METEOROID DAMAGE TO A LARGE SPACE TELESCOPE MIRROR

by

JOSEPH B. HAMILTON

Submitted in partial fulfillment of the
requirements for the
degree of
Bachelor of Science
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ABSTRACT

Meteoroid damage to a mirror system in an outer space environment takes two basic forms. The first form is erosion which is characterized by abrading of the mirror surface by a large number of small meteoroids. The second form of damage is puncture of the mirror by a relatively large meteoroid. Predictions of both forms of damage are presented for various mirror diameters, thicknesses, and materials, versus duration of mission.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Keto Soosaar and Professor Peter Griffith for their advice and supervision. I would also like to thank Jean Poehler for typing this thesis.

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GLOSSARY OF SYMBOLS

A = Effective surface area
Ad = Area of damage due to impacting meteoroid
Adt = Total damaged area
D = Diameter of meteoroid
E = Earth shielding factor
Ge = Defocusing factor due to Earth's gravity
hav = Average crater depth
K_1 = Material constant for puncture
K_∞ = Material constant for cratering
m = Mass of meteoroid
m_c = Mass of meteoroid that will cause a critical crater depth
Nm = Distribution of meteoroid flux
Nt = Cumulative distribution of meteoroid flux
P(o) = Probability of zero impacts
P_I = Penetration depth of meteoroid
P_∞ = Depth of impact crater
r_c = Meteoroid crater radius
V = Velocity of impacting meteoroid
ρ_m = Mass density of meteoroid

INTRODUCTION

A mirror orbiting in space is subject to damage by meteoroids in basically two forms. The first is the continual erosion of the mirror reflecting surface by impacting meteoroids. This is characterized by a large number of small particles, each impacting the surface and leaving an approximately hemispherical crater. The summation of these craters produces an area of less than optically perfect surface that must be taken into account if it is a sizable fraction of the mirror area.

The approach taken was to assume that all the meteoroids impacted the surface at normal incidence, that the density of each meteoroid was $.5\text{gm/cm}^3$, and that all of the meteoroids had a normal velocity relative to the mirror of 20KM/Sec. (Reference #2). Given these assumptions, the area of a crater as a function of meteoroid mass, Ad vs m, was determined for the three candidate materials, aluminum, beryllium, and glass. The distribution of meteoroid flux as a function of mass was determined. This distribution function, Nm vs mass, was multiplied by the area of damage as a function of mass, Ad(m), and then integrated to give the total area of damage per unit area per sec. The limits of integration are from the minimum mass meteoroid that causes discernible optical damage up to m = 1gm. This integral is then multiplied by the appropriate mirror area, duration of mission, and constants determined by the mirror's position in space that affect the meteoroid flux such as defocusing due to Earth's gravity. Figures showing the percentage of damaged area as a function of mission duration, mirror size, and damage criterion are shown. These curves are intended to be of use in choosing the final design of the LST mirror, not to portray a particular design accurately.

The second consideration is the catastrophic cracking of the mirror by a large impacting meteoroid. Curves for the probability of zero punctures vs mirror area and duration of mission are presented.

METEOROID FLUX MODEL

A large number of experiments have been done to determine meteoroid flux in the near Earth environment; unfortunately, the results have not converged into one meteoroid flux vs mass curve. The experiments have been conducted in diverse ways, such as visual, photographic and radar meteor counts, the zodical light model, thin film penetration microphone sensors, and window crater counts. The diversity of methods to some degree explains the divergence of results. Figure #1 from reference #6 shows the results of some thirty experiments to determine this relationship. The two straight lines bracket most of the Ref.#6 data. Also shown are the two curves that formed the basis for the relationship used in this report. The NASA meteoroid environment model (Reference #2) was used for meteoroid mass; $1\text{gm} > m > 10^{-8}\text{gm}$. The SkyLab Model (Reference #7) was used for $10^{-11}\text{gm} > m > 10^{-16}\text{gm}$. A fairing in of the two curves was used for $10^{-8}\text{gm} > m > 10^{-11}\text{gm}$. The two curves are shown in Figure #2 and the resulting Nt vs m that was used for this thesis is shown in Figure #3. This curve represents the

Log_{10} of the number of particles of mass m or greater incident on one square meter per second vs Log_{10} meteoroid mass. This is referred to as the cumulative total flux mass model. To obtain the damaged area relations, we need the distribution of number of meteoroids vs mass or $\frac{dNt}{dm} = Nm$ vs m. This was determined by taking finite increments and letting $\frac{\Delta Nt}{\Delta m} = Nm$. This relationship is shown in Figure #4. Note that it is constantly climbing as m drops. Some earlier models predict a cutoff as $m \rightarrow 10^{-13}$gm.

AREA OF DAMAGE

If the depth of a meteoroid crater is equal to or greater than 51×10^{-8}m then the area of the crater is useless from an optical point of view. Assuming a hemispherical shaped hole (Reference #1 and Reference #40), the average crater depth

$$hav = \frac{\text{crater volume}}{\text{crater area}} = \frac{\frac{2}{3}\pi r_c^3}{\pi r_c^2} = \frac{2}{3} r_c = \frac{2}{3}\text{ crater radius} \quad (1)$$

If $hav \geq 51 \times 10^{-8}$m, the total crater area will be judged damaged. This is equivalent to a minimum crater radius, $r_c = 77 \times 10^{-8}$ m.

For metals, Summers equation (Reference #3) is used to predict the crater depth.

$$P_\infty = K_\infty \ m^{.352} (\rho_m)^{1/6} V^{2/3} \quad (2)$$

where p_∞ = Depth of crater (cm)

K_∞ = Material constant

ρ_m = Density of meteoroid (g/cm^3) = $0.5gm/cm^3$

V = Meteoroid velocity (KM/Sec) = 20KM/Sec

m = Meteoroid mass (gm)

For aluminum K_∞ = .42 (Reference #3)

For beryllium K_∞ = .3 (based on Reference #8)

By equating p_∞ and r_c, the equations for area damaged vs impacting meteoroid mass were obtained.

In hypervelocity impact of glass, an approximately hemispherical main crater is formed. For impact at V = 20KM/Sec, it's radius is estimated (Reference #9) by $r_c = .209m^{.27} \times 10^{-2}$, (3)

where r_c is in units of meters and m is in units of gm. Extending beyond this main crater region is an area of spalled damaged. The total damaged area is based on this spalled area.

The masses (travelling at 20KM/sec) that will cause a crater depth of 77×10^{-6}cm in these three materials are as follows:

Aluminum m_c = 1.16×10^{-13}gm

Beryllium m_c = 3.00×10^{-13}gm

Soda-Lime-
Silica Glass m_c = 1.92×10^{-13}gm

The damage functions are:

Aluminum $Ad(m^2) = 2.388 \times 10^{-3} m^{.704}$ (4.1)

Beryllium $Ad(m^2) = 1.218 \times 10^{-3} m^{.704}$ (4.2)

Glass $Ad(m^2) = 3.17 \times 10^{-2} m^{.78}$ (4.3)

For each material the total damaged area =

$$Adt = \sum_{m=1}^{m=mc} Ad\ Nm\ ATE\ Ge \tag{5.1}$$

$$Adt = ATE\ Ge\ \Sigma\ Ad\ Nm \tag{5.2}$$

where A = Effective surface area (m^2)

T = Duration of mission (sec)

E = Earth shielding factor

Ge = Defocusing factor due to Earth's gravity

For our mission, the radius of orbit is at one times synchronous, so $Ge = .63$ (Reference #2) and $E = .98$.

The results of these summations are shown in Figure #5. If the m_c that is used as a limit in the summation ΣAdNm is varied, the ΣAdNm will vary. This is equivalent to varying the damage criterion for the maximum crater depth that is optically acceptable. This relationship is displayed in Figure #6.

PROBABILITY OF ZERO PUNCTURES

In addition to damage to the mirror surface by micrometeoroid erosion, the mirror itself may be punctured by a large meteoroid. For a thin ductile plate the minimum meteoroid mass that will just puncture the thickness of the plate is described by the following equation from Reference #3,

$$T = K_1 \rho^{1/6} m_c^{.352} V^{.875} \tag{6}$$

where m = Meteoroid mass (gm)

T = Thickness of plate (cm)

ρ = Density of Meteoroid (gm/cm) = .5

V = Impact velocity (KM/sec) = 20

K_1 = Constant that is a function of the plate material

K_1 for beryllium was not found, but given that beryllium is more resistant than aluminum to crater formation we will ratio the K_1's for beryllium and aluminum in the same way that the K_∞'s were done, $K_1AL = .54$, $K_1Be = .383$.

For thickness of aluminum mirror = .3175cm, the minimum meteoroid mass that will just puncture the plate = $m_c = 1.79 \times 10^{-4}$gm.

Assuming a Poisson distribution, the probability of zero penetrating impacts, $P(o) = e^{-NATGe}$ (7)

For .3175cm thickness of beryllium, $m_c = 3.86 \times 10^{-4}$gm.

This data is displayed in Figure #7 and Figure #8.

For the size particles needed to cause glass mirror penetration, a formula determined by Cour-Palais from impact data obtained on the Apollo windows was used. These windows were made of Corning 7940 glass. The penetration depth, in cm, from Reference #10 is as follows:

$$P_I = .234\, D^{1.056} \sqrt{\rho}\, V^{(2D^{.186})} \qquad (8)$$

where D = Diameter of meteoroid (cm)

V = Velocity of meteoroid = 20KM/sec

ρ = Mass density of meteoroid (gm/cm^3)

A plate thickness of $4P_I$ is needed to resist penetration of the entire plate. A thickness of $7P_I$ is needed to prevent spallation of the rear surface. The results of calculations based on these equations are shown in Figure #9 through Figure #14.

RECOMMENDATIONS AND CONCLUSIONS

The risk of catastrophic meteoroid penetration of a mirror in space can be determined from the mirror dimensions, material, and position in space. The damage due to erosion is most conveniently expressed as a percentage of damaged area. As can be seen from Figure #6, the percentage of mirror area damaged is a strong function of the damage criterion. This damage criterion should be determined by the mirror's operational wavelength or wavelength range.

The meteoroid flux model used in this thesis has been reasonably well confirmed in the range 10^{-8}gm < m < 1gm. However, there is a paucity of experimental hypervelocity impact data for the larger masses in this range, especially for glass.

The meteoroid flux model used for the range 10^{-16}gm < m < 10^{-8}gm was judged to be the best available; however, there is less experimental data available to confirm its validity.

Improving the accuracy of the predictions presented in this thesis will depend on further hypervelocity impact experimentation in the larger mass range and more reliable meteoroid flux data in the smaller mass ranges.

FIGURE #1 VARIOUS METEOROID-FLUX MODELS

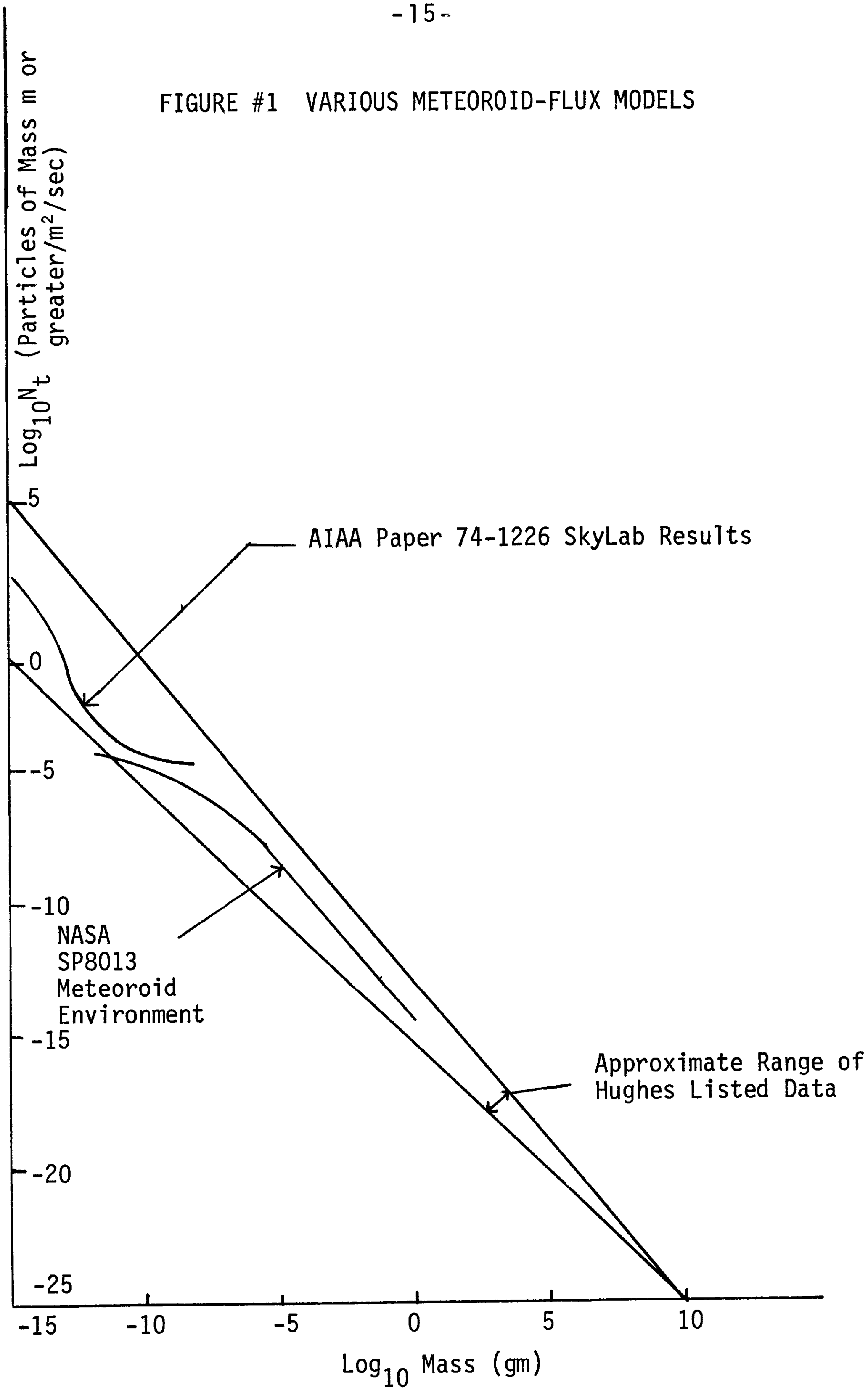


FIGURE #2 CUMULATIVE METEOROID
FLUX-MASS MODEL

Ref. #2 NASA SP 8013

Ref. #7 AIAA Paper 74-1226
SkyLab Data

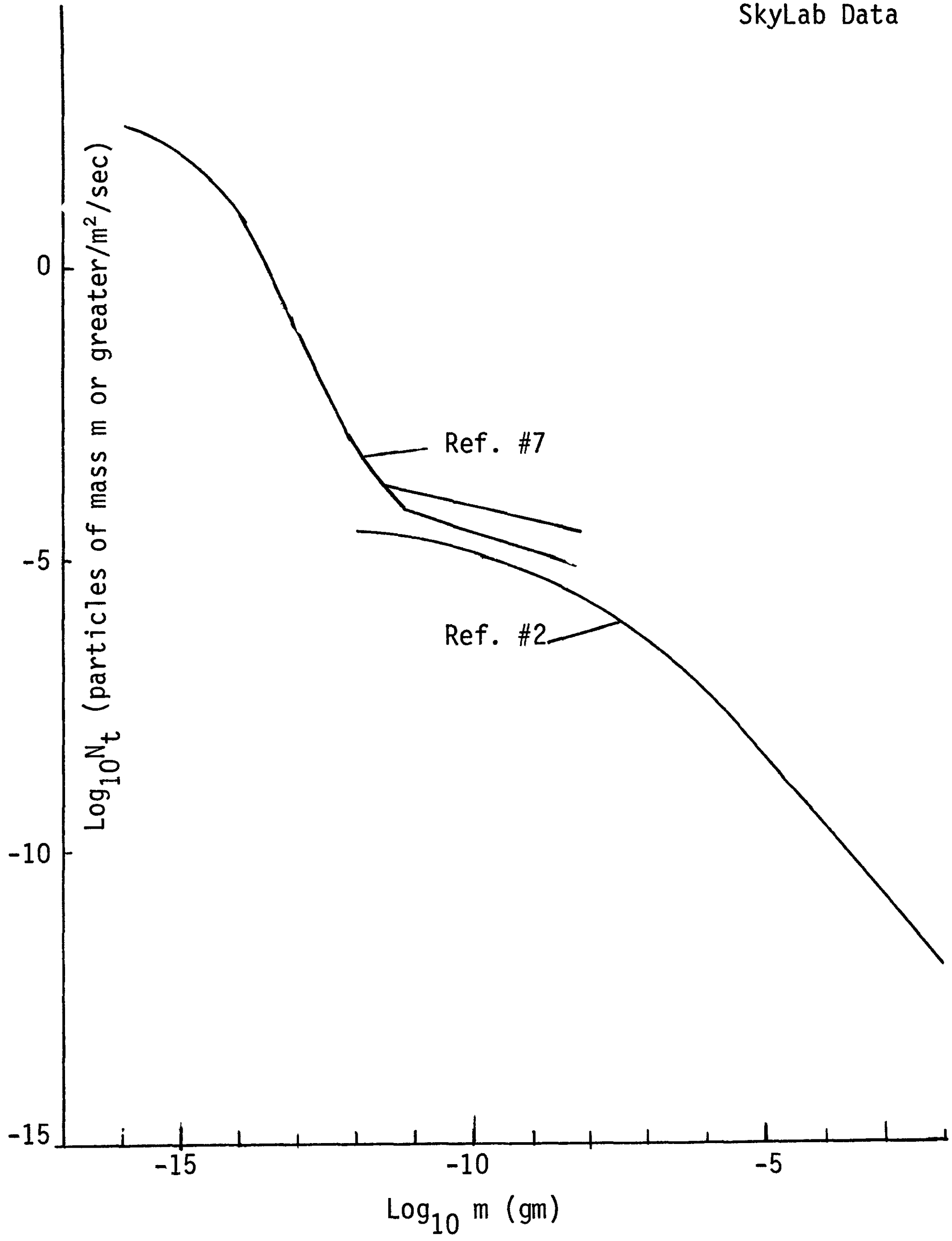


FIGURE #3 CUMULATIVE METEOROID FLUX-MASS MODEL USED FOR THIS REPORT

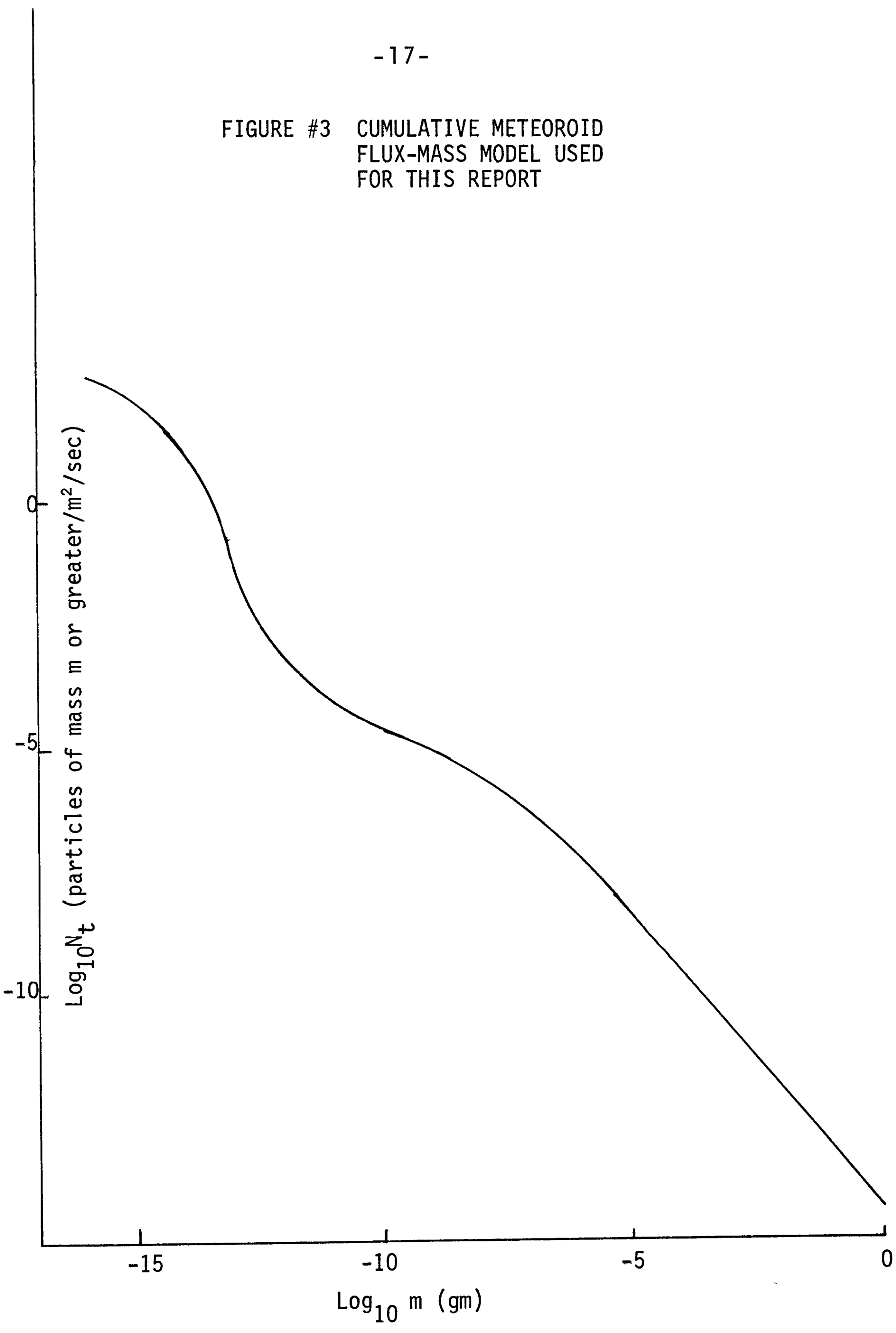
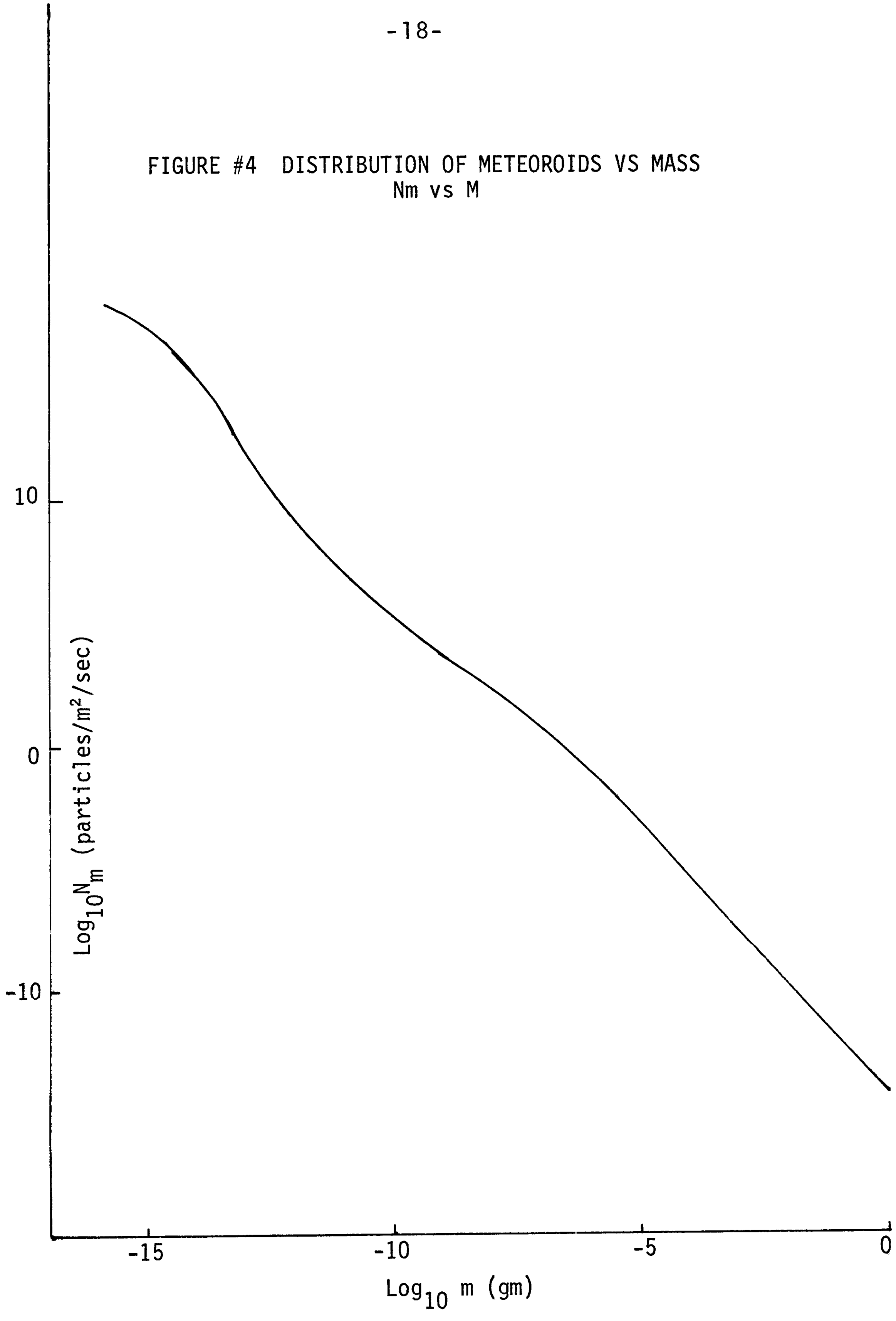


FIGURE #4 DISTRIBUTION OF METEOROIDS VS MASS
Nm vs M



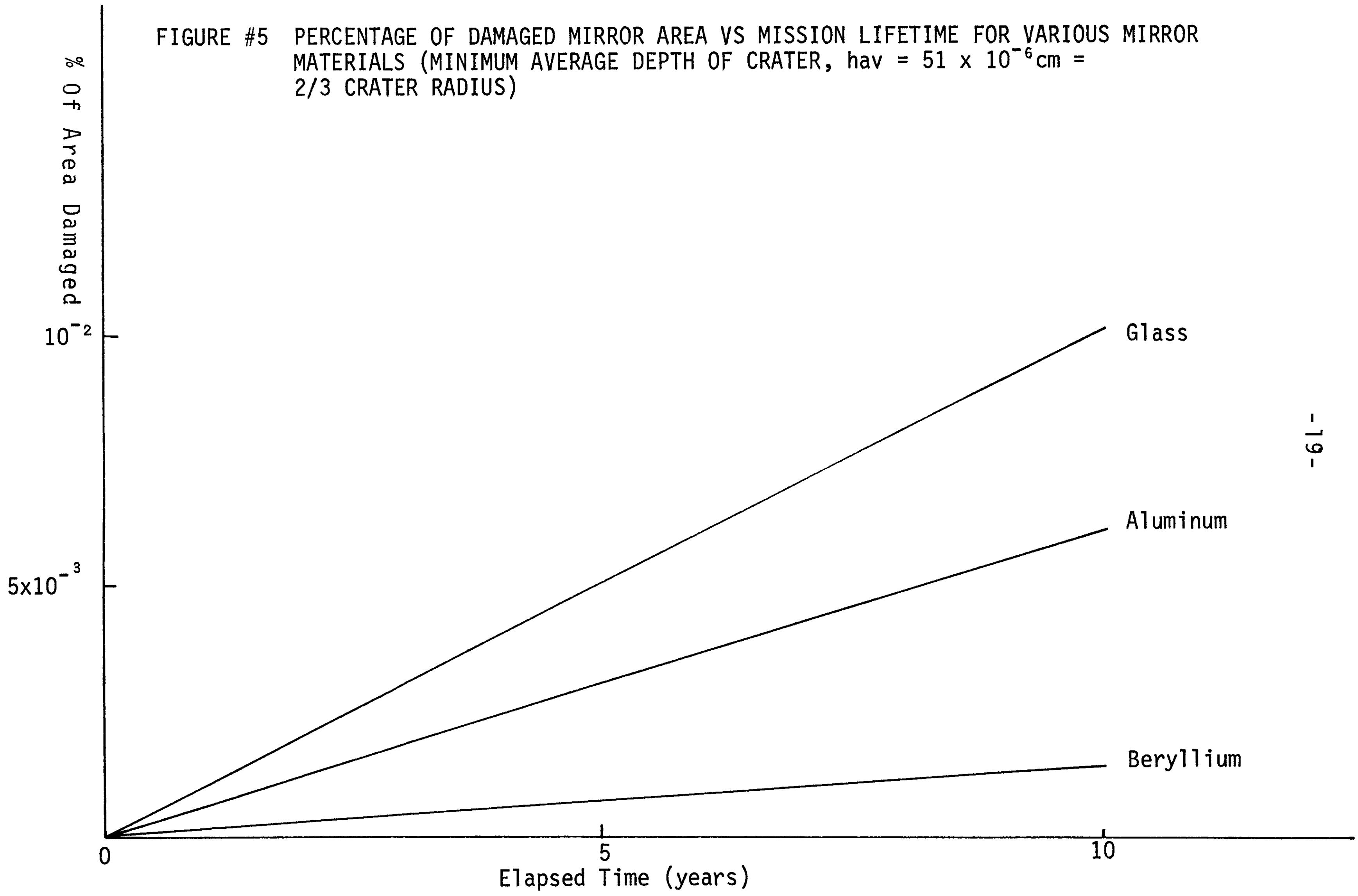


FIGURE #5 PERCENTAGE OF DAMAGED MIRROR AREA VS MISSION LIFETIME FOR VARIOUS MIRROR MATERIALS (MINIMUM AVERAGE DEPTH OF CRATER, hav = 51×10^{-6}cm = 2/3 CRATER RADIUS)

FIGURE #6 PERCENTAGE OF DAMAGED MIRROR AREA VS DAMAGE CRITERION FOR A GLASS MIRROR

HAV = AVERAGE DEPTH(2/3 CRATER RADIUS OF MINIMUM SIZED CRATER THAT IS OPTICALLY DAMAGING)

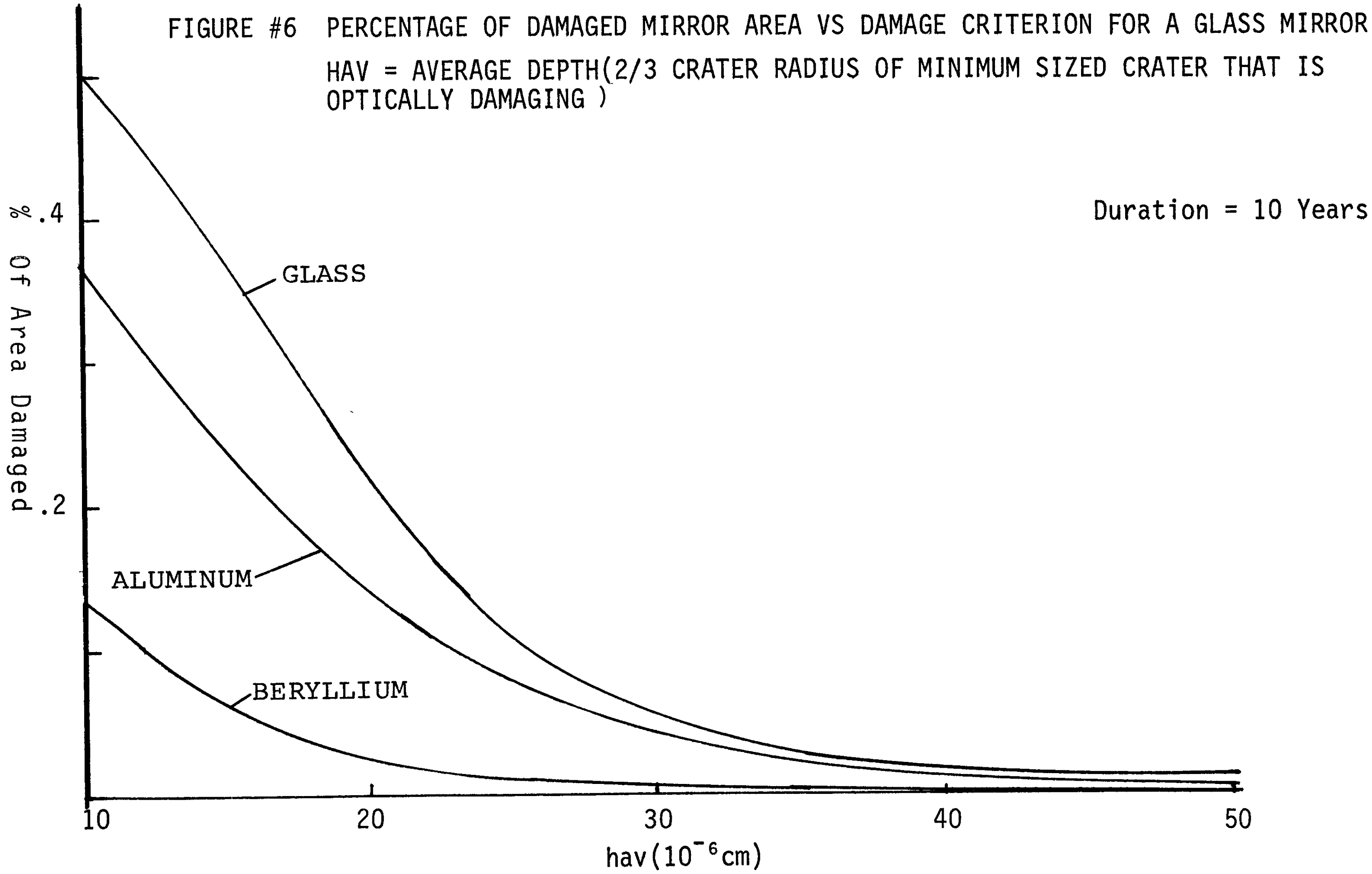


FIGURE #7 PROBABILITY OF ZERO PUNCTURES VS TIME FOR DIFFERENT DIAMETER ALUMINUM MIRRORS

Orbit = 1X Synchronous
Thickness = .3175cm

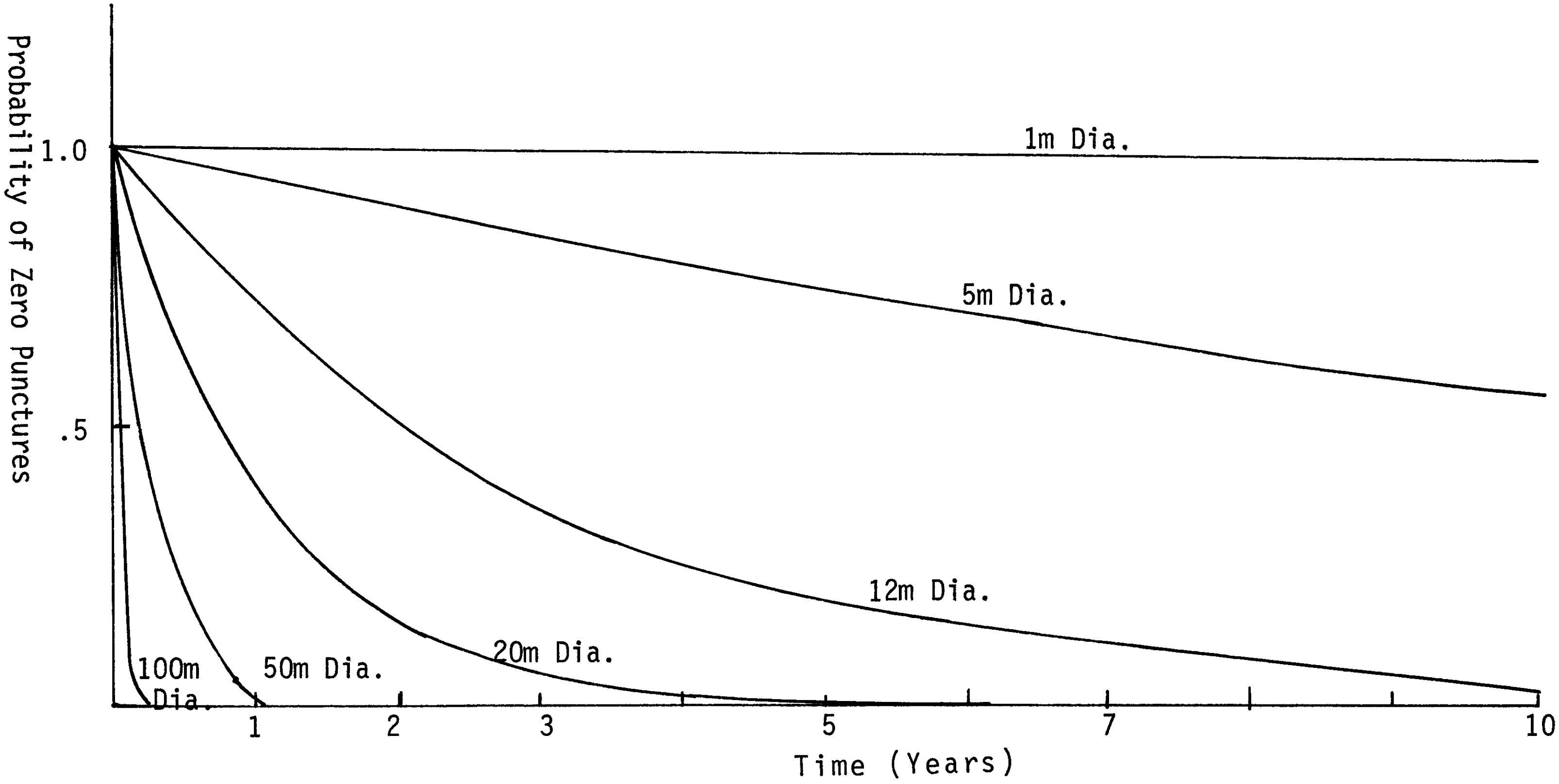


FIGURE #8 PROBABILITY OF ZERO PUNCTURES VS TIME FOR DIFFERENT DIAMETER BERYLLIUM MIRRORS

Orbit = 1X Synchronous
Thickness = .3175cm

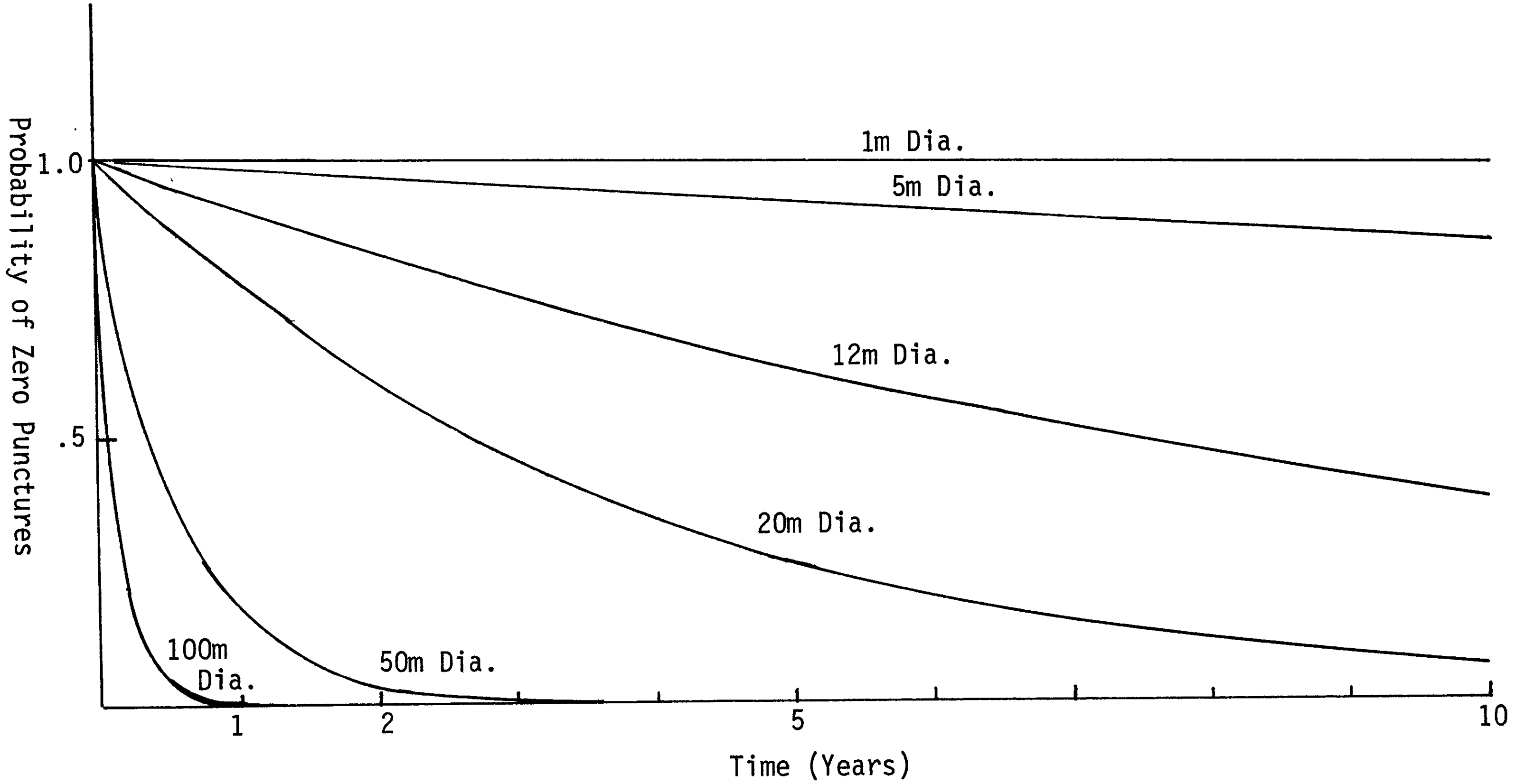


FIGURE #9 PROBABILITY OF ZERO PUNCTURES VS TIME FOR DIFFERENT DIAMETER GLASS MIRRORS

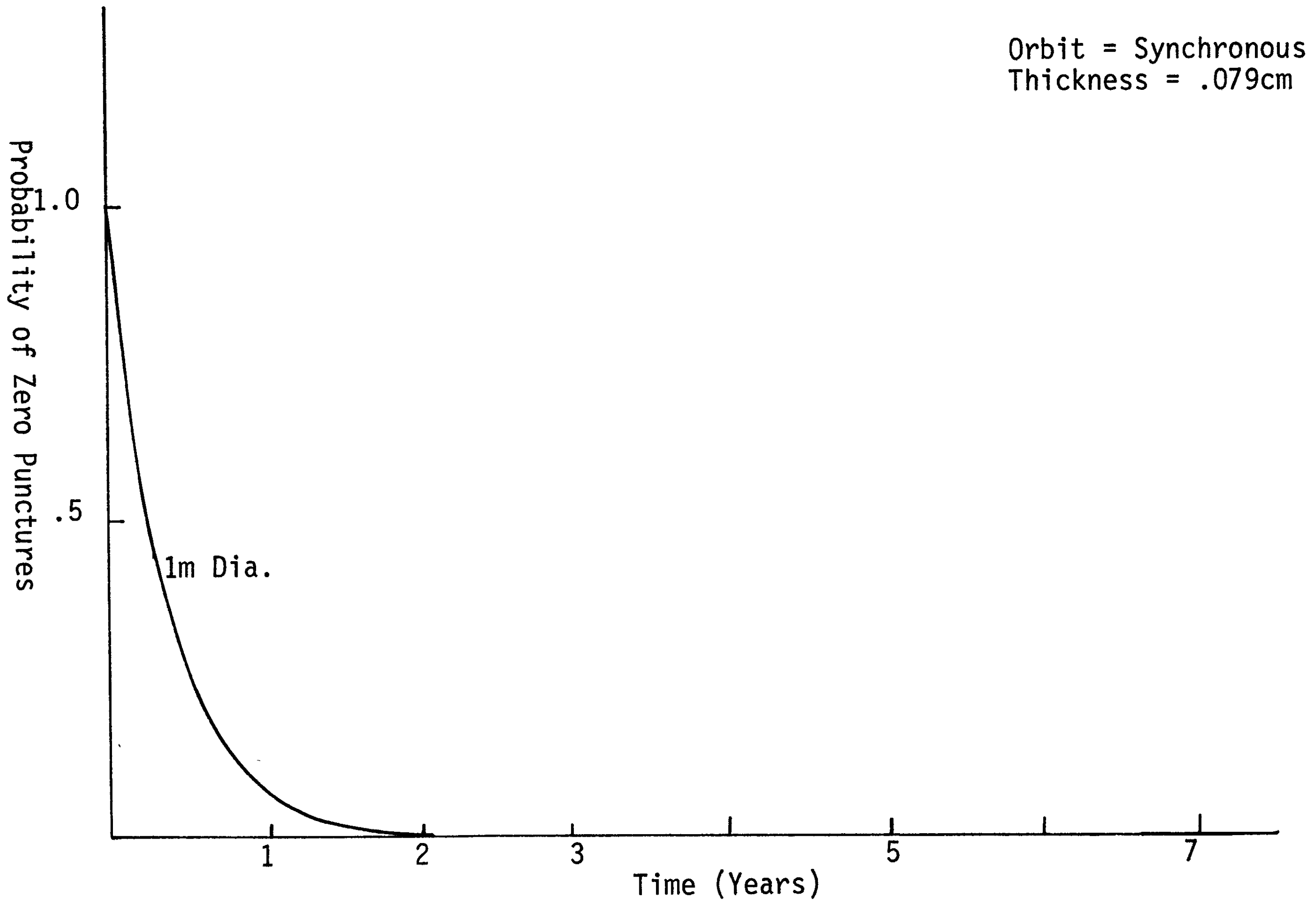


FIGURE #10 PROBABILITY OF ZERO PUNCTURES VS TIME FOR DIFFERENT DIAMETER GLASS MIRRORS

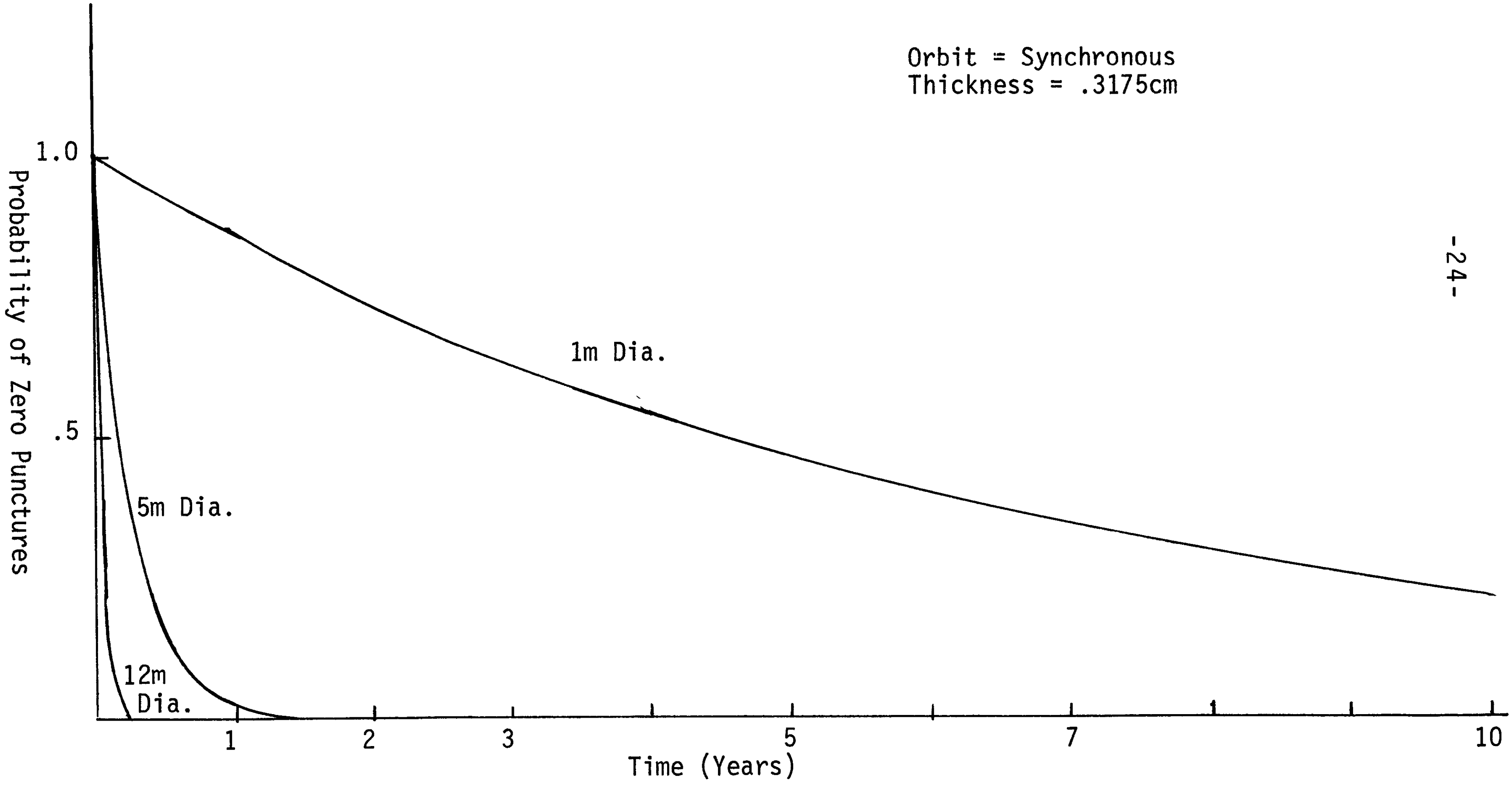


FIGURE #11 PROBABILITY OF ZERO PUNCTURES VS TIME FOR DIFFERENT DIAMETER GLASS MIRRORS

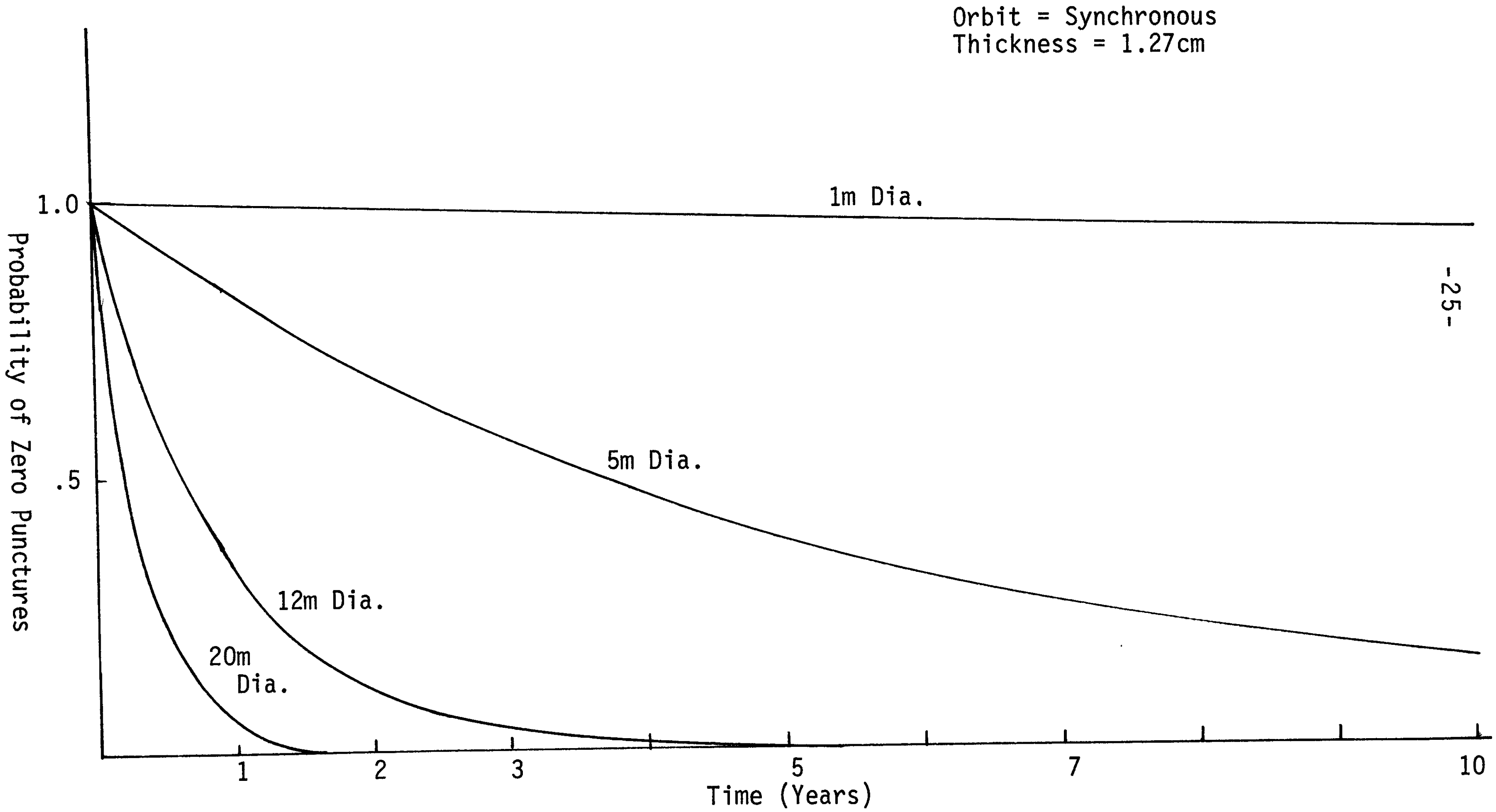

Orbit = Synchronous
Thickness = 1.27cm

FIGURE #12 PROBABILITY OF ZERO HITS WITH REAR SPALLATION FOR DIFFERENT DIAMETER GLASS MIRRORS

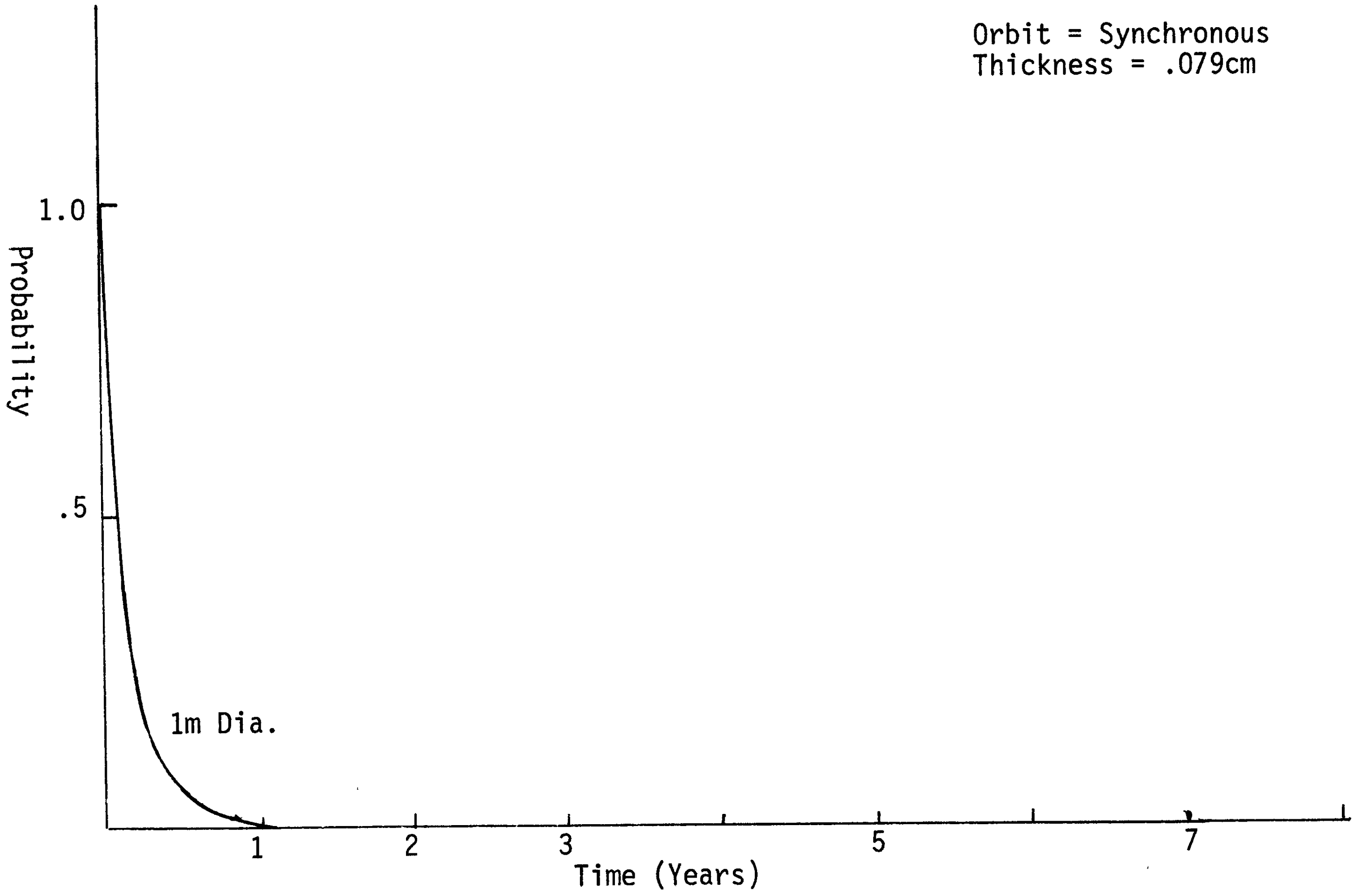

Orbit = Synchronous
Thickness = .079cm

FIGURE #13 PROBABILITY OF ZERO HITS WITH REAR SPALLATION FOR DIFFERENT DIAMETER GLASS MIRRORS

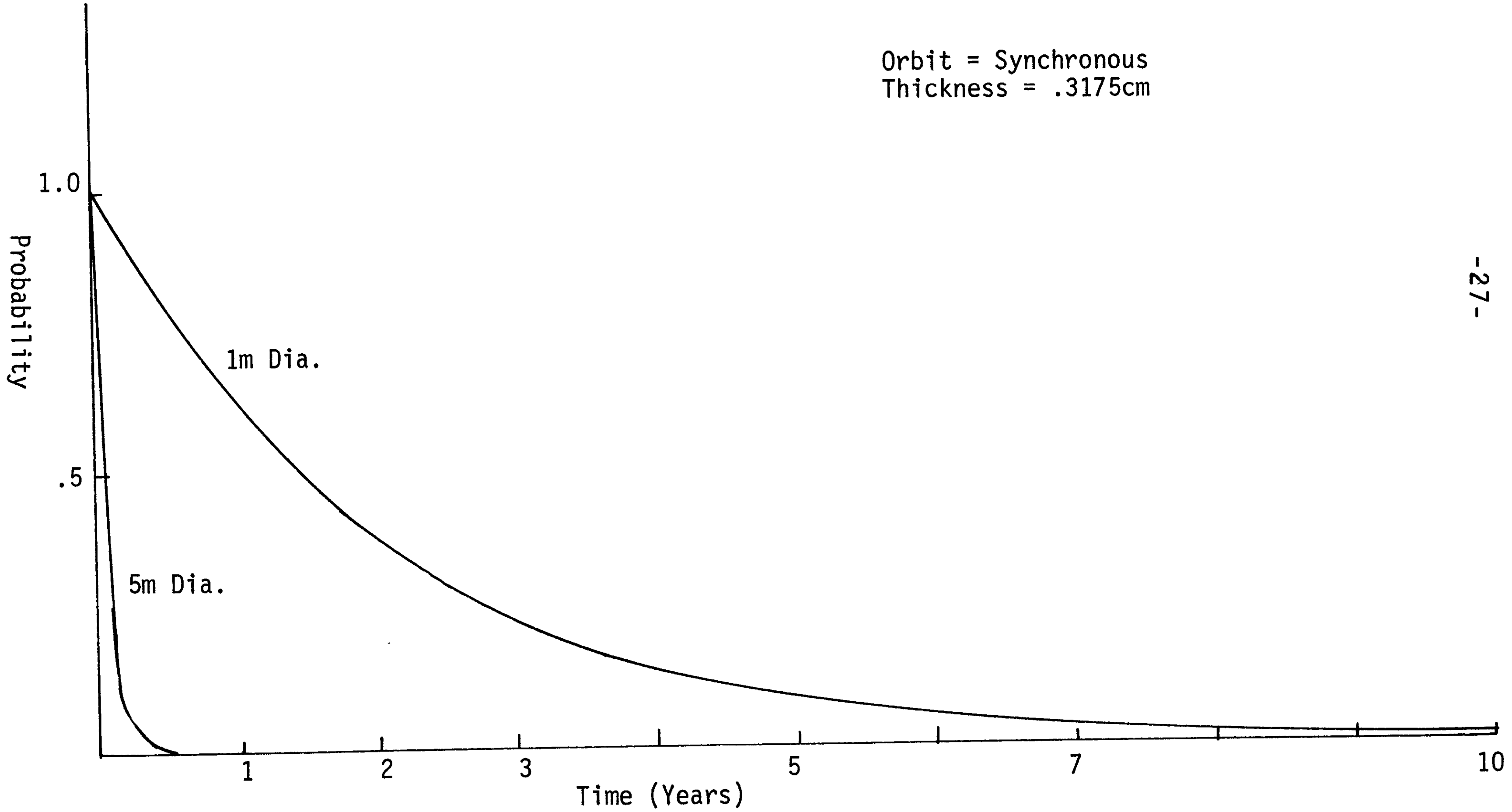
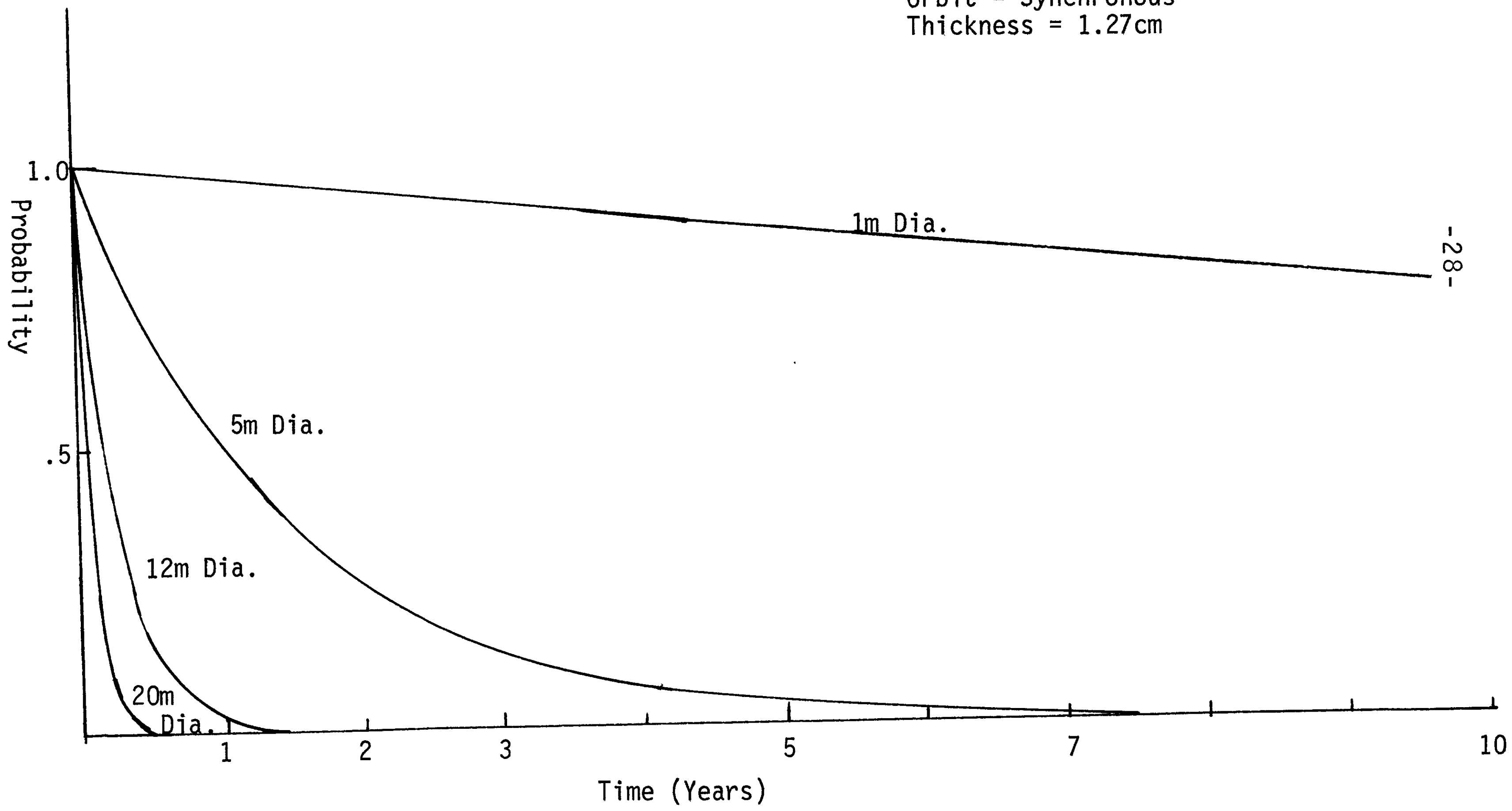


FIGURE #14 PROBABILITY OF ZERO HITS WITH REAR SPALLATION FOR DIFFERENT DIAMETER GLASS MIRRORS


Orbit = Synchronous
Thickness = 1.27cm

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