexibility over a range of low power conditions.

PAC has also investigated variations to the electrode thermal design. In the past, arcjet thermal design was driven by the requirement to minimize thermal energy transfer to the spacecraft and for survivability of anode material. However, because sub-kilowatt arcjet performance is more sensitive to radiative losses, the LPATS anode exterior area was reduced to minimize heat loss due to radiation (see Figure 2).

TEST FACILITY, INSTRUMENTATION, AND PROCEDURES

Both the arcjet performance characterization and the life test were conducted in Cell 12 of PAC's Electric Propulsion Test Facility.[5] The facility includes a low pressure vacuum chamber, a rocker arm thrust stand with a precision force balance and a pressurized hydrazine propellant delivery system. Power is provided by a PAC laboratory PCU. A PC-based system was used to automate and control testing and acquire all performance, pressure, flow rate and temperature data.

Performance characterization consisted of operating the arcjet at a different tank feed pressures to provide multiple flow rates. The feed pressure was set at one level for the limited life test to simulate a regulated feed pressure. All of the tests were conducted with a 500 W input power level.

The arcjet was fully instrumented and placed in the test set up as described above. Performance mapping was accomplished by operating the thruster for a minimum of 30 minutes to assure thermal equilibrium. At the end of a operating session, the data were averaged and corrected for any thermal related zero-offsets to assure accuracy.

Prior to, and after powered operation, a series of unaugmented tests were performed by running the thruster without electrical power until anode temperatures increased less than 1.1°C/minute. Propellant mass flow rate, feed pressure and chamber pressure data were recorded. The purpose of these tests was to provide a reference of thruster health before and after performance and life testing.

LIMITED LIFE TEST

As noted above, the thruster was initially operated with varied flow rates to map thruster performance characteristics. Figures 3 through 5 graphically illustrate the performance characteristics of the low power arcjet thruster. The flow rate versus feed pressure characteristic of the anode is shown in Figure 3. Figure 4 shows the thrust level as a function of flowrate. The specific impulse of this thruster (Figure 5) far exceeded the program goal of 425 seconds. A maximum specific impulse of 495 seconds at 500 W thruster input power was demonstrated, although additional specific impulse capability is expected. A life time goal of over 1000 hours at 450 seconds is also expected. The operating voltage characteristics of the thruster (Figure 6) show the direct variation with flow rate.

The 500 W arcjet was automatically operated for 255 hours. With the exception of a visual inspection at approximately 100 hours, the thruster operated continuously with a duty cycle of 1.0 hour on, 0.5 hours off. Thrust characteristics during the test are illustrated in Figure 7. The initial performance goal of 425 seconds mission average I_{sp} was exceeded during the test. The mission average I_{sp} was determined to be approximately 445 seconds (Figure 8). The mass flow rate showed an unexpected increase over time (Figure 9). Post test inspections indicate that a gas restrictor in the test set up eroded during the test resulting in the reduction in system pressure drop. With a constant feed pressure, the flow rate increased. It is anticipated that the performance would have been higher if the operating flow rate had not increased.

Voltage and current characteristics, shown in Figure 10, are consistent with the increasing flow rate. The initial voltage rise is consistent with cathode tip erosion. Thruster operation during each cycle was very steady and appeared to be normal.

Post test inspection of the arcjet revealed good anode insert to carrier joint integrity. Anode upstream surfaces remain in good condition. Minor arc tracks from start up were present upstream of the constrictor, but were less than those observed on higher power thrusters. Downstream anode surface conditions were pristine. The constrictor was also in good condition.

The cathode tip showed very little erosion, and is not expected to impact thruster life. The only negative observation revealed from the inspection was the evidence of a tungsten water cycle reaction approximately 0.25" from the tip. This phenomenon is commonly observed on the unprotected tungsten surfaces of laboratory arcjets operated with hydrazine. The process, which is caused by the small amount of H_2O found in the hydrazine, is only observed at a specific temperature range. The 500 W arcjet cathode operates within this temperature regime. This process does not affect thruster performance, but could possibly have affected life.

PAC investigated several approaches to either increase cathode temperature or to shield the cathode. After abbreviated cycle tests with up to 15 hours of arcjet operation on the individual concepts, a candidate shielding process was identified and tested for a total of 65 hours. The results proved that the problem is well understood and was eliminated. At this time, no other lifetime limiting problems are expected with the current design.

In summary, the 255 hour demonstration of the LPATS thruster has provided a sufficient degree of confidence to allow PAC to fabricate protoflight hardware. PAC has completed the flight design of a 500 W arcjet thruster which is currently in fabrication.

POWER CONDITIONING UNIT

A flight-prototype power conditioning unit was developed to operate the 500 W arcjet off a 28 +/- 4 V spacecraft bus. The PCU design was based on that for the MR-509 1.6 kW arcjet system, with emphasis placed on modifying only those components necessary for operating the LPATS arcjet off a 28 V bus. For this reason, the PCU mass (9.0 lb.) was not optimized.

The PCU was subjected to extensive bench-top functional tests, and successfully started and operated the LPATS arcjet over a range of mass flow rates. PCU efficiency ranged from 88.4-90.1% over a mass flow range of 35-55 mlb/sec.

LIQUID REGULATOR

PAC has subcontracted the Space Products Division of Moog Inc. to develop and fabricate a flight qualifiable liquid hydrazine pressure regulator. The regulator is capable of operating in a flow rate range of 5 mg/s to over 60 mg/s and deliver an output pressure +/- 5 psi of the set point. The set point range is approximately 100 to 150 psig. The particular unit provided by Moog Inc. (Figure 11) was set at 115 psig.

PAC completed a test series to determine the repeatability of regulator to control output pressure over a wide range of feed pressures and flow rates. The inlet pressures and the flow rates were controlled by varying the upstream and downstream valves shown in the schematic (Figure 12). Feed pressures were varied from 500 down to 80 psia and flow rate from 45 to 13.6 mg/sec.

The test results shown in Figure 13 indicate repeatability to within +/- 3.5 psi. As the feed pressure drops below the regulator set point of 115 psi, the regulator remains open. The regulator does not exhibit any hysteresis as is shown in the results of the repeatability tests. PAC also tested for flow leakage through the regulator at zero flow rate, or "lock up" conditions. Pressure was observed to rise on the downstream side of the regulator indicating leakage. This condition is not considered to be a problem in the arcjet thruster system because of a valve downstream of the regulator and upstream of the thruster.

SUMMARY AND CONCLUSIONS

A 500 W class arcjet system has been developed under the NASA-Lewis Low Power Arcjet Thruster System (LPATS) program. Essential elements of LPATS is the arcjet, power conditioning unit, and liquid hydrazine regulator. Each of these elements has been developed up to the point of flight qualification.

To date, the arcjet has successfully demonstrated over 250 hours of trouble free operation at a mission average I_{sp} of greater than 445 seconds. Other than the nominal cathode tip and constrictor edge erosion, post-test inspection of the thruster identified a tungsten water cycle reaction on the cathode due to the small water content in the hydrazine fuel. A solution to this problem has been identified and demonstrated. Based on the results of this test, thruster life of greater than 1000 hours is expected.

A LPATS power conditioning unit (PCU) has been developed to operate off a 28 V bus, and has been demonstrated to operate the LPATS arcjet. Conditioning efficiency has been measured to be in the 88-90% range.

A liquid hydrazine pressure regulator, developed by Moog inc., has been demonstrated to regulate feed pressure within 3% over a broad range of flow rates and inlet pressures. Further testing and eventual qualification is required before application.

ACKNOWLEDGMENTS

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13 Conversation with J. M. Sankovic, July, 27 1995.

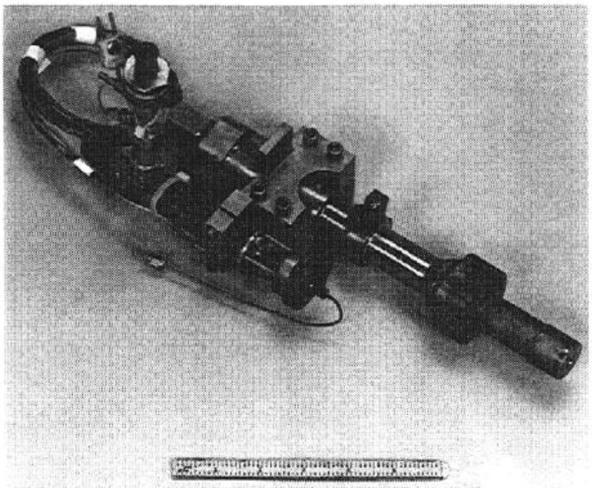

Figure 1. Arcjet thruster test article.

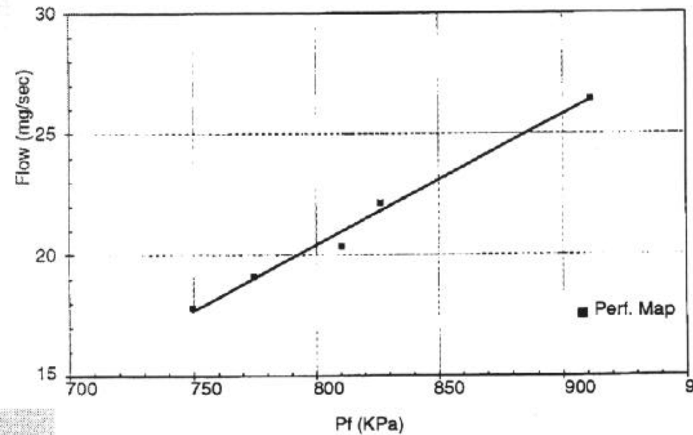

Figure 3. Flow rate versus feed pressure

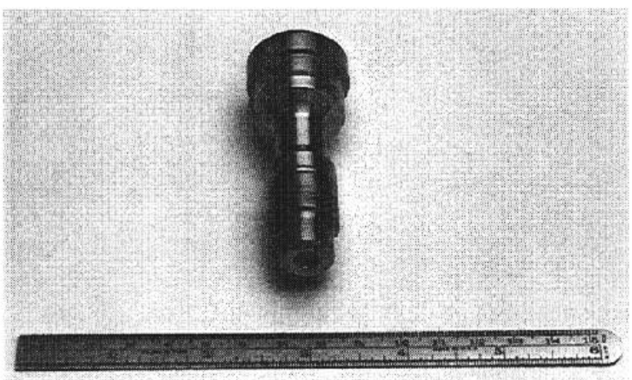

Figure 2. Flight type anode.

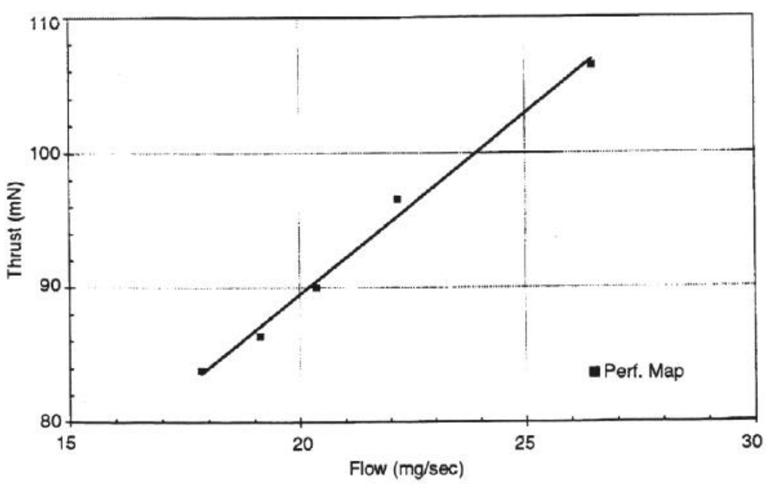

Figure 4. Thrust versus flow rate

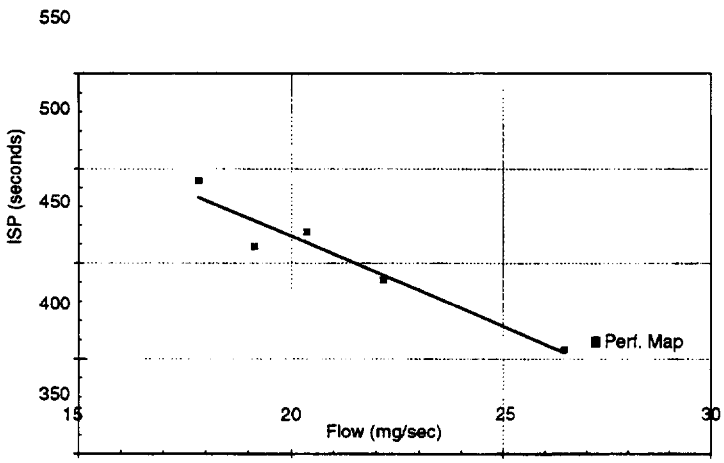

Figure 5. Specific impulse versus flow rate

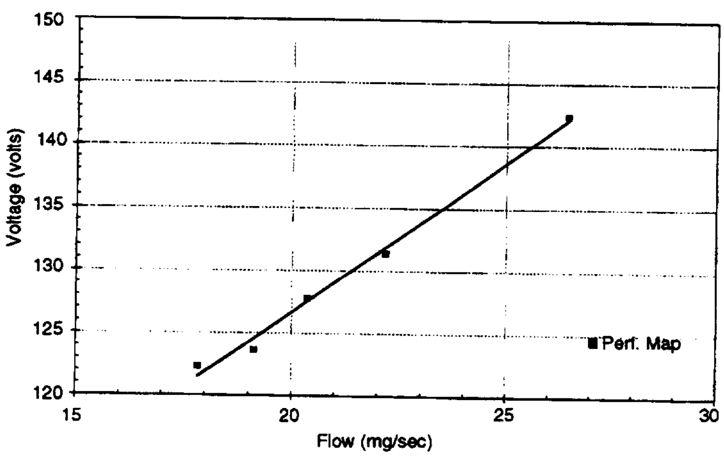

Figure 6. Voltage versus flow rate

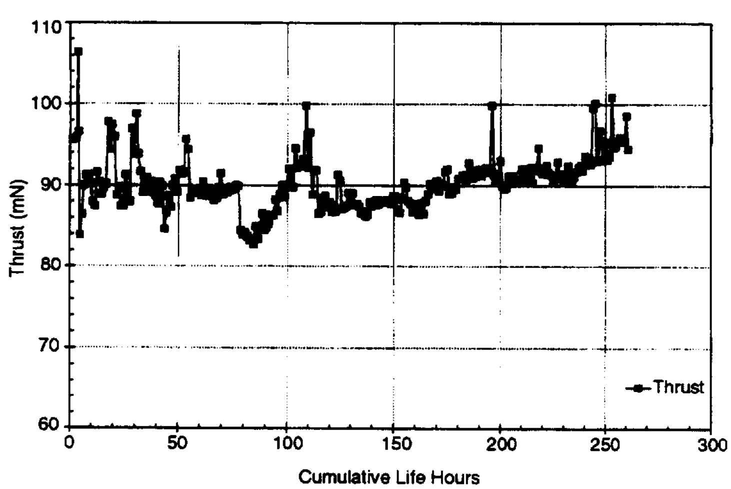

Figure 7. Thrust characteristics

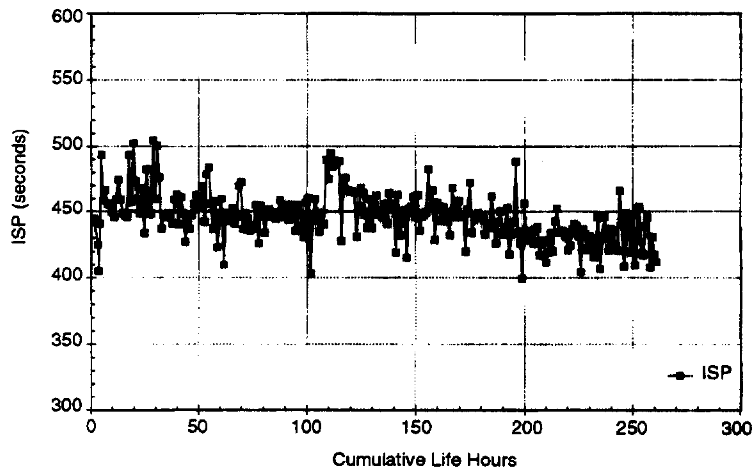

Figure 8. Specific impulse characteristics

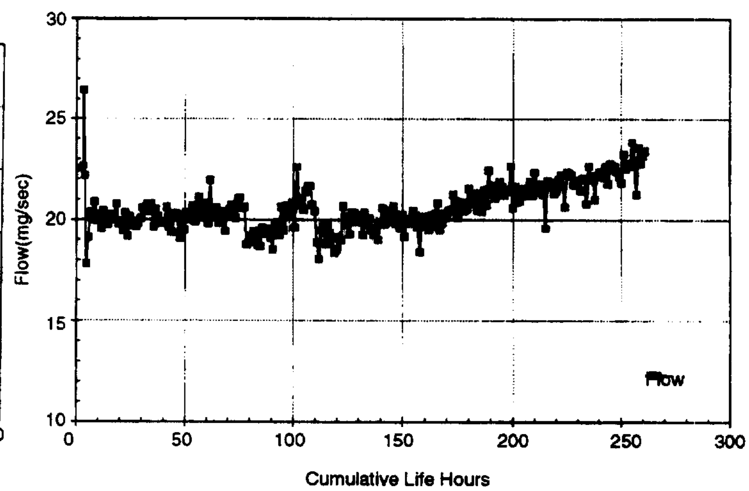

Figure 9. Mass flow characteristics

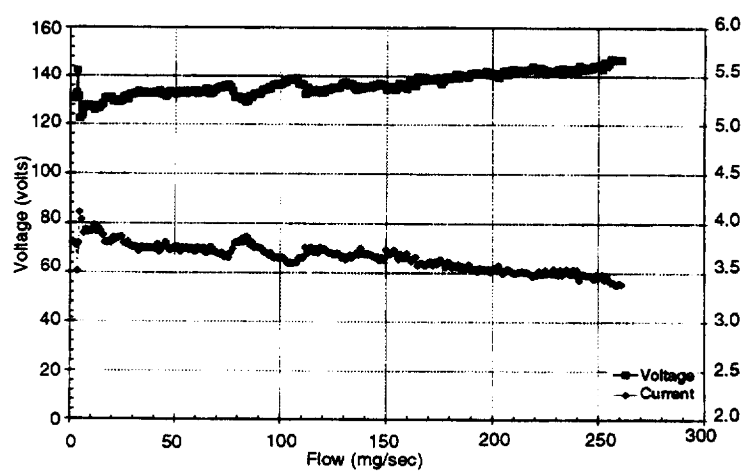

Figure 10. Voltage and current characteristics

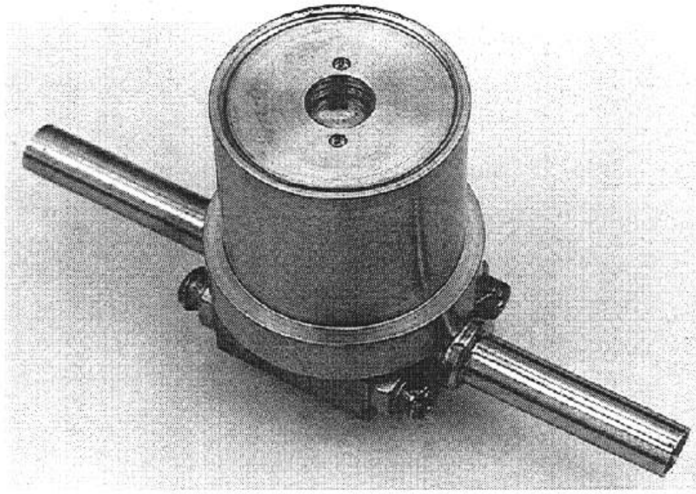

Figure 11. Liquid hydrazine pressure regulator

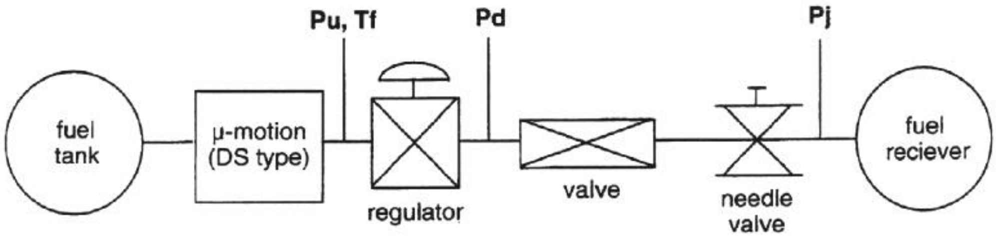

Figure 12. Regulator test setup

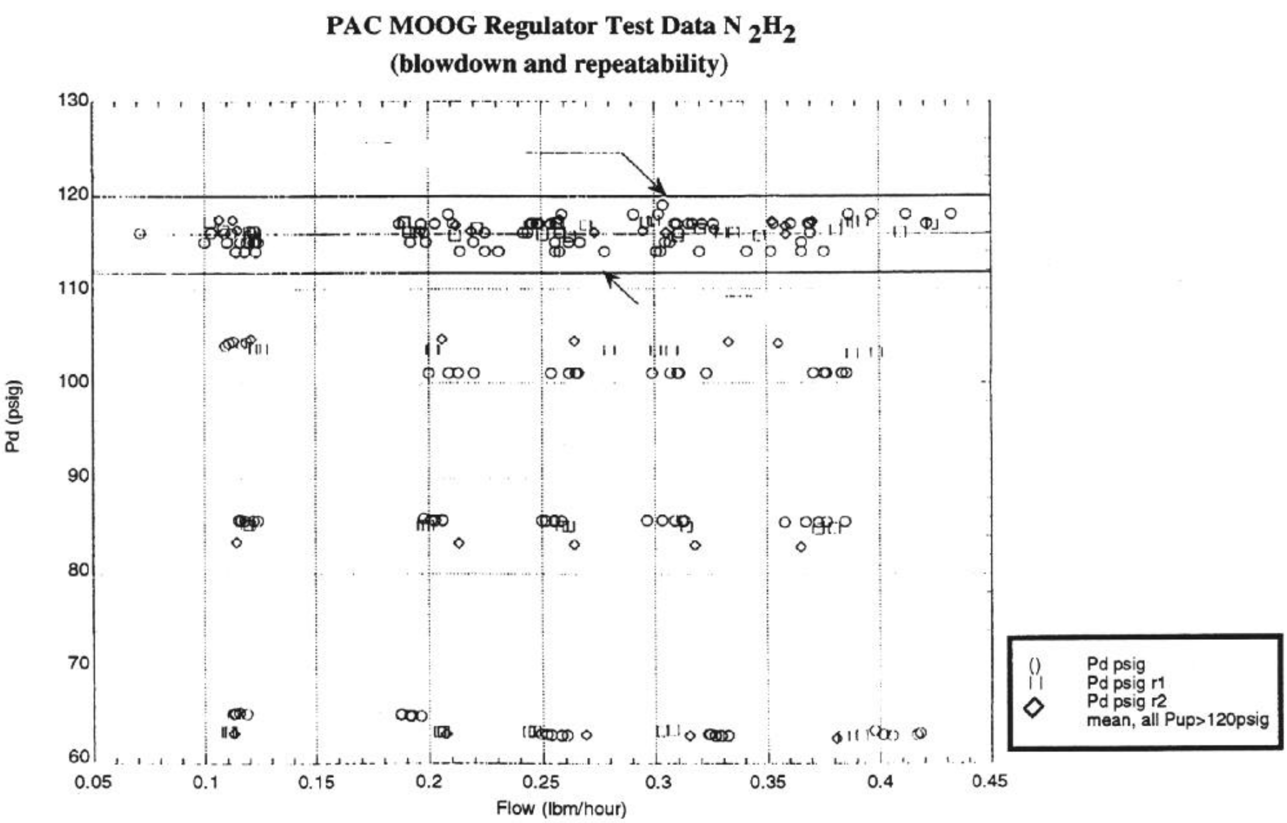

Figure 13. Liquid regulator characteristic