

Experimental and Theoretical Analysis for Designing a Grid Clearing System for the NEXT Ion Propulsion System

John R. Anderson, David Vaughan and Dennis Fitzgerald

Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, California

Screen to accelerator grid shorts have occurred on two NASA spacecraft using ion propulsion systems. This resulted in loss of thrusting capabilities on one of the spacecraft. Since grid shorts are a potential life limiting mechanism for ion thrusters, grid clear circuits have been implemented to provide a method of clearing the fault. A general methodology that can be used to deal with a grid short if it arises during a mission is discussed; this includes examining a variety of techniques including use of a grid clear circuit to clear the short. In addition, experimental and theoretical investigation of a potential grid clear circuit for the NEXT ion thruster has is presented. This includes information on the size and types of material that might cause a grid short. The parameters that influence the ability to clear a short are discussed and experimental data obtained while investigating these parameters is presented.

Introduction

The success of the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) ion propulsion system on the Deep Space 1 spacecraft has stimulated interest in the use of electric propulsion for NASA solar system exploration missions [1]. The NASA Evolutionary Xenon Thruster (NEXT) is being developed with the goal of providing an ion propulsion system with higher power, higher throughput and higher specific impulse capabilities than the 2.3 kW NSTAR thruster [2]. The 36 cm diameter NEXT is designed to be throttled over the range from 0.5 to 7.5 kW.

A potential life-limiting mechanism for NEXT and NSTAR thrusters (as well as other thrusters using grids) is a short caused by conductive debris lodging between the screen and accelerator grids. Potential sources for this debris include material from the launch environment, material left over from the thruster fabrication, and flakes formed when thin films of sputter deposited material spall off of the surface of an ion engine component. Because such a short would preclude use of the high voltage beam supply, the thruster has failed unless the short can be cleared.

Ion thruster systems are designed to handle arcing between grids. The system senses an over-current in either the screen or accelerator grid currents and commands the high voltage off to suppress the arc. The high voltage supplies are off for about one second and then they are commanded back on. If there was simply an arc between the grids this will stop the arc and normal thrusting will resume once the high voltage is reapplied. This sequence of events is known as a recycle. However if debris is shorting the grids, an over-current will again be sensed when the high voltage is applied; this will trip the

recycle circuit again and the system will continuously recycle. The system is designed to command the thruster off when a preset number of recycles occurs in a given time frame. If the thruster is commanded off because of exceeding the recycle limit, a signal is sent to ground control indicating the problem. At that point the flight team must decide how to deal with the situation.

History of Grid Shorts on NASA Spacecraft

This situation has occurred on two NASA spacecraft, namely SERT II which was equipped with two mercury ion thrusters and Deep Space 1 which had one xenon ion thruster.

The SERT II spacecraft was launched in 1970. Both mercury ion thrusters were operated in 1970 until grid shorts developed [3, 4]. Each thruster was automatically turned off after 2 minutes of continuous recycling indicating that a short had developed. There was no grid clear circuit for the SERT II thruster system; therefore, methods to mechanically remove the debris causing the short were used.

Ion thruster 1 shut down due to continuous recycling after operating for 2385 hours; a restart was attempted and the thruster resumed normal operation. Excessive recycling caused ion thruster 1 to be shut down a second time at 3781 hours of operation. This time the short could not be cleared; the fault still existed after 300 thermal cycles and 20 attempts to apply high voltage.

Ion thruster 2 developed a grid short after operating for 2011 hours. This short was cleared in 1974 when the spacecraft was spun at 1 rpm; apparently the centripetal force caused the material shorting the grids to be removed. In 1979 ion thruster developed another grid short at 2561 hours of operation. Several hot restarts were attempted prior to clearing the short with a cold restart application of high voltage. Ion thruster 2 shorted again at 2626 hours of operation; several hot and cold restarts were attempted before the short cleared after a prolonged heating period. Ion thruster 2 developed a short between the thruster body and spacecraft common at 2744 hours. This occurred when the thruster was operated for 53 minutes without a neutralizer after the neutralizer propellant tank was exhausted.

The NSTAR ion optics shorted on Deep Space One about 4.5 minutes after the ion thruster began high voltage operation [1, 5]. In this case the thruster underwent 25 recycles in less than 90 seconds and the thruster was commanded to shut down. Fourteen unsuccessful attempts were made to restart the thruster on the same day that the short occurred. Because the thruster was not needed until later in the mission, two weeks were spent investigating potential methods to clear the thruster. This included testing of the NSTAR grid clear circuit using the spare flight PPU [6]. During this time the thruster went through several thermal cycles by being pointed toward and away from the sun. The thruster system software was modified to provide high speed telemetry during recycles that could help to identify what components were shorted. Two weeks after the fault developed, the thruster was commanded to start with the goal of obtaining telemetry during recycle events. Fortunately the thruster started normally and operated for the rest of the Deep Space One mission without shutting down due to excessive recycles.

Of the 5 instances of grid shorts that occurred on the SERT II thruster all but 2 were cleared by thermal cycling to mechanically remove or break the connection between the grids. Another short was cleared by spinning the spacecraft and one short was not cleared. The short on Deep Space One was cleared through thermal cycling without having to resort to using the NSTAR grid clear circuit.

SERT II did not have a grid clear circuit. Because of the problems encountered on SERT II, subsequent ion thruster systems have been designed to include a grid clear circuit. This provides an additional capability for dealing with grid shorts.

Methods for Dealing with Grid Shorts

Because of the complexity of spacecraft systems and missions using ion propulsion, it is unlikely that all of the scenarios and constraints that must be dealt with when a grid short occurs can be foreseen. Therefore, attempting to go through an exhaustive list of how to handle various scenarios would not be fruitful; instead some general guidelines that should be useful when faced with a grid short will be given.

The first order of business when the thruster shuts down due to excessive recycles is to gather and analyze the available telemetry from the spacecraft to identify the cause of the fault. Because of resource constraints the sampling rate for the ion propulsion system may be too low to provide the temporal resolution required to determine the cause of the shut down. If this is the case, the team dealing with the shutdown should determine what data is needed to determine the fault and how best to obtain it; this might include writing new software.

Once the telemetry has been examined and it has been determined that there is a grid short, all options for dealing with the situation should be listed. Once the list is compiled, the options should be ranked in order of risk; the risk associated with each option may vary with circumstances, so this exercise requires the judgment of the team dealing with the situation. Then the options should be tried in order of increasing risk (or desperation) until the short is cleared or all options have been exhausted.

The list of things to consider will vary depending on the spacecraft and mission; however, a partial list of things that should be considered is given here. The best way to clear a grid short is to mechanically remove the debris causing the short as was apparently done on the Deep Space 1 and the successful clears on the SERT II spacecraft. If the grid clear circuit is used the electrical connection between the grids may be broken but residue from the debris may still be present; this can increase the susceptibility to arcing in the optics system.

Some of the possible methods for mechanically removing the debris from the grid are those used on the SERT II and Deep Space One spacecraft, namely, thermal cycling the grids. Possible ways of doing this include pointing the thruster toward and away from the sun. Another way is to operate the thruster in discharge only mode; this can cause the grids to expand at different rates and may clear the short. Another possibility is to spin the spacecraft, as done on SERT II; this option may not be viable if it would result in permanent damage or loss of crucial spacecraft subsystems. A possibility that has not been tried on spacecraft is to drive the thruster gimbal into the mechanical stops; the impulse provided might dislodge the debris causing the short. This option may damage the gimbal or thruster and probably should be considered as a last resort.

If methods to mechanically clear the short fail or the time available before resumption of thrusting is required is too short, use of the grid clear circuit may be considered. In order to access this option information on the grid clear circuit capabilities is needed.

Two types of grid clear circuits were investigated experimentally; one uses a low voltage high current supply (the discharge power supply in the PPU would be used on the spacecraft) and the other is a high voltage capacitor bank to provide power attempt to vaporize the debris.

If attempts to clear the grid short mechanically fail or would take too long thereby causing loss of mission due to the inability to provide thrust, use of the grid clear circuit would be considered. In order to assess when the grid clear circuit should be used information about its capabilities is needed.

Grid Clear Circuit Types

The NEXT thruster PPU grid clear circuit is similar to that of the DS1 spacecraft. It is designed to connect the discharge supply across the screen and accelerator grids. Under normal operation the negative side of the discharge supply is connected to the screen grid which is held at discharge cathode common and the positive side of the discharge supply is connected to the anode. In order to use the grid clear circuit a relay is used to disconnect the positive side of the discharge supply from the anode and instead connect to the accelerator grid. This design is the simplest to implement because it only requires one extra switch in the PPU. Because the full 24 A from the discharge supply can be driven through the grid short in steady state, the wiring to both the screen and accelerator grids must be sized to survive steady state operation at 24 A.

An alternative to using the discharge supply is to apply the spacecraft bus voltage across the short; this would require two relays, one for each of the screen and accelerator grids. The potential advantage of this approach is that a higher voltage (on the order of 100 V instead of ~30 V provided by the discharge supply) would be available to clear the short. The higher voltage would increase the range of contact impedances that the grid clear circuit could successfully clear. Again the wiring and components must be sized to handle the largest expected steady-state current.

Another alternative approach is to use a high voltage capacitor to discharge energy into the debris to clear it. This would require relays to disconnect the grids from the beam and accelerator grid supplies. The beam supply would then be connected across the capacitor bank and allow it to charge up. The beam supply would then be disconnected from the capacitor bank and the capacitor bank would be connected across the screen and accelerator grids. This type of grid clear circuit is the most complex of the types considered because it has the most components; there is a risk of switches failing or the capacitors shorting out. Because of the additional complexity and experimental results (described later) this type of circuit will not be implemented on the NEXT PPU.

Theoretical Discussion

There are several variables that affect the current required to clear a given size piece of debris. In order to investigate these variables, simple one-dimensional time varying numerical and steady-state analytical models were developed. Assumptions for the

models are that the debris has a constant shape along its length, it is at least as long as the grid gap, and that it is centered in the gap. It is assumed that there are both electrical and thermal contact resistances between the debris and the grids.

The time varying differential equation for the debris in the region spanning the gap is

$$\begin{aligned}
A_{cs}\rho c_p \frac{\partial T}{\partial t} = & A_{cs} \frac{\partial T}{\partial x} \left[k \frac{\partial T}{\partial x} \right] - P_{cs} \varepsilon \sigma (T^4 - T_g^4) + \frac{I^2 \gamma}{A_{cs}} \\
& - A_{cs} \varepsilon \sigma (T^4 - T_g^4) \delta(x = -L/2) - A_{cs} \varepsilon \sigma (T^4 - T_g^4) \delta(x = L/2) \\
& - \frac{(T - T_g)}{R_{thc}} \delta(x = -g/2) - \frac{(T - T_g)}{R_{thc}} \delta(x = g/2) \\
& + I^2 R_{elc} \delta(x = -g/2) + I^2 R_{elc} \delta(x = g/2)
\end{aligned} \tag{1}$$

where,

A_{cs} - debris cross-sectional area (m²)

c_p - debris heat capacity (J/kg/K)

g - grid gap (m)

I - current through the debris (A)

k - debris thermal conductivity (W/m/K)

L - debris length (m)

P_{cs} - length of the perimeter around the cross-section (m)

R_{elc} - electrical contact resistance between debris and grid (Ω)

R_{thc} - thermal contact resistance between debris and grid (K/W)

T - debris temperature as a function of position and time (K)

T_g - temperature of the grids and surrounds for radiation (K)

x - axial position along debris (m)

ε - debris emissivity (dimensionless)

ρ - debris mass density (kg/m³)

γ - debris electrical resistivity (Ω m)

σ - Stefan-Boltzmann constant (5.669×10^{-8} W/m²/K⁴)

$\delta(x = y)$ - delta function indicating that the power is input or extracted at the point y

In this equation the term on the left is the local rate at which thermal energy is stored in a differential volume, the first term on the right is the rate that heat is conducted into the differential volume, the middle term on the right is the rate at which thermal energy is radiated from the surface of the differential volume, the third term is the rate of joule heating in the differential volume, the terms in the second row are the radiation heat flux from the ends of the debris, the terms in the third row are the rate that heat is conducted to the grid through the thermal contact resistance and the terms in the fourth row are the rate of joule heating due to the electrical contact resistance. No current is driven through portions of the debris that extend beyond the grids; therefore, the $I^2 \gamma / A_{cs}$ term on the right of the equation is set to zero in that region.

Because the thermal conductivity of metals is high, the temperature is expected not vary greatly along the length of the wire. Numerical calculations show that in many cases the temperature varies only a few to a few 10s of degrees. Neglecting the small temperature variation a simple steady-state model can be derived for the current required to heat the debris to the vaporization temperature. The model balances the joule heating rate with the rate that energy is lost through radiation from the surface and through the thermal contact resistance. This results in the following expression for the minimum current required to clear the debris.

$$I_c = \sqrt{\frac{A_{cs} \left[\left(\frac{2}{R_{thc}} \right) (T_v - T_g) + \varepsilon \sigma (2A_{cs} + LP_{cs}) (T_v^4 - T_g^4) \right]}{\gamma g + 2R_{elc} A_{cs}}} \quad (2)$$

where,

A_{cs} - debris cross-sectional area (m²)

g - grid gap (m)

L - debris length (m)

P_{cs} - length of the perimeter around the cross-section (m)

R_{elc} - electrical contact resistance, the same value is assumed at both contact points (Ω)

R_{thc} - thermal contact resistance, the same value is assumed at both contact points (K/W)

T_v - temperature required to vaporize the debris (K)

T_g - temperature of the grids and surrounds for radiation (K)

γ - electrical resistivity of the debris (Ω m)

ε - emissivity of the debris (dimensionless)

σ - Stefan-Boltzmann constant (5.669×10^{-8} W/m²/K⁴)

I_c - current required to heat the debris to the vaporization temperature (A)

As noted this expression is derived assuming the debris is at a constant temperature. This model breaks down if there are large temperature gradients along the length of the debris. This can occur if the debris extends significantly beyond the edge of the gap so that there are large regions that do not receive any joule heating. This can also occur if the thermal contact resistance is low and the debris temperature approaches the grid temperature at the point of contact. The grid temperature does not increase significantly due to its high thermal conductivity and large thermal mass, and is assumed to be at ambient temperature.

It is noted that this model is conservative, because it tends to overestimate the current needed to vaporize the debris. If there are temperature variations along the wire the cooler regions will be at lower temperatures than the vaporization temperature used in Equation 2. Therefore the radiation and conduction across the contact resistance are overestimated, resulting in over predicting the current required to heat the wire to the vaporization temperature.

The thermal and electrical contact resistances appearing in Equation 2 can vary between 0 and infinity. These contact resistances can have a large impact on the current required

to clear debris with the grid clear circuit. The thermal contact resistance depends on the contact area and the contact pressure. Unless the debris is clamped or welded to the grid, the thermal contact resistance is large enough that radiation dominates the heat loss and the heat transfer across the contact points can be neglected. The electrical contact resistance must be low ($\sim 1 \Omega$ or less) in order to drive current through the debris with the low voltage (~ 35 V maximum) discharge supply.

The expression for the current in Equation 2 is given in terms of cross-sectional area, perimeter around the cross-section, grid gap and length of the debris and can be used for different geometries. The smallest perimeter for a given cross-sectional area is obtained with a circular cross-section. The largest perimeter for a given cross-sectional area is obtained with a thin foil. It is possible that late in life a large sheet of molybdenum could spall off the screen grid and short to the accelerator grid; if this should occur it is unlikely that the short could be cleared with the NEXT grid clear capabilities. Therefore we are interested in smaller debris and this will typically have to go through at least one of the optics holes to lodge between the grids, thus we are interested in thin foils that have widths that are smaller than a typical ion optics aperture dimension.

For the experimental work circular cross-section wires were used, while it is expected that thin flakes such as the ones found at the conclusion of the NEXT 2 khr test would be more likely in applications. Therefore it is of interest to estimate the difference in the current that is needed to clear debris caused by different geometries of a given cross-sectional area. A simple formula can be derived by assuming that the heat transfer across the contact points can be neglected compared to radiation heat transfer. Under these conditions the ratio of current needed to clear a foil to that needed to clear a wire is

$$\frac{I_f}{I_w} = \sqrt{\frac{2A_{cs} + LP_{csf}}{2A_{cs} + LP_{csw}}} \quad (3)$$

where,

A_{cs} - cross-sectional area for both foil and wire (m^2)

I_f - current needed to clear foil (A)

I_w - current needed to clear wire (A)

L - length for both foil and wire (m)

P_{csf} - perimeter around foil cross-section (m)

P_{csw} - perimeter around wire cross-section (m)

For the wire the perimeter is

$$P_{csw} = \pi d$$

and for the foil it is

$$P_{csf} = 2(w + t)$$

and the cross-sectional area is given by

$$A_{cs} = \frac{\pi}{4} d^2 = wt$$

where,

d - wire diameter (m)

t - foil thickness (m)

w - foil width (m)

Using this, the ratio for the two pieces of debris becomes

$$\frac{I_f}{I_w} = \sqrt{\frac{\frac{\pi}{4} d^2 + L(w + t)}{\frac{\pi}{4} d^2 + L \frac{\pi}{2} d}}$$

Molybdenum flakes were found in the NEXT discharge chamber after the 2 khr test [2]; these were large enough to span the gap between the grids. The dimensions of a typical flake is $w=0.45$ mm, $L=0.7$ mm and $t=0.03$ mm [7]. The diameter that corresponds to the cross-sectional area is $d=0.13$ mm. Using these values for w and d , the current required to clear the thin foil (flake) is 1.5 times that required to clear a wire of the corresponding diameter.

In addition to the contact resistances and geometric factors, material properties—including thermal conductivity, emissivity and electrical resistivity—are needed to estimate the current required to clear a given piece of debris. Information with these and additional property values [8, 9] are presented in Table 1.

Table 1. Physical Properties of Materials

Material	Aluminum	Copper	Molybdenum	Tantalum	Tungsten
Emissivity (dimensionless)	0.03-0.18	0.07-0.22	0.06-0.18	0.14-0.30	0.23-0.28
Thermal Conductivity (W/m/K)	237	401	138	58	174
Resistivity (Ohm-m)	2.65E-08	1.68E-08	5.35E-08	1.31E-07	5.29E-08
Melting Point (K)	933	1358	2896	3290	3695
Boiling Point (K)	2792	2840	4912	5731	5828
Heat of Vaporization (KJ/mol)	293	300	598	743	824
Heat Capacity (J/kg/K)	900	380	250	140	130
Mass Density (kg/m ³)	2700	8920	10280	16650	19250

In order to obtain an idea of the variation in the magnitude of current required to clear various sizes and types of debris, the Equation 1 was solved using the data in Table 1. Although variables—such as emissivity and resistivity—vary with temperature, they were assumed to be constant; the thermal contact resistance was held constant at a value of 10^7 K/W and the electrical contact resistance was set to 0Ω . The grid clear circuit

will be used in space where the pressure is low enough that the metal will transition from solid to vapor phase without becoming liquid. The temperature at which this phase transition occurs depends on the pressure and will be slightly below the melting temperature. For this simplified analysis we will use the melting temperature instead of the sublimation temperature and recognize that this will result in overestimating the current.

As a first example it is assumed that the wire just bridges the gap (it does not extend beyond the gap). Although a more exact analysis can provide more refined estimates, the curves in Figure 1 show that there is a large dispersion in the current needed to clear wires of different materials. The current needed to vaporize a given material is greater if its melting temperature is higher. The materials in Figure 1 are seen to follow this trend; aluminum with the lowest melting point requires the lowest current while tungsten with the highest melting point requires the largest current to clear a give size wire.

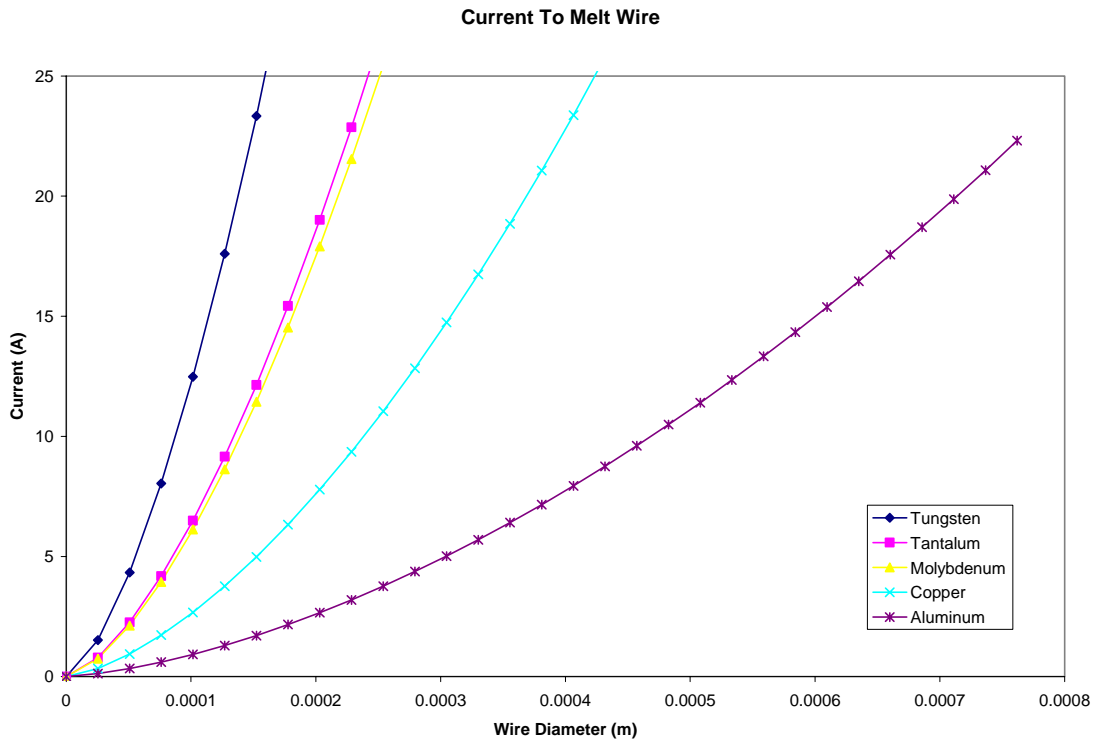


Figure 1. Comparison of Current Required to Clear Wire for Various Materials.

The currents given in Figure 1 are the current required to reach the vaporization temperature; additional power is needed to vaporize the material so higher currents are needed. The length of time required to clear debris of a given size depends on the current. This is illustrated in Figure 2, for a 0.13 mm diameter molybdenum wire using the same assumption used to generate Figure 1. To vaporize the wire in 60 seconds requires 1.17 times the current required to reach the vaporization temperature; while clearing the wire in 5 seconds takes 2.4 times the minimum current.

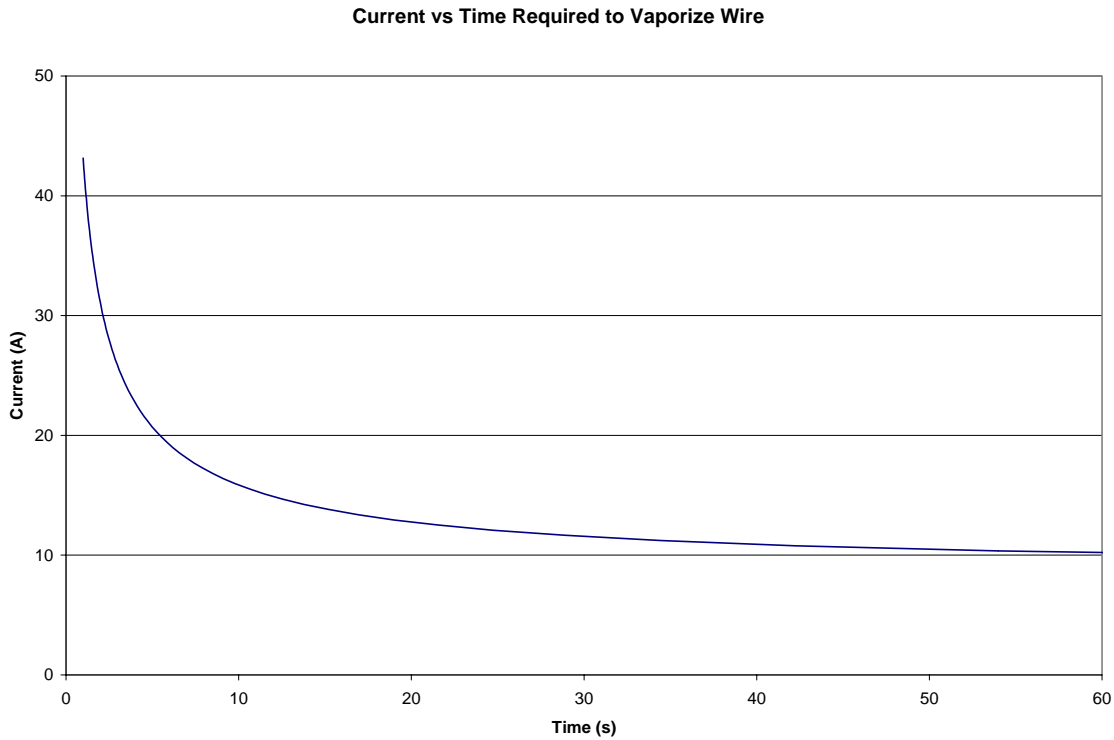


Figure 2. Current as a Function of Time Required to Vaporize Molybdenum Wire

To investigate the effect that electrical contact resistance has on the current required to reach the vaporization temperature, the same assumption for the other variables were used to generate Figure 1 were used for molybdenum. For the model it is assumed that half of the joule heating generated at the contact points goes into the grids and the other half is deposited in the wire. Shown in Figure 3 are the current required to reach the vaporization temperature when the contact resistance is 0 and when it is 0.1Ω . An electrical contact resistance of 0.1Ω is larger than the resistance of the wire so it dominates the heating resulting in a much lower current needed to vaporize the wire. Obviously the current needed to vaporize debris is very sensitive to variations in electrical contact resistance. In an ion thruster operating in space there is virtually no control over the contact resistance; therefore, it is difficult to predict the current required to clear a given size debris. The current required to vaporize a wire decreases with increasing electrical contact resistance until the resistance becomes high enough ($\sim 100 \Omega$ or greater) that the discharge supply can no longer provide the voltage required drive the current through the debris; this results in the inability to heat the wire so the fault will not be cleared.

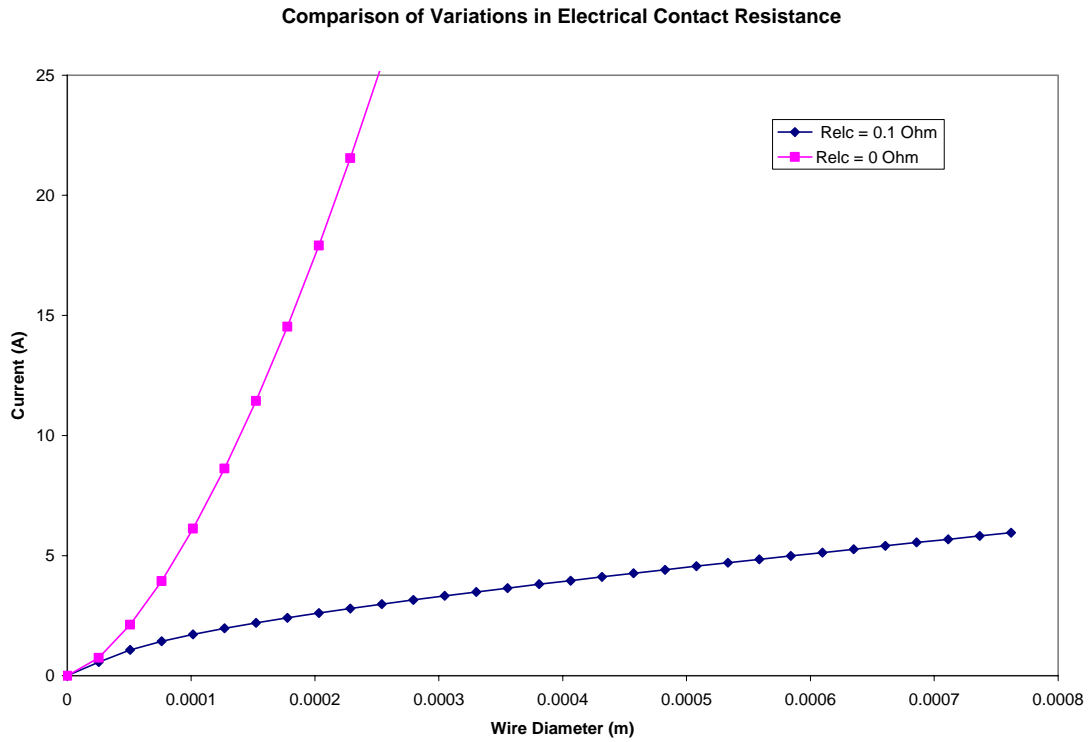


Figure 3. Variation in Vaporization Current with Electrical Contact Resistance

The current required to reach the vaporization temperature is also dependent on the length of the debris. As seen from the curves in Figure 4, the current has approximately the square root dependence on length as predicted by Equation 2. This comparison was made for molybdenum using the values found in Table 1 and assuming an electrical contact resistance of 0.1Ω .

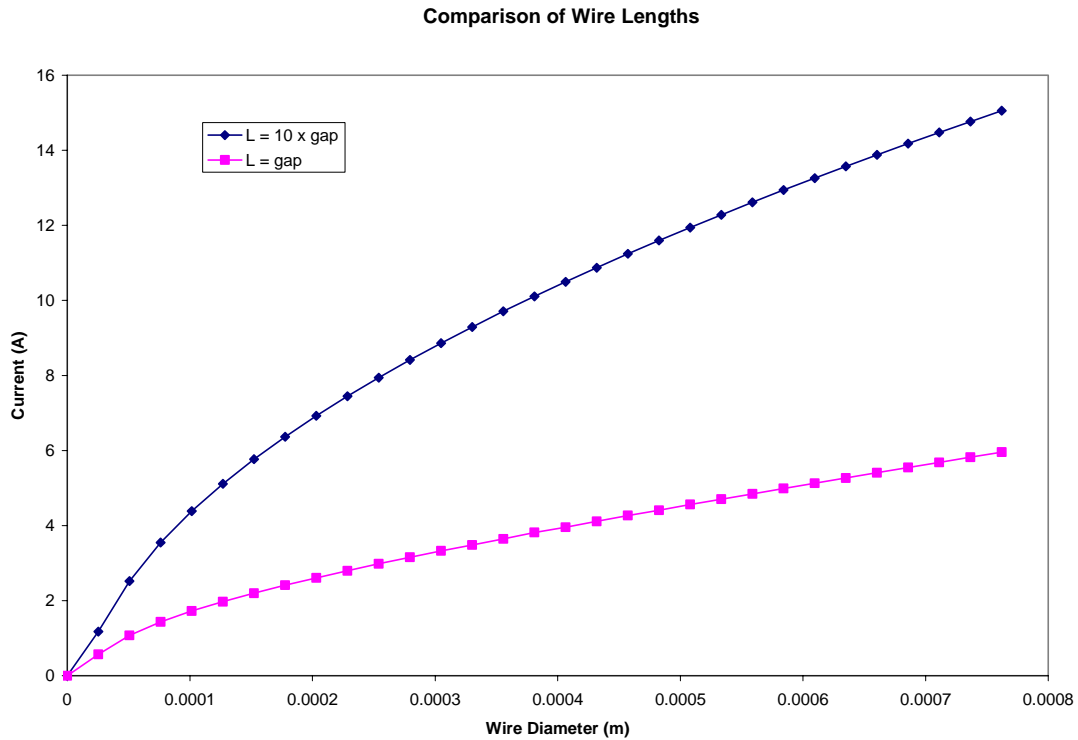


Figure 4. Variation in Vaporization Current with Wire Length

A simple thermal model of the grid clear process was used to investigate the sensitivity of various parameters on the current required to clear debris that could short the screen and accelerator grids in an ion thruster. In addition to geometric and material properties, the current was found to be quite sensitive to contact resistance. Because there is little control over these parameters there is a large dispersion in the current required to clear a grid short. In addition to the theoretical analysis, experimental work was performed to gain further insight into the capabilities and limitations of the grid clear process.

Experimental Results

Two types of grid clear circuits were investigated. Most of the work was performed using a low voltage, high current power supply to clear debris shorting molybdenum grids. Toward the end of the experimental program, some preliminary work was performed using high voltage capacitors to discharge energy into the debris.

The experimental investigation was conducted to determine the size of wires of various materials that could be cleared. The investigation showed that the contact resistance between the wire and the grids is an important parameter; if it is too large, the low voltage power supplies cannot drive current through the wire and the wire is not cleared. Although the low voltage supply sees an open circuit, the high voltage beam supply of an ion thruster will arc through the contact resistance and see a short. The high voltage supply is designed to trip off if there is a short, so the wire must be cleared before the high voltage, needed to produce thrust, can be applied across the grids.

A variety of materials—molybdenum, aluminum, steel, copper, tantalum, and tungsten-25% rhenium—were tested in the configuration shown in Figure 5. A wire was threaded through holes in sections of screen grid and accelerator grid material (molybdenum). The grid sections and the material bridging the two segments were housed in a vacuum chamber that was pumped down into the 10^{-4} Pa (10^{-6} Torr) range. Although the grid clear circuit is designed to use the discharge power supply (35 V, 24 A) to drive current through the wire, the experiments were conducted using a more robust 50 V, 60 A power supply.

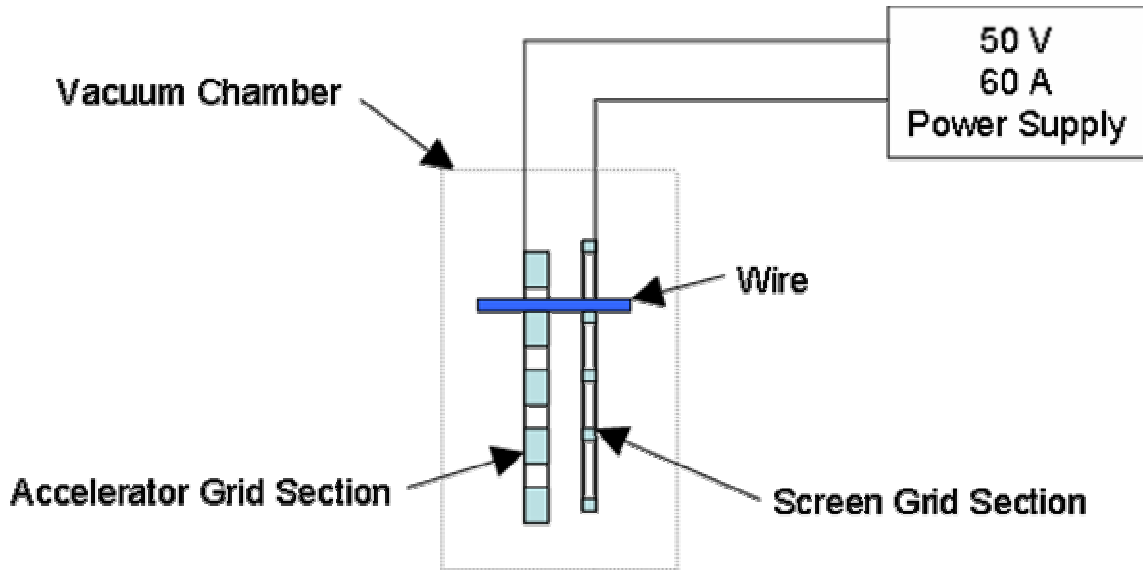


Figure 5. Grid Clear Experimental Setup

Once the vacuum system was pumped down the power supply was turned on and an attempt to drive current through the wire was made. Some grid clear attempts were unsuccessful; however for the successful cases, the current required to clear wires of various materials and diameters is shown in Figure 6. There is scatter in the current required to clear the wire; this scatter is not unexpected since the details of how the material vaporizes differs between cases due in large part to case-to-case variations in the contact resistance between the wire and the grids.

As seen in Figure 6, wires of various materials ranging in size from 1.3×10^{-3} m and 5.1×10^{-3} m diameter were used in the experiments. Wires up to 2.5×10^{-3} m in diameter could be cleared with less than 24 A for most materials. The exception was molybdenum; molybdenum wires with 1.3×10^{-3} m diameter could be cleared but 2.5×10^{-3} m diameter molybdenum wires required over 24 A to clear. There is a large scatter in the current required to clear aluminum wires; some of the 3.2×10^{-3} m diameter wires were cleared with less than 24 A however in some cases more current was required to clear the wire.

Although each of the materials tested is a potential contaminant from the launch environment, the grid material—molybdenum—may be most likely to cause a grid short in NEXT. As discussed previously molybdenum flakes were found in the discharge chamber after the 2,000 hour NEXT wear test. The cross-sectional area of the flake is within 10% of the cross-sectional area for the 1.3×10^{-3} m diameter molybdenum wires that were cleared at currents between 3.4 and 6.4 A. Assuming that the contact resistance

is the same for a foil and a wire and using the previously estimated geometric factor of 1.5, it is estimated that a current of between 5.1 and 10.3 A would be needed to clear the molybdenum flake found in the discharge chamber after the NEXT 2 khr test.

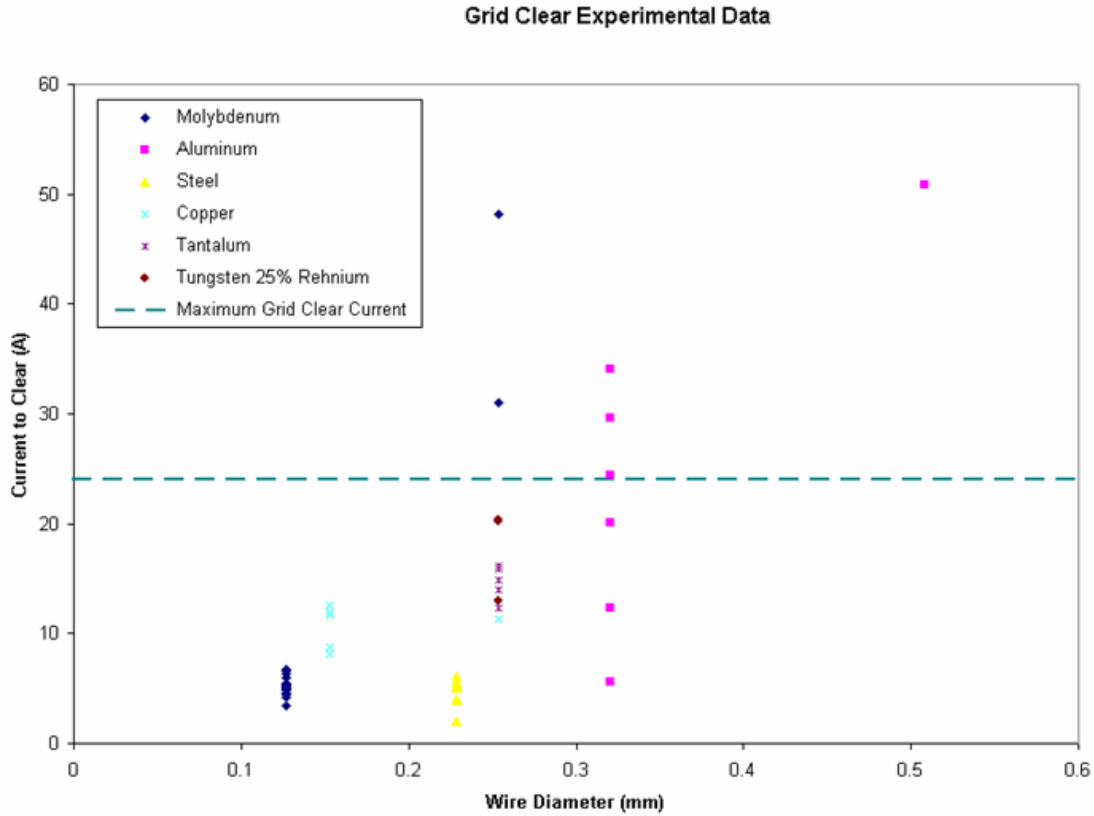


Figure 6. Grid Clear Test Data

As noted previously, not all grid clear attempts were successful. In a significant number of attempts the contact resistance was so high that it was not possible to drive current through the wire; the fraction of attempts that were successful for each material tested are shown in Figure 7. The highest success rate was achieved with tantalum where the wire cleared about 70% of the time. Molybdenum and steel cleared between 50 and 60% of the time, while aluminum, copper and tungsten-25% rhenium cleared in about 30% of the attempts.

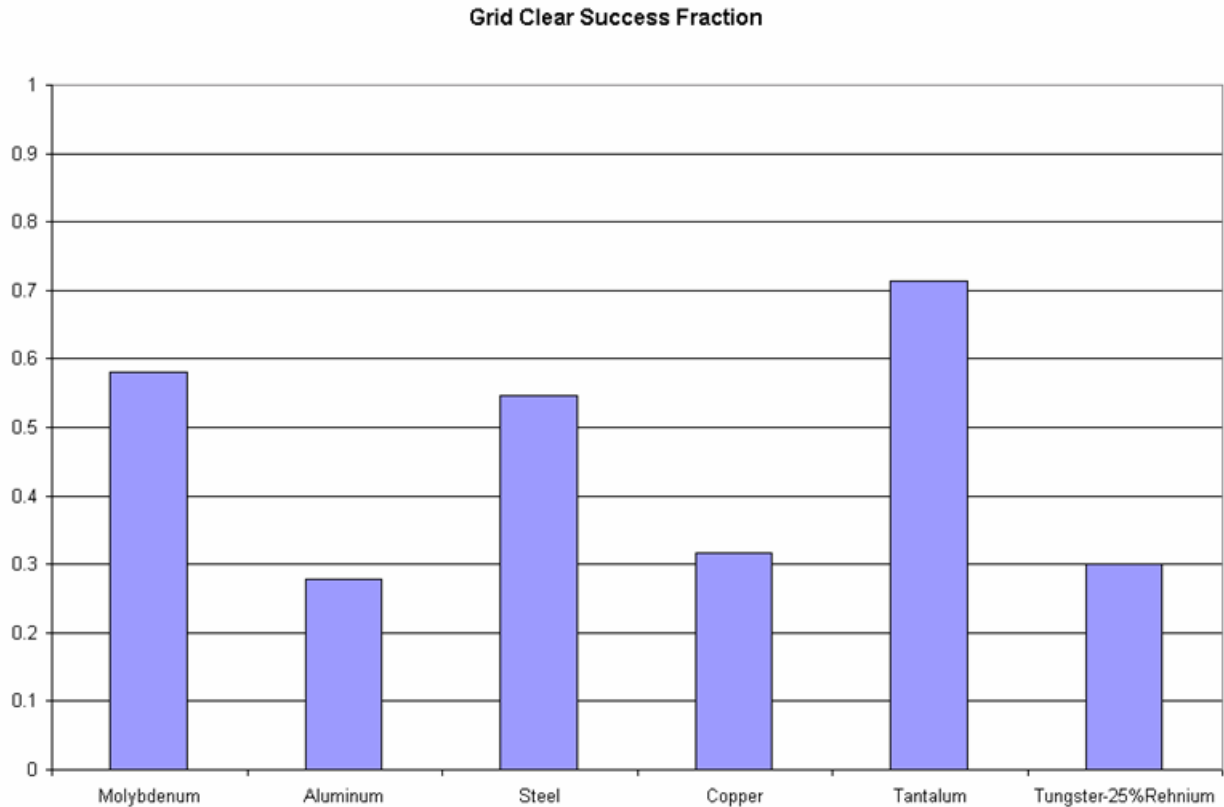


Figure 7. Fraction of Grid Clear Attempts Resulting in Wire Being Cleared

These tests were conducted with gravity used to hold the wire in place on the grid segments. Other tests were conducted with the wire clamped in place with alligator clips; in these cases the contact resistance was low and the wires were cleared. Unfortunately it is unlikely that debris will be clamped to the grids in space and therefore such tests are not considered to be representative of what will occur in space.

One method which might provide better contact between the debris and the grids is turning on the high voltage beam supply. The recycle circuit will turn the supply off but some energy may be deposited into the contact region and “tack” the debris into place. This is unlikely to work if the discharge is on because the plasma will provide the electrical contact between the grids and the debris and little energy will be deposited in the contact region. However, if there is no plasma, the power will be deposited in the contact region and this may provide a low electrical contact resistance.

Because of the inability to drive current through the wires in a large fraction of the cases and alternative grid clear circuit using capacitors was investigated. Prior work using a capacitor circuit was described by Beebe in reference [10]. In that work energy stored in a high voltage capacitor was discharged through chips of debris that had been dropped between the grids; in most cases the debris was cleared. It is not clear exactly what “dropped” means, but presumably the debris was wedged between the grids; if this is the case, there was likely good electrical contact between the grids and the debris.

Some preliminary testing using an existing pulse power supply to discharge capacitors through wires was performed; the experimental set up is shown in Figure 8. The circuit had a high voltage capacitor (1 kV) used to initiate an arc and low voltage capacitors (150 V) to sustain the arc; the capacitors could store up to 4.5 Joules which could be used to clear the wire. In these experiments, 1.3×10^{-3} m diameter molybdenum wire could be cleared if it was clamped using alligator clips. However if gravity was used to hold the wire in place, the circuit would cause an arc but the wire would not clear. The wire did not show signs damage after these clear attempts, so it does not appear that discharging the capacitors will work unless the wire can be welded or clamped in place. Only a few cases were run using this supply and further work is needed to verify and reproduce this result. The additional complexity and mass associated with adding a capacitor circuit to the PPU tends to make it unattractive unless such a circuit can be shown to give a high probability of clearing debris; therefore, it is unlikely that such a circuit will be implemented.

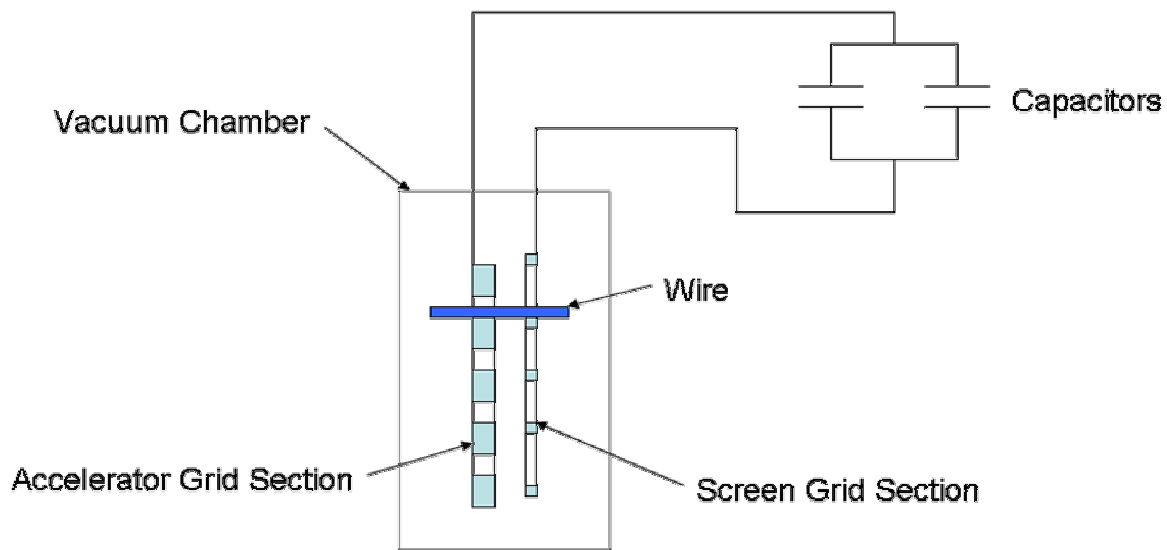


Figure 8. Capacitor Grid Clear Circuit

Conclusions

Screen to accelerator grid shorts have occurred several times on NASA spacecraft using ion thrusters. Methods devised to mechanically remove the debris causing the short where successful in many but not all cases. To provide additional options for dealing with grid shorts, grid clear circuits were implemented on NSTAR and will be implemented on the NEXT PPU. The best way to clear a grid short is to mechanically remove the debris and, if practical, methods to do this should be attempted prior to using the grid clear circuit. Theoretical and experimental work to investigate the capabilities of a grid clear system for the NEXT program was conducted. Based on the results of this testing, the discharge power supply current capability is large enough to clear debris such as the flakes found in the discharge chamber after the NEXT 2 khr test. However there is

roughly a 50% chance that debris that shorts out the high voltage beam supply may not be cleared.

References

1. Polk, J. E., Kakuda, R. Y., Brophy J. R., Katz, I., Anderson, J. R., Rawlin, V. K., Patterson, M. J., Sovey, J., Hamley, J., "Demonstration of the NSTAR Ion Propulsion System on the Deep Space One Mission," IEPC-01-075, 27th International Electric Propulsion Conference, Pasadena, CA, October 2001.
2. Soulas G. C., Kamhawi, H., Patterson, M. J., Britton, M. A., Frandina, M. M., "NEXT Ion Engine 2000 Hour Wear Test Results," AIAA 2004-3791, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, July 2004.
3. Kerslake, W. R., Ignaczak L. R., "Development and Flight History of SERT II Spacecraft," AIAA 92-3516, 28th AIAA/JSASS/DGLR 15th International Electric Propulsion Conference, Las Vegas, NV, April 1981.
4. Kerslake, W. R., Ignaczak L. R., "SERT II Extended Flight Thruster Experiments," AIAA 92-3516, 28th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN, July 1992.
5. Polk, J. E., Kakuda, R. Y., Anderson, J. R., Brophy, J. R., Rawlin, V. K., Patterson, M. J., Sovey, J., Hamley, J., "Performance of the NSTAR Ion Propulsion System on the Deep Space One Mission," AIAA 2001-0965, 39th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2001.
6. Goodfellow, K. D., Ganapathi G. B., Stocky, J. F., "Experimental and Theoretical Analysis of the Grid Clearing Capabilities of the NSTAR Ion Propulsion System," AIAA 99-2859, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Los Angeles, CA, July 1999.
7. Benson, S., "Approx_Flake_Geometry.doc," Private Communication, April 2004.
8. Emissivity data obtained from:
<http://www.omega.com/literature/transactions/volume1/emissivitya.html>
9. All properties except emissivity data obtained from:
<http://en.wikipedia.org/wiki>
10. D. D. Beebe, S. Nakanishi, R. C. Finke, "Electric Arc Discharge Damage to Ion Thruster Grids," NASA TM X-3044, May 1974.