Investigation and Development of a High Voltage Propellant Isolator for Ion Thrusters

IEPC-2005-316

Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005.

Stephen L. Hart*, William Tighe†, and Charles Pearce‡
L-3 Communications Electron Technologies, Inc., Torrance, CA, 90505

Dan M. Goebel§
Jet Propulsion Laboratory, Pasedena, CA, 91109

ABSTRACT: A series of tests have been performed to characterize the high voltage standoff characteristics of xenon propellant isolators for use in ion thrusters. The ultimate goal of the effort is to provide a device capable of holding off more than 10 kV with Xenon propellant flow rates below ~8 mg/s (~80 sccm) for application in the NASA NEXIS program. The ability to hold off voltage in these devices is a function of the gas pressure and the separation over which the voltage is applied. By dividing the isolator into multiple segments these characteristics can be modified to improve the standoff capability for a given flow. Initial work in this area involved testing of a 10-segment propellant isolator that is part of the 25 cm XIPS ion thruster. We will report on the test apparatus, calibrations of the system, the test procedure used and results for 13, 20 and 30-segment isolators.

I. Introduction

In an ion thruster, the gas feed lines between the propellant management system and the thruster must provide electrical isolation to withstand the applied high voltage. The 25 cm Xenon Ion Propulsion System (XIPS) engine manufactured by L-3 Communications Electron Technologies, Inc., (L-3 ETI) uses a multiple-segment isolator for this purpose. The same isolator is employed in the National Aeronautics and Space Administration (NASA) NSTAR ion engine that drives the Deep Space-1 (DS-1) spacecraft. These isolators consist of multiple, fine-mesh elements separated by alumina ceramic insulators. The voltage applied across the isolator is thereby divided across the number of segments permitting high total voltages to be held off at significant xenon flow rates. In the 25 cm XIPS thruster, as used on the Boeing 702 satellite, the isolator is required to hold off 1.2 kilovolts.

Multiple segment isolators have been investigated by others in earlier mercury [1,2] and xenon [3] thruster programs. Other high voltage flow isolator designs have also been studied. Application of a transverse magnetic field was found to improve hold-off capability [4]. Using a mercury propellant, porous media isolators involving the use of both glass beads and porous alumina cores were studied by Pye [5]. Using xenon propellant, Banks et al. [6] at the NASA Glenn Research Center (GRC) developed a propellant isolator test facility and, having carefully examined the requirements for deep space missions, performed an extensive characterization of several selected isolators focusing on variations of particle filled and grooved porous ceramic isolators. The conclusion of this study was that a porous particle filled isolator was the most promising [6].

* Engineer, L-3 ETI, 3100 W. Lomita Blvd., Torrance, California 90505, bldg 230/1005.
† Physicist/Engineer, L-3 ETI, william.g.tighe@L-3com.com, Torrance, California 90505, bldg 230/1026.
‡ Engineer, L-3 ETI, 3100 W. Lomita Blvd., Torrance, California 90505, bldg 230/1005.
§ Principal Scientist, JPL, Pasedena, California, 91109.

While many performance and life-limiting factors need to be considered to fully evaluate the isolator, the primary purpose of the device to withstand the applied voltage under operating conditions. The breakdown voltage as a function of pressure (Paschen curve) for xenon has been studied [7] but found to be quite sensitive to test conditions. Isolator designs can have significantly different geometries and direct measurement of Paschen breakdown is necessary for each application. The physics involved in gas breakdown is well understood [8] though optimization of devices for a particular application requires detailed investigation.

As part of the NASA NEXIS ion thruster program, multiple segment, gas flow isolators were developed at L-3 ETI and tested for high voltage standoff at both L-3 ETI and at the Jet Propulsion Laboratory (JPL). The ultimate goal of the effort was to produce a device capable of holding off more than 10 kV with Xenon propellant flow rates below ~8 mg/s (~80 sccm).

In this paper the apparatus, system calibration, test procedures and results at both L-3 ETI and JPL for various multiple segment isolators will be described. The primary result of this testing was to demonstrate an approximate minimum hold-off voltage of 4 kV for a 13-segment, 6 kV for a 20-segment and 8 kV for a 30-segment device. Extrapolation of these data would imply that a 35-segment device would successfully hold off the required 10 kV.

Alternative designs have also been investigated at L-3 ETI. Providing a tortuous path for the flow demonstrated an improvement in performance using the same segment number. An isolator with reduced periodicity demonstrated slightly higher hold-off voltage in a more compact device while initial attempts to modify the resistive network have, to date, been unsuccessful.

II. L-3 ETI Isolator Tests

A. Experimental Set-Up and Procedures

The isolators (see example in figure 1) are very compact, measuring only 2.8 cm in diameter and, dependent on segment number, are from about 12-15 cm long. They are shadow-shielded by a re-entrant cover to avoid surface deposition or contamination that might result in electrical breakdown or leakage on the outside of the isolator.

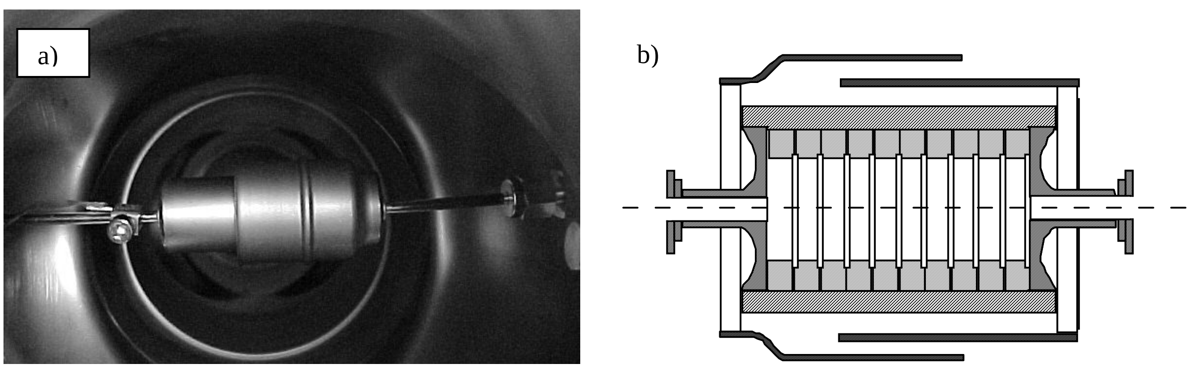

Figure 1. a) *Image of device in test chamber and b) sketch of isolator*

A schematic of the experimental set-up used at ETI is shown in Figure 1. The test device was supported in a vacuum chamber and connected to the gas feed system using standard fittings. A high voltage lead was attached to one side of the isolator while the other side was grounded. An inlet chamber was filled with xenon gas. The pressure was monitored with a capacitance manometer and regulated with a valve to a roughing vacuum pump. Gas then flows from the inlet chamber through a 72 µm diameter orifice into the isolator. The xenon flows through the isolator and into the test chamber. The test chamber was pumped by a 300 l/s turbo-pump. This slow pumping speed for xenon ultimately limited the maximum flow rates achievable.

A high voltage supply (Spellman, 30 kV) was connected through a high voltage connector to the downstream side of the isolator. The upstream side was electrically isolated and connected to a Fowler-Nordheim test box. This is a calibrated high resistance device used to monitor field-emitted current in high voltage testing on Traveling Wave Tubes (TWTs) at L-3 ETI. The output voltage was detected by a digital volt meter. Experimental control and data acquisition were obtained with a computer running LABView© software.

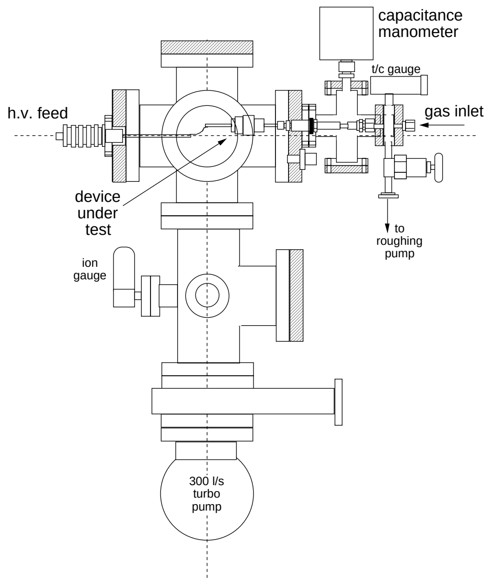

Figure 2. *Schematic Layout of Vacuum Chamber Test Arrangement*

The test procedure began with a baseline measurement of the breakdown voltage under high vacuum. The chamber was pumped to a level of ~2.0 x 10^{-8} torr. High voltage was applied in steps while field emitted current was closely monitored. The initial voltage steps were ~1kV and as the voltage approached the breakdown level the step size was decreased to a minimum of ~200 V. This final step size represents the resolution for determining the breakdown voltage (± 0.1kV). With each increase in applied voltage the system was allowed to stabilize for 20 seconds and an average current measurement was taken in the final 5 seconds of this period.

Following the determination of the voltage breakdown value in vacuum, the test was repeated with the inlet chamber pressurized and propellant flowing through the isolator. Typically the tests were repeated for each device at levels of 15, 30, 45, 80, 120, 200 and 400 torr. The corresponding flow through the orifice was (see below) determined with the maximum flow achievable of ~15 sccm. At this point the chamber pressure was too high for the turbo-pump to operate effectively. This level was below the required test conditions of 80 sccm but, as will be discussed in a later section, the minimum breakdown voltage had already been reached. Furthermore, attempts to go to higher inlet pressures (and so, higher flow) resulted in a voltage breakdown across components external to the propellant isolator. These were felt to be chamber effects that could not be easily removed.

At each voltage step the detected current was recorded. Only under vacuum conditions was any field emission detected (see section C). With gas flowing, the voltage breakdown was detected as a sudden arc. The voltage at which the arc occurred was recorded as the breakdown voltage at the test condition.

B. Flow Calibration

A series of calibration runs on the test equipment were performed using both N_2 and Xe gas. A baratron (capacitance manometer) was used to monitor the backpressure to the flow orifice in the inlet chamber. This unit was calibrated against and found to be in good agreement with a standard convectron gauge outfitted on the same chamber.

To determine the flow for a given inlet chamber pressure, the inlet chamber was filled to 100 torr of N_2. The drop in the chamber pressure was monitored in time and, using a calculated volume for the inlet chamber, the leak rate through the orifice was determined. Simultaneously, the pressure change in the main test chamber was monitored with an ionization gauge. Knowing the pumping speed for the gas being used, the flow rate into this chamber was calculated. The raw data for the rate of change of pressure in the two chambers for 100 torr of N_2 is shown in figure 3. The transition from viscous to molecular flow is indicated by the change in slope. For the tests described here the flow was always in the viscous regime. These tests were repeated using xenon.

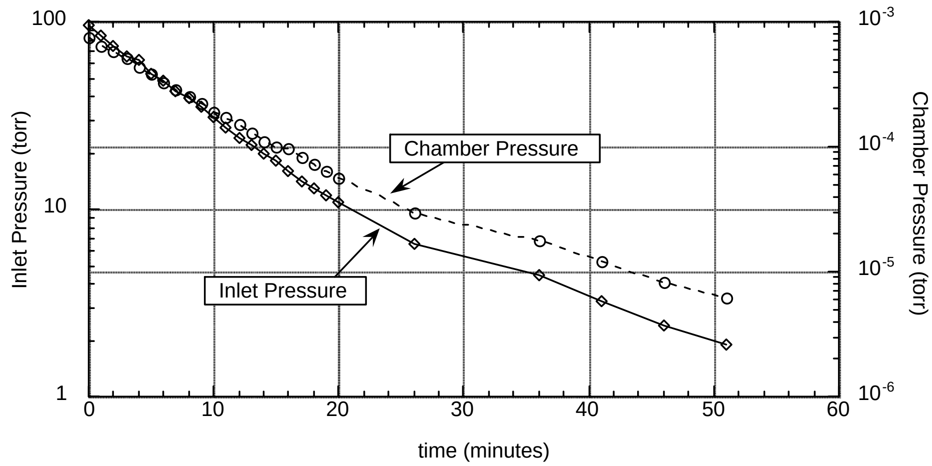

Figure 3. *Chamber pressure as a function of time following pressurizing the inlet chamber to 100 torr of nitrogen*

A plot of the flow rate as a function of backpressure in the inlet chamber is provided in figure 4. Also included in this plot are calculations of the flow rate for nitrogen through a 72 µm diameter orifice. There is good agreement between these values providing confidence in determining the flow rate for Xe using the calibration data described above. To date this calibration has not been performed beyond 100 torr for xenon and so the data have been presented only as a function of inlet chamber pressure and not flow rate.

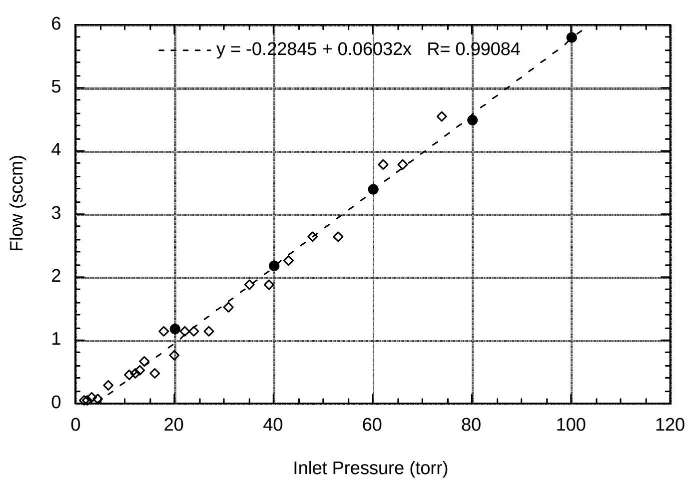

Figure 4. *Determination of xenon gas flow rate for a given inlet gas pressure. Squares indicate flow calculated from the size of the flow orifice, diamonds represent measured values based on the known pumping speed and chamber volume.*

C. L-3 ETI Results

The results of the L-3 ETI testing are shown in figures 5 through 7. In figure 5 a Fowler-Nordheim plot for the 30-segment isolator under high vacuum is presented. This plot shows the characteristic transition from resistive to field-emitted current. In general the test was terminated prior to the formation of a vacuum arc. In figure 6 an example of a Fowler-Nordheim plot under gas flow conditions is presented. Except for different values of the breakdown voltage, virtually every test condition produced a plot identical to this. The high voltage breakdown was observed to be sudden with no field emission.

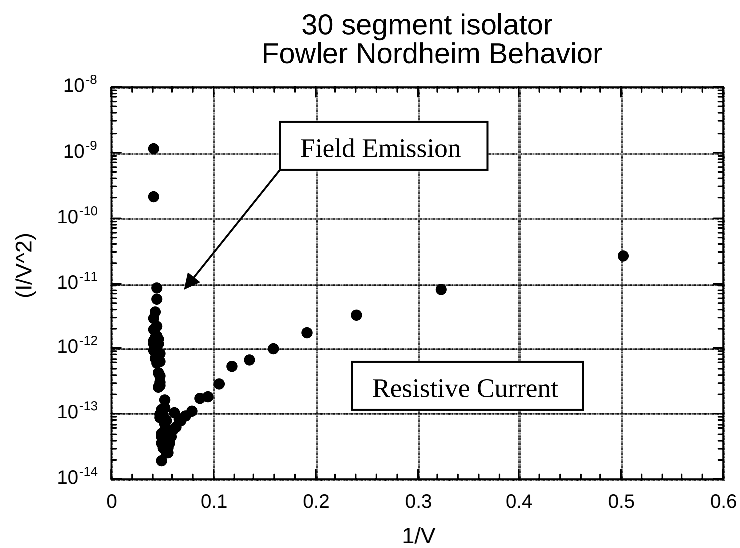

Figure 5. *Fowler-Nordheim Plot for the 30-segment isolator under high vacuum conditions*

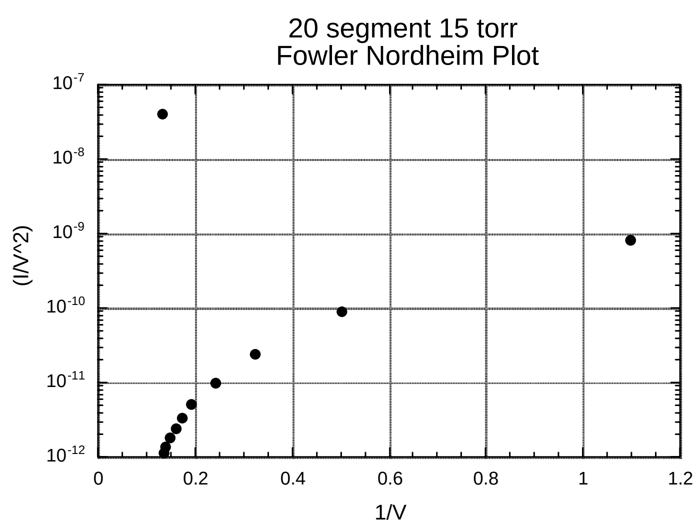

Figure 6. *Fowler-Nordheim Plot for the 20-segment isolator with flow. Inlet pressure was set to 15 torr*

Measurements were repeated several times at each flow level and were very reproducible. Some conditioning was observed in that there was often a small increase in hold-off voltage with increased testing time though no effort was made to extensively condition these test articles.

Hold-off voltages from earlier studies were determined to be 1.5 kV for the 7-segment and 2.5 kV for the 10-segment isolators used in the 13 and 25 cm XIPS thrusters, respectively. Using the present measurement apparatus, breakdown voltages were measured for isolators having 13, 20 and 30 segments. As a baseline, tests were repeated on the 10-segment XIPS isolator. With each new installation of an isolator, dry nitrogen was flowed through the isolator and the feed lines to remove any water or other impurities.

For each isolator, breakdown voltage was measured under various flow conditions in order to determine the minimum of the associated Paschen curve. Curves for the 10-, 13-, 20- and 30-segment isolators are shown in figure 6. While a minimum breakdown voltage could be determined for each isolator, the right side of the Paschen curve did not rise in the expected manner. Under some very high flow conditions (not shown here), it was found that breakdown was occurring to the chamber wall, outside the device under test.

For the 30 segment isolator the minimum hold-off voltage observed in these test was 8.2 kV. The Paschen curve did not display the expected rise with pressure Nevertheless, with the minimum breakdown voltage determined, a plot (shown in figure 7) summarizing the dependence of breakdown voltage on segment number was obtained.

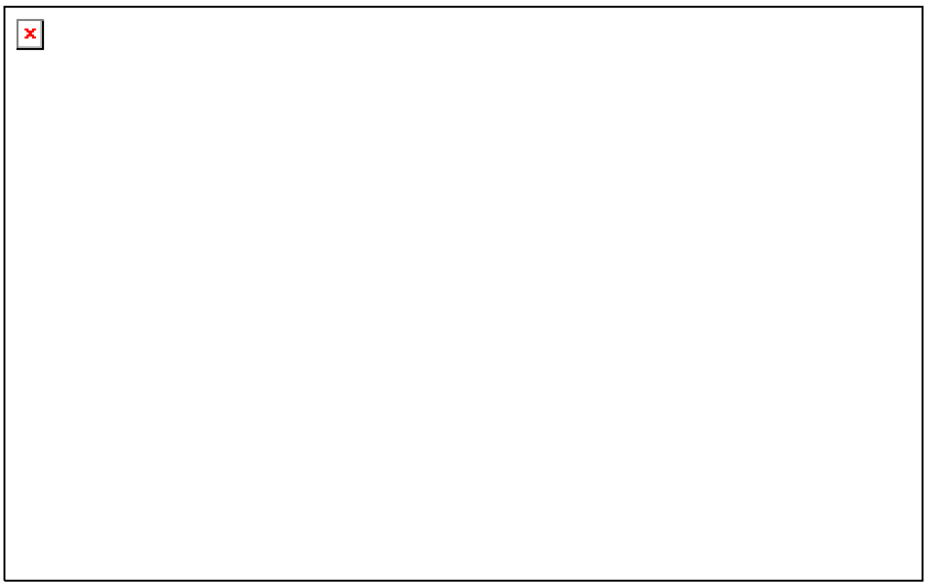

Figure 7. *Breakdown voltage as a function of inlet pressure for 13, 20 and 30 segment propellant isolators. For 20 and 30 segment devices a small upswing in voltage at 10 sccm is indicated.*

III. JPL Isolator Test Results

As mentioned, the L-3 ETI flow isolator tests suffered limitations to the maximum flow achievable and did not provide the classic Paschen curve behavior at higher pressure. To verify the L-3 ETI data, the tests were repeated at JPL using a vacuum test station with a base pressure of 1.5×10^{-8} Torr produced by 2 10-inch CTI cryopumps allowing higher xenon flow levels.

The vacuum chamber had a calibrated xenon flow controller connected to system through the flow isolator. An absolutely calibrated "Baratron" capacitance manometer was installed just upstream of the flow isolator to measure the pressure in the isolator. The other side of the isolator exhausted into the vacuum system and was connected to a Hi-pot tester through a high voltage electrical feed-through. In these tests it was found that a hollow cathode discharge in the chamber could occur in this geometry at higher flow rates and thereby compromise the results. Special care was taken to avoid this as much as possible by installing a gas flow dispersal system covered with a fine mesh at the output of the isolator tubulation. The schematic of the experimental arrangement is shown in Figure 8.

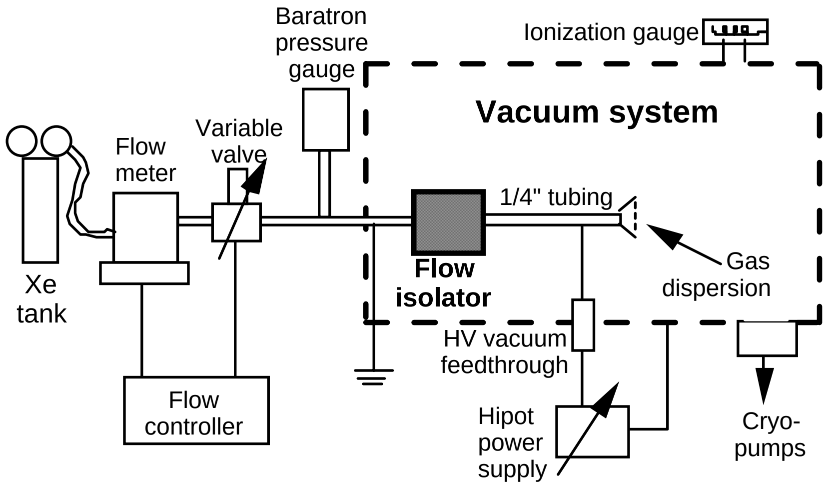

Figure 8. *Schematic of the flow isolator tests at JPL.*

The pressure at the isolator inlet was measured by the Baratron and the pressure in the vacuum system at the outlet of the isolator was measured with a Bayard-Alpert ionization gauge. The 20-segment and 30-segment isolators were tested in vacuum to 12 kV without gas flow, which was the maximum that the high voltage electrical feedthrough could withstand. With gas flow, the 20-segment isolator held a minimum voltage of 6 kV and the 30-segment isolator held a minimum voltage of 8 kV.

The voltage breakdown as a function of xenon gas flow rate for the 20-segment isolator was measured showing that the breakdown voltage increased with higher flow rates and internal pressures, consistent with Paschen breakdown physics.

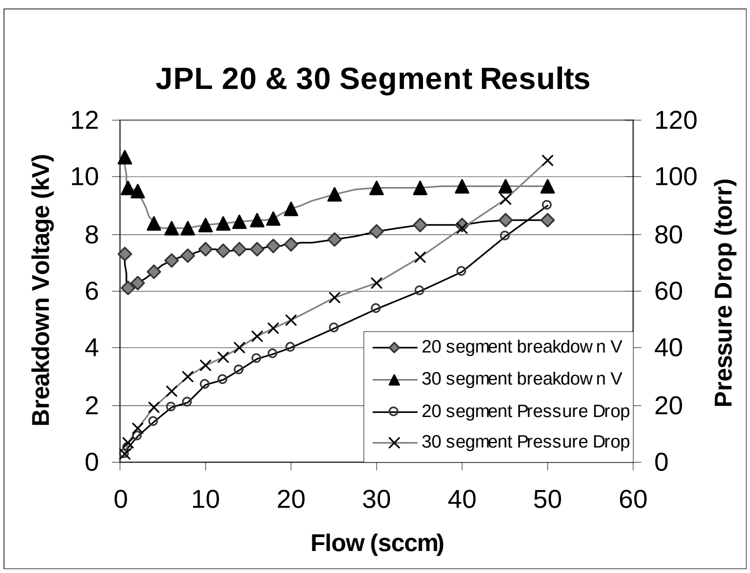

Figure 9. *Voltage hold off of the20 and 30-segment isolator as a function xenon flow rate.*

The voltage hold-off and internal pressure in the flow isolator as a function of the xenon flow rate for the 30-segment isolator is shown in Figure 9. The 30-segment flow isolator also demonstrated a classic Paschen curve behavior in that the voltage hold-off improved at higher internal pressures. Increasing the number of segments in this version with the same diameter and transparency increased the pressure inside the isolator, which produced a higher total voltage hold-off capability of over 8 kV. For gas flow levels in excess of 20 sccm, the isolator held over 9.5 kV meeting the requirement for the NEXIS program.

IV. Segmented Isolator Scaling

The scaling of the segmented isolator voltage stand off capability with the number of segments can be determined from the data taken at JPL and the previous tests at L-3 ETI. Figure 10 shows the minimum breakdown voltage at any flow for these isolators as a function of the number of segments.

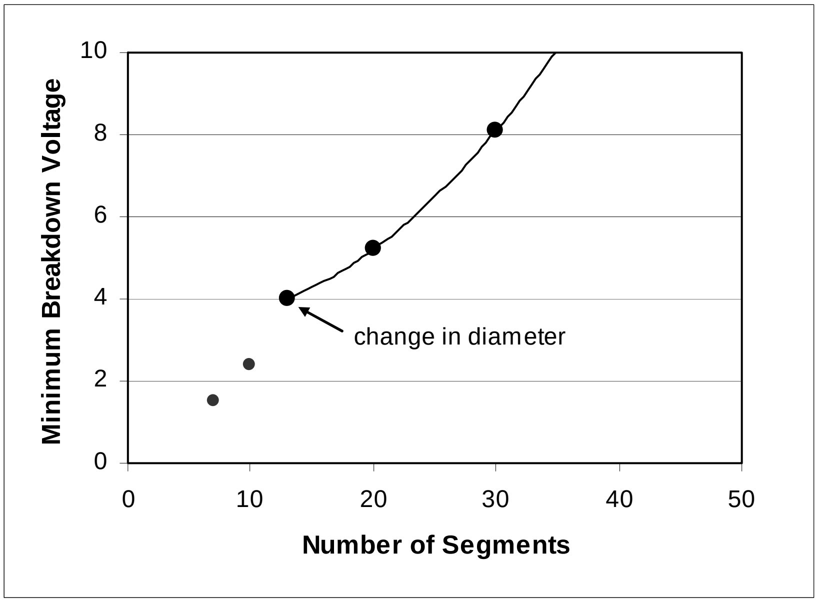

Figure 10. Breakdown *voltage versus number of segments for L-3 ETI gas flow isolators*

We see that a reduction in the diameter of the mesh inside the isolator produced an increased voltage hold-off capability for a given number of segments. This is because this isolator appears to operate primarily on the right hand side of the Paschen curve where higher pressures result in higher voltage hold-off. The smaller diameter mesh elements and a greater number of mesh-segments increased the pressure in the isolator, thereby increasing the total voltage hold-off capability. For the 13, 20 and 30 segment isolator diameters, the fit to the breakdown voltage behavior (shown in Figure 9) indicates that the minimum voltage can be increased to 10 kV by going to approximately 36 segments. This voltage standoff level is not required by the JIMO/NEXIS thruster, however, because the 30-segment isolator already has a 50% voltage hold-off margin for ISPs of up to 7500 sec.

It should be noted that this scaling of voltage hold-off versus the number of segments is for the minimum voltage hold-off point for each isolator, which occurs at low flow rates. In reality, the isolators hold more voltage at the operating flow rates because the pressure is higher inside the isolator. In the JPL tests the 30-segment isolator holds off over 8 kV for cathode flow rates below 10 sccm, and nearly 10 kV for main flow rates on the order of 50 sccm. The 30-segment isolator also held 10 kV at 60 sccm, but testing above this flow rate was limited by the onset of the hollow cathode discharge in the vacuum system outside the isolator.

V. Alternate Design and Additional Testing

A sketch of the basic segmented isolator was shown in figure 1 b). While the design is very compact, the need for more than 35 segments to hold off 10 kV at the minimum of the Paschen curve created a desire to investigate new designs to reduce the dimensions of the device or to hold-off higher voltage. Several approaches have been investigated at L-3 ETI. The most successful of these was obtained by altering the flow through each segment to increase the internal pressure. The hold-off characteristic of a 13-segment isolator with modified flow is shown in figure 11. The hold-off voltage was ~25% higher than that obtained using the standard flow.

Reducing the segment spacing has also been successful in achieving a slightly higher hold-off voltage in a significantly smaller package. A third approach attempting to tailor the resistive drop across each segment to optimize the voltage hold-off capability is only in initial stages and has not as yet been successful.

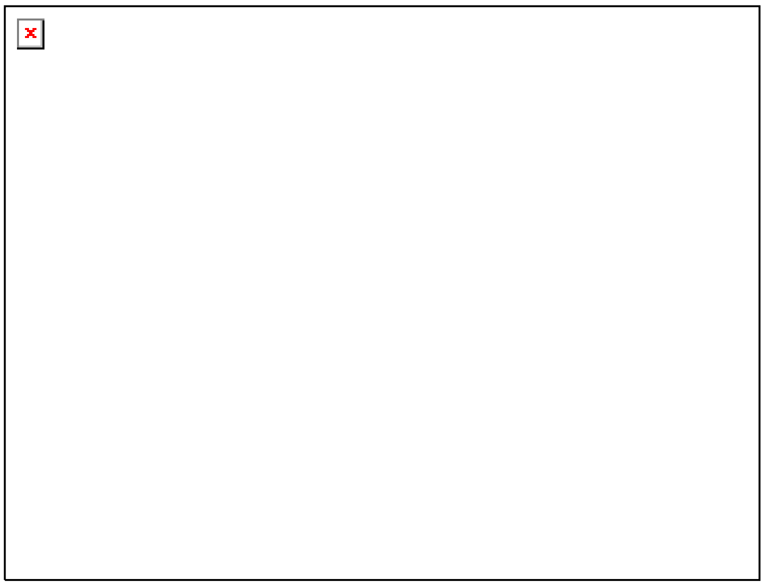

Figure 11. *Paschen curve for the 13-segment, modified flow isolator.*

VI. Conclusion

The L-3 ETI segmented gas-flow isolators demonstrated the voltage hold-off required for the NEXIS thruster, and the 30-segment isolator provided 50% margin in the voltage standoff at the operating flow rates. The isolator was also tested in the NEXIS Laboratory Model thruster to 8 kV at full flow without problem, and operated on the thruster successfully at ISPs in excess of 7000 seconds. The L-3 ETI flow isolators are flight qualified and commercially available.

The primary result of these tests is presented in figure 9. There is a significant dependence on voltage standoff with segment number in this propellant isolator. Extrapolating to a 10 kV hold-off voltage, indicates that a 35-segment isolator would be necessary.

There is also a significant need to model and characterize the breakdown in the isolator in a more detailed manner. A flow and electrical model of the device should be possible to construct and allow predictions of the nature of the breakdown. This could then be used to guide the engineering design of the device to improve performance. Special tests could also be devised to benchmark such a model.

Finally, there should be little concern with respect to life issues. These isolators are constructed entirely of vacuum compatible materials (stainless steel, kovar, high temperature brazes and alumina ceramics) identical to those used in thousands of traveling wave tubes used by NASA and many satellite vendors which have demonstrated over 15 years of voltage hold-off in space. Similar segmented-isolators have demonstrated successful operation in two L-3 ETI life tests in excess of 20,000 hours and one NASA life test (ELT at JPL) in excess of 30,000 hours without any voltage hold-off degradation or leakage onset. In these tests, the isolators were installed directly in the ion thrusters, which is the appropriate environment. In addition, these same types of isolators have been operated for over 16,000 hours in the NSTAR thruster on DS1 and for thousands of hours on L-3 ETI XIPS systems in commercial satellites without a single failure.

Acknowledgments

A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

1. J.R. Beattie and J.N. Matossian, "Mercury Ion Thruster Technology", NAS3-23775, 150 pp., March 1989.

2. J.W. Campbell, R.T. Bechtal, and J.R. Brophy, "J-Series Ion Thruster Isolator Failure Analysis," J. Spacecraft and Rockets, vol. 21, no. 4, 321-322, 1984

3. J.R. Beattie, "Xenon Ion Thruster Technology",

4. J.E Forster, "Transverse Magnetic Field Propellant Isolator," NASA/TM-2000-210333, August 2000.

5. J.W. Pye, "A Gas-Phase High-Voltage Electrical Isolator with Controlled Breakdown," J. Phys. E: Sci. Instrum., vol. 11, 825-829, 1978.

6. B.A. Banks, J.R. Gaier, C-C Hung, P.A. Walters, E. Sechkar, S. Panko, and C.A. Karniotis, "Ultra High Voltage Propellant Isolators for JIMO Ion Thrusters," NASA/TM-2004-213181, AIAA/ASME/SAE/ASEE 40th Joint Propulsion Conference, July 2004.

7. R. Hackam, "Total Secondary Ionization Coefficients and Breakdown Potentials of Monatomic Gases between Mild Steel Coaxial Cylinders," J. Phys. B, ser. 2, vol. 2, 201-215, 1969.

8. R. Papoular, Electrical Phenomena in Gases, American Elsevier Publishing, NY, pg 113-122, 1965.