Ion Thruster Development at L-3 ETI for Small Satellite Applications

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Abstract: The Electric Propulsion division of L-3 Communications, Electron Technologies Inc. (L-3 ETI) presently has 3 ion thruster products – the 13 cm, 25 cm and 30 cm, aimed at the commercial satellite and deep space scientific spacecraft markets. Using the engineering experience gained from the development, testing and flight heritage of this product line, L-3 ETI has designed an 8 cm Xenon Ion Propulsion System (XIPS©) thruster directed toward small satellite or low power applications. The 13 cm XIPS© thruster has been used on the Boeing 601HP commercial communications satellite. In this application, the system consists of four 13 cm xenon ion thrusters and two power processors in a fully redundant configuration to provide north-south station-keeping, momentum dumping and eccentricity control. The 13 cm XIPS© thruster operates at 450 W and provides 18 mN of thrust and 2350 s of specific impulse. The performance of the 13 cm thruster makes it a viable candidate for use on many smaller or medium sized satellites. The 13 cm XIPS© thruster Life-Test completed 21,000 hours and 3,400 cycles over which the thruster performed within its requirements. The 8 cm XIPS© system currently under development is aimed at small satellite and low power applications. The design of an 8 cm thruster that operates at power levels from 100 – 400 W, with 2 – 15 mN of thrust and weight under 2 kG, has been completed along with the preliminary testing of the sub-systems. The design utilizes established technology used in both the 13 cm and the 25 cm XIPS© thrusters as well as the NSTAR 30 cm thruster. A prototype 8 cm thruster is in preparation in order to verify the design performance. Cathode behavior was modeled and expected performance of the 8 cm thruster was calculated using codes developed at JPL.

I. Introduction

Though the term "small satellite" may not have a precise definition; it generally includes satellites with a wet mass below 500 kg. The applications of small satellites (Small Sat) cover a broad range of mission characteristics and requirements. Several studies have shown that a class of these applications could benefit from the use of Electric Propulsion (EP) systems [1-3]. EP offers advantages over chemical rockets with reduced weight, greater precision, and high specific impulse. The nature of Small Sat missions suggests that a light-weight, flexible thruster design would be most useful. This need, along with the successful use of EP on large-class commercial, geosynchronous communication satellites [4] and planetary discovery missions [5,6], has provided the incentive for

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L-3 Communications, Electron Technologies Incorporated (L-3 ETI) to embark on a program to develop a thruster to fill this need.

The main product manufactured by L-3 ETI is the 25-cm XIPS© thruster. It has low (2 kW) and high (4.25 kW) power modes and is used for both orbit-raising and station-keeping functions on the Boeing 702 satellite. In this application 4 thrusters and 2 power supplies make up a single EP system, with full redundancy, on a satellite. To date, 52 25-cm thrusters have been placed in orbit and have accumulated more than 58,000 operational hours. An additional 8 thrusters are in spacecraft integration and 16 more are in production. The 25-cm XIPS© life test has recently been successfully completed [4].

A 13-cm XIPS© thruster, developed after the 25-cm ADM (Advanced Development Model) and with characteristics that may be appropriate for some of the larger Small Sat missions, is used in a similar manner on the Boeing 601 HP satellite. Sixty of these thrusters are presently in orbit and have accumulated more than 120,500 operational hours. Issues associated with the PPU (power processing unit) and the thruster placement resulted in several in-orbit difficulties. None of these difficulties were associated with the basic thruster operation or design and were overcome with improvements made in an upgraded PPU design which was used successfully in later 13 cm flight thrusters. The 13-cm thruster has been successfully life tested and is fully space qualified. A description of the 13-cm XIPS© thruster and life test performance will be presented in section II.

In addition to these products, L-3 ETI has manufactured and tested the 30-cm NSTAR thruster that was designed by NASA GRC [5], successfully life tested at NASA JPL [7], flown on the NASA Deep Space 1 (DS-1) mission [5] and will be launched in September of this year on the NASA DAWN mission to the asteroid belt [6]. The design of this thruster incorporated several weight-saving aspects and flexibility associated with the need for variable power and flow over its' mission life.

Performance and design improvements of both the 25-cm XIPS© and the 30-cm NSTAR thrusters have been incorporated into the design of a new 8-cm XIPS© thruster. The 8-cm design has made use of components that have been proven through life testing and the flight heritage of the earlier thrusters.

The 8-cm XIPS© thruster is a developmental program at L-3 ETI. Completion of a prototype and initial test results are expected this year. Productization of the design configuration, manufacture of an Engineering Model and completion of a qualification program will follow. A description of the 8-cm design and the status of the program will be given in section III.

In section IV, the issues associated with wear testing, life testing and modeling, which are needed for qualification, will be discussed. Finally, in section V, a discussion of possible applications of these thrusters to the Small Satellite missions will be provided along with possible future directions for thruster development and conclusions.

II. 13-cm XIPS© Thruster and Life Test Performance

As indicated in the previous section, the 13-cm XIPS© thruster was developed for use on Boeing 601 HP commercial communication satellite. A cut-away view of the thruster is shown in figure 1. It consists of a cylindrical discharge chamber, a 3-grid optical assembly, and a neutralizer cathode assembly. The discharge chamber plasma is ignited and driven by electrons emitted from the discharge cathode assembly (DCA). The DCA is made up of a hollow cathode insert, a cathode tube and orifice plate, an external heater coil, and a Keeper (see figure 2). Electron trajectories in the discharge chamber are determined by electric and magnetic fields associated with the applied discharge voltage (V_d) and the ring cusp B-field generated by 3 rings of permanent magnets. The discharge chamber is constructed of iron with a stainless steel liner used to trap material deposited on the chamber wall and prevent it from flaking off.

The neutralizer cathode assembly (NCA) is basically identical to the DCA and is used to provide an electron beam that exactly balances (or neutralizes) the ion beam current. This prevents the spacecraft from charging up due to the ejection of positive ions in the thruster beam.

In the XIPS© thruster, the total neutral xenon gas flow is determined by a temperature controlled manifold. From here it is distributed to the main discharge chamber as the primary propellant as well as to both the discharge and the neutralizer cathode assemblies. These three flows are set by fixed orifices that are precisely selected to provide the desired performance. The hollow cathode assemblies require the neutral xenon gas to produce plasma between the cathode orifice and the Keeper. This plasma heats the cathode insert directly through ion bombardment and provides eliminates the space-charge limitations on thermionic emission allowing the required electron current to produce either the main discharge plasma or the neutralizing electron beam to be extracted.

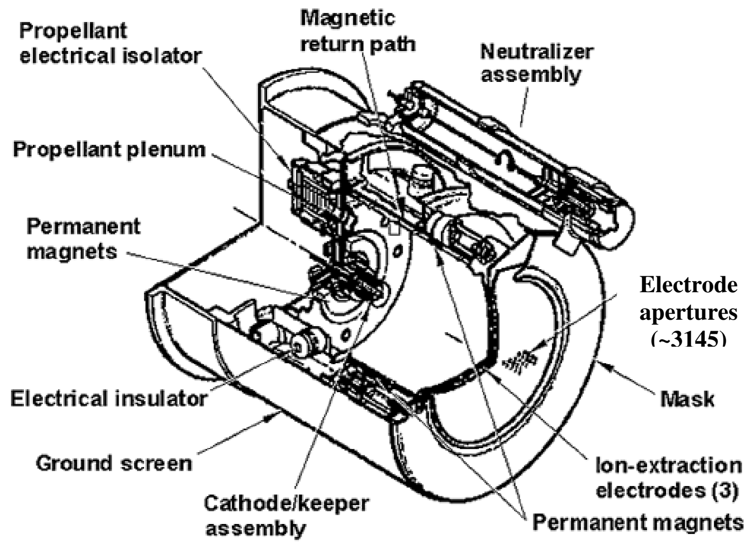

Figure 1. XIPS thruster schematic illustration

One of the life limiting processes for the ion thruster is associated with the depletion of barium from the hollow cathode insert. This can eventually prevent the cathode from igniting and, in turn, the thruster from operating correctly. This process of successful cathode ignition is of particular importance in the XIPS© thruster since, in their primary role of station-keeping, the cathodes need to be ignited every day. A detailed cathode ignition and life model has been developed at L-3 ETI in an effort to better understand the ignition process and accurately predict the cathode life [8].

The XIPS© thruster optics assembly consists of three grids: the Screen, the Acceleration (Accel) and the Deceleration (Decel) grid. Each grid on the 13 cm thruster has 3,145 holes and the 3 grids need to be precisely aligned for efficient beam extraction and to minimize ion impact and erosion of the grid web structure. The Screen is the innermost grid and is effectively an outer wall of the discharge chamber. The Accel grid is used to extract and accelerate xenon ions from the discharge chamber. The Decel grid acts to protect the Accel grid from excessive erosion from returning beam ions. A basic wear mechanism involves the erosion of the Accel grid holes to a diameter that no longer prevents the backstreaming of electrons into the discharge chamber. Erosion of the Screen and the Accel grid web material to a point that causes failure of this support structure can also lead to the failure of the thruster. The presence of the Decel grid reduces these wear mechanisms and provides longer grid life.

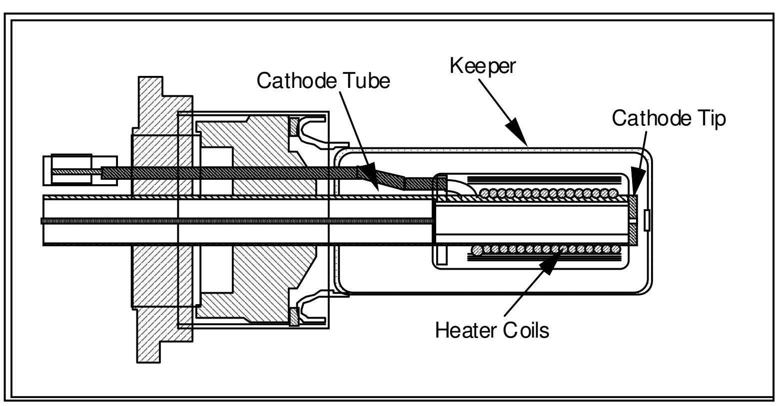

Figure 2. Schematic of the Cathode Assembly

More than 70 13-cm XIPS© thrusters have been manufactured. The performance characteristics are summarized in Table 1. The discharge plasma and the thruster ion beam characteristics have been carefully mapped out using ExB, thrust vector, Langmuir and Faraday probes.

The power processor unit (PPU) controls the thruster and interfaces with the spacecraft. The PPU takes the bus power provided by the satellite and conditions it to the power levels that the thruster needs. A single PPU operates a pair of north-south ion thrusters independently. As a system interface, the PPU provides timing and sequencing for thruster on and thruster off commands, performs fault protection to avoid damage to the thruster and any of the spacecraft components, performs grid clearing in the case of a particle or a flake being caught between two of the electrode grids and, finally, it provides telemetry for the purpose of measuring thruster performance. Table 2 summarizes typical performance characteristics of the PPU.

Table 1. 13-cm XIPS© Ion Thruster Performance

Parameter	Performance
Total Input Power (W)	450
Thrust (mN)	18
Specific Impulse (s)	2350
Electrical Efficiency (%)	68
Mass Utilization Efficiency (%)	72
Beam Voltage (V)	750
Beam Current (mA)	400
Mass (kg)	6.5

Following manufacture, the 13-cm thruster undergoes a test schedule similar to that of the 25 cm thruster [4]. Initial 200 hr conditioning is followed by a vibration test and 8 thermal cycles. For qualification purposes, the number of cycles is increased to a total of 24 cycles.

The Life Test of the 13-cm XIPS© thruster was completed several years ago. Two thrusters, designated Q1 and Q2, were installed in separate, large (10' by 15') vacuum test chambers. The tests were intended to run for 21,000 operational hours using a 5 hour ON and 1 hour OFF duty cycle. A summary of the two tests is given in Table 3. Minute-by-minute data were recorded during the test and upon completion a detailed destructive physical analysis (DPA) was performed on each thruster.

Table 2. 13-cm XIPS© PPU Performance

Parameter	Performance
Total Input Power (W)	530
Bus Input Voltage (V)	49-53
PPU Efficiency (%)	86
Size (cm)	28x20x44
Mass (kg)	14.6

A brief summary of the 13-cm thruster life test and DPA are included in this paper. A detailed report of these results will be presented in a future publication.

As indicated in Table 3, thruster Q1 ended the Life Test prematurely due to excessive erosion of the Accel grid. Additional details will be included later but the primary cause of this erosion was an initial poor alignment of the Screen and Accel grids. This resulted in sputtering of material from the Accel grid and subsequent deposition onto the Screen grid. Localized flaking of this deposited material caused beam ions to be directed into the Accel grid causing rapid milling of both the Accel and Decel grids and the loss of the grid webbing. Relatively large areas of the grids then opened resulting in premature backstreaming and excessive recycling of the thruster.

As a result of this issue, steps were taken to make significant improvements in grid alignment and to prepare the grid surface so that deposited material would have improved adhesion and eliminate the formation of flakes. Other aspects of the grid erosion were consistent with that seen with thruster Q2 suggesting that had these improvements been implemented on thruster Q1, it would have achieved similar life hours.

Table 3. Summary of the 13-cm life test

Thruster	No of cycles	Total Hours	Comments
Q1	3275	16,146	Test terminated due to localized failure of Accel grid
Q2	3369	21,058	Test terminated voluntarily after completing 21,000hrs

Both thruster Q1 and Q2 experienced a decline of ~0.5 – 1.2%/1000hr in both thrust and specific impulse (I_{sp}) over life. The 13-cm XIPS© thruster used only discharge current regulation and did not use beam current feedback control or regulation. For this reason, the beam current, and therefore the thrust, decreased with the discharge voltage (V_d). The operation of the 25-cm XIPS© thruster incorporated a feedback system to adjust the discharge current to provide a constant beam current that maintains constant thrust over life [4]. The behavior of thrust for both Q1 and Q2 over life is shown in figure 3. The strong correlation of the thrust to the V_d is shown in figure 4.

The primary cause of the reduction in V_d over life was determined to be the erosion of the discharge cathode orifice. The constant interaction of the plasma with these surfaces leads to this erosion. Several efforts have been made to model the erosion mechanisms [9, 10] in the cathode. The increase in the orifice diameter will enhance the coupling of the discharge potential to the cathode insert and cause a decrease in the discharge voltage. Additionally, a reduction in pressure will occur in this region that will also influence V_d. More detailed modeling is being performed in order to better understand the various mechanisms involved and will be reported in a future publication.

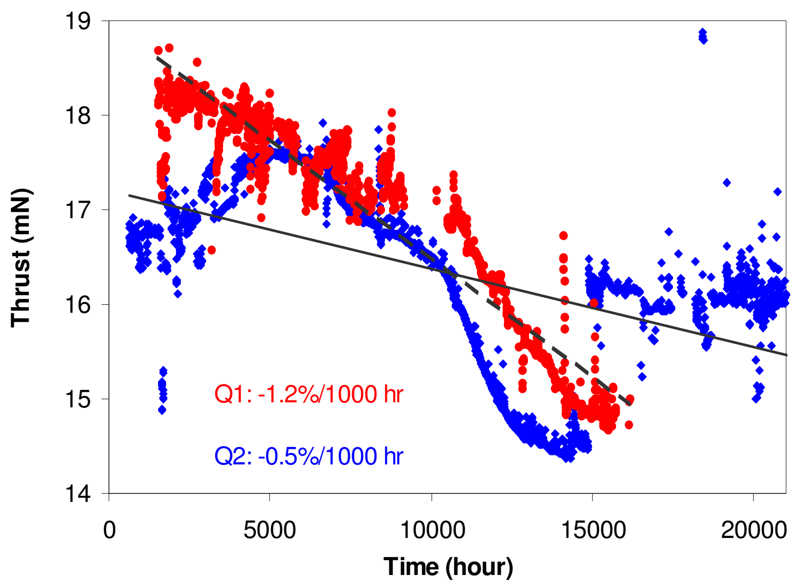

Figure 3. Temporal profile of Thrust, averaged over each burn cycle, for Q1 and Q2 over their life tests

A cross-section of the Q2 discharge cathode is shown in figure 5. The original orifice plate is indicated so that the degree of erosion can be seen. The erosion is quite severe and has resulted in the total loss of the initial 45 degree chamfer.

The outer portion (downstream side) of the discharge cathode Keeper was eroded to about 1/3 of its initial thickness while the inside (upstream side) showed significant deposition of material from the cathode orifice plate. The neutralizer cathode assembly (NCA) displayed much less erosion of both the orifice (see figure 6) and the Keeper which was in excellent condition. Both cathode inserts were carefully inspected and chemical analysis of the outer surfaces and internal structure was performed. Results were consistent with expectations. Modeling of the erosion of both cathodes is being performed and will be presented in a future publication.

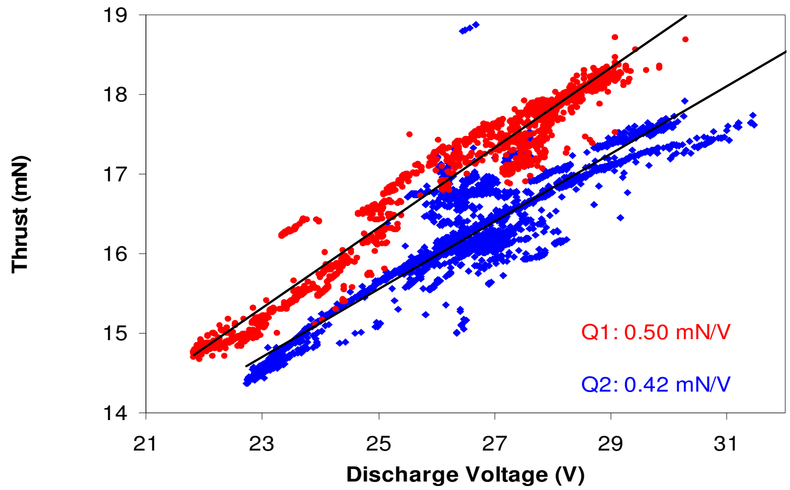

Figure 4. Correlation of Thrust vs. Discharge Voltage

The degree of erosion of the individual grid holes was carefully measured as was the profile of the cross-section of each grid plate. The cause of the Q1 grid failure has been discussed. Individual grid holes experienced a small degree of erosion but not enough to have a significant impact on electron back-streaming. The reduction in the thickness of the Screen grid across its cross-section was more severe over the inner radius than had been expected but not enough to cause concern for mission life. The radial distribution of the erosion of the Accel and Decel grids was consistent with the concentration of charge-exchange ions in the region of the optics. Erosion models have been developed and have accurately described the results of these tests. These results will also be presented in a future publication.

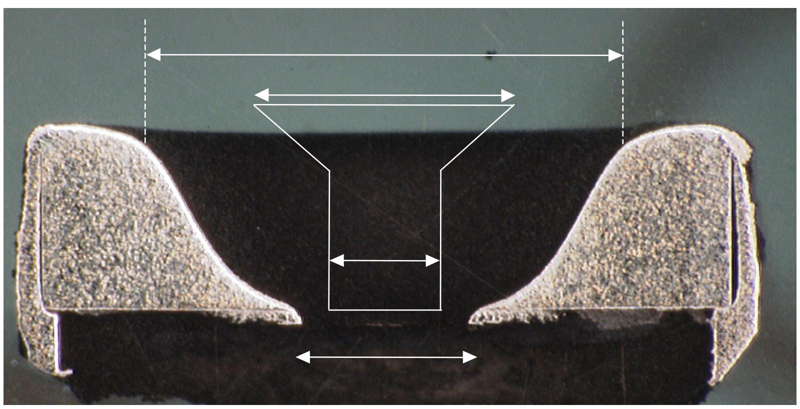

Figure 5. Cross sectional view of the 13Q2 discharge cathode orifice plate at the end of life. The outline of the original orifice cross-section with the 45° chamfer is also shown

Finally, the 13-cm Life Test very successfully demonstrated that the subsystems of the thruster were capable of supplying more than 21,000 hours of mission life.

III. The 8-cm XIPS© Thruster Design and Prototype

Even though the 13-cm XIPS© thruster or modifications of it may meet the needs of a class of small satellite missions, it probably will not be optimal in terms of size and weight. A development project has been undertaken at L-3 ETI to design and manufacture a thruster that would be capable of satisfying the requirements of a larger number of these missions. The design is intended to be light-weight and flexible and maintain the flight heritage of 13-cm and 25-cm XIPS© thrusters and the 30-cm NSTAR thruster.

As with the NSTAR thruster, the 8-cm discharge chamber was designed with both conical and cylindrical sections using light-weight materials. An anode liner, like that used in other XIPS© thrusters, was included in the cylindrical section of the discharge chamber to reduce the risk of the flaking of material deposited on the chamber wall. A 4-ring cusp magnetic field was implemented in order to improve the beam profile (when compared with a 3-ring design [7]). The discharge cathode design followed that of previous XIPS© cathode designs but modified to be lighter and to simplify manufacture and assembly. The design included some flexibility in locating the cathode relative to the axial magnetic field. The heater, cathode tube, orifice plate and insert are identical to that of the 13-cm XIPS© thruster though the thermal characteristics of this design is expected to be improved over earlier ones. As with the DCA, the neutralizer cathode assembly makes use of 13-cm cathode components in an improved design.

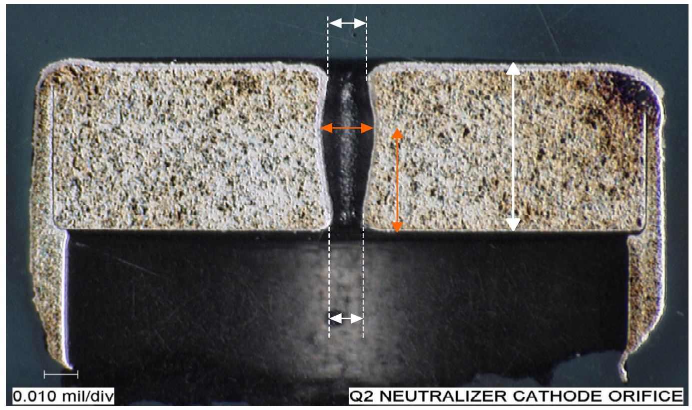

Figure 6. Cross sectional view of the Q2's neutralizer cathode orifice plate at the end of life. The outline of the original orifice diameter is shown

To provide the ability to throttle the thruster, the propellant flow system retained the flexibility of the 30-cm NSTAR design. Flow to the main discharge and to both cathodes is designed to be adjustable and controlled independently.

The optics support ring is the same as that used on other XIPS© thrusters; as are the optics, themselves, which are made up 3 grids: the Screen, Accel and Decel. The grid curvature and hole sizes are identical to those used on other XIPS© thrusters and spacing has been adjusted to provide operational parameters for the thruster that will result in ion beam density, doubly-to-singly charged ion ratio, and neutral gas density that are the same or lower than those for the other thrusters. This is expected to result in similar or improved erosion characteristics.

The thruster discharge chamber design was performed using a 0-D discharge model [9] coupled to a simple thruster performance model to calculate thrust, Isp and efficiency. The model was benchmarked against the 13-cm XIPS thruster [10] to ensure that the predictions for this smaller version thruster are consistent with the experimental data previously obtained. The 13-cm thruster performance parameters [10] were listed in Table 1. Figure 1 shows the discharge loss calculated by the 0-D model for the 13-cm XIPS thruster as a function of the total mass utilization efficiency, and the data point from the nominal operating level of the thruster at about 450 W of total input power. The model provides a prediction of a classic performance curve for this thruster, and gives good agreement with the single data point.

The 8-cm thruster is intended to be operated over a relatively large throttle range so that users can select the optimum performance for their application. The thruster design uses the 13-cm ion optics system to provide heritage and life predictions based on the extensive life test data. The ion optics operate over a limited range in current and voltage due to their finite perveance, which constrains the thrust and Isp available. The present design provides a thrust range of 2 to over 12 mN with a

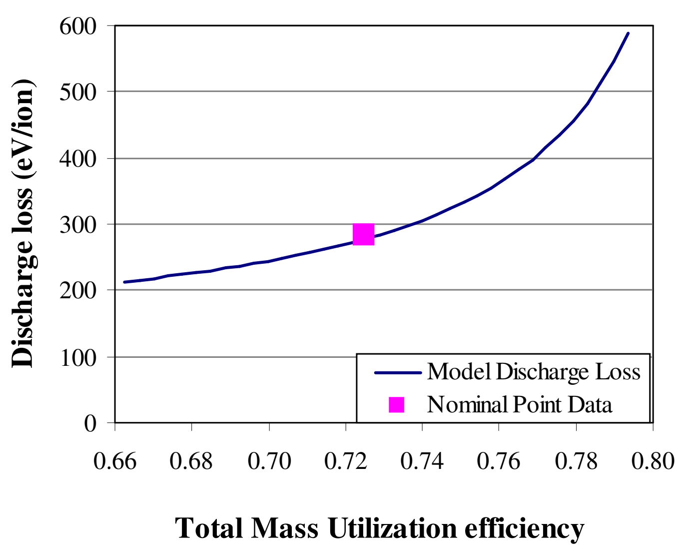

Figure 7. Discharge loss versus mass utilization efficiency calculated for the 13-cm XIPS thruster.

corresponding Isp from about 1500 s to nearly 3000 s.

A physical model and a 3-D drawing of the of the 8-cm XIPS© thruster are shown in Figure 8. Flexibility in the operation of the thruster will be attained by making the input power adjustable from 100 – 350 watts. Over this power range, the flow will also be adjustable as was indicated above. Table 4 contains a list of the expected operational and performance parameters. These estimates were developed using design codes established at the NASA Jet Propulsion Laboratory (JPL).

The discharge chamber was designed using the JPL 0-D particle and energy balance model [9] applied to ring-cusp ion thrusters, and a commercially available code to model the magnetic boundary. The inputs parameters required by the model are:

- Desired beam current
- Discharge voltage
- Discharge chamber surface area and volume
- Magnetic field design
- Grid area
- Grid transparency
- Flatness parameter
- Gas temperature
- Cathode voltage drop

These parameters represent essentially the electrical input parameters to the thruster and the discharge chamber geometry. The grid transparency was assumed to be the same as the 13-cm thruster, and the cathode voltage drop was estimated from probe measurements [11] of the plasma potential inside similar sized cathodes. The 0-D model then self-consistently calculates the neutral gas density, electron temperature, the primary electron density, plasma density, plasma potential, discharge current and the ion fluxes to the boundaries of the discharge chamber. The model is iterated with the magnetic field design from the commercial code and the thruster dimensions to give the desired discharge performance in terms of ion flux to the grids and mass utilization efficiency with an acceptable discharge loss. While the assumption of a nearly uniform plasma is not particularly realistic near the cathode plume, the majority of the plasma in the discharge chamber is very uniform and the model predictions are in excellent agreement with the experimental results from a number of other ion thrusters [9]. The 0-D model output is used in a simple spreadsheet model to calculate the thrust, Isp and total thruster efficiency.

The discharge loss versus mass utilization efficiency predicted for the 8-cm design is shown in Figure 8. The thruster is designed to operate at a nominal total mass utilization efficiency of about 77%, which of course includes the

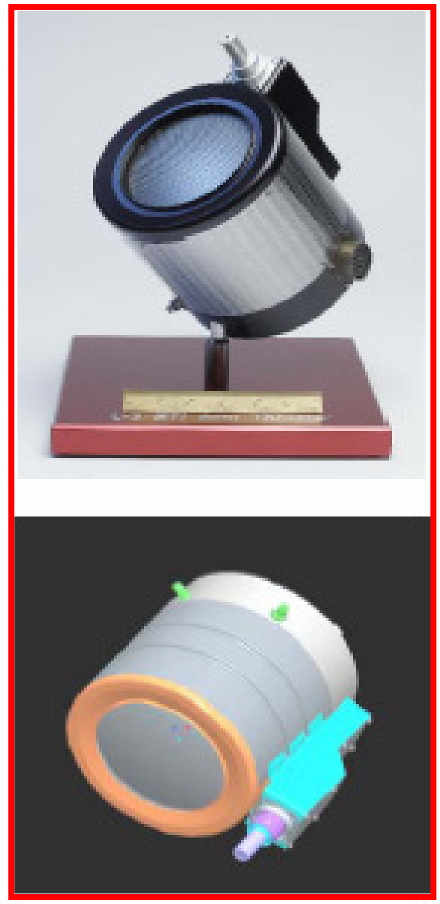

Figure 8. A physical model and a 3-D drawing of the 8-cm XIPS© thruster

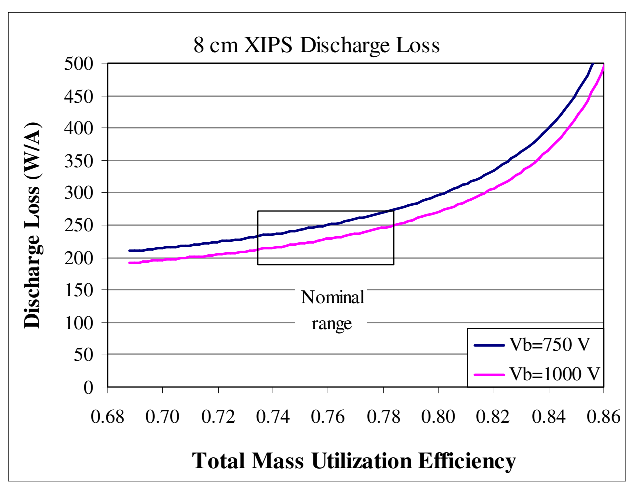

Figure 9. Discharge loss versus mass utilization efficiency predicted for the 8-cm XIPS thruster.

neutralizer flow. Two performance curves are shown to illustrate the impact of operating at different beam voltages. At 1 kV and the nominal mass utilization, the thruster has a discharge loss of about 235 eV/ion. At a lower Isp associated with the lower beam voltage of 750 V, the discharge loss increases due to a change in screen grid transparency to about 260 eV/ion. Increases in the total mass utilization efficiency results in higher discharge losses, which then require higher discharge currents to produce the desired beam current. Since the hollow cathode for the 8-cm thruster is based on the 13 cm thruster, it has more discharge current capability than required by the 8-cm nominal conditions, and higher mass utilizations can be used.

The thrust and Isp predicted for the 8-cm thruster are shown in Fig. 10. Again, two curves are shown for the cases of the beam voltage at 750 V and 1 kV. The thruster provides up to 15 mN of thrust at total input power to the thruster of about 350 W. The thruster runs at 2500 to 3000 s Isp at the high power level, and decreases as the power level is reduced. At the highest power levels, the total thruster efficiency is predicted to exceed 55%, which is excellent for such a small thruster.

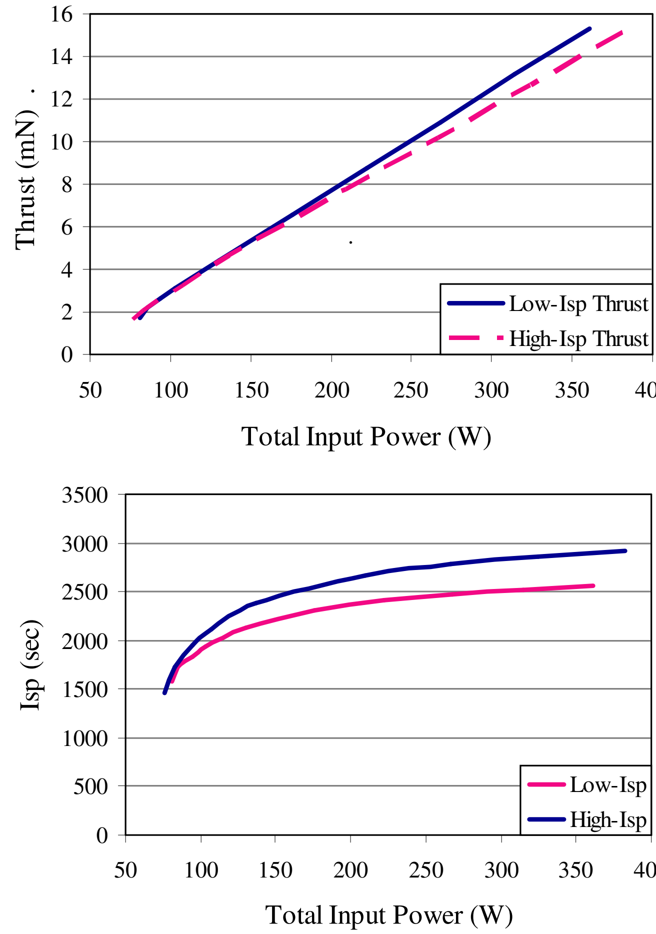

Figure 10. Thrust and Isp versus input power for the 8-cm design.

The construction of an 8-cm prototype thruster is in progress at L-3 ETI. The purpose of this program is to obtain basic measurements of the discharge plasma and beam characteristics. In addition the prototype will be used to identify the need for any design changes.

For initial testing, a 13-cm grid set and NCA have been adapted for use on the prototype. In addition, where possible without affecting performance, alternate materials have been selected. These changes were made to facilitate prototype construction and were chosen carefully so as not to compromise the primary goal of the testing.

At the time of this writing, the prototype discharge chamber, the adaptor rings, the 13-cm grid optics and NCA have been assembled. Manufacture of the 8-cm DCA is still in progress. The magnetic field has been mapped and modeled and some preliminary tests using a discharge chamber simulator have been performed. Installation of the prototype into a large (9'x15') vacuum test chamber is expected this fall. ExB, Faraday, and Langmuir probes are presently being prepared to characterize the discharge plasma and the ion beam.

Table 4. 8-cm XIPS© Ion Thruster Performance Estimates

Parameter	Performance
Total Input Power (W)	100-400
Thrust (mN)	2-15
Specific Impulse (s)	2500-3000
Electrical Efficiency (%)	76
Mass Utilization Efficiency (%)	77
Total Efficiency (%)	55
Beam Voltage (V)	600-1000
Beam Current (mA)	50-350
Weight (kg)	2

IV. Qualification and Wear Testing

In order to finalize product development, productization of the design configuration will be performed following the prototype testing. Following the DFMA, a flight-like engineering model will be manufactured. A thermal balance test will be performed to determine the steady-state characteristics and compare this with engineering models. Qualification testing will be performed. This involves an extended test cycle that will include a 20 hour conditioning run, 16 thermal cycles, a vibration test, and 8 additional thermal cycles to evaluate the effect of vibration. Initial, pre-vibe, post-vibe and final functional testing at room temperature will be used to track and trend the thruster performance parameters. The thermal cycles will transition the thruster through the appropriate range. Ignition characteristics are monitored under both cold and hot conditions.

Because the primary life limiting components have been fully life tested in earlier thrusters, qualification of the 8-cm XIPS© thruster should require only a wear test. The test will be of sufficient duration that the amount of wear can be measured and used to validate existing physical models for cathode and grid life. An independent wear test of the discharge cathode in a simulated discharge chamber is being considered. Models of grid erosion and cathode depletion and erosion at both L-3 ETI and NASA JPL will be used.

V. Discussion and Conclusions

L-3 ETI is the largest supplier of electric propulsion systems in the world. With more than 100 units and about 200,000 hours accumulated in orbit, the XIPS© thruster has an extensive and unique flight heritage. While XIPS© are, at the present time, solely used with geosynchronous commercial communication satellites, studies have shown that small satellite missions may benefit from the use of electric propulsion. The 13-cm XIPS© thruster provides ~20 mN of thrust in a 6.5 kg package and may fill the needs of some of the larger of these satellites. This is a fully space qualified thruster and the results of life tests have demonstrated more than 21,000 hours of operational life with more than 3,000 ON/OFF cycles.

An 8-cm thruster is presently in development at L-3 ETI. This thruster is directed at the requirements of a broader range of small satellite missions. It is expected to deliver 10 – 20 mN of thrust and 2500 s of Isp in a 2 kg package. The 8-cm thruster makes use of the flight heritage of the 13-cm and 25-cm XIPS© thrusters and the 30-cm NSTAR thruster. A prototype and initial testing will be completed this year.

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References

1. M.J. Patterson and S.R. Oleson, “Low-Power Ion Propulsion for Small Spacecraft,” *33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings*, Seattle, AIAA-97-3060, July, 1997.
2. O.A. Gorshkov, “Low-Power Hall Type and Ion Electric Propulsion for the Small Sized Spacecraft,” *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings*, Cleveland, AIAA-98-3929, July, 1998.
3. M.J. Patterson, “Low-Power Ion Propulsion Development Status,” *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings*, Cleveland, AIAA-98-3347, July, 1998.
4. K-R.Chien, S. Hart, W.G. Tighe, M. DePano, T. Bond, and R. Spears, “L-3 Communications ETI Electric Propulsion Overview,” *29th International Electric Propulsion Conference*, Princeton, IEPC-2005-075, Oct., 2005
5. J.E. Polk, D. Brinza, R.Y. Kakuda, J.R. Brophy, I. Katz, J.R. Anderson, V.K. Rawlin, M.J. Patteron, J. Sovey, and J. Hamley, “Demonstration of the NSTAR Ion Propulsion System on the Deep Space One Mission,” *27th International Electric Propulsion Conference*, Pasadena, IEPC-2001-075, October, 2001.
6. J. Brophy, “Implementation of the Dawn Ion Propulsion System,” *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings*, Tucson, AIAA-2005-4071, July, 2005.
7. Sengupta, J. Brophy, J. Anderson, C. Garner, K. de Groh and C. Karniotis, “Summary of 30,000 Hr Life Test of Deep Space 1 Flight Spare Ion Engine,” *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings*, Tucson, AIAA-2005-4397, July, 2005.
8. W.G. Tighe, K-R. Chien, D.M. Goebel, and R.T. Longo, “Hollow Cathode Ignition Studies and Model Development,” *29th International Electric Propulsion Conference Proceedings*, Princeton, IEPC-2005-314, October, 2005.
9. Katz, J.E. Polk, D.M. Goebel, I.G. Mikellides, and S. E. Hornbeck, “Combined plasma and thermal hollow cathode insert model,” *29th International Electric Propulsion Conference Proceedings*, Princeton, IEPC-2005-228, October, 2005
10. Rovey, J. L., Herman, D. A., Gallimore, A. D., “Potential Structure and Propellant Flow Rate Theory for Ion Thruster Discharge Cathode Erosion,” *29th International Electric Propulsion Conference Proceedings*, Princeton, IEPC-2005-022, October, 2005.
11. D.M. Goebel, R. Wirz, and I. Katz, “Analytical Ion Thruster Discharge Performance Model,” *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings*, Sacramento, AIAA-2006-4486, July, 2006.