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Variable Specific Impulse High Power Ion Thruster

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The power, Isp and thrust of ion thrusters are constrained by the fixed grid gap in the ion accelerator, which limits performance and life to a limited range in Isp and thrust. A novel ion optics system has been proposed to provide operation over a large range in Isp in high power ion thrusters. The Variable IsP Electric Rocket (VIPER) utilizes a space-heritage mechanism to adjust the grid gap of high power ion thrusters during flight to enable operation in two different modes: a high thrust, low Specific Impulse (Isp) mode; and a high Isp, low thrust mode. A 56-cm diameter VIPER thruster can operate at Isps of over 9000 s at a nominal grid gap, and can also operate with a reduced grid gap at an Isp of 5000 seconds at power levels on the order of 25 kW to produce significantly higher thrust than the nominal case. The grid gap adjustment mechanism also permits flat grids to be clamped together during launch, which allows thinner grids to survive launch and enables the use of a screen grid with higher transparency. The VIPER accelerator concept results in a 5% increase in thruster efficiency relative to the current state-of-the-art (SOA) by eliminating the beam divergence associated with domed grids and from the use of a higher transparency screen grid. Thruster efficiencies of over 80% are projected, and the higher efficiency can result in a significant wet mass reduction in the spacecraft.

I. Introduction

TheVariable IsP Electric Rocket (VIPER) is an ion thruster concept in which the grid gap of the ion optics assembly can be adjusted during flight. The fixed grid gap in conventional ion accelerators constrains the power level, Isp and thrust of state-of-the-art ion thrusters. The performance is limited to a relatively small range in Isp and thrust for a fixed life of the ion optics. A variable grid gap enables an array of benefits to be obtained in the thruster performance and capabilities. First, flat carbon-based grids can be used and clamped together during launch. This makes it possible to utilize a very thin, transparent screen grid that can survive launch vibrations by being in direct contact with the structurally strong accel grid. The higher transparency screen grid and low beam divergence from the flat grids significantly improves the thruster efficiency. The VIPER accelerator concept provides a projected 5% increase in thruster efficiency for a NEXIS-size engine[1,2] by eliminating the beam divergence associated with domed grids and from the use of the thin screen grid that can still survive launch. Second, the grid gap can be adjusted during flight to enable the Isp of the thruster to be changed to match mission requirements. The thrust and specific impulse can be selected over a much larger range than with a fixed gap, and the near-zero coefficient of thermal expansion of the carbon material provides a stable gap to be maintained at these different operating conditions. For example, the grids can be positioned close together to obtain a low Isp operating point for maneuvering or high thrust requirements in parts of the trajectory, and then the grids can be moved apart for a high Isp operating point that might be used for the long duration cruising phase of the mission. Finally, the grid gap can be cycled open and closed to clear electrical shorts between the grids. Short clearing has been accomplished in the past by passing large currents through the short or maneuvering the spacecraft to cycle the sun loading on the thruster and vary the gap thermally. The VIPER mechanism provides another technique to eliminate this type of failure mechanism in the ion thruster.

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Figure 1. VIPER 56-cm grid-diameter ion thruster.

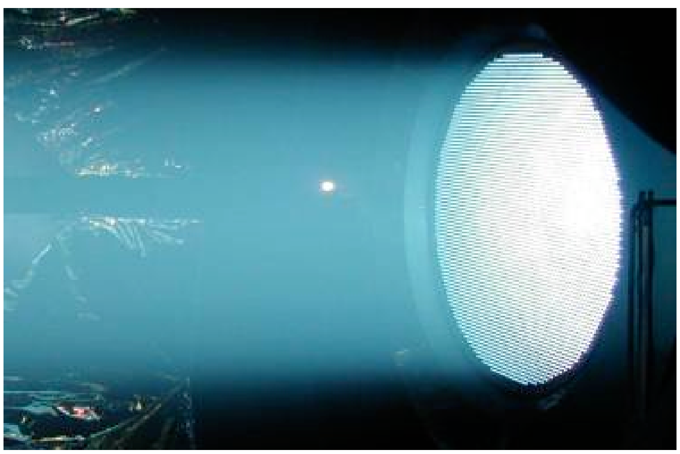

Figure 2. NEXIS Laboratory Model thruster shown producing a well collimated beam from flat grids.

Figure 1 shows a schematic representation of a 56-cm grid-diameter VIPER thruster with the grid-gap adjustment mechanism concept installed. This thruster can operate at the high Isps demonstrated by NEXIS (>9000 sec) at power levels in excess of 50 kW, but can also operate at an Isp of 5000 sec at a power level of about 25 kW to produce significantly higher thrust (>0.8 N) than is possible without the mechanism.

Figure 2 shows a photograph of the xenon ion beam from a 57 cm diameter flat carbon-carbon ion optics assembly tested on the NEXIS thuster. This flat grid set produced the low beam divergence and low thrust-angle loss suggested by the parallel beam in the photo at Isp's of 6000 to 8500 sec.

Mission analysis of the impact of the 5% efficiency increase for a Jupiter Icy Moon Orbiter (JIMO) class mission indicates that VIPER will reduce the fuel mass by over 700 kg. This is illustrated in Figure 3, where the total mass to Callisto is shown versus the flight time for a 100 kW NEP mission. With a projected 9-year trip time, VIPER delivers over 700 kg more mass to the destination than the SOA system operating at the same specific impulse and input power. VIPER can also be used to deliver the same mass with a 6-month shorter trip time. In this figure, a 5% increase in NEXIS efficiency was assumed for VIPER on a Delta 4 Heavy launch of 21000 kg. to 1000 km circular orbit, Earth spiral out and transit to Jupiter, spiral into Jupiter orbit, spiral into 100 km orbit around Callisto. The additional weight associated with installing the mechanism on a thruster is estimated to be a small fraction of this fuel weight savings.

The ability to vary the grid gap in ion thrusters would remove the major performance constraint of this type of thruster and greatly expand the range of thrust and Isp available from ion engines. This not only provides new thruster capability that has system-wide impacts on mass, efficiency and trip time for deep-space-class missions, but also produces a significant efficiency improvement that affects all levels of NASA spacecraft.

II. Grid-gap adjustment mechanism

While there are many possible mechanisms that can be used to change the grid gap in an ion thruster, the Mechanisms Group at JPL developed a conceptual design based on a mechanism with successful flight heritage. Figure 4 shows a schematic drawing of the mechanism applied to the ion optics assembly, which consists of a rotating inclined-slot arrangement that has flown successfully on the Genesis spacecraft. This concept is similar to the lid of a pressure cooker where rotation of a ring with slots vertically moves a lid that has pins inserted in the slot. The axial motion of the accel grid permits positioning of the grid against the thin screen grid for launch, and then movement of the accel grid away from the screen for thruster operation. Figure 5 shows a cross section of the grid support pin in the slotted ring, with the accel grid positioned against the screen grid.

The grid adjustment implementation of this type of mechanism consists of a motor driven adjustment ring that encircles an engine cowling isolated from the high voltage thruster anode by standoff insulators. The ring is

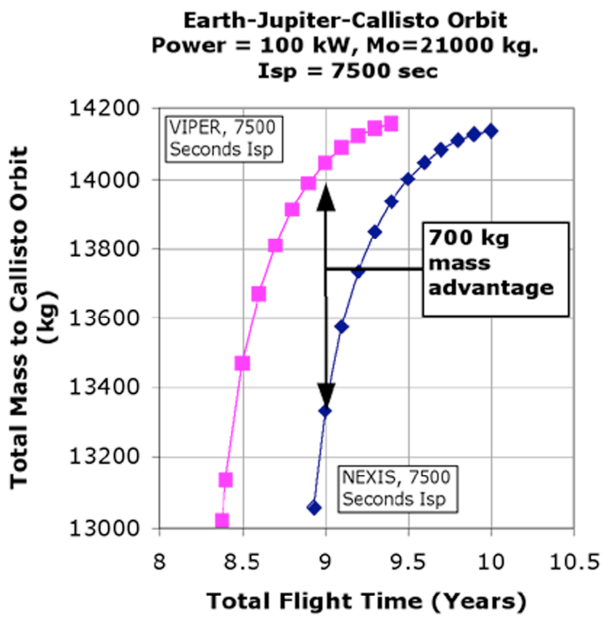

Figure 3. VIPER delivers more mass without power or time of flight penalty, or the same mass in 6 months less time.

kinematically supported on rolling element bearings. The bearings are supported by the engine structure using solid mounting brackets coupled with flexure-mounted brackets. The flexures in the support system for the drive ring insure that the forces on both the engine and the ring do not change as the engine heats up to operating temperature.

Figure 6 shows the rotating ring geometry that permits precision axial grid motion. The slot feature in the ring moves the accel grid axially in the engine as the ring is rotated. The ramp angle of the slot and the plateau sections in the ramp are designed to accurately control the position of the grid along the thrust axis of the engine. In this example, as the ring turns over a 15 degree angle, the grid moves from its closed launch position to a 1 mm spacing (first plateau in the slot feature). An additional 20 degree rotation of the ring (the second plateau in the slot feature) moves the grid to a 2.7 mm spacing. Preliminary analysis indicates that grid alignment within 50 to 70 µm will be possible with this type of mechanism, which is acceptable for the class of high power ion optics that has grid gaps of 1 to 3 mm and screen apertures of about 7 mm.

The downstream accel grid is supported on a ring that has eight radial pins attached to it evenly spaced around the perimeter. These pins extend through the wall of the engine structure and engage the slot feature in the drive ring. The grid support ring is prevented from rotating by the vertical slots in the engine housing. Clearance between the pin and the slot width determines the rotational positioning of the grid, and a minimum tolerance in this region enhances the rotational alignment of the grid apertures. The eight locations of the axial slots in the thruster housing provide alignment of the accel grid apertures with respect to the screen grid mounted directly to the engine. As the drive ring rotates, the slot feature to pin interface moves axially along the engine's thrust axis.

The motor used to operate the grid adjustment mechanism is a brushless dc motor driven by remote drive electronics. In high radiation and temperature (up to 250˚C) environments, the rotor position sensors used in the motor for commutation will be resolvers, which are built using the same fabrication techniques and processes as the stator windings for brushless motors. The technology is extremely robust to high temperature and radiation effects. In addition, the mechanism will likely only be required to move the grids a minimum number of times: once for transitioning from the launch position to the high ISP and then once to the high thrust case. Some number of additional movements will be desired to clear grid shorts or transition to the other thrust mode for mission requirements.

This type of drive mechanism is conceptually similar to the lock ring drive mechanism on the Genesis spacecraft payload canister (motor driven large diameter ring supported on individual roller bearings operating latch devices spaced around the perimeter of the canister). The device on Genesis has successfully performed its function in space.

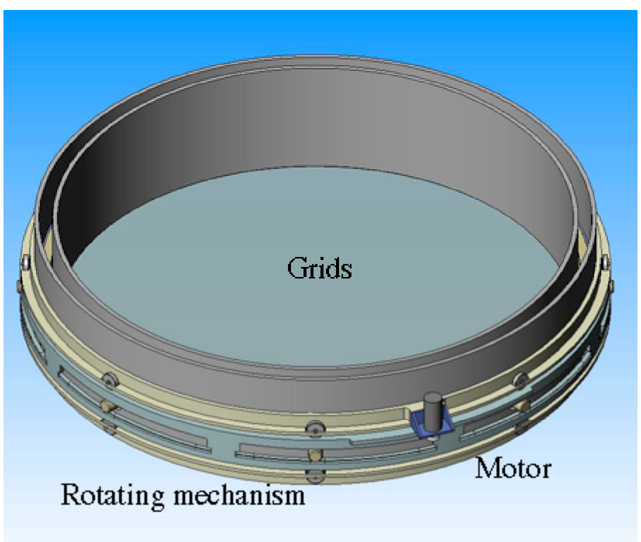

Figure 4. Grid movement mechanism using the rotation of a ring with azimuthal slots to displace a pin supported grid (center) axially.

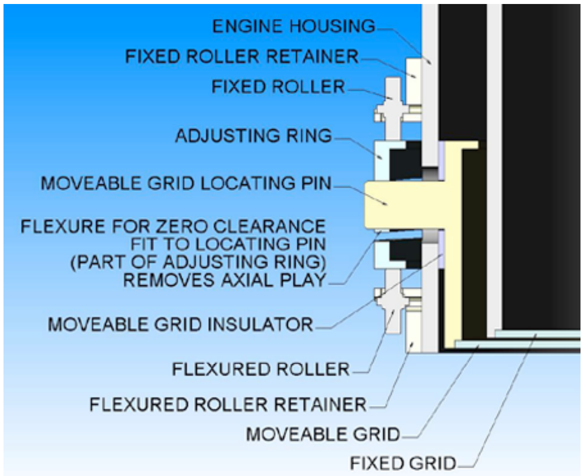

Figure 5. Cross section of one of the grid support pins in the ring slot showing the supporting components.

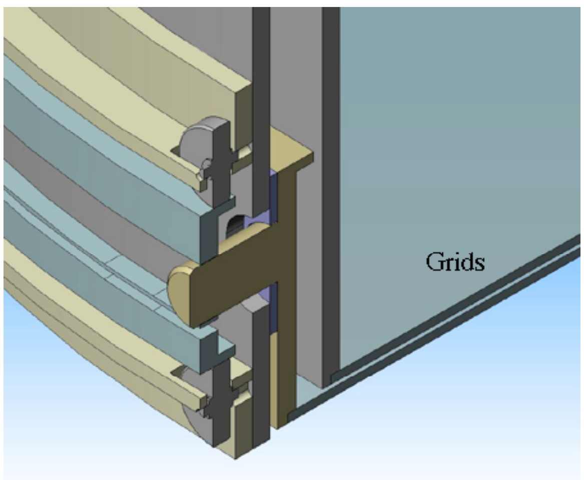

Figure 6. Cutaway of the grid-pin in the ring-slot, where rotation of the ring by a drive motor axially displaces the accel grid axially away from the screen.

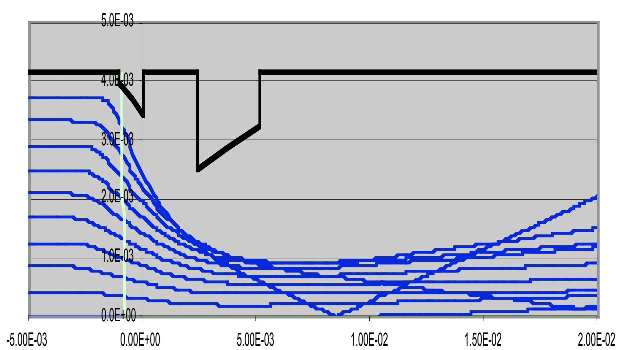

Figure 7. Ion trajectories for the nominal 7500 sec Isp VIPER grid design showing no grid interception.

III. Ion Optics Design

Preliminary ion optics design analysis and life evaluations were performed using the JPL CEX2D ion optics code[3] to validate the VIPER adjustable-grid-set concept. This code solves Poisson's equation for the potential throughout the optics system. Using this potential, beam ion trajectories are computed to obtain the space-charge density. This process of computing the potential and then the beam trajectories is iterated until the code converges on a solution. The neutral gas density is also analyzed in the optics system to obtain charge exchange ion production rates. The fraction of these charge exchange ions that impinge on the accelerator grid are tracked and the sputter erosion rate and life are then calculated.

The VIPER optics conceptual design assumed the use of a 1 mm thick screen grid and an accelerator grid than is 3 mm thick. At nominal operating conditions with an Isp of 7500 sec, the beam current is about 4 A, the beam voltage is 4800 V and the accelerator grid is biased to -500 V to prevent electron backstreaming. For high thrust operation at an Isp of 5000 sec, the beam current is about 10 A, beam voltage is 2435 V and accelerator grid voltage is biased to -1000 V to provide adequate perveance margin.

Figure 7 shows the VIPER optics geometry along with typical beam ion trajectories during the nominal 7500 sec Isp operation, where the bottom axis represents the axis of the beamlet and the bold line represents a plane of symmetry. The trajectories are well behaved with low divergence, and only edge ions from the screen aperture cross over downstream of the accel grid. Figure 8 shows the VIPER beam trajectories during the 5000 sec, high thrust mode. While the beamlet divergence is much greater, the code predicts no direct ion impingement on the accel grid which could limit the grid life. The thrust loss due to the larger beamlet angular divergence is also found to be insignificant. Figure 9 shows the beam current and current density available from this grid design as a function of the net accelerator voltage, where the currents at the two nominal VIPER Isp cases are shown. At the 5000 sec low Isp point, the accelerator is capable of producing about 10 A of beam current without approaching the perveance limit. This corresponds to about 25 kW of power to the thruster.

As with all ion acceleration systems, the grid life will be limited by hole-wall erosion and downstream-face "pits and groves" erosion. Additional calculations using the CEX2D ion optics code indicate that the VIPER grid design has margin

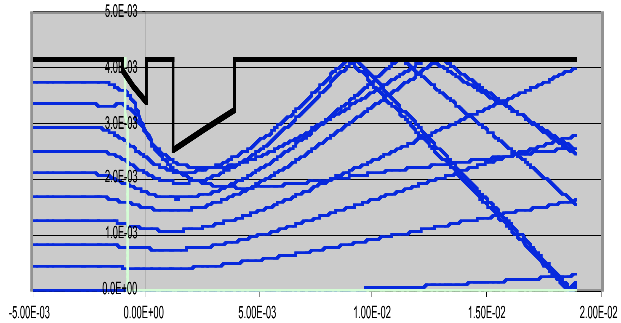

Figure 8. Calculated ion trajectories for the VIPER optics in the high thrust mode showing no direct impingement on the accel grid at 80% of the perverance limit.

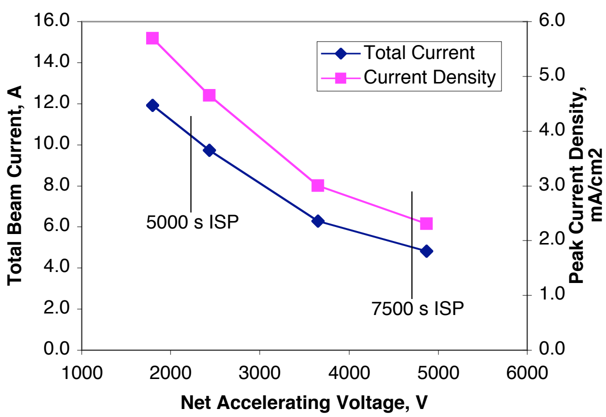

Figure 9. Beam current and peak current density for the preliminary VIPER ion optics design.

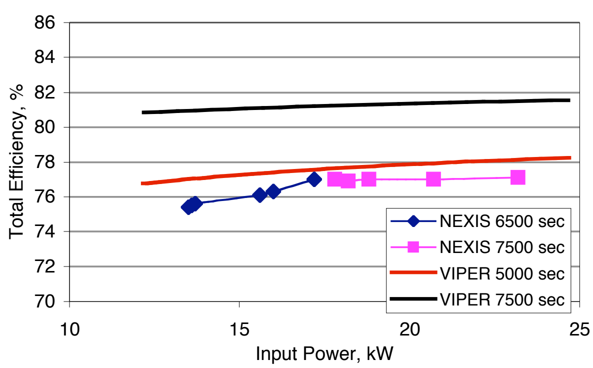

Figure 10. Efficiency versus input power for different Isp's measured for the NEXIS and calculated for VIPER.

for grid life of a factor of 2 for a mission requirement of 100 khr of operation (90 khr nominal, 10 khr at high thrust). The results show that after 100 khr operation, the accelerator grid aperture diameter will erode to 5.5 mm. At this diameter the accelerator grid bias is decreased to –900 V to prevent electron backstreaming, which is well within the capabilities of the accelerator grid supply that must provide up to –1200 V for high thrust operation. Neglecting redeposition of sputtered material (a conservative estimate) in the pits and groves pattern, an acceptable erosion to 1.35 mm depth (45% of the accelerator grid thickness) is predicted after 100 khr operation.

IV. Projected VIPER Performance

A. High thruster efficiency

The variable grid gap mechanism allows thin, flat grids to be used by positioning them together to survive launch vibrations. Flat grids have a lower total beam divergence compared to domed grids (typically about 5˚ compared to 15 to 20˚ with a domed grid), as was shown in Fig. 2. A collimated beam reduces the cosine loss correction to the thrust and thereby increases the efficiency. VIPER technology also enables the use of a thinner screen grid. Thinner screen grids result in a higher transparency than conventional thick domed screen grids that must be designed to survive launch vibration. The higher transparency reduces the discharge loss and increases the thruster efficiency. Figure 10 shows the efficiency calculated for the VIPER thruster at 5000 and 7500 sec Isp as a function of the total input power. In both cases, the efficiency is significantly higher than the SOA NEXIS thruster[2], which was already optimized for high efficiency operation. In addition, the efficiency at over 7000 s Isp exceeds 81%, which approaches the highest efficiency measured for the NEXIS engine at an Isp of 8500 s.

The grid-gap adjustment mechanism permits the grid separation to be optimized for any applied voltage. This enables a significant increase in the accelerator perveance, which describes the amount of beam current that can be extracted at a given voltage. Therefore, the thrust and power are increased compared to a SOA ion thruster. Figure 11 shows the thrust of VIPER as a function of total input power, calculated using the JIMO thruster model that has been updated with the VIPER parameters and compared to the NEXIS results. At high Isp, the VIPER grid set is gapped similarly to the NEXIS grid set in order to hold the higher voltage, and the thrust is similar. However, the ability to bring the grids together permits VIPER to operate at much lower Isp than NEXIS, and to produce significantly higher thrust at a given input power.

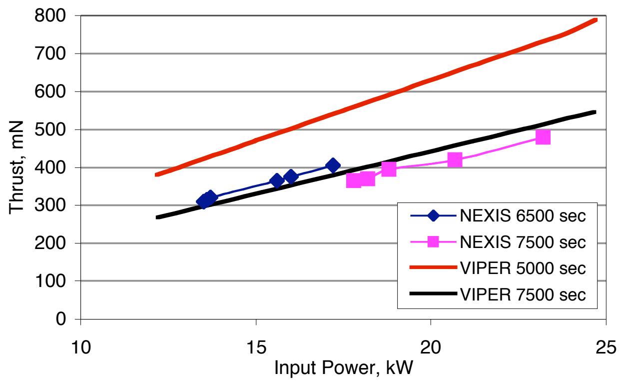

Figure 11. Thrust versus input power for VIPER and NEXIS at various Isp. VIPER produces significantly higher thrust at low Isp than the SOA NEXIS engine.

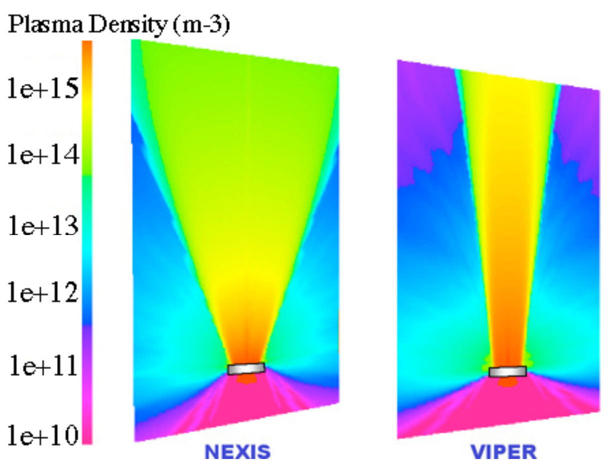

Figure 12. Beam profiles for the NEXIS and VIPER ion optics showing the low plume divergence with the flat grid VIPER system.

B. Smaller plume angles and stay-out zones

Because the VIPER grids are flat, the thruster ion plume is collimated much more than with conventional dished grids. Figure 12 shows a calculation of the thruster plume, including the main ion beam, ions scattered from unionized propellant, and charge exchange ions. The calculation was done using Electric Propulsion Interaction Code (EPIC) developed by the NASA Space Environment and Effects program. Also shown on the same figure is the plume of the NEXIS thruster with the domed grids as presently designed. The 5-cm NEXIS dome height causes a beam divergence of 15° in addition to the divergence of the individual beamlets. The VIPER reduced beam divergence simplifies spacecraft accommodations for the thrusters.

C. Low specific mass

The specific mass (in kg/kW) of the VIPER thruster is nearly the same the SOA NEXIS ion thruster at low Isp, in spite of the additional mass of the grid-gap adjustment mechanism. Specifically, the NEXIS thruster weighs about 28 kg and at it's nominal minimum Isp of about 6500 sec was tested to a power of 16 kW. This results in a specific mass of 1.75 kg/kW. The VIPER engine design with the grid adjustment mechanism is projected to weigh about 40 kg, and at 5000 sec Isp runs at 25 kW of power. This corresponds to a specific mass of 1.6 kg/kW. While there is some uncertainty in the mass of the mechanism, the VIPER engine design does not result in a penalty in the specific mass compared to SOA ion thrusters.

D. Vibration Mitigation

There still might be concern over launch vibrations potentially damaging the flat grids, even if the grids are positioned together by the mechanism described here. Results from a preliminary vibration analysis based on the CBIO program carbon-carbon grid set vibration data[4] indicate that the vibration-induced stress in the 3 mm thick VIPER accel grid would not approach the material strength for a DeltaIV-Heavy launch. The analysis also suggests that while a free-standing screen grid of less than 1.5 mm thick might develop stresses approaching the material strength, the damping of the screen grid oscillations during launch with the screen grid positioned against the thick accel grid would greatly reduce the stress level. While more complete vibration analysis that includes the damping of the grids when clamped together, these results are encouraging.

To further mitigate vibration concern with flat grids, vibration isolators for VIPER-sized thrusters can be investigated. While none of the NASA or Boeing XIPS ion thrusters in space presently use vibration isolation, it is common to use vibration isolators to minimize the transfer of launch vibration loads into both the payload and the propulsion systems. The function of the isolators is to transform input random vibration loads to a level that is acceptable for the propulsion system by changing the natural frequency of the system to a sufficiently low frequency that posses no problems to the propulsion system. Vibration isolation is a standard technique that could be readily incorporated into the VIPER engine support design.

V. Conclusion

A mechanism has been described to adjust the grid gap in a high power ion thruster. This mechanism provides an array of benefits in the thruster performance and capabilities that includes much higher efficiency, variable Isp operation, and the ability to clear grid shorts. Analysis of the thruster performance with this mechanism on a NEXIS-sized ion thruster indicates that power levels of 25 kW and thrust of 0.8 N are possible at an Isp of 5000 sec, and power levels of over 50 kW are possible at Isp's in excess of 8000 sec. This results in significant wet mass savings in deep space missions.

Acknowledgments

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