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EFFECT OF MICROMETEORITE COLLISIONS ON SPHERICAL WIRE-MESH PASSIVE REFLECTORS

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PREPARED FOR:
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

This study was conducted under NASA Contract NASr-21(02), monitored by the Director of Communications Systems, under the Office of Applications. It is one of a series of studies dealing with technical aspects of passive communications satellites, and will be included as an appendix to a forthcoming comprehensive report on passive communications satellite systems.

SUMMARY

This Memorandum investigates the possible effects of micrometeorites in reducing the useful lifetime of a spherical wire-mesh passive-reflector communications satellite. Theoretical conditions are postulated under which a wire composing part of the mesh might be severed by a hypervelocity collision with a micrometeorite. This criterion, taken with the known flux of micrometeorites, is used to compute the probability that such collisions will degrade the electrical performance of such a reflector. It is concluded that they will not significantly affect its useful lifetime.

CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The useful lifetime of an Echo-type spherical reflector can be strongly affected by collisions with micrometeorites, which permit the reflector to deflate and thereby radically alter its scattering cross-section. In the case of a spherical reflector whose surface contains a wire mesh, if a significant number of mesh elements is cut, the principal effect may be an electrical degradation of the scattering cross-section.

The physical effect of such collisions is estimated in this document and the results presented in the form of time plots of the fractional number of surviving (i.e., uncut) mesh elements for a variety of mesh sizes and wire diameters. When the reflector size is very much larger than a wavelength (as it is in all cases of interest) there are many mesh elements and the plots will conservatively approximate the fractional reduction in average scattering cross-section with time. It is concluded that micrometeorite collisions do not significantly affect the useful life of spherical wire-mesh reflectors.

II. MICROMETEORITE FLUX

The essential physical characteristics of the micrometeorite flux in the vicinity of the earth are discussed in Refs. 1-3. Micrometeorites are believed to have the density of stone, viz., 2.8 gm/cc, which leads to an estimate of 10^{-13} gm as the minimum mass which will not be blown from the solar system by radiation pressure.

The range of velocities is from 11 to 72 km/sec where the limits represent, respectively, the earth's escape velocity and the largest velocity with respect to the earth of a closed orbit about the sun; the average velocity is about 30 km/sec. The flux of particles with mass greater than m grams is given by

$$F = 10^{-16}\ m^{-10/9} \quad \text{particles/cm}^2\ \text{sec} \qquad (1)$$

A tenfold diurnal variation is experienced since most of the micrometeorites are encountered on the advancing face of the earth.

III. REQUIREMENT FOR CUTTING A MESH ELEMENT

HYPERVELOCITY COLLISIONS

A hemispherical crater results(4) when a projectile strikes a large body at a velocity greater than about 5 km/sec. Where the projectile and target are both of aluminum, the radius of the crater in cm is given by(1-4)

$$p = 1.09\ (m\ v)^{1/3} \tag{2}$$

where m is the mass of the projectile in grams and v is the component of velocity normal to the surface in km/sec. (A spherical projectile impacting at 30 km/sec produces a crater with a radius almost 4 times the projectile diameter.) The crater departs from a hemispherical shape when the angle of incidence exceeds more than about 65° to 70° from the normal.

If the target is in the form of a slab, then penetration occurs when the radius of the crater exceeds about two-thirds the thickness of the sheet. This is due to the large tensional stress which causes spalling as the shock wave is reflected internally at the opposite face.

THEORETICAL CUTTING CRITERION

The mesh elements can be approximated as right circular cylinders of aluminum with length ℓ and diameter d. The craters produced by micrometeorites much smaller in diameter than the mesh element will be very nearly given by Eq. (2). However, when the crater which would have been produced in a large body approaches the dimensions of the mesh element, the behavior undoubtedly departs from this ideal.

If it is assumed that a slab is actually penetrated even though its thickness is 50 per cent greater than the theoretical crater radius, it can be argued that the damage to the cylindrical mesh elements will also be more severe because of internal reflections. Thus, a conservative criterion is to assume that a mesh element will be cut whenever the cratering diameter given by Eq. (2) equals or exceeds the diameter of the mesh element, i.e.,

$$2\,p \geq d \tag{3}$$

A compensating (and simplifying) assumption, which is fortified by the weak velocity dependence in Eq. (2), is to ignore the effect of the micrometeorite velocity distribution, as well as the effect of nonnormal incidence, by using the average velocity of 30 km/sec. Combining Eqs. (2) and (3) then gives

$$m \geq \frac{d^3}{311} \tag{4}$$

as the lethal micrometeorite mass in grams when the mesh element diameter d is in cm.

WIRE-GRID DETECTORS

Micrometeorite fluxes are usually measured by acoustic detectors in which individual collisions are detected if they exceed a known threshold of momentum. Another technique which is pertinent to the wire-mesh problem employs a wire grid whose electrical continuity is monitored periodically to detect breaks caused by micrometeorite collisions.

If good data were available from wire-grid detector measurements, they would be directly applicable to the wire-mesh problem and would eliminate the need for relating the detection sensitivity (i.e., the cutting criterion) to the expected flux in estimating the probability of severing a wire. Unfortunately, the results to date have been inconclusive. Simultaneous acoustic and wire-grid measurements of micrometeorite flux from satellites $1960\zeta1$ (Midas II) and $1960\alpha1$ (Midas I) appear to differ by about two orders of magnitude.(5) In both instances, the acoustic measurements were roughly consistent with prediction while the wire-grid measurements indicated low micrometeorite fluxes.

Furthermore, the threshold used in the satellite measurements was considerably greater than the theoretical value estimated by Eq. (4) above. The satellite wire grids were 20 microns in diameter and it was assumed that they would be broken by particles 10 microns or larger in diameter; a velocity of 15 km/sec was apparently assumed. A threshold of 5 microns is given by Eq. (4) for the same velocity (which, incidentally, seems somewhat low for an average).

The wire-grid detector calibration reference(6) on which the 10-micron threshold was based actually concludes that "a particle less than 50 microns and probably less than 20 microns in diameter would break the (17 micron) wires on a grid on impacting at meteoric velocities (10 to 14 km/sec)." Inasmuch as the micrometeorite flux is very nearly inversely proportional to the mass, it is clear that an order of magnitude error is involved when the threshold particle diameters [redacted] differ by a factor only slightly greater than 2.

These inconsistencies are presently unresolved. The wire-grid flux measurements are sketchy at best and therefore should not be used here in preference to the acoustic measurements despite their apparent applicability. On the other hand, the experimental wire-grid calibrations, though crude, are probably preferable to the theoretical criterion established in Eq. (4). For this reason, despite Eq. (3), the lethal micrometeorite size will arbitrarily be taken as that which would produce a cratering diameter equal to or greater than twice the mesh element diameter, i.e.,

$$p \geq d \tag{5}$$

yielding a lethal micrometeorite size in grams of

$$m \geq \frac{d^3}{38.9} \tag{6}$$

where the mesh element diameter is in cm.

IV. COLLISION PROCESS

The flux of lethal micrometeorites, from Eqs. (1) and (6) is

$$F = \frac{6 \times 10^{-15}}{d^{3.33}} \quad \text{particles/cm}^2 \text{ sec} \tag{7}$$

while the average physical cross-section of the cylindrical mesh element over all orientations is $(\pi/4)\ell d$. Thus, an individual mesh element will encounter lethal collisions at the rate of

$$r = \frac{3\, \pi \times 10^{-15}\, \ell}{2\, d^{2.33}} \quad \text{collisions/sec} \tag{8}$$

where the dimensions are in cm.

The passage of a mesh element through a field of micrometeorites can be regarded as a succession of independent experiments. During some arbitrary, short interval of time there exists a probability that a collision with a micrometeorite will occur. If there is no collision, the experiment is repeated, in a sense, during the next interval of time but with a new, and independent, set of micrometeorites.

If the individual probabilities are small and a large number of independent "experiments" are performed, then the process is described by a Poisson distribution and the probability of x occurences is given by

$$P(x) = e^{-m}\, m^x/x! \;, \quad m > 0,\ x = 0,\ 1,\ 2,\ \ldots \tag{9}$$

where m is the mean number of occurrences.

The micrometeorite collision process satisfies these requirements, in general. However, the mean number of collisions (i.e., occurrences) in a time t is not simply given by the product of the average hit rate and the length of the interval, since the average micrometeorite flux

[redacted]

displays a diurnal variation. Consequently, the mesh elements will experience significantly fewer micrometeorite collisions when "behind" the earth with respect to its orbital motion.

The fraction of the orbital period during which this occurs will depend of course, on the orientation, shape and altitude of the orbit. Since the time intervals of interest are considerably greater than the orbital periods, the diurnal effect can be accounted for by an arbitrary expansion of the time scale by a factor of 3/2 if the orbital altitude does not exceed a few thousand miles. In effect, this amounts to assuming that micrometeorite collisions occur only two-thirds of the time.

The mean number of occurrences in a time t then becomes (2/3) rt where r is the average hit rate given by Eq. (8). Accordingly, from Eq. (9), the probability of no collisions (i.e., $x = 0$) in a time t is

$$P(0) = \exp\left[-\frac{\pi \times 10^{-15}\,\ell\, t}{d^{2.33}}\right] \tag{10}$$

where the dimensions are in cm and time is in sec. For an ensemble of many mesh elements, this probability is also numerically equal to the fraction of the dipoles surviving unhit after a time t. Equation (10) is plotted in Fig. 1 as a function of time for the mesh element diameters and lengths tabulated below.

MESH ELEMENT LENGTH

Operating Frequency (Mc)	Mesh Element Diameter (mils)			[redacted]
	1	3	10	[redacted]
[redacted]	Mesh Element Length (cm)			[redacted]
2000	1.275	1.5	1.875	
8000	0.394	0.488	0.638	[redacted]

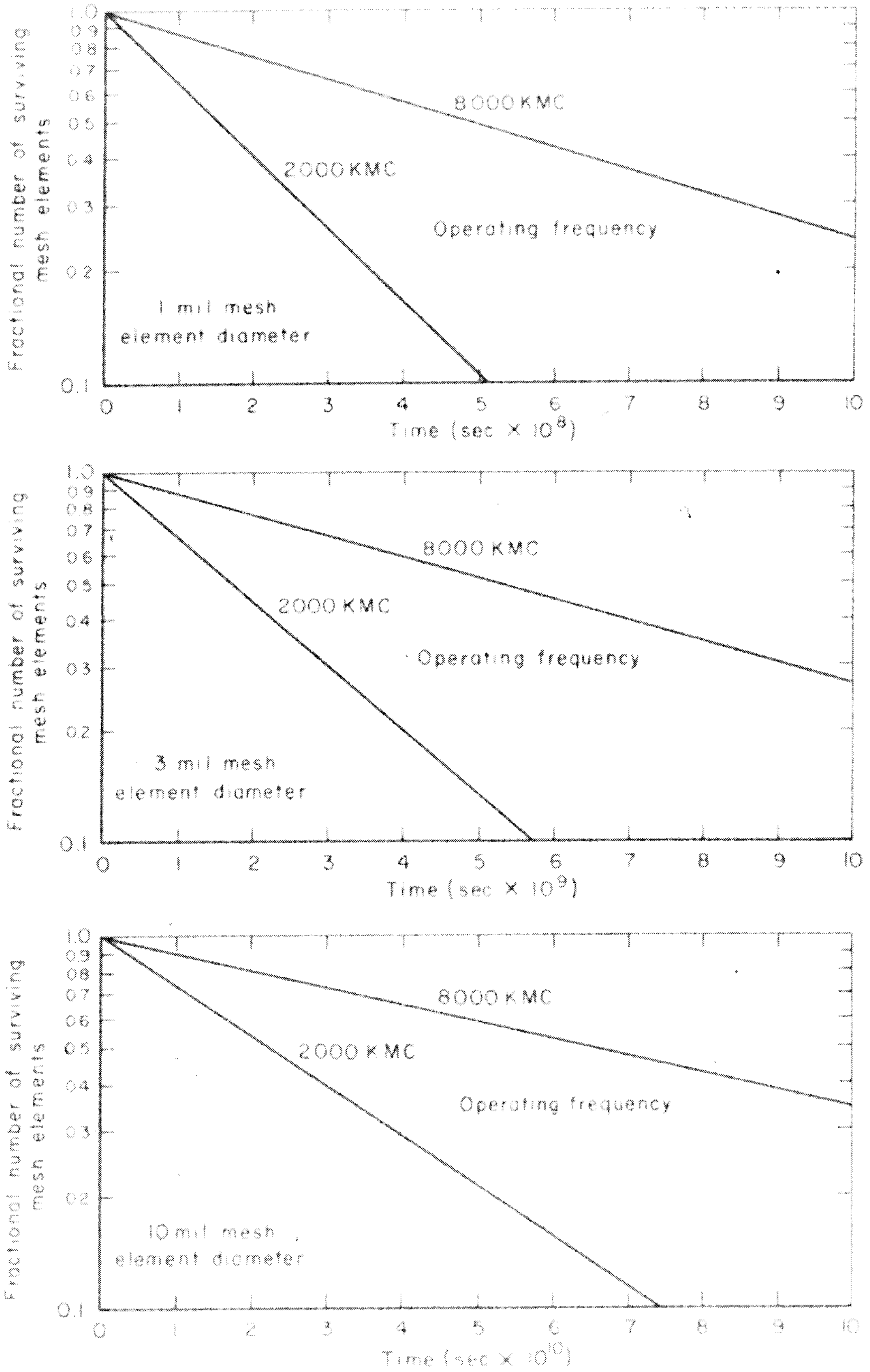

Fig. 1 — Survival rates for orbiting wire-mesh reflectors

V. CONCLUSIONS

The problem of relating the cutting of mesh elements to the reduction in scattering cross-section seems more amenable to experimental than to theoretical analysis. However, it is possible to draw a useful conclusion in this case because the desired result can be bounded from below.

A typical measure of "lifetime" for exponentially decaying processes is the time required for some significant parameter to be reduced to 1/e of its original value. From Eq. (10) the life of the mesh elements can then be taken as

$$T = \frac{d^{2.33}}{\pi \times 10^{-15} \, \ell} \quad \text{sec} \tag{11}$$

which is plotted in Fig. 2 for the two frequencies of interest as a function of mesh-element diameter.

It is not likely that the scattering cross-section will also be reduced to 1/e of its original value in the same period of time because of mutual coupling effects and the presence of many alternate paths for the induced currents. Thus, Eq. (11) constitutes a conservative estimate. Inasmuch as the lifetime predicted by Eq. (11) is generally large compared with the periods of interest in communication satellite systems, it can be concluded that the cutting of elements in spherical wire-mesh reflectors is not a significant factor influencing its useful electrical life, where mesh-element diameters are greater than 1 mil.

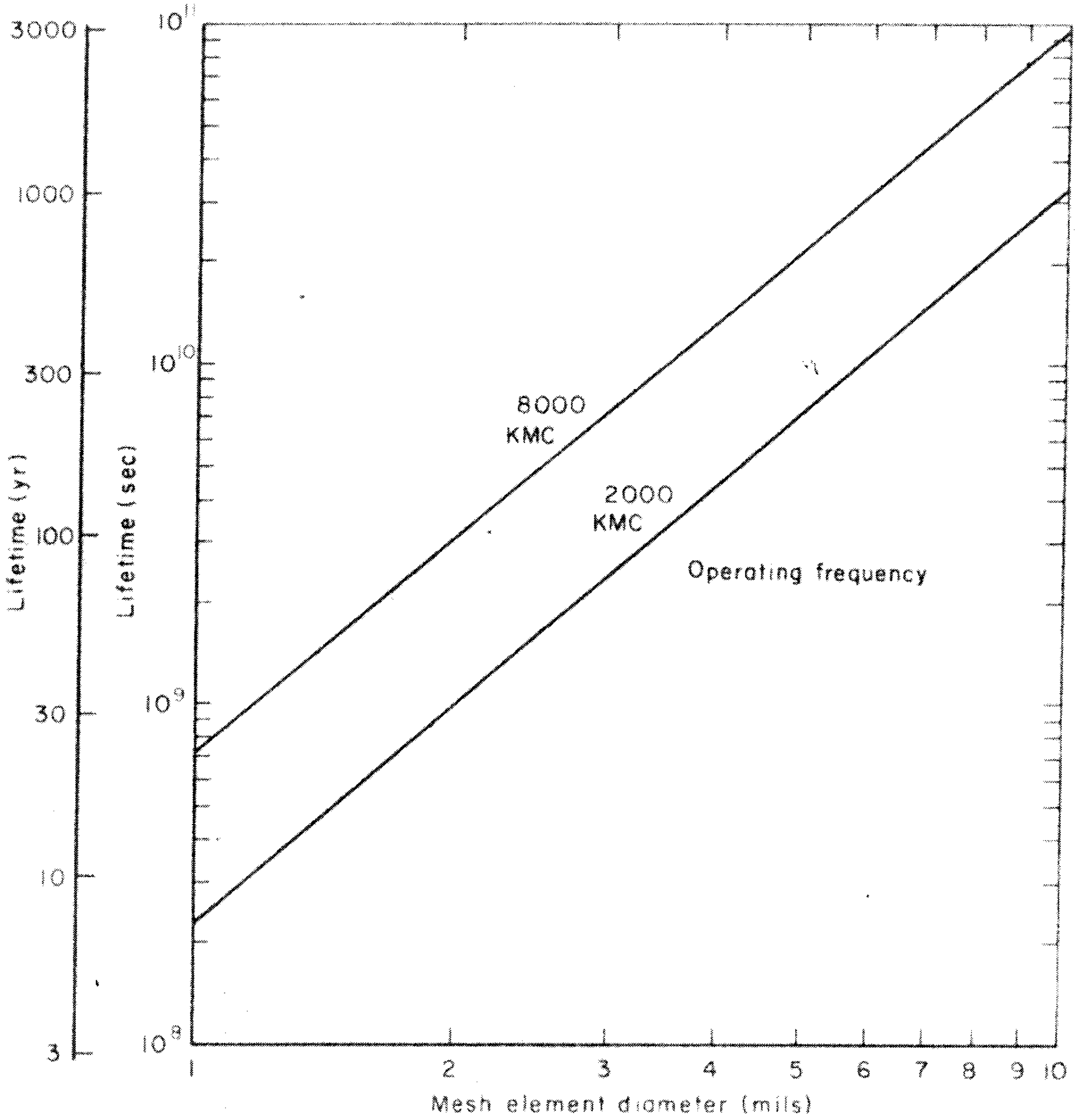

Fig 2 — Lifetime for orbiting wire-mesh reflectors

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