Assessment of the Effects of Space Debris and Meteoroids Environment on the Space Station Solar Array Assembly

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ASSESSMENT OF THE EFFECTS OF SPACE DEBRIS AND METEOROIDS ENVIRONMENT ON THE SPACE STATION SOLAR ARRAY ASSEMBLY

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ABSTRACT

In this paper, the methodology used to assess the probability of no impact of space debris and meteoroids on a spacecraft structure was applied to the space station solar array assembly. Starting with the space debris and meteoroids flux models, the projected surface area of the solar cell string circuit of the solar array panel and the mast longeron, and the design lifetime, the probability of no impact on the solar array mast and solar cell string circuits was determined as a function of particle size. The probability of no impact on the cell string circuits was used to derive the probability of no open circuit panel. The probability of meeting a certain power requirement at the end of the design lifetime was then calculated as a function of impacting particle size. Coupled with a penetration and damage models/correlations which relate the particle size to the penetration depth and damage, the results of this analysis can be used to determine the probability of meeting the power requirement given a degree of redundancy, and the probability of no impact on the solar array mast.

INTRODUCTION

The meteoroids and debris environments consist of particles of different diameter and density moving at high velocities in the space environment. Micrometeoroids range in size from 10^{-4} to 10 cm, with a mean density of 0.5 g/cm^3, and a mean velocity of about 20 km/sec. Although micrometeoroids originate from cometary and lunar sources, space debris are man made and range in size from microscopic particles to particles of 100 cm in effective diameter. Since space debris originate from useless orbiting spacecrafts, they exhibit an average orbital velocity of 9 to 10 km/sec depending on the orbital inclination, with an average mass density of 2.8 g/cm^3 for particles less than 1 cm in diameter. Micrometeoroids and space debris flux models (Fig. 1) can be used to estimate the flux of certain particle diameter or greater (1). The concern for the damage resulting from the impact of particles moving with hypersonic velocities necessitates the assessment of the number of impacts and their effects on the space station photovoltaic solar array integrity and performance.

The purpose of this paper is to analytically assess the probability of success of the space station solar array components (or subassemblies such as the solar array mast and blanket) as a function of the impacting particle diameter for both meteoroids and debris environments. Probability of success of the mast is defined as the probability that the mast meets the lifetime requirement with no impact-induced failure. Probability of success of the blanket is defined as the probability that the blanket meets the power requirement over the mission duration. Determination of the penetrating particle size and correlation of the particle size and damage are not presented in this paper due to the lack of such data as applied to the solar array structure and materials.

DESCRIPTION OF THE SPACE STATION SOLAR ARRAY

The space station solar array consists of two photovoltaic blankets for power generation, a mast for blanket deployment, a canister for mast stowage, two blanket boxes for blanket stowage during launch, and a deployment mechanism for on-orbit array deployment. Each blanket consists of active panels structurally connected by hinge pins. Each panel contains solar cells interconnected by print-etched copper circuits encapsulated between two Kapton[1] layers. The cells are welded to the copper pads and mounted on the Kapton substrate by an adhesive (2). The space station solar array is illustrated in Fig. 2 (3). Figure 3 shows the repeating units that were used to analyze the probability of success (or probability of meeting a power or lifetime requirement) of the mast and blanket of the solar array. These units are the mast bay and the cell string of the panel.

ANALYSIS

Solar Array Mast

The mast and blanket subassemblies of the solar array were under consideration in this analysis. To quantify the impact assessment on the

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[1]Registered trademark of E.I. Dupont De Nemours and Co., Inc.

solar array mast, the probability of no impact on the mast S-glass epoxy longerons was calculated from the flux estimate, the projected surface area and the design lifetime. In estimating the micrometeoroids flux, a defocusing factor of 0.98 which accounts for the defocusing of the particle flux by the Earth gravitation was used to correct for this effect. Similarly, a flux factor (1) of 1.5 which accounts for the directionality of the debris flux with respect to the solar array normal and the velocity vector was used. It was assumed in this computation that a particle impact is damaging, and damage of one or more of the three longerons in one bay results in the mast failure. From the above assumptions, the damage criterion can be conservatively construed as the complete loss of mechanical properties of the impacted longeron which results in mast failure. Probability of impact of at most n particles can be calculated from the cumulative Poisson distribution (1)

$$P(n) = \sum_{r=0}^{n} [e^{(-A*F*T)} * (A*T*F)^r]/r! \qquad (1)$$

where F(particles/m^2-year) is the flux, A(m^2) is the exposed area, T(year) is the time and r is the summation index. Probability of no impact (or zero impact) reduces Eq. 1 to

$$P(0) = e^{-A*F*T} \qquad (2)$$

Given P_i as the probability of no impact of the ith longeron in one bay, and Q_i is the probability of one or more impacts on the ith longeron in the same bay, the following is true (4),

$$P_i = 1 - Q_i \qquad (3)$$

and,

$$\sum_{x=0}^{N} \frac{N!}{x!(N-x)!} P_i^x Q_i^{(N-x)} = 1 \qquad (4)$$

where N = 3 because there are three longerons in parallel in one bay. Considering the impact of one or more longerons in a bay as a bay failure, the probability of one bay meeting the lifetime requirement is

$$P(bay) = 1 - \sum_{x=0}^{2} \frac{3!}{x!(3-x)!} P_i^x Q_i^{(3-x)}$$

$$= P(0)^3 = e^{-3*A*F*T} \qquad (5)$$

Moreover, since there are 75 bays in one mast, and since the failure of one bay affects the whole mast, the probability of the mast meeting the lifetime requirement is given by (5),

$$P(mast) = P(bay)^{75} \qquad (6)$$

Solar Array Blanket

The back surface of the solar cell string, (consisting of eight cells in series and one bypass diode in parallel as shown in Fig. 3), was considered for probability of impact analysis of panels and blanket of the solar array. Impacts on the front surface of the solar cells were not assessed because the solar cell is much thicker than the Kapton substrate. Using the geometry depicted in Fig. 3, the probability of no open circuit panel due to meteoroids and debris impact was calculated from the probability of no impact on both the photo-etched circuits connecting two consecutive cells and the circuits connecting cells with the bypass diode. The probability of no open string that, when open, results in an open panel can be summarized by,

$$P(string) = \left[1 - \left(1 - e^{-A_1FT}\right)^2\right]^6 \left[1 - \left(1 - e^{-A_{2s}FT}\right) \right.$$

$$\left. \left(1 - e^{-A_{2\ell}FT}\right)\right]\left(1 - e^{-2A_3FT}\right) + e^{-2A_3FT} \qquad (7)$$

where the areas A_1, $A_{2\ell}$, A_{2s}, and A_3 are shown in Fig. 3. Since there are 25 strings/panel which can be modeled in series, the probability of no open panel in the meteoroids and debris environments becomes (5),

$$P(panel) = P(string)^{25} \qquad (8)$$

Since there are N panels in one blanket (N = 82 for the space station solar array) and since the panels are protected by blocking diodes, the probability of at least K unopen panels from the N panels/blanket can be obtained by (4 and 5),

$$P(P(panel); K,N) = \sum_{x=K}^{N} \binom{N}{k} P(panel)^x Q(panel)^{(N-x)} \qquad (9)$$

where $\binom{N}{x}$ is the binomial factor given by,

$$\binom{N}{x} = \frac{N!}{x!(N-x)!} \qquad (10)$$

RESULTS

Solar Array Mast

Results from Eq. (6) are displayed as the probability of the mast success as a function of the particle diameter of meteoroids or debris. Figures 4 and 5 show the aforementioned results for 15 years. Assuming that the damaging particle size is known, and the damaging criterion already defined applies, the aforementioned figures can be used to determine the probability of the mast in meeting the design lifetime requirement.

Solar Array Blanket

Equation (9) is used to calculate the probability that at the end of life, at least K panels (from N panels/blanket at the beginning of life) are functional in the meteoroids and debris environments. For a space station solar array blanket, N was taken as 82 and K as 80 panels. Results of analyzing the cases for 15 and 4 year lifetimes are shown in Figs. 6 and 7 for the meteoroids and debris environments.

Figures 8 and 9 show the probability of success of the solar array blanket (which is the probability of success of at least K panels at the end of life from N panels at the beginning of life) for different particle size and different levels of redundancy. It is apparent that the probability increases with redundancy and particle size. The increase with particle size is due to the lower flux at larger diameter. Figure 8 shows that over the design lifetime of 4 years, and for impacting particles of 0.003 and 0.004 cm in diameter, the calculated probability of success of a blanket with 10 redundant panels is practically zero. This is explained by the higher meteoroids flux impinging on the back surface of the blanket. The same feature is illustrated by Fig. 9 for the debris environment for particle size of 0.001 cm or smaller. To calculate the mission time at which the blanket probability of success (or the probability of meeting the power requirement with a specific redundancy) decreases significantly, Eqs. 7 to 9 were evaluated for different lifetimes, and Figs. 10 and 11 were generated.

Figure 10 shows the probability of success of at least 80 panels at the end of life from 90 panels at the begining of life, as function of mission time for the two meteoroid size particles of 0.003 and 0.004 cm. It is shown from this figure that the probability decreases significantly at approximately 0.5 and 1.25 years for the 0.003 and 0.004 cm particle diameter respectively. Figure 11 displays the same type of information with 10 redundant panels and no redundancy for a debris particle size of 0.001 cm in diameter. From Fig. 11, the probability was shown to decrease rapidly at approximately 0.35 and 2.5 years of design lifetime for a blanket with no redundancy and with 10 redundant panels respectively.

CONCLUDING REMARKS

An analysis was performed to assess the probability of success of the space station solar array subassemblies in the meteoroids and debris environment as a function of particle diameter. This analysis could complement a penetration model which determines the damaging particle size, and a damage model which correlates the particle size with the damaged areas. Therefore, a penetration and damage models are needed for the mast and substrate of the solar array blanket in order to compute the probability of the array meeting the power requirement in the meteoroids and debris environment. Such information will help determine the adequacy of the blanket design and the meteoroids and debris environmental oversizing factors used to size the space station solar array.

ACKNOWLEDGMENT

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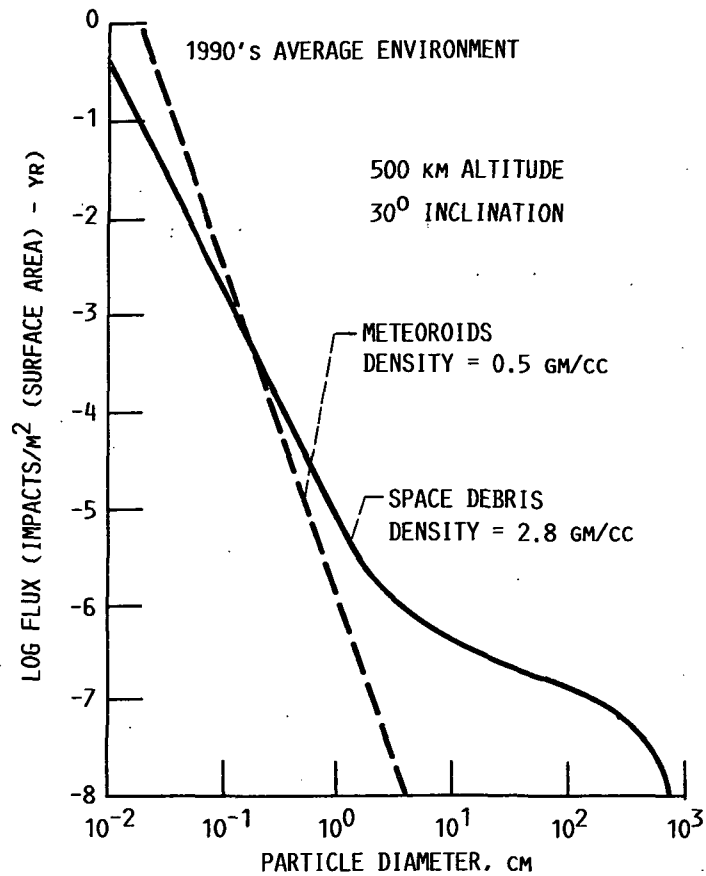
FIGURE 1. - FLUX OF METEOROIDS AND SPACE DEBRIS
AS A FUNCTION OF DIAMETER FOR A 500 KM ORBIT.
THE METEOROID FLUX IS CORRECTED FOR EARTH
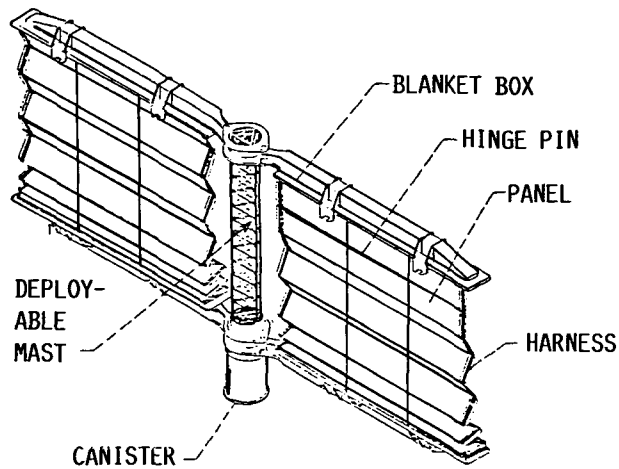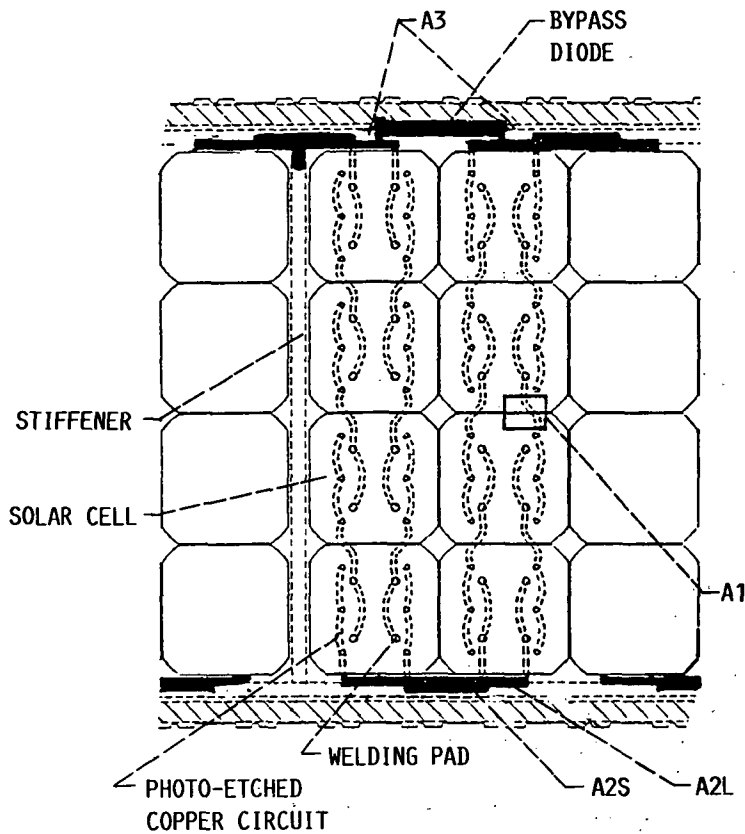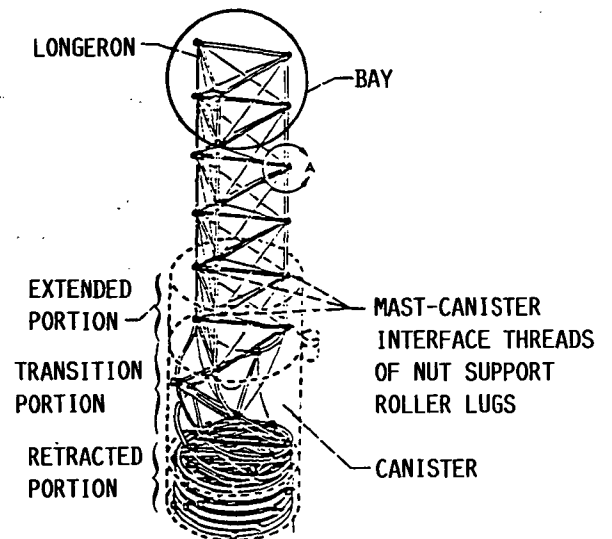SHIELDING.

FIGURE 2. - DEPLOYABLE RETRACTABLE SOLAR ARRAY
STRUCTURE FOR THE SPACE STATION PHOTOVOLTAIC
POWER MODULE.

(A) SOLAR CELL STRING INVESTIGATED FOR OPEN CIRCUIT
PROPABILITY DUE TO PARTICLE IMPACTS.

(B) LONGERON, BAY AND MAST STRUCTURE
INVESTIGATED FOR IMPACT PROBABILITY.

FIGURE 3. - REPEATING STRUCTURES IN THE SOLAR ARRAY MAST AND BLANKET CONSIDERED FOR PROBABILITY OF IMPACT
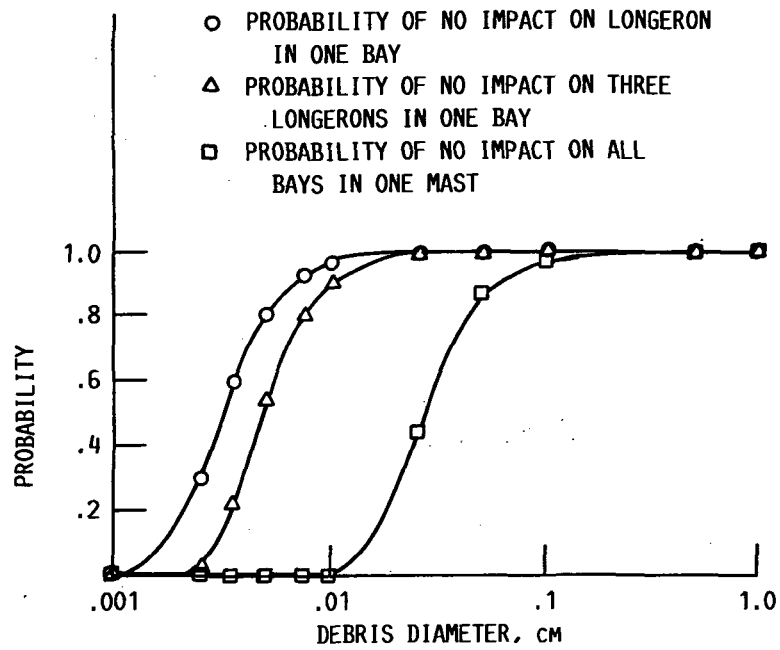ANALYSIS.

FIGURE 4. - PROBABILITY OF SUCCESS VERSUS DEBRIS
FOR LONGERON, BAY AND SOLAR ARRAY MAST FOR 15
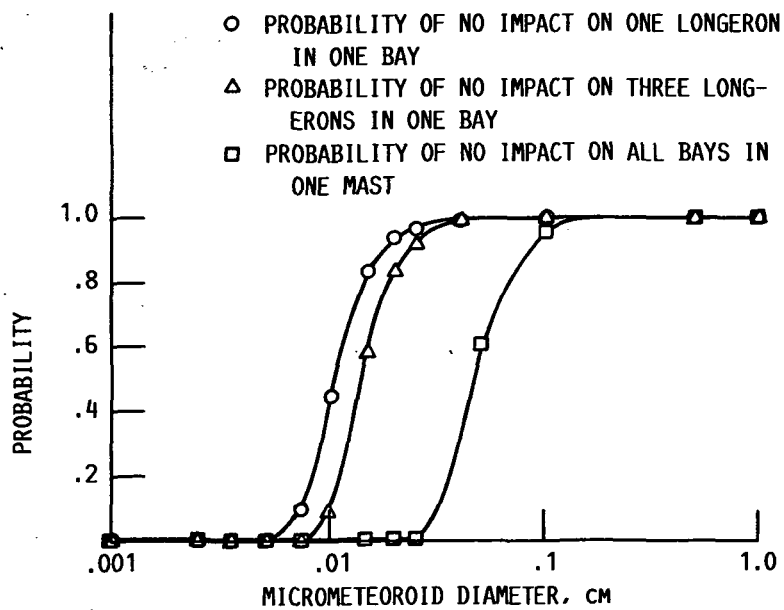YEARS DESIGN LIFETIME.

FIGURE 5. - PROBABILITY OF SUCCESS VERSUS MICRO-
METEOROID DIAMETER FOR LONGERON, BAY, AND SOLAR
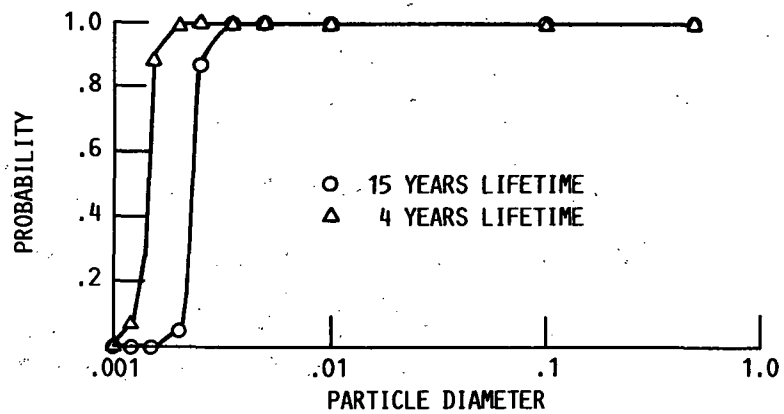ARRAY MAST FOR 15 YEARS DESIGN LIFETIME.

FIGURE 6. - PROBABILITY OF SUCCESS VERSUS DEBRIS
DIAMETER FOR A SPACE STATION SOLAR ARRAY BLANKET
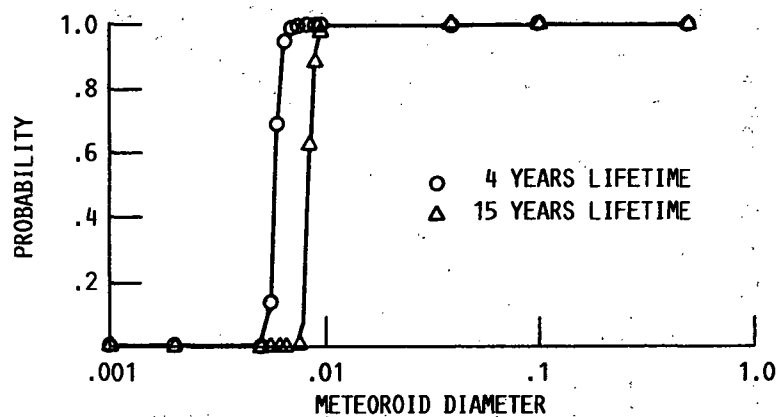WITH TWO REDUNDANT PANELS.

FIGURE 7. - PROBABILITY OF SUCCESS VERSUS METEO-
ROID DIAMETER FOR A SPACE STATION SOLAR ARRAY
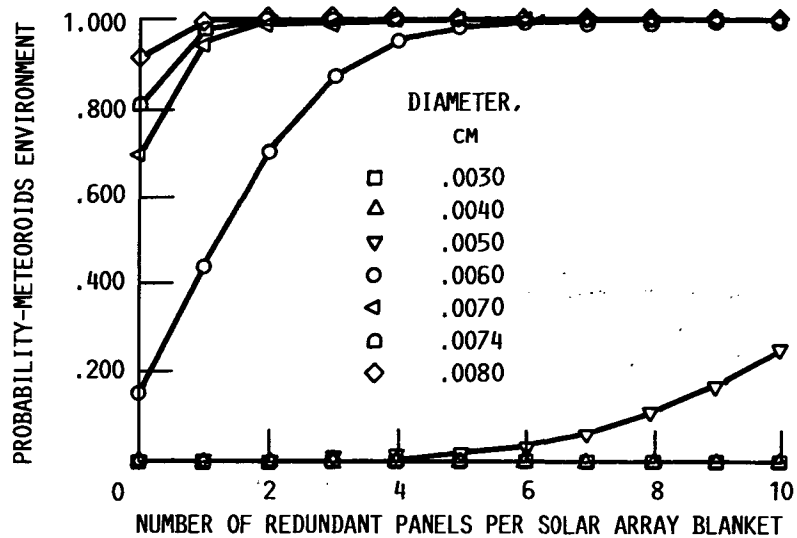BLANKET WITH TWO REDUNDANT PANELS.

7

FIGURE 8. - PROBABILITY OF SUCCESS VERSUS RE-
DUNDANCY OF SOLAR ARRAY BLANKET FOR 4 YEARS
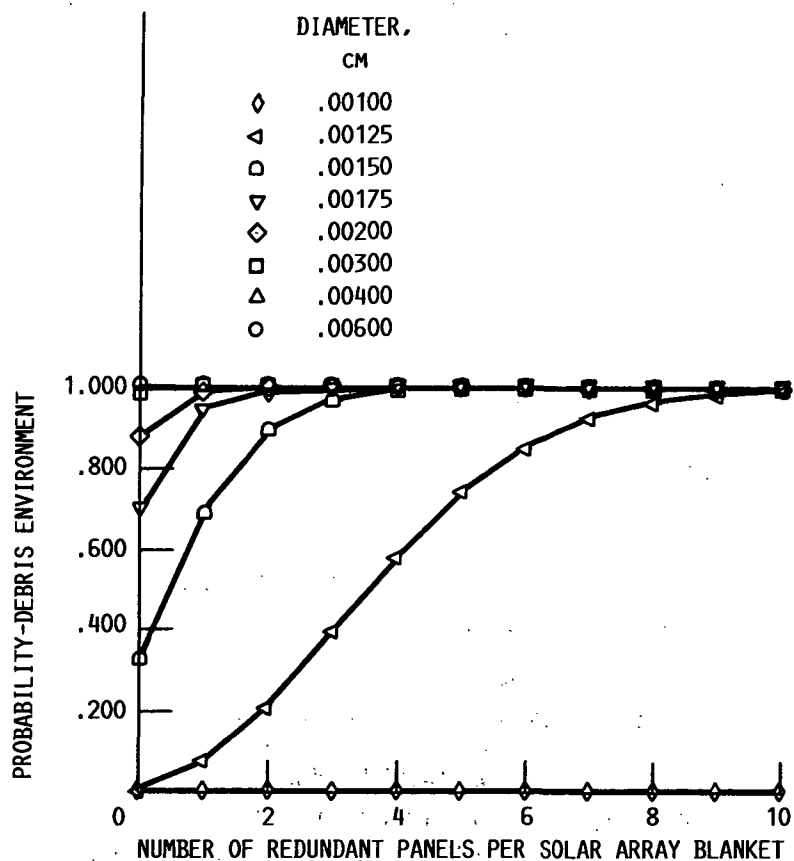DESIGN LIFETIME IN THE METEOROIDS ENVIRONMENT.

FIGURE 9. - PROBABILITY OF SUCCESS VERSUS REDUN-
DANCY OF SOLAR ARRAY BLANKET FOR 4 YEARS DE-
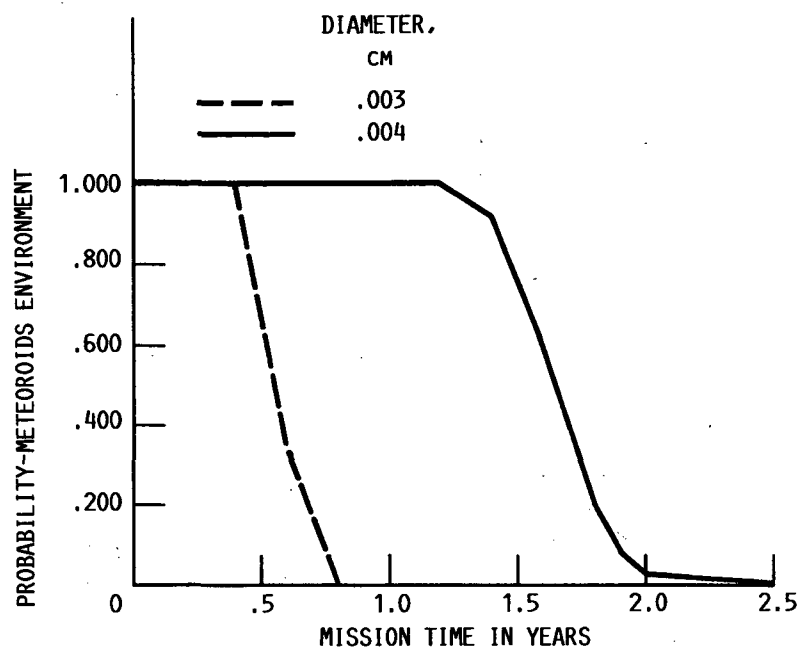SIGN LIFETIME IN THE DEBRIS ENVIRONMENT.

FIGURE 10. - PROBABILITY OF SUCCESS VERSUS MISSION
TIME OF A SOLAR ARRAY BLANKET FOR TWO METEOROID
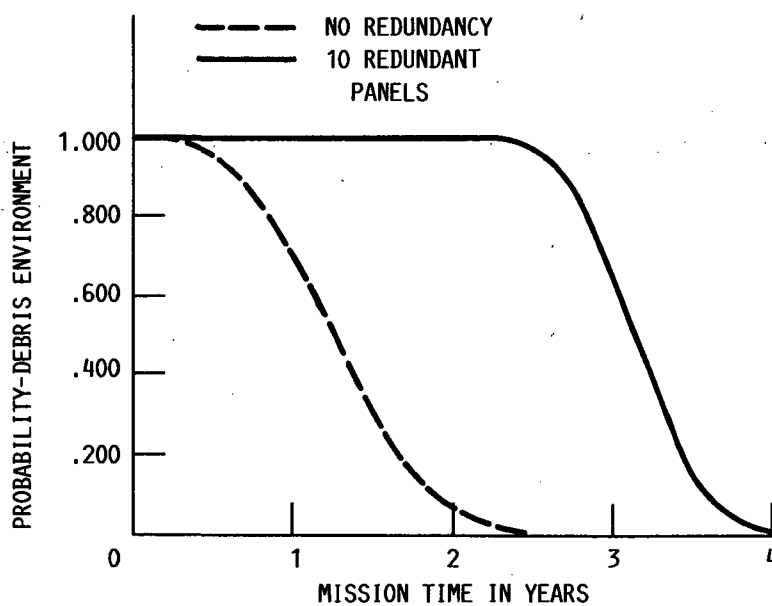DIAMETERS AND 10 REDUNDANT PANELS/BLANKET.

FIGURE 11. - PROBABILITY OF SUCCESS VERSUS MISSION
TIME FOR .001 CM DEBRIS PARTICLE DIAMETER.

Report Documentation Page

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16. Abstract

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