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ORIGINAL PAPER

Quantification of the Lifetime and Reliability of Dual-Mode Ion Thrusters

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ABSTRACT

An approach to quantify the lifetime and reliability of dual-mode ion thruster is presented based on coupling analyses of thruster failure modes, throttle levels, life models, input uncertainties, and throttle profiles. This approach involves lifetime characterization based on each failure mode, a conservative life margin assessment followed by a failure mode reduction and a quantification of life margins and uncertainties which gives a further reduction of the failure modes, Weibull fitting of the sampled lifetimes based on each of the remained failure modes to obtain their reliability functions, and derivation of a combined reliability function according to the throttle profile. The results for LIPS-200E completing a 13kh mission show that the lifetime distribution and mission reliability strongly depend on the throttle profile.

Keywords: Quantification; Reliability; Lifetime; Dual mode; Ion thruster.

INTRODUCTION

The requirement for flexible performance of ion thrusters is leading to a trend of "multimodalization" (Zhang 2015, Zhao *et al*. 2020, Zhang *et al*. 2021a). The quantification of the lifetime and reliability of ion thrusters becomes tricky as multi-mode ion thrusters being applied in engineering, essentially due to the high uncertainty in the maximum lifetime affected by multiple factors and their coupling. Based on the assessment of single-mode ion thrusters, an approach to quantify the lifetime and reliability of a dual-mode ion thruster (DMIT) is presented. This approach applies the quantification of uncertainty and three-parameter Weibull distribution. Examples from a DMIT LIPS-200E were also demonstrated, as a reference to the assessment of multi-mode ion thrusters.

BASICS OF THE LIFETIME ASSESSMENT OF DUAL-MODE ION THRUSTERS

Failure modes of ion thrusters

There are 14 failure modes of ion thrusters examined by previous life tests (Brophy *et al*. 2008, Yim 2017), as shown in Table 1. Each failure mode is marked by FMi, i=1, 2, ..., n; n=14. In a mission or a life test, the first failure mode leading to the failure of

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the thruster is called key failure mode (KFM). The failure modes that are much likely to occur during a certain mission are called engineering failure modes (EFMs). The failure modes that are not likely to occur are called general failure modes. In engineering applications, the failure modes of interest are EFMs, especially the KFM.

Table 1. Credible failure modes of ion thrusters.

Component	Failure mode	Mark
Ion optics	Structural failure of screen grid	FM1
	Structural failure of accel grid	FM2
	Unclearable short between grids	FM3
	Unclearable electrical breakdown between grids	FM4
	Electron backstreaming failure	FM5
Hollow cathodes	Insert depletion resulting in inability to ignite or excessive temperatures	FM6
	Structural failure of keeper	FM7
	Structural failure of orifice plate	FM8
	Orifice clogging preventing proper cathode operation	FM9
	Unclearable short between electrodes	FM10
	Mechanical failure of cathode heaters	FM11
Discharge chamber	Structural failure of harness	FM12
	Insulation failure	FM13
	Magnet field degradation	FM14

FM: failure mode.

As to a specific ion thruster, its KFM and EFMs depend on several factors, collectively called inputs here, including thruster design, throttle levels, throttle profiles, and operating conditions. For example, the KFM of LIPS-200 is FM2, while the KFM of NSTAR is FM5 (Anderson *et al*. 2004), which was avoided in Dawn mission because the thrusters operated mostly at low throttle levels after their 8kh of operation (Garner and Rayman 2018).

Even if the KFM is confirmed, there is still uncertainty in the thruster lifetime, since the lifetime depends on the characteristic parameter of the KFM, which is a function of several inputs with uncertainty themselves (Zhang *et al*. 2021b). For ion thrusters with lifetime above 10 thousand hours, a small difference in the initial value of the inputs may lead to a large difference in the maximum lifetime. As a result, the lifetime based on the KFM is distributed. Generally, the distribution of lifetime depending on wear mechanisms is described with a three-parameter Weibull distribution, as an example of LIPS-200 based on FM2 shows.

Lifetime characteristics of dual-mode ion thrusters

Dual-mode case is the simplest one in multi-mode cases. The throttle levels of a DMIT are marked with TL1 and TL2. Compared with lifetime assessment of a single-mode thruster, there are two outstanding challenges within a dual-mode case. The first one is that there might be a huge difference in the KFM and its corresponding lifetime between TL1 and TL2. Assuming two-life tests, marked with E1 and E2, they were finished at TL1 and TL2, respectively. Their maximum lifetime results are $T_{i,1}$ and $T_{k,2}$ based on KFMs of FM*i* and FM*k*, in which the second subscript is index of throttle level. The lifetime distributions can be described with a three-parameter Weibull distribution applicable with single-mode thrusters as Eqs. 1 and 2:

$$P(T_{i,1}) = \exp\left[-\left(\frac{T_{i,1} - T_{0i,1}}{\alpha_{i,1}}\right)^{\beta_{i,1}}\right] \tag{1}$$

$$P\left(T_{k,2}\right)=\exp\left[-\left(\frac{T_{k,2}-T_{0k,2}}{\alpha_{k,2}}\right)^{\beta_{k,2}}\right] \tag{2}$$

In which: $P(T)$: the distribution function of T; T: thruster lifetime (h); T_0: minimum lifetime threshold (h); α, β and T_0: distribution parameters.
In general, $i \neq k$ and $T_{i,1} \neq T_{k,2}$, due to input differences between TL1 and TL2.

The second challenge is that different throttle profiles will lead to different lifetime results, assuming the KFMs examined by life tests E3 and E4 are FM*i* and FM*k*, respectively. During E3, the thruster operated for duration $T_{i,1}$ at TL1 and $T_{i,2}$ at TL2 just before its failure. During E4, the thruster operated for duration $T_{k,2}$ at TL2 and $T_{k,1}$ at TL1 just before its failure. In these cases, the failure of the thruster is resulted from two segments (marked as SG1 and SG2) of operation at different throttle levels. The distribution in Eqs. 1 and 2 is still applicable for SG1, but no longer for SG2, since SG2 is based on the completion of SG1. As a result, the lifetime distribution based on Eq. 3 is:

$$P\left(T_{i,1}+T_{i,2}\right)=P\left(T_{i,1}\right)P\left(T_{i,2}\middle|T_{i,1}\right)=\exp\left[-\left(\frac{T_{i,1}-T_{0i,1}}{\alpha_{i,1}}\right)^{\beta_{i,1}}\right]P\left(T_{i,2}\middle|T_{i,1}\right) \tag{3}$$

In which the lifetime distribution in SG2 has a form of conditional probability. Similarly, the lifetime distribution based on Eq. 4 is:

$$P\left(T_{k,2}+T_{k,1}\right)=P\left(T_{k,2}\right)P\left(T_{k,1}\middle|T_{k,2}\right)=\exp\left[-\left(\frac{T_{k,2}-T_{0k,2}}{\alpha_{k,2}}\right)^{\beta_{k,2}}\right]P\left(T_{k,1}\middle|T_{k,2}\right) \tag{4}$$

For life tests with different throttle profiles, their KFM and lifetime results are generally different from each other ($i \neq k$ and $T_{i,1} \neq T_{i,2} \neq T_{k,2} \neq T_{k,1}$), which is essentially caused by the coupling among throttle levels, failure modes and operating time.

Apparently, the probability calculation in Eqs. 3 and 4 becomes more complicated as the throttle profile contains more cycles. Considering this complexity, especially for multi-mode cases, the discuss ahead is based on specific examples of failure modes.

Life models and input uncertainties

From the view of causality, thruster lifetime is the consequences (outputs), and the inputs mentioned before are the causes. The relationship between the lifetime and the inputs is called life model, which has a form of Eq. 5:

$$T_{i,j}(\boldsymbol{X})=T_{i,j}(X_1, X_2,...) \tag{5}$$

In which: *i*: index of failure mode; *j*: index of throttle level; $T_{i,j}$: the lifetime; X: the set of inputs.

It is difficult to figure out this model for several reasons. First, the life models for most failure modes are too complicated to describe with analytic functions, so that they can only be obtained by numerical simulations. Second, there are 14 life models corresponding to 14 failure modes, along with a set of inputs for each model, including parameters of design, throttle levels, operating conditions, timing, and sequence. Full consideration of all these failure modes and inputs is not realistic in engineering, so that proper reductions and simplifications are necessary. Third, there are uncertainties in both the inputs and the model itself, including aleatory and epistemic uncertainties. Aleatory uncertainty comes from the inherent randomness of the parameters, and therefore it is irreducible and usually characterized with statistical analysis. Epistemic uncertainty rises from a lack of knowledge (about the accurate model, the distribution type of the parameters, etc.), and therefore it is reducible and usually characterized with certainty models. We need feasible methods to quantify these uncertainties and their propagation through the model, which eventually brings uncertainty to the lifetime result.

For instance, the life model of LIPS-200E based on FM2 is like Eq. 6:

$$T_{2,j}(\boldsymbol{X}) = \frac{\frac{1}{2}\rho_a t_a\left(\frac{\sqrt{3}}{4}l_{cc}^2 - \frac{1}{8}\pi d_a^2\right)}{m_{se}(j)} = \frac{\frac{1}{2}\rho_a t_a\left(\frac{\sqrt{3}}{4}l_{cc}^2 - \frac{1}{8}\pi d_a^2\right)}{23.1 m_a\left[1-\left(\frac{39.3}{V_{aj}}\right)^{2/3}\right]\left(1-\frac{39.3}{V_{aj}}\right)^2 \frac{dN_{CSj}}{dt}} \tag{6}$$

In which: ρ_a: the density of grid material; m_a: the atomic mass of grid material; t_a: the thickness of the accel grid; d_a: the aperture diameter of the accel grid; V_a: the potential of the accel grid; l_{cc}: the grid gap; dN_{cs}/dt: the charge exchange (CEX) ion flux toward the barrel surface of the accel grid; X: the set of these parameters in which the throttle level *j* only affects V_a and dN_{cs}/dt; $m_{se}(j)$: the material mass eroded away from the accel grid.

The uncertainties in ρ_a, t_a, l_{cc}, d_a, m_a and V_a arise from variations in manufacturing runs or power controls, which are aleatory uncertainties, because they will always be present among multiple assemblies. The uncertainty in dN_{cs}/dt is epistemic, since it arises from model accuracy.

Limitations of life tests

A life test of single-mode ion thrusters serves as a sample test, whose sample number is usually set as only one or two due to high cost and long duration of the testing. For DMITs, the test design involves more considerations including test procedure and the duration in each segment. For example, the procedure can either be two thrusters operating in two respective modes, or one thruster operating in both modes circularly. The cumulative operating time in each mode can either be equal or unequal. Different plans will lead to different results, including the KFM and the lifetime.

A reasonable test procedure for a DMIT should derive from its throttle profile. For an all-electric geosynchronous orbit (GEO) satellite, the thrusters operate at high-power levels for orbit transfer and low-power levels for station keeping. According to the cumulative operating time and safety margin for this mission, the test procedure should be high-power operations (considering safety margin) followed by low-power operations for a certain duration (truncated life test) or until the thruster fails. The 25-cm XIPS© life test applied this design (Tighe *et al.* 2009).

It is often required that a thruster model is applicable for multiple missions. However, due to different requirements of these missions, limited life tests can hardly cover all the throttle profiles. Especially when new missions are put forward after previous tests were completed, to conduct a new test or supplemental test for each of these missions would be unrealistic considering the budget and time. How to manage this dilemma is also the biggest challenge in multi-mode ion thruster assessments.

LIFETIME AND RELIABILITY QUANTIFICATION OF DUAL-MODE ION THRUSTERS

Failure criteria and wear models

For a failure event, the characteristic parameter and its threshold are marked by $C_{i,j}$ and $C_{Ti,j}$, respectively. Based on a certain failure mode and throttle level, the thruster fails when $C_{i,j}$ reaches $C_{Ti,j}$, shown as Eq. 7:

$$C_{i,j} = C_{Ti,j} \qquad (i = 1,2,...,14;\ j = 1,2) \tag{7}$$

Take electron backstreaming failure (FM5) as an example. The characteristic parameter and its threshold here are electron backstreaming limit V_{EBS} and V_a, respectively. This failure occurs when $|V_{EBS}|\geq|V_a|$, in which V_{EBS} is defined as the accel grid potential when backstreaming current reaches 0.1% of the beam current. The corresponding failure criterion is Eq. 8:

$$\frac{C_{5,j}}{C_{T5,j}}=\frac{|V_{EBS}|}{|V_a|}=1 \qquad (j=1,2) \tag{8}$$

The characteristic parameter depends on X and time t, and this relationship is called a wear model, as shown in Eq. 9:

$$C_{i,j}(t,\boldsymbol{X})=C_{i,j}(t,X_1,X_2,\ldots) \tag{9}$$

In which: $t = T_{i,j}$.

Eq. 5 is equivalent to Eqs. 7 and 9.

In the previously mentioned test E3, the relationship among characteristic parameter threshold, wear models, operating time and the lifetime is like Eqs. 10 and 11:

$$C_{Ti,0}=C_{i,1}(t,\boldsymbol{X})\Big|_{t=T_{i,1}}+C_{i,2}(t,\boldsymbol{X})\Big|_{t=T_{i,2}} \tag{10}$$

$$T_{i,0}=T_{i,1}+T_{i,2} \tag{11}$$

In which the second subscript 0 stands for the total value for this test. Notice that $C_{Ti,0}$ depends on both throttle levels, due to different wear mechanisms in each mode.

Life margin assessment with wear models

The lifetime assessment of a DMIT involves 28 combinations of two throttle levels and 14 failure modes. However, the life margins against most failure modes are large enough to avoid these failures. FM14 can be eliminated by applying high temperature permanent magnet and temperature derating. FM13 can be eliminated via design of protected or labyrinth insulator. FM4 can be avoided through control of energy deposition in unexpected electrical breakdowns. FM3 and FM10 can be eliminated by preventing deposition flakes from spalling and formation, and also minimizing the flake size. A life margin of more than five times against FM7 can be achieved via application of graphite materials. Through proper design of aperture size and flow margin, and the protection from a graphite keeper, the life margin against FM8 and FM9 can exceed three times the requirement. A life margin of over four times against FM11 can be achieved via heater design. By margin design against insert failure and xenon purity control, the life margin against FM6 can exceed two times the requirement.

The determination of the required life margin for a certain mission, and a subsequent reduction of the failure modes of interest, will remarkably simplify the lifetime quantification for DMITs. This work is usually done with wear tests and wear models.

The required lifetime for a throttle profile is assumed to be T_r, then the required lifetime for this mission is T_R=fT_r with a safety factor of f. In a wear test of duration $T_{i,2}$ at the worst-case throttle level (e.g., TL2), the characteristic parameter measured at the end is $C_{i,2}(T_{i,2})$. Substitute measured data for the inputs in Eq. 9, and the maximum lifetime $T_{mi,2}$ can be calculated from Eq. 7. The corresponding life margin is Eq. 12:

$$M_{i,2}=\frac{T_{mi,2}}{fT_r} \tag{12}$$

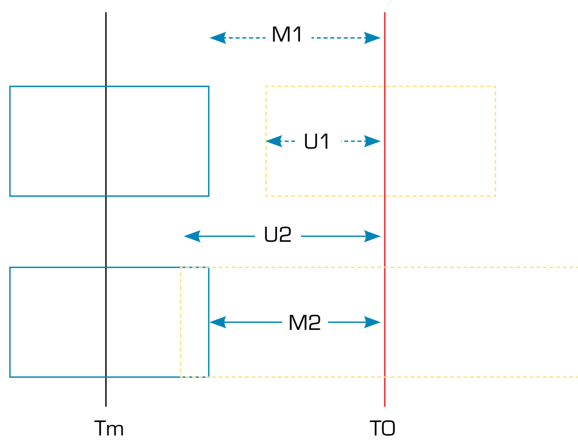
Generally, f ranges from 1.2 to 1.5, and $T_{i,2}$ ranges from $0.1T_R$ to $0.2T_R$. The wear test can be performed on the thruster, or on the assembly only if they share the same wear mechanism. For instance, a test driven by FM6 (insert depletion) can be a standalone cathode experiment, while a test driven by FM7 (keeper structural failure) must be a thruster coupling test. The tests for some failure modes can be accelerated, such as FM6, which could use higher discharge current and temperature, and FM2, which could use higher background pressure in their wear tests.

The assessment based on Eq. 12 is conservative because the worst-case data are applied. A failure mode whose life margin is in the range of 1.0-1.2 and 1.0-1.5 is defined as a KFM and EFM, respectively. A failure mode with a life margin of over 1.5 is called a general failure mode. In general, further assessments are only necessary for EFMs.

If a margin is less than 1.0, thruster modifications followed by more wear tests and lifetime assessments are necessary until each $M_{i,j}$ is greater than or equal to 1. Representative examples include the unacceptable screen grid erosion found after 2031h test of NSTAR engineering model (Patterson *et al.* 1995), and the severe off-center, hexagonal accelerator aperture erosion found after 2031h test of NEXT engineering model (Soulas *et al.* 2004).

Quantification of margins and uncertainties approach for lifetime assessment

To make the assessments less conservative, a quantification of uncertainties in the assessed lifetime is necessary. Assuming the required lifetime for a mission is T_R with a range of $[T_{Rl},T_{Ru}]$, and the maximum rated lifetime T_m is within $[T_{ml},T_{mu}]$. Define the life margin as $M=T_{ml}-T_{Ru}$ and the lifetime uncertainty as $U=T_m-T_{ml}$, then the thruster should satisfy $M/U \geq 1.0$ to eliminate risks. This approach is known as quantification of margins and uncertainties (QMU) (Helton 2009, 2011, Zhang *et al.* 2020). As shown in Fig. 1, the lifetime with $M_1/U_1 > 1.0$ is satisfying while the one with $M_2/U_2 < 1.0$ is not.



M = life margin; *U* = lifetime uncertainty (h); T_m = maximum lifetime (h); T_R = mission required lifetime (h).

Figure 1. Concepts in quantification of margins and uncertainties approach.

An important part of QMU is the quantification of $[T_{Rl},T_{Ru}]$ and $[T_{ml},T_{mu}]$, which is discussed ahead with an example of T_m.

The first step is to make the best estimations of thruster lifetime and model inputs based on each EFM. These estimations are derived from test results, analytical models, simulations, expert reviews, and their combinations. For instance, the best estimations for FM5 and FM2 of LIPS-200 were obtained referring to test results and analytical models (Zhang *et al.* 2021b).

The second step is to characterize the uncertainties in the inputs, which involves the determination of related variables, their uncertainty types (epistemic or aleatory), and their distributions. The best input estimations for FM2 of LIPS-200E is shown in Table 2, in which ρ_a and m_a are taken as constants. The aleatory uncertainties in geometric parameters arise from manufacturing tolerances, while the ones in potentials arise from the accuracy of the power processing unit. It is reasonably assumed that these aleatory uncertainties follow a normal distribution with the nominal value (mean) and variances based on specification values or measurement data. The epistemic uncertainties in CEX ion fluxes arise from the accuracy of the numerical model. These uncertainties follow a uniform or normal distribution with the range derived from an overall assessment.

Table 2. Inputs and uncertainties for LIPS-200E.

Parameter	Rating	Uncertainty	Uncertainty type	Throttle level
t_a/t_s	1.25	±0.05	Aleatory	TL1 & TL2
l_{cc}/t_s	5.50	±0.125	Aleatory	TL1 & TL2
d_a/t_s	3.00	±0.1	Aleatory	TL1 & TL2
V_{a1}	-185 V	±3V	Aleatory	TL1
V_{a2}	-200 V	±5V	Aleatory	TL2
dN_{CS1}/dt	5.2×10^{10}	±10%	Epistemic	TL1
dN_{CS2}/dt	6.5×10^{10}	±10%	Epistemic	TL2

t_a = accel grid thickness (m); t_s = screen grid thickness (m); l_{cc} = the grid gap; d_a = the aperture diameter of the accel grid; V_a = the potential of the accel grid; dN_{cs}/dt = the charge exchange ion flux toward the barrel surface of the accel grid.

The last step is to quantify the lifetime uncertainty based on the input uncertainties via propagation of sampled inputs through the life model. Approaches for this include interval analysis, probability theory, evidence theory, and possibility theory (Swiler *et al.* 2009, Helton *et al.* 2004). See Zhang *et al.* (2021b) for an example of interval analysis of the uncertainty in V_{EBS}. For the convenience of further reliability assessment, a Monte Carlo (sampling-based) procedure (Helton *et al.* 2006) is presented here. There are four basic components that underlie the implementation of a sampling-based uncertainty analysis:

- definition of distributions that characterize the uncertainty in the inputs;
- generation of a sample from the inputs in consistency with their distributions;
- propagation of the sample through the model to produce a mapping [X,*T*] from the inputs to the resulted lifetimes;
- approximation to the distribution of the lifetime, which can be used in reliability assessment.

Reliability quantification with three-parameter Weibull distribution

There are two main features of the failure lifetime of ion thrusters. One is the lifetime fits Weibull distribution, because the failures are driven by wear mechanisms, and the other is that a minimum lifetime threshold exists for each failure mode. The probability that the thruster lifetime reaches a value below this threshold is 1. Based on these features, it is reasonable to describe the thruster lifetime with Weibull distribution function.

The lifetime distribution function for FM*i* and TL*j* is like Eq. 13:

$$P(T_{i,j}) = \begin{cases} \exp\left[-\left(\dfrac{T_{i,j}-T_{0i,j}}{\alpha_{i,j}}\right)^{\beta_{i,j}}\right] & ,T_{i,j} > T_{0i,j} \\ 1 & ,T_{i,j} \le T_{0i,j} \end{cases} \quad (j=1,2) \tag{13}$$

A cumulative distribution curve of lifetime (CDCL) can be obtained based on the samples generated by Monte Carlo sampling, and a Weibull distribution function can be derived by fitting the curve. The CDCL for LIPS-200 in FM2 is shown in Fig. 2, with its distribution function shown in Eq. 14. This expression is also applicable to LIPS-200E since its operating condition at TL1 remains the same with LIPS-200.

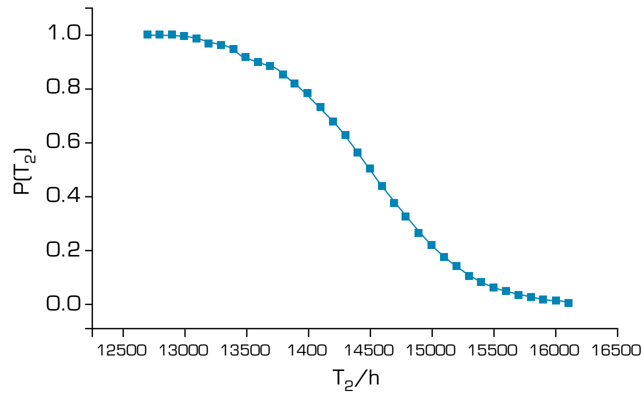


Figure 2. Cumulative distribution curve of lifetime for LIPS-200 in FM2.

$$P(T_{2,1})=\begin{cases}\exp\left[-\left(\dfrac{T_{2,1}-12030}{2681}\right)^{4.285}\right] & ,T_{2,1}>12030\\ 1 & ,T_{2,1}\le 12030\end{cases}\tag{14}$$

Conditional probability distribution of thruster lifetime

For a DMIT, how to achieve the conditional probability as in Eqs. 3 and 4 is also a key to its lifetime assessment. Take test E3 and Eq. 3 as an example. Since the operation at TL2 is based on the operation at TL1, the completion of TL1 operation is the initial condition of the operation at TL2. The conditional probability in Eq. 3 is shown as Eq. 15, in which the distribution parameters also depend on the initial condition.

$$P(T_{i,2}|T_{i,1})=P(T_{i,2})\big|_{T_{i,1}}=\exp\left[-\left(\dfrac{T_{i,2}-T_{0i,2}\big|_{T_{i,1}}}{\alpha_{i,2}\big|_{T_{i,1}}}\right)^{\beta_{i,2}|_{T_{i,1}}}\right]\tag{15}$$

For LIPS-200E, TL1 and TL2 are 1 and 1.5 kW levels, respectively. Assuming the failure mode is FM2, the lifetime distribution for TL1 is the same as Eq. 14, while the one for TL2 is like Eq. 16:

$$T_{2,2}(\boldsymbol{X})=\dfrac{\dfrac{1}{2}\rho_a t_a\left(\dfrac{\sqrt{3}}{4}l_{cc}^2-\dfrac{1}{8}\pi d_a^2\right)-T_{2,1}m_{se}(1)}{m_{se}(2)}\tag{16}$$

In which the last item is the TL2 operating time effective to $T_{2,1}$.

Assuming an uncertainty of ±1 h in $T_{2,1}$, the lifetime distributions from the sampling of Eq. 16 for $T_{2,1}$=5,000 h and 12,500 h are like Eqs. 17 and 18:

$$P(T_{2,2}|T_{2,1}=5000)=\begin{cases}\exp\left[-\left(\dfrac{T_{2,2}-3383}{3917}\right)^{7.215}\right] & ,T_{2,2}>3383\\ 1 & ,T_{2,2}\le 3383\end{cases}\tag{17}$$

$$P\left(T_{2,2}\middle|T_{2,1}=12500\right)=\begin{cases}\exp\left[-\left(\dfrac{T_{2,2}-50}{545.6}\right)^{2.049}\right] & T_{2,2}>50\\ 1 & T_{2,2}\le 50\end{cases} \tag{18}$$

As we can see, the lifetime threshold at TL2 is 3,383 h after a TL1 operation of 5kh, while the threshold is only 50 h after 12.5kh at TL1. Therefore, conditional probability strongly depends on the throttle profile.

Mission reliability quantification

Assuming a throttle profile is to operate for duration T_1 at TL1 and T_2 at TL2, the minimum lifetime required for this mission is $T_r=T_1+T_2$. Each type of failure could happen during the operation, and the lifetimes based on these failure modes are mutually independent. Each lifetime must exceed T_r to ensure the thruster completes this mission, which gives the probability (Eq. 19):

$$P(T_r)=\prod_{i=1}^{n}\exp\left[-\left(\frac{T_1-T_{0i,1}}{\alpha_{i,1}}\right)^{\beta_{i,1}}\right]\prod_{i=1}^{n}\exp\left[-\left(\frac{T_2-T_{0i,2}\big|_{T_{i,1}}}{\alpha_{i,2}\big|_{T_{i,1}}}\right)^{\beta_{i,2}|_{T_{i,1}}}\right] \tag{19}$$

In which n can be reduced to the number of EFMs, or further reduced to 1 if only the KFM is considered. Applying Eqs. 14, 17 and 18, the reliabilities of LIPS-200E to complete a 13,000-h mission with two different throttle profiles are like Eqs. 20 and 21:

$$P(5000+8000)=P(T_{2,1}=5000)P(T_{2,2}=8000|T_{2,1}=5000)=1\times 0.038 \tag{20}$$

$$P(12500+500)=P(T_{2,1}=12500)P(T_{2,2}=500|T_{2,1}=12500)=0.999\times 0.509 \tag{21}$$

Which shows a significant influence of throttle profile on the mission reliability. The huge difference between these two cases is essentially due to a much higher sputter erosion rate at TL2 compared with TL1.

CONCLUSION

An approach to quantify the lifetime and reliability of DMITs is presented based on coupling analyses of failure modes, throttle levels, life models, input uncertainties, and throttle profiles. This assessment is accomplished in the following steps:

- Build life models for the failure modes of interest, which gives the characteristic parameters, their thresholds, and the wear models;
- Apply the worst-case test results to the wear models and make a conservative assessment of the life margins for a certain mission, then identify the EFMs according to these margins;
- Make best estimations of the life model and inputs for the EFMs, then quantify the lifetime's uncertainty and margin. The failure modes satisfying M/U >1.0 can also be eliminated from the EFMs;
- Generate a lifetime sample for each of the EFMs, then fit the CDCL with three-parameter Weibull distribution to obtain a reliability function of each EFM;
- Use conditional probability to derive a combined reliability function according to the throttle profile, then quantify the reliability for completing the mission.

While this approach is theoretically practical, there are still some challenges within its application. First, to make the best estimation of the life model is difficult, especially for newly developed thrusters due to a lack of test results, simulation models and expertise. Second, the uncertainty quantification of the lifetime involves two types of uncertainty and a large number of inputs.

Therefore, a sensitivity study is necessary to weight the inputs and their contributions to the lifetime uncertainty. Lastly, the conditional probability calculation, lifetime sampling, and distribution fitting can be very computationally expensive as the throttle profile becomes more complicated, which is also the most important problem to deal with in multi-mode cases.

AUTHORS' CONTRIBUTION

Conceptualization: Zhang X.; **Formal Analysis:** Zhang X.; **Investigation:** Zhang T., Li D. and Zhang X.; **Methodology:** Zhang T. and Li D.; **Writing – Original Draft:** Zhang X.

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All data generated or analyzed during this study are included in this published article.

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