PROBLEMS OF ELECTRIC PROPULSION ENDURANCE TESTS

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Abstract
Accelerated test methods (ATM) are described, first as a general testing approach, and then with specific examples for a stationary plasma thruster. The use of ATM permit a considerable reduction in the total volume of tests required to assure reliability and endurance for electric space propulsion. Future requirements for operation over broader ranges should only increase the need and value of ATM.

Introduction
The relatively small level of thrust and, at the same time, the large total impulse generated by an electric propulsion thruster (EPT) during its operation on a spacecraft results in a considerable firing time for the EPT, which can be measured in hundreds, thousands, and in some cases by tens of thousands of hours. In such a situation, in addition to the problems of studying the working processes in an EPT with the purpose of improving its performance, there are problems related to the long-duration operation of an EPT, the most important and complex of which is the determination of EPT reliability for operation on a spacecraft in orbit.

Accelerated Test Methods
A single durability demonstration of an EPT cannot determine the reliability of a product. In addition, as calculations can show, reliability determination by ordinary statistical methods is practically impossible, because it would require excessive time and material. To achieve a factor of several reduction of time and material resources for testing it is necessary to develop an accelerated test methodology (ATM), meaning a transition from a purely statistical approach to a physical-mathematical reliability foundation from the detailed analysis and investigation of wear, reliability, causes of malfunction, and so forth.

The development of ATM is based on obtaining and analyzing the prediction of degradation based on the determining parameters (DP), i.e. the parameters that characterize the critical components of the system in which failures most frequently happen, or the parameters for which change results in a loss of operating capability.

For the development of ATM it is possible to define four main stages:

- The selection and optimization of the DP, from the information they contain;
- The construction of physical-mathematical models for the DP;
- The study of the models and the selection of methods for decreasing the test time;
- The execution of accelerated tests with lifetime prediction and the estimation of reliability coefficients.

Examples for Stationary Plasma Thruster
It is evident that the development of ATM is necessary for practically all types of long-lifetime EPT. However, ATM were started using a plasma accelerator with closed electron drift and extended zone of acceleration, which is ordinarily called the stationary plasma thruster (SPT). The scheme of this thruster and its theoretical foundation was suggested by A.I. Morozov in the 1960s, and, starting at the beginning of the 1970s, the SPT was used in systems of attitude control and orbit correction for spacecraft. At present, highly efficient SPT operate over a wide range of power from 0.1 to 10 kW, with the lifetime of single SPT thruster equal 2000 to 4000 hours. It appears that in the next 10 to 15 years, with onboard spacecraft power of 1 to 10 kW, or more, there is no reasonable alternative to the use of SPT, because it has the best characteristics in the range of specific impulse from 1000 to 3000 s which is optimal for a majority of orbital thruster applications. That is why the SPT was chosen as the first subject for the development of ATM for EPT.

The SPT construction scheme is presented in Fig. 1. The thruster consists of two main portions - the main or anode portion and the cathode portion. The anode portion contains the magnetic system, the discharge chamber with the accelerating channel (defined by the dielectric walls), and the anode (placed inside of the channel and serving at the same time as a gas
to a general improvement of thruster performance and characteristics and, as an integral part of this process, an increase in durability. The models typically include relations that describe the critical processes. These relations contain empirical constants, which are determined by the methods of regression analysis and the results of accelerated tests. The studies of erosion processes of the SPT accelerating channel and the hollow cathode-neutralizer show, that for changes of degradation values $Y_w$ and $Y_c$ as functions of time, $t$ (in hr), it is necessary to search for a form of functional dependence with two parameters, such as

$$Y = A \cdot f(\omega, t).$$

where $A$ and $\omega$ are empirical constants, playing, in fact, the role of scale coefficients for variables $Y$ and $t$. In this case the values $A$ and $\omega$ will be not only the formal coefficients in the regression equation, but can have definite physical expressions, which can be obtained as modeling solutions. The studies of the degradation process of accelerator channel wall due to ion sputtering resulted in a basic insulator wear dependence of the form

$$Y_w = A_w \cdot \omega_w / (1 + \omega_w \cdot t).$$

The degradation parameter, $Y_w$, is the insulator erosion at the end of the accelerating channel in mm. The parameter $\omega_w$ has a value of $-10^{-3}$ hr$^{-1}$ and depends on the wall sputtering coefficient, characteristics of the ion flow and other factors. The parameter $A_w$ has a value of $-10$ mm and mainly is determined by ion flow properties. The empirical coefficients in Eq. (2) have been calculated from the experimental data for insulator erosion for $t < 1000$ hr, and the prediction made for interval $1000 < t < 2000$ hr, where experimental data became available, and further - up to 4000 hours.

Figure 2 shows the results of such calculations and the experimental data for insulator erosion for $t < 2000$ hr. On the same Fig.2 there are the results of calculations for different relationships that had been obtained earlier and used for prediction. It is seen that relationships (2) and (3) closely predict the variation. The selection of relationship (2) out of the four shown in Fig. 2 was confirmed by other comparisons using additional criteria.

The erosion of the hollow cathode (HC) used in the SPT as a cathode-neutralizer, in particular the end of the emitting channel of the HC, is usually the small difference of two large values - the removal of mass due to evaporation and ion sputtering being one large value,
This relationship has a universal character, in that it could represent the full range of modeling characteristics for any degradation process of a HC. Applied to channel enlargement, for small operating times, \( Y_c \sim t^{1/2} \), and for large times, \( Y \sim t^{1/3} \). That is, the rate of erosion decreases with operating time, as is ordinarily observed for a HC.

As experiments show, the patterns of change for a SPT thrust value have a very complicated character and depend not only on the thruster itself and its components but on the basic operating principle of the control system. It was shown that for a control system that maintains a constant discharge current and permits the propellant flow to vary, the thrust value change results primarily from the degradation of the accelerating channel wall. For thrust value, \( T \), which is normalized for discharge current, \( I \), and voltage, \( V \), it is possible to write

\[
T = F/[(2m_i/e)^{1/2} V^{1/2}] = a + b Y_w,
\]

where \( m_i \) is the ion mass and \( e \) the electron charge. Taking into account Eq. (2), we can obtain

\[
T = C - A_f \omega_f t/(1 + \omega_f t),
\]

where the constants \( C, A_f \), and \( \omega_f \) can be found experimentally. In fact it is possible to find only two constants, \( A_f \) and \( \omega_f \) if, as the DP is used, not the absolute value of a thrust \( T \), but its change \( \Delta T \),

\[
\Delta T = A_f \omega_f t/(1 + \omega_f t),
\]

because the constant \( C \) is, in fact, the initial thrust value.

The modeling of Eqs. (4) through (6) and the values calculated using \( \omega_f \) and \( \omega_w \) were justified by the experimental study of thrust change with time, in that the experimental data and the predictions practically coincided.

The SPT component most sensitive to transient processes, which occur at startup and shutdown, is the cathode-neutralizer. An increased erosion of the channel in the emissive insert is observed during startup, which not only contributes to wear out, but to malfunctions during thruster startup. This increased erosion is due to the initial stage of the discharge being microspots on the emitter surface, which cause intensive heating and erosion of material surrounding the aperture. Studies show that the degradation process of the HC insert due startups happens to be the similar to the erosion in the steady-state regime, but with the intensity of mass transport increased. From this degradation of the HC...
insert, in particular the enlargement of the channel at the
end closest to the aperture, the prediction relationship
for startups and shutdowns can be assumed to be of the form

$$Y_n = A_n f(\omega_n, N),$$

(7)

where, of course, the parameter $\omega_n$ is not equal to $\omega_c$
for steady-state operation.

There are many ways to reduce the total time and
volume of tests. The two most used accelerated tests
methods are: 1) forced operation at greater than nominal
operating values and 2) operation at nominal conditions
with performance prediction. It should be evident that
for an EPT, the convenient choice is to test in the
nominal regime. This is due to the fact that accelerated
testing at forced regimes is preferable for simple
components, but not for complex systems or for the
complete installation, because it is practically impossible
to choose the forcing factor that equally accelerates all
degradation processes of a complex system.

However, for relatively simple components and
elements of an EPT, forced operation can be quite
suitable. It is still necessary to solve the non-trivial
problem of finding the acceleration coefficient when
testing in the forced regime.

If the objective is to reduce the total volume of tests,
such a goal can be reached through prediction
procedures for individual characteristics of the specific
thruster type, based upon the results of shortened tests at
a nominal regime for a test lifetime, $t_o$, and a desired
lifetime, $t_r$, the acceleration coefficient would be
$$k_a = \frac{t_f}{t_o} > 1.$$ As a result of components or the entire
thruster for the duration $t_o < t < t_r$, one can obtain an
estimation of reliability coefficients for each time
interval, including the interval for $t \to t_r$. In this
manner, for DP such as the degradation of the thruster
channel and the thrust, operation at nominal values with
prediction was chosen as the main method for reducing
the test time for EPT.

The knowledge of erosion mechanisms in the HC
emitter elements has not yet permitted functional relationships
to be obtained for the empirical coefficients $A_n$ and $\omega_c$
in Eq. (3); so the reduction of test time in this case is impossible at present. It appears
necessary to look for possibilities for both forced and
nominal operation, and to compare their effectiveness.

A considerable reduction of time tests for a parameter,
$N$, which characterizes the number of startup-shutdown
cycles, can be obtained by reducing the time duration of
each cycle; i.e. by the exclusion from a cycle the non-
stationary processes of relatively long duration which do
not have a significant influence on the HC lifetime. This
way of reducing the test time by the method of
compression is shown on Fig. 4, where the shaded
regions represent thermal warmup and cooldown before
and after actual operation and are excluded during the
compressed tests.

Fig. 4 Emitter temperature, $T_e$, during an on-off cycle:
A) heating before starting, B) heating by operation,
C) cooling, $t_o$ full cycle, and $t_A$) compressed cycle.

In the processing of results of reduced tests, and
predicting degradation and reliability from DP, it is not
always possible to apply the ordinary methods
of regression analysis, because they are based on the
assumption of a normal distribution of errors in the
measurements. To check this distribution it is necessary
to obtain a large quantity of experimental data, which
may not be practical. In order to obtain more correct
predictions it is necessary to use more robust methods,
which do not depend on distribution functions and are
more stable with the inclusion of random experimental
data.

A further direction for the development of ATM can
be the development of imitation models (IM) for DP in
EPT to better represent the physical-mathematical
degradation process. Such IM, when refined by
multiple comparisons with experiments, can be used to
improve the statistical data and the determination of the
reliability parameters, thereby better accounting for the
probabilities of malfunctions of thruster components and
systems. This improvement in IM can be carried out
together with the accumulation of data about EPT
elements and systems or their alternatives, giving the
necessary volume of statistical data in relatively short
time. The necessity and efficiency of using IM would
increase greatly after the further development of control
theory and control systems for EPT over a broad range
of operating parameters, because of the considerable
increase of tests that would be required without the use
of IM to account for the possibility of degradation.
processes having a non-Markov character, i.e. depending on the previous history.

Concluding Remarks

The application of the ATM for the prediction and confirmation of durability and reliability should permit the total volume of SPT tests to be decreased generally by a factor of 3-5, and in some components by a factor of 10.

References


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