Improved ballistic limit equations for high-speed non-aluminum projectiles impacting aluminum dual-wall spacecraft systems

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Abstract

One of the major design considerations of earth-orbiting spacecraft is the damage that might occur from an impact by a micrometeoroid or orbital debris particle. Ballistic limit equations (BLEs), which predict the response of spacecraft components under impact, are one of the key components of any micrometeoroid / orbital debris risk assessment calculation. However, given that a limited number of BLEs have been developed, analysts will sometimes use a BLE to assess the impact projectile made of a material that was not used in the development of that BLE. This paper presents the results of a two-part study that focused non-aluminum projectiles impacting aluminum dual-wall structures. In the first, results from high-speed impact tests using non-aluminum projectiles were compared against the predictions of a commonly used dual-wall BLE. In nearly all cases, this BLE was found not to work sufficiently well in predicting the high-speed impact response of non-aluminum projectiles. In the second, the dual-wall BLE was modified to more correctly predict the response of such wall systems to the high-speed impact of non-aluminum projectiles. This modified BLE was found to be much improved in predicting whether or not a high-speed non-aluminum projectile would perforate a dual-wall system.

Keywords Space debris · Ballistic limit equation · Hypervelocity impact · Non-aluminum projectiles

Abbreviations

C_L	NNO BLE empirical constant, low impact velocity regime
C_H	NNO BLE empirical constant, high impact velocity regime
$d_{c,L}$	Critical projectile diameter, low impact velocity regime
$d_{c,H}$	Critical projectile diameter, high impact velocity regime
d_p	Projectile diameter
f_L	NNO BLE function, low impact velocity regime
f_H	NNO BLE function, high impact velocity regime
t_b	Bumper wall thicknesses
t_w	Inner (pressure) wall thickness
V_{mb}	Impact velocity at which projectile melt is estimated to begin

V_{mc}	Impact velocity at which projectile melt is estimated to be completed
V_n	Normal component of the impact velocity
V_p	Impact velocity
ρ_p	Projectile material density
σ_w	Yield strength of the inner (pressure) wall material
θ_p	Impact obliquity measured relative to the bumper surface normal

1 Introduction

An important design constraint for spacecraft in earth orbit is the protection of the spacecraft against the damage that might occur from an on-orbit orbital debris particle impact (see, e.g., [1] for more information on the problem of orbital debris). Traditional protective design for

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spacecraft consists of a 'bumper' that shatters an impacting projectile. How well a multi-wall structure performs is usually characterized by its ballistic limit equation (BLE), which predicts the size of the projectile that would cause failure in terms of velocity, impact angle, projectile density, projectile shape, as well as the materials used in the structural system. These equations are often used to optimize the design of a spacecraft wall or component so that it can resist critical damage under a wide range of impact conditions (see, e.g., [2] for additional information on how BLEs are constructed for typical spacecraft systems).

Although ballistic limit equations are an important part of a MMOD risk assessment calculation, these assessments often use BLEs to predict the impact response of projectiles made of materials not used in the development of those BLEs (see, e.g., [3]). This leads to the question of how accurate are the predictions of such BLEs, that is, when they are used in impact scenarios involving projectiles made of materials not used in their development. Furthermore, if the answer to that question is, "not very", the question that arises next is how such BLEs can be adjusted so that the resulting modified BLEs ARE more accurate in their predictive capabilities.

At present, the spacecraft design community must rely on using BLEs developed using aluminum projectiles, even when assessing the risks posed by the impact of non-aluminum projectiles. The spacecraft design process would clearly be more robust if response predictor equations, such as BLEs, were available that matched the expected operating conditions and environmental threats the spacecraft might be expected to encounter. In an effort to answer these questions and to close the gap between the available equations and those that are actually needed, a study was performed with the following objectives.

- (1) To assess the validity of an existing, frequently used, dual-wall aluminum-projectile-based BLE for non-aluminum projectiles.
- (2) To improve, if necessary, the capabilities of this aluminum-projectile-based BLE when used to predict the impact response of non-aluminum projectiles by modifying certain parameters, coefficients, and exponents within the BLE.

The predictive capabilities of the selected BLE before and after its modifications were assessed by comparing its predictions with high-speed impact test results for steel, copper, and Al_2O_3 projectiles (i.e. projectiles that are more dense than aluminum) and glass, nylon and Lexan projectiles (i.e. projectiles that are less dense than aluminum). These projectile materials were considered in this study because ORDEM-3, the NASA debris environment model, now identifies debris populations having particles with

densities approximating these materials [4]. These densities were included in the NASA debris environment model following the detection of steel and copper in the heat tiles of Space Shuttles that returned from their missions.

The high-speed impact tests that generated the data used in this study were performed using a light gas gun at a variety of locations, including the former General Motors Defense Research Laboratory in Santa Barbara, CA; the NASA Johnson Space Center in Houston, Texas; and, the NASA Marshall Space Flight Center in Huntsville, Alabama. A light gas gun is a highly specialized device specifically designed for launching projectiles having mass on the order of several grams (e.g., aluminum projectiles having diameters of 2.5 to 12.7 mm) at speeds up to 7 km/s. Two stage light gas guns use gunpowder in the first stage, and highly compressed hydrogen in the second stage, to accelerate projectiles at such high velocities to simulate orbital debris impacts on spacecraft materials and components (see, e.g., [5] for additional information on light gas gun design and development). A suite of measurement and diagnostic equipment typically accompanies a light gas gun, including, for example, high-speed cameras to capture the motion of the projectile in-flight before the impact and the motion and spread of debris clouds created by the impact of the projectile on the bumper plate. Recent advances in light gas gun technology include the development of three stage guns to reach velocities near 10 km/s with sizeable projectiles [6].

In nearly all cases, the selected aluminum-projectile-based BLE was found not to work sufficiently well in predicting the penetration / no penetration (P / NP) response of non-aluminum projectiles. As will be seen later, in nearly all instances, impact tests that resulted in rear wall perforation were predicted by the selected BLE to be a non-penetration. However, when some adjustments were made to this dual-wall BLE to accommodate the impact of non-aluminum projectiles, its ability to predict the P / NP response of such dual-wall systems dramatically improved. These changes included adjustments to the low-end and high-end transition velocities as well as some coefficients and exponents, as will be discussed in the ensuing sections of this paper.

2 Impact of dual-wall aluminum systems

The dual-wall BLE used in this study is known as the New Non-Optimum, or "NNO", BLE [7] by the spacecraft design community. This BLE was developed for aluminum-on-aluminum impacts and for bumpers that are thick enough so that they are about to cause significant fragmentation of an impacting projectile. The equations for

the low velocity and high velocity regions of the NNO BLE are written, respectively, as follows [7]:

$$V_n = V_p \cos \theta_p < 3 \text{ km/s} : \quad d_{c,L} \\ = f_L(t_b, t_w, \rho_p, \sigma_w) C_L \left[(V_p \cos \theta_p)^{-2/3} \right]^{18/19} \quad (1)$$

$$V_n = V_p \cos \theta_p > 7 \text{ km/s} : \\ d_{c,H} = f_H(t_w, \rho_p, \rho_b, \sigma_w, S) C_H (V_p \cos \theta_p)^{-2/3} \quad (2)$$

In Eqs. (3) and (4), f_L and f_H are functions that contain information regarding the geometry of the particular dual-wall system under consideration (see [7] for more information), and $C_L = (1/0.6)^{18/19} = 1.622$ and $C_H = 3.918$ are empirical parameters that position the BLE in the most appropriate place on the plot of empirical P / NP data points. Between the low and high velocity regimes in Eqs. (3) and (4), the NNO BLE is simply a linear interpolation, beginning and ending at the low-end and high-end transition velocities of 3 km/s and 7 km/s, respectively.

Early work on accounting for higher density particles in the orbital debris environment focused on determining a new value for the high-end transition velocity for the NNO BLE for dual-walls impacted by high-density projectiles [8]. Analysis of test results where steel projectiles impacted dual-wall structures concluded that 9.1 km/s would be an appropriate high-end transition velocity value for steel projectiles impacting aluminum dual-wall structures [8].

The effects of using a 9.1 km/s high-end transition velocity in a BLE developed with aluminum projectiles is shown in Figs. 1 and 2 when it is used with steel projectiles. Figure 1 is for 0° (normal) impact, while Fig. 2 is for a 45° (oblique) impact. Also shown in Figs. 1 and 2 are corresponding hypervelocity impact test results [9].

In Figs. 1 and 2 there are relatively large regions where original NNO predicts rear wall failure would not occur, but the modified NNO BLE predicts that it would (i.e., the regions between the two curves in each figure). Since most of the area between these two curves is in the shatter regime, the higher density steel projectiles and their fragments can perforate the rear wall.

As can be seen in Figs. 1 and 2, the revised BLE more accurately represents the test results for response of this dual-wall system when impacted by steel projectiles, though both show some degree of under-prediction of perforation. It is also interesting to note that no modifications were made to the low-end transition velocity of the NNO BLE based on projectile material alone, that is, it remains at a value of 3 km/s for normal aluminum-on-aluminum impacts as well as for steel-on-aluminum impacts. Some modification of the low-end transition values for more dense projectiles have been proposed, such as that offered by Kalinski [9]. Other changes in the low-end transition velocity have been adopted in multi-wall BLEs either depending on the ratio of bumper thickness to projectile diameter (see, e.g., [10]), or bumper material (see, e.g., [11]). However, until now, no changes to V_L have

Fig. 1 Comparison of empirical data with steel-on-Al BLEs without and with the high-end transition velocity modification for 0° Impacts (aluminum 6061-T6, 2 mm thick bumper; aluminum 2219-T87, 4.83 mm thick rear wall; 11.43 cm stand-off distance)

Fig. 2 Comparison of empirical data with steel-on-Al BLEs without and with the high-end transition velocity modification for 45° Impacts (aluminum 6061-T6, 2 mm thick bumper; aluminum 2219-T87, 4.83 mm thick rear wall; 11.43 cm stand-off distance)

been adopted in a dual-wall BLE solely based on the material of the impacting projectile.

The work reported herein built on these initial efforts by considering projectile materials that were both denser and less dense than aluminum. Comparisons of high-speed impact test results against the predictions of the NNO BLE led to further modifications of the BLE so that it could accommodate the less dense projectiles as well as the more dense ones. These modifications included low-end and high-end transition velocity value adjustments as well as some adjustments of the constants used in the low velocity and high velocity region equations.

3 Initial modifications to the aluminum-projectile-based NNO BLE

Table 1 summarizes the results of a search for high-speed impact testing that was done on non-aluminum projectiles impacting all-aluminum dual-wall systems over the past 50 + years. Other non-aluminum projectiles were also used, such as cadmium, lead, etc., but the tests with those projectiles involved like-material bumpers, and so were not considered in this study.

In order to be able to combine the widely varying test configurations and target geometries of the specimens tested, the NNO BLE was normalized by dividing both sides of the $V_n < 3$ km/s and $V_n > 7$ km/s equations by the functions f_L and f_H , respectively. As a result, only the coefficients $C_L = (1/0.6)^{18/19} = 1.622$ and $C_H = 3.918$ and the velocity terms $[(V \cos \theta)^{-2/3}]^{18/19}$ and $(V \cos \theta)^{-2/3}$ remained on the

Table 1 Overview of Impact Testing Using Non-Aluminum Projectiles

No. of tests	Projectile material	ρ_p gm/cm ³	d_p cm	V_p km/s	θ_p deg	References
14	Copper	8.96	0.02–0.5	3.1–8.0	0, 60	[12–15]
24	Steel	~8.0	0.1–1.0	2.5–9.5	0, 45	[9, 14, 16–19]
12	Al ₂ O ₃	3.98	0.5–0.8	4.4–7.0	0, 45	[9]
16	Pyrex	~2.23	0.15–0.32	3.4–7.3	0	[13, 16, 20]
4	Lexan	~1.21	0.9–1.0	4.2–6.4	0	[18]
11	Nylon	1.15	0.2–1.4	2.9–7.3	0	[13, 15, 21]

right hand side of the $V_n < 3$ km/s and $V_n > 7$ km/s equations, respectively. The resulting equations are referred to as “normalized dual-wall BLEs”, with “normalized critical projectile diameter” being plotted on the y-axis and the normal component of impact velocity on the x-axis. It is important to note that in order to also be able to plot experimental P / NP data on the same grid, experimental projectile diameter values were first normalized using the same scaling factors (depending on impact velocity region of the actual test) and then plotted against normal component of the impact velocity of the actual test.

Subsequent analyses of plots of the NNO BLE and the test data normalized in this fashion revealed some difficulties in how the BLEs and data were transformed from actual to normalized values. These difficulties stemmed from the fact that the normalization factor for the low velocity equation (f_L) differed from that for the high velocity equation (f_H) not only in value, but also in composition. For example, the low velocity normalization factor f_L included bumper thickness, while the high velocity normalization factor f_H did not. Similarly, the high velocity normalization factor f_H included stand-off distance, while the low velocity normalization factor f_L did not.

As a result, data points in the intermediate velocity regime would not scale similarly across the full regime—those closer to the 7 km/s transition point would be strongly affected by the high-velocity scaling factor (and accompanying changes in stand-off distance), while the low-velocity scaling factor (and changes in bumper thickness) would more affect those points closer to the 3 km/s

transition point. In an effort to provide a more uniform and consistent transition from actual conditions to normalized values, an alternative set of normalization factors was developed for the low velocity and high velocity regions. These normalization factors are given as follows:

$$V_n < 3 \text{ km/s} : d_{c,L}^{\text{norm}} = \left(\frac{d_{c,L}}{f_L} \right) \sqrt{\frac{f_H}{f_L}} \quad (3)$$

$$V_n > 7 \text{ km/s} : d_{c,H}^{\text{norm}} = \left(\frac{d_{c,H}}{f_H} \right) \sqrt{\frac{f_L}{f_H}} \quad (4)$$

Of course, in the region where $3 < V_n < 7$ km/s, the NNO BLE is a linear interpolation between the $V_n < 3$ km/s and $V_n > 7$ km/s BLEs. As a result, there is not a single compact expression or factor by which both sides of the NNO BLE could be divided in this velocity region. Instead, and in a manner similar to that of the actual NNO BLE, the normalized NNO BLE for $3 < V_n < 7$ km/s was obtained by simply interpolating between the values of the normalized NNO BLE at $V_n = 3$ km/s and at $V_n = 7$ km/s. Experimental projectile diameter values for test with a normal impact velocity component between 3 km/s and 7 km/s were normalized in a similar fashion.

Figure 3 shows the same information as in Figs. 1 and 2, but this time plotted with normalized projectile diameter values plotted against normalized NNO BLEs, with and without the high-end transition velocity modification suggested in [8]. Both the 0-deg and the 45-deg test

Fig. 3 Normalized impact test data compared against normalized original and modified NNO BLE (see also [22])

results appear on the same plot. Furthermore, there is no longer a 45-deg BLE curve or a 0-deg BLE curve—there is only a normalized BLE curve that incorporates the effect of impact angle.

In Fig. 3 we see that the distribution of the normalized test data points about the normalized original NNO BLE curve and the normalized NNO BLE curve that has had its high-end transition velocity modified is nearly identical to the distribution of the corresponding original test data points about the appropriate non-normalized BLE curves in Figs. 1 and 2. This demonstrates that the normalization scheme proposed herein is successful in combining test data at varying trajectory obliquities. It also indicates that the modifications made to the normalized NNO BLE so that it can capture the P / NP characteristics of normalized test data should transfer back, that is, the un-normalized version of the NNO BLE should also be able to capture the P / NP characteristics of seen in test data (see also [22]).

4 Additional modifications to the aluminum-projectile-based NNO BLE

It is clear from Fig. 4 that additional adjustments are still needed to improve the accuracy of the NNO BLE when predicting the response of dual-wall aluminum systems impacted

by non-aluminum projectiles. The following parameters are available for adjustment in the normalization scheme developed herein to achieve this goal: V_L , V_H , C_L , and C_H .

The values of the transition velocities V_L and V_H depend on where, in terms of velocity, changes in impact response phenomenologies occur, while C_L and C_H are curve-fitting parameters whose values are determined by optimizing the placement of the BLE with respect to the P / NP data on the plotting grid. As a result, changes to C_L and C_H are made only after new “anchor points” V_L and V_H are determined. And, since V_L and V_H are functions of changes in response phenomenologies, which themselves are related to material properties, two sets of modified coefficients and anchor points (and hence two modified BLEs) are needed—one for projectiles that are denser than aluminum, and one for those that are less dense.

The high-end transition velocity V_H is typically taken to be the velocity at which the impact projectile is fully melted. This velocity can be estimated for each of the projectile materials using a 1-D shock physics based calculation. In this process, shock pressures, internal energies, etc., in the projectile and bumper materials are found using the three 1-D shock-jump conditions, a linear relationship between the shock wave velocity and particle velocity in each material, and continuity of pressure and velocity at the impact site. Once the residual internal energies in the projectile and target materials

Fig. 4 Plots of the revised and original normalized NNO BLEs for projectile materials more dense than aluminum and comparisons with experimental data (see also [22])

are found, the percentages of the various states of matter in the resulting debris clouds can also be determined (see, e.g., [23, 24] for a more detailed description of this calculation process).

Tables 2 and 3 presents the calculated percentages of projectile material that is either solid, liquid, or vapor (%S, %L, %V, respectively) for the projectile materials considered in this study. Also shown in Tables 2 and 3 are the impact velocities at which projectile melt is estimated to begin and to be completed, (V_{mb} and V_{mc} , respectively), based on the %S-%L-%V values in the preceding rows for each projectile material.

As can be seen in Tables 2 and 3, for Pyrex projectiles, there is no %S-%L-%V information beyond an impact velocity of 3.1 km/s. A Heat of Fusion for does not exist for Pyrex (or glass in general); hence, the 1-D shock physics calculation process could not be used for Pyrex beyond the velocity at which it begins to melt. After that velocity, Pyrex is taken to be fully melted.

Furthermore, the impact velocities at which aluminum-on-aluminum impacts result in either incipient melt or complete melt agree with previously published values of 5.5 and 7.0 km/s, respectively. This implies that the process used to obtain corresponding values for the other materials can be expected to yield reasonable results as

well (except possibly for Al_2O_3). Also, the impact velocity at which melt is completed for steel projectiles impacting aluminum bumper plates (8.7 km/s) is fairly close to the 9.1 km/s value noted previously.

Considering these points as well as the study's goal of developing single modified BLEs for less dense and more dense projectiles, the following new low-end and high-end transition velocities are proposed:

- *More dense projectile materials:* $V_L = 5.7$ km/s, $V_H = 9.1$ km/s
- *Less dense projectile materials:* $V_L = 2$ km/s, $V_H = 3$ km/s

These values of V_L and V_H are initially based on the V_{mb} and V_{mc} values in Tables 2 and 3, and then subsequently adjusted to secure a better fit to the data. It is important to note that the values of V_{mb} and V_{mc} are used to inform, and not determine the values of V_L for the more and less dense projectile BLEs. These adjustments were made based on changes in values of the sensitivity and specificity ratios obtained for various selections of V_L and V_H values. The velocity V_L is, of course, the limit velocity between the low velocity regime, i.e. the ballistic regime, and the shatter regime. As such, it corresponds to the start of projectile fragmentation due to rarefaction wave interaction [25]. To

Table 2 Results of 1-D shock physics calculations—less dense projectile materials (%S, %L, %V ... percent of projectile material that is solid, liquid, or vapor following shock loading and release)

V_p	Lexan			V_p	Nylon			V_p	Pyrex		
km/s	%S	%L	%V	km/s	%S	%L	%V	km/s	%S	%L	%V
1.97	100.0	0.0	0.0	2.80	100.0	0.0	0.0	3.1-	100.0	0.0	0.0
1.98	98.1	1.9	0.0	2.81	94.0	6.0	0.0	3.1+	0.0	100.0	0.0
2.20	46.6	53.4	0.0	2.90	29.0	71.0	0.0				
2.37	1.7	98.3	0.0	2.93	6.8	93.2	0.0				
2.38	0.0	100.0	0.0	2.94	0.0	100.0	0.0				
V_{mb}	1.97			V_{mb}	2.80			V_{mb}	3.10		
V_{mc}	2.38			V_{mc}	2.94			V_{mc}	3.10		

Table 3 Results of 1-D shock physics calculations—more dense projectile materials (%S, %L, %V ... percent of projectile material that is solid, liquid, or vapor following shock loading and release)

V_p	Aluminum			V_p	Al_2O_3			V_p	Steel			V_p	Copper		
km/s	%S	%L	%V	km/s	%S	%L	%V	km/s	%S	%L	%V	km/s	%S	%L	%V
5.40	100.0	0.0	0.0	10.7	100.0	0.0	0.0	7.00	100.0	0.0	0.0	6.45	100.0	0.0	0.0
5.50	98.7	1.3	0.0	10.8	98.9	1.1	0.0	7.50	99.0	1.0	0.0	6.50	97.9	2.1	0.0
6.00	65.2	34.8	0.0	12.4	54.7	45.3	0.0	8.00	58.2	41.8	0.0	7.00	56.7	43.3	0.0
6.85	1.1	98.9	0.0	14.1	1.9	98.1	0.0	8.65	1.3	98.7	0.0	7.70	0.3	99.7	0.0
6.90	0.0	100.0	0.0	14.2	0.0	100.0	0.0	8.70	0.0	100.0	0.0	7.80	0.0	100.0	0.0
V_{mb}	5.40			V_{mb}	12.4			V_{mb}	7.40			V_{mb}	6.45		
V_{mc}	6.90			V_{mc}	15.9			V_{mc}	8.70			V_{mc}	7.80		

The %S-%L-%V values in this table are "italicized" for Al_2O_3 to indicate that its incipient and complete melt velocities are likely beyond the Mie-Grüneisen EOS's usefulness.

accurately pinpoint this transition velocity would require either a finely tuned experimental program or detailed numerical simulations of the impact phenomenologies involved. However, for the purposes of this investigation, using 1-D shock physics based estimates of V_{mb} and V_{mc} did provide useful insights into possible adjustments to V_L , something that, prior to this study, had not yet been attempted.

Furthermore, as mentioned previously, in addition to modifying the low-end and high-end transition velocities, V_L and V_H , respectively, the two curve-fitting parameters, C_L and C_H , have been modified for each class of projectile material density. These modifications were based on the placement of the normalized P / NP points, and are given as follows:

- *More dense projectile materials:* $C_L = (1/0.33)^{18/19} = 2.855$, $C_H = 3.918$
- *Less dense projectile materials:* $C_L = (1/0.15)^{18/19} = 6.0332$, $C_H = 3.2$

5 Results

Figure 4 and 5 show plots of the revised normalized NNO BLE for the more dense and less dense projectile materials, respectively, based on the V_L , V_H , and C_L , C_H values as noted above.

As can be seen in Figs. 4 and 5, these modifications to the NNO BLE create formulae that more successfully separate regions where penetration occurred from regions where it did not. Furthermore, as indicated thus far by test data, the adjusted parameters are not very sensitive to projectile density for the more dense projectiles (steel, copper) used in the ORDEM-3 model. These figures also demonstrate a viable method of directly comparing results from a range of test conditions that can be evaluated with the NNO BLE.

6 Discussion

In order to assess the “goodness of fit” for the new BLEs and compare it that of the original NNO BLE, we can use **specificity** and **sensitivity ratios**, which are defined as follows (see [26] for additional information regarding these quantities):

- **Sensitivity ratio** = (# of penetrations predicted as penetrations) / (# of penetrations predicted as penetrations + # of penetrations predicted as non-penetrations)
- **Specificity ratio** = (# of non-penetrations predicted as non-penetrations) / (# of non-penetrations predicted as non-penetrations + # of non-penetrations predicted as penetrations)

Fig. 5 Plots of the revised and original normalized NNO BLEs for projectile materials less dense than aluminum and comparisons with experimental data (see also [22])

Table 4 Sensitivity and specificity ratios—more dense projectiles BLE

	$N(P \rightarrow P)$	$N(P \rightarrow NP)$	Sensitivity ratio	$N(NP \rightarrow NP)$	$N(NP \rightarrow P)$	Specificity ratio
Original NNO BLE	14	11	0.56	10	13	0.43
Modified NNO BLE	21	4	0.84	12	11	0.52

Table 5 Sensitivity and specificity ratios—less dense projectiles BLE

	$N(P \rightarrow P)$	$N(P \rightarrow NP)$	Sensitivity ratio	$N(NP \rightarrow NP)$	$N(NP \rightarrow P)$	Specificity ratio
Original NNO BLE	6	0	1.00	18	2	0.90
Modified NNO BLE	6	0	1.00	20	0	1.00

These quantities are frequently used in the medical profession as a means of assessing the reliability of a test to discern between true and false positives and true and false negatives (see, e.g., [27]). Tables 4 and 5 present the specificity and sensitivity ratios for the denser projectile BLE and the less dense projectile BLE, respectively, and compare those values to corresponding values in each case for the NNO BLE. In these Tables, $N(X \rightarrow Y)$ denotes the number of times an X event was predicted as a Y event by a particular BLE.

In Table 4 we see that both the sensitivity and specificity ratios are fairly low for the original NNO BLE, indicating a problem with the testing method or with test repeatability or that BLE is not appropriate for the impact conditions being modelled. Also evident in Table 4 is a significant improvement (increase) in the sensitivity value when the modified NNO BLE is considered. Paired in that particular case with a relatively low specificity ratio, we have can conclude that the modified NNO BLE can be a bit conservative when modelling the P / NP response of more dense projectiles impacting aluminum dual-wall systems. This would be a favorable feature if this BLE were to be used to design human-tended spacecraft, where safety and the protection of human life is paramount.

Regarding the information in Table 5, both the original and the modified BLEs do a good job of modelling the P / NP response of less dense projectiles impacting aluminum dual-wall systems—both sets of values are high, so that both curves in Fig. 5 can be considered to be “fairly accurate”. Of course, the form of the modified NNO BLE results in both ratios being equal to one, indicating that the all of the P and NP data concerned herein fall on the appropriate side of the BLE curve.

Finally, it is interesting to note that the shape of the modified NNO BLE for the less dense projectiles in Fig. 5 resembles more that of a single-wall BLE rather than the more common “bucket shape” of a dual-wall BLE. This

might be explained by the following considerations. In less dense materials like Pyrex, whose sound speed is so much less than that of a more dense material, fracture and melt happens at velocities that are very close to each other. In such a case, the transition regime, while still present, is very short, thereby creating the impression and appearance of a single-wall BLE (see, e.g., [28]).

The importance of these results is that now spacecraft design engineers have available to them BLEs that can be used to assess the response of their spacecraft when it is struck by a high speed orbital debris particle *without* having to assume that the impact particle is made of aluminum. Until now, because dual-wall BLEs were available only for aluminum projectiles, spacecraft design engineers were forced to create an equivalent aluminum projectile if they were interested in predicting the P / NP response of non-aluminum projectiles (most likely through some mass and diameter consistency formulation). However, now that the equations presented in this paper have been developed, that kind of equivalencing is no longer needed—when these equations are included in, for example, a handbook on spacecraft design for the MMOD environment (see, e.g., [29]), spacecraft design engineers will have at their disposal equations tailored for exactly the kinds of projectiles that concern them.

7 Concluding thoughts and suggestions for future work

This paper presented a summary of the work performed to assess the validity of an existing, commonly used, dual-wall aluminum-projectile-based BLE for non-aluminum projectile impacts. Projectile materials considered included steel, copper, and Al_2O_3 (i.e. projectiles that are made of materials that are more dense than aluminum) and glass, nylon and Lexan (which are less dense than aluminum). In the

end, the aluminum-projectile-based BLE was found not to work sufficiently well in the predicting penetration / no penetration response of non-aluminum projectiles. This BLE was then modified so that, when compared to the pre-modifications versions of same BLE, it would much better model the impact response of non-aluminum projectiles.

Based on the work performed, it would appear that several carefully orchestrated hydrocode runs should be performed in areas where there is a dearth of empirical information for projectile materials of interest. These results can then be used to ascertain whether or not the BLEs for more dense and less dense projectiles are well-positioned, or whether or not some additional modifications are needed. Furthermore, considering the clearly differing behavior of dual-wall structures impacted by Al_2O_3 particles (as compared to when such structures are struck by steel or copper particles), it might be worthwhile to repeat the analyses reported on herein, but for more dense metallic projectiles only. These efforts will, in turn, assist in the continuing evolution of the ballistic limit equations used to predict the response of single- and multi-wall spacecraft structures to high-speed impacts.

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Compliance with ethical standards

Conflict of interest The author declares that the content of this work presents no conflict of interest.

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