Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Method for Estimating Atomic Oxygen Surface Erosion in Space Environments

N. John Stevens*
TRW, Inc., Redondo Beach, California

Introduction

ONE of the most serious environmental effects found in the initial Shuttle flights was the surface erosion experienced by various materials in space.[1-3] Dielectrics such as Mylar and Kapton and certain coatings such as silver, aquadag, and some paints were disappearing from spacecraft surfaces after a few days of exposure to the space environment. The surfaces normal to the velocity direction were eroded much more rapidly than other orientations. This erosion is due to the interactions between the surface and the natural atomic oxygen component of the environment.[2,3]

Evidence of atomic oxygen erosion has also been found in the surface samples returned from the Solar Maximum spacecraft. These samples were retrieved on the Solar Maximum Repair Mission (SMRM).[4] The Solar Maximum spacecraft had been in a 500-km orbit since February 1980 and was repaired in April 1984. The sample surface erosion, brought back from the repair mission, ranged from 0.5%-30%.

Subsequent experiment in both ground simulation facilities and in the Shuttle have verified that the erosion exists for a considerable number of materials and coatings used on spacecraft. Protective coatings for minimizing this erosion have been suggested and tested.[5] However, not every aspect of this interaction is well defined. Some investigators have found that the erosion rate is dependent on the incident energy.[6] Others state that there is a threshold in energy for the reaction to occur and, above this level, there is no energy dependence.[7]

Atomic oxygen erosion has serious repercussions in the design of current and future spacecraft systems for low Earth orbit. Thermal blankets and planar solar array designs incorporating thin Kapton films may not be feasible without additional protection from atomic oxygen. A recent paper applied the current atomic oxygen erosion technology to surfaces proposed for use on NASA's Space Station.[8] The surface erosion rate was predicted by computing the flux of atomic oxygen particles striking the surface and multiplying that flux by the reaction efficiency, a value defined as surface erosion in centimeters divided by the atomic oxygen fluence. The predicted erosion rate was given for Kapton and Teflon surfaces. The Kapton surface suffered severe erosion whereas the Teflon surface was only moderately eroded.

The values for reaction efficiency were obtained from experiments conducted on Shuttle flights. To extrapolate these data to a different spacecraft, all surface orientation effects must be entered into the computation of the fluence. This is a reasonable approach if the data from space are available. Ground simulation tests on atomic oxygen surface erosion, however, use monoenergetic fluxes to irradiate samples. There should be a way to relate space results to ground-test data. Such a method would allow the use of ground testing to obtain the susceptability of new materials to atomic oxygen erosion without having to undergo space tests. An analytical technique for accomplishing this is outlined in the following paragraphs. This technique will show how ground-test data can be used to predict the same erosion as the flight results. The Kapton data base is used as an example, and then the technique is generalized to other materials.

Analysis

The analysis is based on data indicating that the mass loss due to atomic oxygen impact on Kapton are functions of the incident particle energy. The data for this relationship, replotted from Refs. 6 and 9, are shown in Fig. 1, and follow the relationship

$$ML = K\,E^b \text{ (g/oxygen atom)} \tag{1}$$

where

$K = 2.49 \times 10^{-24}$

$b = 0.6$

E is in eV

The constants K and b were obtained from the curve in Fig. 1. It must be recognized that the data quoted here come from several different sources and from measurements made with different techniques. The available data below 5 eV to support this curve are sparse. However, a trend does appear to exist as shown in Fig. 1 and it should not be ignored.

The mass loss can be converted to a volume loss by dividing by the material density. For Kapton ($\rho = 1.42$ g/cm^3), this results in the following expression:

$$R = ML/\rho \tag{2}$$

Combining Eqs. (1) and (2) results in

$$R = (1.69 \times 10^{-24})\,E^{0.6} \text{ (cm}^3\text{/oxygen atom)} \tag{3}$$

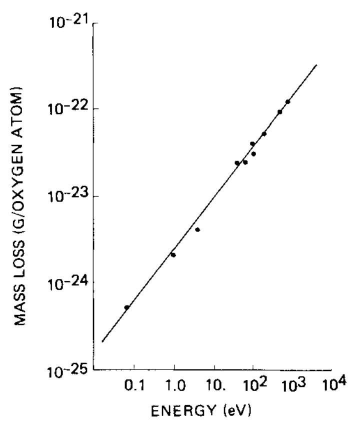

Fig. 1 Mass loss in Kapton samples.[7,10]

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*Senior Staff Engineer, Power Systems and Integration Laboratory. Member AIAA.

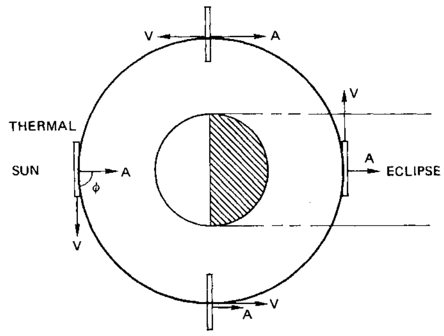

Fig. 2 Changes in velocity orientation over orbit.

The thickness loss rate can be found by multiplying Eq. (3) by the flux of atomic oxygen particles swept out by the surface.

The impact energy of the atomic oxygen under space conditions is dependent on the spacecraft velocity and the orientation of the surface relative to the velocity vector. For this analysis only circular orbits were considered, although the technique can be applied to elliptical orbits. The spacecraft velocity is obtained as a function of the spacecraft altitude. For a specific spacecraft surface, the orientation changes over the orbit for an inertially stabilized spacecraft. If the spacecraft is gravity-gradient stabilized, then one side will always be in the velocity direction, and the material loss for surfaces facing in the velocity direction will be a constant over the orbit. This technique has been worked out for an inertially stabilized spacecraft but can be generalized for other cases.

The inertially stabilized spacecraft are fixed as the spacecraft revolves in orbit. This is illustrated in Fig. 2 showing the orbital positions of a large solar array in equatorial orbit. At local noon and midnight, the panel area normal A and the velocity are at right angles. At dusk and dawn they are aligned. The kinetic energy for collisions between this rotating surface and the assumed stationary atomic oxygen environment is then a function of this angle:

$$E = 1/2\ M(V \cos\phi)^2 \text{ (eV)} \tag{4a}$$

$$E = 8.3 \times 10^{-12}\ (V \cos\phi)^2 \text{ (eV)} \tag{4b}$$

where M is the oxygen mass, V is the spacecraft orbital speed (cm/s), and ϕ is the angle between the surface normal and the velocity. Hence, the mass loss can now be found by inserting Eq. (4) in Eq. (1).

$$ML = 5.59 \times 10^{-31}\ V_{1.2}\ (\cos\phi)^{1.2} \text{ (g/oxygen atom)} \tag{5}$$

The flux of oxygen atoms striking the surface can be computed from the relationship

$$N = ND\ V \cos(\phi) \text{ (number atoms/cm}^2-\text{s)} \tag{6}$$

where ND is the number density (atoms/cm^3), and V is the spacecraft speed.

The atomic oxygen number density can be obtained as a function of solar activity.[10] Day/night variations in the atomic oxygen density have not been considered in this analysis.

Combining all of these effects results in the following mass loss rate:

$$\begin{aligned} MLR &= K \cdot N \cdot E^{0.6} \\ &= 5.59 \times 10^{-31}\quad ND \quad v^{2.2}\ (\cos\phi)^{2.2}\ (g/cm^2-\text{s}) \end{aligned} \tag{7}$$

This relationship predicts that the mass loss depends on the 2.2 power of the angle. From Shuttle flight data, the loss dependence on angle was to the 1.5 power.[3] Considering the variation in the flight data, this is a reasonable agreement.

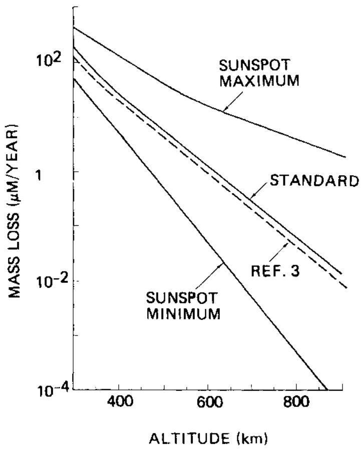

Fig. 3 Predicted material loss as function of altitude single-sided erosion in Kapton.

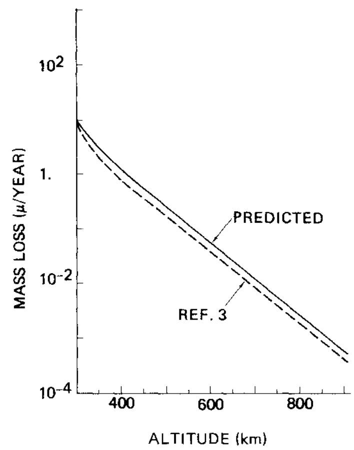

Fig. 4 Predicted material loss in Teflon standard atmosphere.

The exposure time T can be obtained from the orbit period as a function of altitude. Since only one side of the surface will face in the velocity direction for inertially stabilized spacecraft, only half of the orbit period needs to be considered. The material loss due to an interaction with atomic oxygen particles at thermal energies is assumed to be too small to have an impact on the loss. The mass loss per orbit for a specified area can then be obtained by integrating this expression over angles from $+90$ to -90 deg. If both sides of a surface can be eroded by atomic oxygen impacts, then the total loss can be obtained by doubling this result. As stated before, the mass loss can be converted to a change in thickness by dividing by the material density ρ. This will eliminate the need for a specific area and results in the following expression:

$$TL = ML\ *\ (T/\rho) \tag{8a}$$

$$TL = \frac{5.59 \times 10^{-27}}{\rho} ND \int_{-90}^{90} (V \cos\phi)^{2.2}\ T\ d\phi\ (\mu m/\text{orbit}) \tag{8b}$$

This expression is solved on a personal computer by summing the loss in 1-deg increments. The atomic oxygen number density ND varies with the solar cycle, the spacecraft surface velocity V is determined for a specified orbit, and time T is the duration spent in the 1-deg interval. The result can be converted to loss per year by multiplying by the number of orbits per year.

Using the technique proposed in this Note, the projected loss per year as a function of altitude and solar activity is shown in Fig. 3. Also shown in Fig. 3 is the predicted value for Kapton loss using a reaction efficiency of 2.6×10^{-24} cm^3/atom from

Ref. 3. The agreement is excellent. Similar agreement has been found for both minimum and maximum atomic oxygen densities. Hence, this technique relates Kapton ground data to space-flight results.

This analysis can be extended to other materials. If the reaction efficiency is known, then the constant K would be equal to the reaction efficiency times the material density. This approach assumes that the energy dependence remains at 0.6 power. This was done for Teflon, and the results compared with those given in Ref. 3 (see Fig. 4). The Teflon reaction efficiency used in this comparison is 1.08×10^{-25} cm^3/atom. The agreement is still good.

If there were a new material for which atomic oxygen surface erosion rate in space was desired, then it could be obtained from ground tests using this technique. The mass loss would have to be obtained at any two different energies so that a curve similar to Fig. 1 could be obtained. The technique from then on is straightforward.

Concluding Remarks

A technique has been developed that allows the computation of material losses due to atomic oxygen erosion of surfaces on an inertially stabilized spacecraft in a low Earth orbit from ground-based test results. The computations have been compared to the results of Shuttle tests, and the agreement is excellent for Kapton and Teflon. The technique can be applied to gravity-gradient stabilized spacecraft. The advantage of using this approach is that it allows ground-test data to be used to predict surface erosion of newly developed materials and coatings. This alleviates the need for separate space-flight testing of all materials and coatings to qualify them for low Earth orbit operations.

Acknowledgment

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Errata

Optimum Heat Rejection Temperatures for Spacecraft Heat Pumps

D. K. Edwards and R. F. Richards
University of California, Irvine, Irvine, California

[JSR 26, pp. 303–307 (1989)]

ON page 305, the fourth sentence under the heading "Constant ϕ_E, ϕ_R HDHP" was printed incorrectly in the published paper, distorting the authors' intended meaning. The sentence should appear as follows (changes have been italicized):

"The lift rises to 280 K, *the drop rises to 320 K*, and M/M_S rises to 0.80."

Closed-Form Approach to Rocket-Vehicles Aeroelastic Divergence

Dov Elyada
Israel Armament Development Authority
Haifa, Israel

[JSR 26, pp. 95–102 (1989)]

A NUMBER of errors were inadvertently introduced during production of this paper. We apologize for any inconvenience caused to the author or the readers.

Page 97:

The plus sign in Eq. (3) was omitted in the published paper; the equation should appear as follows:

$$\begin{Bmatrix} L_N \\ L_T \end{Bmatrix} = QS_r \begin{bmatrix} C_{L_{\alpha N}} & 0 \\ 0 & C_{L_{\alpha T}} \end{bmatrix} \left(\begin{bmatrix} 1 & -l_N \\ 1 & l_T \end{bmatrix} \begin{Bmatrix} \alpha \\ \dot{\theta}/U \end{Bmatrix} + \begin{Bmatrix} \phi_N \\ \phi_T \end{Bmatrix} \right) \tag{3}$$

In Eq. (7d), "(rigid static margin)" is the meaning of the quantity h_0.