

# An Overview of the Nuclear Electric Xenon Ion System (NEXIS) Activity

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The Nuclear Electric Xenon Ion System (NEXIS) research and development activity within NASA's Project Prometheus, was one of three proposals selected by NASA to develop thruster technologies for long life, high power, high specific impulse nuclear electric propulsion systems that would enable more robust and ambitious science exploration missions to the outer solar system. NEXIS technology represents a dramatic improvement in the state-of-the-art for ion propulsion and is designed to achieve propellant throughput capabilities  $\geq 2000$  kg and efficiencies  $\geq 78\%$  while increasing the thruster power to  $\geq 20$  kW and specific impulse to  $\geq 6000$  s. The NEXIS technology uses erosion resistant carbon-carbon grids, a graphite keeper, a new reservoir hollow cathode, a 65-cm diameter chamber masked to produce a 57-cm diameter ion beam, and a shared neutralizer architecture to achieve these goals. The accomplishments of the NEXIS activity so far include performance testing of a laboratory model thruster, successful completion of a proof of concept reservoir cathode 2000 hour wear test, structural and thermal analysis of a completed development model thruster design, fabrication of most of the development model piece parts, and the nearly complete vacuum facility modifications to allow long duration wear testing of high power ion thrusters.

## I. Introduction

The demonstration of ion propulsion on the Deep Space 1 mission has paved the way for applications of advanced electric propulsion on more demanding future missions such as outer planet orbiters, multiple body rendezvous missions, sample return missions, and interstellar precursor flights. However, the most ambitious of these missions require  $\Delta V$ s ranging from 40 to over 100 km/s. To accomplish these missions with reasonable initial masses and tolerable trip times requires advanced nuclear electric propulsion (NEP) systems capable of processing from 100 to 500 kW of power at specific impulses ranging from 5,000 sec to over 14,000 sec (1). The burn times for these missions range from five to ten years. Future ion propulsion systems must therefore operate at higher power levels, higher specific impulses, and with longer lifetimes than state of the art solar electric propulsions (SEP) systems.

To identify and develop high power thruster technologies that enable NEP missions to the outer planets, the 2nd In-Space Propulsion Program NASA Research Announcement (NRA) was released (1,2). The Nuclear Electric Xenon Ion system (NEXIS) was proposed in response to this NRA and was one of 3 high power EP proposals selected. The NEXIS team is led by the Jet Propulsion Laboratory (JPL) with several partners including Aerojet, the Aerospace Corporation, Boeing, Colorado State University, the Georgia Institute of Technology, and the Marshall Spaceflight Center.

Table 1 shows the nominal NEXIS thruster design operating point, which is a significant step beyond the state of the art NASA SEP Technology Applications Readiness (NSTAR) ion thruster demonstrated on the Deep Space 1 mission (3). The power processing capability, specific impulse, and efficiency are all increased dramatically. Perhaps more importantly, all known wear out failure modes are substantially mitigated by exploiting advanced grids constructed from erosion resistant carbon-carbon, a carbon keeper, a new reservoir hollow cathode, and a new large diameter discharge chamber. These performance and life objectives meet or exceed the requirements of the NRA.

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A further goal of the NEXIS activity is to demonstrate the flexibility of the technologies to operate over a wide range of operating conditions of interest to future missions.

Performance Metric	NSTAR	NRA Requirements	NEXIS	NEXIS Gain Over NSTAR
Power (kW)	2.3	20 - 50	20	8.7 X
Specific Impulse (s)	3170	6000 - 9000	7500	2.4 X
Thruster Efficiency	0.63	> 0.65	0.78	1.2 X
Specific Mass (kg/kW)	3.6	< 3.5	1.5	2.4 X less
Throughput (kg)	230	> 1000	2000	8.7 X

Table1. The NEXIS thruster shows significant performance advantages over the state of the art.

The NEXIS thruster shown in Figure 1 has a 65 cm diameter discharge chamber with six rings of magnets in a ring-cusp configuration. Efficiency  $\geq 78\%$  is achieved by significantly improving propellant utilization through the use of a deep discharge chamber, sharing the neutralizer function between multiple thrusters, and improving the plasma uniformity. To improve the plasma uniformity relative to the state of the art, the chamber is masked to produce a 57 cm diameter ion beam and the ring magnets are tailored to control fringing of the magnetic field at the downstream magnet ring. A key feature of the NEXIS approach is that the propellant efficiency is increased without increasing life limiting parameters such as the double ion content or discharge voltage.

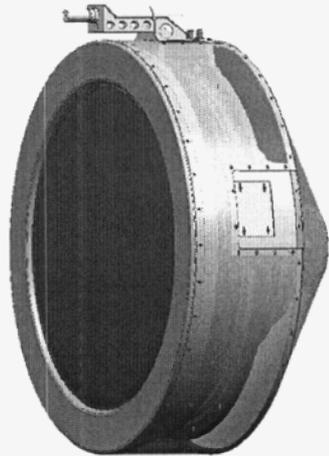


Figure 1. The NEXIS thruster is designed by physics based models validated by the extensive ion thruster test heritage.

Exceptionally long grid life is achieved by the aforementioned improved plasma uniformity which reduces the required peak beam current density, derating the beam current density to nearly one half the NSTAR value, using carbon-carbon grids with a very low volumetric sputtering yield, and designing the grids to operate with a very high perveance margin which reduces charge exchange ion erosion of the grid hole walls. Exceptionally long cathode life is achieved by lowering the temperature of the emitter using a low work function W-Ir emitter and this lifetime can be improved further by the addition of a reservoir cathode which includes 10 times the quantity of low work function material relative to conventional ion thruster cathodes. Exceptionally long discharge chamber life is achieved by using a graphite keeper with a very low volumetric sputtering yield. These design choices, which are defined in greater detail in Reference 1, were driven by the requirements for high power, high specific impulse operation, long life, and high efficiency.

The NEXIS activity is well over a year towards achieving its original objectives with substantial progress already completed. The initial efforts associated with the conceptual design phase are detailed in Reference 1. Within the last year funding for the NEXIS program has moved from the In-Space Propulsion Program NRA to NASA's Project Prometheus under the umbrella of the proposed Jupiter Icy Moons Orbiter (JIMO) mission (2). The

proposed JIMO mission will orbit three Jovian moons starting with Callisto followed by Ganymede and finally Europa with a planned launch in 2015 (4). Due to the transfer in control of the program, the NEXIS performance goals are no longer set by the In-Space Propulsion Program but are instead set by the JIMO project. Although no official changes to the original NRA requirements have been made, the NEXIS activity has made some minor technical changes to support the perceived needs of higher throughput capability and higher thrust density for the JIMO project.

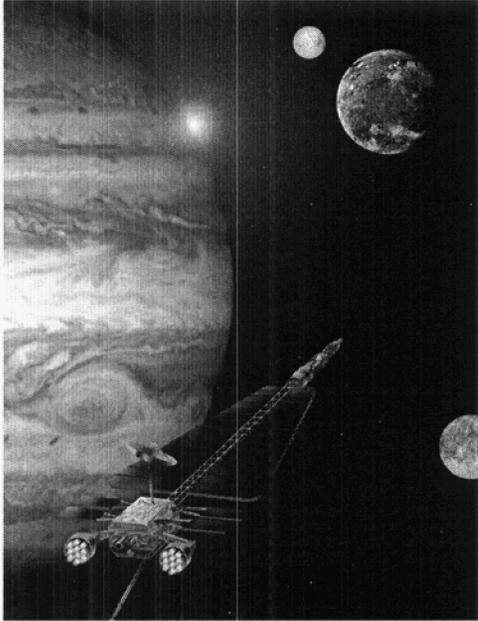


Figure 2. The proposed JIMO spacecraft in the Jovian system approaching Callisto, Ganymede, and Europa.

The current status of the NEXIS activity will be described in the following sections. In summary, a conceptual design has been completed and a lab model thruster version of this design has been fabricated to validate the performance of the discharge chamber and ion optics design. This lab model thruster has been successfully fired and the performance results have met the NRA requirements for efficiency at the required specific impulse and power. Additional component level testing includes the successful completion of a reservoir cathode 2000 hour wear test. Based on the lab model thruster performance results, and the results of thermal, structural, grid optics, and lifetime analysis, a developmental model (DM) thruster design has been completed. Fabrication of piece parts for this NEXIS DM thruster is nearly completion. Preparation of the facility for a 2000 wear test of the NEXIS DM thruster, scheduled to begin in early fall of 2004, is also well underway.

## II. Component Level Testing

Before beginning the fabrication of a NEXIS DM thruster, significant component level proof of concept testing was performed to verify the readiness of the new NEXIS technologies. These efforts include verification of the discharge chamber design by performance testing of a lab model thruster, reservoir cathode testing including a 2000 wear test, and subscale gridlet testing (5-8). This work was quite extensive and is detailed in several other papers and will only be summarized in this work.

The most critical element of the component level testing was the fabrication of a lab model thruster for performance validation of the discharge chamber design. The rationale for the test was predicted on several objectives important to the NEXIS activity. Due to the NEXIS requirement for operation at specific impulse far higher than the state of the art, it was important to verify operation of the beam supply, data acquisition system, software recycle logic, and the characteristic recycle rate of the carbon-carbon grid material at the much higher required voltages. In addition, it was also critical to verify not only the NRA performance goals, but also to verify the performance of the thruster at different specific impulse conditions to insure that the NEXIS design could be easily scaled to meet the potential changing performance requirements of the proposed JIMO mission. Finally, it was also important to measure the detailed elements of the discharge chamber performance, such as the screen grid

ion transparency, so that the performance impact of potential design changes, such as the differences between the lab model thruster and the DM thruster, could be evaluated before the fabrication of costly hardware. To reduce the cost and schedule impacts of costly hardware iterations, the NEXIS activity has relied heavily on the extensive modeling capability developed from the long history of ion thruster development.

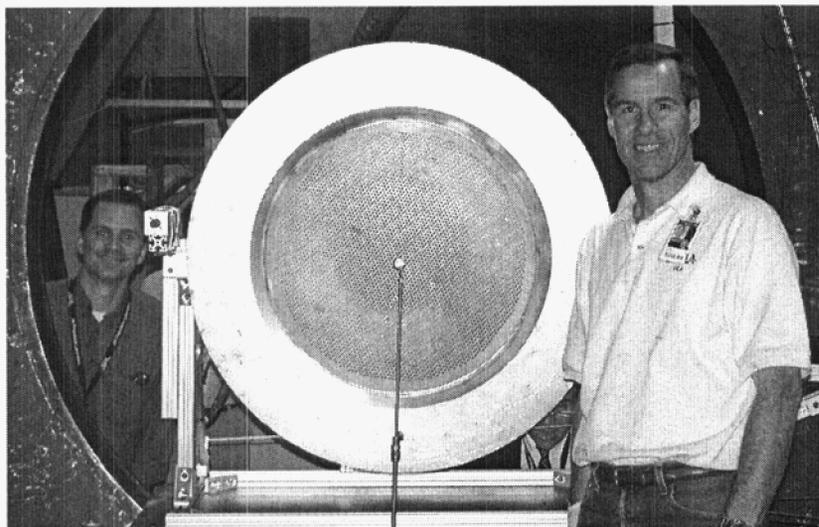


Figure 3. The NEXIS laboratory model thruster used to validate required performance.

The NEXIS lab model thruster integrated into the test chamber is shown in Figure 3. The performance tests of the lab model thruster were conducted in JPL's 148-1 chamber, a 3 meter diameter by 8 meter long stainless steel tank with a graphite beam target. Beam power was supplied by a special lower stored energy 4 Amp, 8000 V beam supply. Ancillary supplies were mounted in a rack modified to reduce noise induced from the high beam voltages. Operation of the thruster, shown in Figure 4, went quite smoothly with excellent discharge chamber stability and a low recycle rate.

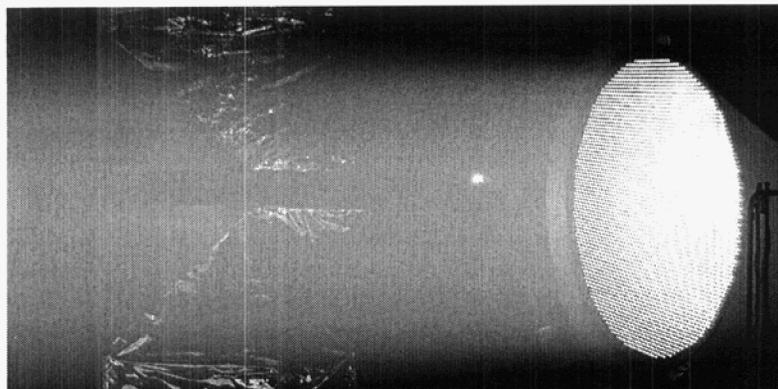


Figure 4. NEXIS thruster operating at 27.4 kW<sub>e</sub>, 8570 s and 80% efficiency with 93% discharge propellant utilization.

Performance of the NEXIS lab model thruster is shown in Figures 5 and 6. Performance calculations were based on measured electrical parameters. Mass flow was corrected for the ingestion of ambient gases using pressure measurements from an ion gauge calibrated on xenon mounted in the chamber over the thruster and the appropriate Clausing factors. Thrust corrections were made for double ions based on a curve fit to data from a J-Series thruster and for beam divergence based on individual beamlet divergence and grid curvature.

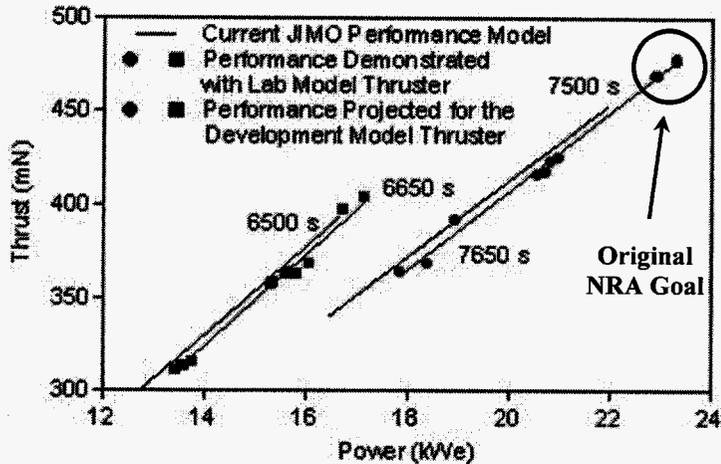


Figure 5. NEXIS lab model thruster meets performance requirements of the NRA and the JIMO performance model.

Performance measurements of the lab model thruster clearly show that NEXIS has met the NRA efficiency requirements at the specified specific impulse and power range and matches the JIMO performance model requirements. Operation at low specific impulses at high powers was constrained by the 4 Amp limit of the beam power supply. The peak performance of the thruster was a measured 0.517 N of thrust at 27 kW of power and a specific impulse of 8700s. At this peak performance point, the measures total efficiency was 0.81 and the propellant utilization efficiency was 0.95 at a discharge voltage of 26 V, a condition consistent with long thruster life. Performance of the thruster was consistent with the JIMO performance model over a wide range of specific impulse conditions; thus the NEXIS thruster has shown great flexibility in being able to adapt to the final performance requirements of the proposed JIMO mission.

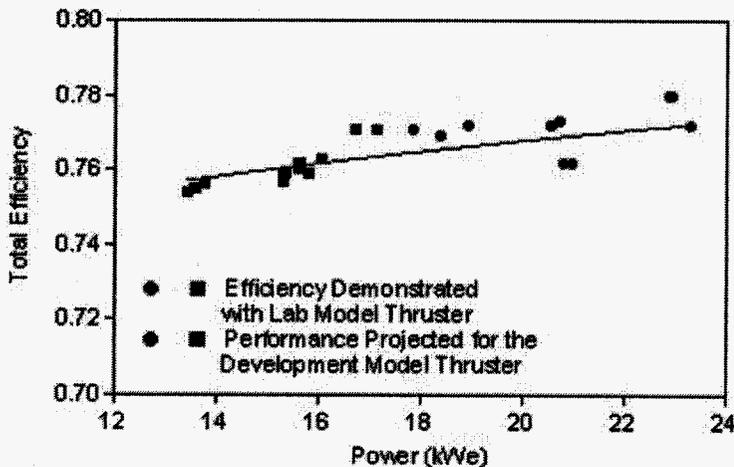


Figure 6. The NEXIS thruster provides excellent total efficiency

Internal and external probing of the NEXIS lab model thruster current density shows a very flat beam profile (Figure 7). This flat beam profile was been achieved by to critical design features of NEXIS. First, the magnetic field has been designed to minimize plasma losses to the wall by constraining the plasma to the center of the discharge chamber. This feature maximizes grid lifetime time by eliminating “hot spots” that would induce early grid failure. Second, the nonuniformity of the plasma at the edge of the discharge chamber is controlled by masking the apertures of the optics assembly down to a diameter of 57 cm while the discharge chamber itself is 65 cm in diameter. This grid hole pattern minimizes neutral xenon losses and simplifies the ion optics design. The beam flatness parameter, define as the average beam current density divided by the peak beam current density, was measured to be 0.8, better than the original conservative design assumption.

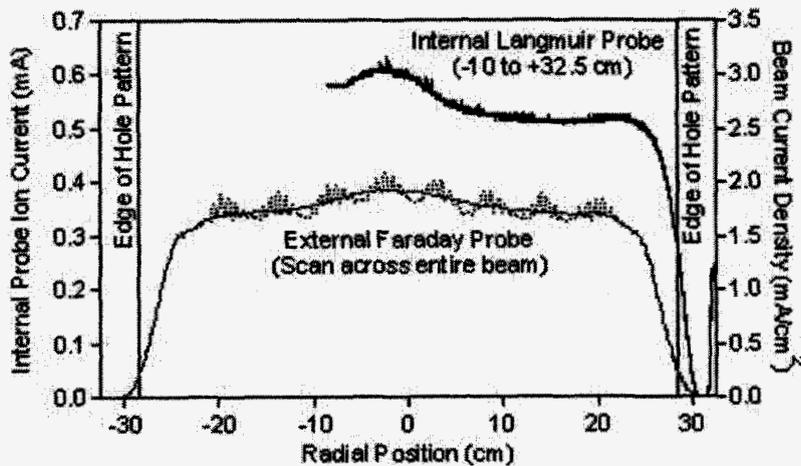


Figure 7. Discharge chamber design yields a very flat beam profile

The performance measurements with beam extraction also allowed the validation of two methodologies important to the development of the NEXIS thruster. First performance measurements of the NEXIS lab model thruster validated the 0-D model used for design of the NEXIS discharge chamber. This model, based on the details of electron diffusion across the magnetic field lines, shows excellent agreement with the measurements made in Figure 8. Measured discharge losses are slightly higher due primarily to the low screen grid transparency of the lab model thruster compared to the value used in the 0-D model. Second, the beam extraction tests were used to benchmark a method of simulating discharge chamber performance without beam extraction. Measurements made using the discharge chamber simulation method described in Reference 9, show excellent agreement with the beam extraction measurements shown in Figure 9. The simulations, performed with only the discharge supply running while the mass flow rate is compensated to account for the loss of ions from the discharge due to beam extraction. This technique is important to the NEXIS activity; because it allows simulation of performance with modified optics, such as a thinner screen grid, and it enables performance evaluation at higher beam currents than the current 4 Amp beam supply limit.

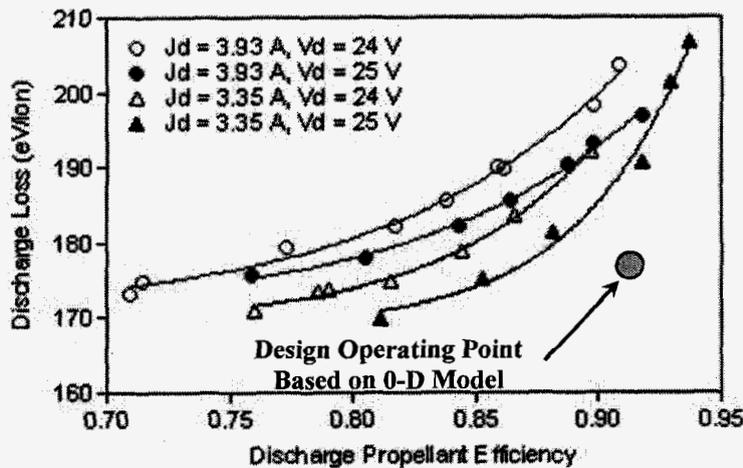


Figure 8. NEXIS lab model thruster performance validates the 0-D model used for design

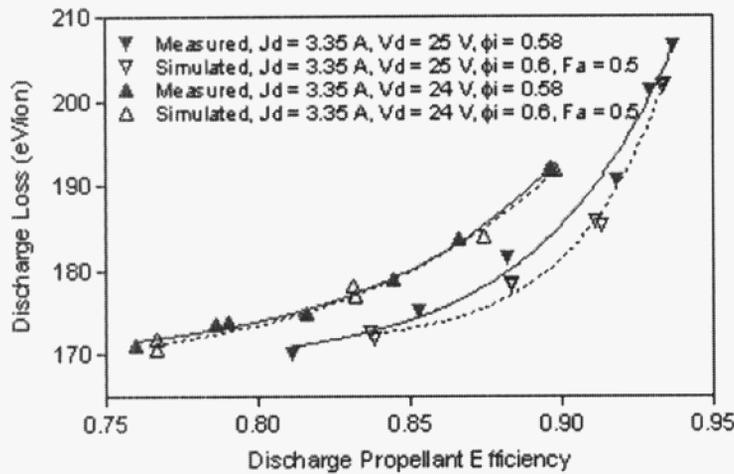


Figure 9. NEXIS lab model thruster beam extraction tests validate discharge only means of performance simulation

The anticipated performance of the NEXIS DM thruster should be very similar to the measurements made for the lab model thruster. Impacts on performance from many small differences between the two thruster models are expected to roughly cancel each other out. The flat screen grids, leading to less beam divergence, leads to elevated performance for the lab model thruster as compared to the use of dished grids for the DM, required to survive vibration loads. This anticipated performance degradation for the DM is compensated by the use of a thicker accelerator grid, leading to lower neutral losses, and a thinner screen grid, leading to higher ion transparency and thus lower discharge losses. The DM thruster will also use a more optimized neutralizer which will lead to lower propellant flow rates. The impacts of these effects on the DM thruster performance has been calculated and the results are compared to the lab model thruster results in Figures 5 and 6 showing very little difference between the two thruster models.

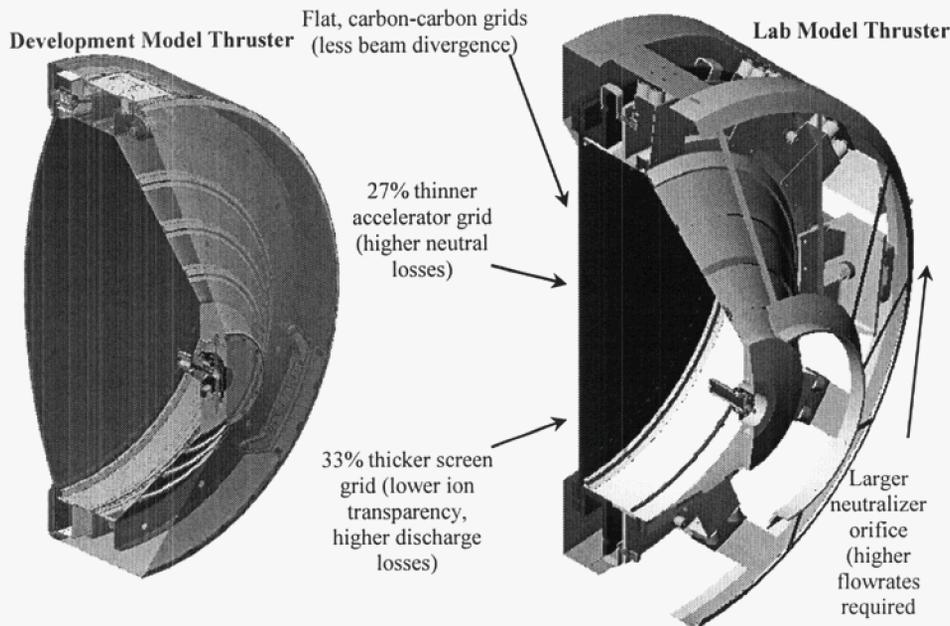


Figure 10. Comparison of the NEXIS lab model thruster and the NEXIS DM thruster

Another critical component level test of the NEXIS thruster development activity is the 2000 hour wear test of the reservoir cathode. The purpose of this test was to validate the weld and braze joints necessary to secure the active material in the reservoir over an extended period of operation. The wear test of a proof of concept reservoir cathode was started in the Marshall Spaceflight Center cathode test facility on February 24<sup>th</sup> 2004 with a tungsten loop keeper and a water cooled anode. The chamber was opened at 1237 hours and a more flight like graphite keeper was added to better simulate the exterior plasma and protect the cathode orifice plate. A picture of the front of the proof of concept reservoir cathode orifice plate, both before and after the test, is shown in Figure 11. The wear of the orifice plate is attributed to the lack of a flight like keeper during operation and not the reservoir cathode itself. The test was completed successfully on June 11<sup>th</sup> 2004 with no significant degradation in cathode performance observed over the course of the test (Figure 12). Although some test instrumentation failed during the course of the test, the surviving upstream thermocouple showed remarkable stable low temperature operation over the test consistent with long cathode life.

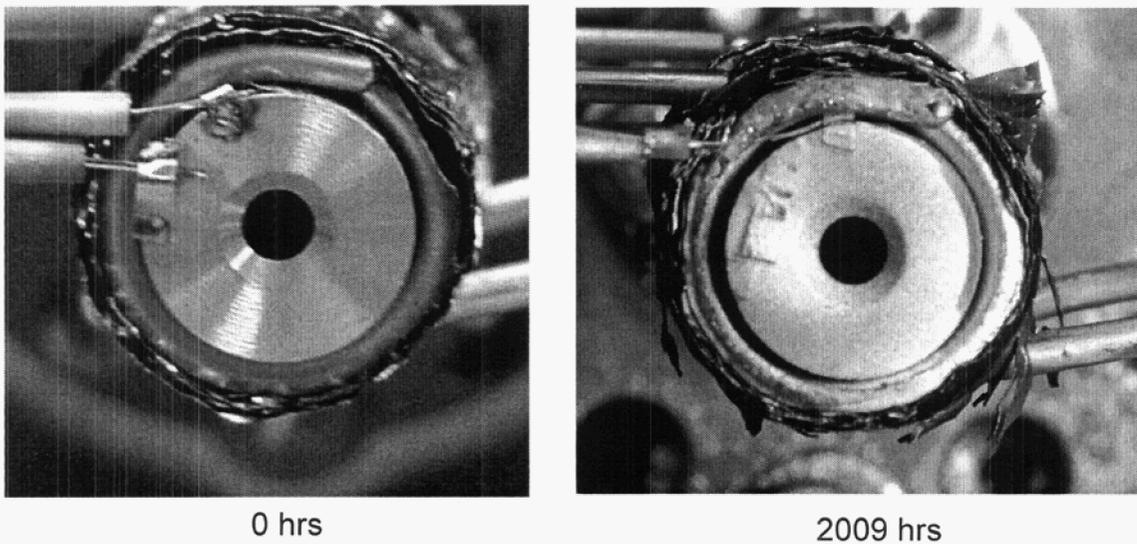


Figure 11. The proof of concept reservoir cathode before and after the 2000 hour wear test.

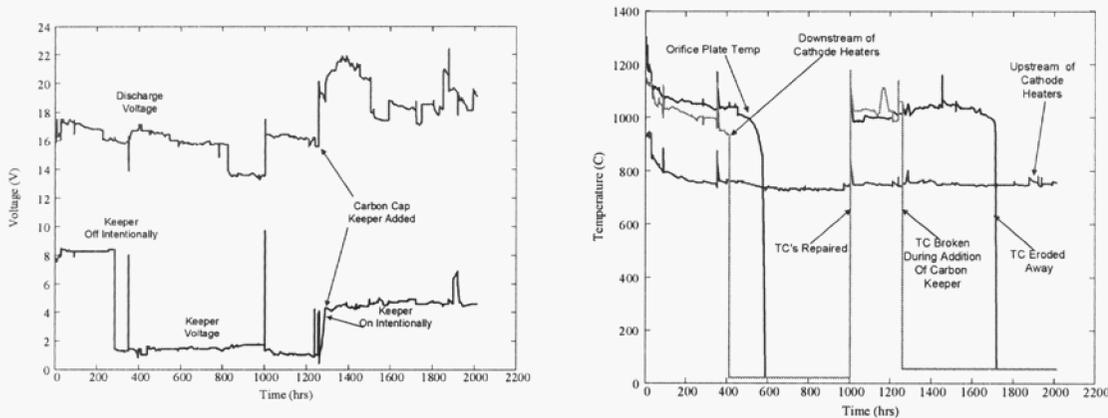


Figure 12. Performance of the reservoir cathode is exceptionally consistent over the 2000 hour wear test

### III. Design Analysis

In addition to the component level proof of concept testing, additional design analysis were performed for the NEXIS DM thruster design in order to identify any critical design weakness and implement design changes to

reduce the risk of failure during structural or performance testing. These design analysis include thermal stress and vibration load analysis of the grids, discharge chamber, and cathode. As an input to all the vibration load analysis, the spectrum from the Delta IV heavy launch vehicle has been used (Figure 13). Additional analysis of the launch vehicle spectrum since the analysis of this work was completed indicates that the spectrum described in Figure 13 is very conservative in the high frequency range. Once again, this analysis work was quite extensive and is detailed in several other papers and will only be summarized in this work (10).

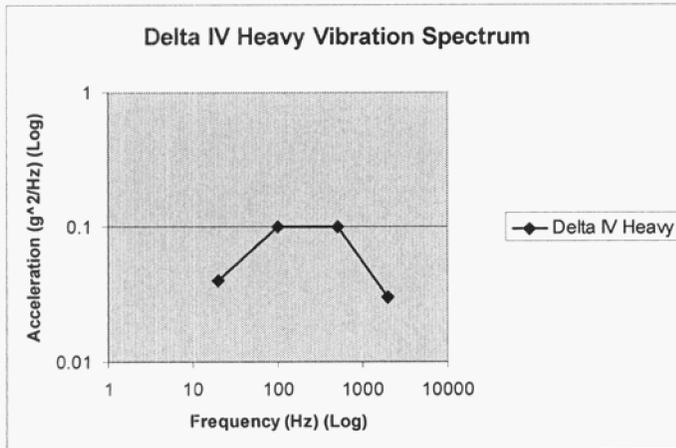


Figure 13. Delta IV Heavy conservative launch vibration spectrum used for the NEXIS structural analysis

Structural load analysis of the launch induced stresses to the grid assembly has been performed by Material Research and Design Inc. Analysis of the first mode, at 356.9 Hz, is shown in Figure 14. In this analysis, material properties of the carbon-carbon grid are degraded by directional dependence with respect to the fibers and by the grid open area fraction. Currently, relatively conservative values for damping are used in the analysis. Results from analysis and test of smaller, 30 cm diameter carbon-carbon grids indicate that these values are conservative. Before performing a qualification level vibration test of the NEXIS DM thruster grid assembly, vibration tests at lower levels are scheduled to be performed this fall to directly measure the grid assembly damping levels. Once these damping values are measured, another analysis will be performed to more accurately determine the strength margin of the grid assembly with respect to the Delta IV Heavy input loads. If any potential problems are discovered after this analysis, it will be possible to add conservatism to the grid mounting design by the use of vibration isolators and improve the probability that the grid assembly will successfully survive qualification level vibration testing scheduled for 2005.

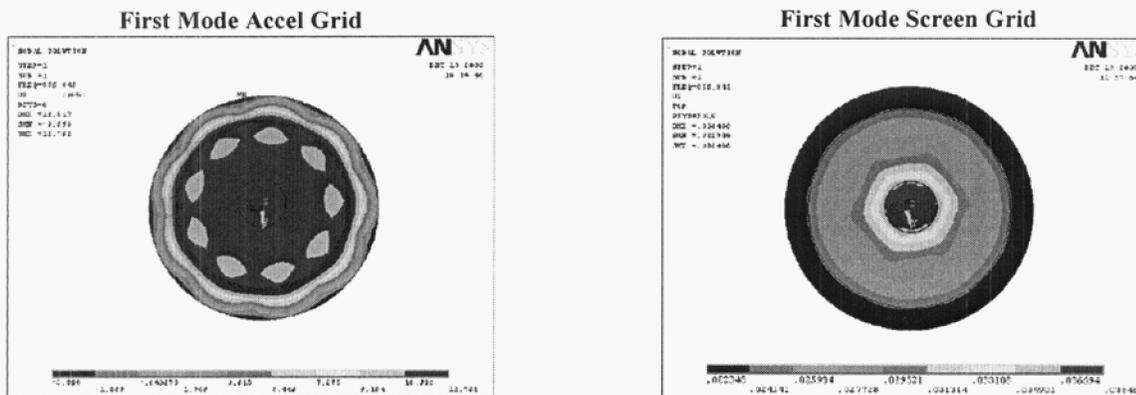


Figure 14. Structural analysis of the first mode of the NEXIS grids (356.9 Hz)

Parametric analysis of grid responses to structural analysis was also performed for different grid thicknesses and dish depths (Figure 15-17). Grid thicknesses were varied from 1 to 3 mm and dish depths were varied from 1 to 3 inches, additionally, a separate analysis was performed for zero dish depth (flat) grids. For low dish depths, the strength margin with respect to failure is dramatically reduced; because the grids are less stiff. Although this analysis is performed with significant conservatism, the margin against failure for zero dish depth becomes exponentially worse indicating that flat grids are an unacceptable design solution. As the dish depth is increased, the energy induced from the launch vehicle loads transfers from the grids to the grid support ring reducing the margin against ring failure at very large dish depths. Fortunately, a moderate dish depth provides acceptable margin for all three of the major grid assembly elements. Increasing the grid thickness also improves the grid resistance to failure by increasing the stiffness; however the resulting additional loads induced by the thicker grids reduces the margin against failure for the grid support ring. Similar to dish depth, a moderate grid thickness provides acceptable margin for all three of the major grid assembly elements.

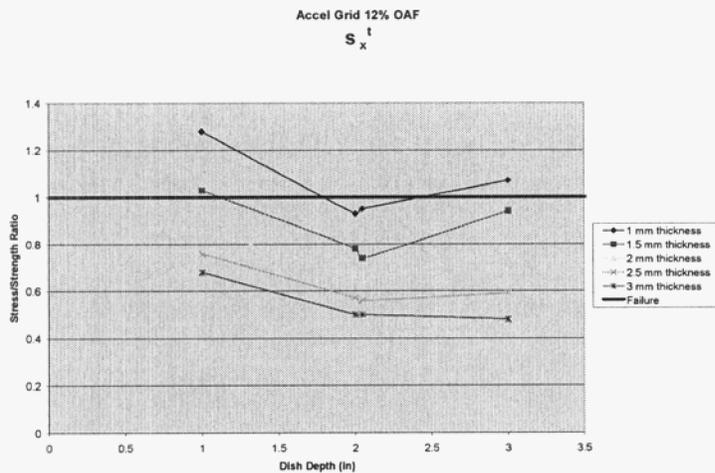


Figure 15. Accelerator grid response for a 12% open area fraction (equivalent to the transition region between the active area of the grid and the masked region)

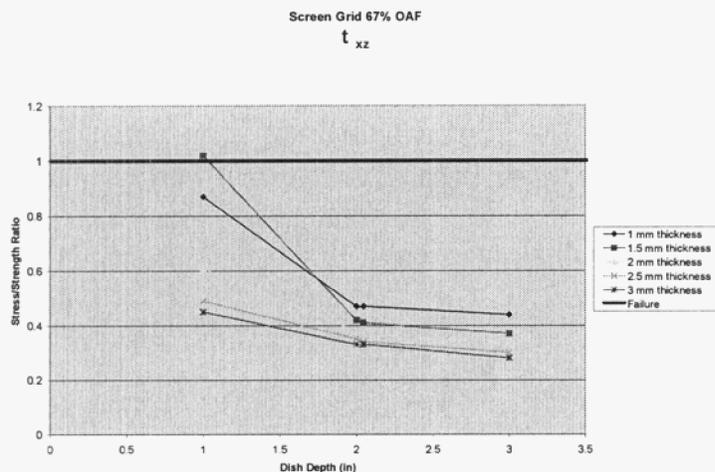


Figure 16. Screen grid response for a 67% open area fraction

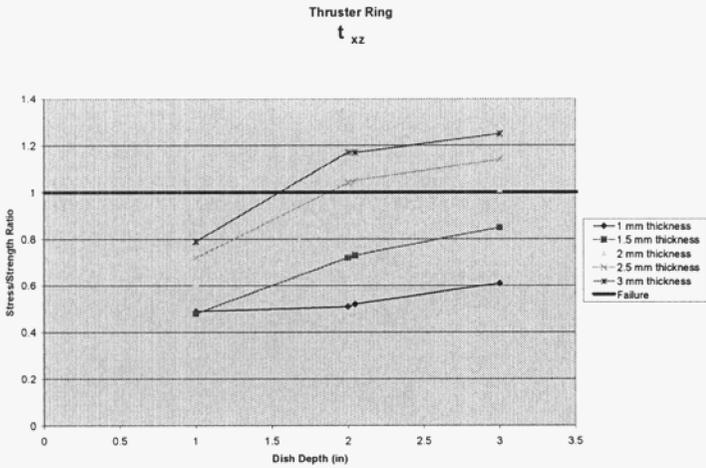


Figure 17. Grid support ring response

Structural load analysis of the thermal and launch induced stresses to the discharge chamber assembly has been performed by Aerojet and is described in much greater detail in Reference 10. One of the primary findings of this analysis was the thermal stresses induced in the grid flexures which provide the mechanical interface between the discharge chamber assembly and the grid assembly. These flexures are required to accommodate the difference in the thermal expansion coefficient between the carbon-carbon grid material and the metallic discharge chamber material. As the discharge chamber temperature increases from room temperature to approximately 300 °C, the grid assembly diameter remains relatively unchanged while the discharge chamber diameter increases by approximately 3 mm. To accommodate this motion, a system of 18 “C” flexures were incorporated into the design (Figure 18). An analysis of the thermal stresses for this design is shown in Figure 19. Due to the high peak thermal stresses from the bolt constraints and the complexity of the interface with the optics (with three bolts per flexure), this design was abandoned in favor of a bipod flexure design shown in Figure 20. The bipod flexure design showed greatly reduced thermal stresses and a much simpler optics interface (9 flexures with one bolt per interface).

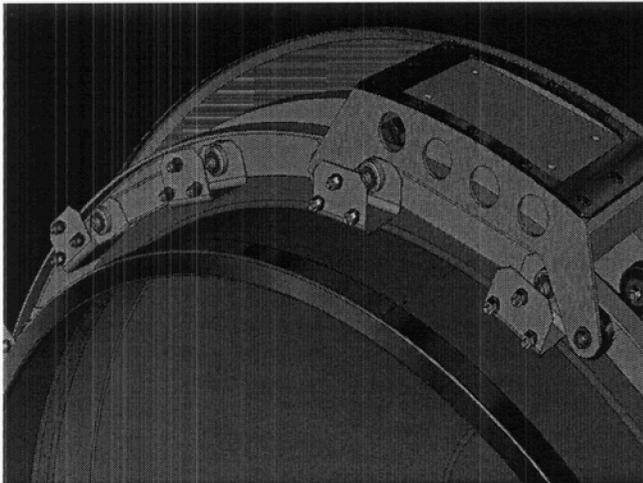


Figure 18. Close up view of the initial grid assembly mounting concept

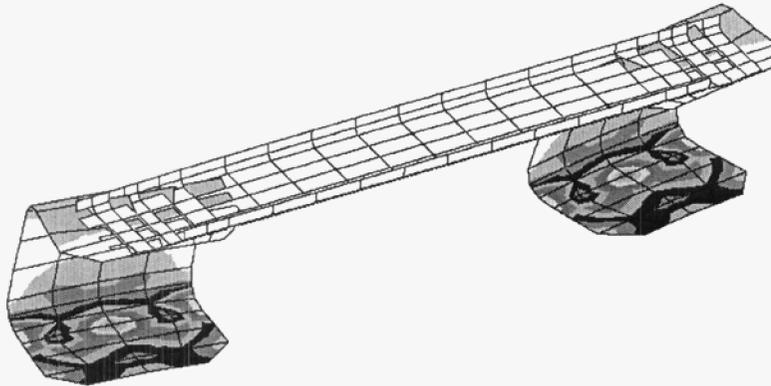


Figure 19. Induced thermal stress in the “C” flexure design (peak stress at the bolt constraints = 150 kpsi)

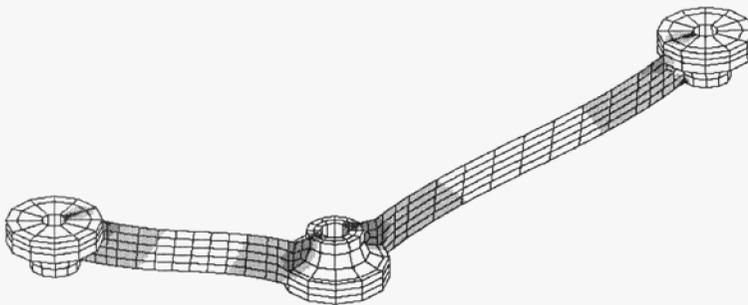


Figure 20. Induced thermal stress in the bipod flexure design (peak stress = 40 kpsi)

Thermal analysis of the reservoir cathode assembly was performed at the Jet Propulsion Laboratory. The goal of the modeling activity was to use the results to determine design constraints, such as wall thicknesses and heater powers, necessary to provide the temperature distribution along the cathode emitter necessary for effective cathode operation. The goal of the original lab model reservoir cathode design was to produce a source material temperature of 1150 °C with less than 100 °C end to end temperature variations along the reservoir. In the original design, the temperatures of the source material varied by too much, sometimes more than 200 °C. Changing the reservoir outer wall thickness produced an acceptable, less than 100 °C, source material temperature change. In the analysis of the development model design, the isolator served as a thermal short between the cathode and isolator mount thereby reducing the reservoir temperatures. The contact was parametrically varied between the isolator and bulkhead tube to see how much the external and self heating dissipations would need to increase for acceptable reservoir temperatures. Ultimately, the thermal contact was reduced to acceptable levels by reducing the bulkhead tube outside diameter and undercutting at the downstream tube diameter step up.



Figure 21. Reservoir cathode thermal model for the lab and development models

Lifetime analysis for the NEXIS thruster has been primarily performed with a separate overall thruster life modeling and test activity under the JIMO project. Preliminary analysis of grid erosion, using a model validated by wear test results from NSTAR and NEXT, indicates that the throughput requirement of 2000 kg can be met in the worst case before the onset of electron backstreaming or grid structural failure (14). Modeling and testing in the keeper region indicate that there should be no significant life limiting issues as long as a very low sputtering material, such as graphite, is used as keeper material to protect the cathode orifice plate (15, 16). More conclusive results for estimating life of the discharge chamber components should be forthcoming in the next year as additional experimental and numerical work is completed. Significant progress has also been made in making fundamental physical measurements for validating the low sputter yields needed for the carbon optics and keeper wear resistance needed to provide the NEXIS thruster with its long life (17,18). Finally, significant progress has been made in evaluating the lifetime of the cathode emitter. Recent experimental results of cathode emitter temperatures, cathode insert plasma properties, and loss rates of barium from the cathode surface exposed to plasma as a function of surface temperature combine with numerical modeling have shown that the depletion of the barium material from the cathode surface, critical to proper cathode operation, is dominated by conventional surface evaporation (7, 19, 16, 20, 21). Because conventional surface evaporation is also the dominant mechanism of barium depletion for vacuum cathodes; the wealth of long duration life test data for vacuum cathodes can now be used to validate the cathode insert lifetime for NEXIS (1).

#### IV. Development Model Thruster Fabrication

After incorporating the lessons learned from laboratory model level component testing and analysis of the DM thruster into the DM thruster design, drawings of the NEXIS DM thruster were released for fabrication of the piece parts. Sufficient parts were ordered to enable the assembly of at least two NEXIS DM model thrusters with additional units fabricated for critical parts that are needed for additional testing. This resulting in ordering at least two units of each discharge chamber parts, five grid assemblies with the requirement for a yield of three acceptable parts, and anywhere from five to thirty of each cathode part to provide multiple units for different material options and parts to verify the various weld and braze joints. The NEXIS DM thrusters were constructed with the intention of meeting all the requirements of the NEXIS NRA, such as life and performance, with at least the intention to also be able to meet those requirements after subsection to qualification thermal and dynamic load environments. The design philosophy of the NEXIS thruster development was to complete the piece part drawings before piece part fabrication; but to develop the majority of the detailed process and assembly instructions and drawings during the assembly of the DM thruster.

Fabrication of the NEXIS DM discharge chamber was relatively similar to conventional ion thrusters with two primary exceptions. First, due to the high power requirements of the thruster, the discharge chamber was significantly larger than previous ion thrusters (Figure 22). This size requirement stretched the limits of some of the

machine shops that had been used in the past and required the introduction of new shops to support the build of some parts. The second exception was the desire to make the manufacturability of the discharge chamber a primary goal. To meet this goal, only the electromagnetic and flow boundary conditions were set by scientist and engineers at JPL. Engineers and designers from Aerojet and Boeing, the two U.S. companies with by far the largest heritage in the production of the flight electric thrusters, were given the freedom to wrap a structure around the magnets, cathode, anode, optics and flow system with the requirement of maximizing the ease of manufacture. The result, shown in Figure 30, is a discharge chamber with a downstream machined ring, to support the tight tolerances required for the optics interface, and a spun upstream cone, to enable simple manufacturing (10). Parts production is currently well underway with the downstream discharge chamber ring already complete (Figure 22).

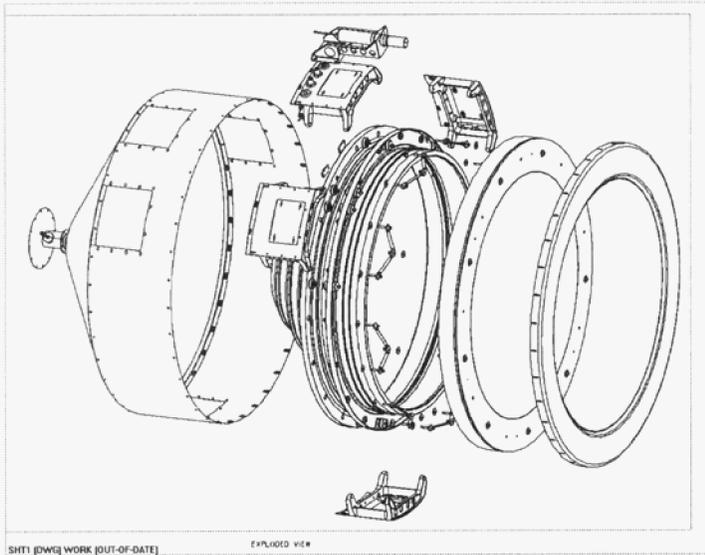


Figure 30. NEXIS DM thruster exploded view.



Figure 22. NEXIS DM thruster discharge chamber ring

Piece part fabrication of the cathode assembly parts is well underway in the support of the production of units for both the NEXIS DM thruster and the various component level cathode tests planned (Figure 23). The primary issue facing fabrication of the reservoir cathode is the qualification of the various welded and brazed joints required to secure both the cathode components and the reservoir material within the reservoir (Figure 24). The original plan for joint 1 was an electron beam (EB) weld; however, in test coupons, the high temperatures and large thermal gradients induced by the weld process led to embrittlement and residual stress in the orifice plate. Test coupons for this joint have been repeated with a brazed process that shows better results. For joint 2, the EB process has worked

well, passing leakage tests; however, brazing is being considered if all the other joints ultimately become brazed. EB welding coupons of joints 3 and 4 have passed leakage tests and indicate that the reservoir material can be kept at sufficiently low temperatures ( $< 1000\text{ }^{\circ}\text{C}$ ) during the process; however the tight process controls required for this EB weld may make it ultimately desirable to move to a brazed joint. For joint 5, the original tungsten piece has proven to be too brittle after the EB welding process, just like the orifice plate in joint 1, so the tungsten material is being replaced by molybdenum/rhenium.



Figure 23. NEXIS DM cathode parts fabrication nearing completion

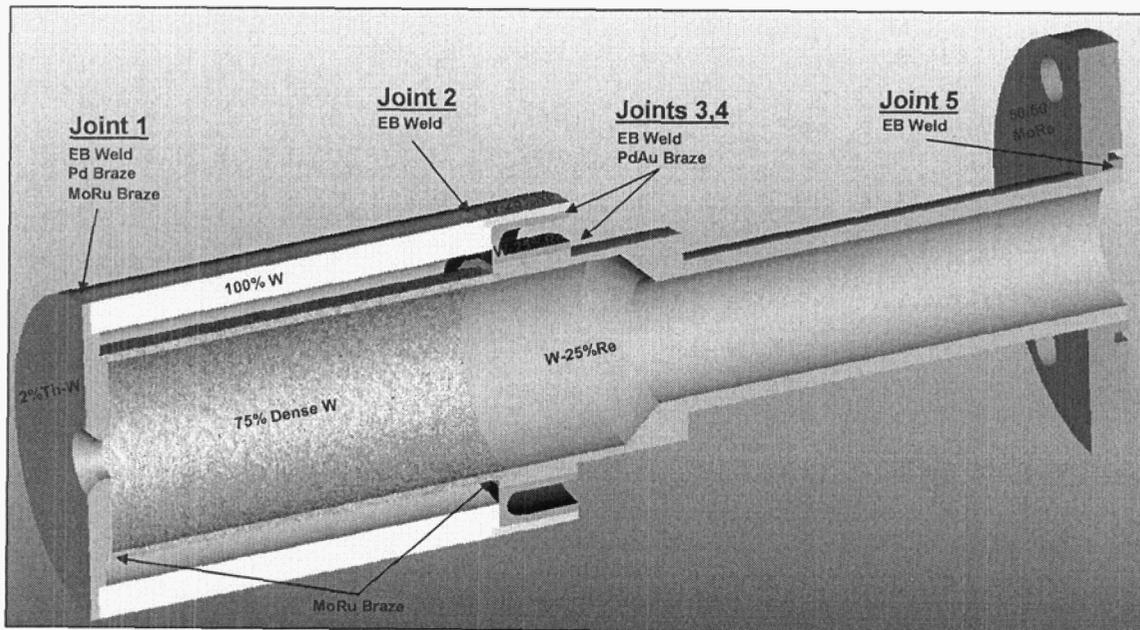


Figure 24. Reservoir cathode welded and brazed joints

One of the largest fabrication challenges facing the NEXIS activity is the development of a consistent manufacturing process for the fabrication of carbon-carbon grids. Carbon-carbon grid technology development has a long history at JPL and the NEXIS carbon-carbon grid technology relies heavily on the recent progress made in the Carbon Based Ion Optics Program (CBIO) (11-13). The NEXIS activity plans to advance the state of the art by both increasing the size of the grids manufactured and by documenting the manufacturing process in much greater detail. Fabrication of carbon-carbon ion optics.

Fabrication of the carbon-carbon grids follows a similar process to that defined in References 11 and 12. Unidirectional fiber tape is laid over graphite molds, placed in a vacuum bag to form the layup shape, then cured at a

moderate temperature. A carbonization step follows, then the material is densified with a chemical vapor infiltration process. Heat treatment is used to stiffen the materials. The grids are laser machined to produce the apertures and assembly features, then bonded to the stiffing rings. The screen grid is additionally bonded to the double-walled cylinder. A final chemical vapor deposition (CVD) process is used to give the assemblies a finishing coat.

The progress of the NEXIS DM grids through this process is shown in Figure 25. The main issue facing the NEXIS grid development is the delamination of 3 of the original 5 accelerator grids and the mounting ring billet identified after the CVD process. Because this phenomena was not observed on the screen grids; the cause of this problem is believed to be the inability of volatiles, produced either in the cure or carbonization process, to escape the grid blank (Figure 26). Bubbles are then formed which lead to delamination. Four new accelerator grids and a new mounting ring billet have been manufactured with a process modified to mitigate the delamination issue. Ultrasonic inspection of the new accelerator grids, after cure, produced with this new process show no indications of delamination providing evidence that this manufacturing process issue has been solved. To be able to effectively determine the cause and institute corrective actions for such problems, the NEXIS activity has implemented a process control plan to clearly identify the exact process that each grid has been fabricated under and an inspection plan to identify manufacturing issues that can lead to damaged grids as they occur. Figure 27 shows the process in action with the dimensional inspection of a grid blank and the detailed set of process control traveler that follow each grid through its fabrication process.

Part Number	Revision	Serial Number	Part Name	Cured	Passed 1st Ultrasonic Inspection		Carbonized	1st CVD	Passed 2nd Ultrasonic Inspection		Graphitized	Machined	Final CVD	Accepted
					Y	N			Y	N				
10232451-1	B	1	Blank Screen Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232451-1	B	2	Blank Screen Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232451-1	B	3	Blank Screen Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232451-1	B	4	Blank Screen Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232451-1	B	5	Blank Screen Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232452-1	B	1	Blank Acceleration Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232452-1	B	2	Blank Acceleration Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232452-1	B	3	Blank Acceleration Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232452-1	B	4	Blank Acceleration Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232452-1	B	5	Blank Acceleration Grid	Y	-	Y	Y	Y	N	N	N	N	-	
10232454-1	B	6	Precursor, Acceleration Grid	Y	Y	N	N	-	N	N	N	N	-	
10232454-1	B	7	Precursor, Acceleration Grid	Y	Y	N	N	-	N	N	N	N	-	
10232454-1	B	8	Precursor, Acceleration Grid	N	-	N	N	-	N	N	N	N	-	
10232454-1	B	9	Precursor, Acceleration Grid	N	-	N	N	-	N	N	N	N	-	
10232455-1	B	1	Mounting Ring	Y	-	Y	Y	-	NA	N	N	N	-	
10232455-1	B	2	Mounting Ring	Y	-	Y	Y	-	NA	N	N	N	-	
10232455-1	B	3	Mounting Ring	Y	-	Y	Y	-	NA	N	N	N	-	
10232455-1	B	4	Mounting Ring	Y	-	Y	Y	-	NA	N	N	N	-	
10232455-1	B	5	Mounting Ring	Y	-	Y	Y	-	NA	N	N	N	-	
10232457	B	Billet #1	Box Ring Structure Billet	Y	-	Y	Y	-	NA	N	N	N	-	
10232457	B	Billet #2	Box Ring Structure Billet	N	-	N	N	-	NA	N	N	N	-	

Figure 25. Carbon-carbon grid manufacturing process under control

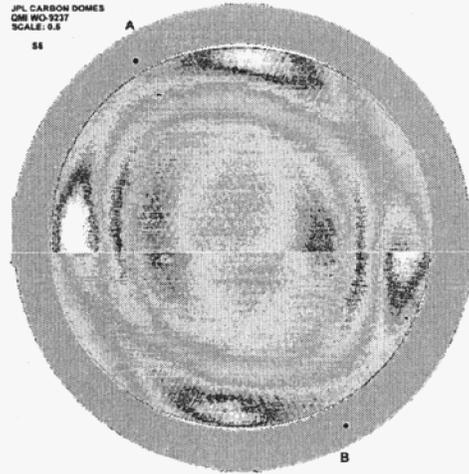


Figure 26. Ultrasonic inspections of the accelerator (A5) and screen grids (S5) after carbonization, the black areas represent delaminations

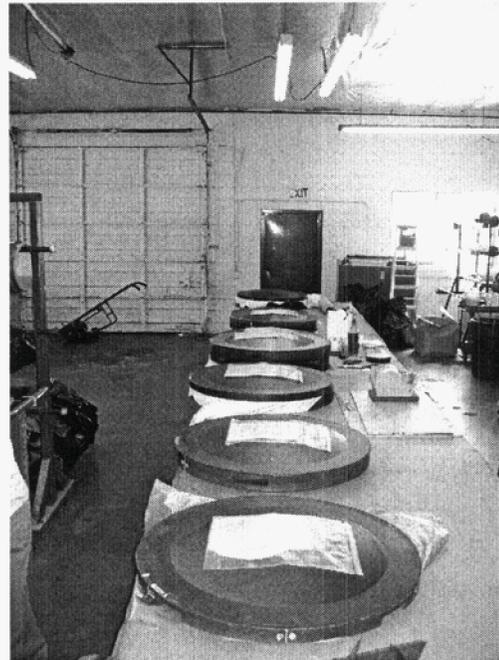
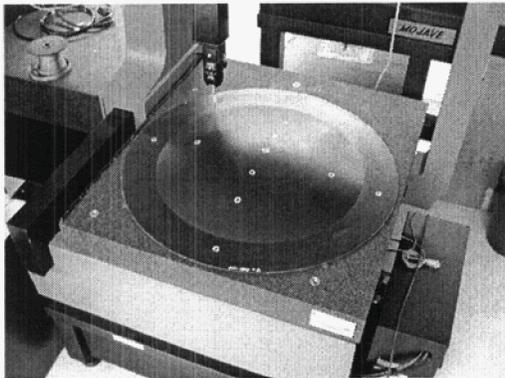


Figure 27. The NEXIS grid manufacturing process under control by dimensional inspection and process control documentation

## V. Thruster Life Test Facility Preparation

After the NEXIS DM thruster is completely assembled, it will be fired in a new vacuum facility modified to accommodate long term operation of high power. JPL vacuum chamber 148-1, where initial performance measurements were made for the NEXIS laboratory model thruster, is inadequate for such long duration testing. First, the temperature would rise significantly over the course of lab model thruster testing, due to inadequate cooling capacity; thus test durations were limited to about one hour. Also, the size of vacuum chamber 148-1 is inadequate to insure that backsputtered material from the tank walls will not significantly impact wear measurements of the thruster components. Finally, the low pumping speed of the 148-1 facility results in high densities of charge exchange ions which can significantly enhance the erosion of the thruster accelerator grid well beyond what would be observed in space.

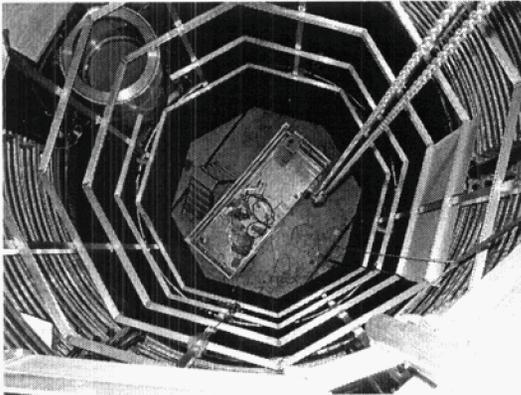


Figure 28. View down from work platform in NEXIS thruster life test facility during facility modifications

Fortunately, a new facility has become available in building 248. This new vacuum chamber, now identified as 248-1, has a slightly larger diameter (10 ft) and is much longer (10 m) than facility 148-1. Additionally, chevrons and low sputtering materials are being designed into the beam target. This combination of factors will reduce the backsputtering rate of tank wall material back to the thruster significantly. The pumping speed of facility 248-1 has been enhanced beyond the capability of facility 148-1 by the addition of several new cryopumps; thus the facility charge exchange induced erosion levels on the accelerator grids has been reduced to acceptable levels. Finally, heat rejection from the greater than 20 kW thruster beam has been effectively dealt with using a liquid nitrogen cooled beam target. Integration of diagnostics, power consoles, data acquisition and control systems, feed system component, and a thrust stand are well underway and should be completed in time for the start of a 2000 hour thruster wear test scheduled for early fall of 2004.

## VI. Conclusion

Although only funded for a little more than a year, the NEXIS activity has already completed several significant milestones that validate technology required for the high power, high specific impulse, long life needs of nuclear electric propulsion missions to the outer planets. Discharge chamber testing of a lab model thruster has validated the design model for the NEXIS thruster. The validation of this performance models allows the prediction of performance for the small design changes required for the development model thruster and allows reasonable predictions of performance for requirements changes generated from Project Prometheus. Beam extraction performance tests of the NEXIS lab model thruster have successfully demonstrated the performance required by the original NRA. Finally, a 2000 hour wear test of a proof of concept reservoir hollow cathode has demonstrated long duration operation of reservoir cathode technology.

Significant progress has also been made toward completing the upcoming milestones described in the NEXIS activity top level schedule shown in Figure 29. Thermal and structural analysis of the DM thruster design provide significant confidence in successful completion of upcoming DM thruster tests. Although several fabrication issues have been identified, parts fabrication for the DM thruster is proceeding with only minor schedule slips. Preparation of the thruster life test facility is well on the way towards successful completion. The NEXIS activity is in excellent shape to begin a DM thruster wear test by the end of summer 2004 with a high probability of success.

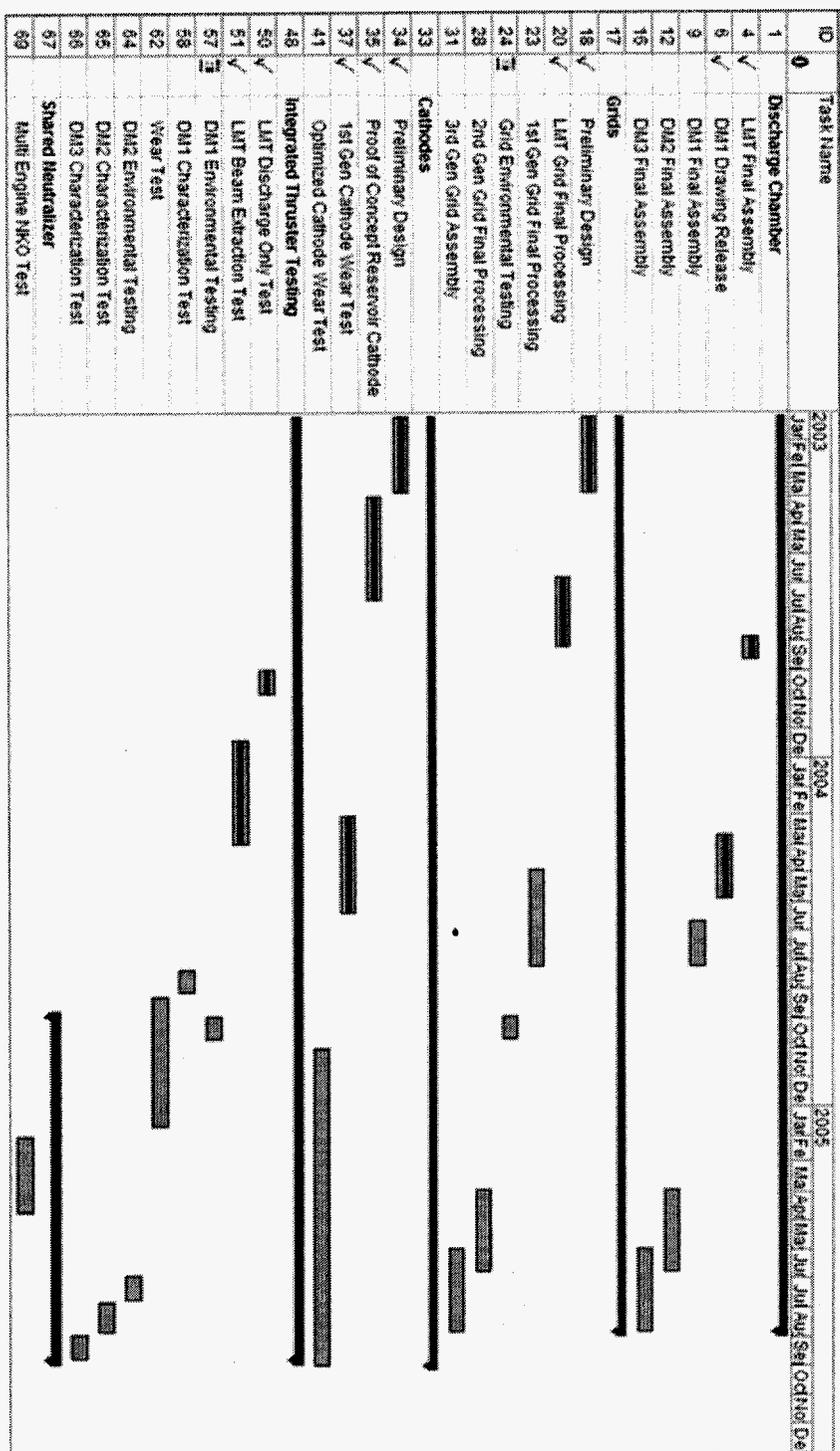


Figure 29. NEXIS activity top level schedule

## Acknowledgments

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