Abstract

The accelerator grid in two-grid ion optics systems is subject to sputter erosion by charge exchange ions created in the ion beam. One potential engine failure mode is accelerator grid structural collapse due to wear. A probabilistic model of accelerator grid service life in which uncertainties about input parameters are treated quantitively reveals that service life with acceptable failure risk is shorter than deterministic analysis using nominal parameter values suggest. The NASA 30-cm ion engine with molybdenum grids has a very short service life at 4.65 kWe input power, although derating the thruster to 2.3 kWe or using carbon grid materials can significantly increase service life. Uncertainties about the eroded geometry at failure, the net sputter yield and the impingement ion current in space are the primary risk drivers. Efforts to acquire more information about these drivers and design improvements that decrease the sputter erosion and the required service life have been initiated.

Introduction

Because of their high specific impulse and high efficiency, ion engines offer significant savings in spacecraft mass and, in certain cases, trip time. They are being considered for use in a number of earth orbital applications including stationkeeping, orbit-raising and repositioning as well as in planetary missions. However, because they are low thrust devices, very long periods of operation are required to achieve useful total impulses. During a typical mission an ion engine would be required to operate reliably for thousands of hours. The primary failure mechanism identified in two-grid ion systems is sputter erosion of the downstream grid by ion impingement. A description of the physical process involved in grid erosion, a general approach to assessing service life probabilistically, and an application of this approach to ion engine accelerator (accel) grid erosion are presented in the following.

Accelerator Grid Erosion Phenomena

A diagram of the electrode system in a two-grid ion thruster is shown in Fig. (1). Discharge ions produced upstream are drawn through a sheath that forms at the entrance to the apertures in the screen grid and are accelerated by an axial electric field in the inter-electrode gap. A radial electric field in this region focusses the individual ion beamlets. The accelerator grid is biased negative relative to the ambient space plasma potential to prevent electrons that neutralize the primary ion beam downstream of the engine from backstreaming into the discharge chamber. This creates a negative potential well which decelerates the primary ion beamlets. The beamlets are also subject to radial electric fields in this region which cause them to diverge.

The accel grid may be impacted directly by primary beam ions, although this source of impingement current can be practically eliminated by proper design and operation of the ion optics. In addition, the
not have sufficient energy to escape from the potential well and are therefore drawn to the accel grid. Experiments and particle simulations indicate the existence of a slight potential hump downstream of the deceleration zone in the beamlets. In contrast, the potential appears to decrease monotonically toward the accel grid between adjacent beamlets [1,2]. Therefore, a fraction of the slow ions generated in the weak electric field downstream of the neutralization plane can be collected if their velocity is back toward the grid when they are created. In space, most of the neutrals emitted from the discharge chamber have velocities directed away from the grids, so very few of the charge exchange ions created downstream of the deceleration zone will be collected [3]. In addition, the density decreases rapidly in the axial direction, so fewer ions are generated downstream. However, in ground test facilities the ambient neutrals have an isotropic velocity distribution and a significant quantity of the ions created downstream will impinge on the accel grid. In fact, the charge exchange ions generated from the background gas appear to dominate the impingement current in ground-based tests [3,1].

The impingement ions follow trajectories that are dictated by their origin and the structure of the potential near the grid. Particle simulations show that most of the ions impinge on the downstream face of the electrode and are focussed into the central part of the webbing between holes by the radial electric fields of adjacent beamlets [2,4]. The characteristic erosion pattern observed on the downstream face of the accel grid in long duration tests reveals the damage caused by the impingement ions. The photograph in Fig. (2), taken after a long duration test described in [5], shows a series of grooves between holes forming a hexagonal pattern with deeper pits at the intersection points between three holes where the impingement current density peaks.

The mass loss in the pits and grooves is caused by sputtering, a collisional process in which incident ions can eject surface atoms. Sputtering occurs only when the incident ion energy exceeds a certain threshold and sufficient energy is transferred in the collision to overcome the surface binding forces. At energies near the threshold the ejected atoms are usually directly involved in collisions with the incident ion, although at higher energies they may be part of a collision cascade initiated by the incident ion.
Sputtering is characterized by the yield, which is defined as the expected number of atoms ejected per incident ion. The yield is a function of the ion energy, the masses of the ions and target atoms, the surface binding energy and the incident angle, reaching a maximum value at a particular oblique angle \[ \theta \]. It does not generally depend on the current density, but is a function of the total dose. This is primarily due to changes in the geometry as the grid wears. Initially the impingement ions are normally incident on a flat surface, and most of the sputtered atoms escape. As the grooves form, the incident angle may increase, causing the absolute yield to rise. However, redeposition of sputtered atoms in the groove can reduce the net yield \[ \Delta \text{yield} \]. As the pits and grooves penetrate the accel grid, sputtered atoms can escape upstream through the grid, as well as downstream.

When the pits wear completely through the grid, the ions incident in that region are either reflected in the interelectrode gap and strike the upstream face or are focussed along the channels. Grid penetration then proceeds along the channels as shown in Fig. (2) until complete structural failure occurs. Loss of grid structural integrity as a result of sputter erosion in the characteristic hexagonal groove pattern is one potential failure mechanism. Loss of strength caused by grid erosion can cause shorts as individual ringlets or sections of the accel grid collapse and bridge the interelectrode gap under the electrostatic stresses. Even if shorts are avoided, it becomes impossible to properly focus the primary ions and prevent electron backstreaming as large holes in the grid form.

Accelerator grid sputter erosion can be minimized by proper environmental conditions and thruster operation, but is unavoidable at some level. Uncertainty in our description of the physical processes of grid erosion in addition to their intrinsic variability makes it impossible to calculate grid life exactly. Relying on extensive testing to characterize grid life with high confidence would be prohibitively costly and time-consuming. It is therefore useful to model accelerator grid erosion probabilistically, using available information from tests and knowledge of the physical processes that lead to failure.

### Probabilistic Service Life Assessment

In the assessment of accel grid service life presented here, test information and analytical models are used in a statistical structure in which uncertainties about failure prediction are quantitatively treated. This probabilistic analysis can be performed with the information available at any particular time to obtain a probabilistic estimate of service life that is warranted by what is known about a failure mode at that time. This probabilistic method is applicable to failure modes which can be described by analytical models of the failure phenomena, even when such models are uncertain or approximate.

By conducting service life sensitivity analyses probabilistically, sources of unacceptable failure risk can be identified and corrective action can be delineated. Design revision, additional characterization of environments, improvement of analytical model accuracy, and improved characterization of material behavior are among the options for controlling risk that can be quantitatively evaluated by probabilistic sensitivity analyses. Using sensitivity analysis results, test and analysis programs focused on acquiring information about the most important risk drivers can be
defined, enabling limited financial resources to be allocated more effectively to achieve life goals.

Probabilistic service life assessment can be employed in the design and development process to avoid compounding design conservatisms and margins that unnecessarily increase cost or weight. Probabilistic analysis is of particular value when uncertainties exist about important governing parameters or when design conservatism and redundancy used in the past must be reduced to meet more stringent cost, weight, or performance requirements.

Information from test or service experience can be combined with information from analytical modeling to estimate failure risk quantitatively using the approach shown in Fig. (3). Probabilistic failure modeling is based on available knowledge of the failure phenomenon and of such governing parameters as ion impingement current and sputtering yield. The prior failure risk distribution of Figures (3) and (4) is derived from probabilistic failure modeling. This prior distribution can be modified to reflect available success/failure data in a Bayesian statistical analysis. The probabilistic service life assessment approach shown in Figures (3) and (4) is discussed in detail by Moore, et al. [8,9,10].

Experience includes physical parameter information in addition to success/failure data. Information about physical parameters can be derived from measurements taken during tests or service, from analyses to bound or characterize parameter values, from applicable experience with similar systems, or from laboratory tests. Measurements of physical parameters used in analytical modeling, e.g., grid impinge-

![Figure 3: Probabilistic failure risk assessment.](image)

![Figure 4: Probabilistic failure modeling.](image)
A driver for which uncertainty is to be considered must be characterized by a probability distribution over the range of values it can assume. That distribution expresses uncertainty regarding specific driver values within the range of possible values. A driver probability distribution must represent both intrinsic variability of the driver and uncertain knowledge or limited information on which to base the driver characterization.

Stochastic drivers are characterized by using the information that exists at the time of analysis. If driver information is sparse, the probabilistic characterization of such a driver must reflect that sparseness. If extensive experimental measurements have been performed for a driver, its nominal value and characterization of its variability can be inferred directly from empirical data. However, if little or no directly applicable empirical data is available, analysis to characterize a driver or experience with similar or related systems must be used. Driver distributions must not overstate the precision implied by the available information.

Some general guidelines for characterizing stochastic drivers have emerged from case studies conducted to date as given in Moore, et al. [8,9,11]. For drivers which have physical bounds, such as controlled dimensions or parameters with physical upper limits, the Beta distribution parameterized with location, shape, and scale parameters has been successfully used. If only bounds are known, a Uniform distribution is appropriate. For a driver whose variation can be thought of as due to the combined influence of a large number of small independent effects, the Normal distribution can be used. Past experience in characterizing a particular driver such as a material property may suggest the use of a particular distribution, for example, Weibull, Normal, or Lognormal.

A hyperparametric structure for driver distributions has been found useful in describing available information about a driver. For example, to characterize a driver, information from engineering analysis might be used to establish upper and lower bounds. In order to capture the fact that the mean value may not be known with certainty, the mean value may be represented by a Uniform distribution between the upper and lower bounds. This Uniform distribution is the hyperdistribution which represents uncertainty about the true mean value, and its parameters are the associated hyperparameters.

Monte Carlo simulation has been used as the principal computational method in probabilistic failure modeling because it is a general method that can be used with failure models of any complexity. Continually increasing computer power due to improving hardware and software is steadily expanding the practical application of Monte Carlo simulation. Efficient Monte Carlo techniques can be used to reduce the number of simulation trials when computational time is an issue. Certain analysis methods such as plasma particle simulation models, may be too computationally intensive for practical use in Monte Carlo simulation. However, the output of these models can be represented as response surfaces over the range of variation of significant parameters, see Moore, et al. [9,10]. The uncertainties of response surface representations must be treated as drivers if significant.

Alternative computational methods, for example, FORM/SORM, see Madsen, et al. [12], may fail to give accurate results for problems in which significantly nonlinear models are employed and driver uncertainty is large. Computational methods are discussed further by Moore, et al. [11,10].

Accelerator Grid Erosion Analysis

The deterministic erosion model used in this analysis describes the mass loss due to ion sputtering and is imbedded in the Monte Carlo simulation procedure outlined in Fig. (5). This model expresses the time to initial structural failure of the grid as a function of drivers which may be either deterministic or stochastic. The drivers consist of geometry, current and accelerator grid voltage, material properties and accuracy factors which account for uncertainties in the analysis.

A basic structural unit of the grid can be defined by the triangular region shown in Fig. (6). End of life is defined as the point at which the first structural unit is divided in two by erosion in the central channel. This will generally occur first in the center of the grid where the erosion rate is the highest. This failure criterion can be expressed quantitatively in terms of the fractional mass loss in the structural unit by the relationship

\[ \frac{M_e}{M_{su}} = \left( \frac{M_e}{M_{su}} \right)^f. \]  

(1)

The parameter \((M_e/M_{su})_f\) is the allowable fractional
mass loss before the unit is cut in two, and is a function of the grid geometry and the geometry of the channel at failure. \( M_e \) is the eroded mass in the channel, and \( M_{su} \) is the initial mass of the structural unit,

\[
M_{su} = \rho_s A_{su} t,
\]

where \( \rho_s \) represents the density of the grid material, \( A_{su} \) is the initial structural unit webbing area and \( t \) is the initial grid thickness. The webbing area is given by the expression

\[
A_{su} = \frac{\sqrt{3}}{12} l_{cc}^2 - \frac{\pi d_h^2}{24},
\]

where \( l_{cc} \) is the center-to-center hole spacing and \( d_h \) is the hole diameter.

The fractional mass loss averaged over a structural unit after a cumulative operating time \( \tau \) due to sputtering from singly charged ions is given by the expression

\[
\frac{M_e}{M_{su}} = \frac{J_{a, su} \tau Y_{net} m_g}{e M_{su}},
\]

where \( J_{a, su} \) is the average ion impingement current in the structural unit, \( Y_{net} \) is the average net sputter yield in atoms per incident ion, \( m_g \) is the mass per atom of grid material and \( e = 1.6 \times 10^{-19} \) C is the fundamental electron charge. These two equations define the time to structural failure, given proper specification of the drivers: grid geometry, geometry of the channel at failure, impingement current \( J_{a, su} \) and the net sputter yield \( Y_{net} \).

Although there have been significant advances in modeling the local distribution of impingement ion flux and energy in the erosion pattern using particle simulation methods [2,3], these codes are too computationally intensive to include in the failure simulation. The failure model has therefore been expressed as approximate relationships in terms of observable parameters averaged over the structural unit.

The failure criterion can be defined by the expression

\[
\left( \frac{M_e}{M_{su}} \right)_f \approx \frac{L_c A_c}{t A_{su}},
\]

where \( A_c \) represents the cross-sectional area of a
channel which just divides the structural unit. This channel shape is assumed to be constant along the the length \( L_c \), as shown in Fig. (6). The effective channel length is approximated by

\[
L_c = \frac{\sqrt{3}}{6} l_{cc}.
\] (6)

Use of this approximation slightly overestimates the mass lost at the apex of the structural unit from a channel of uniform cross section. This is not expected to significantly bias the life calculations, because in practice much of the impingement ion current generated by three adjacent beamlets is focused into the central region (the intersection of the channels bisecting the three structural units) and causes more severe erosion than in the rest of the channels. The channel cross-sectional area is modeled as

\[
A_c = \frac{2}{3} \lambda_s w_c t,
\] (7)

where \( w_c \) is the width of the channel at the downstream surface. This expression represents a parabolic cross section modified by the shape factor \( \lambda_s \), which describes uncertainty about the channel shape. The channel width can be expressed in the form

\[
w_c = l_{cc} + (l^2_{cc} - 12\alpha A_{su}/\sqrt{3})^{1/2},
\] (8)

where \( \alpha = A_s/A_{su} \) is the eroded area fraction, the projected area of the erosion groove \( A_s \) compared to the structural unit webbing area. Equations (2) to (8) permit the failure criterion in Eq. (1) to be expressed in terms of the grid geometry parameters \( d_h, t \) and \( l_{cc} \) and the channel shape parameters \( \alpha \) and \( \lambda_s \).

The current in the structural unit in the center of the grid (which is subject to the highest impingement current) can be expressed as the product of the structural unit area and the average local impingement current density \( j_{a,peak} \) (ignoring local current density variations due to the discrete ion beamlets),

\[
J_{a,su} = j_{a,peak} A_{su} = \left( \frac{J_a}{J_b} \right) \frac{J_b A_{su}}{A_b (1 - F_{oaa})(FP)_a}
\] (9)

where \( J_a/J_b \) is the ratio of total impingement current to beam current, \( A_b \) is the active beam area, \( F_{oaa} \) is the open area fraction of the accel grid and the impingement current density flatness parameter is defined as

\[
(FP)_a = \frac{J_a}{A_b (1 - F_{oaa}) j_{a,peak}}.
\] (10)

The impingement current density flatness parameter can be equated to the flatness parameter describing the beam current density distribution,

\[
(FP)_a = (FP)_b,
\] (11)

if the ratio of local average current densities \( j_a/j_b \) is constant over the entire grid. The assumption that \( j_a \) is proportional to \( j_b \) locally is valid for charge exchange ions if they strike the accel grid at radial and azimuthal positions close to those where they were created. This should be satisfied in space, where the impingement ions originate inside the deceleration region and the local electric fields guarantee that they intercept the grid near their point of origin. In ground test facilities, however, the majority of the impingement ions are created downstream of the neutralization plane and may drift to radial and azimuthal locations very different from where they were created before being captured by the accel grid. This has the effect of making \( (FP)_a \) somewhat larger than \( (FP)_b \). The assumption that the constant of proportionality between \( j_a \) and \( j_b \) does not vary over the grid is accurate only if the axial neutral density profile and the effective length from which charge exchange ions are drawn do not vary with radial position.

The average net sputter yield is assumed to be proportional to the yield at normal incidence,

\[
Y_{net} = \lambda_Y Y_{\theta=0},
\] (12)

where \( \lambda_Y \) is a stochastic factor representing variations of the average net yield from the yield at normal incidence due to dose effects (primarily redeposition of sputtered material and oblique incidence of bombarding ions). The available yield data for krypton and xenon incident on molybdenum can be fit well with an empirical relationship of the form

\[
Y_{\theta=0} = a E_i^c \left( 1 - \frac{E_0}{E_i} \right)^d \left( 1 + \frac{m_i E_0}{E_i} \right)^{1/d},
\] (13)

where \( E_i \) is the incident ion energy, \( E_0 \) is the threshold for sputtering, and \( m_i \) is the atomic mass of the
incident ion. The data for xenon on carbon can be represented by a linear relationship of the form

$$Y_{s=0} = a + bE_i. \quad (14)$$

The parameters $a$, $b$, $c$ and $d$ can be estimated from the data for sputtering yield as a function of incident ion energy and mass. In calculating accel grid life, the incident ion energy is given by the relationship,

$$E_i = eV_a, \quad (15)$$

where it has been assumed that all of the ions strike the grid with the maximum possible energy, given by the accel grid potential $V_a$. This is appropriate for testing in ground-based facilities where most of the impingement ions originate outside of the potential well surrounding the accel grid, but is a conservative assumption for space conditions where many of the ions created inside the deceleration zone will not fall through the entire potential.

With the equations discussed above, the complete model of grid life can be represented in terms of the geometry drivers $d_h$, $l_{cc}$, $F_{aba}$, $A_5$ and $a$, the drivers representing operating conditions $(J_d/J_b)$, $(J_b/F_P)b$ and $V_a$, the material properties $a$, $b$, $c$, $d$, $E_0$, $g_s$, $m_g$ and $m_1$, and the drivers characterizing model uncertainty $\lambda_x$ and $\lambda_y$.

Calculations of Accelerator Grid Life

Four test cases were examined using the model presented above. The deterministic model of grid life was used to calculate the time to failure for the input parameter values listed under "Case 1" in Table (1). These values correspond to the geometry, operating conditions and material properties for the endurance test described in [5] in which a 30 cm two-grid ion engine was operated until grid failure under accelerated test conditions. The full probabilistic model was used to assess the lifetime of the accel grid in the 30 cm ring-cusp thruster [13,14], which is currently baselined for use in the NASA SEP (Solar Electric Propulsion) Technology Applications Readiness (NSTAR) program, a NASA-sponsored experiment on the Air Force Space Track and Autonomous Reposition (STAR) mission. The failure probability was calculated for conventional molybdenum optics at 4.65 kWe engine power (5 kWe power input to the power processing unit) and at 2.3 kWe (2.5 kWe total power), the design point for the NSTAR experiment. The 4.65 kWe condition was then reexamined assuming the use of carbon as the grid material. Graphite, carbon-carbon composites and diamond are now being considered as advanced grid materials because of superior sputter resistance [15,16,17,18,19]. The driver distributions used in these analyses are also shown in Table (1). In this section a detailed description of the driver characterization will be followed by a discussion of the calculated lifetime distributions and the analyses performed to determine the driver sensitivity.

Specification of Driver Distributions

The initial grid geometry is specified by the hole diameter, center-to-center spacing, open area fraction, beam area and grid thickness. These parameters were assigned the fixed values given in Table (1).

The channel geometry at failure is described by the eroded area fraction and the shape factor. The eroded area fraction is fundamentally determined by the ion trajectories, and examination of the grid used experimentally, 0.4, was used as the nominal value. Detailed examination of the test-to-failure grid [5] confirms that the channels do maintain an approximately parabolic shape (although with rounded edges) as they progress into the grid. However, after penetration of the grid occurs, undercutting by ions reflected in the interelectrode gap and further ero-
<table>
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<tr>
<th>Geometry</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
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<td>$F_{oa}$</td>
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<td>.242</td>
<td>.242</td>
<td>.242</td>
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<td>Xe/Mo</td>
<td>Xe/Mo</td>
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<td>1</td>
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Table 1: Driver values used in test cases.

The engine operating parameters that affect accel grid life are the beam current, accel grid voltage, the ratio of impingement current to beam current and the flatness parameter. The beam current and grid voltage were fixed at the values shown in Table (1), since there exists no significant variability or uncertainty regarding their values. The probabilistic calculations were performed for engine operation in space, and the ratio of impingement current to beam current was chosen to reflect this. The impingement current measured in ground tests with noble gas propellants is not applicable to conditions in space due to higher tank pressures. Mercury data is expected to be representative of that found with xenon in space because the propellant utilization efficiency and charge exchange cross sections are similar for these propellants in optimized engines and at operating conditions considered in this analysis [13]. The impingement current fraction was characterized on the basis of data from 30 cm thrusters at low back pressures with mercury as the propellant. The impingement current fractions measured in [22] were characterized by a Beta distribution ranging from a lower bound of zero to an upper bound of 0.3 percent.

The flatness parameter used in this model serves primarily to account for macroscopic nonuniformity in the mass loss distribution across the grid. For the test-to-failure the true radial mass loss distribution was determined by sectioning the grid into concentric rings and weighing them. The measured mass loss distribution can be represented by a flatness parameter of about 0.71, which is broader than the ex-
Table 2: Measured values of eroded area fraction.

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</table>

Table 2: Measured values of eroded area fraction.

The normal yield parameters a, b, c, and d in the sputtering model, Eq. (13), were estimated using data for krypton and xenon on molybdenum corrected for secondary electron emission [7]. The data in [7,24] for xenon on carbon are well represented by the linear model given in Eq. (14). The samples used in [7] were of an unspecified form of carbon, while those in [24] were pyrolytic graphite cut parallel to the net plane. Because the sputter yield for carbon can vary depending on the type and crystallographic orientation of the material [25], these data may not be representative of all the proposed carbon grid materials. The available yield data appear to be free from systematic biases due to residual chamber gases, multiple ion production, oblique ion incidence and backscattering of sputtered atoms [26] and the data exhibit little random variation, so the parameters were given fixed values. The sputtering yields are shown in Fig. (7) and the estimated parameters are given in Table (1).

There is very little information on the extent to which the net sputtering yield can vary from the value at normal incidence on smooth surfaces, although limited data suggest that it is decreased by surface
roughness [7]. The yield factor $\lambda_Y$ was therefore conservatively set equal to unity.

Results

The test described in [5] was terminated after 633 hours when a flake of sputter-deposited material shorted the two electrodes. Post-test examination of the accelerator grid showed that it was also very near structural failure caused by pits and grooves formed by sputtering. The total mass loss calculated from the initial grid geometry and the mass measured after the test was 62 g. A total mass loss at failure of 62 g is predicted by the model with the same assumptions for the initial grid geometry if a channel shape factor of 1.31 is assumed. The calculated time to failure using the driver values in Table (1) is 510 hours. If intrinsic variability in the normal sputter yield is small and the sputtering factor $\lambda_Y$ is actually equal to unity, the measured time to failure and that given by the deterministic calculation should be comparable, because all other drivers were measured directly. The discrepancy is indicative of model specification error, which most likely appears in the value chosen for $\lambda_Y$. This implies a slight lowering of the net sputter yield due to redeposition of sputtered atoms. A true value of 0.8 for $\lambda_Y$ is sufficient to explain the discrepancy. If this interpretation is correct, the error associated with $\lambda_Y = 1$ results in conservatism in the probabilistic calculations.

Figures (8), (9) and (10) show the calculated failure distributions for the 30 cm engine with molybdenum grids at 4.65 and 2.3 kWe and with carbon grids at 4.65 kWe. The peak of the curves represents the B501 life, and corresponds approximately to the value of life that would be predicted deterministically using the nominal driver values. The uncertainty captured by the stochastic drivers $J_a/J_b$, $(FP)_b$ and $\lambda_s$ serves to decrease the accel grid life considerably from that calculated with the nominal values. Deterministic calculations using the nominal driver values can therefore provide a false sense of security, because they do not reveal the impact of uncertainty in assessing service life. The predicted life is also strongly dependent on the chosen value of the eroded area fraction $\alpha$.

At the 4.65 kWe operating point the 30 cm design with molybdenum grids has insufficient life. With a value of 0.4 for the eroded area fraction a failure probability of 50 percent after only 4070 hours of operation is calculated, and the B.1 life is about 2100 hours. This nominal value for the eroded area fraction was chosen because it is the lowest observed in the ground-based tests summarized in Table (2), but we cannot say with any certainty that it will not be lower in space.

Recognizing the risk associated with operation at 4.65 kWe, the 2.3 kWe operating point was proposed for the NSTAR experiment. As Fig. (9) shows, a combination of lower beam current and lower accel grid voltage at this derated condition results in a factor of five increase in life compared to the 4.65 kWe point. With an eroded area fraction of 0.4 the B50 life is in excess of 20,000 hours and the B.1 life is 10,600 hours.

The impact of advanced grid materials is shown by the life assessment of carbon optics in Fig. (10). A lower sputter yield and higher atom number density result in an order of magnitude increase in life compared to molybdenum grids. Even at the demanding 4.65 kWe operating condition the B.1 life is nearly 22,000 hours and the 50 percent failure probability occurs at 42,000 hours.

The parametric study of the eroded area fraction shows that it is one of the most important drivers in determining accel grid life. An analysis of the sensitivity to the other stochastic drivers was also conducted and is shown for operation with molybdenum grids at 2.3 kWe in Fig. (11). In this analysis individual drivers were allowed to vary while the other parameters were held fixed at the nominal values and the results compared with that in which all drivers were allowed to vary. The results show which drivers contribute the most to the reduction in life from the fixed driver case. For the designs considered here, the uncertainty in the impingement current contributes the most to the failure risk, with flatness parameter and channel shape factor playing slightly lesser roles. Sensitivity analyses conducted for the other two cases yielded similar results.

In Fig. (12) the life distribution with variation of all drivers is compared to calculations in which the shape
Figure 8: Probabilistic life assessment for operation at 4.65 kWe with Mo grids.

Figure 10: Probabilistic life assessment for operation at 4.65 kWe with C grids.

Figure 9: Probabilistic life assessment for operation at 2.3 kWe with Mo grids.

Figure 11: Probabilistic sensitivity analysis for 2.3 kWe operation with Mo grids (\( \alpha = 0.4 \)).
factor \( \lambda_s \) was held fixed at the nominal value and the upper and lower bounds of the specified distribution. The curve generated by sampling from a Uniform distribution between the two extremes merges with the curve fixed at the nominal value of 1.25 at the B50 point, as expected. For lower values of the failure probability, however, the curves diverge and the probabilistic calculation moves toward lower lives. The left-hand tail of the failure probability distribution is affected by the more conservative portions of the driver distributions.

**Approaches to Managing Risk**

The probabilistic accel grid service life model clearly demonstrates that the risk is driven by lack of knowledge, particularly with respect to the eroded area fraction \( \alpha \), the sputtering factor \( \lambda_Y \) and the impingement current fraction \( J_a/J_b \). Subsequent activities will be directed toward acquiring more information on these drivers as well as implementing design improvements which reduce the sputter erosion and decrease the required grid service life.

**Information Acquisition**

A number of experiments involving examination of erosion patterns in thin copper films deposited on a molybdenum accel grid are planned at JPL to determine how the eroded area fraction varies with tank pressure, beam current, accel grid voltage and propellant species. Use of thin films permits determination of the areas subject to the highest impingement current density in relatively short duration tests. In addition, ERC, Inc. will continue the development of plasma simulation codes to predict impingement ion trajectories [3]. The objective of these efforts is to determine bounds on the value of \( \alpha \) that can be incorporated in the probabilistic analysis.

A simulation code is also being developed at JPL to track the trajectories of sputtered atoms and the growth of the erosion grooves. This will provide information on the effect of redeposition on the net yield that can be incorporated in the analysis as a probability distribution for the parameter \( \lambda_Y \). Refinements to the plasma simulation codes developed by ERC, Inc. and further experiments and analytical modeling at Colorado State University [1] should provide additional information on the value of \( J_a/J_b \) in space.

In the near future, relative sputter yield measurements will be performed at JPL on samples of molybdenum, graphite, carbon-carbon sheets and diamond films to improve the materials model. Absolute sputter yields may also be measured to supplement the limited database found in the literature.

Technology development for the NSTAR program will also yield additional driver information. For example, further development of the 30 cm ring-cusp thruster at the NASA Lewis Research Center will provide a better characterization of operating parameters such as the beam flatness. In addition, two 2000 hour tests and one 12,000 hour endurance test are planned as part of NSTAR. The 2000 hour tests, to be conducted in two different facilities with different tank pressures, are too short to affect failure risk estimates for long duration missions, but will provide valuable information on the operating conditions and erosion patterns and may reveal unanticipated failure modes. The 12,000 hour test will yield additional information on drivers and the success or failure of this test can be used directly to improve the prior distribution.

**Design Improvements**

The model demonstrates the tremendous potential of improved grid materials. Development of graphite [15], carbon-carbon \([16,17,18]\) and diamond
grids [19] is continuing. In addition, screen-accel-
negative decel (SAND) three-grid optics are being
studied as one approach to reducing sputter ero-
sion [27,15]. In this optics configuration a third grid
located downstream with a negative bias somewhat
less in magnitude than that on the accel grid. This
electrode then collects most of the charge exchange
ions at a low enough energy to avoid rapid sputter-
ing, effectively shielding the accel grid. The accel grid
voltage can also be lowered in this configuration, so
that the ions that do impinge on it cause less damage.

Use of segmented ion engines is another risk man-
agement approach which exploits the throttling re-
quirements of certain mission applications to reduce
the grid service life requirements [28,15]. In this ar-
chitecture, four or more ion sources are used with a
common neutralizer and power processing unit to
form a single engine. Throttling is accomplished by
turning off segments, effectively saving them for use
later when other segments have reached their design
life. Depending on the mission throttling require-
ments, this approach can result in a significant re-
duction in the required grid service life.

Conclusions

A probabilistic assessment of accel grid service life
incorporating uncertainty about the governing pa-
rameters reveals that the service life at an acceptable
failure risk is considerably shorter than determinis-
tic calculations suggest. Conventional 30 cm molyb-
denum grids have very limited life at the 4.65 kWe
operating point. Derating the engine to 2.3 kWe or
using carbon grid materials yields a substantial in-
crease in service life. Using the probabilistic model
to study driver sensitivities shows that uncertainties
about eroded area fraction, net sputter yield and im-
pingement current fraction in space are the major risk
drivers. Efforts to obtain more information about
these drivers have been initiated, as well as the de-
velopment of improved engine designs centering on
the use of carbon materials and changes in ion optics
and engine configuration.

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