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A COMPARISON OF SPACECRAFT PENETRATION HAZARDS

DUE TO METEOROIDS AND MANMADE EARTH-ORBITING OBJECTS

By

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November 1976

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16. Abstract

The ability of a typical double-walled spacecraft structure to protect against penetration by high-velocity incident objects is reviewed. The hazards presented by meteoroids are compared to the current and potential hazards due to manmade orbiting objects. It is shown that the nature of the meteoroid number-mass relationship makes adequate protection for large space facilities a conceptually straightforward structural problem. The present level of manmade orbiting objects (an estimated 10,000 in early 1975) does not pose an unacceptable risk to manned space operations proposed for the near future, but it does produce penetration probabilities in the range of 1-10 percent for a 100-m diameter sphere in orbit for 1000 days. The number-size distribution of manmade objects is such that adequate protection is difficult to achieve for large permanent space facilities, to the extent that future restrictions on such facilities may result if the growth of orbiting objects continues at its historical rate.

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A COMPARISON OF SPACECRAFT PENETRATION HAZARDS

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SUMMARY

A recent analysis of the probability of Earth-orbiting spacecraft colliding with manmade objects in space is re-examined in terms of spacecraft penetrations. A typical double-wall spacecraft structure is utilized to compare the penetration hazard from naturally occurring meteoroids with that of manmade objects. It is shown that the structure is very effective in preventing meteoroid penetrations. For incident objects having a mass of more than about 0.1 gm, the penetration probability due to manmade objects is about equal to that from meteoroids, being on the order of 1-10 percent for a 100-m diameter sphere in orbit at 500-800 km for 1,000 days. Whereas additional protection can reasonably be provided against meteoroids, the size distribution of manmade objects, ranging from entire spacecraft to small explosion fragments, is such that an equivalent increase in protection is difficult to achieve. For example, the penetration probability for meteoroids of mass greater than or equal to 1 gm incident against a 100-m sphere is only about 0.6 percent, but for manmade objects, it is still in the range of 1-10 percent. The present level of orbiting manmade objects does not constitute a hazard to current space activities, including the space transportation system planned for operational status in the 1980's. However, the historically documented growth trend in the orbiting population will eventually lead to future restrictions on large permanent space facilities unless steps are taken to prevent growth in the orbiting population from continuing at its present rate.

INTRODUCTION

The probability of impact with manmade objects in space has been treated recently (ref. 1) in a parametric fashion for a variety of Earth orbits. A principal result is that there are already orbits for which the probability of collision exceeds 10 percent for a 100-m diameter sphere during a 1,000-day period. While this impact probability level does not now pose an unacceptable risk for manned operations in much smaller spacecraft, the historical record of continuous growth in the orbiting population foreshadows a future with severe restrictions on our use of near-Earth space. Current knowledge of manmade objects in orbit is based on that part of the total population which can be consistently monitored by current radar systems--objects typically no smaller than about 0.1 m^2. The history of this part of the population is given in figure 1, which shows a current growth rate of about 280 trackable objects per year. A total of more than 3,500 trackable objects at the start of 1975 should be equivalent to a total population of about 10,000 objects (including those too small to be tracked) according to the orbiting population model developed in reference 1.

The matter of actual spacecraft penetrations, as opposed to impacts, was not treated in reference 1. In the case of meteoroids, it is well known that double-wall spacecraft structures are quite effective against the expected incident flux of naturally occurring particles, and that penetrations of spacecraft with such protection are rare compared to impacts. This memorandum will review the effectiveness of a typical manned spacecraft structure as protection against meteoroids, and compare the results with those of a similar analysis for the manmade orbiting population.

SYMBOLS

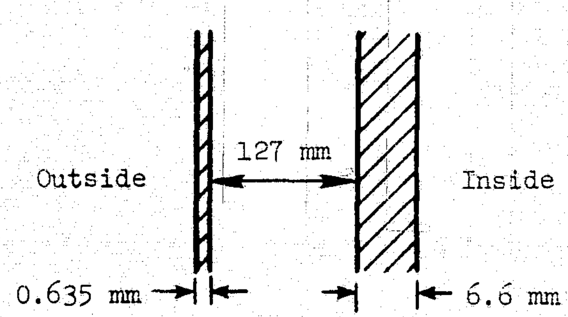
A	Area of a spacecraft structure, m^2
F_i	Fraction of the total orbiting manmade population having a speed $v_i \pm 0.5$ km/sec
m	Mass, gm
N_i	Fraction of the total orbiting manmade population having sufficient mass to penetrate a spacecraft structure on impact at relative speed v_i
P	Probability
v	Speed, relative to a spacecraft structure, km/sec
t	Time, sec
ρ	Density, gm/cm^3
ϕ	Flux against a spacecraft structure, impacts per m^2 per sec
ϕ_{unit}	A unit incident flux, one impact per m^2 per sec
#	Number

Subscripts:

coll	Collision or impact
p	Penetration
T	Total
i	A summation index, see equation (3) and table 3

EFFECTIVENESS OF A DOUBLE-WALL SPACECRAFT STRUCTURE IN PREVENTING METEOROID PENETRATION

A cross section of a typical double-wall spacecraft structure is shown in sketch (1) below. Such structures have been used for manned spacecraft in the past; unpublished work at NASA Langley Research Center shows that the dimensions assumed yield a structure equivalent to a Skylab wall.



Sketch (1)-Double-wall aluminum spacecraft structure (not to scale)

The thin outer wall is separated from the primary structural wall and serves to fragment incoming meteoroids so that their energy is dispersed over a large area, making it more difficult to penetrate the inner wall. Meteoroids are assumed to have an average density of about 0.5 gm/cm^3, and unpublished impact tests with lightweight glass and resin projectiles (ρ = 0.7 gm/cm^3) show that the minimum mass which will penetrate the inner wall of the above structure is

$$m_p = \frac{47.92}{v^2} \qquad (1)$$

(the units of m_p and v are gm and km/sec, respectively.)

Meteoroid speeds relative to the Earth range from about 10 to 70 km/sec, with an average of about 20 km/sec; the distribution function is given in reference 2. For a speed of 20 km/sec, the minimum penetration mass would be 0.1198 gm according to equation (1).

The number-mass distribution of meteoroids up to 1 gm at 1 astronomical unit (the Earth's orbit) has also been modeled in reference 2, and the results are shown in figure 2, where number densities (particles/m^3) have been multiplied by a constant average speed of 20 km/sec to compute incident flux ϕ. This flux is assumed to be isotropic, on the average, with respect to a randomly oriented object. For spacecraft in orbit around the Earth, the flux values in figure 2 for any given cumulative mass (that is, the flux for all meteoroids greater than or equal to a given mass) must be multiplied by a defocussing factor and a shielding factor to account for the Earth's gravitational focussing of meteoroids and also for the shielding provided by the Earth (ref. 2). For a typical Skylab orbit at 425 km, the product of these two factors is about 0.65. Thus, the average cumulative penetration ϕ_p flux against a spacecraft in a 425-km orbit is 3.6×10^{-14} impacts/m^2-sec. The corresponding probability of penetration (assuming that this number is much less than 1) is related to flux through a Poisson distribution:

$$P_p = \phi_p Ate^{-\phi_p At} = \phi_p At \left(1 - \phi_p At + \frac{\phi_p^2 A^2 t^2}{2} - \ldots\right) \qquad (2)$$

Using the Skylab area of 145 m^2 and a time of 1 year ($At = 4.573 \times 10^9$ m^2-sec) gives $P_p = 0.000166$, showing that a typical manned spacecraft provides extremely good protection against penetration by naturally occurring objects.

THE PENETRATION FLUX OF MANMADE OBJECTS

Analogously to studies involving meteoroids, calculation of the penetration flux of manmade objects incident on a particular structure involves a knowledge of the mass and speed distributions of the incident objects as well as details of the structure itself. Number versus apparent radar cross-section data given in reference 1 for various classes of orbiting objects (table 5 and fig. 10-15) have been used as the basis for a normalized number-versus-mass relationship by assuming a flat-plate shape and a density of 2.7 gm/cm^3 (aluminum). The results are listed in table 1 and plotted in figure 3. According to these calculations, the smallest assumed orbiting fragment has a mass of 8.29×10^{-4} gm. A normalized number-mass relationship has been chosen because the total number of manmade orbiting objects cannot be determined directly due to the large percentage of objects which cannot be tracked from the ground. Based on the observed history of known objects, the total population is thought to be constantly increasing and has been extrapolated to the future in reference 1. A total level of 10,000 objects is appropriate for early 1975; the analysis in reference 1 can be used to extrapolate the assumed total of orbiting objects to future dates. Note, that whereas the meteoroid number-mass relationship is a linear log-log relationship in the mass range from 10^{-6} to 1 gm, (see fig. 2), the distribution for manmade objects levels off at a mass of about 10^{-3} g (fig. 3) as a result of the depletion of smaller objects through orbital decay. (A similar leveling off, although for totally different physical reasons, can be seen (fig. 2) in the meteoroid population for masses nine orders of magnitude smaller.)

For manmade objects, it is not sufficient to treat the incident speed as a constant average value, as can be done to good approximation for meteoroids. Also, the relative speed distribution cannot be assumed isotropic, and is instead strongly dependent on the target orbit parameters. In table 2, the probability distribution for incident speeds is given for several representative orbits, including ones which give nominal and "worst-case" collision probabilities according to reference 1. As the calculations required for this analysis can be made easily from these data in their present form, no attempt has been made to model the speed distributions or to represent them analytically. Note that for some of the target orbits at low altitudes and low inclinations the distributions are fairly uniform compared to higher altitudes and inclinations which show strongly the effect of encountering most objects in a retrograde orientation (high relative velocity).

It remains now to determine the relationship between penetration mass and velocity appropriate to manmade objects, corresponding to equation (1) for meteoroids. An obvious expected difference arises from the fact that, whereas meteoroids are of low density, manmade objects tend to be metallic and of accordingly higher density. Another difference is the speed range of incident particles, which for the manmade population is expected to range from 0 to about 16 or 17 km/sec (twice the orbital speed). In figure 4, a penetration threshold model for aluminum projectiles ($\rho = 2.7$ gm/cm^3) is given, based on unpublished high-velocity impact tests against the structure shown in sketch (1). The breaks in the curve approximate experimental results and illustrate behavior which is typical of double-wall structures. As the relative speed increases, some fragmentation of incoming projectiles starts to occur at the first break (3 km/sec). Then, as the incident speed increases beyond 3 km/sec, the mass of the incoming projectile must be increased before the fragments can penetrate the inner wall. At speeds higher than 6 km/sec, the penetration behavior of projectile fragments returns to a negative slope. The performance of double-wall structures has been reported extensively in the literature (ref. 3).

The preceding data are sufficient to calculate the penetration flux resulting from a unit incident flux ϕ_{unit}. Table 2 gives 16 speed increments and the fraction $F_i(v)$ of the total population associated with the increment $v_i \pm 0.5$ km/sec for selected orbits. Figure 4 gives the mass m_p required to penetrate at each speed increment and figure 3 (or interpolation between the values in table 1) gives the fraction of the total population $N_i(m_p)$ which is capable of penetration. It is reasonable to assume that the relative speed and mass distribution of manmade objects are mutually independent so that the penetrating flux for a unit incident flux is:

$$\phi_p = \sum_{i=1}^{16} F_i(v) N_i(m_p) \tag{3}$$

As an example, consider a 500-km orbit at 28 1/2° inclination (due east launch from Cape Canaveral). The speed distribution of manmade objects incident on a spacecraft in this orbit is given in table 2. Details of the penetration flux calculations can be followed by reference to table 3, which lists the 16 relative speed increments, v_i, with the speed distribution, $F_i(v)$, mass required for penetration, $M_p(v)$, fraction of the population which will penetrate, $N_i(m_p)$, and fraction of a unit incident flux, ϕ_{unit} which becomes a penetrating flux ϕ_p. The sum of the entries in the last column shows that 82 percent of the incident flux results in a penetration. The penetration flux ϕ_p is given for a unit incident flux in table 4 for several representative orbits. Clearly, the penetration flux is nearly independent of orbit parameters for the range of orbits considered.

COMPARISON OF PENETRATION HAZARDS DUE TO METEOROIDS AND MANMADE OBJECTS

The determination of actual levels of penetrating flux, or the probability of penetration, for manmade objects requires a knowledge of the levels of incident flux associated with manmade objects. Since the equivalence between flux and probability has been established in equation (2), the impact probability analysis in reference 1 may be applied equally well to specifying the incident flux so that spacecraft hazards associated with both natural and manmade objects may be compared on an equivalent basis. Reprograming of the probability analysis described in reference 1 and new calculations of probability have yielded revised impact data for 500 and 800 km circular orbits which are given in figure 5. These results indicate that the probability data for some target inclinations were underestimated by about an order of magnitude in figure 17 of reference 1.

This numerical error in no way affects the qualitative argument proposed in reference 1 to explain the shape of the probability curves, nor does it affect the population model which represents a substantial portion of the work documented in reference 1.

The impact and penetration comparisons between natural and manmade objects encountered in Earth orbit are contained in table 5. The first line shows the total incident flux of meteoroids greater than or equal to 10^{-12} gm, at 500 and 800 km. The slight differences are due to correction for shielding and gravitational focussing, which are dependent on altitude (ref. 2). Against the 100-m diameter sphere used as a standard target in reference 1, the flux produces about 7×10^{7} impacts in 1000 days. There is no equivalent data for manmade objects, as the size of these has been limited to masses greater than or equal to about 8×10^{-4} gm as previously discussed (fig. 3). Accordingly, the second line compares the flux of meteoroids having a mass equal to or greater than the assumed smallest orbiting manmade object with the flux from the assumed total manmade orbiting population. Note that more than 40 meteoroid impacts are expected during the 1,000-day period. The flux of manmade objects is computed from equation (2), using the corresponding probability range of 0.018 - 0.157; it is 3 orders of magnitude less than the meteoroid flux.

At this point, it is tempting to conclude that the hazard from manmade objects is negligible compared to meteoroids. However, the relative situation changes dramatically on the next line. Here, consideration shifts to the flux of <u>penetrating</u> objects against the standard target. Recalling that the double-wall structure protects against meteoroids of less than 0.12 gm, the meteoroid penetration flux is 9 orders of magnitude smaller than the total flux and 3 orders of magnitude smaller than the meteoroid flux corresponding to the mass of the smallest orbiting manmade object. However, the probability of meteoroids penetrating the standard target is still about 10 percent over 1,000 days. The corresponding flux of penetrating manmade objects has dropped very little, remaining at 82 to 86 percent of the total according to table 4. As a result, the corresponding penetration probability has dropped from 0.018-0.157 to 0.015-0.135, using the 82-percent level at low inclination and 86 percent at the higher inclinations. Now the penetration hazard from manmade objects is about the same as the meteoroid hazard.

The last line of data in table 5 carries the comparison between meteoroids and manmade objects one step further. It assumes that a hypothetical structure has been developed which increases penetration protection by an order of magnitude over the double-walled structure shown in sketch 1. Specifically, it is assumed that equation (1) reads $m_p = 479.2/v^2$ and that the vertical scale of figure 4 is multiplied by 10 for equivalent added protection against manmade objects. For meteoroid protection, this is apparently a reasonable step to take because the meteoroid distribution is such that the penetration flux (or probability) is consequently decreased by more than an order of magnitude. The distribution of manmade objects results in no comparable decrease; a repeat of the calculations described above for the new penetration requirements shows that a large percentage of objects can still penetrate--from 72 to 78 percent of the total, for low and high inclinations, respectively. Now the penetration hazard from meteoroids is approaching safe levels even for the large standard target, while the hazard due to manmade objects is still in the range from 1 to 10 percent. This property of the distribution of manmade objects is evident from figure 3, which shows that more than half of the population is larger than 100 gm.

An important point regarding the data in table 5 is that the impact and penetration levels shown do not indicate the existence of a hazardous environment for present levels of space operations. Recall that on the basis of calculations presented earlier, the penetration probability for Skylab was less than 0.0002 for its year in orbit. For the space shuttle orbiter, the surface area($\approx 1000\ m^2$) is roughly 30 times smaller than the standard target and so for a year in orbit, the penetration probabilities in table 5 (for a 1,000-day period) are decreased by a factor of 100 at the altitudes considered. The population distributions in reference 1 show that at 400 km the probability should be decreased by another factor of 2 and at 200 km by an order of magnitude.

CONCLUDING REMARKS

Using models of the meteoroid and orbiting manmade object environments, it is possible to compare the relative collision and penetration hazards due to both types of objects. Qualitatively, the conclusions follow from the functional form of each model, and they are not very sensitive to the precise numerical values of the model parameters. The log-log relationship between meteoroid number and mass results in very low penetration probabilities for current spacecraft structures and missions, with clearly defined requirements for increased protection, if required, for large space facilities in the future.

The average total meteoroid flux is constant with time and can be considered predictable to the extent that meteoroid models have been and continue to be verified by experimental data. The present hazard due to manmade objects is also negligible, but prospects for the future are uncertain. The number-size distribution is such that an order-of-magnitude increase in structural resistance to penetration does not produce a corresponding decrease in penetration probability. Historical evidence suggests a continuing increase in the orbiting population with no direct way to monitor the actual total level in the foreseeable future. Thus, the estimated penetration probability for manmade objects of 1-10 percent for a 100-m sphere in orbit for 1,000 days, which now exists, is expected to increase between now and the time when permanent space facilities of this size become a reality, with no accurate means of ascertaining the actual magnitude of the problem. (Reference 1 predicts a level of 25,000 objects before 1995.) Furthermore, there is no reason to expect that the future average distribution of manmade objects will differ substantially from the present, so that the difficulty in providing increased protection will remain.

Conceptually, it is easy to offer solutions to a dangerous space environment of the future (ref. 4). Space facilities could have automatic onboard detection and maneuvering capability to prevent collisions. An alternative could involve "garbage collection" missions to rid space of hazardous material. As a practical matter, both of these solutions are tasks which could consume sizeable technical resources which should be available for more constructive endeavors. A better solution is to halt the growth of manmade space objects by altering the manner in which space is used, even as the level of use increases. Natural processes of orbital decay will eventually clear the near-Earth space of small objects, reducing the total population and increasing the percentage of orbiting objects which can be tracked from the ground. Then, not only will the hazard be reduced, but the ability to monitor and control the space environment will be enhanced.

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TABLE 1

NORMALIZED NUMBER-VERSUS-MASS RELATIONSHIP FOR THE EARTH-ORBITING POPULATION OF MANMADE OBJECTS

Mass[a] (gm)	Normalized number (Cumulative percentage)
8.29×10^{-4}[b]	100
10^{-3}	99.5
10^{-2}	93.8
10^{-1}	86.7
10^{0}	78.3
10^{1}	67.7
10^{2}	55.7
10^{3}	42.9
10^{4}	29.4
10^{5}	17.0
10^{6}	9.0
2.66×10^{7}[c]	2.1

[a] $\rho=2.7$ gm/cm^3

[b] apparent radar cross section of 10^{-6} m^2

[c] apparent radar cross section of 10^{1} m^2

TABLE 2

RELATIVE-SPEED PROBABILITY DISTRIBUTION FUNCTIONS FOR COLLISIONS WITH MAN-MADE OBJECTS IN SELECTED EARTH ORBITS

v (km/sec)	Orbit parameters - altitude and inclination[a] 500 km 28 1/2° $F_i(v)$	500 km 82°	500 km 118°	800 km 28 1/2°	800 km 80 1/2°	800 km 113°
0.5	0.0116	0.0026	0	0.0135	0.0008	0
1.5	0.0390	0.0076	0	0.0328	0.0113	0.0007
2.5	0.0444	0.0252	0.0009	0.0416	0.0257	0.0009
3.5	0.0394	0.0248	0.0009	0.0562	0.0136	0.0009
4.5	0.0738	0.0166	0.0010	0.0852	0.0094	0.0015
5.5	0.0864	0.0107	0.0018	0.1299	0.0076	0.0057
6.5	0.0925	0.0155	0.0021	0.1154	0.0145	0.0107
7.5	0.1609	0.0164	0.0074	0.1427	0.0155	0.0074
8.5	0.0787	0.0224	0.0046	0.0899	0.0154	0.0062
9.5	0.0954	0.0185	0.0040	0.0768	0.0171	0.0058
10.5	0.1068	0.0237	0.0039	0.1123	0.0228	0.0064
11.5	0.0663	0.0329	0.0039	0.0384	0.0259	0.0076
12.5	0.0226	0.0430	0.0043	0.0208	0.0367	0.0087
13.5	0.0301	0.0472	0.0056	0.0270	0.0528	0.0117
14.5	0.0109	0.1355	0.0139	0.0027	0.7093	0.5811
15.5[b]	0.0412	0.5574	0.9457	0.0148	0.0216	0.3447

[a] includes nominal (28 1/2°) and worst case (118° or 113°) orbits defined in reference 1. 28 1/2° corresponds to a due East launch from Cape Canaveral.

[b] includes all relative speeds ≥ 15 km/sec.

TABLE 3

PENETRATION FLUX CALCULATIONS FOR A SPACECRAFT IN A 28 1/2° 500 km ORBIT SUBJECTED TO A UNIT INCIDENT FLUX

v_i (km/sec)	$F_i(v)$	$m_{p(v)}$ [a] (gm)	$N_i(m_p)$	ϕ_i
0.5	0.0116	24.48	0.6349	0.008
1.5	0.0390	1.59	0.7618	0.030
2.5	0.0444	0.448	0.8138	0.036
3.5	0.0394	0.344	0.8232	0.032
4.5	0.0738	0.472	0.8120	0.060
5.5	0.0864	0.608	0.8030	0.069
6.5	0.0925	0.560	0.8047	0.074
7.5	0.1609	0.436	0.8148	0.131
8.5	0.0787	0.339	0.8237	0.065
9.5	0.0954	0.271	0.8317	0.079
10.5	0.1068	0.222	0.8387	0.090
11.5	0.0663	0.185	0.8452	0.056
12.5	0.0226	0.157	0.8510	0.019
13.5	0.0301	0.134	0.8566	0.026
14.5	0.0109	0.117	0.8615	0.009
15.5 [b]	0.0412	0.102	0.8663	0.036
			ϕ_p =	0.820

[a] aluminum projectile, p=2.7 gm/cm^3

[b] includes all relative speeds ≥ 15 km/sec

TABLE 4

PENETRATION FLUX IN SELECTED ORBITS,
FOR A UNIT INCIDENT FLUX

Orbit parameters		
altitude (km)	inclination (deg)	ϕ_p
500	28 1/2	0.820
500	82	0.854
500	118	0.865
800	28 1/2	0.817
800	80 1/2	0.853
800	113	0.861

TABLE 5

SUMMARY OF IMPACT AND PENETRATION FLUXES AND NUMBER OF IMPACTS, COLLISION PROBABILITY, OR PENETRATION PROBABILITY FOR A 100-m DIAMETER SPHERICAL SPACECRAFT IN ORBIT FOR 1000 DAYS

Description of flux	Alt. (km)	Meteoroids[d] ϕ $(\#/m^2.sec)$	Meteoroids[d] Number of impacts or probability	Manmade orbiting objects[e] ϕ[f] $(\#/m^2.sec)$	Manmade orbiting objects[e] Probability of impact or penetration
Total impact flux, $\geq 10^{-12}$ gm	500	2.62×10^{-5}	7.11×10^{7}	-	-
	800	2.74×10^{-5}	7.43×10^{7}	-	-
Impact flux, $\geq 8.29 \times 10^{-4}$ gm[a]	500	1.55×10^{-11}	42	0.68×10^{-14}-1.58×10^{-14}	0.018-0.041 (P_{coll})
	800	1.62×10^{-11}	44	1.98×10^{-14}-6.98×10^{-14}	0.051-0.157 (P_{coll})
Skylab structure penetration flux $\geq .1198$gm[b]	500	3.71×10^{-14}	0.091 (P_p)	0.56×10^{-14}-1.34×10^{-14}	0.015-0.035 (P_p)
	800	3.88×10^{-14}	0.095 (P_p)	1.62×10^{-14}-5.82×10^{-14}	0.042-0.135 (P_p)
Penetration flux for hypothetical structure protected against meteoroid masses < 1.198 gm[c]	500	2.27×10^{-15}	0.0061 (P_p)	0.49×10^{-14}-1.22×10^{-14}	0.013-0.032 (P_p)
	800	2.37×10^{-15}	0.0064 (P_p)	1.42×10^{-14}-5.17×10^{-14}	0.037-0.122 (P_p)

[a] minimum mass assumed part of the orbiting population, corresponding to a rectangular aluminum projectile with apparent radar cross section of 10^{-6} m^2.

[b] protection against meteoroids according to equation (1) and against manmade objects as shown in figure 4.

[c] see text for protection assumed against the man-made orbiting population.

[d] flux values corrected for Earth shielding and gravitational focussing.

[e] 10,000 orbiting objects assumed.

[f] range of values to include range of orbital inclinations.

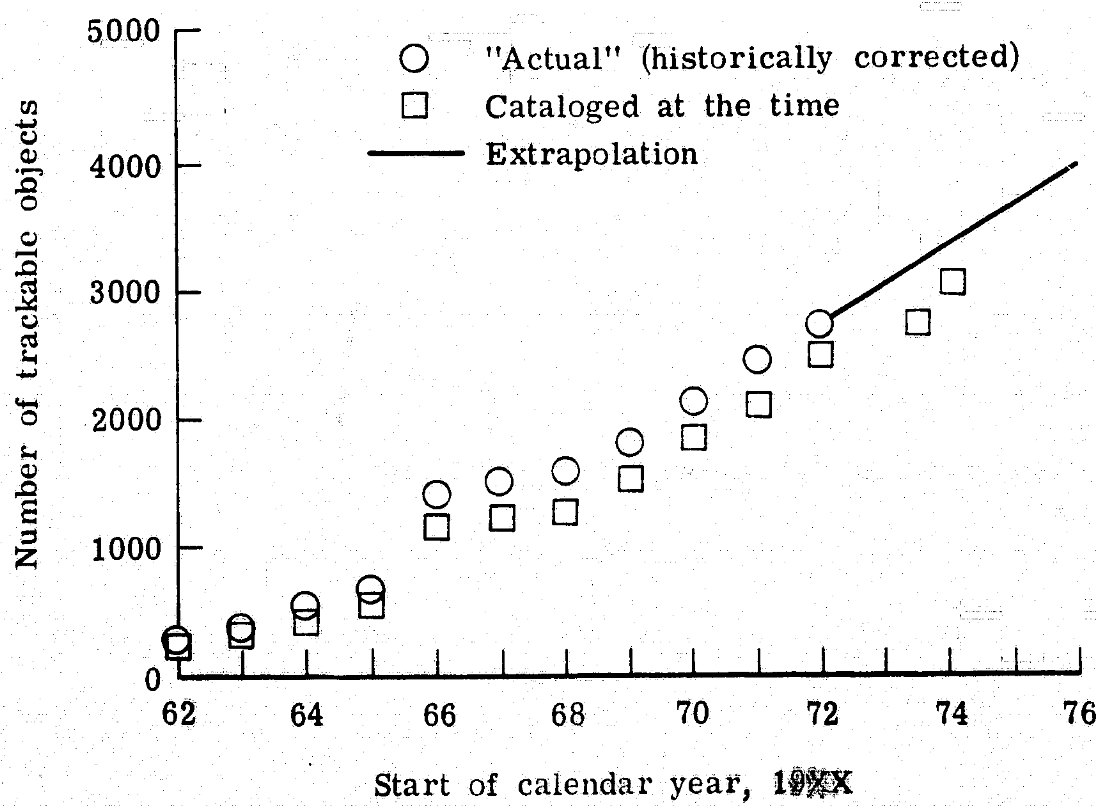


Figure 1.- Population history of trackable Earth-orbiting objects (effective radar cross section ≳ .01 m^2).

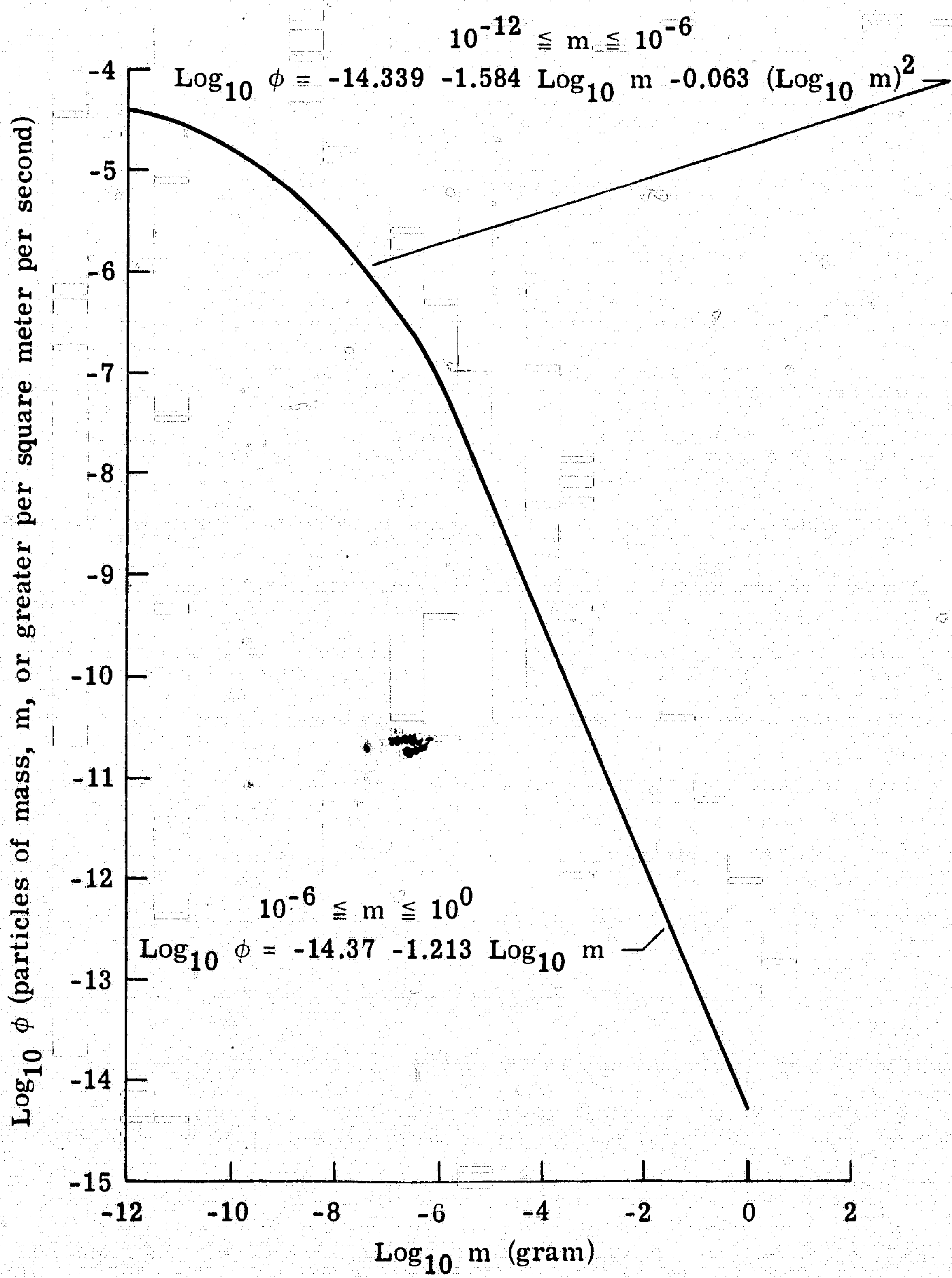


Figure 2.- Average cumulative total meteoroid flux-mass model for 1 A.U. (ref. 2).

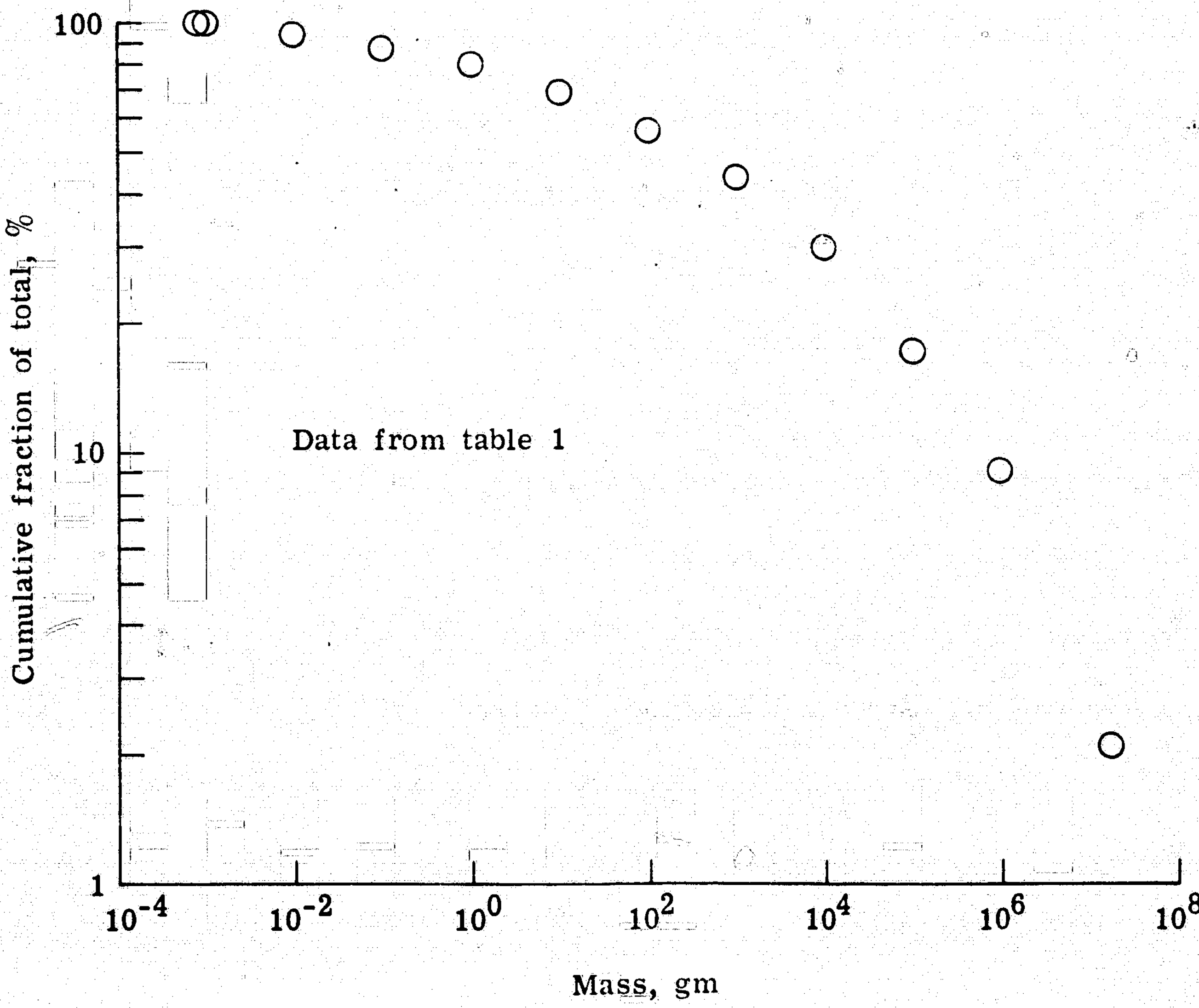


Figure 3.- Normalized number-versus-mass relationship for the Earth-orbiting population of man-made objects.

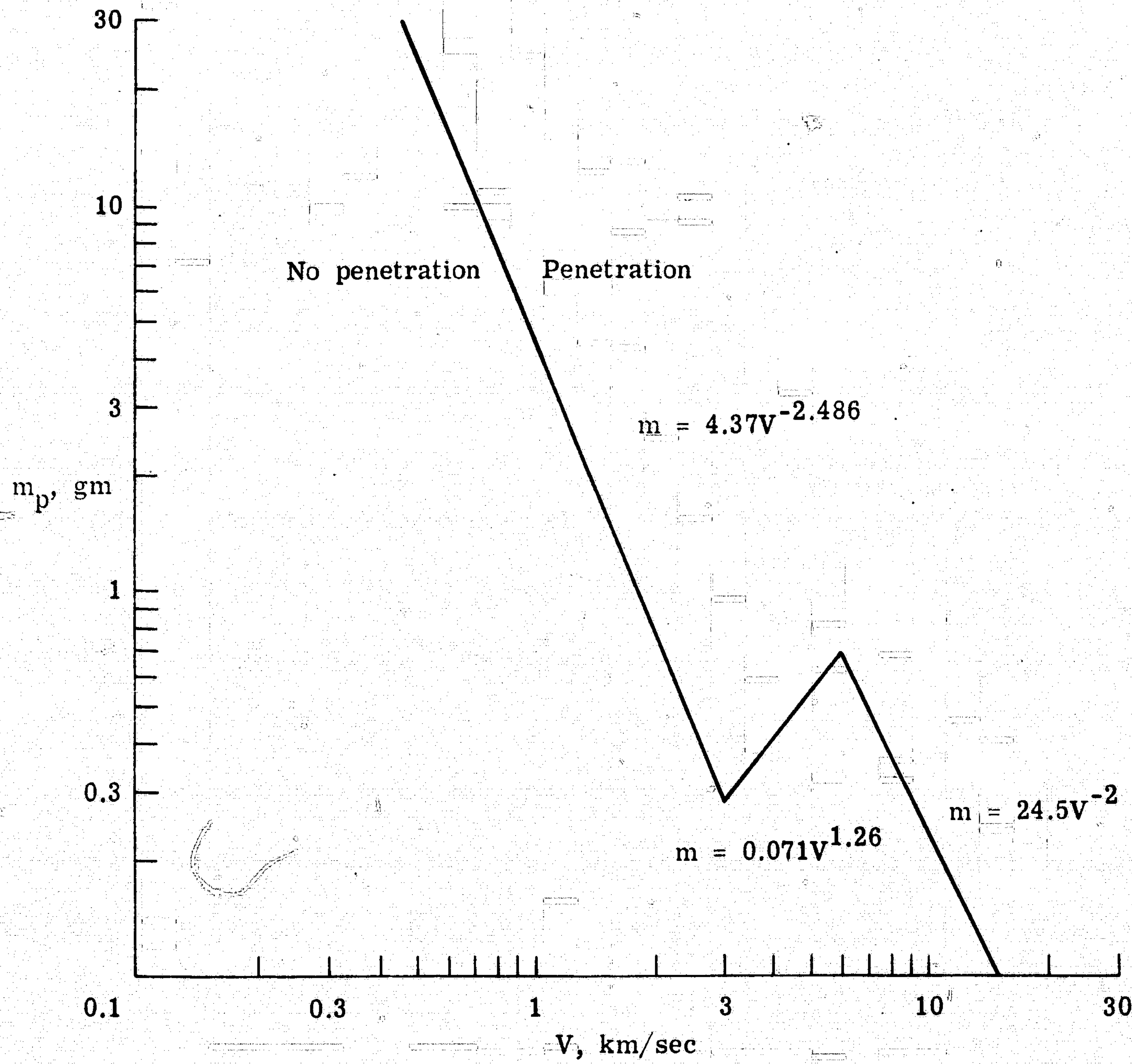
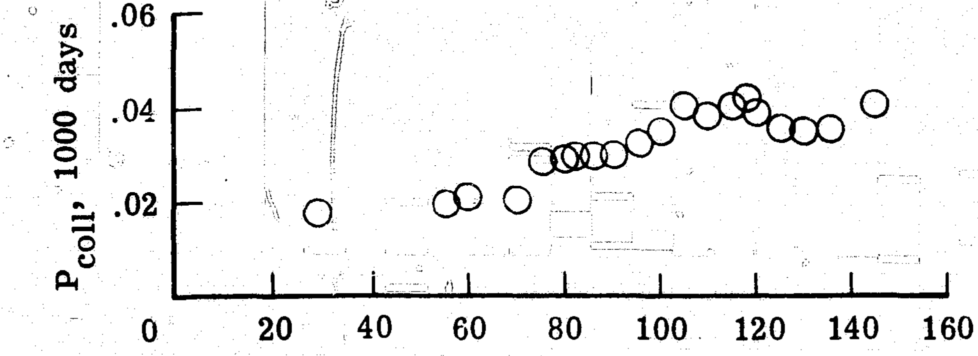
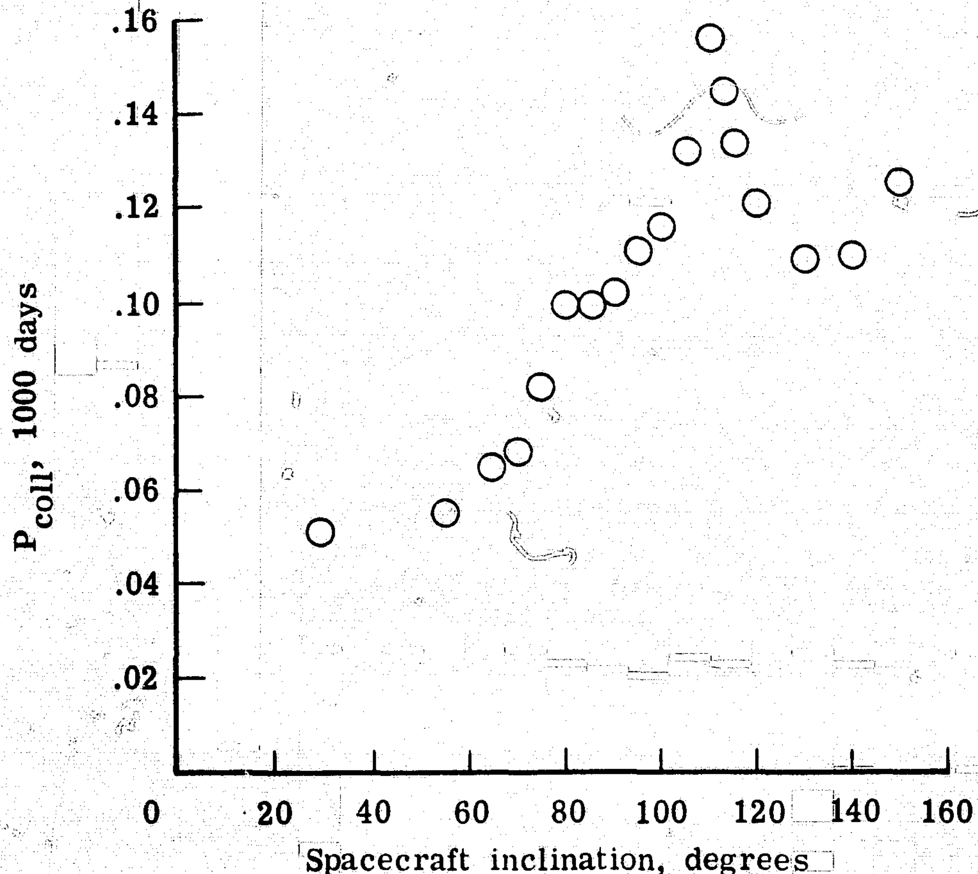


Figure 4.- Penetration threshold for aluminum projectiles (ρ = 2.7 gm/cm^3) incident on a Skylab-equivalent double-wall spacecraft structure (from unpublished impact tests).



(a) Spacecraft altitude = 500 km..



(b) Spacecraft altitude = 800 km..

Figure 5.- Probability of colliding with a 100 m diameter sphere in orbit for 1000 days, based on the analysis of reference 1, for an assumed total orbiting population of 10,000 objects.