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**TECHNOLOGIES TO IMPROVE ION PROPULSION SYSTEM
PERFORMANCE, LIFE AND EFFICIENCY**

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Introduction

The performance of nuclear electric spacecraft critically depends on the ability of the electric propulsion system to reliably provide high specific impulse (*Isp*) thrust with great efficiency. Missions to the outer planets will require thrusters to operate for the order of ten years, several times the life of the state of the art NSTAR thruster. Propulsion system efficiency is a multiplying factor in the overall system efficiency “alpha”, the determining parameter in how well a nuclear electric spacecraft performs on deep space missions. In order to help make nuclear electric propulsion systems a reality, at JPL we are developing models of the physical processes that control ion thruster performance, life and efficiency. We are using these models to aid in the design advanced technology ion thrusters and thruster components that we are presently building and testing.

In this paper we present ion thruster design concepts created using the new computer codes that model performance limiting and erosion mechanisms. Presently, the codes model extraction grid ion optics and both discharge and neutralizer hollow cathodes. Work is underway on a thruster discharge chamber model. Basic plasma physical processes including ionization, electron transport, and charge exchange, are modeled in the codes. The grid ion optics and erosion model have been validated with NSTAR life test results, and are presently being applied to grid design in the Carbon Based Ion Optics program. The cathode models have been compared with data from the space station hollow cathode life test. As an example of the power of the computer models, we show how they are being used to design the Nuclear Electric Xenon Ion System (NEXIS) 7500 second *Isp* ion thruster for operation at 20kW (Figure 1.).

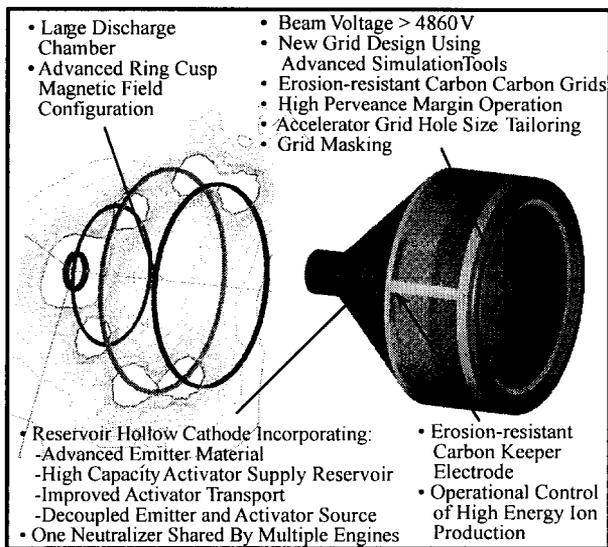


Fig. 1. The Nuclear Electric Xenon Ion System (NEXIS) thruster includes new technologies needed for long life and high efficiency.

The NEXIS grids will have a projected throughput life in excess of 1000kg when fabricated from carbon-carbon materials. The NEXIS cathodes have projected life times well in excess of 50,000 hours.

Performance Metric	State-of-the-Art (NSTAR)	NEXIS Thruster
Power (kWe)	2.3	20
Isp (s)	3170	7500
Thruster Efficiency	0.63	0.78
Specific Mass (kg/kWe)	3.6	1
Throughput (kg)	200	1000
Run Time (khrs)	27	48

Table 1. Nuclear Electric Xenon Ion System (NEXIS) thruster design goals compared with today's NSTAR thruster.

Mission needs

Advanced ion thruster technologies are necessary to support exciting potential outer planet missions that may use nuclear electric propulsion (NEP). Today's NSTAR thruster and next generation solar electric propulsion (SEP) thrusters provide capabilities that satisfy the needs of near term missions with ΔV 's of 10-30 km/s. The ambitious missions shown on the right side of Fig. 2 demand much higher ΔV 's and are only possible with NEP. Systems analyses show that these missions require significant thruster technology advances. Table 1 shows the NEXIS goals for a 100 kWe class system and illustrates that this technology is a dramatic leap beyond current SEP technology. This new technology enables near term outer planet missions with 100-kWe NEP systems.

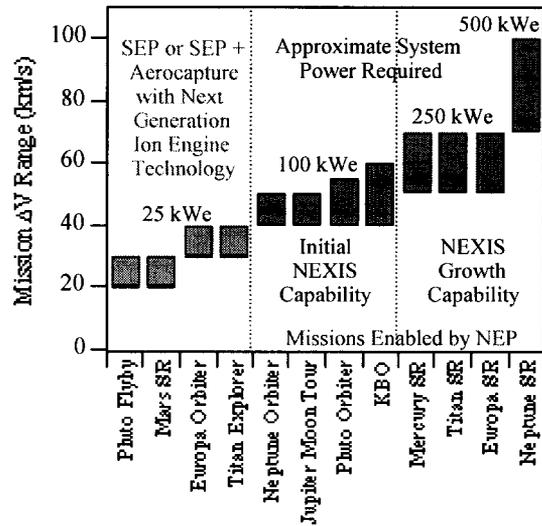


Fig. 2. Nuclear Electric Propulsion (NEP) enables missions with ΔV 's > 40 km/s (SR refers to Sample Return missions).

Once NEP has been demonstrated, there will be a demand for shorter flight times and for improved performance to enable even more difficult missions, such as outer planet sample returns. Both of these require higher ΔV 's, higher power and higher Isp . System power may grow to 250 kWe or more and Isp will exceed 10,000s. The approach described in this paper offers a clear path to these future needs by providing computer models to design the grids with long life at Isp 's greater than 7500 s. Engine thrust and power can both be increased with no thruster hardware changes other than the ion optics grids.

Ion Thruster Component Technologies

An ion thruster consists of a discharge chamber, two hollow cathodes (discharge chamber & neutralizer), ion extraction grids, and propellant feed system including high voltage isolators. For large diameter thrusters, the discharge chamber magnetic design configuration is not a critical design issue. In a high power, high Isp ion thruster, the ion extraction grids are the most important factor in both the life and performance. Hollow cathode life may also be an issue.

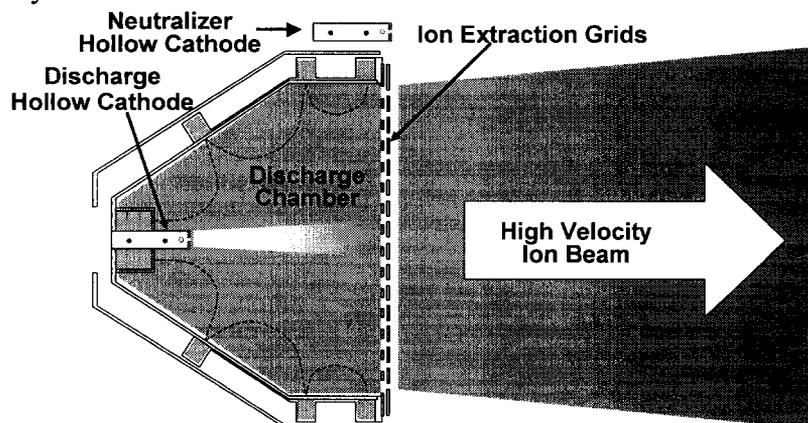


Figure 3. Ion thruster showing ion extraction grids and hollow cathodes

NEXIS Thruster Technologies
<i>Beam Voltage > 4860 V</i>
<i>Large Diameter Thruster</i>
<i>New Grid Design</i>
<i>CC Grid Material</i>
<i>High Perveance Margin Design and Operation</i>
<i>Accelerator Grid Hole Size Tailoring</i>
<i>Grid Masking</i>
<i>Reservoir Hollow Cathode</i>
<i>Carbon Keeper Electrodes</i>
<i>Shared Neutralizer</i>

Table 2. Ion thruster technology advances needed for nuclear electric propulsion.

Approach to High I_{sp} and High Power Operation

Thruster efficiency is dominated by the ratio of energy required to ionize the propellant to the kinetic energy imparted to the propellant during extraction through the ion optics grids. For a given propellant, increasing the I_{sp} (proportional to the square root of the propellant kinetic energy) results in increased thruster efficiency. Higher I_{sp} is achieved by operating at higher beam voltage, V_b . The thruster size can be chosen to give a beam current density consistent with the required life. The growth strategy of raising power by only increasing V_b and modifying the grid geometry is illustrated in Fig. 4.

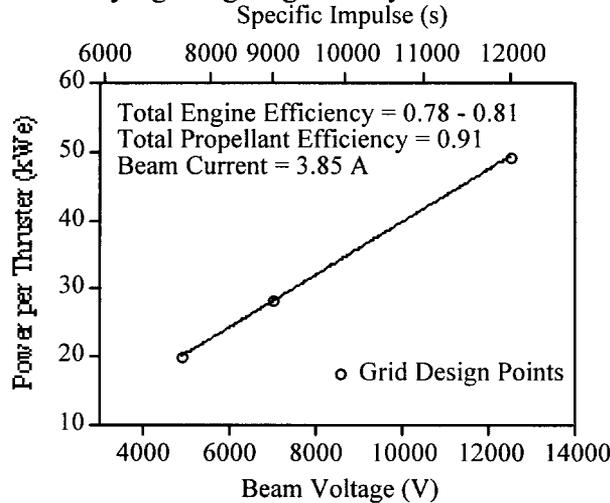


Fig. 4. Significant power growth capability is enabled through operation at higher I_{sp} .

The key to high power, high I_{sp} thrusters is the grid design. Challenges include developing a geometry that extracts the required current density with proper beamlet focusing over the range of plasma densities produced upstream of the grids with a realistic electric field. Underfocusing in the high density regions in the center of the grid and overfocusing at the periphery can cause direct ion impingement on the hole walls in the downstream grid. In addition, the voltage on the downstream grid must be chosen to prevent electron backstreaming.

At JPL, grid designs are developed using state-of-the-art 2D and 3D plasma simulation tools that have been validated with NSTAR data [1,2]. These codes accurately calculate

the upstream grid transparency to ions, the ion beamlet current density, the ion trajectories and the electrostatic potentials required to prevent electron backstreaming. They also model the generation, flow and resulting grid erosion of ions created by charge exchange reactions between beam ions and neutral xenon.

Candidate high *I_{sp}* designs were evaluated using simulation results for dozens of potential geometries and voltages. The codes were used to identify designs that handled the required range of current densities without direct impingement. For example, Fig. 5 shows proper focusing of a beamlet through a single aperture for the two bounding cases most susceptible to direct ion impingement. The simulation results were subsequently verified in subscale grid tests. An example for 7500 s operation shown in Fig. 6 confirms that the required NEXIS operating range is within the grids' capabilities.

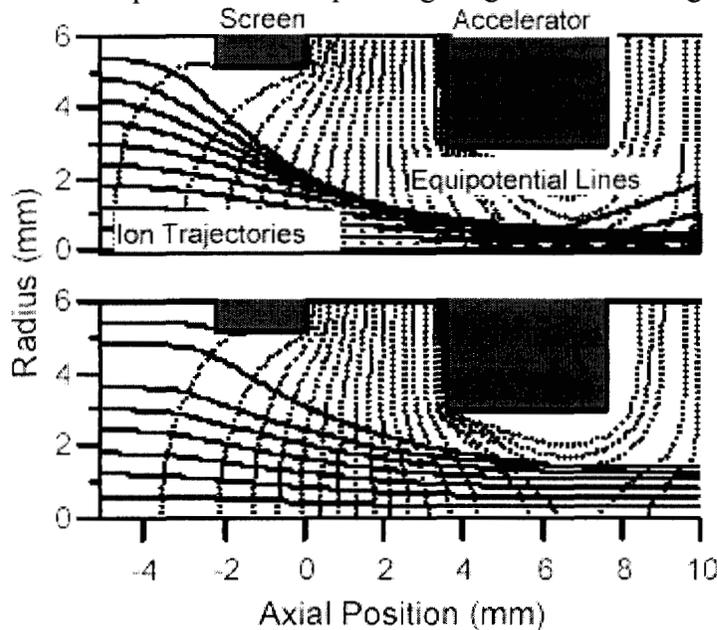


Fig. 5. The NEXIS grid design provides proper beamlet focusing at low densities (top) and high densities (bottom).

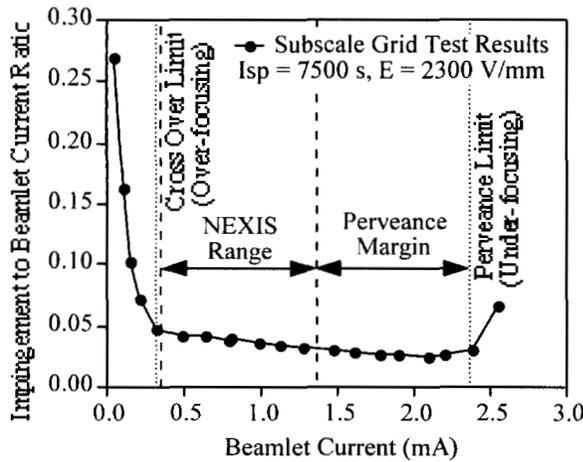


Fig. 6. Beam extraction tests with subscale grids that were designed using our computer codes show that the grids have the desired beam extraction characteristics.

Grid Erosion

Erosion of the accelerator grid by charge-exchange ions is one of the major failure mechanisms limiting the life of ion engines and operation at higher specific impulses aggravates this erosion. Computer modeling is the key to cost-effectively designing advanced ion accelerator systems. We have performed two and three-dimensional numerical simulations to investigate the physics of accelerator grid erosion by charge-exchange (CEX) ions. The computer codes model ion beamlet trajectories through a single pair of screen and accelerator grid apertures in the self-consistent electric potentials found by solving Poisson's equations. The codes follow both primary ions formed inside the discharge chamber, and ions generated beyond the screen grid by charge exchange between un-ionized propellant atoms and primary ions.

Computer simulations provide a wealth of information regarding the behavior of the CEX ions including the locations where CEX ions are created, where they go, and for those ions that hit the accelerator grid, incidence angle and energy they have. This capability enables the problem of the accelerator grid hole wall erosion to be separated from the erosion on the downstream side of the grid (Fig. 7).

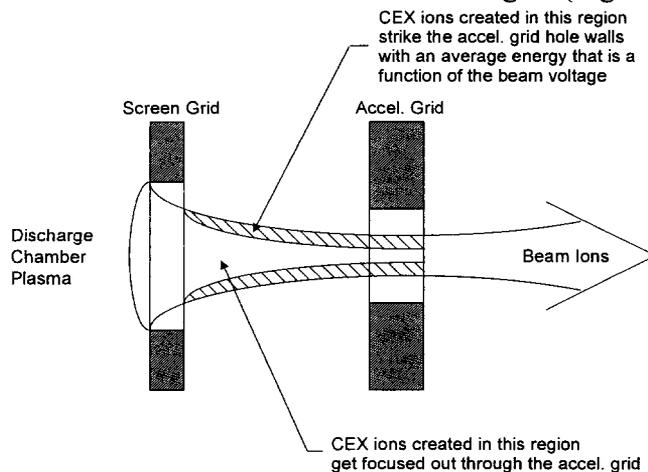


Fig. 7. The location of CEX ion production affects where these ions go and how much energy they acquire.

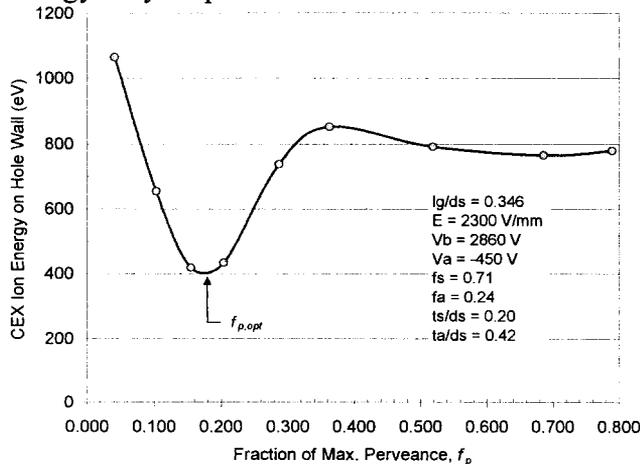


Fig. 8. There is an optimum value for perveance fraction that minimizes the average CEX ion energy hitting the accelerator grid hole walls

The calculated average energy of the CEX ions hitting the accelerator hole is given in Fig. 8. These data indicate that there is an optimum value for the fraction of the maximum perveance that minimizes the energy of the CEX ions that hit the accelerator hole walls. Furthermore, this fraction is relatively small, roughly only 20% of the theoretical maximum. Operation at 67% of the theoretical maximum, as the NSTAR thruster does at full power, results in much more energetic CEX ions hitting the hole walls for operation at high I_{sp} and more rapid enlargement of the accelerator grid apertures.

The explanation for this behavior is illustrated in Fig. 9 which shows the locations where CEX ions are formed that subsequently hit the walls of the accelerator grid as a function of the perveance fraction. As the perveance fraction decreases toward the optimum, fewer CEX ions that hit the hole walls are created in the region between the grids. Only CEX ions created between the grids can obtain energies proportional to the beam voltage, so eliminating these ions significantly reduces the average energy of the CEX ions hitting the hole walls

Grids designed for nuclear electric propulsion will be designed employing strategies that reduce erosion rates significantly:

1. Use of carbon-carbon grids. Carbon grids have a mass loss rate 4-10 times lower than state-of-the-art (SOA) molybdenum grids.
2. Derating by use of very low beam current density. The flux of ions to the grid is minimized by operating at low current densities. The chosen grid area results in an average current density of 1.51 mA/cm^2 and a peak density of 2.52 mA/cm^2 . This is 46% of the peak density of NSTAR at full power
3. Reducing energy of ions striking hole walls by operating with high perveance margin (low plasma density and high voltage, so that ions are strongly focused away from the hole walls).

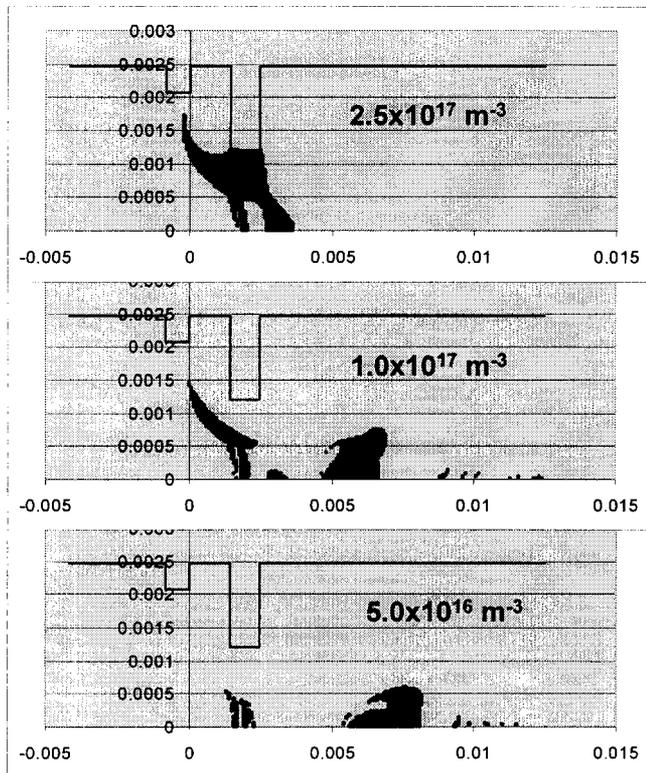


Fig. 9. The locations where CEX ions are formed that hit the accelerator grid hole walls depends on the perveance fraction

Hollow cathode life

The very high propellant throughput required for NEP applications demands extended cathode life. An approach that uses a reservoir hollow cathode with an advanced emitter material addresses all known cathode insert failure modes.

The electron emitter of a conventional SOA hollow cathode is an impregnated porous tungsten tube (the “insert”). The key to long insert life is to maintain a low temperature through the establishment of a layer of adsorbed oxygen and barium atoms that lowers the surface work function. In SOA impregnated cathodes Ba and BaO are supplied by barium calcium aluminate source material (the “impregnant”) incorporated in the pores of the tungsten. Ba and BaO are released in interfacial reactions between the tungsten matrix and the source material. The Ba and BaO then diffuse through the pores to the surface and replenish barium adsorbates lost by evaporation.

SOA impregnated cathodes have demonstrated over 16,000 hours of operation on DS1 [3] and over 27,000 hours in a ground test of the DS1 flight spare engine [4]. The longest demonstrated life was in a ground test of a cathode that failed after 28,000 hours [5]. The demonstrated lifetime of SOA hollow cathode insert technology is far short of that required for NEP missions.

Cathode life is limited by insert degradation and erosion of the orifice and keeper electrode [6]. There are four main processes that degrade the barium adsorbate layer and can lead to insert failure [7]:

1. Depletion of the barium source material.
2. Insufficient production of Ba and BaO because of reaction product buildup at the interface between the impregnate and the tungsten matrix.
3. Inadequate transport of Ba and BaO from impregnate deep in the matrix through the pores to the surface.
4. Closure of the surface pores by deposition of tungsten. The tungsten is likely transported as tungsten oxide vapor, which then dissociates in the emission zone.

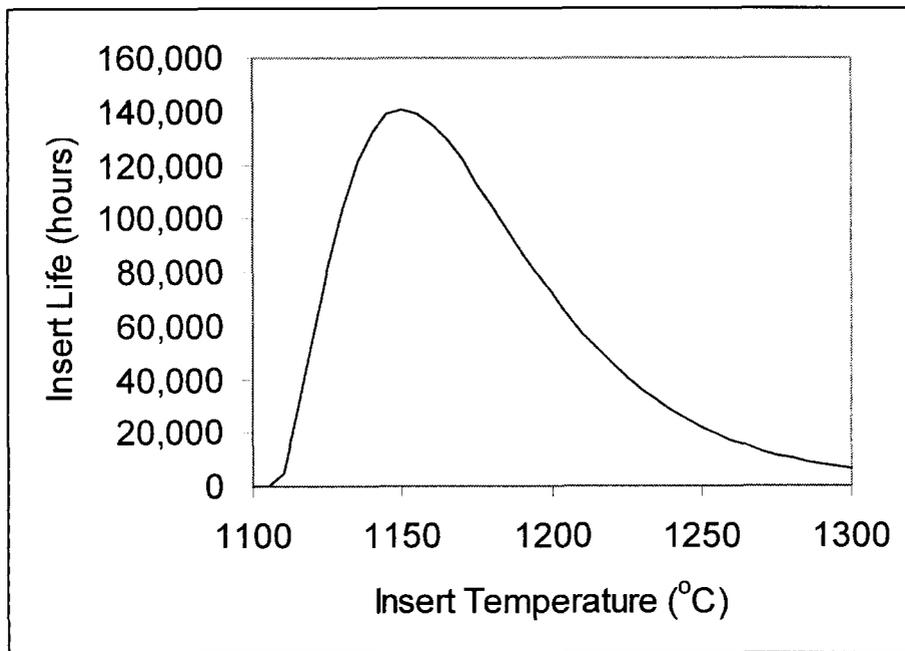


Figure 10. Expected life for the space station cathode barium impregnated insert as a function of insert temperature

Several innovations are being investigated to eliminate the causes of insert failure and obtain the required cathode life.

1. Low insert operating temperature. While the space station plasma contactor insert failed at less than 28,000 hours of operation, analysis has shown that the insert was operating at a relatively high temperature. The discharge cathode in the on-going NSTAR extended life test shows no signs of age after over 27,350 hours. Analysis [10] performed at JPL and shown in Fig. 10, suggests that every 40 C reduction in insert temperature results in doubling the insert life. Even with conventional inserts, the temperature can be controlled by orifice diameter, flow rate, and insert diameter.
2. Reservoir hollow cathodes. Reservoir cathodes exploit all four design variables to achieve long life. The cylindrical porous emitter is a 52% tungsten, 48% iridium alloy, but is not impregnated with the source material. The source material is contained in a reservoir surrounding the central emitter.

The porous emitter serves as the emission substrate which provides controlled passage of Ba and BaO liberated from the enclosed source material to the emitting surface. A fine tungsten powder mixed with the source material serves as a reducing agent to liberate Ba and BaO, so the porous emitter structure does not need to react with the source material as it does in the impregnated cathode. Decoupling the source material from the emitter surface in the reservoir insert eliminates all four insert failure modes.

3. Advanced impregnated inserts. Tungsten-iridium (W-Ir) cathodes have a work function 0.2-0.25 eV lower than impregnated tungsten [8], which reduces the operating temperature by up to 100°C. This temperature reduction slows barium loss by a factor of six or more resulting in a lifetime improvement consistent with experience in the dispenser cathode industry [9].

Summary

Nuclear electric propulsion for solar system exploration requires major advances in thruster performance and life compared with the present NSTAR thrusters. Operating voltages will increase from 1100 V to over 5000V, the thruster life from 2 years to the order of ten years, and every increase in thruster efficiency reduces the requirements on the nuclear power system.

We have identified the ion extraction grids and the hollow cathodes as the critical components that limit ion thruster performance and life. We are in the process of developing detailed computer models of these components and validating them with flight and laboratory data from NSTAR and other thrusters.

Using these new models, we have developed and are in process of testing ion thrusters and thruster components that can meet the aggressive schedule of a near term nuclear electric mission.

Acknowledgement

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