Conceptual Design of the Nuclear Electric Xenon Ion System (NEXIS)

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In support of the NEXIS program, Aerojet-Redmond Operations, with review and input from JPL and Boeing, has completed the design for a development model (DM) discharge chamber assembly and main discharge cathode assembly. These efforts along with the work by JPL to develop the carbon-carbon-composite ion optics assembly have resulted in a complete ion engine design. The goal of the NEXIS program is to significantly advance the current state of the art by developing an ion engine capable of operating at an input power of 20 kW, an Isp of 7500 sec and have a total xenon throughput capability of 2000 kg.

In this paper we will describe the methodology used to design the discharge chamber and cathode assemblies and describe the resulting final design. Specifics will include the concepts used for the mounting of the ion optics along with the concepts used for the gimbal mounts. In addition, we will present results of a vibrational analysis showing how the engine will respond to a typical Delta IV heavy vibration spectrum.

I. Introduction

As a member of the NEXIS team, Aerojet-Redmond Operations role is to design and analyze both the main discharge chamber and the main cathode for the ion engine. This ion engine is designed to operate at a specific impulse of 7500 sec and a total input power of 20 kW consistent with the NRA requirements for a nuclear electric propulsion mission. In addition, because of the near-term flight opportunity presented by JIMO, the design approach used by the design team is to reduce the inherent risk by utilizing as much flight heritage as possible while still eliminating all the identified life limiting failure mechanisms. As a result of this approach the NEXIS engine is a ring cusp design with a conical discharge chamber with a single thermionic cathode similar to NSTAR and NEXT engines. However, the NEXIS design team has tried to mitigate some of the manufacturing and lifetime deficiencies associated with the NSTAR design.

II. Discharge Chamber Design

The goal of the NEXIS program is to design a 20 kW ion engine that can operate at a specific impulse of 7500 sec and has a total throughput capability of greater than 100 kg/kWe. Also as part of the design we are trying to minimize the specific mass of the engine with the goal of a very ambitious 1 kg/kWe. The specific NRA requirement, however, is to be better than the present NSTAR design of 3.6 kg/kWe. Using these requirements and data from the NSTAR testing, JPL established the magnetic field, the discharge chamber diameter and the active beam area. They determined that a 6-ring magnetic field configuration was optimal and that the discharge chamber

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diameter should be 65 cm to get a uniform 57-cm diameter ion beam. Using these requirements, Aerojet developed the conceptual design presented in Fig. 1.

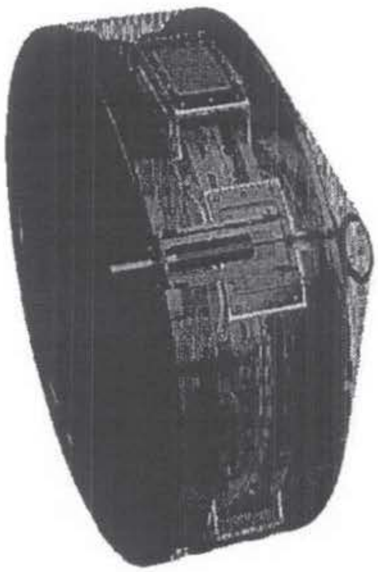

Figure 1 Conceptual view of the 20 kWe NEXIS ion engine showing two of three gimbal mounts and the neutralizer

A. Challenges and Technical Solutions:
In addition to the aggressive design requirements, several design challenges were identified including manufacturability, structural integrity, and sub-component integration. Specifically, these sub-components involve mounting the ion optics to the discharge chamber, the introduction of the xenon propellant, and the main discharge cathode.

1. Manufacturability:
One of Aerojet's core competencies is in the design and manufacturing of flight qualified propulsion system hardware and in the NEXIS program we have leveraged this expertise to design an ion engine that satisfies the technical requirements while still being cost effective and manufacturable. Pictured in Fig. 2 is a view of the discharge chamber showing the two major elements of the chamber. The first is a machined component that forms the cylindrical section of the chamber and is also the main structural element from which the majority of the other components are mounted. The second is a spun-form part that creates the back conical section of the chamber. Onto this conic section are mounted the magnet rings and the main discharge cathode. Using this combination of machined and spun parts allows a precision machined component to control the critical dimensions associated with the mounting of the ion optics and gimbal pads, while a less expensive spun part is used for the less tolerance critical components such as the back conic section. The greatest advantage to using a machined part within the discharge chamber is that it removes the tolerance issues that arise from using several spun-form parts to create tight tolerance assemblies, as is the case for the current state of the art designs. In addition to providing good dimensional control, this machined part serves as the main structural member for the engine and having it machined from solid stock allows the freedom to tailor the design as required to ensure that we have an optimal structural design.

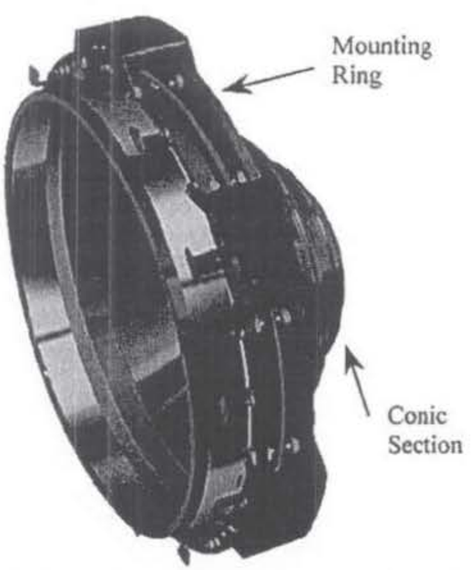

Figure 2 Sub-Elements of the NEXIS discharge chamber. The chamber is constructed from two main elements, the mounting ring and the back conic section

2. Ion Optics Mounting:
One of the life-limiting wear mechanisms that has been identified for ion engines is erosion of the ion optics leading to either excessive electron back-streaming or structural failure of the grids. To eliminate this wear-out mechanism from the NEXIS ion engine, JPL has designed a set of carbon-carbon composite ion optics. While this new ion optics design minimizes the erosion of the grids, it introduces a new set of design complications. The first of these is the difference in the thermal coefficient of expansion between the carbon-carbon and the metallic discharge chamber. As the discharge chamber temperature increases from room temperature to ~300 °C, the grid set diameter

remains unchanged while the discharge chamber diameter increases by ~3 mm. This can cause localized overstressing of the ion engine or worse cause a local deflection in the grid set changing the local preveance. To minimize this possibility, an ion optics mounting structure was designed that is stiff along the thrust axis yet fairly compliant in the radial direction. A picture of the mounting flexures is presented as Fig. 3. The rectangular cross-section of the mounts creates a very large bending moment in the thrust direction while the thin webbing allows for compliance in the radial direction. To provide the necessary strength to hold the mass of the optics, there are 9 pairs of flexures equally spaced around the circumference of the discharge chamber.

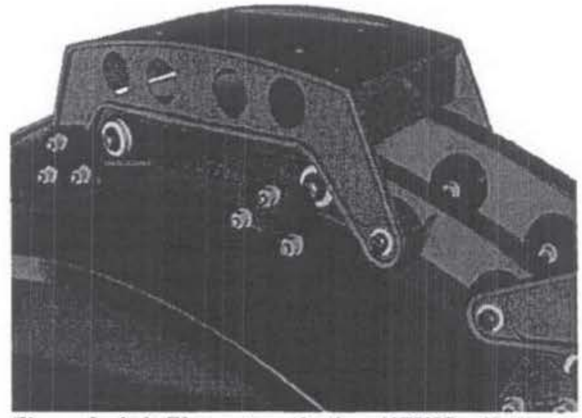

Figure 3 Sub-Elements of the NEXIS discharge chamber. The chamber is constructed from two main elements, the mounting ring and the back conic section

3. Propellant Injection:

Based upon flow modeling performed by JPL, it was determined that an optimal location for injecting the xenon propellant into the discharge chamber was halfway upstream the cylindrical section of the discharge chamber and with an initial angle of 45° upstream. To satisfy these requirements a special plenum section was designed into the main structural element as depicted in Fig. 4. This figure is a close-up view of the cylindrical section of the discharge chamber and for reference the downstream direction is indicated on the figure. The propellant plenum is created by machining a triangular channel into the structural member and then covering this small channel with a thin strip of either sheet or flake retention material. The propellant entered the discharge chamber through a series of small holes creates in the thin covering material. To assure good propellant uniformity, the pressure drop along the length of the plenum was

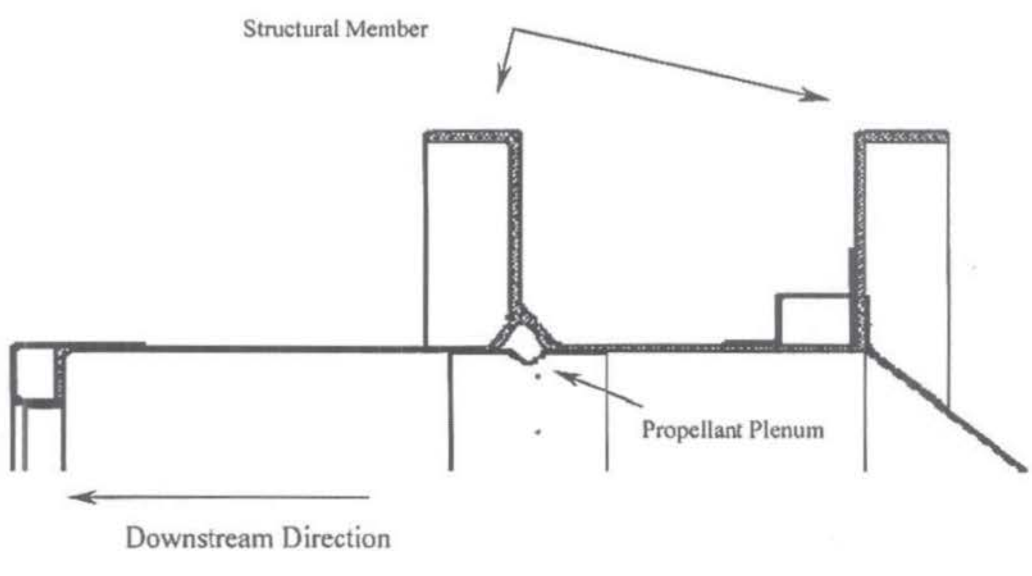

Figure 4 Cross-sectional view of the propellant injection. Based upon modeling performed at JPL the optimal performance is expected to occur with the propellant injected at a slight angle upstream.

computed using a Hagen-Poiseuille flow approximation. Using this approximation, the pressure drop for a specified length of tubing can be computed as $\Delta P = \dfrac{128\mu d_c \dot{m}}{\rho d^4}$ where μ is the viscosity, ρ is the density, $\dot{m}$ is the mass flow rate, d_c is the discharge chamber diameter, and d is the characteristic diameter of the flow plenum. For the flow rates associated with the NEXIS engine, the pressure drop along the length of the plenum was computed to be less than 1 psi for an inlet pressure of 5 psi.

4. High Voltage Isolation Design:

The 7500 sec specific impulse requirement of the NRA together with the assumed engine efficiency indicated that the NEXIS ion engine will be required to operate at a beam voltage of ~5600 V which is significantly above the current state of the art for ion engines. To give the design some more operational margin and added flexibility, it was decided that the ion engine would be designed to operating at a beam voltage of 7,500 V and the isolators would be designed to hold off ~10,000V. This gives a 30% operational margin and an 80% design margin. Using conventional design criteria, the rough dimensions of the various high voltage isolation components were computed. To satisfy the conventional vacuum and surface breakdown limits, the isolators were designed to have a vacuum gap of at least 2.5 mm between the different potential surfaces. In addition, to prevent surface conduction along the surface of the ceramics, they need to be at least 2 cm in length. The voltage isolation between the gimbal mounts and the main structural element of the discharge chamber is accomplished using a compressed isolator design similar to that used on the NSTAR engine. Presented on Fig. 5 is a cross-sectional view of the isolator design used to mount the gimbal pads to the discharge chamber. This isolator consists of 4 ceramic insulators that provide the separation between the two potential surfaces and a polymer sleeve to provide alignment between the insulators and the bolt. Since ceramics do not handle tensile loads well, a through bolt is used to provide a significant compressive load on the insulator stack ensuring that the ceramic will remain in compression and will not separate during vibrational loading. The final element presented in the figure are the four sputter shields that prevent sputtered material from being deposited on the insulator surfaces, decreasing the voltage stand-off capability.

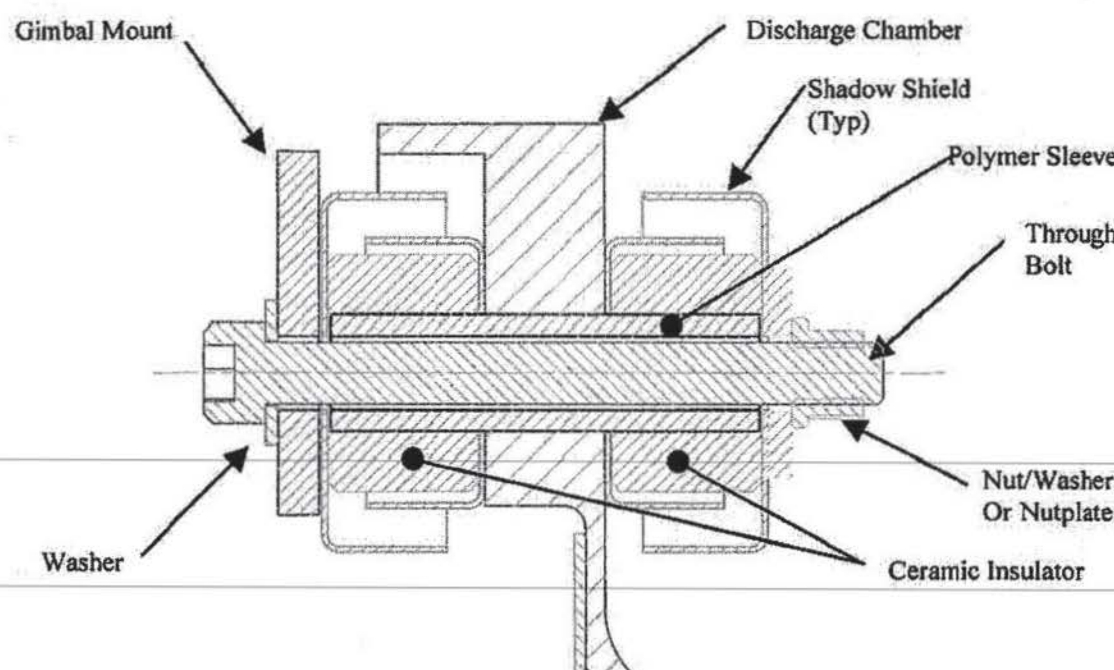

Figure 5 High voltage isolator design that can provide up to 10 kV of isolation. Similar to the current state of the art, this isolator is designed to have the ceramics remain in compression throughout its loading.

III. Discharge Cathode Design:

Because of the high throughput required by the NRA, a new discharge cathode design was developed. This new cathode design was a collaborative effort where JPL developed the emitter portion, BEDD developed a brazed graphite keeper assembly, and Aerojet developed the structure to interface these components with the discharge chamber. The magnetic field modeling completed by JPL determined that the cathode orifice had to be placed a very specific distance downstream of the upstream face of the cathode magnet ring and centered within the magnetic field. Based upon these requirements, the NEXIS team developed the cathode design presented in the exploded view of Fig. 6. As shown in the figure, the cathode design utilizes two snap rings to hold the cathode tube within the ceramic isolator and to hold the entire assembly to the mounting flange. This design is in contrast to the current state of the art cathodes that are typically a completely brazed assembly. This eliminates the concerns with a completely brazed assembly in that any problems that may occur during the final braze step can result in scrapping a high-value part. In addition, the high throughput of the NEXIS engine requires that extreme care be taken to prevent contaminating the barium source material within the discharge cathode. This in turn requires that extreme care must be taken with the discharge cathode once it has been filled with the source material. As an example, once the temperature of the barium source material has been raised above 1000 °C it becomes active and from that point on it should always be stored in an inert, dry environment. These requirements also have impacts upon how the cathode is manufactured. For example, once the reservoir cathode tube is received, no processing step in the manufacturing of the final assembly should involve temperatures higher than 1000 °C or involve high temperatures in an oxidizing environment. This means that the number of braze steps for the final assembly should be minimized and those that are required must be done at temperatures less than 1000 °C.

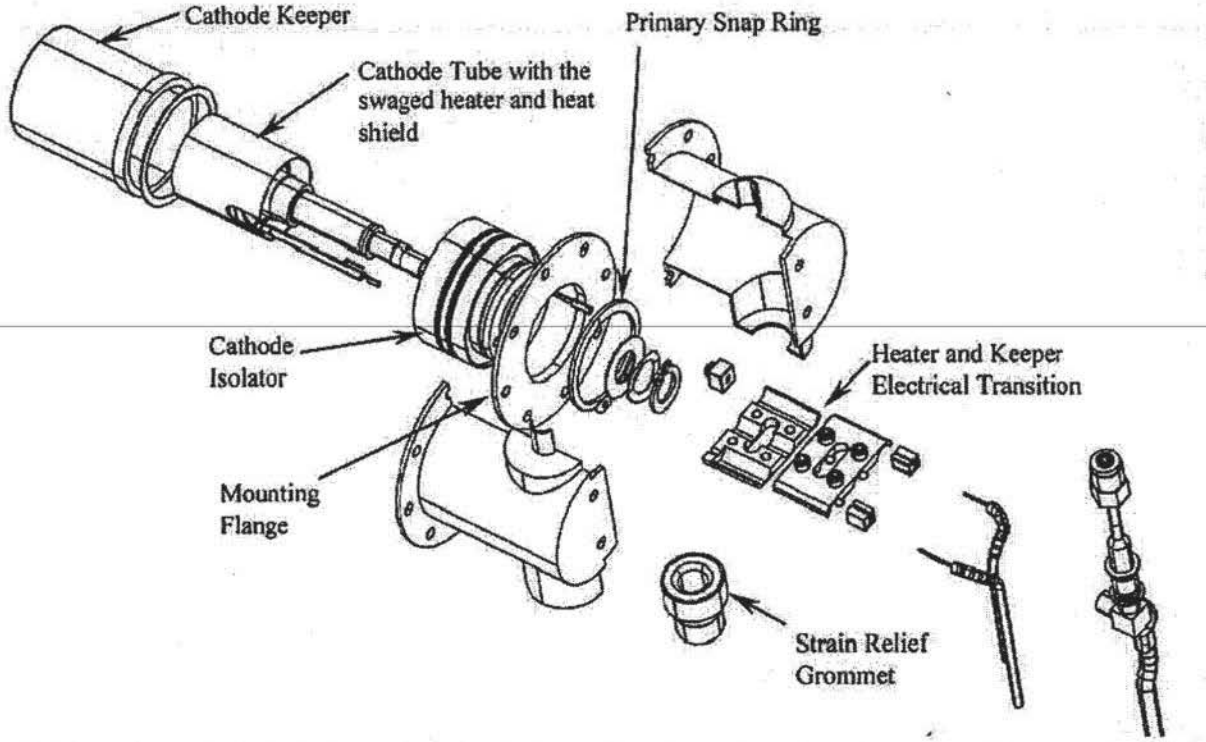

Figure 6 Exploded View of the NEXIS Main Discharge Cathode. This cathode has been designed to be easily assembled as well as serviceable during initial development testing

IV. Structural Design

Upon completion of the conceptual design, a structural analysis was performed on the discharge chamber to determine both its fundamental frequencies and its response to a random vibration excitation. For this analysis a mass of 19 kg was used for the discharge chamber, 5.5 kg for the ion optics, and 0.32 kg for the discharge cathode. The initial modal analysis calculated approximately 350 modes in the frequency range from 82 to 2000 Hz with 50 of them being below a frequency of 600 Hz. The majority of the high frequency modes are complex plate movements of the discharge chamber and are not significant. The lowest frequency determined in the analysis was 82 Hz and it was an axial movement of the neutralizer bracket as pictured in Fig. 7. Although this frequency is higher than the minimum requirement of 80 Hz, to give the design more robustness the neutralizer will be moved closer to the discharge chamber and a second anchor point will be added. The next vibration mode in the design occurs at 90 Hz and is pictured in Fig. 8. In this mode the gimbal mount pads rotate around the main structural element of the discharge chamber.

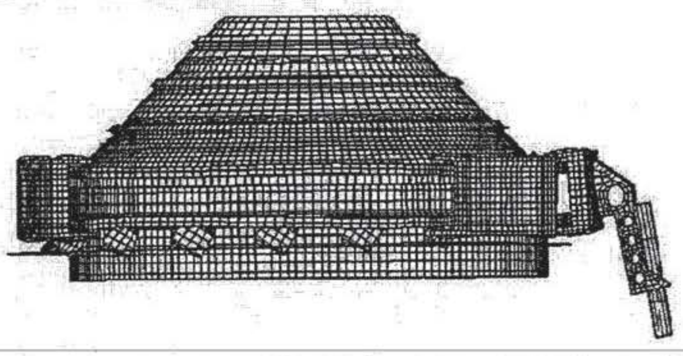

Figure 7 The first fundamental frequency of the present NEXIS discharge chamber is an axial movement of the neutralizer mounting bracket. NOTE: The displacements indicated by this figure are greatly enhanced for clarity

The first frequency involving the grid set, which is of primary concern due to the brittle nature of carbon-carbon composites, occurs at 110 Hz. This mode, pictured on Fig. 7, involves the grid set rotating circumferentially around the discharge chamber in unison. It should be noted that since the material characteristics of the carbon-carbon composite grid set are not well known, it was modeled as a rigid plate fixed to the flexures having a mass of 5.5 kg. The next highest frequency mode found in the design occurred at 113 Hz, and is shown in Fig. 10. This mode involves the discharge cathode oscillating axially up and down like a bass speaker. The rest of the modes found in the analysis are high frequency, complex movements of the conic sections of the discharge chamber such as the 624 Hz mode shown Fig. 11. It should be noted that because of the high frequency of this mode, the energy levels are small and the deflections do not induce any significant stresses in the discharge chamber. Hence, this and the other high frequency modes can in general be ignored.

V. Conclusion

As part of the JPL NEXIS program, Aerojet - Redmond Operations along with help from JPL, and BEDD have developed a conceptual design for a 20 kW ion engine. This engine can operate at a specific impulse of 7500 sec and has a total throughput capability of greater than 50 kg/kWe. The design also minimizes the specific mass of the engine, surpassing the requirement of less than 3.6 kg/kWe. The current design of the engine , including the ion optics, has a mass of approximately 29 kg. This results in a specific mass of approximately 1.5 kg/kWe. The discharge chamber has been designed with a sufficient margin to allow it to operate from a specific impulse of 7,500 sec to over 9,000 sec.

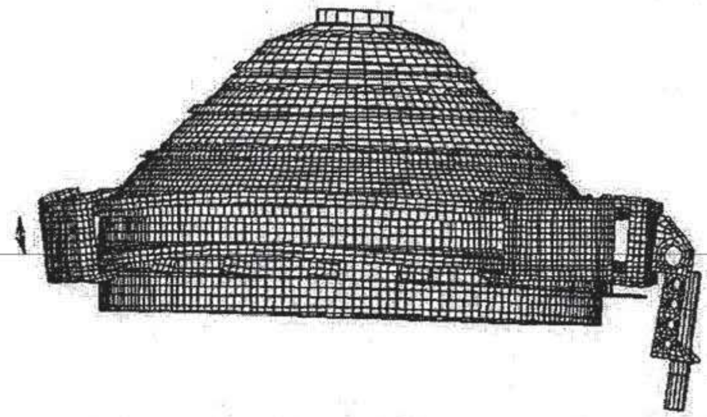

Figure 8 The rotation of the gimbal mount brackets around the structural frame of the discharge chamber occurs at 90 Hz. NOTE: The displacements indicated by this figure are greatly enhanced for clarity

VI. Acknowledgements

The authors would like to thank Dan Giles, Dave Hobson, and Phil Flugstad of Aerojet-Redmond Operations for their hard work on the design of the NEXIS engine. Also Steve Hart and Mike De Pano of Boeing Electron Dynamic Devices deserve recognition for their efforts in both conveying the current state of the art as well as adding numerous ideas to further this design. Lastly, thanks are due to Nils Juhlin for his hard work performing the structural analysis.

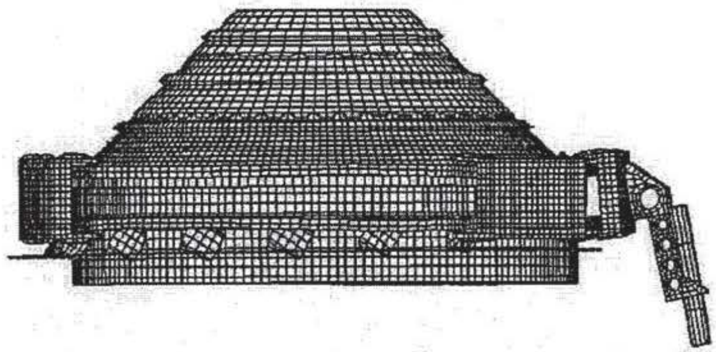

Figure 9 The first mode associated with the grid flexures is a rotational mode that occurs at about 110 Hz. NOTE: The displacements indicated by this figure are greatly enhanced for clarity.

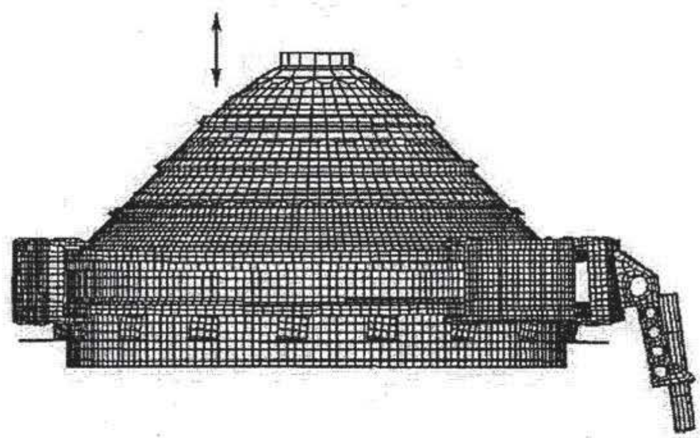

Figure 10 "Speaker" mode of vibration induced by the mass of the cathode resonating up and down like the cone of a speaker. NOTE: The displacements indicated by this figure are greatly enhanced for clarity.

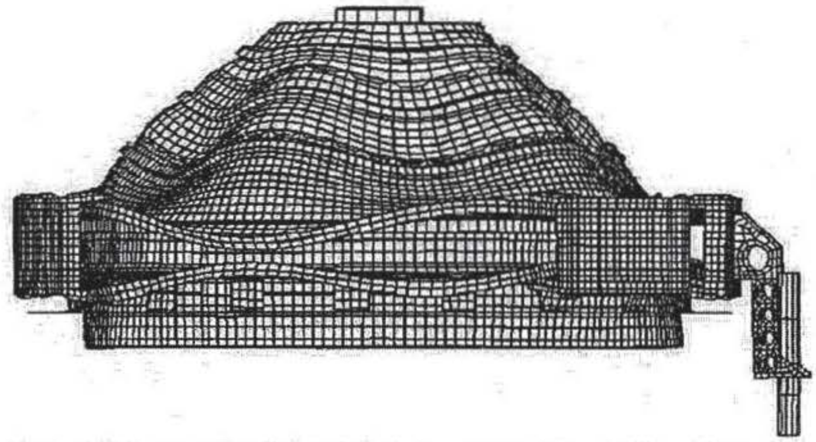

Figure 11 An example of the high frequency complex motion of the conic sections of the discharge chamber. This mode occurs at 624 Hz and hence has very little energy to cause damage to the engine. NOTE: The displacements indicated by this figure are greatly enhanced for clarity.

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