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HUBBLE SPACE TELESCOPE METEOROID/DEBRIS PROTECTION ANALYSIS

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16. ABSTRACT

A system level failure could occur if the Hubble Space Telescope's (ST) capability to operate as a facility on-orbit is critically reduced or when a significant reduction in the quality of science data is registered. Failure could occur if a meteoroid/debris impact damages a component of a major support subsystem or if a meteoroid/debris penetration causes straylight contamination in the light shield, forward shell, aft shroud, or through the aperture door.

The ST was analyzed to find the probability of no critical penetration. A straylight leakage repair technique was recommended for the aft shroud, the region found most likely to be critically penetrated.

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HUBBLE SPACE TELESCOPE METEOROID/DEBRIS PROTECTION ANALYSIS

INTRODUCTION

An increasing concern with the consequences of meteoroid/debris impacts on space vehicles has brought to attention the threat of critical damage to the Hubble Space Telescope (ST). This report contains an analysis of the ST's structure and components, determining the probability of the occurrence of a critical penetration. The analysis also shows the region of the ST most likely to be critically penetrated.

A critical penetration is one which will reduce the ST's ability to operate as a facility on orbit, or will significantly reduce the quality of science data. A critical penetration could cause (1) damage to a component of a major support subsystem, or (2) straylight contamination of the ST's light shield, forward shell, aft shroud, or aperture door. Straylight is any light which enters the ST other than the light from the object(s) being viewed. Therefore, a penetration of the outer shell would allow straylight to interfere with the ST's observation capabilities.

ANALYSIS METHODS

Analysis of the ST began with calculation of the probability of no penetration for each unique component or structural region (Fig. 1). These probabilities are based on the time the ST will be exposed to the meteoroid/debris environment, the meteoroid/debris flux at the ST's 500 km altitude, and the ST area exposed to the environment [1]. This analysis determines the particle sizes and respective velocities that the specific structure or component can defeat. This structural characteristic is called the "ballistic limit" of the structure or component. The ballistic limit for a single-wall structure is the thickness required to stop a projectile of a given mass at a specified velocity. For a double-wall structure, the ballistic limit is defined as the required total thickness for the front and back plates that stop the specified particle from going through both plates. The ballistic limit depends on the structure's material density, the plate spacing, and the particle size, velocity, and density.

Components

The critical or noncritical status of the components of the major ST support subsystems is based on the following criteria: (1) the components are housed inside the ST structural walls; (2) the components have small exposed areas to the meteoroid/debris environment; (3) the components are orbital replacement units (ORU); and/or (4) the components have high damage tolerances.

Those components housed inside the ST structure are surrounded by structural walls and materials which are sufficiently massive to allow us to assume that these components would be virtually unaffected by meteoroid/debris impact.

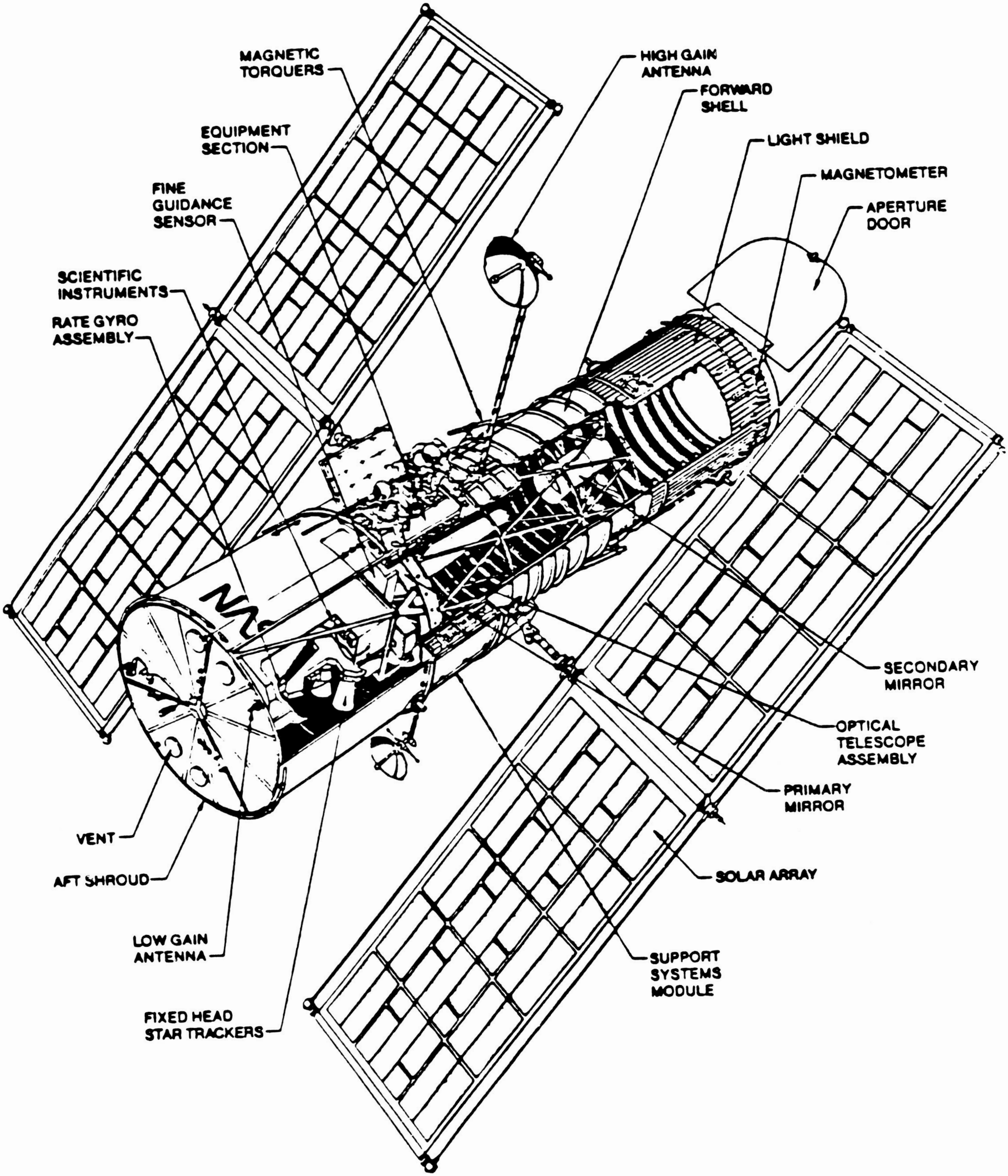

Figure 1. Hubble Space Telescope.

The components which have small areas exposed to the meteoroid/debris environment have negligible probabilities of penetration because the small areas provide less target area for the particles (see Appendix 1). These components include the high gain antenna dish, and the high gain antenna feed.

The ORU's are not considered critical to the ST's operation since, by definition, they can be replaced if damaged [2]. Therefore, we did not include these in our calculations: the low gain antenna, the solar arrays, the OTA (optical telescope assembly) equipment section, and the space support module equipment section.

The remaining critical components of the ST which are exposed to the meteoroid/debris environment are the magnetic torquers, the waveguides for the high gain and low gain antennas, and the few exposed electrical cables (see Appendix 2). The cables, however, are redundant and thus have high damage tolerance. The magnetic torquers also have a high tolerance to damage since they are small in area, and have thick walls which resist penetration. The waveguides have none of the four characteristics above. They have their own unique characteristics in that they can withstand penetration resulting in a 0.5- to 0.75-in. diameter hole, but cannot tolerate surface ripples introduced by lesser impacts. For this case, impacts resulting in surface ripples cannot be predicted without more extensive testing than has been completed at this time. Therefore, only an analysis which predicts penetration for the hole sizes above was completed for the waveguides.

Structural Regions

One method of analyzing the meteoroid/debris protection capability of the structural regions of the ST is to assume that any penetration would be critical; that any straylight would critically reduce the telescope's visual capability. With this assumption, we calculated the probability that no penetration would occur on any ST structural region (see Appendix 3). The regions include the aperture door, the light shield, the forward shell, four unique aft shroud regions, and the aft shroud bulkhead. First, each region was assessed for plate material, plate thickness, and number of plates, and whether it had any additional protection, such as multi-layer insulation (MLI) or fozar tape [2,3]. Next, ballistic limit equations were used to find the particle mass and velocity which would penetrate each region [4]. Finally, the probability that this particle size and larger would impact (and thus penetrate) the structure was found with the flux calculated for this particle size [1,5-8] (see Appendix 4).

TESTING

Hypervelocity impact tests were required to validate the ballistic limit analyses of the ST structures. Small-bore, light-gas guns were used in the tests for their ability to shoot small particles at large velocities, approximating particle impact (see Appendix 5).

The tests show the effects of impact on each unique structure. Particle material, velocity, and mass were recorded for each shot. Corresponding penetration hole sizes were also measured and recorded for one of each structure type.

TESTING/ANALYSIS INTEGRATION FOR ST STRUCTURES

The test results were integrated with the previously mentioned analysis techniques. In the analysis it was assumed that any penetration would be critical. In contrast, in the test/analysis integration, the "critical penetration" is one which would allow an amount of straylight into the ST structure causing a decrease in the ST observation capabilities. Straylight is that light entering the ST from other than the light path from the direction being viewed. Therefore, penetration of smaller particles resulting in smaller holes and less straylight, could be allowed.

The allowable penetration hole sizes for minimally degraded, degraded, and severely degraded performance levels were determined by the Optical Systems Branch, EB23, MSFC. The hole sizes which result in minimally degraded performance levels were defined by straylight allowances and determined for each ST region (Table 1). Degraded performance is a level 10 times the minimal, and severely degraded is a level 100 times the minimal [9].

The particle sizes from testing were adjusted so that the respective hole sizes for each region affected by straylight would equal the hole sizes of the performance levels. With the adjusted sizes, the fluxes and then the probabilities of having one critical penetration were found for each of these regions: the light shield, the aft shroud, the aft shroud bulkhead, and the aperture door [1,5-8].

The particle sizes mentioned above were adjusted by assuming that the kinetic energy of a particle is proportional to the hole size it will produce upon impact. Since the performance levels are defined by hole sizes allowed in each region, the allowed hole sizes were directly compared to the hole sizes measured from the tests. Then, the test-mass measurements were adjusted to larger or smaller masses by the factor resulting from the hole comparison. This method resulted in one mass for each performance level, for each ST region. In turn, these masses were used to calculate the fluxes, and then the probabilities of penetration. An example of one particular probability is "the probability of one or less meteoroid penetration which would cause a minimally degraded performance in the visual capabilities of the Light Shield over a 2-year period." The probabilities were calculated for service times of two, five, ten, and fifteen years, and for both meteoroid and debris protection.

The areas used in the calculations are the areas exposed to the environment. They are dependent on the particle type. For meteoroids, the surface area was used; for debris, the "effective" area was used. The effective area, based on the directional particle flux of debris, is calculated by using "flux factors" [5].

TABLE 1. STRAYLIGHT REQUIREMENTS

Region of Spacecraft	Allowed Area Penetration
Aft Shroud	10^{-2} mm^2/m^2
Forward Shell	2 mm^2/m^2
Light Shield	10 mm^2/m^2
Aperture Door	10 mm^2/m^2

In the aperture door analysis, an assumption was made to account for lack of test data. It was assumed that the aperture door has at least the ability of the light shield to stop a given particle. Therefore, the particle and resulting penetration hole size used in the light shield analysis were also used in the analysis of the aperture door.

The forward shell was not included in the straylight analysis because any complete penetration would violate the straylight criteria. Therefore, the ballistic limit probabilities for no penetration of the forward shell were the critical ones, and were used in the final overall probability calculations (see Appendix 6).

RESULTS

The results of the analysis of the Hubble ST meteoroid/debris protection capabilities are shown in Tables 2 through 6. The area of a component or components exposed to the meteoroid/debris environment is a major factor in determining the probabilities. The larger areas are more likely to be hit by a particle, and more likely to be critically damaged, than smaller areas (assuming other factors remain constant). Also, the components which have thinner walls and/or less spacing between inner and outer walls are more likely to be hit by a particle and critically penetrated.

Straylight Violations

Table 2 shows probabilities of no straylight violations considering meteoroid penetrations only, with the worst probabilities being for the aft shroud bulkhead, ranging from 0.0519 to 0.9999 (from minimal to severe degradation of the ST's observation capabilities in 2 years). Table 3 shows probabilities of no straylight violations considering debris penetrations. Again, the worst probabilities are for the aft shroud bulkhead, ranging from 0.2744 to 0.9986 (from minimal to severe degradation of the ST's observation capabilities in 2 years).

No Critical Penetrations

Tables 4 and 5 show the probabilities of no critical penetrations by meteoroids and debris, respectively. From these two tables, the magnetic torquers have the worst probabilities of critical damage [0.9625 (meteoroids) and 0.9897 (debris)].

Total Penetrations

Table 6 shows the combined total probabilities for the ST's meteoroid/debris protection capability. This table shows that the probability of penetrations by meteoroids is greater than by debris (meteoroid particles are more numerous and have greater impact velocities). All the probabilities of no penetrations decrease with increasing time; and they increase with increasing allowable damage.

CONCLUSIONS

This report shows that the Hubble ST will have a probability of no critical penetrations of 92.25 percent for a 2-year service life. This probability is for the most severe amount allowed of degradation of the ST's observation capabilities.

Since the aft shroud area is most likely to be critically penetrated, the development of a straylight leakage repair technique is recommended for this area. Fozar tape and MLI (multi-layer insulation) blankets have been suggested as possible repair materials.

TABLE 2. METEOROID ANALYSIS PROBABILITY OF NO STRAYLIGHT VIOLATIONS

Region	Years	Minimal	Degraded	Severe
Aft Shroud 2C	2	0.6164	0.9968	0.9999
	5	0.1557	0.9819	0.9999
	10	0.0100	0.9366	0.9997
	15	0.0005	0.8746	0.9993
Aft Shroud 2B	2	0.2470	0.9879	0.9999
	5	0.0088	0.9364	0.9997
	10	0.0000	0.8034	0.9988
	15	0.0000	0.6546	0.9973
Aft Shroud (MAG-MLI)	2	0.6164	0.9968	0.9999
	5	0.1557	0.9819	0.9999
	10	0.0100	0.9366	0.9997
	15	0.0005	0.8746	0.9993
Aft Shroud (AL-AL)	2	0.2470	0.9879	0.9999
	5	0.0088	0.9364	0.9997
	10	0.0000	0.8034	0.9988
	15	0.0000	0.6546	0.9973
Aft Shroud Bulkhead	2	0.0519	0.9657	0.9999
	5	0.0001	0.8372	0.9991
	10	0.0000	0.5779	0.9963
	15	0.0000	0.3644	0.9920
Light Shield	2	0.9999	0.9999	0.9999
	5	0.9999	0.9999	0.9999
	10	0.9999	0.9999	0.9999
	15	0.9999	0.9999	0.9999
Aperture Door	2	0.9999	0.9999	0.9999
	5	0.9999	0.9999	0.9999
	10	0.9999	0.9999	0.9999
	15	0.9999	0.9999	0.9999
	2	0.0012	0.9363	0.9993
	5	0.0000	0.7076	0.9981
	10	0.0000	0.3271	0.9931
Total	15	0.0000	0.1194	0.9851

TABLE 3. DEBRIS ANALYSIS PROBABILITY OF NO STRAYLIGHT VIOLATIONS

Region	Years	Minimal	Degraded	Severe
Aft Shroud 2C	2	0.8624	0.9959	0.9999
	5	0.5193	0.9766	0.9995
	10	0.1664	0.9196	0.9978
	15	0.0457	0.8439	0.9952
Aft Shroud 2B	2	0.6920	0.9882	0.9998
	5	0.2313	0.9368	0.9983
	10	0.0244	0.8043	0.9936
	15	0.0019	0.6635	0.9861
Aft Shroud (MAG-MLI)	2	0.8624	0.9959	0.9999
	5	0.5193	0.9766	0.9995
	10	0.1664	0.9196	0.9978
	15	0.0457	0.8439	0.9952
Aft Shroud (AL-AL)	2	0.6920	0.9882	0.9998
	5	0.2313	0.9368	0.9983
	10	0.0244	0.8043	0.9936
	15	0.0019	0.6635	0.9861
Aft Shroud Bulkhead	2	0.2744	0.9462	0.9986
	5	0.0119	0.7630	0.9918
	10	0.0000	0.4475	0.9699
	15	0.0000	0.2347	0.9379
Light Shield	2	0.9999	0.9999	0.9999
	5	0.9999	0.9999	0.9999
	10	0.9996	0.9999	0.9999
	15	0.9991	0.9999	0.9999
Aperture Door	2	0.9999	0.9999	0.9999
	5	0.9999	0.9999	0.9999
	10	0.9997	0.9999	0.9999
	15	0.9993	0.9999	0.9999
	2	0.0977	0.9163	0.9978
	5	0.0002	0.6385	0.9872
	10	0.0000	0.2448	0.9531
Total	15	0.0000	0.0736	0.9031

*Debris Environment not imposed on ST spec.

TABLE 4. METEOROID ANALYSIS COMPONENTS NOT AFFECTED BY STRAYLIGHT

Years	Probability of No Critical Penetrations			
	2	5	10	15
HGA (Waveguide) Mast (For 1 of 2)	0.9988	0.9971	0.9942	0.9913
Magnetic Torquers (For 1 of 2)	0.9625	0.9090	0.8262	0.7510
LGA Waveguides (Total)	0.9996	0.9991	0.9981	0.9972
Forward Shell	0.9993	0.9982	0.9964	0.9946
Total	0.9232	0.8193	0.6710	0.5497

TABLE 5. DEBRIS ANALYSIS COMPONENTS NOT AFFECTED BY STRAYLIGHT

Years	Probability of No Critical Penetrations			
	2	5	10	15
HGA (Waveguide) Mast (For 1 of 2)	0.9999	0.9999	0.9998	0.9997
Magnetic Torquers (For 1 of 2)	0.9897	0.9744	0.9494	0.9251
LGA Waveguides (Total)	0.9999	0.9999	0.9999	0.9999
Foward Shell	0.9985	0.9962	0.9924	0.9887
Total	0.9880	0.9705	0.9419	0.9143

*Debris environment not imposed on ST spec.

TABLE 6. OVERALL PROBABILITY OF NO CRITICAL PENETRATIONS (WITH NO REPAIRS)

	Years	ST Performance Levels		
		Minimal	Degraded	Severe
Meteoroid	2	0.0012	0.8644	0.9225
	5	0.0000	0.5797	0.8177
	10	0.0000	0.2195	0.6663
	15	0.0000	0.0656	0.5415
Debris*	2	0.0965	0.9053	0.9858
	5	0.0002	0.6197	0.9581
	10	0.0000	0.2306	0.8977
	15	0.0000	0.0673	0.8257
Combined Total	2	0.0001	0.7825	0.9094
	5	0.0000	0.3592	0.7834
	10	0.0000	0.0506	0.5981
	15	0.0000	0.0044	0.4471

*Debris environment not imposed on ST spec.

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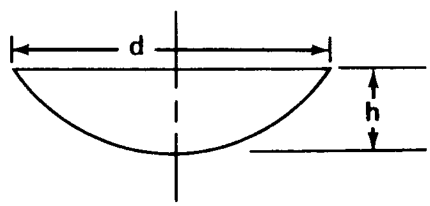
APPENDIX 1

HIGH GAIN ANTENNA DISH

$$\text{PARABOLIC AREA} = \frac{2\pi}{3p}\left[\sqrt{\left(\frac{d^2}{4} + p^2\right)^3} - p^3\right]$$

$$\text{WHERE } p = \frac{d^2}{8h}$$



INNER SURFACE	OUTER SURFACE
d = 50.76"	d = 51.2"
h = 12.69"	h = 12.94"

> INNER SURFACE $\quad p = \frac{(50.76)^2}{8\,(12.69)} = 25.38$

$$A = \frac{2\pi}{3\,(25.38)}\left[\sqrt{\left(\frac{(50.76)^2}{4} + 25.38^2\right)^3} - 25.38^3\right]\frac{1}{144}$$

$$= 17.13 \text{ FT}^2 = 1.59 \text{ m}^2$$

> OUTER SURFACE $\quad p = \frac{(51.2)^2}{8\,(12.94)} = 25.32$

$$A = \frac{2\pi}{3\,(25.32)}\left[\sqrt{\left(\frac{(51.2)^2}{4} + 25.32^2\right)^3} - -25.32^3\right]\frac{1}{144}$$

$$= 17.49 \text{ FT}^2 = 1.625 \text{ m}^2$$

> TOTAL SURFACE AREA = 1.625 + 1.59 = 3.215 m^2

THE HGA DISH IS .25" THICK HONEYCOMB GRAPHITE EPOXY.

ASSUME THE MATERIAL ACTS SIMILAR TO ALUMINUM WITH A THICKNESS OF .25", .635 cm.

$$t = K_1 \; m^{.352} \; V^{.875} \; \rho^{1/6}$$

FOR METEOROID:

$$.635 = .57 \; m^{.352} \; 20^{.875} \; .5^{1/6}$$

$$m = .00110 g$$

MET. FLUX:

$$Nc = 2.88325 \text{ X } 10^{-15} \; (.00110)^{-1.213}$$

$$= 1.11 \text{ X } 10^{-11} \; / \; m^2 \, . \, \text{SEC}$$

$$Po = e^{-NAT} = e^{-\left(1.11 \text{ X } 10^{-11}\right)(3.215)\left(6.3072 \text{ X } 10^7\right)}$$

$$= .9979$$

FOR DEBRIS:

$$.635 = .57 \; m^{.352} \; 10^{.875} \; 2.81^{1/6}$$

$$m = .00272 \text{ g} \rightarrow \text{dia.} = .1227 \text{ cm}$$

$$Aeff = \left(1.86 \, \pi \, r^2\right) + (1.19)\,(2/3 \text{ hd})\; 2$$

$$= \pi \; (51.2)^2 \; (.0929/144)\; (1.86) + (1.19)\; (2/3 \text{ X } 12.94 \text{ X } 51.2)\left(\frac{.0929}{144}\right) = 3.48$$

DEBRIS FLUX:

$$\text{LOG } Nc = -2.52 \text{ LOG } (.1227) - 5.46$$

$$Nc = 6.8566 \text{ X } 10^{-4}/m^2 . \text{ YR}$$

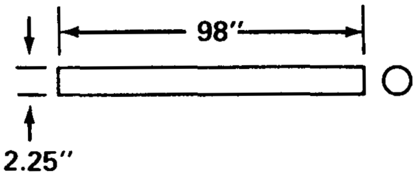
$$Po = e^{-\left(6.8566 \text{ X } 10^{-4}\right)(3.48)\,(2)} = .9952$$

TOTAL PROB. OF NO PENETRATION = (.9956) (.9979) = $\underline{.9931}$

APPENDIX 2

MAGNETIC TORQUERS

STAINLESS STEEL



HOLLOW, $t = .035'' = .0889$ cm

$$t = K_1\, m^{.352}\, \rho^{1/6}\, V^{.875}$$

$$\begin{aligned} A &= 2\,\pi rh + 2\,\pi r^2 \\ &= 2\,\pi\,(1.125)\,(98) + 2\,\pi\,(1.125)^2 \\ &= 4.87\ \text{ft}^2 = .452\ \text{m}^2 \end{aligned}$$

FOR METEOROID:

$$.0889 = .32\, m^{.352} (.5)^{1/6}\, 20^{.875}$$

$$m = .0000213\ \text{g}$$

$$Nc = 2.88325 \times 10^{-15}\, (.0000213)^{-1.213}$$

- 2 YRS: $Po = e^{-NAT} = e^{-(1.339 \times 10^{-9})\,(.452)\,(6.3072 \times 10^{7})}$
  $= .9625$

5 YRS: $Po = .9090$

10 YRS: $Po = .8262$

15 YRS: $Po = .7510$

*SQUARE THE PROBABILITY TO GET THE TOTAL FOR 2.

FOR DEBRIS:

$$.0889 = .32\, m^{.352}\left(2.81^{\,1/6}\right)\left(10^{.875}\right)$$

$$m = .0000527\ g$$

$$d = \left(\frac{6m}{\pi \rho}\right)^{1/3} = \left(\frac{6(.0000527)}{\pi\ (2.81)}\right)^{1/3}$$

$$d = .0330\ cm$$

$$LOG\ N = -2.52\ LOG\ (.0330) - 5.46$$

$$N = .01876/m^2 \cdot YR$$

$$Aeff = \left((2.25 \times 98) \times 1.86 \times \frac{.0929}{144}\right) + \left(\pi\ (2.25)^2 \times 1.19 \times \frac{.0929}{144}\right)$$

$$= .2646 + .0122 = .2768\ m^2$$

2 YRS: $Po = e^{-(.01876)(.2768)(2)}$

$= .9897$

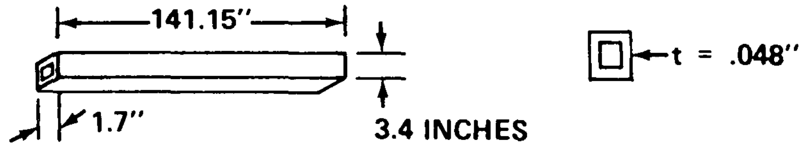
5 YRS: $Po = .9744$

10YRS: $Po = .9494$

15 YRS: $Po = .9251$

WAVEGUIDES – IT WAS ASSUMED THAT A PARTICLE PRODUCING GREATER THAN A 1/2INCH DIAMETER HOLE WOULD BE CRITICAL.

- HGA MAST – (ALSO ACTS AS A WAVEGUIDE)
  GRAPHITE AI (ASSUME AI BEHAVIOR)



$$\text{AREA} = (1.7 \times 2 \times 141.15) + (3.4 \times 2 \times 141.15)$$

$$= 1439.73\ \text{IN}^2 = 10.0\ \text{FT}^2 = .93\ \text{m}^2$$

FOR A 1/2" HOLE, $D = 1/2" = 1.27$ CM

$d = ?$

$t = .048$ IN. $= 0.122$ cm

$V = 20$ km/s

$$D/d = \left(0.9 + 0.45\, V\, (t/d)^{2/3}\right)$$

FOR METEOROID: GUESS $d = .138$ cm ← PARTICLE DIAMETER

$1.27/.138 = 0.9 + (.45)(20)(.122/.138)^{2/3}$

$9.20 = 9.19$

$$m = \rho V = (.5)\left(\pi\ \frac{.138^3}{6}\right) = .000688\ \text{g}$$

FLUX: $Nc = 2.88325 \times 10^{-15}\ (.000688)^{-1.213}$

$= 1.976 \times 10^{-11}\ /\text{m}^2 \cdot \text{sec}$

2 YRS: $Po = e^{-\left(1.976 \times 10^{-11}\right)(.93)\left(6.3072 \times 10^{7}\right)}$

$Po = .9988$

5 YRS: $P_o = .9971$

10 YRS: $P_o = .9942$

15 YRS: $P_o = .9913$

FOR DEBRIS: GUESS $d = .47$

$$D/d = \left(0.9 + 0.45\, V\, (t/d)^{2/3}\right)$$

$$2.7 = 2.7$$

$$m = \rho V = (2.81)\left(\pi \frac{.47^3}{6}\right) = .15276 \text{ g}$$

FLUX:

$$\text{LOG } N_c = -2.52\,(\text{LOG } d) - 5.46$$

$$N_c = 2.32 \times 10^{-5} / m^2 \cdot YR$$

EFFECTIVE AREA:

$$A_{eff} = \left[(141.15 \times 3.4) \times \left(\frac{.0929}{144}\right) \times 1.86\right] + \left[2\,(141.15 \times 1.7) \times \left(\frac{.0929}{144}\right) \times 1.19\right]$$

$$= .944 \text{ m}^2$$

<u>2 YRS:</u> $P_o = e^{-NAT} = e^{\left(2.32 \times 10^{-5}\right)(.944)(2)}$

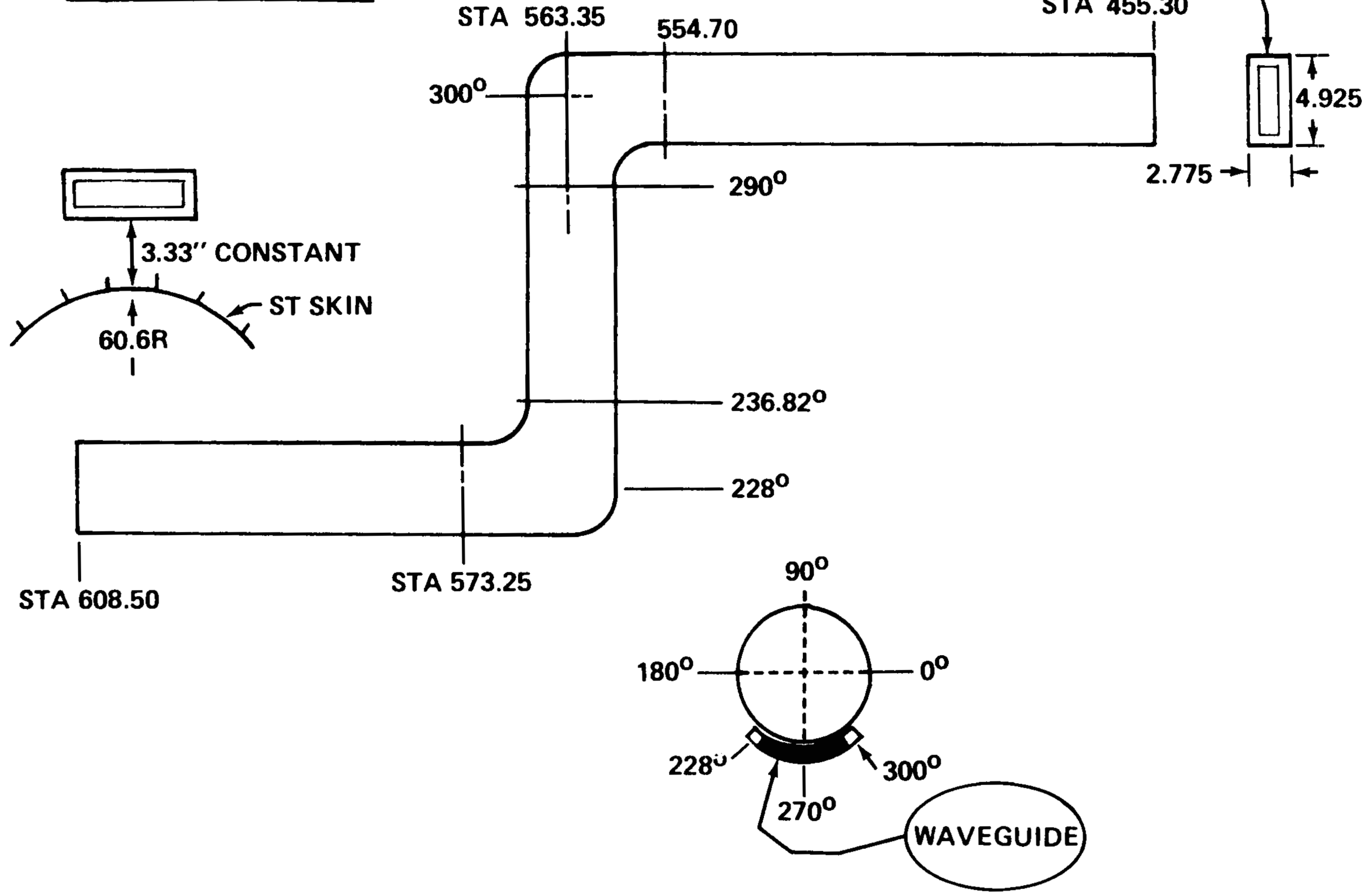
$$= .9999$$

<u>5 YRS:</u> $P_o = .9999$

<u>10 YRS:</u> $P_o = .9998$

<u>15 YRS:</u> $P_o = .9997$

– LGA WAVEGUIDE NO. 1



FOR MET.: $$*\text{AREA} = [(2.775 \times 2) + (4.925)]\ [(608.5 - 563.35) + (563.35 - 455.3) + ((300 - 228) \times \pi/180 \times (60.6 + 3.33))]$$

$$= 17.0\ \text{FT}^2$$

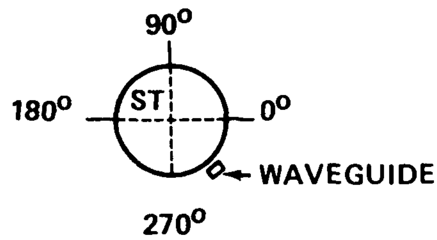
FOR DEBRIS: $$A_{eff} = (1.19)(2.775)(2)\ [(608.5 - 563.35) + (563.35 - 455.3) + ((300 - 228) \times \pi/180\ (60.6 + 3.33))]$$

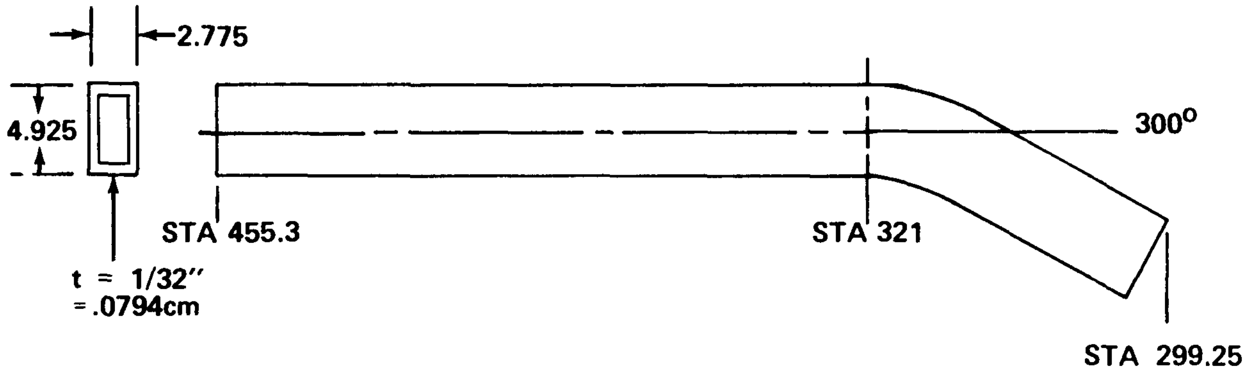
$$+ (1.86)(4.925)\ [(608.5 - 563.35) + (563.35 - 455.3) + ((300 - 228) \times \pi/180\ (60.6 + 3.33))]$$

$$= 10.71 + 14.86 = 25.57\ \text{FT}^2 \quad \text{(ASSUMING WORST CASE)}$$

*AREA IS A CLOSE APPROXIMATION, NOT EXACT

– LGA WAVEGUIDE NO. 2 –





FOR MET.: *AREA = [(2 X 2.775) + 4.925] [455.3 – 299.25]

= 11.35 ft^2

FOR DEBRIS: Aeff = [(2 X 2.775 X 1.19) + (4.925 X 1.86)] [455.3 – 299.25]

= 17.08 ft^2 (ASSUMING WORST CASE)

TOTAL AREAS FOR LGA WAVEGUIDES:

FOR MET.: 17.0 + 11.35 = 28.35 ft^2 = 2.63 m^2 = AREA

FOR DEBRIS: 25.57 + 17.08 = 3.96 m^2 = EFF. AREA

FOR A 1/2" PENETRATION HOLE, D = 1/2" = 1.27 cm

d = ?

t = .0794 cm

V = 20 km/s

*AREA IS AN APPROXIMATION, NOT EXACT.

$$D/d = (0.9 + 0.45V\,(t/d)^{2/3})$$

METEOROID

GUESS d = .25 cm

$$(1.27/.25) = (.9 + .45\,(20)\,(.0794/.25)^{2/3})$$

$$5.08 = 5.09$$

$$m = \rho V = (.5)\left(\frac{\pi\,.25^3}{6}\right) = .00409\text{ g}$$

$$\text{FLUX} = Nc = 2.88325 \times 10^{-15}\,(.00409)^{-1.213}$$
$$= 2.27 \times 10^{-12}/m^2 \cdot \text{SEC}$$

2 YRS: $\quad Po\ \text{critical} = e^{-\left(2.27 \times 10^{-12}\right)(2.63)\left(6.3072 \times 10^{7}\right)}$
$\quad = .9996$

5 YRS: $\quad$ Po critical = .9991

10 YRS: $\quad$ Po critical = .9981

15 YRS: $\quad$ Po critical = .9972

DEBRIS

GUESS d = .63 cm

$$(1.27/.63) = (.9 + .45\,(10)\,(.0794/.63\,)^{2/3})$$

$$2.02 = 2.03$$

$$m = \rho V = (2.81)\left(\pi\,\frac{.63^3}{6}\right) = .36790\text{ g}$$

FLUX: $\text{LOG Nc} = -2.52\ (\text{LOG d}) - 5.46$

$\text{LOG Nc} = -2.52\ (\text{LOG } .63) - 5.46$

$\text{Nc} = 1.11 \text{ X } 10^{-5}/\text{m}^2 \,.\, \text{YR}$

2 YRS: $\text{Po critical} = e^{-\text{NAT}} = e^{-(1.11 \text{ X } 10^{-5})\ (3.96)\ (2)}$

$= .9999$

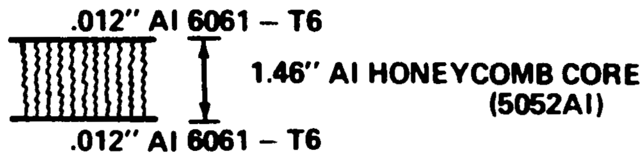
5 YRS: Po critical = .9999

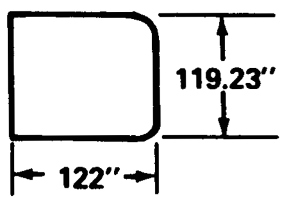
10 YRS: Po critical = .9999

15 YRS: Po critical = .9999

APPENDIX 3

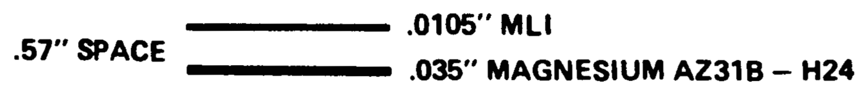
APERTURE DOOR (REF. 2)

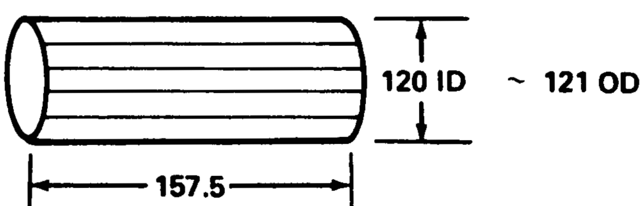




AREA = 119.23 X 122 ÷ 144 = 101.0 FT^2

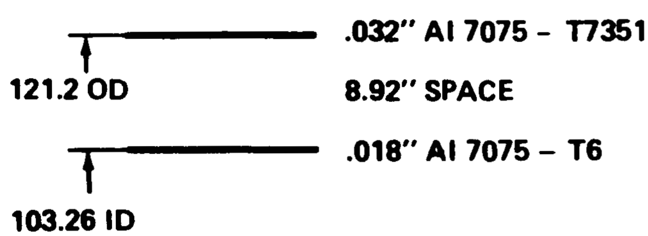
LIGHT SHIELD (REF. 2)

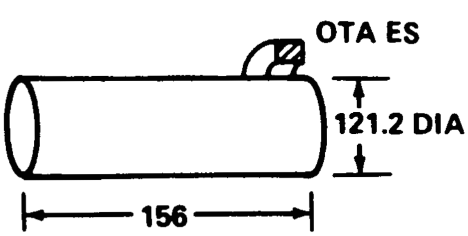




AREA = π (121) (157.5) ÷ 144 = 415.77 FT^2

FORWARD SHELL (REF. 2 & DRAWING # 679-5795 MAIN BAFFLE ASS'Y)

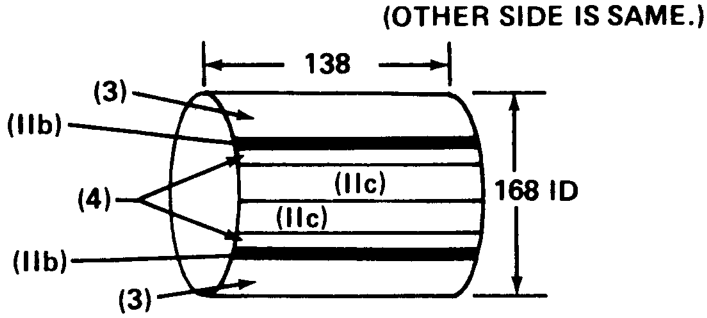




$$\text{AREA} = \left[\pi\,(121.2)\,\frac{(156)}{144} \right] - (\text{OTA ES})$$

$$= [\,412.49\,] - (55.73) = 356.76\ FT^2$$

AFT SHROUD (REF's 2 & 3)



(IIc)

[4 – 30° SECTIONS]

FOSR
.050" MAGNESIUM AZ31B – H24
3 " SPACE
.012" ALUMINUM 7075 – T7351

AREA = (120°) (π/180) (168/2) (138)/144 = 168.6 FT²

(IIb)

[4 – 15° SECTIONS]

FOSR
.032" ALUMINUM 7075 – T7351
3" SPACE
.0065" MLI

AREA = (60°) (π/180 (168/2) (138)/144 = 84.30 FT²

3

[4–30° SECTIONS]

FOSR
.050" MAGNESIUM AZ31B – H24
3" SPACE
.0105" MLI

AREA = (120°) (π/180) (168/2) (138)/144 = 168.6 FT²

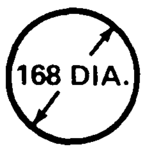
4

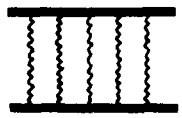
[4–15° SECTIONS]

FOSR
.035" ALUMINUM 7075 – T7351
3" SPACE
.012" ALUMINUM 7075 – T7351

AREA = (60°) (π/180) (168/2) (138)/144 = 84.3 FT²

AFT SHROUD BULKHEAD (REF's 2 & 3)





.005" FOZAR

.020" ALUMINUM 7075 – T6

2" Al HONEYCOMB CORE 7075 – T6, .25" CELLS

.020" ALUMINUM 7075 – T6

.006" MLI

$$\text{AREA} = \pi\, r^2 = \pi \left(\frac{168}{2}\right)^2 / 144 = 153.9\ \text{FT}^2 = 14.3\ \text{m}^2$$

APPENDIX 4

– EXAMPLE OF CALCULATIONS FOR NO PENETRATION OF ST STRUCTURE –

LIGHT SHIELD

.0105" MLI

.57" SPACE

.035" MAGNESIUM AZ31B

MLI: ρ = 1.741 g/cm^3, e = 0.50 in/in

MAG.: ρ = 1.769 g/cm^3, e = 0.08 in/in

$$K_1 = 0.816 / \left(e^{1/18} \; \rho^{1/2}\right)$$

e = MATERIAL ELONGATION cm/cm

ρ = MATERIAL DENSITY gm/cm^3

$$K_1 \text{ (MLI)} = 0.816 / (.50)^{1/18} (1.741)^{1/2} = 0.643$$

$$K_1 \text{ (MAG)} = 0.816 / (.08)^{1/18} (1.769)^{1/2} = 0.706$$

$$K_1 \text{ (Al)} = 0.816 / (.08)^{1/18} (2.81)^{1/2} = 0.560$$

FIND THE EQUIVALENT ALUMINUM THICKNESSES FOR THE MLI AND THE MAGNESIUM.

$$t = K_1 \, m^{.352} \; \rho_m^{\;1/6} \; V^{.875}$$

FOR m, ρ , & V CONSTANT , $\dfrac{t_1}{t_2} = \dfrac{K_1}{K_2}$

$$t_{Al} = \frac{K_{Al}}{K_{MLI}} t_{MLI} = \frac{(.560)}{(.643)} (.0105) = .0091'' \text{ Al}$$

$$t_{Al} = \frac{K_{Al}}{K_{MAG}} t_{MAG} = \frac{(.560)}{(.706)} (.035) = .0278'' \text{ Al}$$

METEOROID
NYSMITH:

$$B.\,L. = 2.88 \times 10^{-3} \left(\frac{t_1}{d}\right)^{1.9} \left(\frac{t_2}{d}\right)^{3.6} \left(\frac{h}{d}\right)^{5}$$

t_1 = BUMPER THICKNESS, mm = 0.231 mm

t_2 = HULL THICKNESS, mm = 0.706 mm

h = SPACING, mm = 14.478 mm

d = PARTICLE DIAMETER, mm

B. L. = PARTICLE VELOCITY, BALLISTIC LIMIT, km/sec

= 20 km/sec for meteoroid

$$20 = 2.88 \times 10^{-3} \left(\frac{.231}{3}\right)^{1.9} \left(\frac{.706}{d}\right)^{3.6} \left(\frac{14.478}{d}\right)^{5}$$

d = 1.047 mm = .1047 cm

$$\text{MASS} = (.5\ \text{g/cm}^3)\ (\pi/6)\ (.1047)^3 = .00030\ \text{g}$$

$$\text{FLUX} = N_c = 2.88325 \times 10^{-15}\ (.00030)^{-1.213}$$
$$= 5.409 \times 10^{-11}/\text{m}^2 \cdot \text{SEC}$$

FOR 2 YEARS

$$P_o = e^{-NAT} = e^{-(5.409 \times 10^{-11})\ (416\ \text{FT}^2 \times .0929\ \text{m}^2/\text{FT}^2)\ (6.3072 \times 10^7\ \text{SEC})}$$
$$= .8765$$

FOR 5 YEARS P_o = .7192

FOR 10 YEARS: P_o = .5173

FOR 15 YEARS: P_o = .3721

DEBRIS

$$BL = 10\,km/s = 2.88 \times 10^{-3}\left(\frac{.231}{d}\right)^{1.9}\left(\frac{.706}{d}\right)^{3.6}\left(\frac{14.478}{d}\right)^{5}$$

$$d = 1.116\ mm = .1116\ cm$$

$$MASS = \left(2.81\ g/cm^3\right)\ (\pi/6)\ (.1116)^3 = .00205\ g$$

$$FLUX:\ LOG\ N = -2.52\ LOG\ (.1116)\ -5.46$$

$$N = .0008707/m^2 .\ YR$$

<u>FOR 2 YEARS:</u> $Po = e^{-NAT} = e^{-(.0008707)\ (416 \times .0929)\ (2)}$

$= .9349$

<u>FOR 5 YEARS:</u> $Po = .8451$

<u>FOR 10 YEARS:</u> $Po = .7143$

<u>FOR 15 YEARS:</u> $Po = .6037$

Appendix 5--Test Results

Shot No.	Sample Origin	Test Location	Vel(km/s)	Mass(mg)	Results
Light Shield (2a)					
804 *	MSFC	JSC	7.83	2.56	PENETRATED
805 *	MSFC	JSC	7.86	2.49	PENETRATED
811 *	MSFC	JSC	7.56	2.54	PENETRATED
812 *	MSFC	JSC	5.8	2.35	NOT PENE- TRATED
814 *	MSFC	JSC	6.65	2.47	PENETRATED
815 *	MSFC	JSC	5.998	2.5	PENETRATED
816 *	LMSC	JSC	6.14	2.425	NOT PENE- TRATED; MLI EXPANDED
818 *	MSFC	JSC	6.88	2.436	PENETRATED SMALL HOLE
819 *	MSFC	JSC	6.19	2.47	PENETRATED
820 *	MSFC	JSC	6.13	2.44	PENETRATED PINHOLE
821 *	LMSC	JSC	6.25	2.47	PENETRATED
822 *	LMSC	JSC	6.03	2.44	PENETRATED LARGE HOLE (MLI DROOPED)
4-0346***	LMSC	UNIV. OF DAYTON	4.18	45.6	PENETRATED
4-0388**	LMSC	UNIV. OF DAYTON	5.03	5.0	PENETRATED
4-0382***	LMSC	UNIV. OF DAYTON	4.99	5.2	PENETRATED (HOLE AREA: .05 SQ CM)
Aft Shroud (2b)					
4-0383***	LMSC	UNIV. OF DAYTON	5.02	5.0	PENETRATED
4-0390**	LMSC	UNIV. OF DAYTON	5.12	5.0	PENETRATED
4-0392**	LMSC	UNIV. OF DAYTON	6.02	5.0	PENETRATED
4-0414**	LMSC	UNIV. OF DAYTON	5.97	2.1	PENETRATED (HOLE AREA: .039 SQ CM)
Aft Shroud (2c)					
4-0384***	LMSC	UNIV. OF DAYTON	5.07	5.0	PENETRATED
4-0391**	LMSC	UNIV. OF DAYTON	5.00	4.9	PENETRATED
4-0393**	LMSC	UNIV. OF DAYTON	6.05	4.9	PENETRATED
4-0412**	LMSC	UNIV. OF DAYTON	5.98	2.1	PENETRATED (HOLE AREA: .0175 SQ CM)
Aft Shroud Bulkhead					
898*	LMSC	JSC	6.49	4.87	DENTED AL BACK SHEET. SHOT MADE TOO CLOSE TO EDGE OF SAMPLE--BLEW OUT SIDE. DID NOT PENETRATE MLI.

Shot No.	Sample Origin	Test Location	Vel(km/s)	Mass(mg)	Results
902***	LMSC	JSC	4.77	5.06	SMALL HOLE IN AL BACK SHEET. DID NOT PENE-TRATE MLI.
903***	LMSC	JSC	5.51	4.96	3 SMALL HOLES IN AL BACK SHEET. ALMOST PENETRATED MLI--ALL BUT LAST 2 LAYERS.
904*	LMSC	JSC	4.36	2.31	DID NOT DAMAGE AL BACK SHEET.
905*	LMSC	JSC	7.43	2.37	DID NOT PENE-TRATE AL BACK SHEET--MIGHT HAVE IF HAD NOT BLOWN OUT SIDE OF SAMPLE.
906***	LMSC	JSC	5.66	5.0	PENETRATED MLI. TWO HOLES APPROX 1/16 & 1/8 DIAM.
907***	LMSC	JSC	5.19	4.83	PENETRATED MLI. ONE HOLE APPROX 1/16 DIAM.
908***	LMSC	JSC	6.69	5.02	DENTED AL BACK SHEET. DID NOT PENETRATE MLI.
930***	LMSC	JSC	5.6	5.93	TWO HOLES IN AL BACK SHEET APPROX 1/16" DIAM EA. MLI PENETRATED TWO PLACES, APPROX 1/16" DIAM EA (SLIGHTLY SMALLER).

* NYLON (1.13 g/cc)
** PYREX (2.23 g/cc)
*** ALUMINUM (2.81 g/cc)

MSFC: Lab Support Branch EH15, Engineering Physics Division
Materials and Processes Laboratory
Marshall Space Flight Center, Huntsville, Alabama
JSC: Hypervelocity Impact Gun Facility, SM12
Johnson Space Center, Houston, Texas
LMSC: Lockheed Missiles & Space Company, Inc.
Sunnyvale, California
Univ. of Dayton: Hypervelocity Impact Testing Facility
University of Dayton, Dayton, Ohio

APPENDIX 6 – TESTING/ANALYSIS INTEGRATION WITH STRAYLIGHT REQUIREMENTS

EXAMPLE – LIGHT SHIELD

FROM THE TEST SAMPLE, A 5.2 mg Al$\left(\rho = 2.81 g/cm^3\right)$ PROJECTILE AT 4.99 km/sec PRODUCED THE EQUIVALENT OF A .050 cm^2 HOLE (DIA. = .0042 cm)

METEOROID ANALYSIS

CONVERT THE PARTICLE MASS AND VELOCITY TO THAT OF A METEOROID PARTICLE:

$$m_{MET}^{.352}\left(20^{.875}\right)\left(.5^{1/6}\right) = \left(5.2 \times 10^{-3^{.352}}\right)\left(4.99^{.875}\right)\left(2.81^{1/6}\right)$$

m_{MET} = .00037 g AT 20 km/sec (DIA. = .1126 cm)

MINIMALLY DEGRADED

ALLOWABLE HOLE SIZE PER SQUARE METER: 10 mm^2/m^2 = .1 cm^2/m^2

TOTAL ALLOWABLE HOLE FOR LS = $(.1\ cm^2/m^2)$ (415.77 X .0929)

= 3.863 cm^2

COMPARE TO HOLE SIZE FROM THE TEST $\left\{ \dfrac{3.863}{.050} \right.$ = 77.26 TIMES LARGER

ASSUMING AN INCREASED KINETIC ENERGY RESULTS IN A PROPORTIONALLY INCREASED HOLE AREA, THEN 77.26 TIMES THE MASS FROM THE TEST WILL RESULT IN THE HOLE AREA ALLOWABLE FOR MINIMALLY DEGRADED PERFORMANCE.

MASS X 77.26 = .00037 X 77.26 = .028857 g

THEN USE THIS MASS TO FIND THE FLUX:

$$Nc = 2.88325 \times 10^{-15} (.028857)^{-1.213}$$
$$= 2.126 \times 10^{-13}/m^2 . SEC$$

FOR 2 YEARS: $P_1 = e^{-(2.126 \times 10^{-13})(415.77 \times .0929)(6.3072 \times 10^7 SEC)}$

$= \underline{.9999}$

THIS IS THE PROBABILITY THAT IN 2 YEARS THERE WILL BE ONE OR LESS PENETRATIONS OF A PARTICLE WHICH WOULD RESULT IN MINIMALLY DEGRADED PERFORMANCE OF THE LS VISUAL CAPABILITIES

FOR 5 YEARS: $P_1 = .9999$

FOR 10 YEARS: $P_1 = .9999$

FOR 15 YEARS: $P_1 = .9999$

<u>DEGRADED</u> (10 X MINIMAL)

$$m = 10 \times .028857 = .28857 \text{ g}$$

$$Nc = 2.88325 \times 10^{-15} (.28857)^{-1.213} = 1.302 \times 10^{-14}/m^2 . SEC$$

FOR 2 YEARS: $P_1 = e^{-(1.302 \times 10^{-14})(415.77 \times .0929)(6.3072 \times 10^7)} + (e^{-NAT}\, NAT)$

$= .9999$

FOR 5 YEARS. $P_1 = .9998$

FOR 10 YEARS $P_1 = .9997$

FOR 15 YEARS: $P_1 = .9995$

SEVERELY DEGRADED (10 X DEGRADED)

$$m = 10 \text{ X } .28857 = 2.8857 \text{ g}$$

$$Nc = 2.88325 \text{ X } 10^{-15} (2.8857)^{-1.213}$$
$$= 7.97 \text{ X } 10^{-16} / m^2 . \text{SEC}$$

FOR 2 YEARS: $P_1 = e^{-\left(7.97 \text{ X } 10^{-16}\right)(415.77 \text{ X } .0929)\left(6.3072 \text{ X } 10^7\right)} + \left(e^{-NAT}\ NAT\right)$
$= .9999$

FOR 5 YEARS: $P_1 = .9999$

FOR 10 YEARS: $P_1 = .9999$

FOR 15 YEARS: $P_1 = .9999$

DEBRIS ANALYSIS

CONVERT THE TEST PARTICLE TO A DEBRIS PARTICLE:

$$m_{DEB}{}^{.352}\left(10^{.875}\right)\left(2.81^{1/6}\right) = \left(5.2 \text{ X } 10^{-3}\right)^{.352}\left(4.99^{.875}\right)\left(2.81^{1/6}\right)$$

$m_{DEB.}$ = .00092 g AT 10 Km/sec

MINIMALLY DEGRADED

ALLOWABLE HOLE SIZE PER SQUARE METER: 10 mm^2/m^2 = .1 cm^2/m^2

TOTAL ALLOWABLE HOLE FOR LS = 3.863 cm^2

COMPARE TO HOLE SIZE FROM TEST $\left\{\frac{3.863}{.05}\right.$ = 77.26 TIMES

MIN. DEG. MASS = .00092 g X 77.26 = .07108 g

DIA. = .3642 cm

FLUX: LOG N = −2.52 LOG (.3642) − 5.46

$N = 4.4 \times 10^{-5}/m^2 \cdot YR$

$Aeff = 22.87\ m^2$

FOR 2 YEARS: $P_1 = e^{-\left(4.4 \times 10^{-5}\right)(22.87)(2)} + \left(e^{-NAT}\ NAT\right)$

$= .9999$

FOR 5 YEARS: $P_1 = .9999$

FOR 10 YEARS: $P_1 = .9999$

FOR 15 YEARS: $P_1 = .9999$

WHERE $Aeff = (1.86)\,(121 \times 157.5)\left(\frac{.0929}{144}\right)$

$\uparrow$ FLUX FACTOR FOR DEBRIS (FRONT PROJECTED AREA)

$Aeff = 22.87\ m^2$

<u>DEGRADED</u>

$MASS_{DEGRADED} = 10 \times MASS_{MIN\text{-}DEG.}$

$= 10 \times .07108\ g = .7108\ g$

$DIA. = .7847\ cm$

FLUX: $\text{LOG } N = -2.52 \text{ LOG } (.7847) - 5.46$

$N = 6.39 \times 10^{-6}/m^2 \cdot YR$

FOR 2 YEARS: $P_1 = e^{-\left(6.39 \times 10^{-6}\right)(22.87)(2)} + \left(e^{-NAT}\ NAT\right)$

$= .9999$

FOR 5 YEARS: $P_1 = .9999$

FOR 10 YEARS: $P_1 = .9999$

FOR 15 YEARS: $P_1 = .9999$

SEVERELY DEGRADED

$$MASS_{SEV.\ DEG.} = 10 \times MASS_{DEG.}$$

$$= 10 \times .7108 = 7.108\ g$$

DIA. = 1.6905 cm

FLUX: $LOG\ N = -5.444 - 1.358\ LOG\ (1.6905) + .352\ \left(LOG\ (1.6905)\right)^2$

$N = 1.84 \times 10^{-6}/m^2 \cdot YR$

FOR 2 YEARS: $P_1 = e^{-\left(1.84 \times 10^{-6}\right)(22.87)\ (2)} + \left(e^{-NAT}\ NAT\right)$

$= .9999$

FOR 5 YEARS: $P_1 = .9999$

FOR 10 YEARS: $P_1 = .9999$

FOR 15 YEARS: $P_1 = .9999$

APPROVAL

HUBBLE SPACE TELESCOPE METEOROID/DEBRIS PROTECTION ANALYSIS

By Jennifer Horn and Juan Maldonado

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

A. A. McCOOL
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