

## EMPIRICAL MODELS FOR SPACECRAFT DAMAGE FROM ORBITAL DEBRIS PENETRATION AND EFFECTS ON SPACECRAFT SURVIVABILITY

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### Abstract

Semi-empirical models of hole diameter and tip-to-tip crack length for some of the multi-wall shielding systems being developed for the International Space Station are presented herein. These equations were developed using light gas gun test data at impact velocities near 6.5 km/sec and inhibited shaped charge test data at an impact velocity of 11.3 km/sec. These hole diameter and crack length models are then incorporated into a survivability analysis using the Manned Spacecraft Crew Survivability (MSCSurv) computer code to determine whether or not module unzipping or crew incapacitation would occur under a specific set of impact conditions.

**Keywords:** Hypervelocity impact, hole size, depressurization, fracture, orbital debris, crack length, survivability, Monte Carlo models.

### 1. INTRODUCTION

Long duration spacecraft in low earth orbit such as the International Space Station (ISS) are highly susceptible to hypervelocity impacts by pieces of debris from past earth-orbiting missions. With an increased likelihood of debris impact over longer mission time comes a responsibility on the part of a spacecraft design engineer to quantify, and subsequently reduce, the hazardous effects on a spacecraft and its crew should penetration occur.

Among the various hazards that accompany the penetration of a pressurized manned spacecraft module are unstable crack propagation in the module wall (i.e. the so-called 'unzipping' of the module) and depressurization-related phenomena, such as crew hypoxia and uncontrolled thrust due to air rushing out of the module wall hole. These phenomena are directly related to the effective pressure wall hole diameter and maximum tip-to-tip crack lengths that result in a spacecraft wall following a penetration. For the purposes of this paper, *effective pressure wall hole diameter* is defined as the diameter of a circle whose area equals the see-through area of the hole in the pressure wall. In the event that a pressure wall hole is accompanied by large petals and cracks, the

*maximum tip-to-tip crack length* is taken to be the largest distance between two crack tips in the star-shaped petal pattern. When there are two or more holes present, the definition of hole diameter includes a circle whose area equals the total see-through area of all the holes present. In those cases where petals and cracks were not formed, the hole in the pressure wall was typically an irregular shape with some eccentricity. In such cases, the maximum tip-to-tip crack length is simply defined as the maximum width of the hole.

Figure 1 shows the normal impact of a multi-wall structure impacted by a spherical projectile. In such a system, the outer and inner bumpers protect the pressure wall against perforation by causing the disintegration of the impacting projectile and the creation of a debris cloud which imparts a lower impulse per unit area to the pressure wall. The pressure wall area over which the impulsive load is distributed is governed by the extent to which the projectile and bumper materials fragment, melt, or vaporize, by the location of the inner bumper within the dual-wall system, and the spacing between the bumpers and the pressure wall.

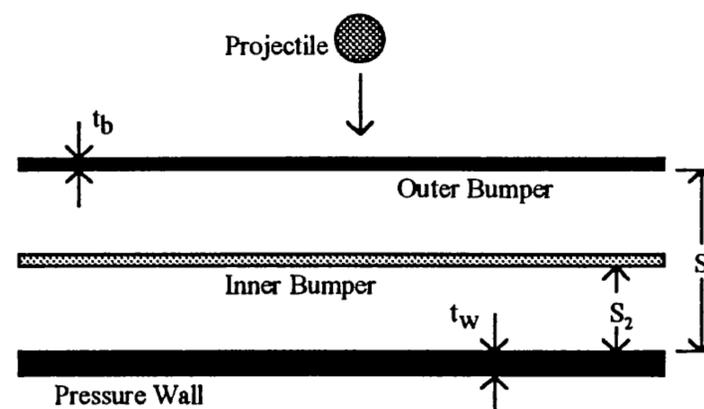


Figure 1. Impact of a Multi-Wall Structure

### 2. HOLE AND CRACK SIZE MODELS

A well-known semi-empirical model describing damage to the pressure wall of a spacecraft was proposed by Burch<sup>1</sup> in 1967. In his study, Burch describes a parameter  $D_{90}$  which encompasses roughly 90 percent of the impact damage on the surface area of the pressure wall. Burch states that this parameter may be viewed as an estimate of the through-hole size in the pressure wall of a

perforated spacecraft wall. In 1992, Lutz and Goodwin<sup>2</sup> suggested that a factor of 2 be applied to  $D_{90}$  to model the maximum tip-to-tip crack length based on preliminary data from Space Station Freedom hypervelocity tests. Several more recent empirical models for hole diameter and maximum tip-to-tip crack length were proposed by Schonberg and Williamsen for an impact velocity of 6.5 km/s<sup>3,4</sup>, with several extensions to 11.3 km/sec<sup>5,6</sup>.

The empirical predictor equations for hole diameter and crack length used herein were all in the following non-dimensional form:

$$X = A (\cos^B \theta_p) [1 - e^{-C(D_p/D_{bl}-1)}] (V_p/6.5)^D \quad (1)$$

where: X is either the hole diameter or maximum tip-to-tip crack length at a desired impact velocity  $V_p$  between 6 and 12 km/sec; A, B, and C are regression constants using data at 6.5 km/sec;  $\theta_p$  is the projectile trajectory obliquity from the bumper surface normal;  $D_p$  is the projectile diameter; and,  $D_{bl}$  is the ballistic limit diameter for the multi-wall system at the impact velocity of interest.

The values of the constants A, B, and C were obtained for hole diameter and tip-to-tip crack length for a variety of ISS multi-wall shielding systems through a simplex curve fitting algorithm using data generated at the NASA/Marshall Space Flight Center at 6.5 km/sec. These values, as well as the correlation coefficients for the various equations, are given in Tables 1a,b for the ISS shielding systems that are pertinent to this study.

**Table 1a. Hole Diameter Constants for 6.5 km/s Impacts<sup>3</sup>**

SHIELD SYSTEM	Effective Hole Diameter			
	A (cm)	B (—)	C (—)	R <sup>2</sup> (—)
U.S. LAB CYLINDER	6.960	0.859	2.424	0.95
U.S. LAB ENDCONE	19.27	1.970	0.873	0.95
ENHANCED U.S. LAB CYLINDER	20.95	0.869	3.54	0.77
RUSSIAN RESEARCH CYLINDER	4.323	0.416	1.474	0.83
ENHANCED RUSSIAN RES. CYL.	18.98	0.758	3.031	0.99

**Table 1b. Crack Length Constants for 6.5 km/s Impacts<sup>3</sup>**

SHIELD SYSTEM	Max. Tip-to-Tip Crack Length			
	A (cm)	B (—)	C (—)	R <sup>2</sup> (—)
U.S. LAB CYLINDER	9.827	1.041	2.772	0.81
U.S. LAB ENDCONE	34.57	3.670	1.908	0.99
ENHANCED U.S. LAB CYLINDER	25.96	0.503	4.81	0.71
RUSSIAN RESEARCH CYLINDER	4.892	0.498	9.518	0.79
ENHANCED RUSSIAN RES. CYL.	19.33	0.565	6.308	0.99

The nature of the exponent D in Eqn. (1), which governs the growth of hole diameter and crack length with increasing projectile impact velocity  $V_p$ , has been the subject of several recent studies. Most recently, Schonberg and Mohamed<sup>7</sup> considered the effects of both shape and velocity on hole diameter and crack length using test data generated at MSFC (at 6.5 km/sec) and at the Southwest Research Institute (at 11.3 km/sec) for a variety of space station shielding systems. This study showed that values obtained for the constants A, B, and C at 6.5 km/sec could be used to predict hole diameters and crack lengths for velocities up to 12 km/sec by using D=1.

That is, both hole diameter and crack length seemed to grow linearly with increasing velocity when other projectile impact parameters (i.e. mass and obliquity) were held constant. It is interesting to note that the observation of damage diameter growing linearly with increasing projectile momentum (i.e. velocity to the first power) is consistent with the observations made by Burch<sup>1</sup> from a series of regressions using data obtained at impact velocities ranging from 5 to 8 km/sec.

Figure 2 shows a plot of effective hole diameter versus projectile diameter for the baseline U.S. Lab Cylinder shielding system at for normal impact at 6.5 km/s using the Schonberg-Williamsen (S-W) model, Eqn. (2), and the Burch D90 model. Note that the S-W model generally reaches a lower hole diameter asymptote than does the Burch model.

Figure 3 shows the effect of impact velocity on pressure wall hole diameter for the baseline U.S. Lab Cylinder and the Enhanced U.S. Lab Cylinder shielding systems. The major difference between these shields is the presence of a heavy Nextel and Kevlar blanket between the bumper and the pressure wall in the enhanced system.

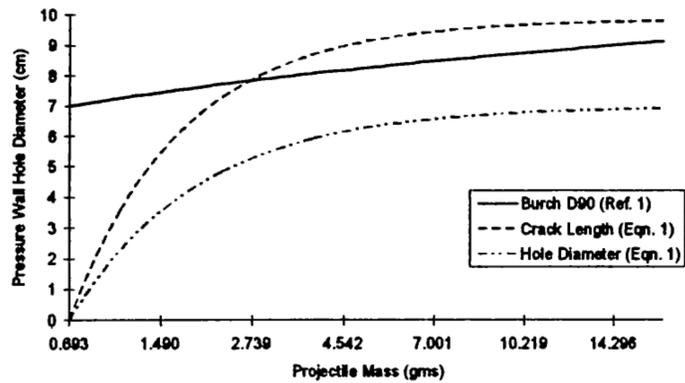


Figure 2. Hole Diameter Predictions, Baseline U.S. Lab Cylinder Shield System

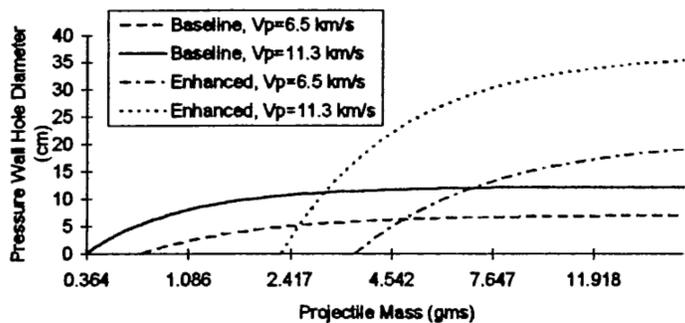


Figure 3. Hole Diameter Comparisons, Baseline vs. Enhanced U.S. Lab Cylinder Shield Systems

In Figure 3 we note that while using an enhanced shielding system has significantly raised the ballistic limit of the shield configuration, it has also increased the diameter of the pressure wall hole in the event of a penetration. That is, holes could be expected to happen far less often in spacecraft using an enhanced shielding system, but would be much larger when (and if) they occurred. The trade-off between increased resistance to penetration and larger holes in the event of a penetration with regard to spacecraft survivability is addressed in the next section.

### 3. SPACECRAFT SURVIVABILITY

For a number of years, NASA has used the BUMPER computer code to determine the likelihood of spacecraft penetration by meteoroids or orbital debris over a period of time ( $P_{PEN}$ ). Recently, NASA has also developed a computer program called the Manned Spacecraft Crew Survivability (MSCSurv) code to determine the

likelihood of spacecraft or crew loss given that a penetration has occurred ( $P_{LOSS/PEN}$ ). Together, these quantities can be used to compute  $P_{LOSS}$ , the probability of spacecraft or crew loss for a single particle impact, as follows:

$$P_{LOSS} = P_{PEN} \times P_{LOSS/PEN} \quad (2)$$

In the case of multiple penetrations during a long mission, if  $N_{PEN}$  is the number of expected penetrations during spacecraft or mission lifetime, then we have the following relationship between  $P_{PEN}$  and  $N_{PEN}$ :

$$P_{PEN} = 1 - \exp(-N_{PEN}) \quad (3)$$

Furthermore, in the case of multiple penetrations,  $P_{LOSS}$  is obtained using the following equation:

$$P_{LOSS} = 1 - \exp(-N_{PEN} \times P_{LOSS/PEN}) \quad (4)$$

We note that the product in Eqn. (4) is also the number of expected crew or station losses expected over the duration of the mission, or

$$N_{LOSS} = N_{PEN} \times P_{LOSS/PEN} \quad (5)$$

Thus, Eqn. (4) can also be written as

$$P_{LOSS} = 1 - \exp(-N_{LOSS}) \quad (6)$$

Tools such as BUMPER and MSCSurv allow the spacecraft design engineer to assess the advantages of increased penetration resistance and reduced damage to the spacecraft following penetration. MSCSurv is a Monte Carlo-style computer program which performs as shown in Figure 4. The program first generates thousands of particle diameters, velocities, and approach directions from the known M/OD environment. Next, it determines which combinations of impact parameters will cause penetration and one of the following five failure modes to occur -- critical cracking, thrust-induced structural failure, critical equipment loss, crew injury, and crew hypoxia.

In MSCSurv, controllable variables such as depressurization sensor locations, hatch closure positions, oxygen mask placement, crew sleep position, escape rates and paths, etc. are input by the user in order to lower the likelihood of station or crew loss given a penetration ( $P_{LOSS/PEN}$ ). Of the failure modes examined by MSCSurv, critical cracking and hypoxia are driven strongly by tip-to-tip crack length and hole size models.

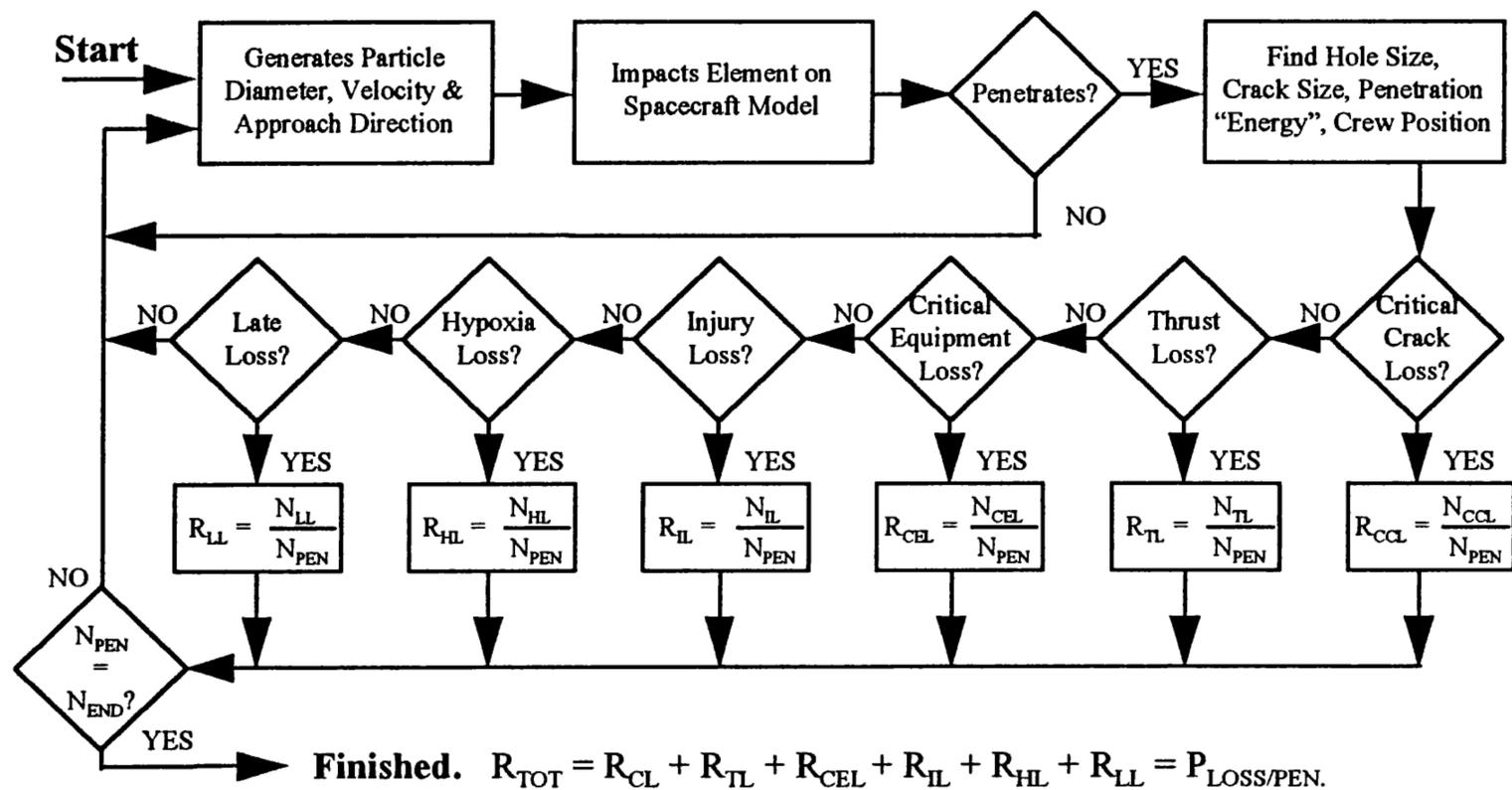


Figure 4. MSCSurv Overview

Table 2 shows  $P_{LOSS/PEN}$  values for 5 different modules and for the 25 manned module cluster of the Space Station using (1) "baseline" operations and (2) improved internal equipment and crew operations. This analysis uses the Schonberg-Williamsen hole and crack size model described in Section 2. The modules considered in this study use a variety of different shields types.

For example, the U.S. Lab and Hab modules, as well as the ESA Columbus module, all use a combination of the shielding systems listed in the first three rows of Table 1. The RSA FGB and Service modules use variations of the enhanced and baseline Russian Research Cylinder shielding systems, respectively.

In performing the MSCSurv analysis, care was taken to ensure that the shielding systems used in the generation of data to derive the hole diameter crack length predictor equations given in Table 1 matched as closely as possible to actual module wall configurations. While some discrepancies in wall thickness or spacing may exist, these discrepancies are typically less than 25% of the actual module wall geometric parameters. For ISS modules where S-W type hole diameter and crack length models were not available, the more generic Burch D90 model was used.

According to Table 2, the total  $P_{LOSS/PEN}$  for the five critical failure modes shown drops from 0.34

to 0.21 with improved operations and internal equipment design. As a result, the likelihood of long term station downtime or possible loss is also lowered dramatically by use of the improved operations and internal design features. We also note from Table 2 that modules with more effective shields, such as the U.S. Lab and Hab modules, have much higher  $P_{LOSS/PEN}$  than modules with less effective shields, such as the RSA Service Module and the FGB module.

However, MSCSurv provides only half of the information required to assess the probability of station or crew loss. The values of  $P_{LOSS/PEN}$  in Table 2 must be multiplied by appropriate  $P_{PEN}$  (or  $N_{PEN}$ ) values to obtain the total value of  $P_{LOSS}$ . Table 3 presents values for all three terms in Eqn. 2 ( $P_{PEN}$ ,  $P_{LOSS/PEN}$ , and  $P_{LOSS}$ ) for the five different modules considered herein. Probabilities of penetration ( $P_{PEN}$ ) were computed using the BUMPER program by the ISS Program Office<sup>10</sup>. Note that even though the  $P_{LOSS/PEN}$  term is higher for modules with more effective shields (such as the U.S. Lab and Hab modules), the decreased likelihood of penetration resulting from use of these shields in these modules lowers their overall  $P_{LOSS}$  values.

Thus, we see that the "stronger" shields will result in lower overall  $P_{LOSS}$  values despite their higher  $P_{LOSS/PEN}$  values. This result was checked by re-computing  $P_{LOSS}$  values for the U.S. Lab and Hab

**Table 2. Probability of Loss Given a Penetration ( $P_{LOSS/PEN}$ ) for the International Space Station**

<b>MODULE TYPE</b>	<b>Critical Cracking</b>	<b>Thrust Failure</b>	<b>Critical Equipment</b>	<b>Crew Injury</b>	<b>Crew Hypoxia</b>	<b>Total 5 Modes</b>
<b>U.S. Lab Module</b>	.00	.00	.03	0.05	.30	.38
<b>U.S. Hab Module</b>	.10	.00	.02	0.11	.43	.75
<b>ESA Columbus Module</b>	.25	.00	.02	.03	.20	.50
<b>RSA FGB Module</b>	.00	.00	.06	.03	.34	.43
<b>RSA Service Module</b>	.04	.04	.06	.13	.03	.31
<b>Average 25 Modules</b>	.02	.02	.06	.08	.16	.34

**BASELINE OPERATING MODE**

- 1994 orbital debris environment, 400 km altitude, 51 degrees inclination, solar flux 70 Janskys.
- No oxygen masks -- hatches open -- no hole location devices -- crew sleeps in Hab and Service modules.

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<b>U.S. Lab Module</b>	.00	.00	.03	0.05	.22	.30
<b>U.S. Hab Module</b>	.10	.00	.02	0.11	.35	.68
<b>ESA Columbus Module</b>	.24	.00	.02	.05	.06	.37
<b>RSA FGB Module</b>	.00	.00	.06	.04	.09	.19
<b>RSA Service Module</b>	.04	.04	.06	.15	.03	.32
<b>Average 25 Modules</b>	.02	.03	.04	.09	.03	.21

**IMPROVED OPERATING MODE**

- 1994 orbital debris environment, 400 km altitude, 51 degrees inclination, solar flux 70 Janskys.
- Oxygen masks present -- selected hatches closed -- hole location devices present.

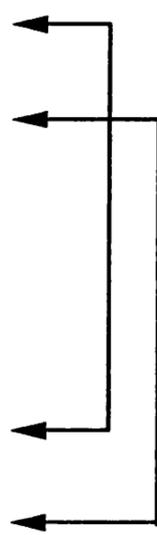
modules with standard "Whipple-type" shields instead of the enhanced shields. In this manner, geometric and crew location issues associated with comparing  $P_{LOSS}$  values for different modules were removed. The results of these computations are presented in the last two rows of Table 3.

A comparison of the value of  $P_{LOSS}$  in these two rows with appropriate values in the rows above reveals that higher  $P_{LOSS}$  values still result from using Whipple shields. Thus, the lower  $P_{LOSS}$  values obtained when enhanced shields are used are a function of the shield type, and not any other

extraneous consideration. There are, of course, more than 5 modules in the ISS. However, the trends evident in the modules considered herein are expected to exist upon application of MSCSurv to the entire ISS module system. Furthermore, it is important to note that while lowering the  $P_{LOSS/PEN}$  value can also lower the overall  $P_{LOSS}$  value, there is a larger uncertainty associated with  $P_{LOSS/PEN}$  calculations than with  $P_{PEN}$  calculations. This is due to the larger number of random variables and lower confidence in the internal damage equations used in  $P_{LOSS/PEN}$  calculations as compared to the equations used in the  $P_{PEN}$  calculations. Therefore,

**Table 3. Ten Year Loss Probability for Selected Space Station Manned Modules**

MODULE TYPE	$P_{PEN}$	$N_{PEN}$	$P_{LOSS/PEN}$	$N_{LOSS}$	$P_{LOSS}$
U.S. Lab with Enhanced Shields	.007	.007	.38	.0026	.0025
U.S. Hab with Enhanced Shields	.016	.016	.75	.012	.012
ESA Columbus Module	.014	.014	.50	.007	.007
RSA FGB Module	.095	.100	.43	0.043	.042
RSA Service Module	.223	.250	.31	0.078	.075
U.S. Lab with Whipple Shields	.023	.028	.12	.0033	.0032
U.S. Hab with Whipple Shields	.078	.081	.48	.039	.038



qualification of spacecraft shields should be based largely (if not entirely) on probability of penetration calculations. By lowering the likelihood of penetration ( $P_{PEN}$ ), enhanced shields also lower the expected cost of repair and downtime that are associated with penetrations. While not directly related to immediate crew safety, the lowered cost expectation from the reduced penetration likelihood associated with using enhanced shields on habitable spacecraft modules should not be ignored in making spacecraft shielding design decisions.

#### 4. SUMMARY

This paper provides an overview of empirical equations that characterize the hole formation and cracking phenomena associated with the penetration of some of the multi-wall systems being considered for the International Space Station (ISS). These equations were successfully incorporated into the Manned Spacecraft Crew Survivability (MSCSurv) computer program to determine whether or not station or crew losses would occur. The results obtained indicate that heavier shields are more effective in lowering the overall  $P_{LOSS}$  for the Space Station manned modules despite the generally larger holes that may accompany their penetration. By lowering the likelihood of penetration, these shields also lower the expected cost of repair and downtime that are associated with penetrations.

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#### 6. REFERENCES

1. Burch, G.T., 1967. Multi-Plate Damage Study. AFATL-TR-67-116, Eglin Air Force Base, Florida.
2. NASA Level 2 Forward Action Team, 1993. Integrated Meteoroid and Orbital Debris Assessment -- Interim Report. Grumman SSEIC Activity Report GSS-310-M093-084, Washington, D.C.
3. Schonberg, W.P., 1995. Pressure Wall Hole Size and Maximum Tip-to-Tip Crack Length Following Orbital Debris Penetration. Final Report, NASA/ASEE Summer Faculty Fellowship Program, Marshall Space Flight Center, Alabama.
4. Schonberg, W.P., and Williamsen, J.E., 1996. "Space Station Module Wall Hole Size and Crack Length Following an Orbital Debris Penetration at 6.5 km/s". Proceedings of the SPACE 96/Comet Day II Symposium. Vol. 1, pp. 1-7, Albuquerque, New Mexico.
5. Williamsen, J.E., Grosch, D.J., and Schonberg, W.P., 1996. "Empirical Prediction Models for Hole and Crack Size in Space Station Shielding from 6 to 12 km/s". Proceedings of the SPIE Symposium on Orbital Debris Impact Modeling and

- Penetration Effects. Paper No. 2813-20, Denver, Colorado.
6. Schonberg, W.P., and Williamsen, J.E., 1997. "Empirical Hole and Crack Length Models for Dual-Wall Systems Under Hypervelocity Projectile Impact". Int. J. Impact Engng., Vol. 20, in press.
  7. Schonberg, W.P., and Mohamed, E., 1997. An Analytical model for Predicting Hole Diameter and Crack Length in Perforated Spacecraft Module Multi-Wall Systems. NASA Contractor Report, in press.
  8. Williamsen, J.E., 1994. Vulnerability of Manned Spacecraft to Crew Loss from Orbital Debris Penetration. NASA-TM-108452, Marshall Space Flight Center, Alabama.
  9. Williamsen, J.E. and Guay, T.D., 1996. "International Space Station--Quantifying and Reducing Risk Following Orbital Debris Penetration". AIAA Paper No. 96-4240, AIAA Space Programs and Technologies Conference, Huntsville, Alabama.
  10. Hyde, J.L., 1996. International Space Station Integrated Meteoroid and Debris Threat Assessment, Issue D. Lockheed Martin Space Mission Systems and Services, Report LMES 32316, Johnson Space Center, Houston, Texas.