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Assessing the Predictive Capability of the NNO Ballistic Limit Equation for Low-Density Projectile Impact

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Abstract: The design of nearly all Earth-orbiting spacecraft includes some sort of added shielding that protects the spacecraft against impacts by meteoroids and orbital debris. The effectiveness of the shielding is typically assessed using ballistic limit equations (BLEs) that are developed using data from high-speed impact tests on key spacecraft components and elements. These equations predict whether or not a particular system or structural element will sustain a critical failure following a specific impact event. As such, they are essential components of spacecraft system design as well as any quantitative spacecraft risk assessments that may need to be performed as part of that design process. Previous high-speed impact test programs have typically used medium-to-high density materials as surrogates for the kinds of materials that populate the orbital debris environment surrounding the Earth. However, with the advent of several new interplanetary spacecraft being designed, it is important to be able to predict and assess the performance of candidate spacecraft shields under impacts by projectiles made of materials that such spacecraft might be expected to encounter throughout their missions. To begin to address that issue, we assess how well a frequently used BLE, the New Nonoptimum (NNO) BLE, is able to predict the response of a commonly used shielding system when it is subjected to less dense materials that are often used as surrogates for icy meteoroids. In the end, it is shown that this BLE might require some modification when used to predict the response of such a system under the impact these kinds of projectiles.
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Introduction

The design of nearly all Earth-orbiting spacecraft includes some sort of built-in shielding that protects the spacecraft, and if applicable, its inhabitants, against high-speed impacts by meteoroids and orbital debris. A ballistic limit equation (BLE) is an equation that is used to predict whether or not a particular system or structural element will sustain a critical failure following a specific impact event. The effectiveness of the shielding (usually referred to as a bumper) is assessed using such BLEs, which are developed using data from high-speed impact tests on key spacecraft components and elements. In this manner, BLEs are essential components of spacecraft system design as well as any quantitative spacecraft risk assessments that may need to be performed as part of that design process. There are basically two different basic types of BLEs used in spacecraft design, and each is obtained in a unique way.

The first kind of BLE is based on a damage predictor equation and is typically a statistically based curve fit to damage measurements. An example of a damage predictor equation is one that predicts penetration depth into a structural element in terms of impact parameters (impact velocity and obliquity), material properties of the projectile and the impacted element materials, and the geometries involved (e.g., impacted element thickness, projectile dimensions, projectile shape, and so on). Once a critical/maximum acceptable damage level in the impacted element is identified (e.g., a maximum allowable penetration depth), the damage predictor equation is manipulated into a form that yields the critical particle diameter, in terms of all the other parameters whose impact would result in the specified maximum acceptable damage level.

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The second kind of BLE is effectively based on a hand-drawn discriminant line. An example of a discriminant line BLE is one that separates regions of projectile diameter and impact velocity combinations that would result in the perforation of the rear wall of a dual-wall Whipple Shield from those that would not. And unlike damage predictor equations, discriminant line BLEs are not statistically derived curve fits, but are rather simply lines of demarcation between parameter-based regions where something either does or does not happen.

Considering the manner in which they are derived, it is important to note that both kinds of BLEs are specific for the structural element or system and the impact conditions used in the test programs that generate the data upon which they are based. They are also a function of the criteria used to define failure thresholds for the particular system or structural element under consideration. Schonberg (2016) presented a history of the development of the BLEs frequently used in the design of long-duration spacecraft, such as the International Space Station.

Although both meteoroid and orbital debris environments are considered in spacecraft design, the prevailing wisdom is that the primary high-speed impact threat in low Earth orbit is that posed by orbital debris. As a result, many previous and ongoing high-speed impact test programs (and much of the attendant BLE development activities over the last 40 years or so) have focused and continue to focus on dual-wall and multiwall systems that can reduce the threat of such impacts. These test programs typically used medium-to-high density materials (e.g., aluminum, aluminum oxide, copper, steel, and so on) as surrogates for the kinds of materials that populate the orbital debris environment.

However, with the advent of several new interplanetary spacecraft being designed (e.g., those that are part of the Mars Sample Return Mission), it is important to be able to predict and assess the performance of candidate spacecraft shields under high-speed impacts by projectiles made of the kinds of materials that such interplanetary spacecraft might be expected to encounter throughout their (either one-way or round-trip) missions. As surrogates for the lighter, less-dense materials that populate the icy meteoroid environment, high-speed impact test programs have often used projectiles made out of materials like nylon (polyamide; density = 1.14 g/cm^3), Lexan (polycarbonate; density = 1.2 g/cm^3), and Inlyte (a foamed silicate; density = 0.70 − 0.73 g/cm^3).

A frequently used BLE for dual-wall configurations (often referred to as Whipple Shields) is the New Nonoptimum (NNO) BLE (Christiansen 1993), given as follows:

$$d_c = [(t_w(\sigma/40)^{0.5} + t_b)/(0.6(\cos\theta)^{5/3}\rho_p^{0.5}V^{2/3})]^{(18/19)},\quad V_n < 3\text{km/s} \qquad (1)$$

$$d_c = 3.918 t_w^{2/3}\rho_p^{-1/3}\rho_b^{-1/9}(V\cos\theta)^{-2/3}S^{1/3}(\sigma/70)^{1/3},\quad V_n > 7\text{ km/s} \qquad (2)$$

where d_c = ballistic limit diameter; V_n = normal component of the impact velocity V (km/s); S = distance between the bumper and the rear wall (cm); σ = yield strength of the rear wall material (ksi); t_b and t_w = bumper and rear wall thicknesses (cm), respectively; and ρ_b and ρ_w = bumper and rear wall material densities (g/cm^3), respectively. Between 3 and 7 km/s, the BLE is a linear interpolation between its values at 3 and 7 km/s.

This BLE was developed using high-speed impact test data involving primarily aluminum projectiles striking primarily aluminum dual-wall and multiwall targets having outer walls, or bumpers, that are presumed to be sufficiently thick so that they can cause significant fragmentation of an impacting projectile. Considering the frequent use of the NNO BLE by the Earth-orbiting as well as interplanetary spacecraft design communities, it is imperative to evaluate its ability predict the response of such wall configurations against a variety of projectile materials, especially those not used to as great an extent in its development as, say, aluminum.

Schonberg (2020) performed this evaluation for projectiles that are more dense than aluminum and offered suggestions for how the NNO BLE can be modified so that it more accurately predicts whether or not the rear wall of a dual-wall system will be perforated by the high-speed impact by such (more dense) projectiles. In this paper, we present the results of the companion assessment, now focused on materials that are less dense than aluminum, such as nylon, Inlyte, and Lexan. In the end, we show that the NNO BLE might require some further modifications if it is to be successfully used to predict the response of dual-wall systems under the impact of such (less dense) projectiles.

Overview of Test Program Parameters

Experimental results from previous high-speed-impact test programs using low-density projectiles were assembled into a database and subsequently used to assess how well the NNO BLE is able to predict the response of dual-wall structures under the impact of such projectiles. This database consists of 69 tests involving a variety of impact conditions, bumper materials and thicknesses, stand-off distances, and rear wall materials and thicknesses. Tables 1 and 2 present a summary of the impact conditions, and the materials and geometries in these previous high-speed-impact test programs, respectively.

Table 1. Summary of impactor data and conditions in previous relevant high-speed impact test programs

References	No. of tests	Projectile material	Projectile shape	Projectile diameter (cm)	Impact velocity (km/s)	Obliquity (degrees)
McMillan (1968)	11	Nylon, Inlyte	Sphere	0.42, 0.49	2.9–7.9	0
Christiansen (1986)	7	Nylon	Cylinder	~0.2	5.4–7.4	0
Christiansen (2003)	2	Nylon	Sphere	0.32, 1.46	6.7, 7.4	0
Fujiwara and Kadono (1990)	5	Nylon	Sphere	0.7	3.5–3.9	0
Nahra et al (2010)	2	Nylon	Sphere	0.2, 0.36	6.9–7.0	0
Schonberg and Darzi (1992)	4	Lexan	Cylinder, sphere	0.89, 1.1	4.3–6.4	0
Lundeberg et al. (1965)	3	Lexan	Cylinder	0.172	3.0–8.4	0
Friend et al. (1969)	7	Lexan	Cylinder	~1.2	6.0–9.6	0
Gough (1970)	13	Lexan	Cylinder	~1.23	6.7–8.6	0
Ferguson (1966)	10	Lexan	Cylinder	0.65, 1.02	6.5–7.0	0
Clough et al. (1966)	5	Inlyte	Sphere	~0.37	7.4–7.7	~0

Table 2. Summary of target materials and geometries in previous relevant high-speed impact test programs

References	Bumper material	Bumper thickness (mm)	Stand-off distance (cm)	Rear wall material	Rear wall thickness (mm)
McMillan (1968)	Al 1100-0	0.3–1.02	5.08	Al 7075-T6	6.35, 12.7
Christiansen (1986)	Al 6061-T6	1.9–2.8	10.16	Al 6061-T6	0.81
Christiansen (2003)	Al 6061-T6	0.25, 4.83	5.08, 10.16	Al 2024-T3	0.81, 6.35
Fujiwara and Kadono (1990)	Al 1100-0	0.10	0.5–4.5	Al 1100-0	0.10
Nahra et al. (2010)	Al 6061-T6	0.97	27.9	Ti-6Al-4V	1.27
Schonberg and Darzi (1992)	Al 6061-T6	1.02	10.16	Al 2219-T87	3.18
Lundeberg et al. (1965)	MgLi	0.254	1.52	Al 2024-T3	0.127
Friend et al. (1969)	Lead	0.25	7.61	Al 2024-T3	1.27
Gough (1970)	Lead	0.25	7.5–30.0	Al 2024-T3	0.4–6.6
Ferguson (1966)	Lead	0.51	7.62, 15.24	Al 2219-T87, Ti-5Al-2.5Sn[a]	0.81–3.18
Clough et al. (1966)	SS316	0.46	1.4–1.5	SS316[b]	0.635–1.9

[a]Rear walls were held in a biaxial stress fixture.

[b]Targets were actually shielded steel radiator tubes.

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Some Comments on the Data

As can be seen in Table 2, some previous high-speed-impact studies with low-density projectiles have also used lead as a bumper material and shielded steel radiator tubes as the target configuration. Although the NNO BLE did not consider this bumper material or target configuration in its development, results from these tests have also been included in the current investigation for completeness.

In some of the testing programs, the rear walls of the dual-wall targets were held in a test fixture that allowed a biaxial stress field to be applied and developed within the rear walls in such targets; these tests were also included in the database. Although the presence of a stress field (biaxial or otherwise) in the rear wall of a perforated dual-wall target may affect the extent of a hole or a crack in a rear wall, it was shown to not affect whether or not the rear wall will be perforated (Schonberg and Ratliff 2015). Hence, it made sense to include the data for the targets with stressed rear walls along with that for dual-wall targets having unstressed rear walls.

Finally, in the case of cylindrical projectile impact, the projectile diameters in Table 1 have been calculated from the dimensions of the actual cylindrical projectiles using a volume equivalence and the same projectile material. Although projectile shape can undoubtedly affect the response of a dual-wall system under high-speed impact, the length-to-diameter (L/D) ratios of the cylindrical projectiles were all close to unity. Hence, in the tests listed in Table 1 as having cylindrical projectiles, this effect is assumed to be minimal—that is, whether or not the rear wall is perforated by the impact of an $L/D \sim 1$ cylindrical projectile is expected to be mimicked by the impact of a spherical projectile made of the same material and having the same mass (or volume).

Results and Analysis

For each of the tests noted in Tables 1 and 2, the ratio of the diameter of the impacting projectile to the critical projectile diameter (i.e., the ballistic limit diameter) in each test as predicted by the NNO BLE was found. In an ideal world, tests that resulted in rear-wall perforation (P) would have ratio values greater than 1 (i.e., the actual projectile diameter would exceed the critical projectile diameter as predicted by the NNO BLE), whereas those that resulted in a nonperforation (NP) would have ratio values less than 1 (i.e., the actual projectile diameter would be less than the critical projectile diameter as predicted by the NNO BLE).

The effectiveness of the NNO BLE in predicting rear wall perforation or nonperforation was assessed by noting the distribution of these ratios relative to unity, and how consistently the ratios for perforating and nonperforating tests were above and below unity, respectively. Using this assessment tool, Figs. 1–3 demonstrate the ability of the NNO BLE to predict rear wall perforation or nonperforation for the tests noted in Tables 1 and 2 for nylon, Inlyte, and Lexan projectiles, respectively. In these three figures, open markers indicate rear wall perforation, and solid markers indicate nonperforation.

In Figs. 1–3, open markers above the dark horizontal line at an ordinate value of unity correspond to tests having rear wall perforations failures caused by projectiles with diameters larger than the predicted ballistic limit diameters and indicate successful predictions by the NNO BLE. Conversely, an open marker below the dark horizontal line at an ordinate of unity corresponds to a test with rear wall perforation caused by a projectile with a diameter smaller than the predicted ballistic limit diameter, and indicates a nonsuccessful prediction (that is, the NNO BLE predicted a nonperforation of the rear wall, but instead a perforation occurred).

Similarly, solid markers above the dark horizontal line correspond to tests without rear wall perforations, but with projectiles having diameters larger than the predicted ballistic limit diameters, and also indicate nonsuccessful predictions by the NNO BLE (that is, the NNO BLE predicted rear wall perforation, but it did not occur). Conversely, solid markers below the dark line correspond to tests without rear wall perforation and with projectiles having diameters smaller than the predicted ballistic limit diameters, and indicate successful NNO BLE predictions.

In Fig. 1 (i.e., for nylon projectile impact), all of the open markers are above the dark horizontal line at an ordinate of unity, whereas all the solid markers, for both kinds of bumper materials as well as both kinds of rear wall materials, are below that line. From these results, it would appear that the NNO BLE is quite adept at predicting the rear wall perforation/nonperforation (P/NP) response for this projectile material and the various rear wall materials used to generate this data. Also in Fig. 1, the ×15 for the five open square data points indicate that the actual projectile diameters used in those five tests were 15 times the diameter values that would be read off Fig. 1, so it is not surprising those tests resulted in rear wall perforation.

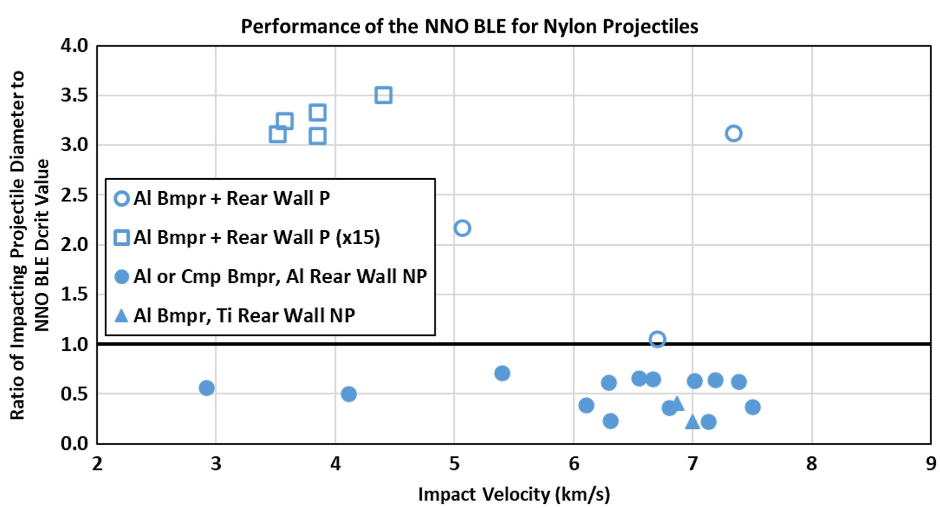

Fig. 1. Comparison of NNO BLE predictions and experimental results for nylon projectiles.

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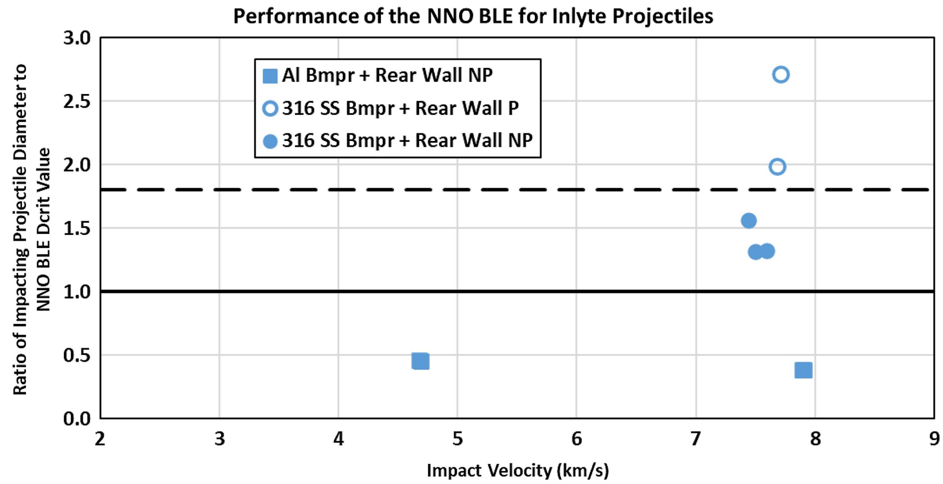

Fig. 2. Comparison of NNO BLE predictions and experimental results for Inlyte projectiles.

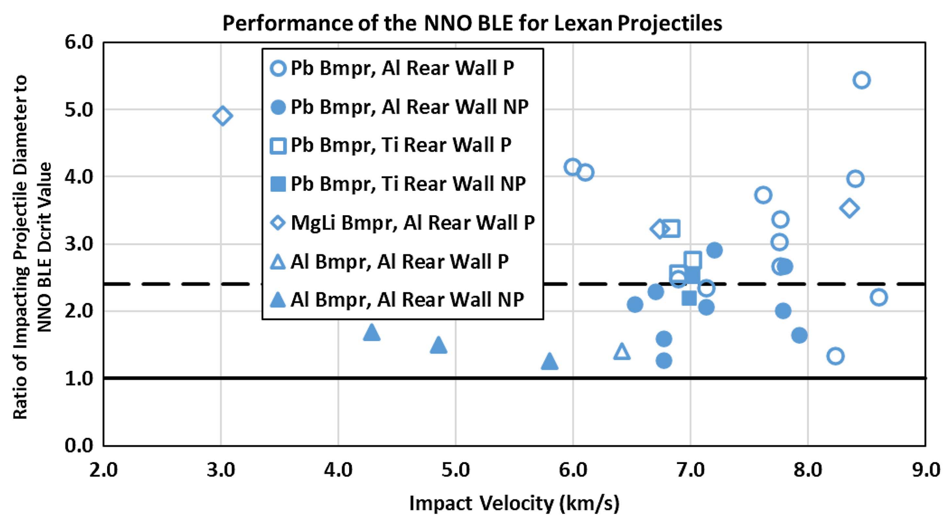

Fig. 3. Comparison of NNO BLE predictions and experimental results for Lexan projectiles.

However, as can be seen in Fig. 2 (i.e., for Inlyte projectile impact), not only all of the open markers but also some of the solid markers are above unity (the purpose of the dashed line in Fig. 2 will be discussed in the next section). This indicates that the NNO might need to be adjusted if it is to be used for Inlyte projectiles because it apparently, in its current form, appears to underpredict the ballistic limit diameters of Inlyte projectiles. This adjustment could, for example, be in the form of a multiplicative constant that would serve to increase the ballistic limit diameter calculated by the NNO BLE for Inlyte projectile impacts.

However, as can be seen in Fig. 3, all of the open markers and all of the solid markers are both above the dark horizontal line at an ordinate of unity (the purpose of the dashed line in Fig. 3 will also be discussed in the next section). This indicates that the NNO in its current form also appears to underpredict the ballistic limit diameters of Lexan projectiles, and so might also need to be adjusted if it is to be used for projectiles made of this material. As for the Inlyte projectiles, this adjustment could also be in the form of a multiplicative constant that would serve to increase the ballistic limit diameter calculated by the NNO BLE for Lexan projectile impacts. A point of interest is that Coronado et al. (1987) also noted that the analytical BLE developed in that study, which was quite successful when modeling the P/NP response of dual-wall systems under aluminum projectile impact, did also underpredict the P/NP response of dual-wall systems under Lexan projectile impact.

Some Thoughts on NNO BLE Modifications for Low-Density Projectiles

If it is desired to extend the applicability of the NNO BLE to model the response of dual-wall systems more accurately with bumper and rear wall materials other than aluminum under the high-speed impact of low-density projectiles, some modifications to the BLE are likely to be necessary. For example, the dashed lines in Figs. 2 and 3, placed at ordinates of 1.8 and 2.4, respectively, are much better lines of demarcation between rear wall perforations and non-perforations for Inlyte and Lexan projectiles, respectively. These values, then, are indications of multiplicative adjustment factor values that might be needed to improve the predictive accuracy of the NNO BLE for very light projectile materials.

Thus, if the NNO BLE predictions of critical projectile diameter for these two materials are multiplied by 1.8 and 2.4, the end result will be that most of the solid markers in Figs. 2 and 3 will lie below the (new) demarcation lines at unity, whereas most of the open markers will be above. There will still be some spillage of some solid markers above the (new) demarcation lines and some open markers below, but this is not at all unusual. Rather, as frequently seen before in these kinds of plots (e.g., Schonberg and Compton 2008), this kind of data spillage is more the norm than the clean separation evident in Fig. 1. Furthermore, the impact of cylindrical projectiles adds to the variability in the Lexan projectile results seen in Fig. 3. In such cases, it is not always possible to control the orientation of the projectile at the moment of impact on the bumper, which could in turn lead to unexpected rear wall perforation or nonperforation results.

It is also evident that the values of these multiplicative adjustment factors for Inlyte and Lexan projectiles track with the densities of these two materials. There is then the question of whether or not the ballistic limit diameter values predicted by the NNO BLE for nylon projectiles when actual projectile material densities are used in the NNO should be adjusted upward as well to maintain the correlation between adjustment factor value and projectile density. This would require a multiplicative factor of approximately 2.2 for the ballistic limit values predicted by the NNO BLE for nylon projectiles (using the density of nylon), which would likely result in the lowest open marker in Fig. 1 being placed below the new demarcation line for that projectile material.

There are two other points to consider as well. First, assuming that the predictions of the NNO BLE for aluminum projectiles are considered to be reliable, this upward trend of multiplicative factor values with increasing projectile density must eventually turn downward and approach unity again as projectile density nears that of aluminum. Second, if projectile density were to instead decrease, multiplicative adjustment factors for even less dense projectiles should eventually either level off or increase because ever larger projectiles (made of ever lighter materials) would be required to perforate the rear wall of a dual-wall system. These uncertainties and as yet unconfirmed expectations would indicate additional testing or simulation is needed using low-density projectile materials if the NNO BLE is to be properly adjusted so that it is able to correctly predict the P/NP response of dual-wall systems under hypervelocity impact.

Summary and Conclusions

A study has been performed to assess how well the NNO BLE performs when predicting the perforation/no-perforation response of dual-wall systems (i.e., Whipple Shields) under the high-speed impact of low-density projectile materials such as nylon, Inlyte, and Lexan. In the end, it was found that the current version of the NNO BLE does a respectable job predicting the response of dual-wall shields under nylon projectile impact, but requires some modifications if it is to be used to predict the response of such systems under the impact of Inlyte and Lexan projectiles. If these modifications were to include nylon projectiles as well, then additional perforating and nonperforating tests with nylon projectiles are needed to confirm the value of the adjustment factor for that material more accurately. The NNO BLE formulation should therefore be revisited to determine the best approach for including projectile materials much less dense than that of aluminum. One possible adjustment to the NNO BLE could be a modification of the low-end and high-end transition velocities so that it more accurately models the P/NP response of dual-wall systems under the high-speed impact of projectiles made of such materials.

Data Availability Statement

All data used in this study appear either in this article or in a publicly available document referenced in this article.

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