SOME FURTHER COMMENTS ON THE NEW W-S HABITABLE MODULE WALL DAMAGE PREDICTION EQUATIONS

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ABSTRACT

In the early 1990 NASA engineers developed a tool that would allow them to determine what percentage of ISS penetrations resulting from on-orbit impacts by micrometeoroid and orbital debris particles might be survivable. These efforts resulted in the development of the *MSCSurv* computer code to determine the overall probability of no catastrophic failure of the ISS or its crew due to impacts by these particles over the lifetime of the ISS. As part of this calculation, *MSCSurv* first determines the size of the holes and cracks caused by any penetrations for the different ISS wall configurations. In light of the significant role played by module wall hole size and crack length calculations in survivability assessments, new hole-size and crack-length models were recently developed that were more realistic and improved fits to hole size and crack data. However, the hole and crack sizes predicted by these new models may be unrealistically large when both orbital debris and meteoroid models are considered. In this paper we review the new hole and crack size models and present additional supporting results to reinforce their versatility and utility. We also examine the particle velocity distribution of NASA's current meteoroid environment model as compared to that of its orbital debris model. Some possible approaches at capping the hole and crack sizes predicted by our models are then discussed.

1 INTRODUCTION

The approach of spacecraft designers and operators in computing and reducing the consequences of micrometeoroid and orbital debris (MMOD) penetrations and their link to catastrophic failure has evolved over time. For earlier, relatively small spacecraft, the probability of catastrophic failure was considered as being roughly equal to the probability of penetration. However, the advent of large space structures such as the ISS allowed scenarios where many MMOD penetrations could be survivable.

As the threat of the orbital debris population increased in the 1980s and early 1990s, NASA engineers began to develop a tool that would allow them to determine what percentage of ISS penetrations might be survivable for the crew and the ISS, and how to improve that survivability percentage with improved operations and tools. These efforts culminated in the development of the *MSCSurv* computer code to determine the overall probability of no catastrophic failure (PNCF) of the ISS or its crew due to impacts by MMOD particles over the lifetime of the ISS.

The quantity PNCF is directly related to the station's PNP, or probability of no penetration, as calculated by *Bumper*, the code used by NASA, its contractors, and the international partners (Japan Aerospace Exploration Agency, Russian Federal Space Agency) to perform MMOD risk assessments. As part of its process to calculate PNCF, *MSCSurv* determines the size of the holes and cracks caused by any penetrations for the different ISS wall configurations.

In light of the significant role played by module-wall hole-size and crack-length calculations in survivability assessments, new hole-size and crack-length models that were more physically real in terms of the phenomenology involved in the formation of holes and cracks in habitable modules were recently developed [1]. In addition to being more realistic, these new empirical models were improved fits to hole size and crack data when compared to equations currently being used to predict those quantities [1].

A recent enhancement of *MSCSurv* has been the implementation of the NASA meteoroid environment model (MEM) to supplement the orbital debris model already encoded in *MSCSurv*. However, initial *MSCSurv* runs have shown that at very high velocities, the hole and crack sizes predicted by these new models may be unrealistically large when both the orbital debris and meteoroid models are taken into consideration.

In this paper we review the new hole and crack size models and present additional supporting results to reinforce its versatility and utility. We also review some of the results obtained when *MSCSurv* is run with the MEM option turned on, and discuss some possible approaches to capping the hole and crack sizes predicted by our models. These caps are based, at least in part, on the standoff distance between the bumper and rear wall and provide a rudimentary check on the extent to which inner wall damage is calculated in the event of an on-orbit meteoroid or orbital debris penetration.

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2 OVERVIEW OF NEW HOLE-SIZE/CRACK-SIZE MODELS

A generic hole diameter- or crack-length-vs-projectile diameter curve is shown in Figure 1 for a given impact velocity, trajectory obliquity, and shield system geometry that can be expected in the formation of holes and cracks in habitable modules such as those found on the International Space Station. The general type of phenomenology shown in Figure 1 is broken up into 3 regions; each region corresponds to a certain type of projectile response and pressure wall hole or crack growth pattern.

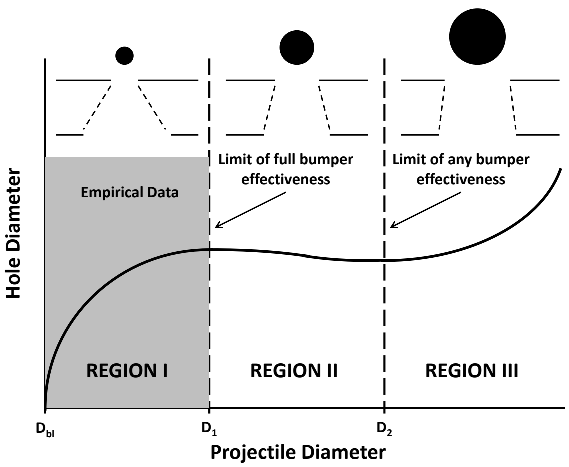


Figure 1. Generic Pressure Wall Hole Diameter as a Function of Projectile Diameter [1]

Naturally, the nature and extent of the various regions in Figure 1 (i.e. large, small, or non-existent) depend on the geometric and material properties of the particular dual- or multi-wall system under consideration. The first region is shaded to indicate where hole diameter and crack length data are currently available. The shape of the curve shown in each of these three regions is based on the following considerations.

Initially, the hole diameter (and the cracking) phenomena are governed by the nature of the debris cloud loading on the module pressure wall. This case corresponds to Region I of the curve shown in Figure 1. In Region I, the projectile is completely shattered upon impact and the degree of fragmentation increases with increasing projectile diameter. As a result, spread of the debris cloud created by the initial impact also increases as does the effective diameter of the hole in the pressure wall.

However, at a certain projectile diameter (labeled D_1 in Figure 1), the projectile is too large for it to be completely shattered by the outer bumper or shielding system. Hence, for projectile diameters beyond this point (i.e. in Region II), the amount of projectile fragmentation decreases with increasing projectile diameter as does the spread of the debris cloud and the size of the hole in the pressure wall.

Finally, in Region III (i.e. for $D_p >> D_2$), the projectile diameter is very large when compared to the ballistic limit diameter value, perhaps even as large as the spacing between the bumper and the pressure wall. In such cases, the multi-wall system can be expected to act as a single thin plate. Hence, the form of that part of the curve should be similar to that generated by single plate hole diameter equations. In this case, the pressure wall hole diameter again increases with increasing projectile diameter.

In light of these phenomenological observations, the new Williamsen-Schonberg Hole and Crack Size Model (or W-S Model, for short) consists of three parts: (1) a data-based equation for Region I of Figure 1, (2) an interpolation equation for Region II that decreases from the value reached at the end of Region I, and (3) a single-wall equation for Region III that begins at that projectile diameter where the bumper ceases to be effective in fragmenting an impacting projectile. Figure 2 below presents a sketch of this three-part equation (thick solid line) that is intended to model the response as outlined previously (still shown as the thinner line with dashes and dots).

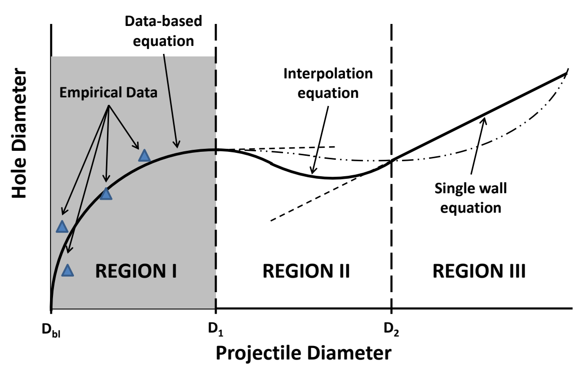


Figure 2. Representation of a Three-Part Hole Diameter or Crack Length Equation

Figure 2 also includes some generic empirical data to support the premise that the first part of each three-part equation is empirically-based. The thinner dashed lines are shown only to indicate extensions or precursors of the data-based and single-wall equations, respectively, and are not actually used by the model in the regions where they are drawn.

Based on these considerations, the following equation form was used to model hole diameter (D_h) and crack length (L_{tt}) in Region I:

$$D_h \text{ or } L_{tt} = A(V_p/6.5)\cos^B\theta_p\{1-\exp[-C(D_p/D_{BL}-1)]\} \quad (1)$$

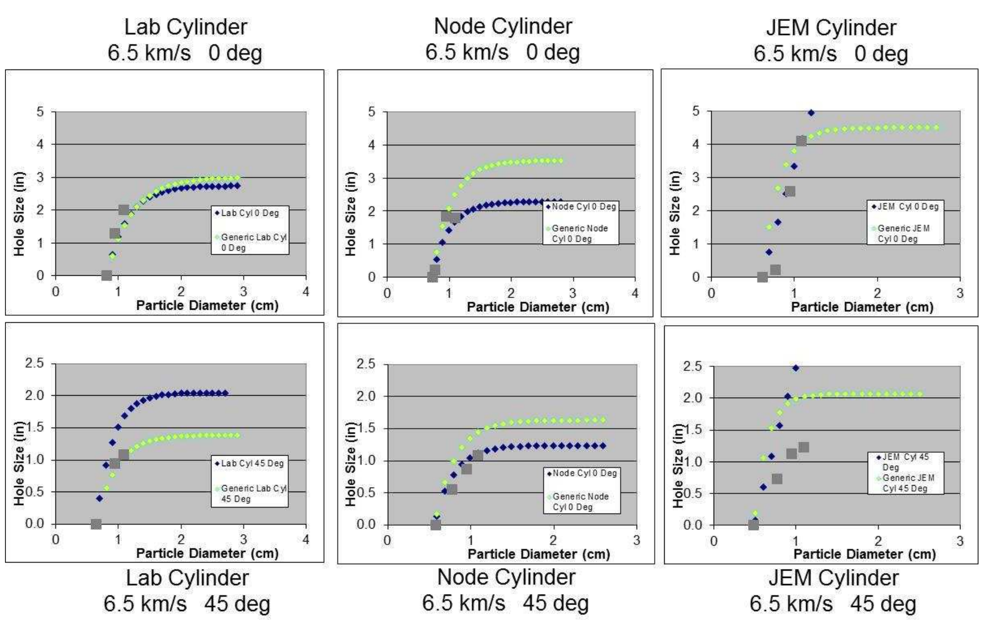
where expressions for the constants A, B, and C for the hole size and crack length versions of equation (1) are given in [1].

In Region II, the hole diameter and crack length equations for Region I are extended to larger projectile diameters to account for the decreasing effectiveness of bumpers in breaking up the debris cloud. The hole size values between $D_p=D_1$ (i.e. the Region I / Region II interface) and $D_p=D_2$ (i.e. the Region II / Region III interface) are obtained by interpolating between the values predicted by empirical equation developed for Region I (and extended into Region II) and the values obtained using a single wall hole size prediction equation (as described in the next paragraph). The values of D_1 and D_2 are likely to be dependent on the material properties and geometric parameters of the shield design, as well as on impact velocity and trajectory obliquity.

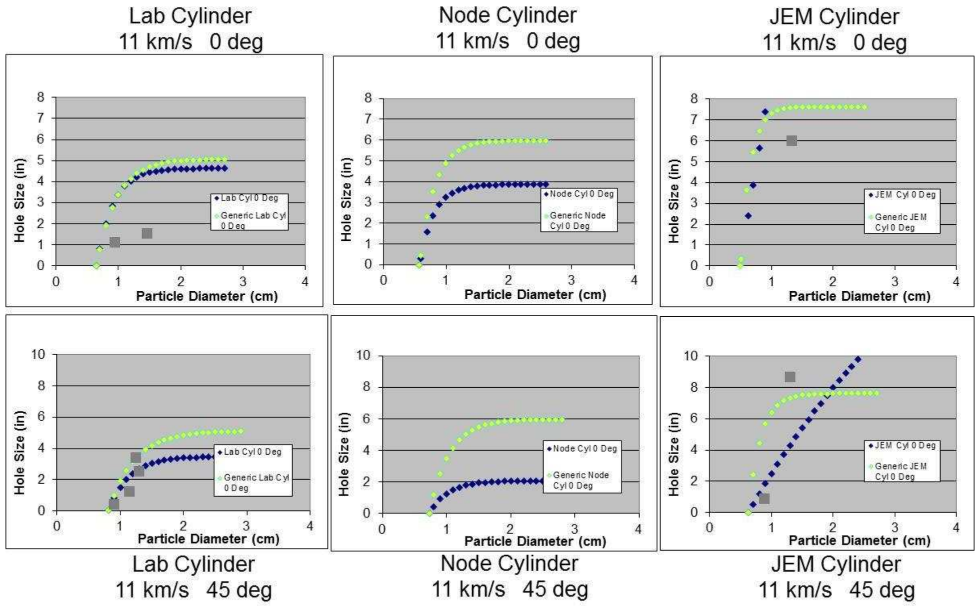
Finally, in Region III, the hole diameter and crack length equations for Region II are extended to larger projectile diameters. The hole prediction equation is extended using the method proposed in the Russian Space Agency's probabilistic risk assessment [2]. In this approach, it is presumed that the particle size is so large that the bumper thickness is inadequate to fragment the particle upon impact. In this case, bumper perforation occurs without significant particle fragmentation or erosion, and the particle impacts the rear wall nearly intact. Under such conditions cracks would not be expected to emanate from the hole in the rear wall caused by the large impacting particle; in effect, the "maximum tip-to-tip crack length" in such a case could be taken as simply the diameter of the hole created in the rear wall. Under these assumptions and conditions, the size of the hole in the rear wall of the dual-wall system in this impact regime can be calculated using any number of equations that predict the size of a hole in a single thin plate following a perforating hypervelocity impact. The diameter of the particle impacting the rear wall would be taken to be the same as the diameter of the original projectile and its impact velocity would be slightly reduced from the original impact velocity because of momentum conservation (see again [1] for details).

3 COMPARISON OF MODEL PREDICTIONS AND EXPERIMENTAL RESULTS

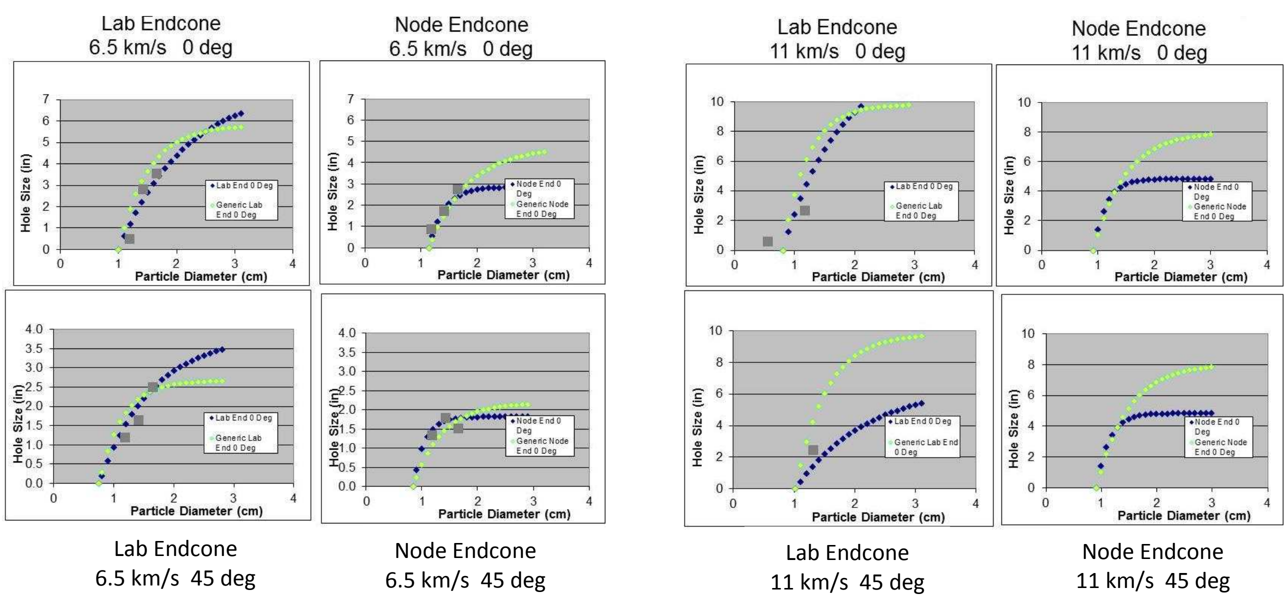
Figures 3-12 show comparisons of hole size predictions for several different ISS wall systems as given by the previous hole diameter and crack length models and the new W-S Model, for impact velocities of either 6.5 or 11 km/s and at trajectory obliquities of either 0-deg or 45-deg. In these figures, 1 in ~ 2.5 cm. Also presented in these figures, where available, are data obtained through light gas gun testing of the various wall systems. The full suite of crack length prediction comparative plots can be found in Reference [3].



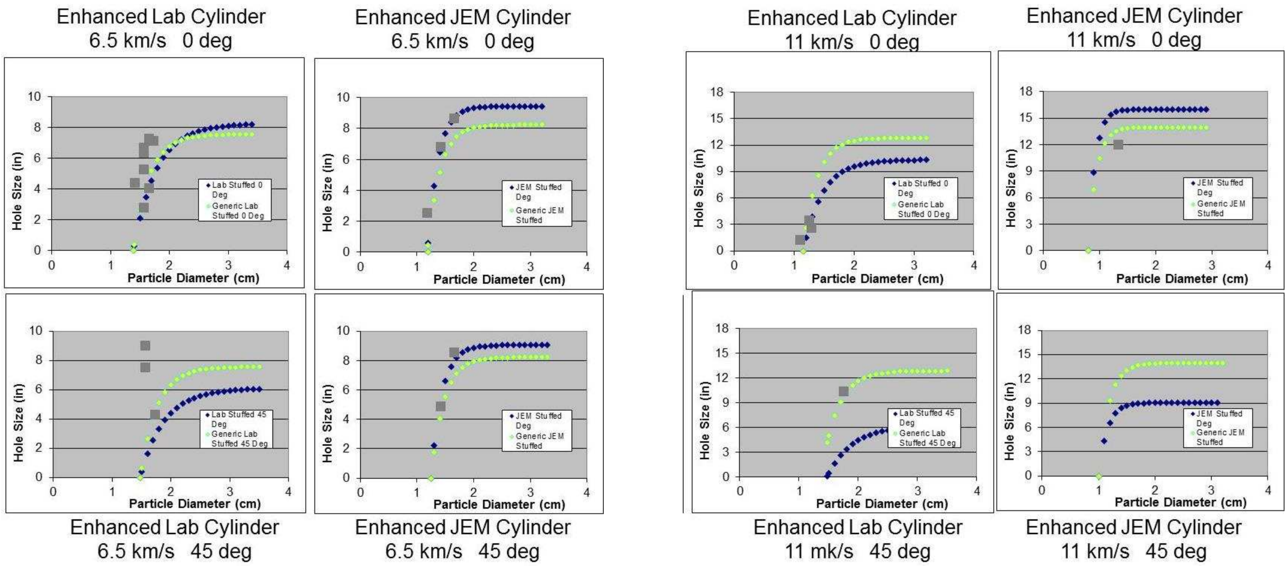
Figures 3a-f. Hole Size Predictions and Comparisons for ISS Lab Cylinder, Node Cylinder, and JEM Cylinder Wall Systems, 6.5 Impact Velocity, 0^o and 45^o Impact Obliquities



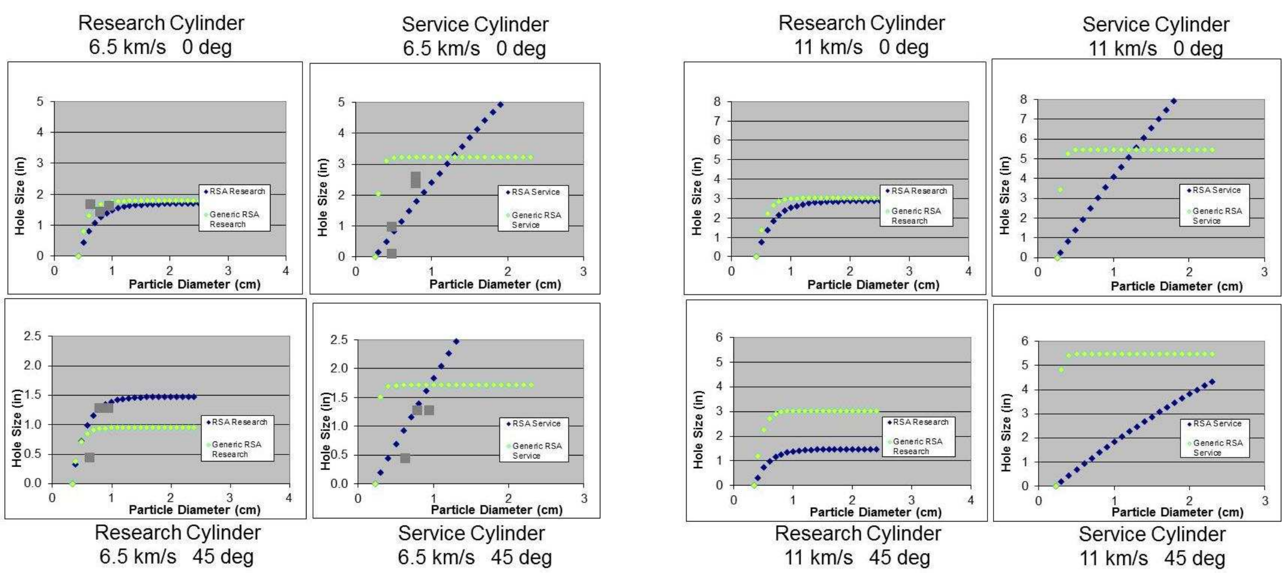
Figures 4a-f. Hole Size Predictions and Comparisons for ISS Lab Cylinder, Node Cylinder, and JEM Cylinder Wall Systems, 11 km/s Impact Velocity, 0^o and 45^o Impact Obliquities



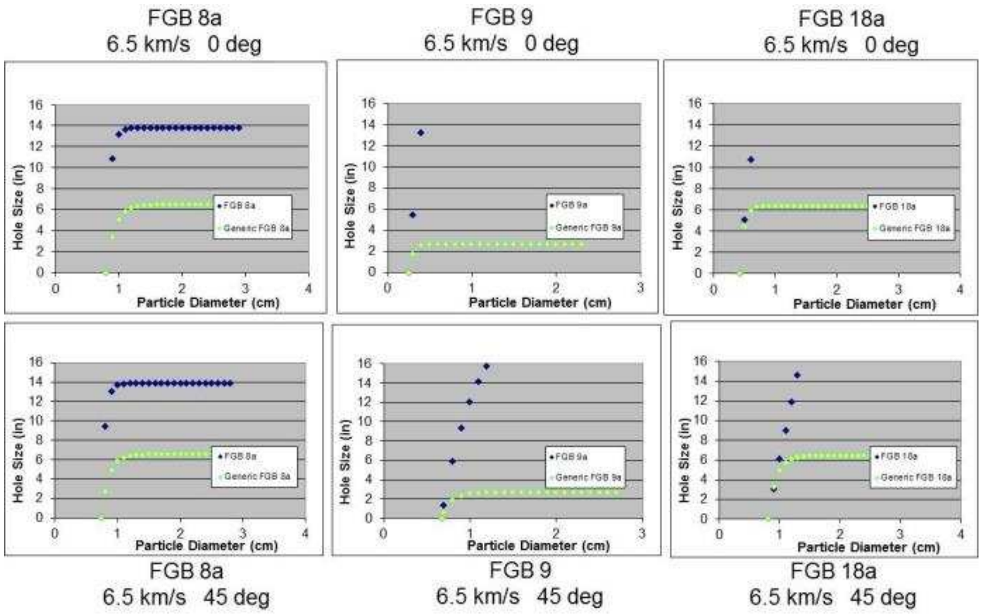
Figures 5a-d, 6a-d. Hole Size Predictions and Comparisons for ISS Lab Endcone and Node Endcone Wall Systems, 6.5 and 11 km/s Impact Velocities, 0^o and 45^o Impact Obliquities



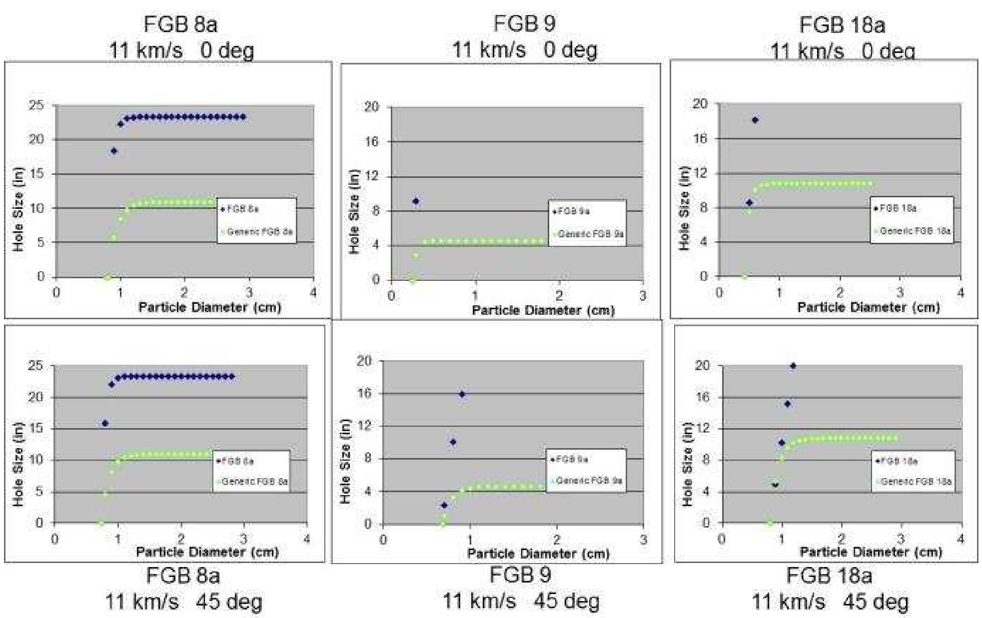
Figures 7a-d, 8a-d. Hole Size Predictions and Comparisons for ISS Enhanced Lab Cylinder and Enhanced JEM Cylinder Wall Systems, 6.5 and 11 km/s Impact Velocities, 0^o and 45^o Impact Obliquities



Figures 9a-d, 10a-d. Hole Size Predictions and Comparisons for ISS RSA Research and RSA Service Module Wall Systems, 6.5 and 11 km/s Impact Velocities, 0^o and 45^o Impact Obliquities



Figures 11a-f. Hole Size Predictions and Comparisons for ISS RSA FGB Module Wall System, 6.5 Impact Velocities, 0^o and 45^o Impact Obliquities



Figures 12a-f. Hole Size Predictions and Comparisons for ISS RSA FGB Module Wall System, 11 km/s Impact Velocities, 0^o and 45^o Impact Obliquities

In Figures 3-9 (especially Figures 3a-f, 5a-d, 7a-d, and 9a-d) we see that where the models fit the data well, so did the new W-S Model. However, the significance of the W-S model is seen in Figures 3c,f; 4c,f; 9b,d; 10b,d; 11bc,e,f; and 12b,c,e,f. In these figures, we see that the previous model either did not fit the data well, or in those cases where the fit was reasonable, its plot was irregular in that it did not show the expected behavior as projectile diameter increased beyond the ballistic limit. In these cases, the new W-S Model not only fit the data just as well or better, but also replicated the anticipated phenomenological response. Taking these results and others like it under consideration, we believe that the new W-S Model for hole diameter and crack length is a marked improvement over the previous hole and crack size models used by *MSCSurv* (i.e. those in versions prior to Version 9).

4 MEM HOLE-SIZE PREDICTIONS

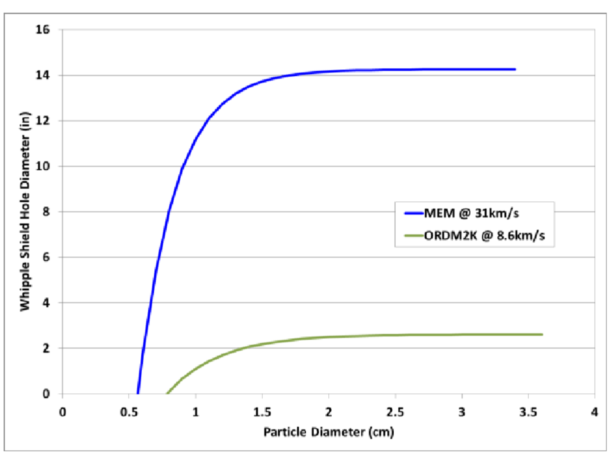
MSCSurv has recently been modified to include a meteoroid environment model (MEM) for the first time. However, the hole and crack models presented in this report were developed to address orbital debris impact scenarios. It is important to note, then, that the velocity distribution is much higher in the MEM model than in the orbital debris model currently used by NASA (ORDEM2000). Table 1 shows the mean and median particle velocities for both environments for a "typical" ISS configuration. The penetrating flux is of more interest than the impacting flux in this case as we are concerned with holes and cracks that would result from a penetrating impact.

Table 1. Media/Mean Environment Model Velocities

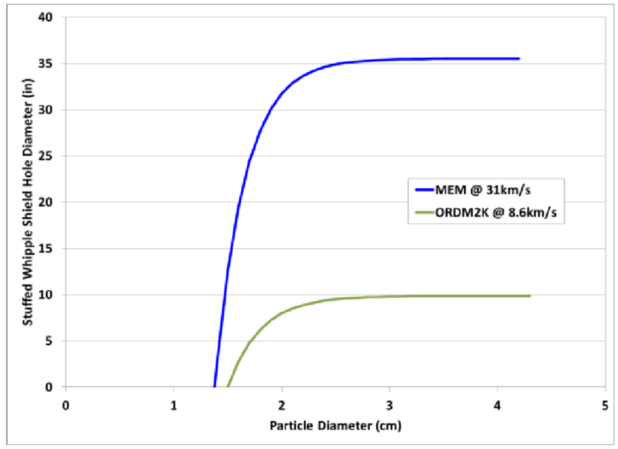
	Penetrating Flux*		Impacting Flux*	
	Median Velocity (km/s)	Mean Velocity (km/s)	Median Velocity (km/s)	Mean Velocity (km/s)
ORDEM2000	8.6	8.3	8.8	8.3
MEM	30.9	32.3	21.5	23.1

*Above minimum thresholds.

Since the hole and crack models predict that hole/crack sizes will increase linearly with velocity and that the obliquity effect (which reduces hole/crack sizes) will be phased out as the velocity increases (being completely eliminated at 11km/s), the holes and cracks predicted become very large at MEM velocities. Figure 13 shows a hole-size curve at the median penetrating velocities for the two environments for a typical Whipple shield and a typical stuffed Whipple shield. The hole sizes are so large on the MEM curves that questions naturally arise regarding the validity of those values. Are such large holes (or cracks) realistic? Should some sort of cap be applied in some instances?



(a) Whipple Shield



(b) Stuffed Whipple Shield

Figure 13. Typical Whipple and Stuffed Whipple Hole-Size Curves at Median Penetrating Velocities and 45-deg Impact Obliquities

Two possibilities were examined in an initial, cursory look at applying a cap to predicted hole sizes and crack lengths. The first was simply applying a maximum cone or spread angle value to the debris fragment cloud created by the impact and impinging on the innermost module wall. In this case, the hole diameter would be capped by the diameter of the debris cloud as it struck the inner wall assuming equal velocities in the "spread" direction as in the "forward" direction.

However, problems arose when trying to apply this method to oblique impacts. At a 45-degree impact obliquity and greater, the expansion of the fragment cloud would theoretically become infinite, and so be of no help. Furthermore, it was not clear how one would deal with the two fragment clouds that are typically created in an oblique impact. Would both inner wall impact areas need to be considered?

This capping method was examined using available empirical data. In at least one case (namely, for the impact of the enhanced lab cylinder at a 0-degree obliquity at an impact velocity of approx. 11 km/s), the hole size predicted by the model developed herein far exceeded the cone-angle predicted size. We believe that there are likely to be other similar cases as well; hence, this method is not recommended for use.

The second possible approach to capping predicted hole and crack sizes received more scrutiny. In this case, the equation developed in Reference [4] for predicting damage area for Whipple shields (i.e. Eq. 3.7) was applied as a cap, and then hole and crack size data was compared to see if any of it exceeded the predicted cap. It is important to note that this equation was developed empirically from testing performed using aluminum projectiles fired at much lower velocities than seen with the MEM environment. One and two standard deviations were provided for use with the equation, where the one-standard deviation value was used to cap hole sizes while the two-standard deviation value was used for capping crack lengths. The findings were:

- the hole size cap always exceeded actual test results for Whipple (dual-wall) configurations;
- the hole size cap did not always exceed actual test results for stuffed Whipple (multi-wall configurations);
- applying the two-sigma crack cap to hole-size data did not lift the cap high enough to capture all the multi-wall configuration data; and,
- the crack cap did not always exceed actual test results for dual wall or multi-wall configurations.

Based on these findings, this method is also not recommended for general use, with the possible exception of hole size capping, but only for Whipple shields.

5 CONCLUSIONS

NASA currently uses the *MSCSurv* computer code in conjunction with *Bumper* to calculate the probability of no catastrophic failure, or PNCF, of the International Space Station due to MMOD particle impact. As part of this calculation, *MSCSurv* must determine hole and crack sizes following on-orbit penetrations for each of the many different shield types on board the ISS. In this paper we have reviewed a new model for calculating these quantities. This new model has been incorporated in *MSCSurv (Version 9)*. By comparing the predictions of the new model against the predictions of the previous hole and crack size models and against empirical data, we found that

(1) the predictions of the new model fit the empirical data just as well as, if not better than, the previous model, and that

(2) the new model displayed the appropriate phenomenological hole size and crack length response characteristics as the diameter of the impacting projectile increased beyond the ballistic limit of a particular wall system.

However, with the addition of a meteoroid environment model in *MSCSurv (Version 10)* and the resulting higher velocity distributions, the holes and crack sizes predicted by the W-S model are much larger than those that would occur at the lower velocities of an orbital debris model. There is now a critical need to re-examine and, if needed, improve these current hole/crack models so that they are also applicable in the higher velocity regions.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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