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William P. Schonberg
Missouri University of Science and Technology, wschon@mst.edu

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The Development of Ballistic Limit Equations for Dual-Wall Spacecraft Shielding: A Concise History and Suggestions for Future Development

William P. Schonberg[1]
Missouri University of Science and Technology, Rolla, Missouri 65409

All earth-orbiting spacecraft are susceptible to impacts by orbital debris particles, which can occur at extremely high speeds and can damage flight- and mission-critical systems. The traditional damage mitigating shield design for this threat consists of a "bumper" that is placed at a relatively small distance away from the main "inner wall" of the spacecraft. The performance of a hypervelocity impact shield is typically characterized by its ballistic limit equation, which is typically drawn as a line of demarcation between regions of rear-wall perforation and no perforation; when graphically represented, it is often referred to as a ballistic limit curve. Once developed, these equations and curves can be used to optimize the design of spacecraft wall parameters so that the resulting shields can withstand a wide variety of high-speed impacts by orbital debris. This paper presents some comments and observations on the development of the three-part ballistic limit equation used by NASA to predict the response of dual-wall structural systems under hypervelocity projectile impact. The paper concludes with some insights into the limitations of the current version of BUMPER II, NASA's risk analysis code, and with several suggestions regarding how BUMPER II could be improved and modified so that, for example, it could be used as an integral part of a probabilistic risk assessment exercise.

I. Introduction

All earth-orbiting spacecraft are susceptible to impacts by orbital debris particles, which can occur at extremely high speeds and can damage flight- and mission-critical systems. The traditional damage mitigating shield design of a "bumper" placed at a relatively small distance away from the main "inner wall" of a spacecraft has been studied extensively in the last four decades as a means of reducing the perforation threat of hypervelocity projectiles. The performance of a hypervelocity impact shield is characterized by its ballistic limit equation (BLE), which typically defines the threshold particle size that would cause perforation of the innermost wall of a multi-wall system. BLEs are typically drawn as lines of demarcation between regions of rear-wall perforation and no perforation in two-dimensional spherical projectile diameter-impact velocity space; when graphically represented, they are often referred to as ballistic limit curves (BLCs). Figure 1 below shows generic dual-wall and single-wall BLCs, and highlights some of the important phenomenology that occurs in various impact velocity regimes[1].

NASA and ESA continue to develop BLCs for their structural configurations of interest. The majority of previous NASA and ESA efforts have been directed towards developing BLCs for dual-wall systems such as those that can be found on the International Space Station. Data obtained using spherical aluminum projectiles fired in light gas guns at impact velocities between 3 and 7 km/s is typically was fitted with scaled single-wall equations below 3 km/s, and with theoretical momentum/energy based penetration relationships above 7 km/s to obtain BLCs that cover the full range of impact velocity.

This paper presents some comments and observations on the development of the three-part BLE currently used by NASA to predict the response of dual-wall structural systems under hypervelocity projectile impact. In particular, this paper traces the history of the development of this three-part equation, beginning in the 1960s and 1970s when early work focused on obtaining so-called "sizing equations", moving into the 1980s when work centered on developing a risk analysis tool for the Space Station Freedom project, and ending in the late 1990s/early2000s as the three-part BLE was adapted to serve the needs of other projects and programs. The paper

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[1] Professor and Chair, Civil, Architectural and Environmental Engineering Department, 1401 N. Pine Street, Associate Fellow.

concludes with some insights into the limitations of the current version of BUMPER II, NASA's risk analysis code, and with several suggestions regarding how BUMPER II could be improved and modified so that, for example, it could be used as an integral part of a probabilistic risk assessment exercise.

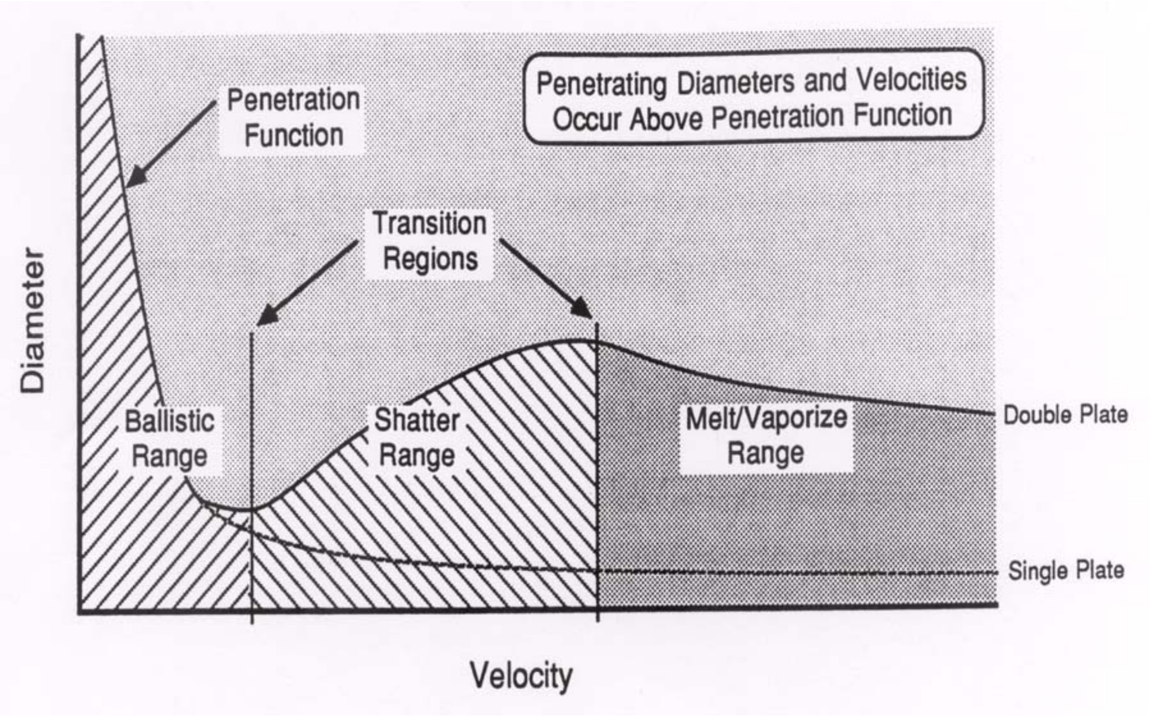


Figure 1. Generic Single-wall and Double-Wall Ballistic Limit Curves[0]

In the mid-1960s, Boeing and the General Motors Defense Research Laboratories both performed studies that led to two generic types of ballistic limit equations for a given multi-wall structural configuration as functions of impact velocity, projectile diameter, etc: (a) the number of sheets penetrated; and, (b) the total thickness required to stop rear or main wall penetration. The Type (b) equations usually had a hump around V=3 km/s for aluminum projectiles impacting aluminum dual-sheet targets[2-7]. This early work gave rise to initial "sizing equations" for rear wall thickness to prevent perforation of a given multi-wall system[8].

At the onset of the Apollo Project in 1964, one of the many engineering tasks undertaken by then North American Rockwell (NAR) was the calculation of the meteoroid hazard to the Command Service Module (CSM) Vehicle. In the 1964 to 1969 time period the Discrete Particle Analysis (DPA) method was developed for NASA by a NAR team[9].

The early 1970s saw some phenomenological studies sponsored by the United States Air Force that continued to examine the effects of material composition on multi-wall system response in terms of material phase changes[10,11]. The late 1970s and early 1980s saw an increase in the interest in the response of multi-wall targets to hypervelocity impacts and the development of ballistic limit wall thickness equations for such systems because of several then upcoming Comet Halley probe missions[12,13]. Building on the initial work on sizing equations in the 1960s and the work for the Apollo Project by Richardson, et al, in the late 1960s, efforts at NASA/JSC in the 1970s and early 1980s focused also on developing sizing equations for upcoming missions and spacecraft, including the Space Shuttle and what was to eventually become the International Space Station.

III. The 1980s and 1990s

In the late 1970s and during the 1980s, Rockwell engineers completed several Space Shuttle studies to determine the hazard posed by impact of hypervelocity particles, including both meteoroids and space debris. The DPA program was applied again to determine the failure particle mass for numerous Space Shuttle components[14].

At around the same time, in the mid-1980s, Boeing (and Martin Marietta), under contract to the NASA/Marshall Space Flight Center, participated in the Space Station Freedom Phase B micrometeoroid and orbital debris testing and analysis program. Boeing was ultimately selected as the prime contractor for the Space Station following this effort, and published a multi-volume report documenting its Phase B activities[15,16]. This report presents the first three-part Whipple Shield BLE with a bucket at V=3 km/s (actually, it presents three different versions of the three-part Whipple Shield BLE).

The rationale for the various forms of each of the three parts in each BLE is also presented and discussed in the Phase B final report. In the beginning of the effort, Boeing used a version of the THOR 47[17] equations for the low speed part of the curve. The intermediate speed equations came from their work in the mid-1960s, while the high speed was based on Wilkinson's penetration equation[18]. This set of equations was called "the original equation." At the end of the effort, Boeing replaced the original equation with a set of equations called "the regression fit." In this new set, the low speed portion used an updated version of the PEN4 equation[14], the intermediate speeds used a regression fit to the Phase B impact test data, and the high speed part remained Wilkinson's equation[19]. This Boeing effort formed the foundation of BUMPER I, a risk assessment tool developed by Boeing for the Space Station Freedom project.

The late 1980s saw additional work at the NASA/Johnson Space Center in the area of bumper and rear wall sizing equation development as new materials and new configurations were being considered for the Space Station Freedom wall configurations[20-22]. NASA/MSFC also began to study the effects of debris particle shape on the three part ballistic limit equation using hydrocodes[23].

In the early 1990s, BUMPER I came under configuration control at the NASA/JSC and became known as BUMPER II. Whipple Shield modification testing continued at NASA/JSC, Boeing, and NASA/MSFC to improve the damage resistance of the original Whipple Shield configuration[24-27]. The initial emphasis continued to be on sizing equations for both bumper thickness and pressure wall thickness. The three-part ballistic limit equations became the coin of the realm at NASA in the mid-1990s as work on sizing equations appeared to be phased out[28-31].

Also in the mid-1990s, Housen and Schmidt[32] proved that the three-part projectile diameter vs. impact velocity (i.e. d_p vs. V) Whipple Shield BLE developed by Boeing in the mid-1980s and the wall thickness required to stop penetration vs. impact velocity (t_w vs. V) curves drawn in the mid-1960s are inverses of each other. That is, a plot of t_w vs. V at fixed d_p is approximately $1/d_p$ vs. V at fixed t_w. Figure 2 below shows a generic sizing plot from 1967[5]. Superposed on it, as a dashed line, is its inverse. The shape of this dashed line is highly reminiscent of the three-part BLE developed by Boeing and NASA in the mid-1980s.

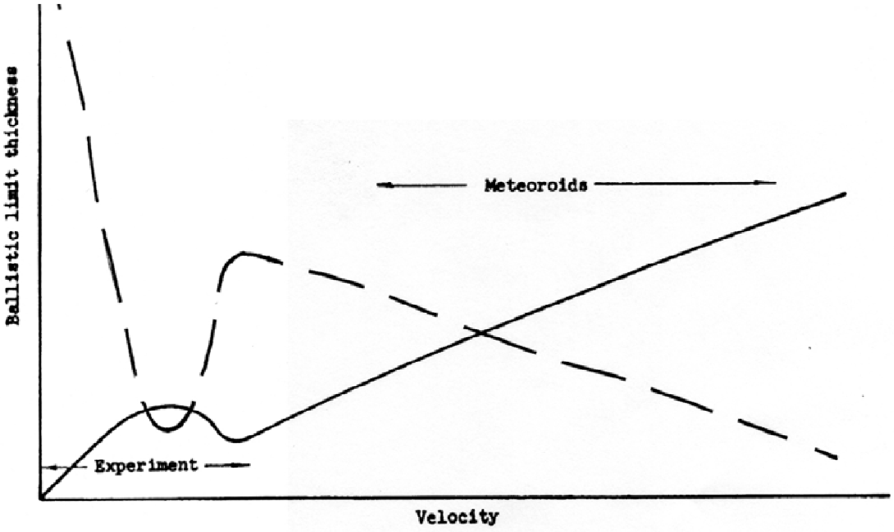


Figure 1. Generic Thickness Sizing Equation[5] and its Inverse

Work on refining the three-part Whipple Shield BLE has continued. Recent improvements include, for example, a term that incorporates the effects of optional multi-layer insulation placed between the bumper and the pressure wall. In the most current version[33,34], its high velocity region for normal impacts begins at 7 km/s, and can be verified by light gas gun data up to approximately 8 km/s. Its transitional velocity region (3 to 7 km/s for normal impacts) takes the form of a linear interpolation between the low and high velocity regions. As such, the accuracy of predictions in this hypervelocity region depends to a degree on the "anchor point" predictions from the low velocity regime (up to the 3 km/s).

IV. Bumper II Limitations And Uncertainty Considerations

NASA uses the BUMPER II computer program to provide point estimate predictions of MMOD risk for the Space Shuttle and the ISS. While BUMPER II is a powerful tool, it does have limitations. BUMPER II results provide a point estimate of MMOD risk with no assessment of its associated uncertainty. Reporting risk predictions with uncertainty bounds enables those performing the program's probabilistic risk assessments (PRAs) to fold the results into those assessments and put them in perspective with the other risk contributors. Risk predictions can also be used to help prioritize research programs to reduce the highest contributors to risk and uncertainty first. However, the uncertainties associated with underlying BUMPER II input models are still largely unknown.

BUMPER II uses a variety of equations to predict damage to shuttle or ISS components in terms of an impacting particle's density, velocity, and angle of impact. Some equations are developed by simply drawing a curve through fail/no-fail test data (the BLEs), while others are developed by performing statistical curve-fits to empirical data (the damage predictor, or DP, equations). Considering the different approaches used to derive them, the DP equations and BLEs in BUMPER II belong to two different classes of empirical equations.

The DP equations are simply, curve-fits to empirical data, that is, they are the results of statistical regression analyses of available test data. As such, uncertainty bounds and/or confidence intervals can be obtained at the time that the regression analyses are being performed to form the DP equations. However, unlike the DP equations, the BLEs are not statistically based. They are *not* curve-fits, but are rather simply lines of demarcation between regions of penetration and non-penetration. As a result, and also *un*like the DP equations, it is simply *not* possible to obtain uncertainty bounds and/or confidence intervals as part of the current procedure that is used to derive the BLEs. Alternative, innovative approaches must be developed to derive the BLEs using a statistics-based approach so that uncertainty information is forthcoming out of the analyses along with the equations themselves.

V. A Statistics-Based Approach To BLE Uncertainty Modeling

In order to allow one to make a statement that, for example, a given BLE is accurate to within +/-X% with a confidence of Y%, the BLEs must be derived using a consistent, statistics-based approach. Such an approach was proposed and used by Williamsen and Jolly[35] to develop preliminary BLEs for the Space Station Freedom manned module multi-wall orbital debris shields. In Ref. 35, data were regressed to develop an empirical equation that defined a **penetration parameter** P_m in terms of impact parameters for a given set of target material properties and geometry, that is,

$$P_m = f(d_p, V_p, \theta_p) = \alpha d_p^{\beta} V_p^{\gamma} \cos^{\delta} \theta_p + \varepsilon \tag{1}$$

In Eq. (1), α through ε are coefficients obtained through a standard nonlinear regression of P_m data. In its simplest form P_m may be visualized as a measure of the depth of penetration through an entire multi-wall shield system. It includes crater depth data prior to perforation of a critical target region as well as witness plate data after the perforation of a critical target region.

In the context of a multi-wall shield, if the impact event results in a perforation of the bumper, but no penetration of the pressure wall, P_m=0. If the pressure wall is penetrated, then $P_m = t_w$, the thickness of the pressure wall. If the first witness plate is also perforated, then $P_m = t_w + t_{wp1}$, where t_{wp1} is the thickness of the first witness place; if the second is perforated, $P_m = t_w + t_{wp1} + t_{wp2}$; etc. If the pressure wall is cratered, but not perforated, then $0<P_m=d_c<t_w$, where d_c is the depth of the deepest pressure wall crater. Setting the penetration parameter equal to a predetermined value (i.e. t_w) allowed Williamsen and Jolly to solve for critical diameter in terms of impact velocity that would result in just barely perforating the pressure wall. That is, using a statistics-based approach, the authors were able to arrive at BLEs for a variety of multi-wall systems.

If this approach were to be adapted to rederive the BLEs currently within BUMPER II, two important results would follow. First, we would have statistics-based (and not simply hand-drawn) BLEs for a variety of shuttle components and ISS wall configurations. Second, we would be able to obtain, for each BLE so derived, the statistics-based uncertainty information that would allow us to make the statement that a given BLE is accurate to within +/-X% with a confidence of Y%. Since this is the type of information that is needed to develop overall uncertainty bounds for MMOD predictions, it would appear that this approach is the appropriate one to take[36].

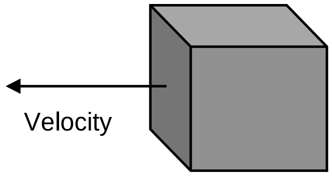
VI. Orbital Debris Shape And Orientation Considerations

Until now, NASA's orbital debris risk assessments for the Space Shuttle, International Space Station and other satellites have assumed that orbital debris particles are spherical in shape. However, spheres are not expected to be a common shape for orbital debris; rather, orbital debris fragments might be better represented by other regular or irregular solids. A major recommendation from a recent review by the NASA Engineering Safety Center[37] called for NASA to establish shape and material parameters in future orbital debris environments, and to characterize the effect of these shapes on orbital debris damage predictions. Potential candidate orbital debris shapes considered by NASA's Standard Breakup Model (SBM)[38] include cubes (a common assumption used in many aircraft vulnerability models to simulate fragments), and flakes. The SBM "flake" shape was derived from examining fragment shapes from ground-based hypervelocity impact tests against actual satellite structures, and is considered representative of actual orbital debris in the 1mm to 10mm size range. Its aspect ratio changes as it increases in size (becoming more potato chip-shaped) in order to better reflect the actual aspect ratio of orbital debris as measured in terms of radar cross section (RCS).

The **characteristic length** is a measure of orbital debris size described in the SBM that is derived from the "average" value of three major dimensions of a given particle, and can be directly related to its average radar cross section (RCS). By deriving particle ballistic limits on the basis of their characteristic lengths, the risk of orbital debris penetration by different particle shapes can be directly derived using NASA's orbital debris environment models. Williamsen, et al[39] and Schonberg, et al[40] used hydrocode assessments to derive ballistic limit curves for a variety of shapes and orientations. Most recently, Williamsen, et al used the FATEPEN model and prior hydrocode data to extend this technique, examining the effects of shape and orientation considering the SBM "flake" shape on ballistic limit curves as well as on satellite penetration risk[41]. Tables 1 and 2 summarize the predicted orbital debris penetration risk for simple cube shaped spacecraft when the BLEs derived by Williamsen, et al for "flake" and cube shapes are placed into BUMPER II, and compare them to predictions obtained a spherical-projectile-based BLE. It can be seen in these tables that SBM "flakes" produced only about half the penetration risk of a sphere of the same characteristic length for normal impact obliquity and for various impact orientations. **These results indicate the presence of a strong, inherent bias towards overdesign of orbital debris shields using current shielding design procedures because these procedures typically approximate the actual shape of orbital debris particles as merely spherical, and do not consider realistic impactor shapes in their assessments.**

Table 1. Results of Spacecraft Orbital Debris Risk Analyses for a Dual-Wall Shield Using Simplified Cube and Flake Ballistic Limit Curves, and Current Sphere Ballistic Limit Curves in BUMPER Code[41]

Shape	Case	Expected Penetrations	Orientation Likelihood
Spheres	All Obliquities	5.85E-05	100%
	Normal Obliquity Only	8.29E-05	100%
Cube	Face On	1.59E-05	23%
	Edge On	3.89E-05	46%
	Point On	5.90E-05	31%
SBM Flake	Face On	2.32E-05	8%
	Edge On	7.49E-05	15%
	Point On	1.07E-04	15%
	A-C Edge On	2.12E-05	31%
	A-B-C Point On	2.23E-05	31%



ORDEM 2000 debris environment
1 meter cube
Altitude 400 km
57 degree orbit
1 year duration (2007)

Table 2. Comparison of Spacecraft Risk Resulting from Assuming Cubes and Flakes Compared to Current Spherical Particle Assumption for a Dual-Wall Shield[41]

	Weighted Number of Penetrations	**Penetration Risk Compared to Sphere (Normal Impact Case)**
Sphere (All Obliquities)	5.85E-05	71%
Sphere (Normal Obliquity)	8.29E-05	100%
Cube (Normal Obliquity, All Orientations)	3.97E-05	48%
SBM Flake (Normal Obliquity, All Orientations)	4.32E-05	52%

VII. Conclusions

Meteoroid and orbital debris ballistic limit equations have historically consisted of formulas that include general features such as momentum or energy scaling and are supported by judiciously chosen impact tests. However, due to testing capability limitations and testing costs, only a limited number of impact tests have been conducted against materials that do not (and cannot) fully sample the relevant impact variables. Test facility limitations constrain the maximum particle velocity that can be achieved in the derivation of the damage prediction equations and do not represent the full spectrum of MMOD threat velocities.

Many equations for a number of material and shield configurations have little data, and are derived from their assumed similarity to other empirically based damage equations. These characteristics result in different levels of confidence in the accuracy of the various equations used (depending on the relevance and extent of the data used in their derivation) and a concern regarding uncertainties in the accuracy of the equations as a whole.

Statistical uncertainties for these damage prediction equations could be more rigorously derived from a closer examination of the original data or from additional test data (and possibly hydrocode analyses). Shields that are most likely to sustain critical MMOD failure should have higher expectations for statistical confidence in their underlying damage prediction equations, and their testing should be biased towards conditions that are as representative as possible of MMOD encounters (in impact velocity and obliquity).

Many radar, in-situ, and ground-based studies have shown that orbital debris is not composed of spheres, but consists of fragments of varying sizes and shapes. Until now, orbital debris risk assessments have concentrated on spheres, primarily due to limitations in computer and test resources. Studies indicate that we may be over-predicting orbital debris risk by a factor of two for dual-wall shields by limiting our analyses to spheres instead of considering more representative debris shapes, such as cubes and flakes, along with a particle's characteristic length. Considering these more representative debris shapes also carries with it the advantage of improving the quality and accuracy of our spacecraft risk analyses.

There will always be a place for simple, initial risk analyses using ballistic limit equations that assume spherical orbital debris shapes. However, the availability of improved, fast running PC-based computer models such as FATEPEN, and user-friendly, computationally efficient codes, such as AutoDyn (with its many modules, including SPH), renders the consideration of alternative debris shapes as a practical, cost-saving alternative to simply launching heavier-than-necessary shields.

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