CENTRALIZED PULSED PLENUM GAS DELIVERY SYSTEM FOR HYDRAZINE ARCJETS

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Abstract

TRW has designed and evaluated a Pulsed Plenum Gas (PPG) low flow hydrazine feed system that has been demonstrated to provide decomposed hydrazine at flow rates of 10.6-1.7 x 10^{-5} lbm/sec (48.0-7.8 mg/sec) over a blowdown range of 350-100 psia. These operating parameters are consistent with typical requirements of a 0.5-2.0 kW arcjet feed system. Demonstration of the PPG system was conducted utilizing a concept that has over 10 years of flight heritage from the Air Force Defense Support Program (DSP). Integration of the PPG system with a NASA LeRC 500 W laboratory arcjet has been performed to resolve system issues and evaluate performance of the PPG system with an arcjet. The advantages of the PPG system are (1) it provides a singular, centralized flow system that can supply hydrazine decomposition products (HDP) to multiple thrusters; (2) the system provides constant output pressure over any hydrazine system blowdown range, resulting in an increase in arcjet thruster performance over a straight blow down schedule; (3) alleviates thermal operational issues associated with current steady state hydrazine gas generators operating at low (> 30 mg/sec) propellant mass flow rates; (4) it minimizes the effects of non-volatile residue (NVR) which can occur in low flow rate gas generator injector tubes; (5) it may be able to use monopropellant grade hydrazine without degradation of the gas generator and (6) alleviates the problem associated with entrainment of pressurant gas in the propellant. This paper describes this patented low flow system and provides performance data recently collected with this system.

Introduction

TRW has recently patented a low flow hydrazine feed system for use with arcjet thrusters which has been demonstrated to provide decomposed hydrazine at flowrates of 10.6-1.7 x 10^{-5} lbm/sec (48.0-7.8 mg/sec) over a blowdown range of 350-100 psia. Demonstration of this system was conducted as an internal research and development (IR&D) program by TRW in 1994 utilizing a concept that has over 10 years of flight heritage from the Air Force Defense Support Program.

Evaluation of the Pulsed Plenum Gas (PPG) low flow hydrazine feed system was performed using a NASA LeRC hydrazine arcjet modified to provide similar flow and thermal characteristics of current 500 W arcjet technology, as developed by Primex Aerospace Company under the Low Power Arcjet Thruster Program (LPATS) contract to NASA LeRC. A 500 W arcjet system was selected for the system integration testing due to the thermal stability and NVR deposition issues in steady state hydrazine gas generators at the low propellant flow rates dictated by the performance of a 500 W arcjet.

The purposes of this paper are to describe efforts completed in 1997 to further understand the capabilities of the TRW patented system, and describe how the system could be used in a low power arcjet system.

TRW Pulsed Plenum Gas System

For over 10 years, the Air Force's DSP satellites have utilized a warm gas system to supply decomposed hydrazine to low level attitude control thrusters. This low flow system consists primarily of a gas generator (GG), propellant valve, gas plenum, filters, and pressure transducers. An illustration of this system is shown in Figure 1.1. The system operates by cycling the propellant valve which controls the flow of pressurized hydrazine into the GG. The HDP expel into the plenum where they are stored and ultimately expanded through small nozzles for attitude control. A controlled feedback system monitors the plenum pressure with the

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downstream pressure transducer and controls the plenum pressure by cycling the propellant valve accordingly. In 1994, TRW recognized the potential of the DSP PPG system as a low flow feed system for low power arcjets.

That same year, TRW performed a Low Power Arcjet Gas Supply Demonstration IR&D test[1]. The purpose of this test was to demonstrate the PPG system's capability to supply HDP at low power arcjet thruster flow rates (between 10-40 mg/sec) over a typical hydrazine system blowdown range. In this test, the hydrazine supply pressure was decremented in 50 psia steps from 350 to 100 psia, simulating a typical hydrazine system blowdown range.

PPG System Advantages

Use of the PPG system provides several major benefits over the traditional, steady state operation gas generators currently used on flight arcjet systems. Use of a robust, centralized hydrazine decomposition system to supply multiple arcjet thrusters decreases system complexity and increases reliability. Typical north-south stationkeeping (NSSK) arcjet applications using four thrusters[3] could receive propellant from a single PPG system.

Arcjet thrusters are capable of operation over a narrow band of propellant mass flow rate, dictated by the blowdown range of the spacecraft propellant feed system. A flight arcjet system may only be capable of stable operation over a blowdown range of 1.35:1, where the spacecraft may have a blowdown range of 3.5:1. The PPG system alleviates this problem by providing a constant pressure to the arcjet, independent of the spacecraft supply pressure. Operation of an arcjet at constant feed pressure also results in a higher average specific impulse over the operational life of the thruster. For a 500 W arcjet with a constant feed pressure, the specific impulse increase can be as great as 17%[2].

Typical hydrazine gas generators react liquid hydrazine within a catalytic bed, exothermically generating the gaseous HDP. The liquid is injected into the catalytic bed through a small diameter injector tube. Steady state hydrazine gas generators have a lower limit to the propellant flow rate at which they can operate due to the thermal interface at the point of propellant injection into the catalyst bed. Decreasing propellant flow rate decreases the injection velocity into the propellant bed, moving the point of reaction back to the injector tube. This effect results in two potential failure mechanisms of the gas generator. If the point of reaction moves back to the injector face, the heat of the reaction can cause the injector tube to fail. This failure results in a non-functional gas generator. Even at slightly higher propellant flow rates, the additional heat load can cause propellant in the injector tube to evolve into NVR, plugging the injector and limiting the life of the generator. The propellant pulses driving the PPG system are at relatively high flow rates, increasing penetration of the catalytic bed, and increasing the cooling effects of the propellant during injection. The catalytic reactor in the PPG system is not affected by the operational and life limiting issues associated with steady state, low flow gas generators. This thermally cooler design may also allow for the use of monograde propellant with the arcjet PPG system.

Entrainment of pressurant gas in satellite propellant systems is not critical to standard catalytic thruster designs, but can result in damage to arcjet thrusters from decreased flow during operation. Flow drop outs that occur while the thruster is operating can permanently damage the electrodes with the passage of a single bubble, limiting the life of the thruster. The plenum of the PPG system effectively isolates the arcjet from any entrained gas and maintains a constant flow of propellant to the thruster when even large bubbles are introduced into the PPG system gas generator.

Arcjet

Arcjet Operation

Arcjet start-up is accomplished by initiating the flow of propellant and sending a high voltage pulse between the anode and the cathode. Propellant is swirled around the cathode by a vortex injector immediately upstream of the cathode/anode interface. The start pulse results in an arc breakdown between the anode and cathode upstream of the anode throat. Momentum of the propellant flow forces the arc through the throat, where it attaches diffusely in the diverging section of the nozzle, and remains there during steady state operation. Thruster operation with the arc attached upstream of the throat is called low mode operation.

During low mode operation, an arc spot attaches to the anode surface as it moves toward the thruster throat, producing high thermal loading, material melting and degradation. High amounts of life limiting erosion occur during low mode operation, hence minimization of low mode duration increases thruster life.

Arc-off operation of an arcjet thruster is termed unaugmented operation. Augmented thruster operation occurs after the arc has been initiated and is operated with diffuse attachment of the arc in the diverging section of the anode. A significant increase in flow restriction occurs in the thruster throat after augmented operation is achieved due to heat addition from the arc.

Arcjet Propellant Feed Systems (PFS)

Figures 1.1, 1.2 and 1.3 show schematics of three arcjet propellant feed systems. The Primex propellant feed system provides constant pressure liquid hydrazine to the thruster. The NASA LeRC propellant feed system supplies a mixture of bottled gasses, simulating the byproducts of decomposed hydrazine, to the thruster at a continuous flow rate. The TRW PPG system provides constant pressure HDP to the arcjet thruster. Both the Primex system and the TRW PPG system have considerable flight heritage.

All three PFS are tailored to achieve similar propellant mass flow rates during augmented operation achieving identical thruster performance.

Fluid Response to Start Transients

Figures 2.1 and 2.2 show typical arcjet plenum pressure and mass flow rate transients for the three types of propellant feed systems. Plenum pressure for these discussions is the pressure in the arcjet electrode immediately upstream of the vortex injector.

The NASA LeRC propellant delivery method provides a constant propellant mass flow rate to the thruster during unaugmented operation, and through the transition into augmented operation.[4] Arcjet plenum pressure increases between the unaugmented and augmented operational conditions.

The Primex constant liquid pressure delivery system results in a decrease in propellant mass flow rate between unaugmented and augmented operating conditions. Arcjet plenum pressure increases between unaugmented and augmented operating conditions.

The TRW PPG system provides constant plenum pressure to the arcjet during unaugmented operation, and through the transition into augmented operation. The propellant mass flow rate to the thruster decreases during the same transition to account for the increased flow restriction.

Arcjet Operational Concerns

The different manners in which the PFS systems respond to the arcjet start transients requires a tailored series of propellant pressure drops to optimize thruster performance. Higher unaugmented propellant flow rates typically yield shorter low mode operation times, but low mode duration is also dependent on thruster geometry. Careful thruster design optimizes performance with each of the three systems described.

Testing

In 1997, several tests were performed to further characterize TRW's PPG system. Unaugmented and augmented testing of the modified NASA LeRC laboratory arcjet were performed at NASA LeRC's Tank 4 diffusion pumped facility. These test data were used to define the baseline performance of the thruster. An existing NASA LeRC power processor and power supply were used to operate the thruster in conjunction with NASA LeRC's simulated hydrazine decomposition PFS.

The thruster was brought to TRW and integrated into a vacuum chamber with the PPG system. A 500 W power processor was developed for TRW by NASA LeRC to run the arcjet. The TRW PPG system was operated with the modified NASA LeRC arcjet for unaugmented performance data, and with a 0.007" diameter orifice to simulate an operational 500 W thruster.

Arc breakdown of the modified NASA LeRC arcjet in the TRW hot fire facility was verified.

Test data from the Primex 500 W LPATS developed under contract to NASA LeRC was used for comparison to the data obtained at NASA LeRC and TRW.

TRW Test Facility

The arcjet testing facility consists of a stainless steel, cylindrical tank 4 feet in diameter and 8 feet long, employing a mechanical blower and forepump. A hinged 4 foot diameter door allows access to the chamber at one end of the tank. The arcjet system is located immediately inside the chamber door.

Evacuation of the chamber is performed by two Stokes Microvac forepumps and a Roots Rotary Lobe vacuum blower. The pump assembly is connected to the chamber by way of a 12 inch diameter steel pipe. A set of bellows mounted between the vacuum pipe and chamber is used to damp any mechanical vibrations generated by the pump. The chamber is capable of operating at 15 millitorr during engine operation. Chamber pressure is monitored during pump down and engine operation using a TC gauge

Laboratory PPG System

The laboratory PPG system consists of a gas generator, gas plenum, propellant valves, relief valves, and filters. The PPG system can be described as a single string system between the hydrazine supply and the arcjet. A schematic and a photograph of the PPG system are shown in Figures 3.0 and 4.0, respectively. The operation of the PPG system is similar to the DSP system. The propellant valve controls the flow of hydrazine to the GG, whereupon the hydrazine is catalytically decomposed and the resulting HDP expel into the plenum. (In this particular test set up, the system's plenum is interchangeable. This allows for parametric studies of the effect of plenum volume on system stability, and the optimization of the plenum volume.) With the control valve downstream of the plenum open, the HDP will ultimately expand through the arcjet. The control valve allows for the plenum to be locked up between tests and to isolate the arcjet from the rest of the system. Filters are present in the liquid and gas sections of the PFS to prevent particulate contamination. Using the pressure transducers downstream of the plenum, the data acquisition system monitors the plenum pressure and uses this feedback to cycle the propellant valve accordingly to maintain the plenum pressure.

Instrumentation

Instrumentation for the arcjet facility includes pressure transducers, thermocouples, mass flow burette and a linear potentiometer. As seen in Figure 4.0, four pressure transducers are employed by the PFS. Two transducers measure the hydrazine supply pressure, and the other two monitor the gas pressure in the plenum and the arcjet. A total of seven thermocouples are used to monitor the temperatures of the propellant valve, gas generator, arcjet, hydrazine, and the HDP at several points throughout the PFS.

The mass flow burette works in conjunction with the linear potentiometer to measure the mass flow rate of hydrazine into the vacuum chamber. The burette consists of a small volume, piston, inlet, and outlet. During a test, the burette is remotely filled with hydrazine, after which the inlet is sealed from the supply hydrazine. As the propellant valve cycles during a test, hydrazine is drawn from the burette through its outlet. As the hydrazine is drawn, the piston moves with the flowing hydrazine. A linear potentiometer, attached to the piston, tracks its position relative to time. Once calibrated, the potentiometer is capable of measuring the hydrazine flow relative to piston position.

Laboratory Arcjet

The arcjet employed during this testing is a NASA LeRC laboratory thruster. Figure 5.0 shows the arcjet in TRW's hot fire facility. TRW provided modified cathode, vortex injector, and anode designs to simulate geometrical requirements for a 500 W arcjet (Figure 6.0). The cathode was a modified NASA LeRC design made from 2% ThO_2/W, with a machined 30° half angle conical tip. The vortex injector disk had a single 0.012 inch diameter injection hole and was manufactured from CRES 304L. The anode insert has conical converging and diverging sections with 30° and 20° half angles, respectively, with a throat diameter of 0.012" and a throat length of 0.012". The expansion ratio of the anode was 1000:1.

The anode-cathode gap was set to 0.015 inches.

Test Data to Date

Figure 7.0 shows arcjet end-of-run plenum pressure data for both the TRW modified NASA LeRC thruster and preliminary test data from the Primex 500 W LPATS.

Unaugmented performance of the PPG system at TRW matched the trend of the performance measured at NASA LeRC. The augmented simulation testing performed at TRW matched the augmented testing performed at NASA LeRC.

Plenum pressure data of the Primex 500 W LPATS is also presented in Figure 7.0. The pressure flow rate data trend is similar to both the augmented NASA LeRC data and the augmented simulation data at TRW, with lower pressures at a given flow rate due to a larger 0.015" diameter anode throat used during this testing.

The TRW augmented simulations were performed over a range of hydrazine feed pressures and plenum pressures. Simulation of the augmented mode was achieved by employing a 0.007" orifice, as opposed to the 0.012" orifice used in unaugmented testing. This smaller orifice represents the effective diameter caused by thermal choking within the arcjet during augmented operation. Throughout these tests, the pressure set-point was maintained within ±2.0%. Propellant valve duty cycles between 0.5 to 4.0% were required to maintain the plenum pressures throughout the tests.

In Figure 8.0, the plenum pressure history for an augmented simulation test is shown. This specific test is characterized by a hydrazine supply pressure of 350 psi and a target plenum pressure of 125 psi. The peaks shown in Figure 8.0 are plenum pressure responses to propellant valve cycling, which occur in less than 20 milliseconds. The control system maintains the plenum pressure within 1.6% of the set pressure. The slight drift in the plenum pressure, apparent in the figure, is attributed to thermal drift start up transients of the system.

PPG Flight System

A brief assessment was performed to determine the basic characteristics of a flight PPG system. Much of the PPG's components, including valves, filters, and pressure transducers, are all available as flight qualified components. Items, such as valve heaters, insulation, and integration hardware, have similar flight heritage.

The GG used in the 1997 testing is essentially a modified TRW MRE-1 thruster; the modification being the replacement of the MRE-1 thruster nozzle with a section of tubing. The MRE-1 differs from the GG by having a shorter catalyst bed, simpler catalyst bed heater design, and lighter weight. A comparison of the two devices is provided in Table 1. Despite these differences, the MRE-1 thruster GG provides the same performance as the GG, specifically in throughput and flow rate range.

The plenums used in both the 1994 and 1997 IR&D testing were oversized for the low power arcjet feed system. Determining the optimal plenum size for the PPG system is a focus of future testing.

PPG System Mass Properties

A listing of system component masses for a four arcjet NSSK system is provided in Table 2. The actual weights of the final components selected for a specific flight system may vary slightly from what is listed. A detailed mass property analysis was not conducted for the heaters, insulation, harness, integration hardware, and propellant lines, but their total weight was estimated to be approximately five pounds. The PPG system is estimated to have a total mass of 15.4 pounds. A comparable four arcjet system utilizing steady state gas generators weighs approximately 17 pounds as estimated in Table 3. The weight savings are the result of the centralized feed system approach.

Conclusion and Recommendations

TRW's Low Power Arcjet Gas Supply Demonstration 1994 IR&D test verified that an existing TRW hydrazine flow system could provide HDP at the flow rates needed by low power arcjets. In 1997, TRW's PPG system IR&D program verified the PPG feed system with a low power arcjet and power conditioning unit.

The performance of the PPG system compared well with similar data collected during low power arcjet testing by both NASA LeRC and Primex. The pressure response of the PPG system was controlled to within ± 2 % of the pressure set point.

Although the low flow feed system has considerable flight heritage, there are three design issues specific to the low power arcjet system that still need to be addressed in this effort.

Parametric testing with different volume plenums can provide the data necessary to determine the smallest plenum volume that allows adequate system stability. Also, whether system pressure oscillations effect arcjet thruster life needs to be evaluated.

Also, current arcjet thrusters have been qualified for operation with ultra-pure hydrazine. As mentioned earlier, this system's hardware has been qualified for use with monopropellant grade hydrazine. The key difference between these two propellants is the amount of allowable aniline, which can result in increased NVR deposition in steady state low flow hydrazine gas generators. Additional testing with the PPG system will evaluate the thermal performance of the GG and determine whether monopropellant grade hydrazine can be successfully used.

Acknowledgments

TRW would like to thank NASA Lewis Research Center for use of a laboratory arcjet and power conditioning unit in these tests. This arrangement was possible through a Space Act Agreement.

Engine Parameter	PPG System Gas Generator	MRE-1 Thruster
Approximate Envelope (width x length)	0.5 x 5.5 inches	2.25 x 4.4 inches
Weight	0.7 kg (1.6 lbm)	0.5 kg (1.2 lbm)
Life - Maximum throughput (pulse mode)	> 60 lbm	> 450 lbm
- Maximum cycles	116,995 demonstrated	457,849
Operating Pressure Range	0 to 600 psia	8 to 565 psia
Operating Voltage Range	20 to 28 Vdc	20 to 28 Vdc
Heritage	12 flown on Defense Support Program (DSP)	500 flown on spacecraft such as Tracking and Data Relay Satellite System (TDRSS)
Random Vib Design Level	23.1 G_{rms} total	21 G_{rms} total

Table 1.0 Gas Generator/MRE-1 Thruster Comparison

References

1. B. Jackson, "Test Report: Low Power Arcjet Gas Supply Demonstration", TRW Technical Document M220.94.BJ-021, July, 1994 P. G.

2. Lichon, C. H. McLean, C. E. Vaughn, J. M. Sankovic, "Development of a 500 Watt Class Arcjet Thruster System", IEPC-95-237, September, 1995

3. C. H. McLean, P. G. Lichon, J. M. Sankovic, "1000 hour Demonstration of a 600-Second Arcjet", AIAA-95-2817, July 1995

4. J. M. Sankovic, F. M. Curran, " A Low Erosion Starting Technique for High Performance Arcjets", NASA Technical Memorandum 106627

Component	Unit Mass (lbm)	Quantity	Total Mass (lbm)
Propellant Valve	0.6	5	3.0
MRE-1 GG	0.9	1	0.9
Gas Plenum	3.0	1	3
Pressure Transducer	1.15	2	2.3
Liquid Filter	0.4	1	0.4
Gas Filter	0.4	1	0.4
Flow Orifice	0.1	4	0.4
heaters, insulation, harness, integration hardware, propellant lines, etc.	5.0	1	5.0
		TOTAL	15.4

Table 2.0 Four-Arcjet NSSK PPG System Mass Estimate

Component	Unit Mass (lbm)	Quantity	Total Mass (lbm)
Propellant Valve	1.2	4	4.8
GG	1.2	4	4.8
Flow Restrictor	0.5	4	2
Flow Orifice	0.1	4	0.4
heaters, insulation, harness, integration Hardware, propellant lines, etc.	5	1	5
		TOTAL	17

Table 2.1 Four-Arcjet NSSK System Mass with Steady State Gas Generators

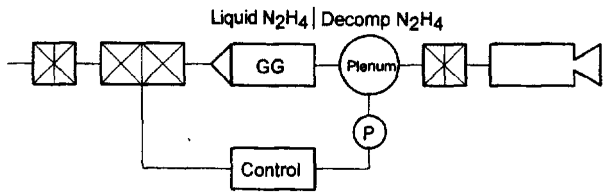


Figure 1.1. TRW PFS

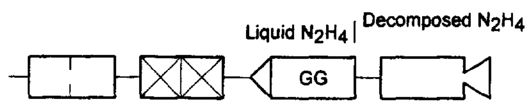


Figure 1.2. Primex Arcjet PFS

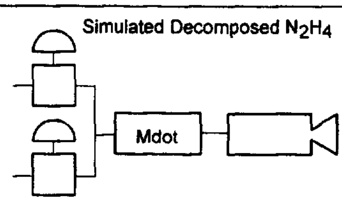


Figure 1.3. NASA LeRC PFS

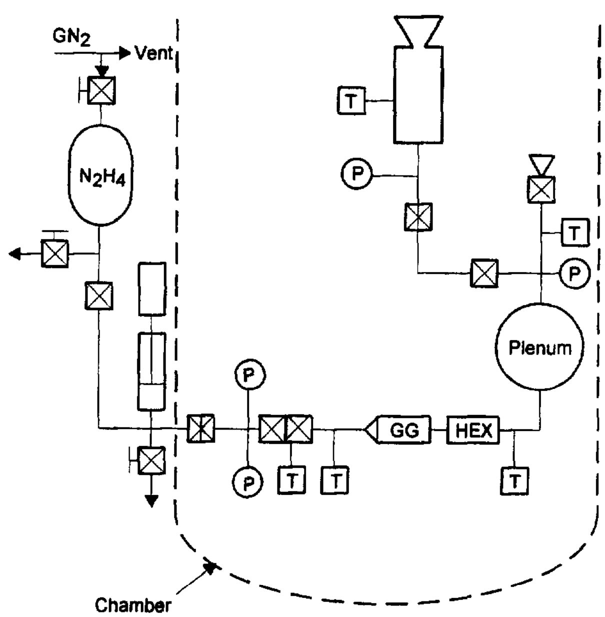
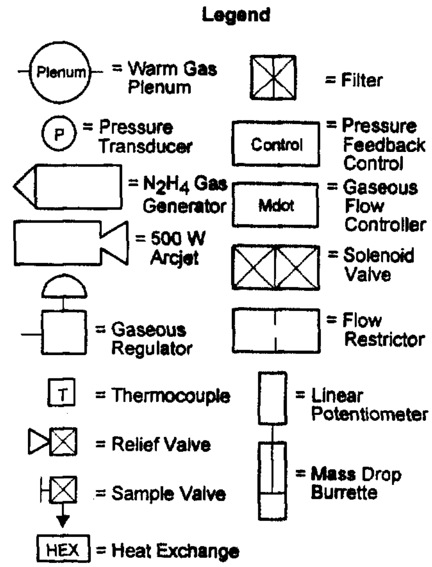


Figure 3.0. Laboratory PPG System/Arcjet Test Setup



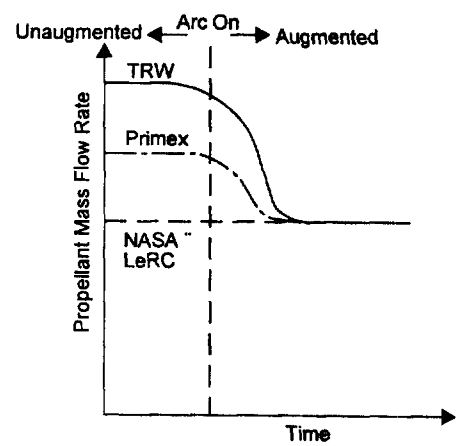


Figure 2.1. Arcjet Mass Flow Transients

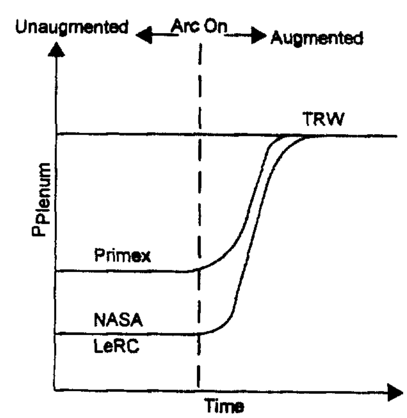


Figure 2.2. Arcjet Plenum Response Transients

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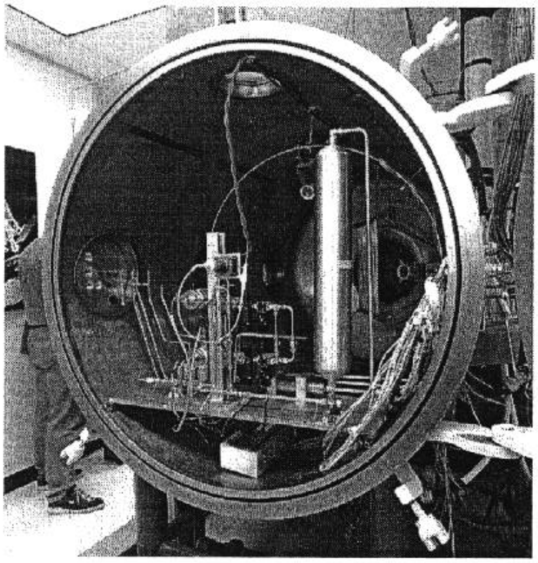

Figure 4.0 Laboratory PPG System

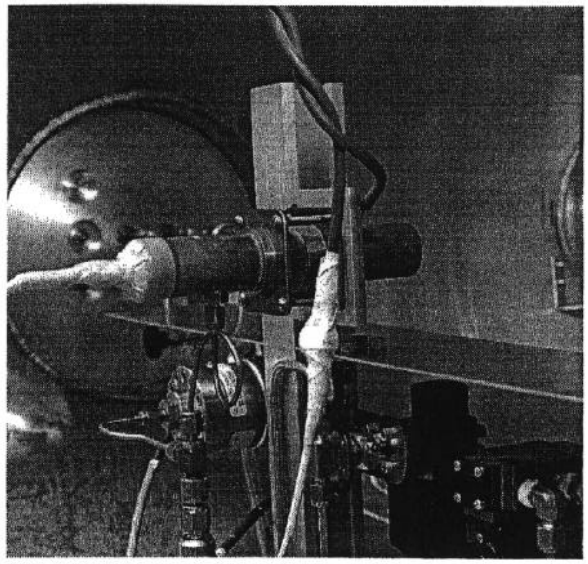

Figure 5.0 Low Power Arcjet

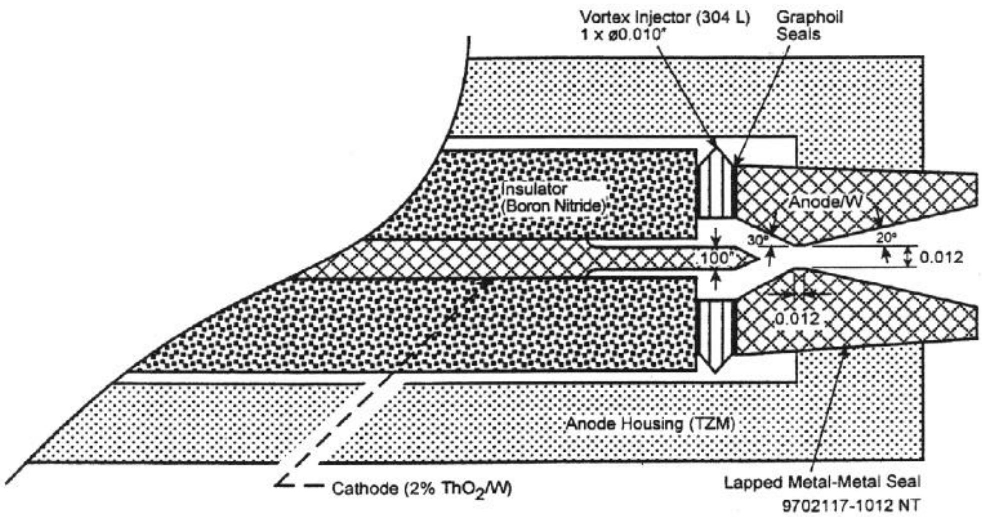

Figure 6.0. Modified NASA LeRC 500W Arcject

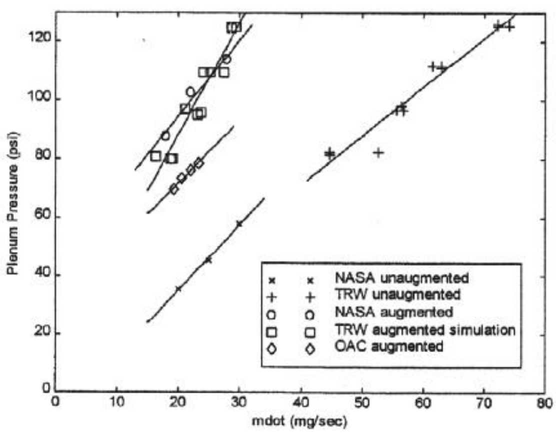

Figure 7.0 Arcjet Performance Comparisons

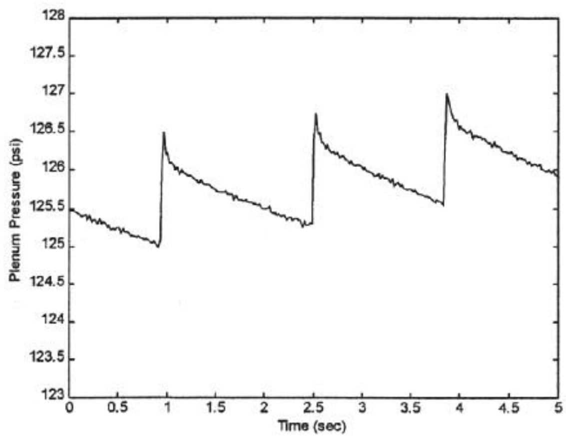

Figure 8.0 Plenum Pressure Response