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SPACE ENVIRONMENTAL CONSIDERATIONS  
FOR A  
LONG-TERM CRYOGENIC STORAGE VESSEL

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PRESENTED AT THE  
CRYOGENIC FLUID MANAGEMENT TECHNOLOGY WORKSHOP  
NASA LEWIS RESEARCH CENTER  
CLEVELAND, OHIO  
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SPACE ENVIRONMENTAL CONSIDERATIONS  
FOR A  
LONG-TERM CRYOGENIC STORAGE VESSEL

QUESTIONS RELATED TO THE ENVIRONMENT

- O PROTECTION NEEDED AGAINST IMPACT AND PERFORATION BY METEORIODS AND SPACE DEBRIS
- O LONG-TERM EFFECTS ON THERMAL CONTROL SURFACES
- O VACUUM JACKET TO GUARD AGAINST ABOVE

The material for this presentation is based on a cursory study undertaken to consider some questions related to the space environment and a long-term cryogenic storage vessel in space.

First, what kind of protection is needed against impact and perforation by meteoroids and space debris?

Second, what are the long-term effects of the space environment on thermal control surfaces and coatings?

Third, should the insulation and the thermal control surfaces be encased in a vacuum jacket shell to serve both of the above needs as well as to avoid the MLI pump-out problem during launch ascent?

DEGRADATION OF THERMAL CONTROL SURFACES

- 0 EXPOSURE TO SPACE RADIATION, MICROMETEORIDS
- 0 ATOMIC OXYGEN ATTACK
- 0 DISCUSSED IN PIR THRM-109 SUBMITTED TO CFM PROJECT OFFICE BY ANALEX CORP.

It is well known that thermal control coatings and insulating materials undergo long term degradation in space. This is especially true with polymers exposed to space radiation and to atomic oxygen. These issues are addressed in a project information report, PIR THRM-109, submitted to the CFM project office by Analex Corporation.

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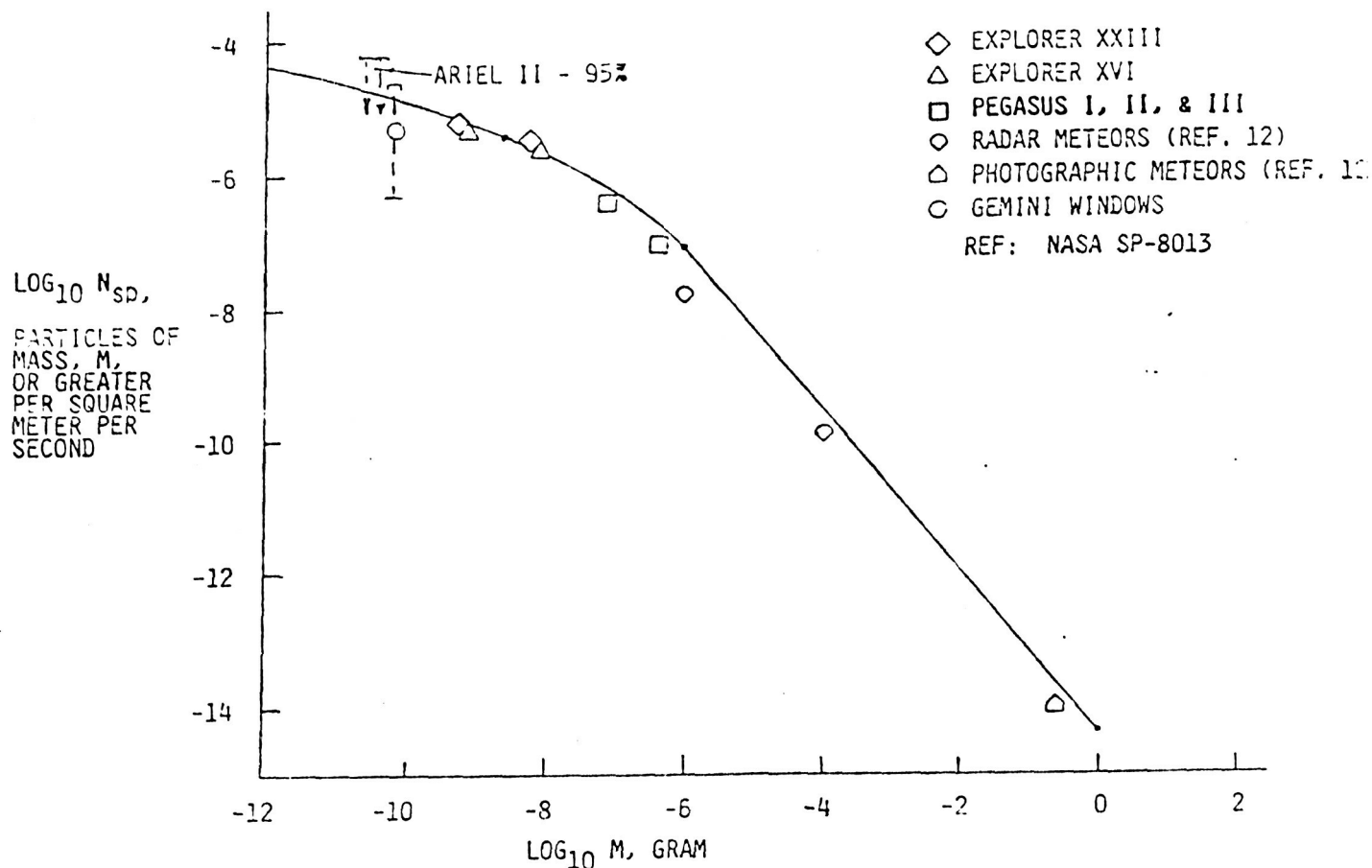
METEOROID AND DEBRIS HYPERVELOCITY IMPACTS

- 0 SPACE ENVIRONMENT MODEL
- 0 PROBABILITY OF IMPACT
- 0 DAMAGE EFFECTS OF IMPACT
- 0 IMPLICATIONS ON A TWO YEAR FLIGHT EXPERIMENT

The first question deals with the issue of hypervelocity impacts by meteoroids and space debris. The initial step is to examine models of the space environment for these particles. Using a model, the probability of impact with a spacecraft or a cryogenic storage vessel in space can be calculated. the effects of this impact can be estimated from empirical relationships based on ballistic studies. Finally, the implications of the space environment on a two-year life flight experiment model of a cryogenic system will be discussed.

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CUMULATIVE METEOROID FLUX-MASS



This shows a model of the space environment found in NASA SP-8013 published in 1979 by B. G. Cour - Palais and his committee. There may be other more recent models. The data sources for this model were various satellites with impact detectors, radar tracking, and photographed meteors.

The flux of particles which are of cometary origin decrease with particle mass. Each value of flux,  $N$ , is the integrated value of the number of particles having mass,  $m$ , or greater per sq. meter per second. Since  $N$  decreases logarithmically with  $m$ , within an ensemble of  $N$  particles, the most prevalent particle would have a mass,  $m$ .

For example, for particle mass  $m = 10^{-6}$  gm the flux rate would be  $10^{-7}$  particles per sq. meter per second and the most likely particle size to impact is  $10^{-8}$  gm. It is important to note that with a flux of  $10^{-7}$ , to get one particle to hit a 1 sq. meter area, it would take an average of  $10^7$  seconds which is about 3.8 months.

TYPICAL METEOROID FLUX-MASS MODELS

NOMENCLATURE

WHEN N = FLUX RATE OF PARTICLES OF MASS, M OR GREATER PER SQ. M PER SECOND  
M = PARTICLE MASS, GM  
P = DENSITY G/CC

$$\text{LOG}_{10} N_{SP} = -14.339 - 1.584 \text{ LOG}_{10} M - 0.063 (\text{LOG}_{10} M)^2$$

$$\text{LOG}_{10} N_{SP} = -14.41 - 1.22 \text{ LOG}_{10} M$$

$$\text{LOG}_{10} N_T = -14.37 - 1.213 \text{ LOG}_{10} M$$

$$\text{LOG}_{10} N = -17.0 - 1.70 \text{ LOG}_{10} M$$

$$\text{LOG}_{10} N = -1.07 - .39 \text{ LOG}_{10} M$$

$$\text{LOG}_{10} N = -13.80 + 2 \text{ LOG}_{10} (.44/P) - \text{LOG}_{10} M$$

$$\text{LOG}_{10} N = -14.23 - \text{LOG}_{10} M$$

$$\text{LOG}_{10} N = -17.01 - 0.7 \text{ LOG}_{10} M$$

$$\text{LOG}_{10} N = -14.38 - \text{LOG}_{10} M$$

$$\text{LOG}_{10} N = -11.89 - \text{LOG}_{10} M$$

$$\text{LOG}_{10} N = -12.29 - 1.34 \text{ LOG}_{10} M$$

$$\text{LOG}_{10} N = -14.48 + 2.68 \text{ LOG}_{10} (.44/P) - 1.34 \text{ LOG}_{10} M$$

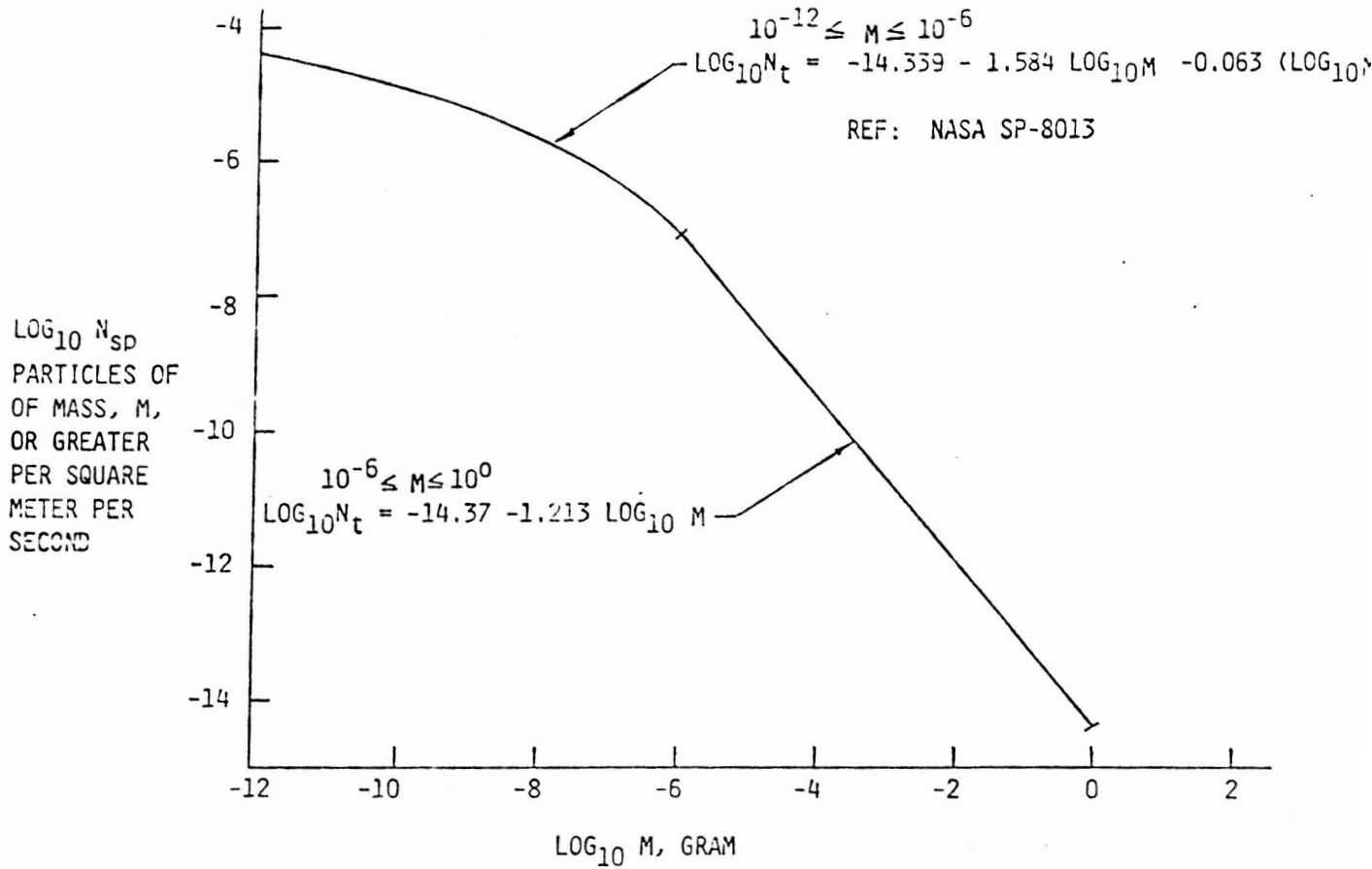
This shows some typical models of the meteoroid flux-mass proposed by different sources. Characteristically, they all vary as one over the mass raised to some power. A few models also include the meteoroid density.

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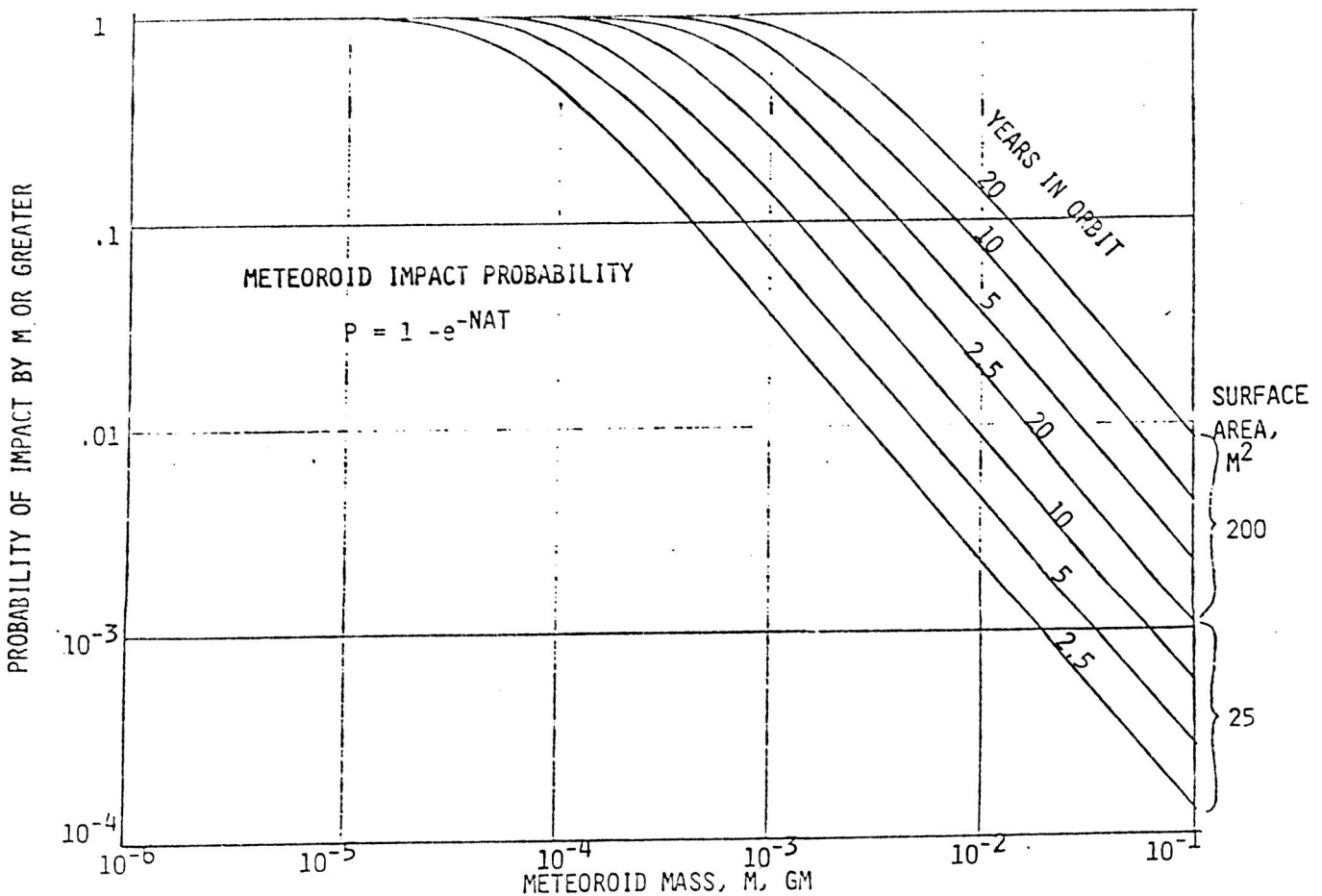
AVERAGE METEOROID FLUX-MASS MODEL FOR 1 A.U.

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This shows the average flux-mass model used for the study. It is for a distance in space of 1 A.U. For much larger distances, a gravitational defocusing factor can be applied which tend to reduce the flux values.

From the shape of the curve, for the region above  $10^{-6}$  gram, the equation is for a straight line. Below  $10^{-6}$  gm the equation is a second order polynomial curve fit.



The hypervelocity impact probability was calculated from queuing theory for a stream of random events in which the probability of at least one event occurring in time T is given by  $1 - e^{-NAT}$ . This equation is based on a Poisson process of a stream of random events like calls coming in on a telephone line, or particles monitored by a Geiger counter, or cars pulling up to a gas station. Each event is just like the previous one, and there are no after effects on the occurrence of the next event.

Looking at the equation, the impact probability is zero only when the flux, target area, or time is zero. At the other limit, when these parameters are large, the impact probability is one. Both limiting conditions, therefore, seem to fit.

In the present problem, N is the flux of particles of mass, m, or larger per unit area per unit time, A is the target area, and T is time. From the previous meteoroid model, the flux N decreases as mass increases but the most likely mass to hit is m, and a single impact of this mass is considered to be catastrophic. Smaller masses, however many, are not considered to be catastrophic. This criterion will be used later to calculate impact damage.

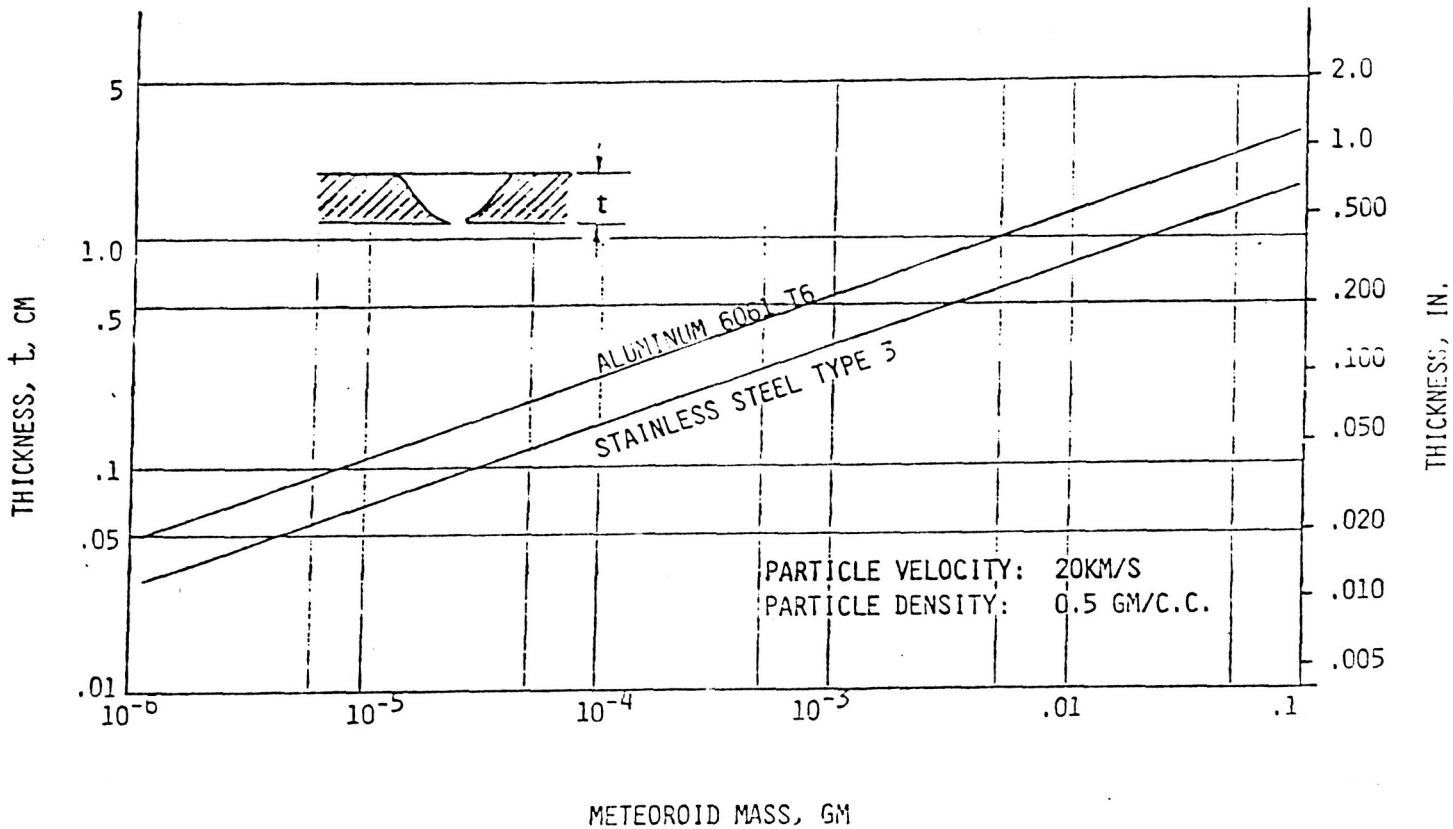
For a given surface area and time in orbit, smaller meteoroids and correspondingly higher flux rates make an impact almost a certainty. Large masses are very sporadic, and the probability of even a single impact drops rapidly. As expected, the probability of impact decreases for smaller areas.



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THRESHOLD PENETRATION, NORMAL IMPACT  
REF: NASA SP-8042



This shows a sketch of threshold penetration damage in material thickness, t. The impact energy is sufficient to just break through the opposite side causing light to penetrate or pressure to leak through.

The equation to calculate the thickness is proportional to the particle mass, density, and velocity to various powers. This equation is given in NASA SP-8042 and correlated from a large data base of ballistic tests. A certain degree of extrapolation is involved because the muzzle velocities of artillery shells, anti-aircraft, and M-1 rifles range from .5 - 1.0 km/sec. Recent rail gun tests have attained velocities up to 10 km/sec. The standard average velocity for meteoroids is 20 km/sec.

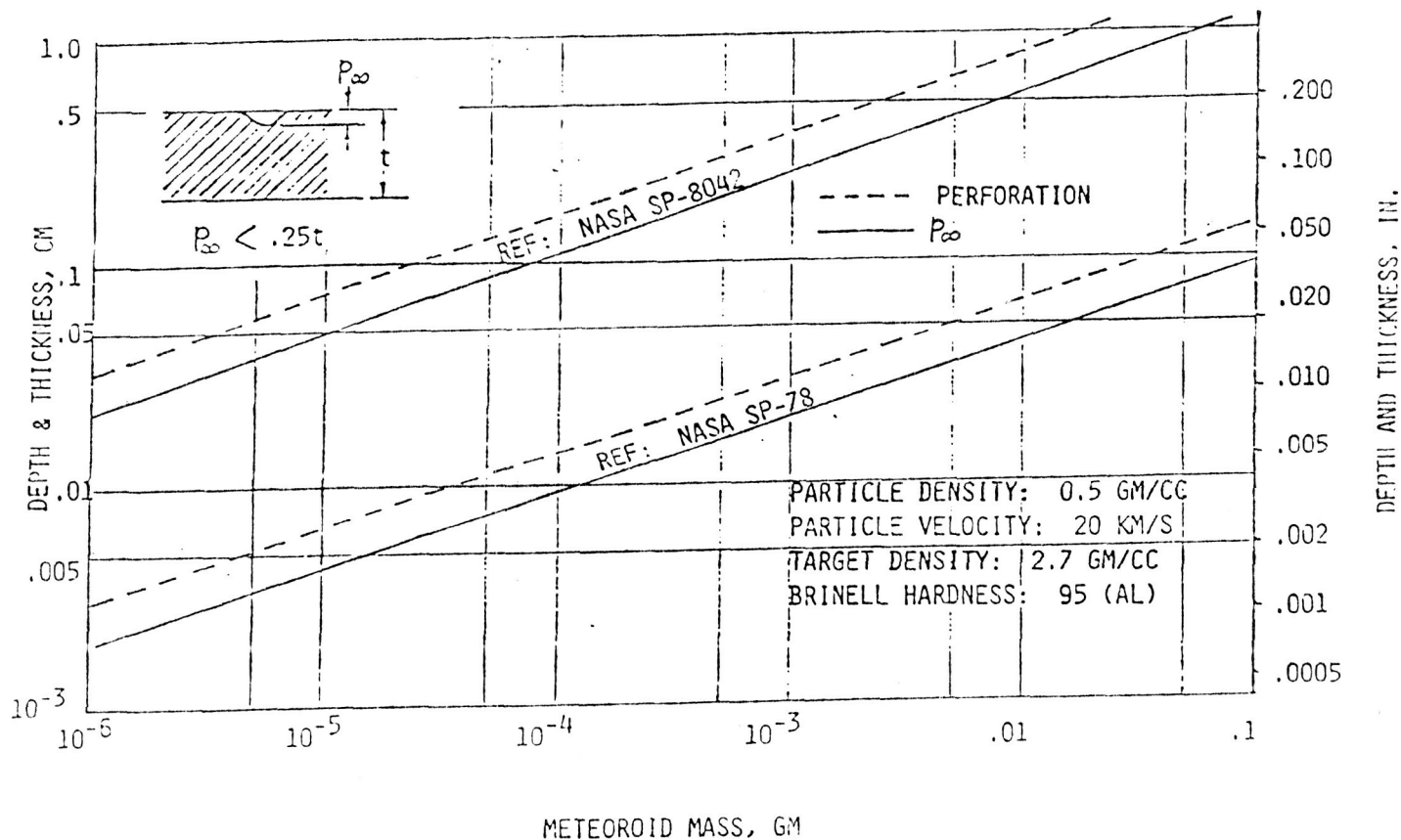
Because kinetic energy varies as  $v^2$  even a .01 gm meteoroid carries a lot of energy and can penetrate over a centimeter of aluminum.

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SEMI-INFINITE PENETRATION AND PERFORATION IN ALUMINUM 6061



The second type of damage is perforation. This slide shows a sketch of the penetration depth,  $P_{\infty}$ , in a semi-infinite solid. The depth of penetration is inhibited by the material underneath the point of impact. The equations for this penetration depth is limited to 25% of the material thickness.

The perforation thickness is given as 1.5 times the penetration depth: that is, perforation occurs in a material thickness which is 1-1/2 times the penetration depth in a semi-infinite solid under the same impact conditions. Both NASA SP-8042 and SP-78 have equations for the semi-infinite penetration depth. For the same meteoroid properties, the calculated results differ by an order of magnitude. The large difference is not too reassuring, but both are still less than the threshold penetration thickness which agrees with intuition.

BETTER ANALYTICAL MODEL NEEDED FOR IMPACT DAMAGE

- PARTICLE VELOCITIES TO 20 KM/SEC
- LAWRENCE LIVERMORE LABORATORY RESEARCH
  - DR. DAVE BENSON MODEL
  - DYNA3D FINITE ELEMENT
  - CRAY XMP/84

Clearly, it would be desirable to have an analytical model which can accurately predict hypervelocity impact damage for particle velocities up to 20 km/sec. Recently, Dr. Dave Benson of Lawrence Livermore Laboratory has developed a finite element code called DYNA3D to simulate hypervelocity impact damage. Slides of the computer simulation on a Cray XMP/84 are available. The simulated results look remarkably like the pattern left by bullets through a thin plate. He says much more work is needed, but his initial results look promising.

## SPACE DEBRIS

- SOURCE
  - EXPLOSIONS OF ROCKETS AND SPACECRAFTS
  - PROLIFERATION BY IMPACTS
  
- POPULATION
  - 11,665 OBJECTS LAUNCHED BY DECEMBER 1979
  - 4,549 STILL IN ORBIT
  - DEBRIS BELT; ALTITUDE, INCLINATION
  
- NORAD TRACKING
  - 10 CM AT 1000 KM
  - 4 CM AT 400 KM
  - TOTAL POPULATION MUST INCLUDE UNOBSERVED OBJECTS

Aside from meteoroid impact damage, it is believed by many that space debris poses an equal or greater threat to spacecraft and structures. The following information is based largely on the work of Don Kessler at the Johnson Space Center.

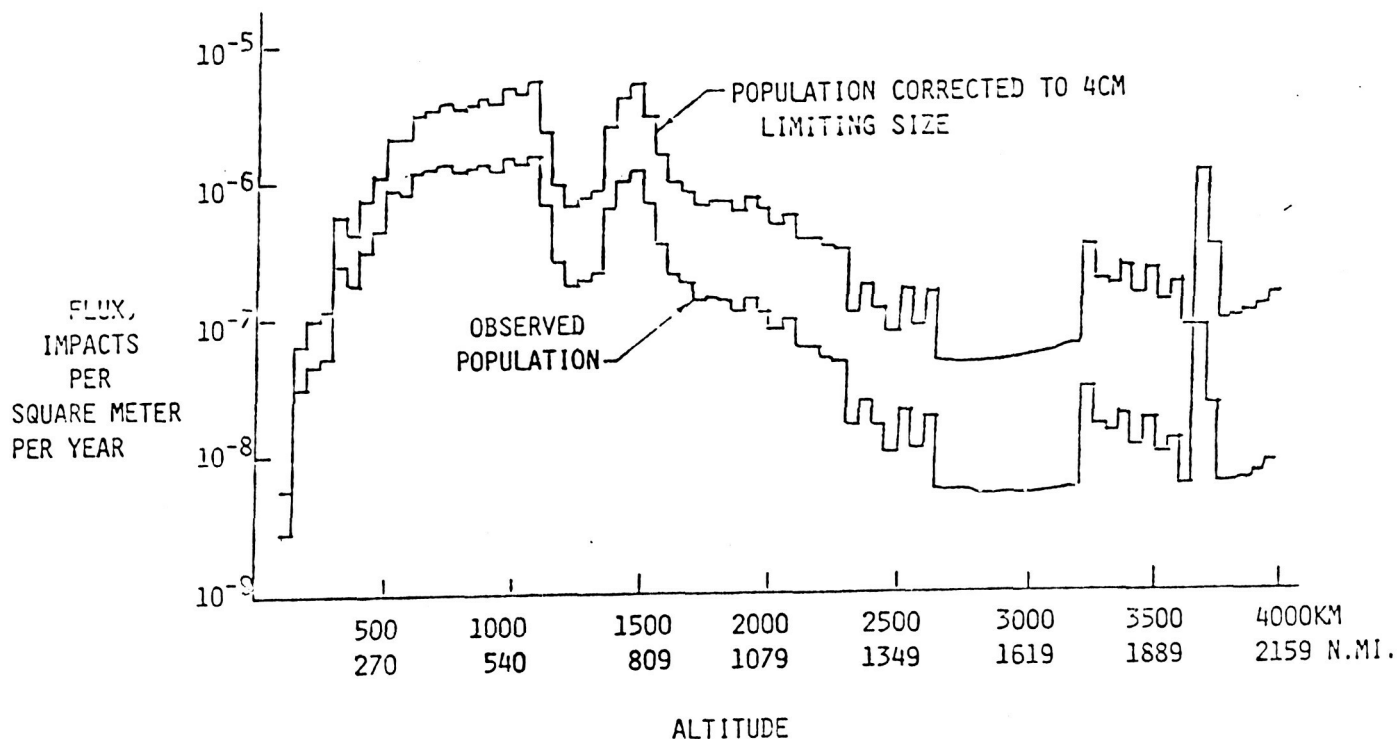
The main source of space debris is explosions of rockets and spacecrafts. The debris is therefore distributed in a debris belt which varies with altitude and inclination. Large debris upon impact with each other can proliferate smaller debris and could conceivably be regenerative. The very small debris, especially at lower altitudes, are swept out by atmospheric drag.

As of December 1979, almost 12,000 objects were launched and almost 5000 of these are still in orbit. Norad can track objects to 4cm size at 400 km. The total population including unobserved objects is known to be much greater.

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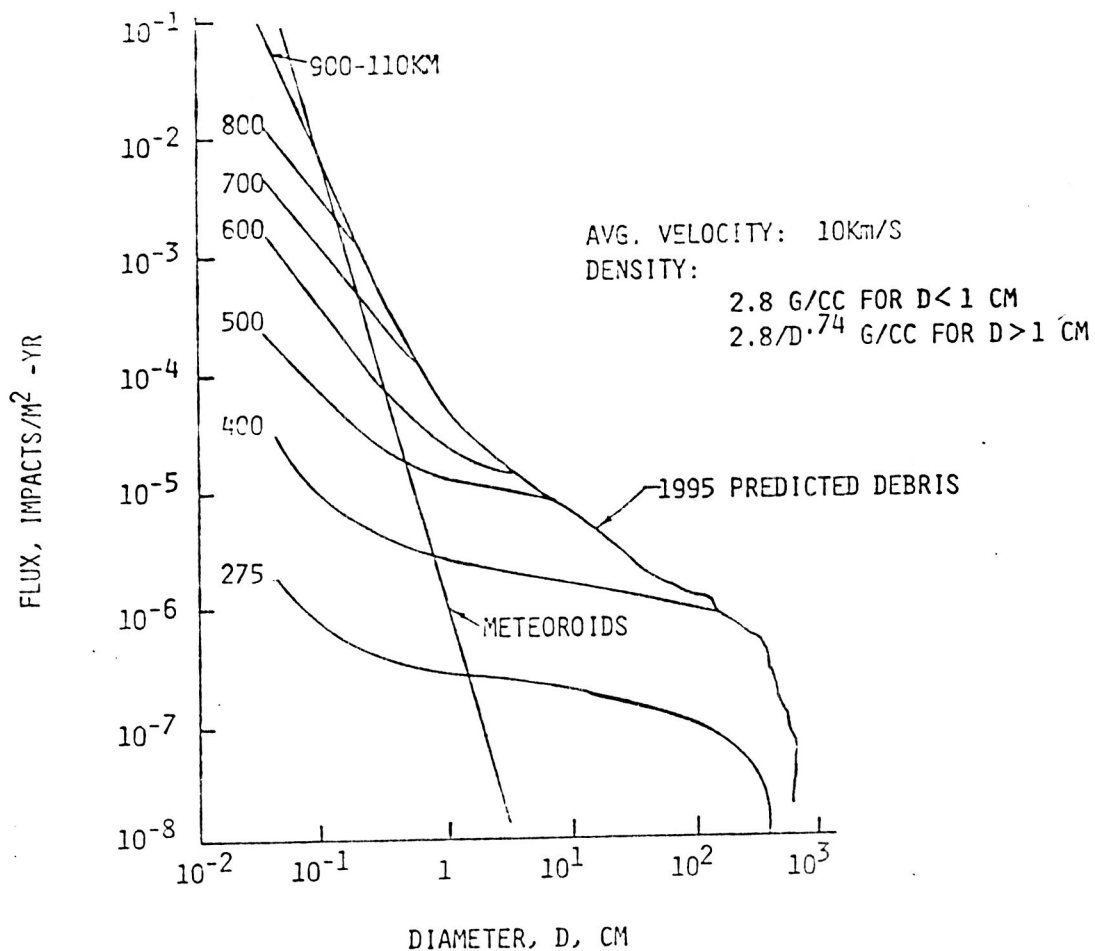
SPACE DEBRIS FLUX



This shows the debris population as a function of altitude. The lower curve is based on the observed population. The upper curve is corrected for the fact that the tracking limit is 4cm and hence includes the unobserved population. At a space station altitude of around 400 km, the total population is believed to be about 2-1/2 times the observable population.

SPACE DEBRIS FLUX-SIZE

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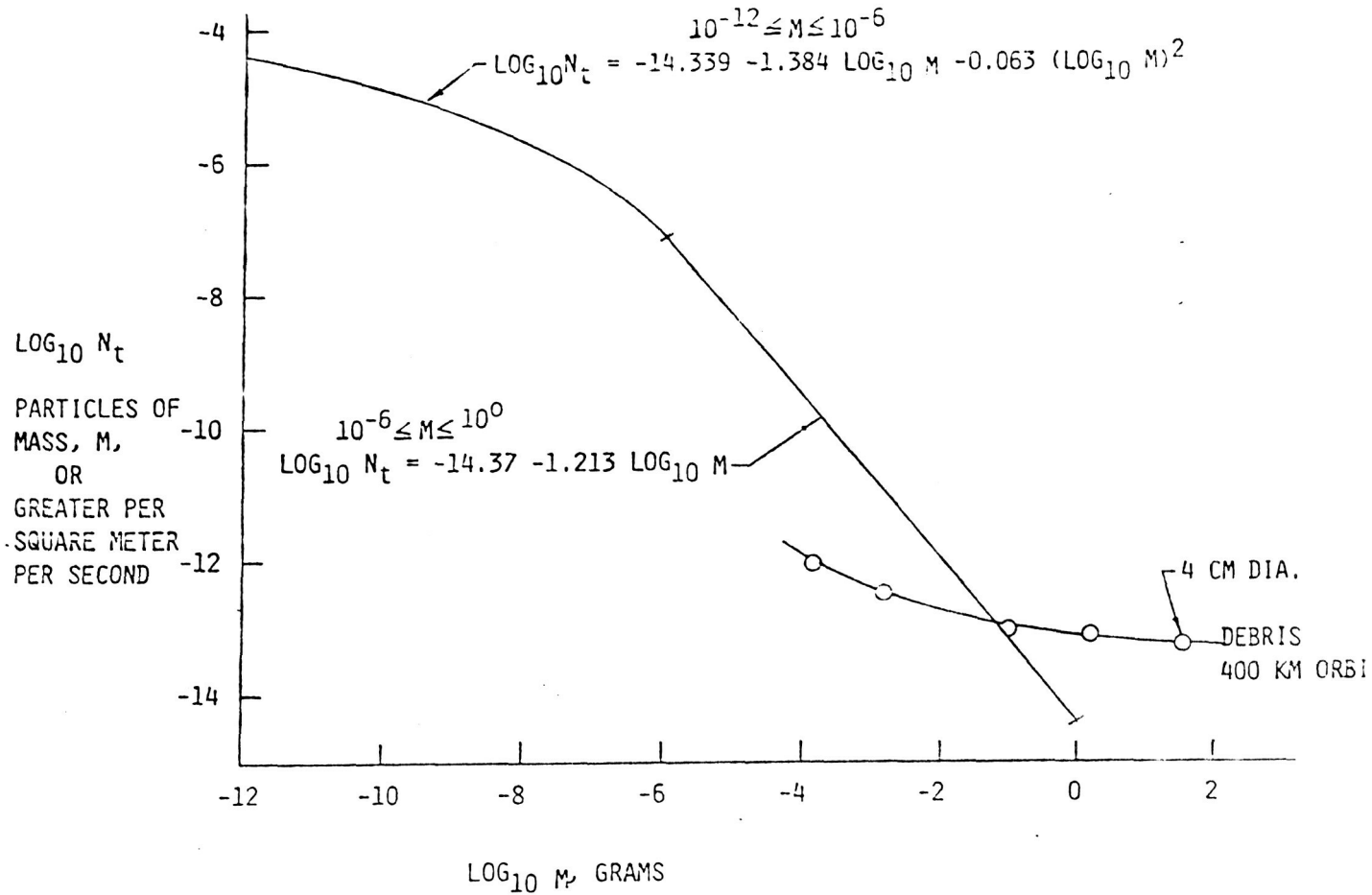
The predicted flux of orbital debris by the year 1995 is shown in this slide. The population of small debris is kept down by atmospheric drag at the lower altitudes. At space station altitudes, the flux of debris smaller than 1cm is lower than meteoroid flux. As the debris size increases, the flux rate decreases but more slowly than meteoroids so that above 1cm, the debris-flux is higher.

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METEOROID & DEBRIS FLUX-MASS MODEL

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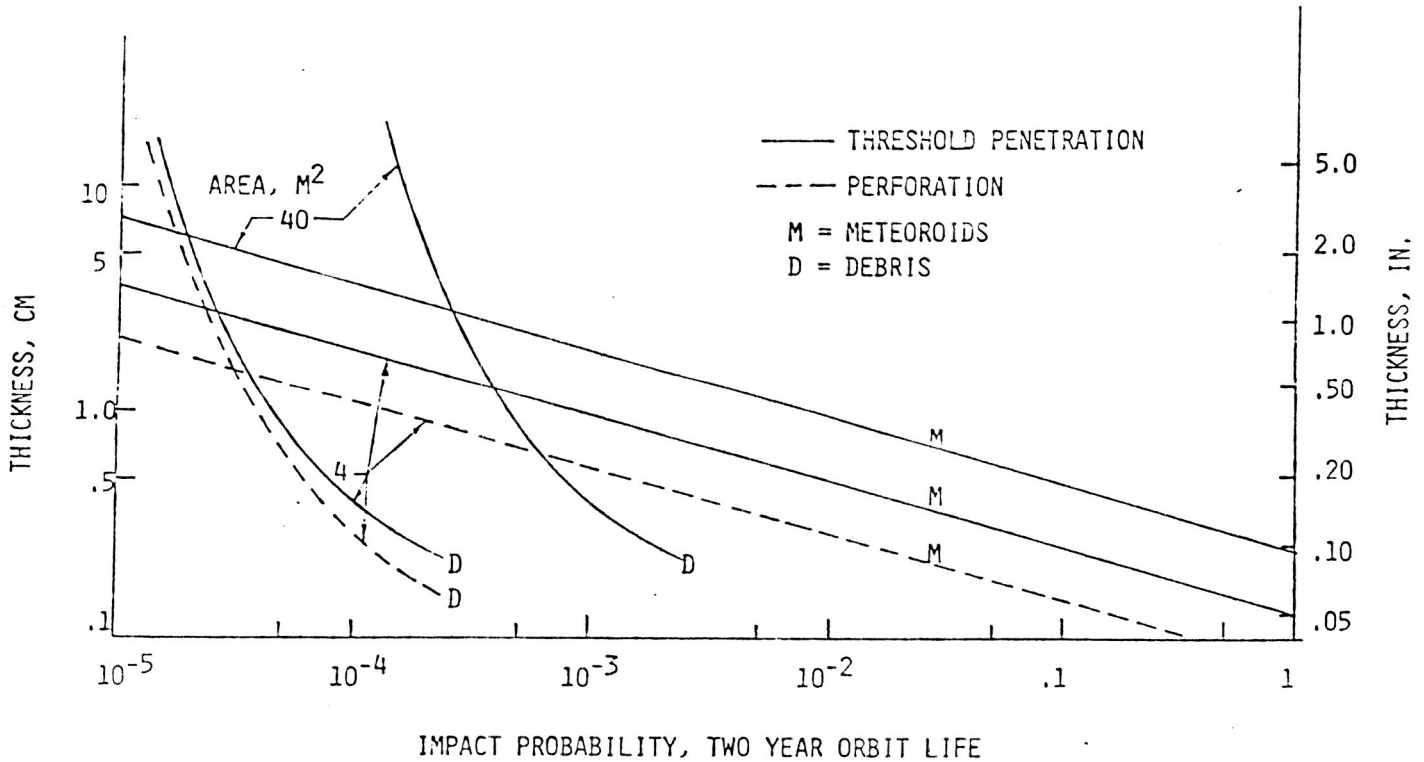


This slide shows the debris flux-mass model at 400 km superimposed on the meteoroid model. The cross-overpoint occurs at a mass of about 0.1 gm. Because of the differences in average density, 0.1 gm meteoroid is a sphere about 4mm dia. A typical debris of the same mass is 2mm dia.; about the size of a B.B. shot.

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REQUIRED WALL THICKNESS, ALUMINUM 6061

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From the previous models, it is possible to assess the hypervelocity impact hazard for an experimental spacecraft in orbit for two years. The particle masses were calculated for two spacecraft areas using the flux mass models for meteoroids and debris at 400 km altitude at various impact probabilities. The resulting masses were used to calculate the threshold penetration and perforation thicknesses in aluminum. These thicknesses are shown for various impact probabilities. As expected, the high probabilities are for small masses and hence require thinner materials. The threshold penetration limit results in thicker walls so our concern can be limited to that mode of damage. For a relatively short orbit life, a decision will be needed on the level of risk to be assumed. The large particle masses are capable of more damage requiring prohibitively thick protective walls. On the other hand, large particles are few and far between, and they might not hit within a two-year period. Rather than gamble on the risk, a more rational approach may be to determine very precisely what the damage potential is, and to trade off risk with a limit design.



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### CONCLUSIONS

- O ANALYSIS TO ESTIMATE METEOROID AND DEBRIS DAMAGE TO AN ORBITING CRYOGENIC STORAGE VESSEL PERFORMED.
- O PROBABILITY OF A SINGLE IMPACT BY PARTICLES OF A GIVEN MASS OR LARGER DECREASES LOGARITHMICALLY WITH INCREASING PARTICLE MASS.
- O IMPACT DAMAGE ASSESSMENT IS EMPIRICAL. HIGHER VELOCITY TEST DATA ARE REQUIRED.
- O PRECISE DAMAGE ASSESSMENT MIGHT ALLOW HIGHER RISK AND THINNER WALLS.

A cursory analysis has been performed to estimate the protection requirements of a cryogenic storage vessel exposed to meteoroids and space debris. A space environment model developed around 1970 was used although more recent and better models might be available.

The probability of a single impact calculated from a Poisson process decreases logarithmically with increasing meteoroid mass because of the rapid decrease in flux rate.

The impact damage assessment is largely empirical and would require definitive tests particularly with higher impact velocities.

For short term flight tests up to two years, with modestly sized storage vessels, a more precise assessment of damage potential might allow higher risk, and thinner walls. A final practical design might well include a thick bumper shield over the vulnerable areas and a thin wall for the vacuum jacket, if deemed desirable.