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A comment on the use of ballistic limit equations for spacecraft risk assessment

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Abstract

The fundamental components of any meteoroid/orbital debris risk assessment calculation are environment models, damage response predictor equations, and failure criteria. Response predictor equations typically take the form of ballistic limit equations (or BLEs) that define the threshold particle sizes that would cause the failure of a spacecraft component. When performing a spacecraft MOD risk assessment, the need for a BLE often arises for components where one doesn't exist. In such cases, it is common to use an existing BLE after first equivalencing actual materials to the materials of the existing BLE. The question naturally arises regarding how close the predictions are of such an 'adapted BLE' to the response characteristics of the actual materials/wall configurations. A study was conducted to compare the predictions of a commonly used BLE when applied to a Soyuz wall configuration against those of a new BLE that was developed specifically for that wall configuration. It was found that the critical projectile diameters predicted by the new Soyuz BLE can exceed those predicted by the existing BLE by as much as 50 percent of the existing BLE values. Thus, using the adapted version of the existing BLE in this particular case would contribute to a more conservative value of assessed risk. This finding could have significant implications on the validity of other MOD risk values that were obtained using a similar process.
Keywords: ballistic limit equations, meteoroid, orbital debris, risk assessment.

1 Introduction

The fundamental components of any meteoroid/orbital debris (MOD) risk assessment calculation are the meteoroid and orbital debris environment models,

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the damage response predictor equations for the various components that comprise the spacecraft, and the failure criteria for those spacecraft components. In the case of a spacecraft destined to operate in low earth orbit, the response predictor equation typically takes the form of a ballistic limit equation, or BLE, that characterizes the performance of a hypervelocity impact shield. Such an equation defines the threshold particle sizes that would cause, for example, perforation or detached spall from the inner wall of a multi-wall system as a function of velocity, impact angle, particle density, shield and inner wall thicknesses, and particle shape. BLEs are typically drawn as lines of demarcation between regions of inner-wall failure and no failure in two-dimensional projectile diameter-impact velocity space, and when graphically represented in this manner they are referred to as BLCs.

The high-speed impact testing that provides data for the development of BLEs and BLCs typically use spherical projectiles fired in light gas guns at impact velocities between 3 and 7 km/s (although some can reach velocities up to 10 km/s now). These data are then fitted with scaled single-wall equations below approximately 3 km/s, and with theoretical momentum and/or energy-based penetration relationships above approximately 7 km/s to obtain three-part BLCs that cover the full range of impact velocity from approximately 0.5 to 16 km/s. The transitional velocity region (from approximately 3 to 7 km/s for normal aluminum-on-aluminum impacts) takes the form of a linear interpolation between the low and high velocity regions. Figure 1 shows a typical BLC for a dual-wall system (i.e., Whipple shield) under normal projectile impact.

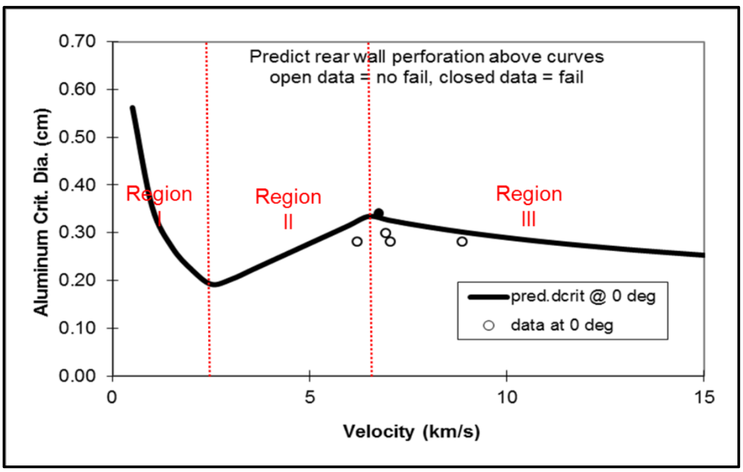

Figure 1: Typical BLC for a dual-wall system, normal projectile impact.

In Region I, the projectile is deformed following its impact on and passage through the outer (i.e. bumper) plate, but remains mainly intact as it travels towards and eventually strikes the inner wall of the dual-wall system. For aluminum projectiles impacting aluminum bumpers, Region I is typically impact velocities below 3 km/s. In Region I, the form of the BLC is analogous to that of a single-wall curve. In Region II, the projectile is fragmented and the energy of the impacting projectile and ejected shield material is dispersed over an increasingly larger area of the inner wall. As a result, the ability of the dual-wall system to resist inner-wall failure (whether defined as a perforation or detached rear-side spall) increases as reflected in the curve. This gives rise to the bucket shape of the BLC for a dual-wall system. In Region III (which typically starts at 7 km/s for aluminum-on-aluminum impacts), the projectile is completely melted and the impulse delivered to the rear wall is increasingly more difficult to resist.

In preparation for a risk assessment calculation during the design of a spacecraft, the need for a BLE often arises for spacecraft components where one doesn't exist. In such cases, it is a common procedure to use an existing BLE after first equivalencing the actual materials and/or wall thicknesses to the materials that were used in the development of that existing BLE.

The BLE sketched in Figure 1 is frequently referred to by the spacecraft design community as the NNO BLE [1]. This BLE was developed primarily for aluminum-on-aluminum impacts and for dual-wall configurations with bumpers or shields that are sufficiently thick so as to cause significant fragmentation of an incoming projectile. This BLE has been adapted to other target types and applied to various other materials, including lightweight multi-layer thermal insulation blankets, by equivalencing those materials and wall thicknesses to aluminum on a mass density basis. For example, in the event of a non-aluminum bumper of a specified thickness and having a certain density (ρ), the thickness (t) of an equivalent aluminum shield can be calculated as follows:

$$\rho_{alum} t_{bumper}^{equiv\ alum} = \rho_{bumper}^{actual} t_{bumper}^{actual} \tag{1}$$

so that

$$t_{bumper}^{equiv\ alum} = (\rho_{bumper}^{actual} / \rho_{alum}) t_{bumper}^{actual} \tag{2}$$

The question naturally arises regarding how close are the predictions of such an 'adapted BLE' to the response characteristics of the actual materials/wall configurations under high speed projectile impacts. In an attempt to begin addressing this issue, a study was conducted to compare the predictions of the NNO BLE as applied to the Soyuz OM wall configuration against those of a new BLE that was developed specifically for that Soyuz wall configuration.

2 Application of the NNO BLE to the Soyuz OM wall configuration

In 2013, NASA developed a BLE that would be applicable to the case of high density projectiles impacting a very specific and specialized wall configuration, namely, that of the Soyuz orbital module (OM) [2]. This wall configuration (illustrated in Figure 2) can be, ostensibly, considered to be a dual-wall configuration. If the array of the Soyuz OM bumper materials is equivalenced to a single aluminum wall, then the NNO BLE could, in theory, also be used to predict the response of the Soyuz OM wall system to high density projectile impact. The Soyuz OM wall system can therefore be used to see how well the modified NNO BLE predicts the response of a dual-wall system for which it was not developed, but can nonetheless be used following appropriate equivalencing of the original system's configuration parameters.

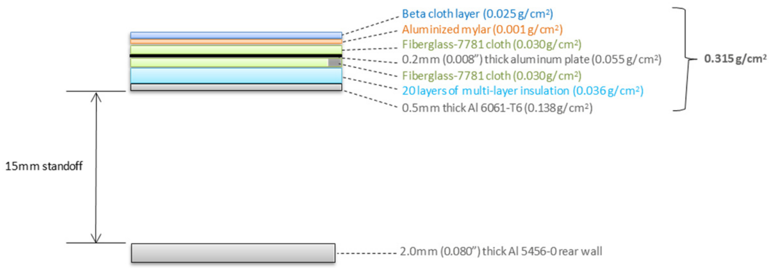

Figure 2: Soyuz OM wall composition.

In this study, the predictions of the NNO BLE as applied to the Soyuz OM wall configuration were compared against those of the new Soyuz OM BLE for 30° and 45° impacts of steel projectiles. If the predictions of the two BLEs were found to be relatively close, that would give some confidence to the practice of using modified NNO BLEs in situations involving projectiles impacting wall configurations for which BLEs do not currently exist. However, if the predictions were found to be not very close, some testing would certainly be called for to assess the validity of this equivalencing approach and/or its continued use.

To be able to apply the NNO BLE to the Soyuz OM wall system, the multi-material Soyuz OM bumper was first equivalenced to a monolithic aluminum bumper on a mass density basis. Specifically,

$$\rho_{aluminum} t_{bumper}^{equiv\ aluminum} = \rho_{areal\ density}^{actual\ Soyuz\ OM\ bumper} \tag{3}$$

so that

$$t_{bumper}^{equiv\ aluminum} = \rho_{areal\ density}^{actual\ Soyuz\ OM\ bumper} / \rho_{aluminum} \tag{4}$$

All other geometric parameters (inner wall thickness and stand-off distance) were kept the same as in the Soyuz OM wall system.

Figures 3 and 4 compare the recently developed BLE for the Soyuz OM and the NNO BLE for the geometric parameters of the Soyuz OM wall configuration. Figure 3 compares the BLEs for 30° impacts while Figure 4 presents the comparison for 45° impacts.

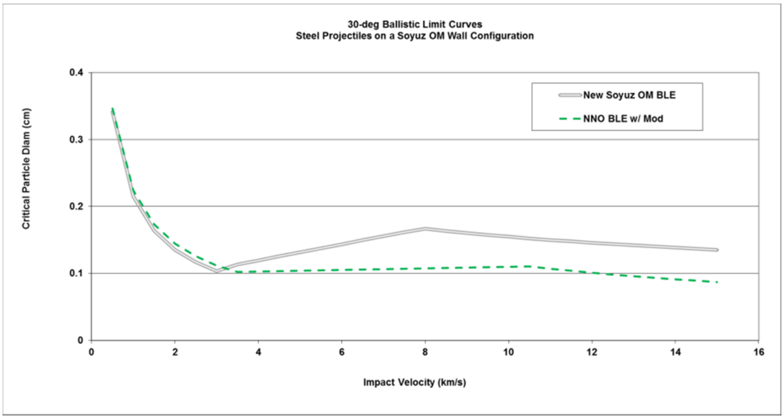

Figure 3: Comparison of new Soyuz OM and NNO BLEs, 30° impacts.

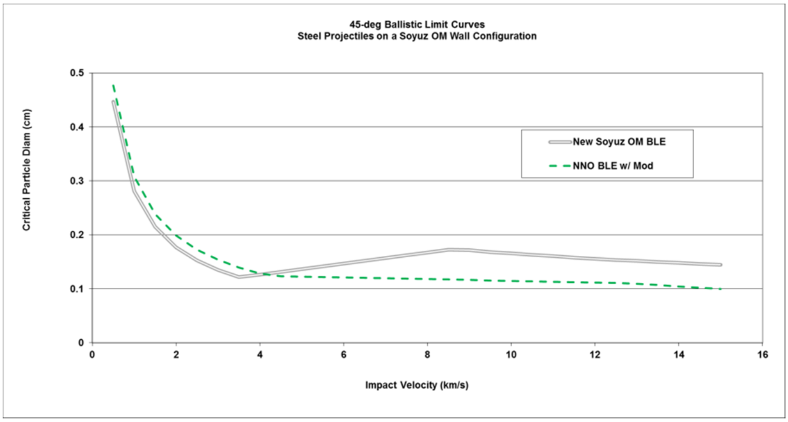

Figure 4: Comparison of new Soyuz OM and NNO BLEs, 45° impacts.

Figures 3 and 4 show the modified NNO BLE and the new Soyuz OM BLE are fairly close until the low-end transition velocity (approx. 3 km/s for 30° impacts, and 3.5 km/s for 45° impacts). However, above the low-end transition velocity the two curves diverge – the new Soyuz BLE has the canonical "bucket" shape while the adapted NNO BLE more resembles the BLE of a single wall, not a dual-wall, system.

In fact, above 9–10 km/s, the critical projectile diameters predicted by the new Soyuz OM BLE can exceed that of the NNO BLE by as much as 50% of the NNO BLE values. Thus, adapting the NNO BLE for use in this particular case would contribute to a more conservative value of assessed risk. If the same trends hold true for other types of wall configurations, then it is also possible that using modified NNO BLEs in risk assessments might also result in more conservative (i.e. higher) values of assessed risk.

3 Conclusions

A study was performed to assess how well an existing BLE could be used to predict the response of a spacecraft wall system that was not used in the development of that BLE. Specifically, the predictions of the NNO BLE as applied to the Soyuz OM wall configuration were compared against those of a BLE that was developed specifically for that wall configuration. It was found that the critical projectile diameters predicted by the actual Soyuz wall BLE exceeded those predicted by the adapted use of the NNO BLE by as much as 50% of the NNO BLE values. Thus, using the NNO BLE in this case would contribute to a more conservative value of assessed risk. If the same were to hold true for other wall types, then it is also possible that using existing BLEs, even after they have been adjusted for differences in materials, etc., may result in predictions of smaller critical diameters (i.e., increased assessed risk) than would using BLEs purposely developed for the spacecraft walls of interest. This finding could have significant implications on the validity of MOD risk values obtained using a similar process.

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