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SOLAR CONCENTRATOR DEGRADATION IN LOW EARTH ORBIT (LEO)

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ABSTRACT

The use of parabolically or spherically-shaped mirrors is being considered in order to increase the solar energy intensity on solar cells. Their use will significantly decrease the size and number of the cells needed for a particular application, hence the total array cost. Questions arise, however, regarding the long-term (five to ten years) efficiency of these devices. Performance degradation of the mirror surfaces might result from known hostile elements in the low earth orbit (LEO) environment (150-350 nautical miles). This study addresses the degradation issue in light of present knowledge of this environment.

The following characteristics of the LEO environment are identified for study: (1) the vacuum of space; (2) sputtering by the residual atoms and particles in space; (3) solar electromagnetic radiation; (4) contamination of the mirror surface; (5) atomic oxygen interactions with the surface; (6) bombardment of the surface by meteoroids; and (7) irradiation of the surface by ionizing particles (protons). Using the best available information for the magnitudes of the necessary quantities, we carry-out a mathematical analysis, where possible, to determine the degradation in reflectance or other loss caused by each characteristic. Otherwise, reasonable estimates are made of corresponding losses, based on already published data.

It is concluded that vacuum effects on a reflecting surface are negligible for the temperatures expected in space. Also, negligible is the effect of bombardment of the surface by meteoroids. Solar electromagnetic radiation is found to cause a slight (two percent to six percent) degradation in reflectance within the first year or two of exposure, after which no further change is expected. Atomic oxygen interactions pose great danger to a reflecting surface, because large effects have already been observed on relatively short Space Shuttle missions.

Based on the results and studies of solar radiation and atomic oxygen interactions, both of which are fairly well defined at LEO, it seems likely that these two will combine to produce a degradation in reflectance of at least 10 percent over a five to ten-year period. The low energy (<20 kev) protons could play a major role in the degradation in the reflectance. If the flux is as high as 10^{10} /cm^2/sec, the degradation is likely to be much higher than 10 percent. This will also be the case if atomic oxygen interactions turn out to be considerably higher than assumed here. On the other hand, if the flux is less than 10^8/cm^2/sec, proton effects will probably be negligible.

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INTRODUCTION

As the space program expands and the Space Station becomes a reality, there will be more, and no doubt, larger devices needing electrical power. At least part of this need is likely to be satisfied by the use of solar cells, continuously changed in position to track the sun. In order to minimize the number needed (and hence cost) of these rather expensive devices, consideration is now being given to the use of concentrators that will increase the intensity of energy falling on each cell. The concentrators are likely to be of some parabolic or spherical design, with a reflective coating of aluminum, nickel, silver, or some other suitable material. The mirror coatings may or may not be protected by a thin, transparent outer oxide layer of silicon, depending on circumstances. For both kinds (coated and uncoated), but particularly the bare unprotected surfaces, there is some concern that their initially high reflectivities might decrease significantly before the period of planned use (five to ten years) has expired, as a result of their exposure to the LEO environment. The purpose of this study is to investigate the long-term (five to ten years) effect that the near-earth (150-350 nm) environment is likely to have on the specular reflectance of these mirrors.

THEORY AND RESULTS

At LEO, we will consider the following known characteristics of space as being potentially damaging to optical surfaces: (a) the vacuum of space; (b) sputtering phenomena; (c) solar electromagnetic radiation; (d) contamination by thin films; (e) atomic oxygen interactions; (f) bombardment by meteoroids; and (g) irradiation by ionizing particles.

The Vacuum of Space

At a distance of 125 miles from the surface of the earth, atmospheric pressure is about 10^{-6} mm of Hg. At this low value, there is the possibility that molecules of the solid reflective surface will evaporate into the surrounding vacuum much faster than they return to it. The Langmuir equation (1) describes this process and is written:

$$(1) \quad W = P/17.14\ (M_s/T)^{1/2} \quad \text{where}$$

W = rate of evaporation ($gm/cm^2/sec$)

P = vapor pressure of the material (mm Hg)

T = temperature (^0K)

M_s = molecular weight of the surface material in the gas phase

The vapor pressure of Al is 10^{-10} atm at 744^0C. Using these figures in equation (1), one finds an evaporation rate of 0.084 mm/year. This is a rather large rate but poses no serious problem, because the temperature is much higher than will be encountered at LEO. At LEO temperatures (-70^0C to $+50^0C$), the vapor pressures of all commonly used reflecting metals are considerably smaller than 10^{-10} atm. It is believed, therefore, that this effect will at most cause a very slow decrease in optical reflectivity due to possible differences in evaporation rates in different grains of the metal.

Sputtering Phenomena

The removal of atoms from the reflecting surface as a result of its bombardment by low energy (<1 mev) atoms and ions in the environment is called "sputtering". A threshold energy exists for doing this that depends on the nature of the impinging atom or ion and of the surface. For protons hitting an aluminum surface, this threshold is found to be about 0.5 kev, while it is about 0.1 kev for nitrogen or oxygen atoms. For atoms and ions with energies above their threshold values, it can readily be shown that

$$(2)\quad \Delta t_s = \phi\, \varepsilon\, M_s/\rho A_v \quad \text{where}$$

Δt_s = rate of decrease in thickness of the film (cm/sec)

ϕ = incident flux of atoms or ions (no/cm^2/sec)

ε = yield, the number of surface atoms liberated/incident atom

ρ = density of the reflective material (gm/cm^3)

A_v = Avogadro's Number

The greatest uncertainties in the use of equation (2) for LEO are in the yield factor and the incident flux of protons. Using the best available estimates of these, we find the sputtering loss due to residual air (oxygen and nitrogen) will be about 0.15 Å/year. This is considered a negligible amount. On the other hand, the low energy protons at LEO will potentially sputter off about 100 Å/year, which is a relatively large amount.

Solar Electromagnetic Radiation

The effect of ultraviolet radiation on a bare aluminum surface has been studied (2), and a reproduction of one of the graphs resulting from this study is shown in figure 1. In this study, a mercury-arc lamp was used as the source of U-V radiation. The most striking feature of these curves is the saturation effect that appears after about 2,000 Equivalent Space Sun Hours (ESSH). After this time, there is essentially no further change in reflectance. If one assumes continuous sun exposure, 2,000 hours will be accumulated in about three months. At an exposure of 8 hours/day, one sees that maximum degradation of two percent to six percent will occur in about nine months.

Contamination by Thin Films

At every stage in the assembly and deployment of a mirror, great care must be taken to see that the surface is kept clean. Additionally, a thin film of carbon or other contaminant material can form from organics used in surrounding parts of the structure, if they outgass significantly. Bremer (3) has calculated the maximum allowable contaminant film thickness that will lead to a degradation of 10 percent in reflectance. His conclusion is that a film about one nanometer thick will produce such a loss. In a study of this problem, Gillette (2) used a source of protons. It has been observed over the years in the laboratory that radiation, too, can cause the buildup of a contaminant film. He estimated that a film from 0.5 to about 1.5 nanometers accumulated in three to four hours exposure at 16 kev, $10^{13}/cm^2/sec$. If one assumes that the buildup time varies inversely with beam intensity, then at the assumed intensity of the protons in LEO ($\sim 10^{10}/cm^2/sec$) a 10 percent degradation in reflectance, due to this effect, might be expected to occur in about five or six months of exposure. On the other hand, if the flux is less than $10^8/cm^2/sec$, as has been estimated in another source (8), no film buildup will occur.

Atomic Oxygen Interactions

On the first three missions of the Space Shuttle, it was observed that physical changes occurred in some of the commonly used materials after exposure to the space environment. Following this observation, a series of specially selected materials was set up in an experiment designed to investigate this effect. A report of the results of this exposure has been made (4). In the series were a group of thin films (100 Å - 2,000 Å) of silver, carbon, and osmium. The osmium was completely lost through evaporation, while the silver was completely oxidized. In another test, aluminum was exposed, but the results were inconclusive. It is now thought that these changes are due to the chemical action of oxygen in the environment on the surface atoms. Because of its similarity to sputtering, this process is sometimes considered to be a form of it. (8) No loss rates have been established for the metals likely to be used as reflector coatings. On the other hand, a large loss of 5.25 mils is predicted for kapton and mylar over a ten-year period. On the basis of the size of this effect, the behavior of silver in a very short time, and the uncertainty in the behavior of aluminum, one has to be concerned about this interaction.

Bombardment by Meteoroids

Meteoroids are very small solid particles moving in interplanetary space. A model of the flux-mass distribution has been constructed and is given in figure 2. (5) To simulate the behavior of these particles striking a mirror surface, Bjork designed a mathematical model. (6) This model, which has been verified experimentally, predicts that the bombardment will result in hemispherical craters being formed in the mirror surface. The radius of a crater is given by:

$$(3) \quad r = C\,(mv)^{1/3} \quad \text{where}$$

r = radius (cm)

m = mass of projectile (grams)

v = impact velocity (km/sec)

C = a constant that depends on the target

Bjork found C = 1.09 for Al on Al, and 0.606 for Fe on Fe. In this study, we set C = 1. The analysis of meteoroid damage consists of calculating the fraction of the total area of a reflector damaged by strikes. It is assumed that no two particles strike the same area, that all are moving with the average speed of 20 km/sec (5), that the damaged area has a lower constant average reflectance, and that meteoroids have the mass and flux distribution given in figure 2. The result of this analysis is that there will be no damage from this source, because of the smallness of the flux and masses of the meteoroids.

Irradiation by Protons

While the very low energy protons will be unable to penetrate the reflecting surface and will interact basically by sputtering, those at some slightly higher energies will penetrate to depths that depend on their energies. If the energy is too high, they will pass through the thin film with little or no damage. In the range of energies that result in their being stopped in the film, radiation damage may occur. This phenomenon was observed for a bare aluminum reflector by Gillette. (2) He found that severe blistering of the film resulted from an exposure of 10^{17} protons/cm^2 of 16 kev energy. He estimated their range in Al to be 3500 Å. Using these figures, one readily finds this to be a radiation dose of 2.7×10^{11} rads (1 rad = 100 ergs/gm). Fuller (7) estimates that radiation damage occurs for an exposure between 10^8 and 10^{12} rads. Another estimate (8) places this threshold at about 10^{14} rads for Al and other metals. Gillette's results tend to support the smaller estimate. We have previously assumed a flux of $10^{10}/cm^2/sec$ of low energy solar protons. Their average energy, however, is lower than 16 kev. Assuming this value is say 2 kev, we find the dose rate to be 8.54×10^{11} rads/year. On the basis of the above results, one would certainly expect blistering of this material under these conditions.

CONCLUSIONS

Since all of the processes that have been considered are actually occurring simultaneously in LEO, the question naturally arises as to their combined effect on a reflecting surface. There does not appear to be a way, a priori, of combining these effects. Nevertheless, some reasonable conclusions can be drawn.

Vacuum effects on a reflecting surface are negligible for the temperatures expected in space. Also negligible is the bombardment of the surface by meteoroids. Of the remaining five characteristics considered, protons are involved in three. The remaining two, solar electromagnetic radiation and atomic oxygen interactions, are both fairly definite processes that have already been observed, and to some extent studied. Based on these studies, it appears likely that they will combine to produce a degradation in reflectance of at least 10 percent over a five to ten-year period. Such a minimum degradation will be independent of the material used, its size, or how it is exposed (bare or protected) to the environment. The fact that protons are involved in three of the characteristics emphasizes the need to know this flux distribution more accurately. If the flux is as high as we generally assumed ($10^{10}/cm^2/sec$), the degradation in reflectance is likely to be much higher than 10 percent. This will also be the case if atomic oxygen interactions turn out to be considerably higher than assumed here. On the other hand, if the flux is less than $10^8/cm^2/sec$, proton effects will probably be negligible.

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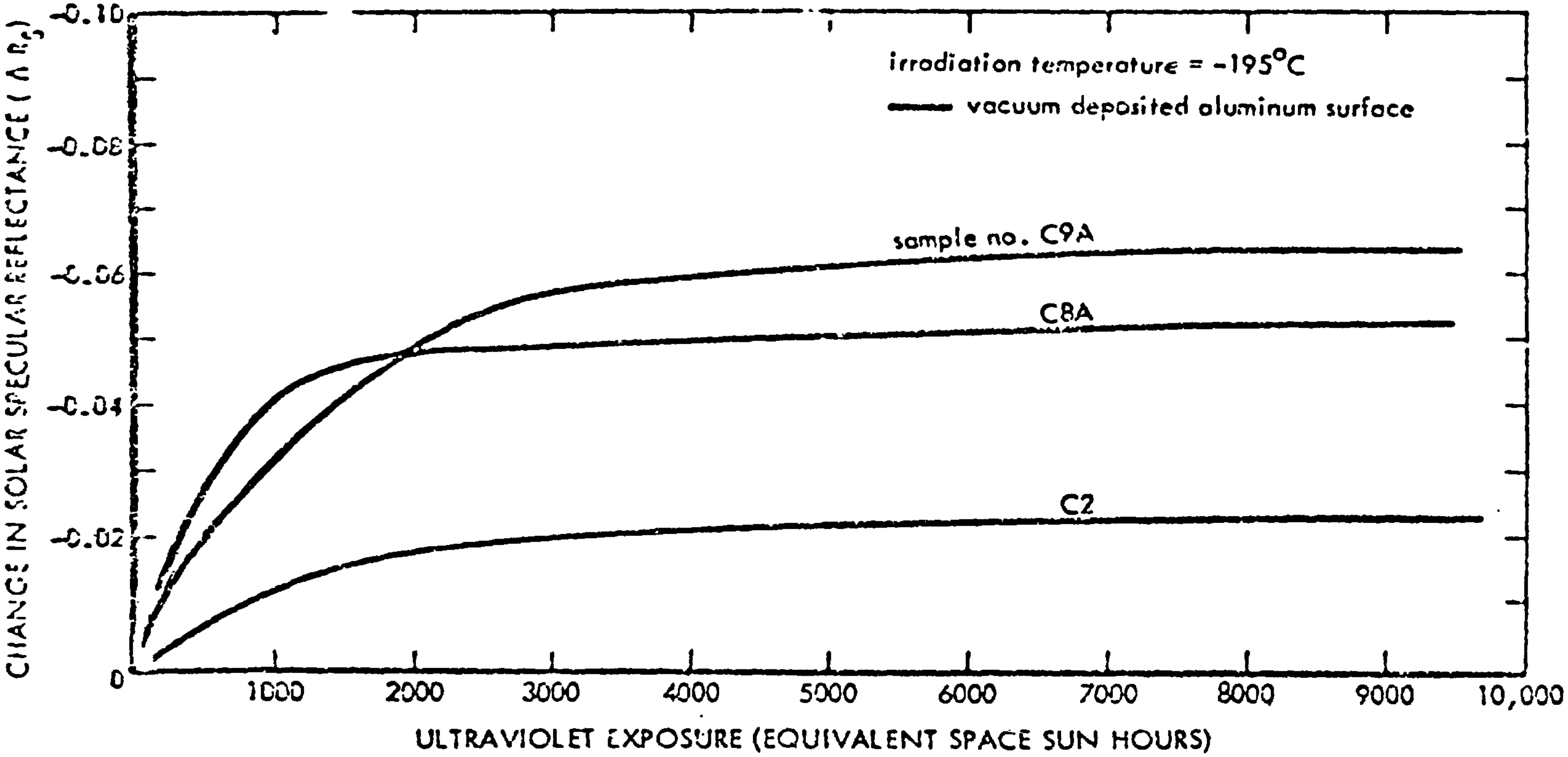

Figure 1. Effect of Ultraviolet Radiation on Solar Specular Reflectance of Nickel Substrate Mirrors (From Reference 2)

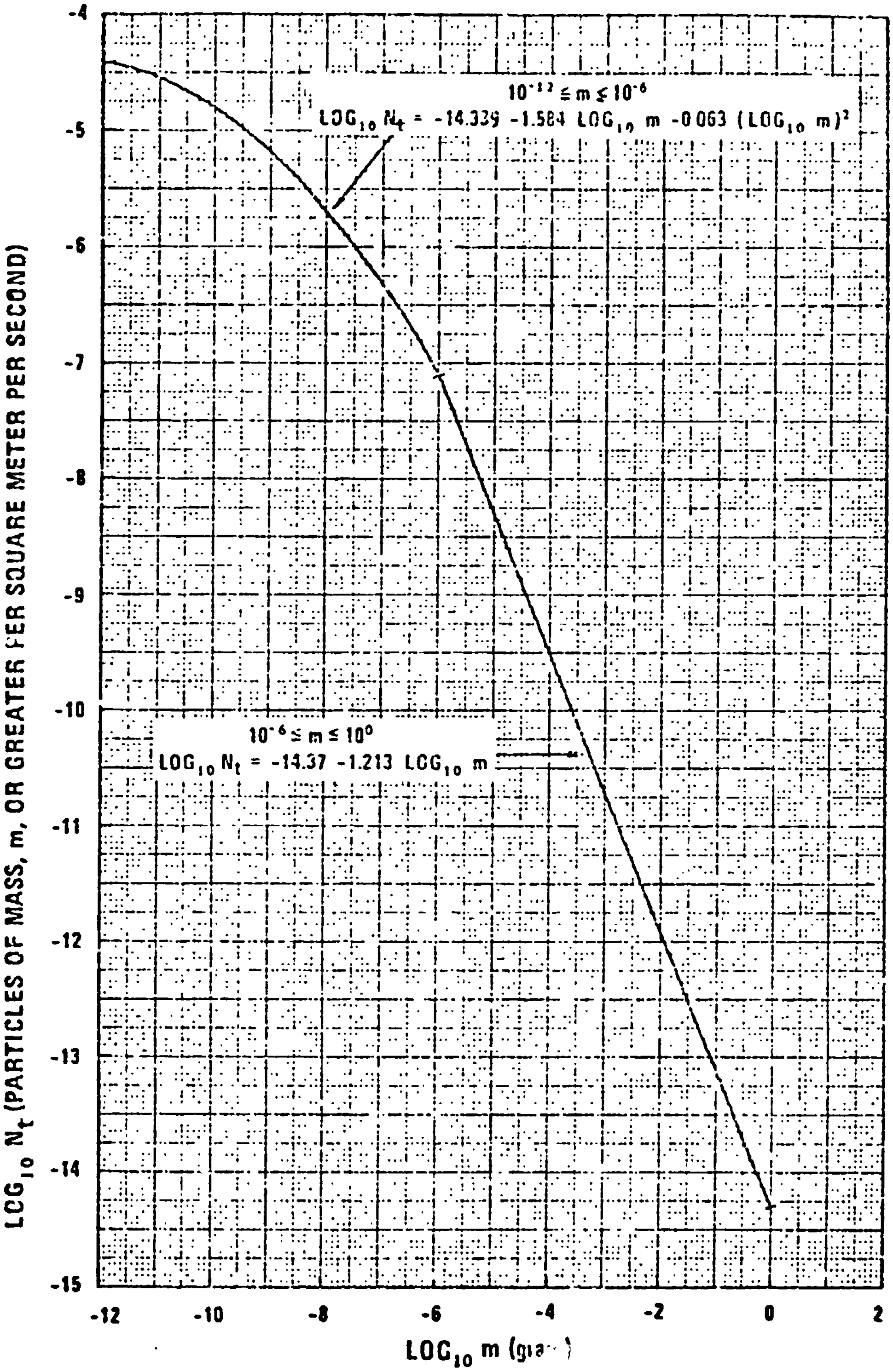

Figure 2. Average Cumulative Total Meteoroid Flux-mass Model for 1 A.U. (From Reference 5)

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