N86-24512

1985

NASA/ASEE SUMMER FACULTY RESEARCH FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

METHODOLOGY OF DESIGN AND ANALYSIS OF EXTERNAL WALLS OF SPACE STATION FOR HYPERVELOCITY IMPACTS BY METEOROIDS AND SPACE DEBRIS

Prepared by:	Fahim A. Batla, Ph.D., P.E.
Academic Rank:	Visiting Faculty
University and Department:	Purdue University - Indianapolis Mechanical Engineering Department
NASA/MSFC: Division: Branch:	Structures and Propulsion Lab Structures Division Structural Development Branch EP-13
MSFC Counterpart:	Erich E. Engler

Date:	August 9, 1985
Contract No.:	NGT 01-008-021 The University of Alabama in Huntsville

METHODOLOGY OF DESIGN AND ANALYSIS OF EXTERNAL WALLS OF SPACE STATION FOR HYPERVELOCITY IMPACTS BY METEOROIDS AND SPACE DEBRIS

BY

Dr. Fahim A. Batla
Mechanical Engineering Department
Purdue University - Indianapolis, Indiana

ABSTRACT

The study is directed towards the development of criteria and methodology for the design and analysis of Space Station wall elements for collisions with meteoroids and space debris at hypervelocities. These collisions will occur at velocities of 10 km/s or more and can be damaging to the external wall elements of the Space Station. The wall elements need to be designed to protect the pressurized modules of the Space Station from functional or structural failure due to these collisions at hypervelocities for a given environment and population of meteoroids and space debris. The design and analysis approach and the associated computer program presented herein is to achieve this objective, including the optimization of the design for a required overall probability of no penetration. The approach is based on the presently available experimental and actual data on meteoroids and space debris flux and damage assessments and the empirical relationships resulting from the hypervelocity impact studies in laboratories. Validation of this approach by further experimental work, specially using various structural and debris materials, is strongly recommended.

ACKNOWLEDGEMENTS

The author appreciates the opportunity of this research at NASA Marshall Space Flight Center and for the professional development and knowledge achieved through this project.

The successful conclusion of this research project is greatly due to the contributory efforts of author's NASA associates and he wishes to express his gratitude to everyone related to this project, especially to Mr. Erich E. Engler and Mr. Juan Maldonado of the Structural Development Branch of Structures and Propulsion Laboratory at MSFC.

A very special word of thanks to Dr. Jim Dosier and Mr. Leroy Osborn, the NASA Directors, and to Dr. Gerald Karr, the UAH Director of the NASA/ASEE Summer Faculty Research Fellowship Program, for making author's visit to MSFC a highly pleasant and memorable experience.

1. INTRODUCTION

In the past two decades a substantial amount of engineering and scientific research and collection of data has been done to determine the environment and population of meteoroids and man-made debris in space and the damage that may occur to the space structures by the collisions with these meteoroids and space debris at hypervelocities of 10 km/s or more. At present, there is a need to design the external wall elements of the Space Station for protection from functional and structural failures due to hypervelocity impacts for a given environment and population of meteoroids and space debris and the overall probability of no penetration. Although a large number of research papers, reports and other publications are presently avaiable on this subject, the basic phenomena and mechanisms involved in the hypervelocity impacts and the related empirical equations for structural design and analysis are still far from being well-defined or reliable.

The purpose of this report is to present the most "reasonable" methodology of structural design and analysis of the external wall elements of the Space Station for hypervelocity impacts by meteoroids and space debris and the associated computer program to be used as a preliminary working tool by the designers and analysts. The approach is based on the presently available actual data and the extrapolated assessments of meteoroid and space debris flux and the empirical relationships of the structural design parameters resulting from the hypervelocity impact studies in laboratories.

The report first presents the basic experimental and theoretical information that provides the basis for the development of copmuter program. The later part of this report presents illustrative numerical examples using this program. It is strongly suggested that the users of the computer program presented herein be familiar with the entire report, including its references, and the detailed program manual in order to clearly understand the theories and the experimental data used in the development of this program, and the extent of its usefulness, accuracy and limitations.

A listing of the computer program is provided in the Appendix.

2. METHODOLOGY

Meteoroid and Space Debris Flux and Probability of No Penetration

If N is the flux of meteoroids or space debris defined as particles of mass `m' or diameter `d' and greater per unit area per unit time impacting the spacecraft, and P_x is the probability of impacts by `n' particles or less, the flux and the probability are related as follows (1).

$$P_{x<n} = \sum_{r=0}^{r=n} \frac{e^{-NAT} (NAT)^{r}}{r!} \qquad (1)$$

Where:

A = exposed surface area for meteoroids or projected area for space debris

T = time of exposure in space

The probability of exactly `n' impacts is

$$P_{n} = \frac{e^{-NAT} (NAT)^{n}}{n!} \qquad (2)$$

and the probability of zero impact, P_o , by any particle of mass `m' or diameter `d' and greater is then given by the following equation.

$$P_{o} = e^{-NAT} \qquad (3)$$

If the external wall elements of the Space Station are designed for no penetration by any particle of mass `m' or diameter `d' and smaller, the probability of no penetration is also P_o. Equation 3 is therefore used to determine the flux for the required probability of no penetration and the flux-mass or flux-diameter models described in the following sections are used to determine the mass and the diameter of the particle that should accordingly be used for the design and analysis of the wall elements.

It should be noted that the overall probability of no penetration is expressed in terms of the individual probabilities of no penetration as follows.

$$\text{Overall } P_o = P_{o1} \times P_{o2} \times P_{o3} \times - - - - \quad (4)$$

<u>Meteoroid</u> <u>Flux-Mass</u> <u>Model</u>

The meteoroid flux-mass model is described in detail in Reference 2 and is illustrated in Figures 1 and 2. The model states that the average annual comulative total flux, N, in impacts per square meter per second of meteroids of mass `m' or greater in grams impacting on a spacecraft is

$$\log N = - 14.37 - 1.213 \log m + \log G + \log S \quad (5)$$

$$\text{for } 10^{-6} \leqslant m \leqslant 10^{0}$$

Where:

$$G \text{ (gravitational defocusing factor)} = 0.568 + 0.432 \sin\theta$$

$$S \text{ (earth shielding factor)} = \frac{1 + \cos\theta}{2}$$

$$\sin\theta = \frac{R}{R + H}$$

and R = radius of earth

H = altitude above the earth surface in km

Equation 5 is used to determine the mass of meteoroid particle corresponding to the previously calculated flux.

<u>Space</u> <u>Debris</u> <u>Flux-Diameter</u> <u>Models</u>

The space debris flux-diameter models are taken from Reference 3 and are further illustrated in Figure 3. The cumulative flux, N, of debris particles between 1 mm and 1 cm diameter and defined as impacts per square meter per year of debris particles of diameter `d' or greater in cm impacting on a spacecraft is given by the following equations.

a) At 400 km altitude, $\log N = - 5.82 - 2.42 \log d$

(6)

b) At 500 km altitude, $\log N = - 5.46 - 2.52 \log d$

AVERAGE TOTAL MASS – FLUX MODEL
(INCLUDES A 10% STREAM CONTRIBUTION AT 1 gm, VANISHING AT 10^{-6} gm)

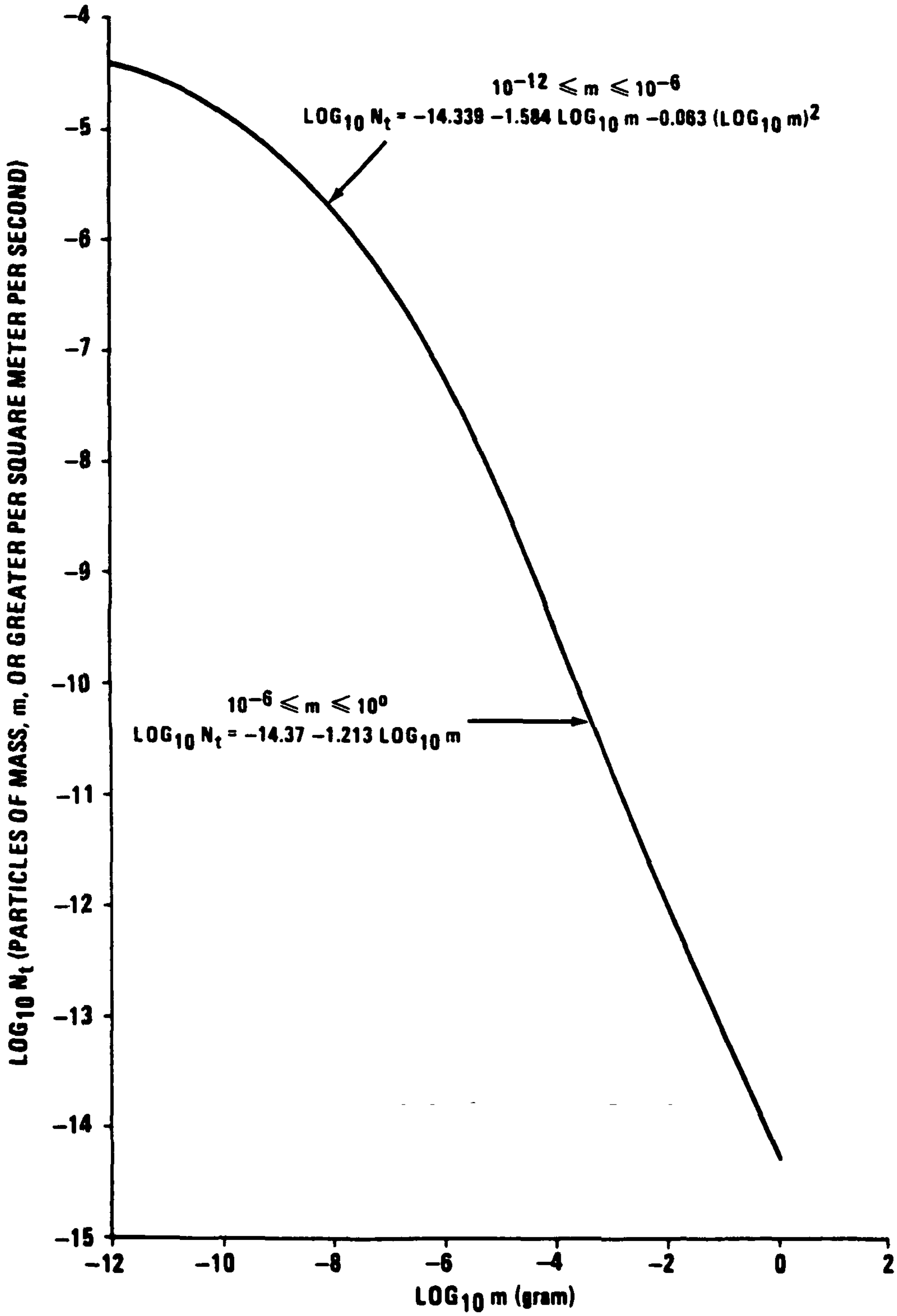


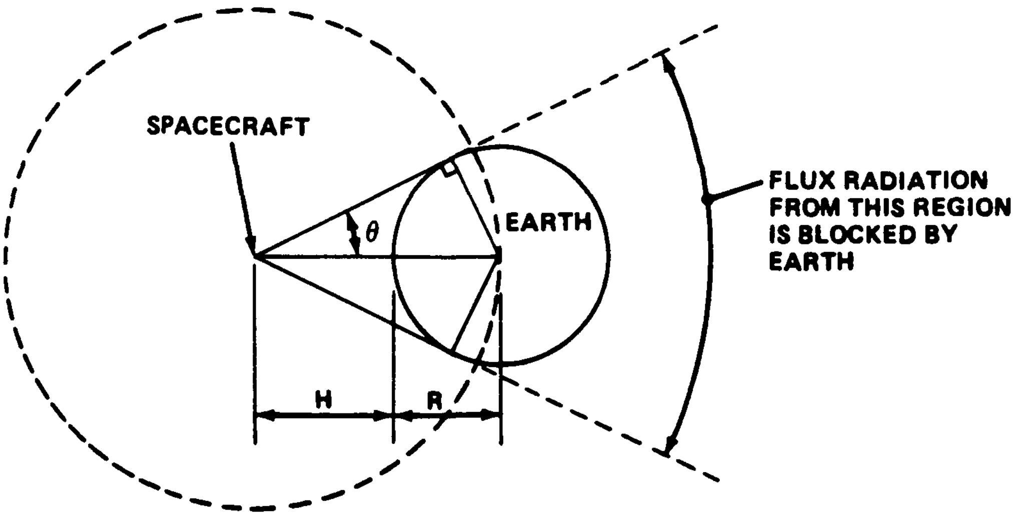
Figure 1

GRAVITATIONAL DEFOCUSING FACTOR

$$G = 0.568 + \frac{0.432}{r}$$

r ⟶ DISTANCE FROM EARTH CENTER IN EARTH RADII

EARTH SHIELDING FACTOR, S (RANDOMLY ORIENTED SPACECRAFT)



$$\text{SIN}\,\theta = \frac{R}{R + H}$$

$$S = \frac{1 + \text{COS}\,\theta}{2}$$

Figure 2

FUTURE DEBRIS FLUX

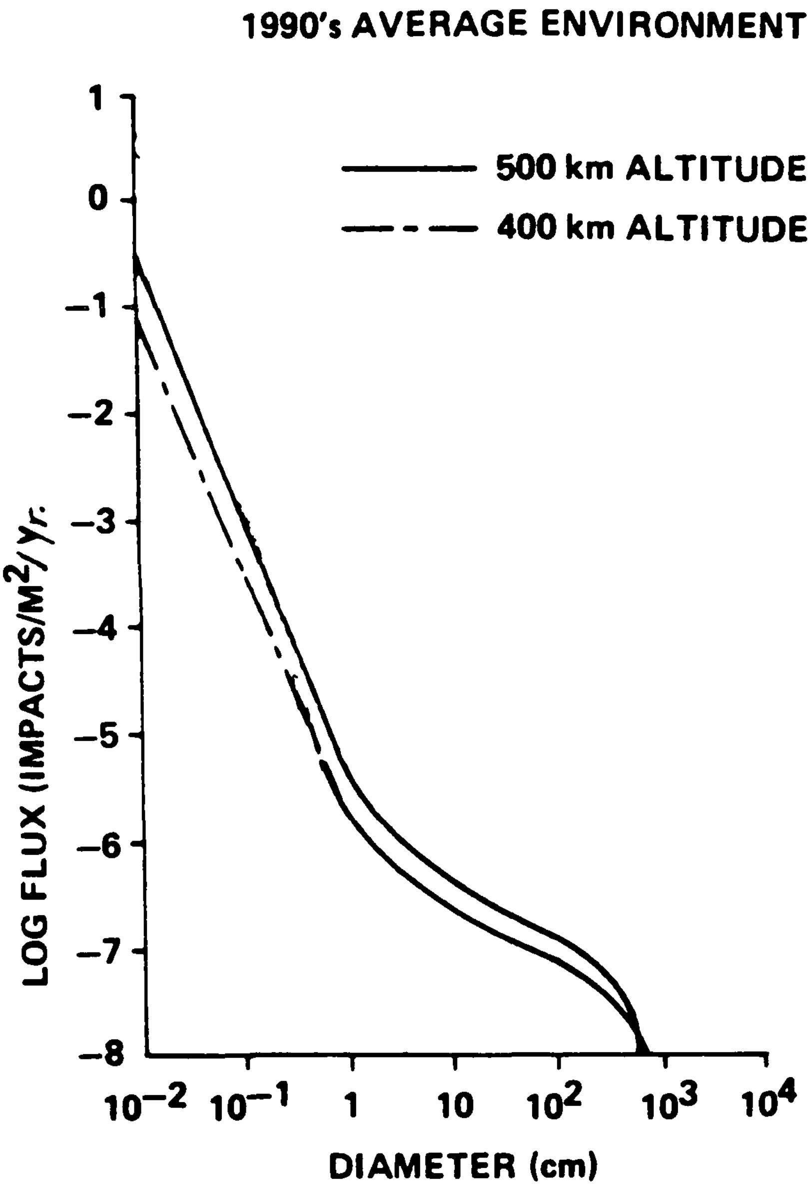


Figure 3

The debris flux for particles smaller than 1 cm is highly uncertain and is expected to change as new data on man-made space debris becomes available. The current uncertainty in the projected 1 cm flux is estimated to be a factor of 3, and for the 1 mm flux, a factor of 10 (3).

References 3 and 4 (Figure 4) are used to approximate the cumulative flux for debris particles between 1 cm and 4 cm diameters yielding the following equations.

a) At 400 km altitude, $\log N = -5.82 - 1.13 \log d$

b) At 500 km altitude, $\log N = -5.46 - 0.90 \log d$ (7)

Equations 6 and 7 are used to determine the diameter of the debris particle corresponding to the previously calculated magnitude of flux.

Single Wall Design Equations

Based on the hypervelocity impact mechanics and experimental studies (5,6,7), the following equations are used for the single wall design (1,2).

For thick plates:

$$P_\infty = k_\infty m^{0.352} \rho_m^{1/6} V^{2/3} \quad (8)$$

For thin plates:

$$t = k_1 m^{0.352} \rho_m^{1/6} V^{0.875} \quad (9)$$

Where:

P_∞ = penetration depth in thick plate, cm

t = thickness of thin plate, cm

k_∞ and k_1 = material constants

m = mass of particle, gm

ρ_m = density of particle material, gm/cu. cm

<u>SPACE DEBRIS</u>

OBSERVED FLUX

NORAD CURRENTLY TRACKS 5000 OBJECTS > 4 cm DIA,
AVERAGE VELOCITY ≈ 10 km/s, VARIOUS DIRECTIONS.

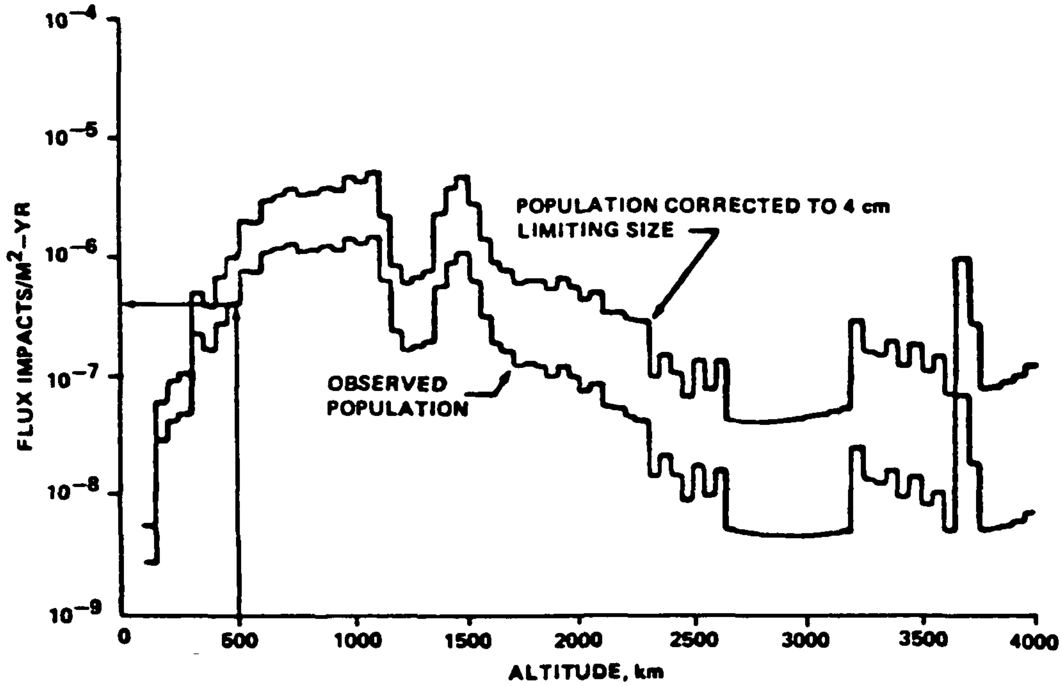


Figure 4

and V = velocity of particle, km/s

Equations 8 and 9 are further illustrated in Figure 5.

Double Wall Design Equations

The following paragraphs present two alternate equations for the the design of double wall system which consists of an exterior shield and a backup wall called bumper and hull, respectively (Figure 6).

The first equation

$$t_2 = \frac{5.08\, V^{0.278}\, d}{(t_1/d)^{0.528}\,(h/d)^{1.39}} \qquad (10)$$

is suggested by Nysmith (12).

Where:

t_1 = bumper thickness, cm

t_2 = hull thickness, cm

d = diameter of particle, cm

h = spacing between walls, cm

Equation 10 was developed using the data from tests on the ballistic limit of aluminum double wall structures impacted by pyrex-glass spherical particles . Nysmith (12) suggests the following optimum ratios if Equation 10 is to be used for the double wall design.

$t_1/d \leqslant 0.5$

$t_2/d \leqslant 1.0$

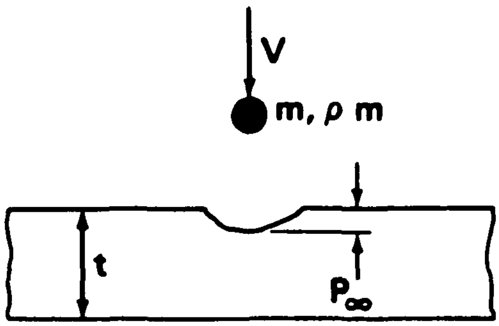
$h/d \leqslant 100$

$t_1/t_T = o.35$

CHARACTERISTICS:

HIGH PRESSURE (1 TO 10 MEGABARS)
COMPLETE PULVERIZATION OF TARGET AND
PROJECTILE LOWER BOUND, 1–10 km/s

THICK PLATES



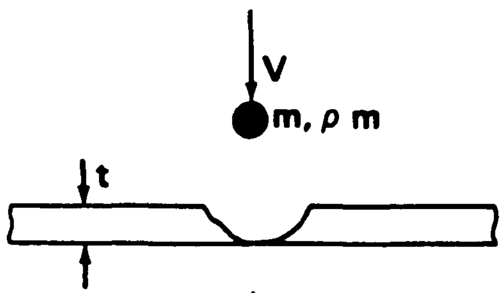
$P_\infty < t/4$

$$P_\infty = K_\infty m^{0.352} \rho_m^{1/6} V^{2/3}$$

$K \longrightarrow$ CONST. $\approx$ 0.42 (Al)

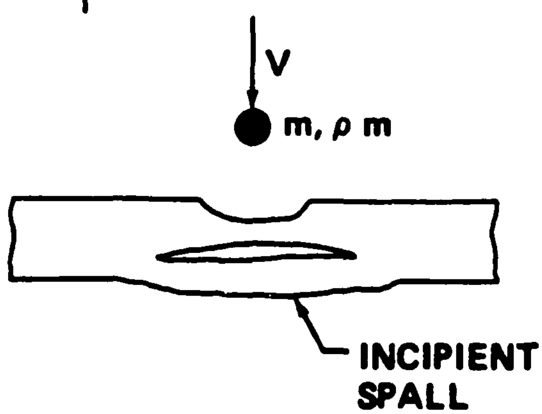
THIN PLATES

"BALLISTIC LIMIT" OR "THRESHOLD THICKNESS"



$$t = K_1 m^{0.352} \rho_m^{1/6} V^{0.875}$$

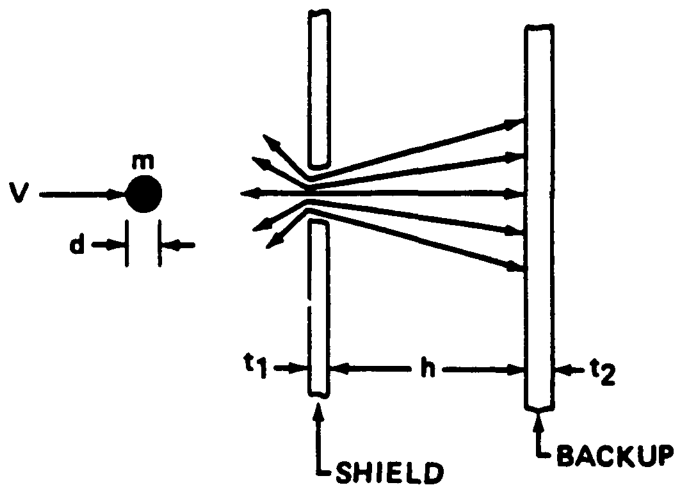
$K_1 \longrightarrow$ CONST. $\approx$ 0.57 (Al)



$$t_{SPALL} \approx 1.5\,t$$

Figure 5

METEOROID SHIELDS (BUMPERS)



BALLISTIC LIMIT OF DOUBLE–WALLED STRUCTURES

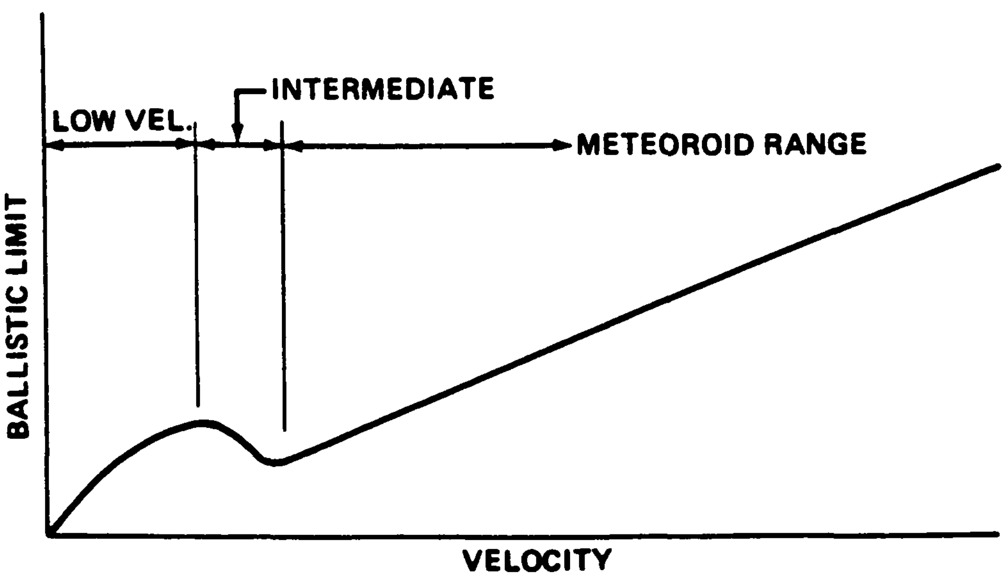


Figure 6

Where:

t_T = total thickness of both walls

The second equation

$$t_2 = \frac{0.055\,(\rho_m \rho_t)^{1/6}\, m^{1/3}\, V}{h^{1/2}} \left(70000/F_y\right)^{1/2} \qquad (11)$$

is developed by Cour-Palais (13,14).

Where:

ρ_t = density of bumper material, gm/cu. cm

F_y = 0.2 percent yield stress for hull material, lb/in^2

Cour-Palais (13) suggests the following optimum ratios if Equation 11 is to be used for the design of double walls.

$t_1/d \cong 0.16$

$t_2/d \cong 0.51$

$h/d \leqslant 25$

$t_1/t_T \cong 0.25$

The bumper/total thickness ratios mentioned above are used to determine the design of the double wall system for the given overall probability of no penetration, protecting the hull from metroids and, as well as, from space debris.

3. NUMERICAL EXAMPLES

Design Data

The design data used for the illustrative examples presented herein is as follows. It should be noted that this data does not necessarily represent the actual data that is to be used for the design of Space Station.

Exposed projected area (for debris)	= 228.41 sq. m
Exposed surface area (for meteoroid)	= 831.64 sq. m
Time of exposure in orbit	= 10 years
Orbital altitude	= 500 km
Velocity of debris	= 10 km/s
Velocity of meteoroids	= 20 km/s
Density of debris material	= 2.81 gm/cu. cm
Density of meteroid material	= 0.5 gm/cu. cm
Density of bumper material	= 2.81 gm/cu. cm
0.2 percent yield stress for hull material	= 70000 lb/sq. in

Example 1

For a 0.985 probability of no penetration for debris, the debris particle mass and diameter are as follows.

Mass = 0.682 gm
Diameter = 0.774 cm
(Equations 3 and 6)

For a 0.995 probability of no penetration for meteoroid, the meteoroid particle mass and diameter are as follows.

Mass = 0.208 gm
Diameter = 0.926 cm
(Equations 3 and 5)

Example 2

Using the double wall system with 10.16 cm spacing between walls and a bumper/hull thickness ratio of 0.5, and the data from Example 1, following are the required bumper and hull thicknesses according to Equation 11 (13).

a) For debris protection:

Bumper thickness = 0.107 cm

Hull thickness = 0.214 cm

b) For meteoroid protection:

Bumper thickness = 0.108 cm

Hull thickness = 0.216 cm

Example 3

In this example the design of the double walls is optimized for a required overall probability of 0.982.

a) Using Equation 10 (12):

Bumper thickness	= 0.284 cm
Hull thickness	= 0.527 cm
and Maximum debris mass	= 1.028 gm
Maximum meteoroid mass	= 0.150 gm
Maximum debris diameter	= 0.887 cm
Maximum meteoroid diameter	= 0.831 cm
Probability of no penetration by debris	= 0.989
Probability of no penetration by meteoroid	= 0.993

b) Using Equation 11 (13):

Bumper thickness	= 0.071 cm
Hull thickness	= 0.223 cm
and Maximum debris mass	= 0.770 gm
Maximum meteoroid mass	= 0.228 gm
Maximum debris diameter	= 0.806 cm
Maximum meteoroid diameter	= 0.955 cm

Probability of no penetration by debris = 0.986

Probability of no penetration by meteoroid = 0.996

4. SUMMARY AND CONCLUSIONS

The methodology and an associated computer program for the design and analysis of the external wall elements of the Space Station has been presented in this report. The program can be used with the following options.

i) Single or double-wall design.
ii) For a given individual probability of no penetration, design for protection from space debris or meteoroid.
iii) Design optimization for a given overall probability of no penetration.
iv) Thick or thin plate design for the single wall.
v) Design of double wall system by Equation 10 (12) or by Equation 11 (13).
vi) Analysis of a given design for all the options mentioned above.

The program is based on the presently available data on meteoroid and space debris environment and population and hypervelocity impact studies. This data is mostly experimental, empirical or extrapolation of the actual data. The resulting empirical design relationships are based on a very limited number or narrow-ranged theoretical and experimental studies leading to very highly unreliable designs. For example, the design results of the double wall system of Example 3 using Equation 10 (12) and Equation 11 (13) differ by a wide margin.

The computer program presented in this report should therefore be used with good judgement and caution and only as a preliminary working tool and should be updated as soon as any new and more reliable information on this subject becomes avaiable.

In conclusion, there is a need of further and extensive study of the phenomena and mechanisms involved in the design of the external wall elements of the Space Station for protection from hypervelocity impacts by meteoroids and space debris, including experimental verifications, in order to achieve a more reliable criteria and methodology of design and analysis. Use of a wide range of materials in these tests and studies, including composites, is highly recommended for the purpose of providing a higher degree of accuracy in the resulting empirical relationships and for the fact that these tests may lead to the most suitable structural material for the design of the Space Station.

REFERENCES

1. Frost, V. C., "Meteoroid Damage Assessment," NASA SP-8042, May 1970.

2. Susko, M., "A Review of Micrometeoroids Flux Measurements and Models for Low Orbital Altitudes of the Space Station," NASA TM-86466, September 1984.

3. Cour-Palais, B. G., Private Communication consisting of a section from the Space Station Customer Services Handbook being compiled at the Goddard Space Center, July 9, 1984.

4. Kessler, D. J., "Sources of Orbital Debris and the Projected Environment for Future Spacecraft," J. Spacecraft, pp. 357-360, Vol. 18, No. 4, July-August 1981.

5. Kinslow, R., Ed., "High-Velocity Impact Phenomena," Academic Press, 1970.

6. Fu, T., "Analytical Methods for Calculating Vulnerability of Meteoroid Impacts," Teledyne Brown Engineering, ASD-ASTN-1490, March 1972.

7. Zukas, J. A., Ed., "Impact Dynamics," John Wiley and Sons, 1982.

8. Frost, V. C., "Aerospace Meteoroid Environment and Penetration Criterion," Aerospace Corporation, TOR-269 (4560-40)-2, August 1964.

9. Nevins, C. D., "Analysis of Meteoroid Impact on Spacecraft Structures," unpublished report, Structures and Propulsion Laboratory, MSFC, April 1977.

10. Swift, H. F., and Hopkins, A. K., "The Effects of Bumper Material Properties on the Operation of Space Hypervelocity Particle Shields," AFML-TR-68-257, September 1968.

11. Madden, R., "Ballistic Limit of Double-Walled Meteoroid Bumper Systems," NASA TN D-3916, April 1967.

12. Nysmith, C. R., "An Experimental Impact Investigation of Aluminum Double-Sheet Structures," AIAA Hypervelocity Impact Conference, Cincinnati, Ohio, Paper No. 69-375, April 30 - May 2, 1969.

13. Cour-Palais, B. G., "Meteoroid Protection by Multiwall Structures," AIAA Hypervelocity Impact Conference, Cincinnati, Ohio, Paper No. 69-372, April 30 - May 2, 1969.

14. Cour-Palais, B. G., "Space Vehicle Meteoroid Shielding Design," Comet Halley Micrometeoroid Hazard Workshop, Proceedings of the International Workshop sponsored by the European Space Agency held in ESTEC, Noordwijk, Netherlands, pp. 85-92, April 18-19, 1979.

APPENDIX

COMPUTER PROGRAM LISTING

```
10 DECLARE DOUBLE PR(2),PD(2),PM(2),MASS(2),DIA(2),PROB(2),AR(2),PO(2),VP(2)
20 DECLARE DOUBLE XX,T1,KM,TP,DD,FLUX,GE,SH,YY,OP,T2,S1,S2,SP,TE
30 PRINT "* * * * * * * * * * * * * * * * * * * * * * * * * * * * *"
40 PRINT "* Welcome to program 'NONAME'                             *"
50 PRINT "* This program is developed by Fahim A. Batla             *"
60 PRINT "* in summer 1985 for design/analysis of space             *"
70 PRINT "* station exterior wall for hypervelocity impact          *"
80 PRINT "* by metreoroid/debris.                                   *"
90 PRINT "* Consult Program Manual for development and usage        *"
100 PRINT "* of this program.                                       *"
110 PRINT "* * * * * * * * * * * * * * * * * * * * * * * * * * * * *"
120 PRINT \ PRINT "Enter 'yes' if a hardcopy of output is desired,"
130 PRINT "otherwise enter 'no'."
140 PRINT \ INPUT ZZ$
150 IF ZZ$='no' GOTO 190
160 IF ZZ$='yes' GOTO 180
170 PRINT \ PRINT '*****Input Error'\ PRINT \ GOTO 120
180 OPEN 'lp:' FOR OUTPUT AS FILE #9
190 PRINT
200 REM design input
210 PRINT "Enter exposed projected area in square meters"
220 INPUT AR(2)\ PRINT
230 PRINT 'Enter exposed surface area in square meters'
240 INPUT AR(1)\ PRINT
250 PRINT "Enter time of exposure in years"
260 INPUT TE\ PRINT
270 PRINT "Enter altitude in km - use 400 or 500"
280 INPUT AL\ PRINT
290 REM PRINT "Enter meteoroid density"
300 PR(1)=.5
310 REM PRINT "Enter debris density"
320 PR(2)=2.81
330 LO=-LOG10(365.25*24*3600/(10^14.37))
340 IA=0
350 PRINT " Enter 'design' or 'analysis' "
360 INPUT CC$\ PRINT
370 IF CC$='design' GOTO 420
380 IF CC$='analysis' THEN IA=1
390 IF CC$='analysis' GOTO 700
400 PRINT \ PRINT "*****Input error"\ PRINT
410 GOTO 340
420 PRINT "Enter probability of no penetration for debris in decimal form"
430 INPUT PO(2)\ PRINT
440 PRINT 'Enter probability of no penetration for meteoroid in decimal form'
450 INPUT PO(1)\ PRINT
460 PRINT "***** Check input data"\ PRINT
470 PRINT 'Projected Area=';AR(2)\ PRINT 'Surface Area=';AR(1)
480 PRINT "Time=";TE\ PRINT "Altitude=";AL
490 PRINT "Meteoroid Density=";PR(1)\ PRINT "Debris Density=";PR(2)
500 PRINT "Meteoroid Probability=";PO(1)
```

```
510 PRINT 'Debris Probability=';PO(2)\ PRINT \ PRINT \ PRINT
520 PRINT "Enter 'next' if all the input data is correct,"
530 PRINT "otherwise enter 'repeat'."\ PRINT \ PRINT
540 INPUT CC$\ PRINT
550 IF CC$='repeat' GOTO 190
560 IF CC$='next' GOTO 590
570 PRINT '*****Input Error'\ PRINT
580 GOTO 520
590 FL=-1*LOG(PO(1))/AR(1)/TE
600 FLD=-1*LOG(PO(2))/AR(2)/TE
610 REM For Debris
620 IF AL=500 GOTO 660
630 PD(2)=(FLD*10^5.82)^(-1/2.42)
640 IF PD(2)>1 THEN PD(2)=(FLD*10^5.82)^(-1/1.13)
650 GOTO 680
660 PD(2)=(FLD*10^5.46)^(-1/2.52)
670 IF PD(2)>1 THEN PD(2)=(FLD*10^5.46)^(-1/.9)
680 PM(2)=PI*PR(2)*PD(2)^3/6
690 REM For Meteoroid
700 STH=6371/(6371+AL)
710 CTH=SQR(1-STH^2)
720 GE=.568+.432*STH
730 SH=(1+CTH)/2
740 IF IA=1 GOTO 960
750 FLM=FL/GE/SH
760 PM(1)=(FLM*10^LO)^(-1/1.213)
770 PD(1)=(6*PM(1)/PI/PR(1))^(1/3)
780 PRINT \ PRINT
790 PRINT TAB(15%);'For Debris',TAB(30%); For Meteoroid'\ PRINT
800 PRINT 'Flux',FLD;TAB(10%),FLM
810 PRINT 'Projectile'\ PRINT 'Diameter',PD(2);TAB(10%),PD(1)
820 PRINT 'Projectile'\ PRINT 'Mass',PM(2);TAB(10%),PM(1)
830 PRINT \ PRINT
840 IF PD(2)>4 THEN PRINT "***** IMPORTANT NOTE"\ PRINT
850 IF PD(2)>4 THEN PRINT "      If debris diameter is greater than 4 cm,"
860 IF PD(2)>4 THEN PRINT "      the computed diameter and mass for debris"
870 IF PD(2)>4 THEN PRINT "      is incorrect."
880 IF PD(2)>4 THEN PRINT \ PRINT
890 PRINT "If you desire to change any input data enter 'repeat',"
900 PRINT "otherwise enter 'next' to continue."
910 INPUT CC$\ PRINT
920 IF CC$='repeat' GOTO 200
930 IF CC$='next' GOTO 950
940 PRINT "*****Input Error"\ PRINT \ GOTO 890
950 PRINT
960 PRINT 'Enter debris projectile velocity in km/sec.'
970 INPUT VP(2)\ PRINT
980 PRINT 'Enter meteoroid projectile velocity in km/sec.'
990 INPUT VP(1)\ PRINT
1000 PRINT "Enter 'single' for a single wall design"
```

```
1010 PRINT "or 'double' for a double wall design."
1020 INPUT CC$\ PRINT
1030 IF CC$='single' GOTO 1060
1040 IF CC$='double' GOTO 2700
1050 PRINT '*****Input Error'\ PRINT \ GOTO 1000
1060 PRINT "Enter 'thick' for thick plate design"
1070 PRINT "or 'thin' for thin plate (threshold thickness) design."
1080 INPUT CC$\ PRINT
1090 IF CC$='thick' GOTO 1120
1100 IF CC$='thin' GOTO 1190
1110 PRINT '*****Input Error'\ PRINT \ GOTO 1060
1120 DD=2/3
1130 PRINT "Enter K (material constant) for thick plate design."
1140 INPUT KM\ PRINT
1150 PRINT 'Enter thickness/penetration ratio (>=4.0)'
1160 PRINT 'for thick plate design.'
1170 INPUT TP\ PRINT
1180 GOTO 1270
1190 DD=.875
1200 PRINT 'Enter K1 (material constant) for thin plate design.'
1210 INPUT KM\ PRINT
1220 TP=1
1230 IF IA=0 GOTO 1270
1240 PRINT 'Enter thickness of the plate in cm.'
1250 INPUT T1\ PRINT
1260 GOTO 2080
1270 PRINT "Enter 'optimize' if, for a given overall probability and"
1280 PRINT "the existing design data , the single wall thickness is"
1290 PRINT "to be minimized. Otherwise enter 'next'."\ PRINT
1300 INPUT DD$\ PRINT
1310 IF DD$='optimize' GOTO 2010
1320 IF DD$='next' GOTO 1340
1330 PRINT '*****Input Error'\ GOTO 1270
1340 PRINT 'For the design data to be used,'
1350 PRINT "enter 'debris' or 'meteoroid'."
1360 INPUT BB$\ PRINT
1370 I=0
1380 IF BB$='meteoroid' THEN I=1
1390 IF BB$='debris' THEN I=2
1400 IF I>0 GOTO 1420
1410 PRINT '*****Input Error'\ PRINT \ GOTO 1340
1420 IF I=1 THEN J=2
1430 IF I=2 THEN J=1
1440 T=KM*TP*(PM(I)^.352)*(PR(I)^(1/6))*(VP(I)^DD)
1450 PRINT 'Single ';CC$;' plate thickness for ';BB$;' = ';T;' cm'
1460 PRINT \ PRINT
1470 MASS(I)=PM(I)
1480 DIA(I)=PD(I)
1490 IF CC$='thick' THEN DD=2/3
1500 IF CC$='thin' THEN DD=.875
```

```
1510 MASS(J)=PM(I)*((PR(I)/PR(J))^(1/2.112))*((VP(I)/VP(J))^(DD/.352))
1520 DIA(J)=(6*MASS(J)/PI/PR(J))^(1/3)
1530 XX=MASS(1)^(-1.213)/(10^LO)
1540 FLUX=XX*GE*SH
1550 PROB(1)=EXP(-1*FLUX*AR(1)*TE)
1560 IF AL=500 GOTO 1600
1570 IF DIA(2)>1 THEN YY=-1.13
1580 IF DIA(2)<=1 THEN YY=-2.42
1590 FLUX=DIA(2)^YY/(10^5.82)\ GOTO 1630
1600 IF DIA(2)>1 THEN YY=-.9
1610 IF DIA(2)<=1 THEN YY=-2.52
1620 FLUX=DIA(2)^YY/(10^5.46)
1630 PROB(2)=EXP(-1*FLUX*AR(2)*TE)
1640 PRINT \ PRINT
1650 PRINT '***** For plate thickness=';T;'cm,'
1660 PRINT '      designed for ';BB$;' protection,'
1670 PRINT '      following are the comparisons between'
1680 PRINT '      debris and meteoroid.'
1690 PRINT \ PRINT
1700 PRINT TAB(15%);'For Debris',TAB(30%);'For Meteoroid'\ PRINT
1710 PRINT 'Projectile'\ PRINT 'Velocity',VP(2);TAB(10%),VP(1)
1720 PRINT 'Projectile'\ PRINT 'Diameter',DIA(2);TAB(10%),DIA(1)
1730 PRINT 'Projectile'\ PRINT 'Mass',MASS(2);TAB(10%),MASS(1)
1740 PRINT 'Probability',PROB(2);TAB(10%),PROB(1)
1750 PRINT \ PRINT \ IF DIA(2)>4 THEN PRINT '*****IMPORTANT NOTE'\ PRINT
1760 IF DIA(2)>4 THEN PRINT 'Computed probability for debris is incorrect'
1770 IF DIA(2)>4 THEN PRINT 'as the diameter of projectile is greater'
1780 IF DIA(2)>4 THEN PRINT 'than 4 cm.'
1790 PRINT \ PRINT
1800 PRINT "*****Enter 'repeat' if you want to compute the thickness"
1810 IF I=1 THEN PRINT "for debris or for different velocities etc.,"
1820 IF I=2 THEN PRINT "for meteoroid or for different velocities etc.,"
1830 PRINT "or enter 'start' to start all over,"
1840 PRINT "or enter 'next' to continue,"
1850 PRINT "or enter 'end' to stop."
1860 INPUT DD$\ PRINT
1870 IF DD$='repeat' GOTO 950
1880 IF DD$='next' GOTO 1920
1890 IF DD$='start' GOTO 120
1900 IF DD$='end' GOTO 4900
1910 PRINT '*****Input Error'\ PRINT \ GOTO 1800
1920 PRINT "Enter 'optimize' if, for a given overall probability and"
1930 PRINT "the existing design data , the single wall thickness is"
1940 PRINT "to be minimized. Otherwise enter 'start' to start"
1950 PRINT "all over, or enter 'end' to stop."
1960 INPUT DD$\ PRINT
1970 IF DD$='optimize' GOTO 2010
1980 IF DD$='end' GOTO 4900
1990 IF DD$='start' GOTO 120
2000 PRINT '*****Input Error'\ PRINT \ GOTO 1920
```

```
2010 T1=0
2020 PRINT 'Enter overall probability'
2030 INPUT OP\ PRINT
2040 INC=1
2050 K=0
2060 K=K+1
2070 T1=T1+INC
2080 XX=T1/KM/TP/(PR(1)^(1/6))/(VP(1)^DD)
2090 MASS(1)=XX^(1/.352)
2100 XX=T1/KM/TP/(PR(2)^(1/6))/(VP(2)^DD)
2110 MASS(2)=XX^(1/.352)
2120 DIA(1)=(6*MASS(1)/PI/PR(1))^(1/3)
2130 DIA(2)=(6*MASS(2)/PI/PR(2))^(1/3)
2140 XX=MASS(1)^(-1.213)/(10^LO)
2150 FLUX=XX*GE*SH
2160 PROB(1)=EXP(-1*FLUX*AR(1)*TE)
2170 IF AL=500 GOTO 2210
2180 IF DIA(2)>1 THEN YY=-1.13
2190 IF DIA(2)<=1 THEN YY=-2.42
2200 FLUX=DIA(2)^YY/(10^5.82)\ GOTO 2240
2210 IF DIA(2)>1 THEN YY=-.9
2220 IF DIA(2)<=1 THEN YY=-2.52
2230 FLUX=DIA(2)^YY/(10^5.46)
2240 PROB(2)=EXP(-1*FLUX*AR(2)*TE)
2250 IF IA=1 GOTO 2400
2260 IF K>25 GOTO 2290
2270 IF (PROB(1)*PROB(2))>OP GOTO 2320
2280 GOTO 2060
2290 PRINT \ PRINT \ PRINT '***** No optimization as thickness is getting'
2300 PRINT '      very large or very small.'
2310 GOTO 2520
2320 IF ABS(INC)=.001 GOTO 2360
2330 T1=T1-INC
2340 INC=INC/10
2350 GOTO 2050
2360 PRINT \ PRINT
2370 PRINT '***** For overall probability of';OP;', the required'
2380 PRINT '      minimum thickness is';T1;'cm. The comparisons'
2390 PRINT '      between meteoroid and debris are as follows.'\ GOTO 2420
2400 PRINT '***** For single plate thickness =';T1;'cm. the comparisons'
2410 PRINT '      between meteoroid and debris are as follows.'
2420 PRINT \ PRINT
2430 PRINT TAB(15%);'For Debris',TAB(30%);'For Meteoroid'\ PRINT
2440 PRINT 'Projectile'\ PRINT 'Velocity',VP(2);TAB(10%),VP(1)
2450 PRINT 'Projectile'\ PRINT 'Diameter',DIA(2);TAB(10%),DIA(1)
2460 PRINT 'Projectile'\ PRINT 'Mass',MASS(2);TAB(10%),MASS(1)
2470 PRINT 'Probability',PROB(2);TAB(10%),PROB(1)
2480 PRINT \ PRINT \ IF DIA(2)>4 THEN PRINT '*****IMPORTANT NOTE'\ PRINT
2490 IF DIA(2)>4 THEN PRINT 'Computed probability for debris is incorrect'
2500 IF DIA(2)>4 THEN PRINT 'as the diameter of projectile is greater'
```

```
2510 IF DIA(2)>4 THEN PRINT 'than 4 cm.
2520 PRINT \ PRINT
2530 IF IA=0 GOTO 2610
2540 PRINT "Enter 'repeat' if analysis for different thickness is desired."
2550 PRINT "otherwise enter 'start'  to start all over or 'end' to stop."
2560 INPUT CC$\ PRINT
2570 IF CC$='repeat' GOTO 1240
2580 IF CC$='start' GOTO 120
2590 IF CC$='end' GOTO 4900
2600 PRINT '*****Input Error'\ PRINT \ GOTO 2540
2610 PRINT "Enter 'repeat' if you want to minimize the thickness"
2620 PRINT "for different overall probability,"
2630 PRINT "or enter 'start' to start all over,"
2640 PRINT "or enter 'end' to stop."
2650 INPUT EE$\ PRINT
2660 IF EE$='repeat' GOTO 2010
2670 IF EE$='start' GOTO 120
2680 IF EE$='end' GOTO 4900
2690 PRINT '*****Input Error'\ PRINT \ GOTO 2610
2700 IF IA=1 GOTO 2800
2710 PRINT "Enter 'optimize' if, for a given overall probability"
2720 PRINT 'and the existing design data, the double wall'
2730 PRINT "design is to be optimized, otherwise enter 'next'."
2740 INPUT CC$\ PRINT
2750 IF CC$='next' GOTO 4020
2760 IF CC$='optimize' GOTO 2780
2770 PRINT '*****Input Error'\ PRINT \ GOTO 2710
2780 PRINT 'Enter overall probability.'
2790 INPUT OP\ PRINT
2800 PRINT "Enter 'Cour-Palais' or 'Nysmith' for design method to be used."
2810 INPUT CC$\ PRINT
2820 IF CC$='Cour-Palais' GOTO 2850
2830 IF CC$='Nysmith' GOTO 2910
2840 PRINT '*****Input Error'\ PRINT \ GOTO 2800
2850 IO=1
2860 PRINT 'Enter bumper material density in gm/cu. cm.'
2870 INPUT RB\ PRINT
2880 PRINT 'Enter 0.2 percent yield stress for hull material in PSI.'
2890 INPUT FY\ PRINT
2900 GOTO 2920
2910 IO=2
2920 PRINT 'Enter spacing between walls in cm.'
2930 INPUT SP\ PRINT
2940 IF IA=0 GOTO 3000
2950 PRINT 'Enter bumper thickness in cm.'
2960 INPUT T1\ PRINT
2970 PRINT 'Enter hull thickness in cm.'
2980 INPUT T2\ PRINT
2990 GOTO 3100
3000 T2=0
```

```
3010 INC=1
3020 IF IO=2 GOTO 3070
3030 XX=.0075*(RB^(1/3))*(70000/FY)
3040 S1=XX*PR(1)*(VP(1)^2)
3050 S2=XX*PR(2)*(VP(2)^2)
3060 IF SP<=0 THEN SP=(S1+S2)/2
3070 K=0
3080 K=K+1
3090 T2=T2+INC
3100 IF IO=2 GOTO 3150
3110 XX=T2*(SP^(1/2))/(RB^(1/6))/((70000/FY)^(1/2))/.0443
3120 DIA(1)=XX/(PR(1)^(1/2))/VP(1)
3130 DIA(2)=XX/(PR(2)^(1/2))/VP(2)
3140 GOTO 3170
3150 DIA(1)=.5122*(T2^.5236)*(SP^.4764)/(VP(1)^.0953)
3160 DIA(2)=.5122*(T2^.5236)*(SP^.4764)/(VP(2)^.0953)
3170 MASS(1)=PI*PR(1)*DIA(1)^3/6
3180 MASS(2)=PI*PR(2)*DIA(2)^3/6
3190 XX=MASS(1)^(-1.213)/(10^LO)
3200 FLUX=XX*GE*SH
3210 PROB(1)=EXP(-1*FLUX*AR(1)*TE)
3220 IF AL=500 GOTO 3260
3230 IF DIA(2)>1 THEN YY=-1.13
3240 IF DIA(2)<=1 THEN YY=-2.42
3250 FLUX=DIA(2)^YY/(10^5.82)\ GOTO 3290
3260 IF DIA(2)>1 THEN YY=-.9
3270 IF DIA(2)<=1 THEN YY=-2.52
3280 FLUX=DIA(2)^YY/(10^5.46)
3290 PROB(2)=EXP(-1*FLUX*AR(2)*TE)
3300 IF IA=1 GOTO 3420
3310 IF K>25 GOTO 3340
3320 IF (PROB(1)*PROB(2))>OP GOTO 3360
3330 GOTO 3080
3340 PRINT \ PRINT \ PRINT '***** No optimization as thickness is getting'
3350 PRINT '       very large or very small.'\ GOTO 3830
3360 IF ABS(INC)=.001 GOTO 3400
3370 T2=T2-INC
3380 INC=INC/10
3390 GOTO 3070
3400 IF IO=1 THEN T1=.32*T2
3410 IF IO=2 THEN T1=.35*T2/.65
3420 T1D1=T1/DIA(1)
3430 T1D2=T1/DIA(2)
3440 T2D1=T2/DIA(1)
3450 T2D2=T2/DIA(2)
3460 TTD1=T1D1+T2D1
3470 TTD2=T1D2+T2D2
3480 SPD1=SP/DIA(1)
3490 SPD2=SP/DIA(2)
3500 TT=T1+T2
```

```
3510 T1TT=T1/TT
3520 T2TT=T2/TT
3530 PRINT \ PRINT
3540 IF IA=0 GOTO 3600
3550 PRINT '*****  For bumper thickness=';T1;'cm..'
3560 PRINT '              hull thickness=';T2;'cm.. and'
3570 PRINT '        spacing between walls=';SP;'cm..'
3580 PRINT '        following are comparisons between meteoroid and debris.'
3590 GOTO 3650
3600 PRINT '***** For overall probability of';OP;', the required'
3610 PRINT '        minimum bumper thickness is';T1;'cm..'
3620 PRINT '        hull thickness is';T2;'cm. with spacing of';SP;'cm.'
3630 PRINT '        The comparisons between meteoroid and debris'
3640 PRINT '        are as follows.'
3650 PRINT \ PRINT
3660 PRINT TAB(15%);'For Debris',TAB(30%);'For Meteoroid'\ PRINT
3670 PRINT 'Velocity',VP(2);TAB(10%),VP(1)
3680 PRINT 'Diameter',DIA(2);TAB(10%),DIA(1)
3690 PRINT 'Mass',MASS(2);TAB(10%),MASS(1)
3700 PRINT 'Probability',PROB(2);TAB(10%),PROB(1)
3710 PRINT 'Bumper/Dia.',T1D2;TAB(10%),T1D1
3720 PRINT 'Hull/Dia.',T2D2;TAB(10%),T2D1
3730 PRINT 'Total T/Dia.',TTD2;TAB(10%),TTD1
3740 PRINT 'Spacing/Dia.',SPD2;TAB(10%),SPD1
3750 PRINT \ PRINT '           Bumper/Total T=';T1TT
3760         PRINT '             Hull/Total T=';T2TT
3770         PRINT '    Overall Probability=';PROB(1)*PROB(2)
3780 STOP
3790 PRINT \ PRINT \ IF DIA(2)>4 THEN PRINT '*****IMPORTANT NOTE'\ PRINT
3800 IF DIA(2)>4 THEN PRINT 'Computed probability for debris is incorrect'
3810 IF DIA(2)>4 THEN PRINT 'as the diameter of projectile is greater'
3820 IF DIA(2)>4 THEN PRINT 'than 4 cm.'
3830 PRINT \ PRINT
3840 IF IA=0 GOTO 3930
3850 PRINT "Enter 'repeat' if analysis for different thicknesses and"
3860 PRINT "spacing is desired. "
3870 PRINT "Otherwise enter 'start' to start all over or 'end' to stop."
3880 INPUT CC$\ PRINT
3890 IF CC$='repeat' GOTO 2700
3900 IF CC$='start' GOTO 120
3910 IF CC$='end' GOTO 4900
3920 PRINT '*****Input Error'\ PRINT \ GOTO 3850
3930 PRINT "Enter 'repeat' if you want to optimize the double wall design"
3940 PRINT "for different overall probability,"
3950 PRINT "or enter 'start' to start all over,"
3960 PRINT "or enter 'end' to stop."
3970 INPUT EE$\ PRINT
3980 IF EE$='repeat' GOTO 2710
3990 IF EE$='start' GOTO 120
4000 IF EE$='end' GOTO 4900
```

```
4010 PRINT '*****Input Error'\ PRINT \ GOTO 3930
4020 PRINT 'For the design data to be used.'
4030 PRINT "enter 'debris' or 'meteoroid'."
4040 INPUT BB$\ PRINT
4050 I=0
4060 IF BB$='meteoroid' THEN I=1
4070 IF BB$='debris' THEN I=2
4080 IF I>0 GOTO 4100
4090 PRINT '*****Input Error'\ PRINT \ GOTO 4020
4100 IF I=1 THEN J=2
4110 IF I=2 THEN J=1
4120 PRINT 'Enter spacing between walls in cm.'
4130 INPUT SP\ PRINT
4140 PRINT 'Enter bumper/hull thickness ratio.'
4150 INPUT T1T2\ PRINT
4160 PRINT "Enter 'Cour-Palais' or 'Nysmith' for design method to be used."
4170 INPUT CC$\ PRINT
4180 IF CC$='Cour-Palais' GOTO 4210
4190 IF CC$='Nysmith' GOTO 4310
4200 PRINT '*****Input Error'\ PRINT \ GOTO 4160
4210 PRINT 'Enter bumper material density in gm/cu. cm.'
4220 INPUT RB\ PRINT
4230 PRINT 'Enter 0.2 percent yield stress for hull material in PSI.'
4240 INPUT FY\ PRINT
4250 ZZ=.0443*(PR(I)^.5)*(RB^(1/6))*VP(I)*((70000/FY)^.5)
4260 T2=ZZ*PD(I)/(SP^.5)
4270 XX=T2*(SP^(1/2))/(RB^(1/6))/((70000/FY)^(1/2))/.0443
4280 DIA(1)=XX/(PR(1)^(1/2))/VP(1)
4290 DIA(2)=XX/(PR(2)^(1/2))/VP(2)
4300 GOTO 4350
4310 ZZ=5.08*(VP(I)^.278)*(PD(I)^2.918)/(T1T2^.528)
4320 T2=(ZZ/(SP^1.39))^(1/1.528)
4330 DIA(1)=.5122*(T2^.5236)*(SP^.4764)/(VP(1)^.0953)
4340 DIA(2)=.5122*(T2^.5236)*(SP^.4764)/(VP(2)^.0953)
4350 MASS(1)=PI*PR(1)*DIA(1)^3/6
4360 MASS(2)=PI*PR(2)*DIA(2)^3/6
4370 XX=MASS(1)^(-1.213)/(10^LO)
4380 FLUX=XX*GE*SH
4390 PROB(1)=EXP(-1*FLUX*AR(1)*TE)
4400 IF AL=500 GOTO 4440
4410 IF DIA(2)>1 THEN YY=-1.13
4420 IF DIA(2)<=1 THEN YY=-2.42
4430 FLUX=DIA(2)^YY/(10^5.82)\ GOTO 4470
4440 IF DIA(2)>1 THEN YY=-.9
4450 IF DIA(2)<=1 THEN YY=-2.52
4460 FLUX=DIA(2)^YY/(10^5.46)
4470 PROB(2)=EXP(-1*FLUX*AR(2)*TE)
4480 T1=T1T2*T2
4490 T1D1=T1/DIA(1)
4500 T1D2=T1/DIA(2)
```

```
4510 T2D1=T2/DIA(1)
4520 T2D2=T2/DIA(2)
4530 TTD1=T1D1+T2D1
4540 TTD2=T1D2+T2D2
4550 SPD1=SP/DIA(1)
4560 SPD2=SP/DIA(2)
4570 PRINT \ PRINT
4580 PRINT '***** For bumper thickness=';T1;'cm. and hull thickness=';T2;'cm.,
4590 PRINT '       designed for ';BB$;' protection.'
4600 PRINT '       following are the comparisons between'
4610 PRINT '       debris and meteoroid.'
4620 PRINT \ PRINT
4630 PRINT TAB(15%);'For Debris',TAB(30%);'For Meteoroid'\ PRINT
4640 PRINT 'Velocity',VP(2);TAB(10%),VP(1)
4650 PRINT 'Diameter',DIA(2);TAB(10%),DIA(1)
4660 PRINT 'Mass',MASS(2);TAB(10%),MASS(1)
4670 PRINT 'Probability',PROB(2);TAB(10%),PROB(1)
4680 PRINT \ PRINT 'Bumper/Dia.',T1D2;TAB(10%),T1D1
4690 PRINT 'Hull/Dia.',T2D2;TAB(10%),T2D1
4700 PRINT 'Total T/Dia.',TTD2;TAB(10%),TTD1
4710 PRINT 'Spacing/Dia.',SPD2;TAB(10%),SPD1
4720 STOP
4730 PRINT \ PRINT \ IF DIA(2)>4 THEN PRINT '*****IMPORTANT NOTE'\ PRINT
4740 IF DIA(2)>4 THEN PRINT 'Computed probability for debris is incorrect'
4750 IF DIA(2)>4 THEN PRINT 'as the diameter of projectile is greater'
4760 IF DIA(2)>4 THEN PRINT 'than 4 cm.'
4770 PRINT \ PRINT
4780 PRINT "*****Enter 'repeat' if you want the double wall design"
4790 IF I=1 THEN PRINT "for debris or for different velocities etc.,"
4800 IF I=2 THEN PRINT "for meteoroid or for different velocities etc.,"
4810 PRINT "or enter 'start' to start all over,"
4820 PRINT "or enter 'next' to continue,"
4830 PRINT "or enter 'end' to stop."
4840 INPUT DD$\ PRINT
4850 IF DD$='repeat' GOTO 4020
4860 IF DD$='next' GOTO 4900
4870 IF DD$='start' GOTO 120
4880 IF DD$='end' GOTO 4900
4890 PRINT '*****Input Error'\ PRINT \ GOTO 4780
4900 END
```