Will it Leak? Will it Burst?
COPV Perforation and Rupture after a MMOD Impact

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ABSTRACT

Most spacecraft have at least one pressurized vessel on board. Because of the serious damage that might result following a high-speed on-orbit space debris particle impact, a primary design consideration is the anticipation and mitigation of that damage. Depending on pressure vessel design and impact / operating conditions, a pressure vessel impacted at hypervelocity may experience either only relatively shallow damage; a through-hole, perhaps with localized liner cracking or composite peeling; or catastrophic failure (rupture). While a puncture and the resulting leak could de-stabilize an orbiting spacecraft, an on-orbit rupture could not only lead to spacecraft loss, but for human missions, possibly loss of life. Herein we present the development of a ballistic limit equation (BLE) and a rupture limit equation (RLE) for composite overwrapped pressure vessels. Similar to a BLE that can be used to characterize whether or not a pressure vessel would be punctured by a high-speed impact, an RLE is designed to differentiate between regions of operating and impact conditions that, given a perforation, would result in either a rupture or would result only in a relatively small hole or crack. In a risk assessment that considers the various failures that might occur following debris impact, both types of equations are required. Comparisons of the RLE and the BLE developed herein with experimental results shows that both equations are able cleanly separate the regions of rupture from non-rupture, and perforation from non-perforation. As such, the equations presented are both highly accurate in predicting the response of the COPVs and impact conditions considered.

1 INTRODUCTION

Most spacecraft have at least one pressurized vessel on board. Because of the serious damage that might result following an on-orbit micro-meteoroid or orbital debris (MMOD) particle impact, a primary design consideration is the anticipation and mitigation of that damage. Considerable effort has been expended in the study of flat unstressed spacecraft components under conditions intended to simulate those of a debris particle impact.

However, pressurized tank walls will develop bi-axial stress fields. Numerous challenges have limited the testing conducted using pressurized elements, especially composite overwrapped pressure vessels (COPVs). To address this issue, a program was undertaken to characterize the hypervelocity impact response of COPVs.

Depending on COPV design and impact / operating conditions, a COPV impacted at hypervelocity may experience either only relatively shallow damage; a through-hole, perhaps with localized liner cracking or composite peeling; or catastrophic failure (rupture). While a puncture and the resulting leak could de-stabilize an orbiting spacecraft, an on-orbit rupture following an MMOD particle impact could not only lead to spacecraft loss, but for human missions, possibly loss of life.

Whether or not a structural element is perforated is typically characterized by ballistic limit equations (BLEs). These equations are traditionally derived from data-based curves which are drawn to distinguish between regions of perforation and non-perforation (P/NP) in terms of impact parameters and element configuration materials, geometries, etc.

Similar to a BLE, a rupture limit equation (RLE) can be used to characterize whether or not rupture would occur following a perforating impact. Such an equation can be developed in a fashion again similar to that used in BLE development, namely, by forming a curve that distinguishes between regions of rupture and non-rupture (R/NR) in terms of impact parameters, element configurations, geometries, etc.

In a risk assessment that considers the various failures that might occur following debris impact, both types of equations are required. Herein then we present the development of these two types of equations for COPVs impacted by hypervelocity particles. The RLE is designed to differentiate between regions of operating and impact conditions that, given a perforation, would result in either a rupture or only a relatively small hole or crack. Similarly, the BLE is constructed so that it distinguishes between impact and operating conditions that would result in a front side puncture (without rupture) from those that would not.

Data from over 50 impact tests on 3 different types of COPVs are pooled together and used in the development of the RLE and the BLE. Operating conditions were parameterized as the hoop stress in the tank, while impact conditions were parameterized using momentum. A comparison of the RLE and the BLE with experimental results shows that both equations are able cleanly separate the regions of rupture from non-rupture, and perforation from non-perforation. As such, the equations presented are both highly accurate in predicting the response of the COPVs and impact conditions considered.

2 TEST PARAMETERS OVERVIEW

Tables 1 and 2 present a summary of the test conditions and the geometric parameters and material properties of the COPVs used in the test programs that provided the data upon which the RLE and BLE developed herein were based.

Table 1. Overview of Impact Test Conditions

Parameter			Units
Projectile	Material	Al 2017-T4, 440C SS	
Projectile	Diameter	1.0 – 3.0	mm
Trajectory	Obliquity	0, 45, 60	deg
Trajectory	Velocity	~4, ~7	km/s
Contents		Air, Water, GN2	
Pressure		0, 20 – 50	MPa

Table 2. Geometric and Material Properties of COPVs

Parameter			Units
COPV Diameter (O.D.)		10.0 – 42.5	cm
COPV Length (cylinder)		25 – 55	cm
Composite	Fiber	T1000	
Composite	Matrix	LRF-092, HARF-53, SIREZ	
Composite	Thickness[a]	1.91 – 6.95	mm
Liner	Material	Al 6061-T6, Inconel	
Liner	Thickness[a]	0.81 - 2.30	mm

[a]Nominal composite and liner thicknesses in cylindrical portions of COPVs

3 RUPTURE LIMIT EQUATION DEVELOPMENT

3.1 Comments on the Data

It is important to note that only tests in which the projectile impacted the cylindrical portion of the COPV were considered in the development of the RLEs. While a number of tests were conducted with impacts occurring on the shoulder or hoop-to-dome-transition region (HTDTR), these tests were not included because of the complexity of the stress fields in this region. While hoop stresses in the cylindrical portion of a COPV could be reasonably approximated using fundamental mechanics-based equations, the dependence of the HTDTR hoop stress on dome shape as well as internal pressure, thickness, etc., precluded the development of a simple equation from being developed and used in subsequent analysis and curve development.

3.2 Equation Development

The RLE was developed using R/NR data from a number of studies involving high-speed impact of COPVs (see, e.g., [1-3]). To render the equation as broadly applicable as possible, the operating conditions (x-axis) were parameterized as the hoop stress in the tank (non-dimensionalized by the uni-directional ultimate stress of the tank wall composite material), and the impact conditions (y-axis) were parameterized as impact momentum (non-dimensionalized by a number of appropriate tank wall material properties). This approach was used successfully to model the R/NR response of cylindrical and spherical metallic tanks [4], COPVs under cryogenic operating conditions [5], and flat composite material plates under high-speed projectile impact [6].

Following on the successful application of this approach in the previous studies noted above, a simple power law form was chosen for the RLE to be developed. Specifically, the power law for the curve that separates regions of rupture and non-rupture was chosen as follows:

$$\textit{Non-dimensional Projectile Momentum} = A\left(\frac{\sigma_{hoop}}{\sigma_{ult}^{comp}}\right)^{B} \quad (1)$$

where $\sigma_{hoop} = p_{int}r_{OD}/t_{tot}$ and σ_{ult}^{comp} are the COPV hoop stress and uni-directional ultimate stress of the COPV composite material, respectively; $t_{tot} = t_{comp} + t_{liner}$ is the total nominal thickness of the cylindrical portion of the composite material overwrap, p_{int} is the internal pressure in the COPV, and r_{OD} is the COPV outer radius.

The non-dimensional form of projectile momentum was taken initially to be given as follows:

$$\textit{Non-dimensional Projectile Momentum} = \frac{m_{proj}V_{proj}^{norm}}{(\rho_{comp}t_{tot}^{3})\sqrt{\frac{\sigma_{ult}^{comp}}{\rho_{comp}}}} \quad (3)$$

where V_{proj}^{norm} is the normal component of the impact velocity. The first term in the denominator in Eq. (3) has units of mass while the second has units of velocity, thereby rendering the right-hand-side of Eq. (3) unitless, or non-dimensional, so long as there is consistency in the units of mass and velocity used in its numerator and denominator.

To include the effects of other material parameters, Eq. (3) was modified through the addition of a number of other unitless terms, with the following result:

$$\textit{Non-dimensional Projectile Momentum} = \frac{m_{proj}V_{proj}^{norm}}{(\rho_{comp}t_{tot}^{3})\sqrt{\frac{\sigma_{ult}^{comp}}{\rho_{comp}}}}\left(\frac{\rho_{proj}}{\rho_{comp}}\right)^{Q}\left(1+\frac{\sigma_{ult}^{liner}}{100}\right)^{S}\left(1+\frac{\sigma_{yld}^{liner}}{100}\right)^{T} \quad (4)$$

where the ultimate and yield stresses of the liner material, σ_{ult}^{liner} and σ_{yld}^{liner}, respectively, are in MPa. The liner material yield and ultimate stress values were divided by 100 so the terms involving these quantities can have a meaningful effect without being excessively large compared to the values of the other terms in the equation. Combining Eqs. (1) and (4) yields the final form of the RLE as follows:

$$\frac{m_{proj}V_{proj}^{norm}}{(\rho_{comp}t_{tot}^{3})\sqrt{\frac{\sigma_{ult}^{comp}}{\rho_{comp}}}}\left(\frac{\rho_{proj}}{\rho_{comp}}\right)^{Q}\left(1+\frac{\sigma_{ult}^{liner}}{100}\right)^{S}\left(1+\frac{\sigma_{yld}^{liner}}{100}\right)^{T} = A\left(\frac{\sigma_{hoop}}{\sigma_{ult}^{comp}}\right)^{B} \quad (5)$$

The particular forms of the non-dimensionalized hoop stress and impact momentum seen in Eqs. (1)–(5) were motivated by the desire to include those terms that not only characterized the impact loads and internal pressurize conditions, but at the same time included material parameters that were seen to differ among the various test programs considered herein.

Furthermore, the ability to use these equations does not rely on having to know the exact lay-up or stacking sequence of the composite laminae in the COPV – all that is needed is the uni-axial ultimate strength of the material. This serves to increase the ease of use of these equations and their potential applicability to a wider family of COPV constructions.

The exponents Q,S,T in Eq. (4) were selected so as to allow, as much as possible, a natural separation between the ruptured and non-ruptured data points. This would, in turn, facilitate the development of a RLE that would, again, as much as possible, lie between those two regions.

The attractiveness and benefit of this approach is that if additional tests results were to become available, the exponents Q,S,T in Eq. (3) could again be adjusted to allow the incorporation of whatever new R/NR becomes available and the subsequent development of a new RLE. For the data available thus far, the values of the exponents Q,S,T used in the non-dimensionalization scheme in Eq. (4) are give as follows: Q = 0.1, S = -1.0, and T = -1.0.

The constants A and B in Eq. (1) were determined using a regression-based analysis of the R/NR data. This regression was performed by creating a function that is a linearized form of Eq. (5) which would take on values of +1 or -1 depending on whether a particular test resulted in a rupture or a non-rupture. Once the constants of this function are obtained, the values A and B are found to be A = $2.166\text{x}10^{-3}$, and B = -0.943; the correlation coefficient of the regression was approx. 74.3, which indicated a fairly good fit of the linearized curve to the R/NR data.

The values of A and B noted above are updated values from Ref. [7]. This update was required following new information that was received regarding composite overwrap and liner thickness values at the impact site for several of the tests conducted with internal pressures having non-dimensional hoop stress values between 0.10 and 0.15.

3.3 Comparison of RLE against Empirical R/NR Results

Figures 1 and 2 show plots of the RLE developed using the process outlined in the previous section and compared to experimental rupture / non-rupture results. These figures also show plots of $\pm$ one standard deviation curves and $\pm$ two standard deviation curves about the RLE curve. Figure 1 is a plot of all the data, while Fig. 2 is a "zoomed-in" version of Fig. 1 to allow closer inspection of the cluster of data at lower momentum values.

In Figs. 1 and 2, the orange data points represent those tests that resulted in tank rupture, while the green data points show those that did not rupture, but did sustain a perforation through the composite overwrap and internal metallic liner. The blue data points correspond to those tests in which perforation of the COPV liner did not occur, although in such tests the composite overwrap did sustain damage, even down to the metallic liner in some cases.

The $\pm$ one and $\pm$ two standard deviation curves about the RLE curve shown in Figs. 1 and 2 were obtained using the statistical information forthcoming as part of the linear regression exercise that yielded the coefficients that lead to the constants A and B using well-established formulations (see, e.g. [8]). A closer look the RLE curve and the $\pm$ one and $\pm$ two standard deviation curves about the RLE curve in Figs. 1 and 2 reveals several points of interest.

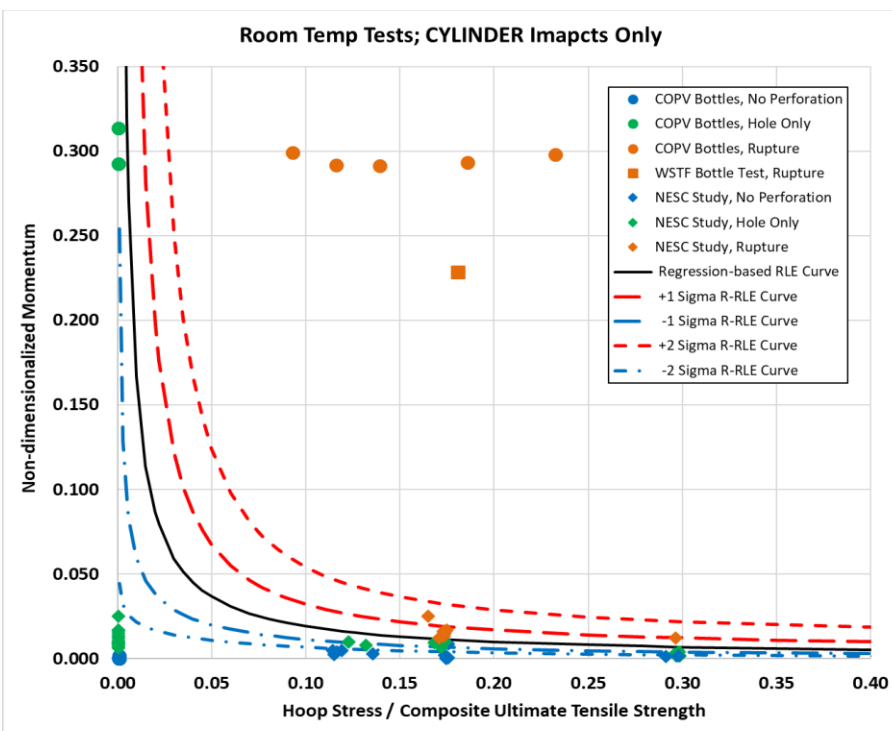

Fig. 1. Plots of Regression-based RLE Curve, Standard Deviation Curves, and Experimental Rupture/Non-rupture Data

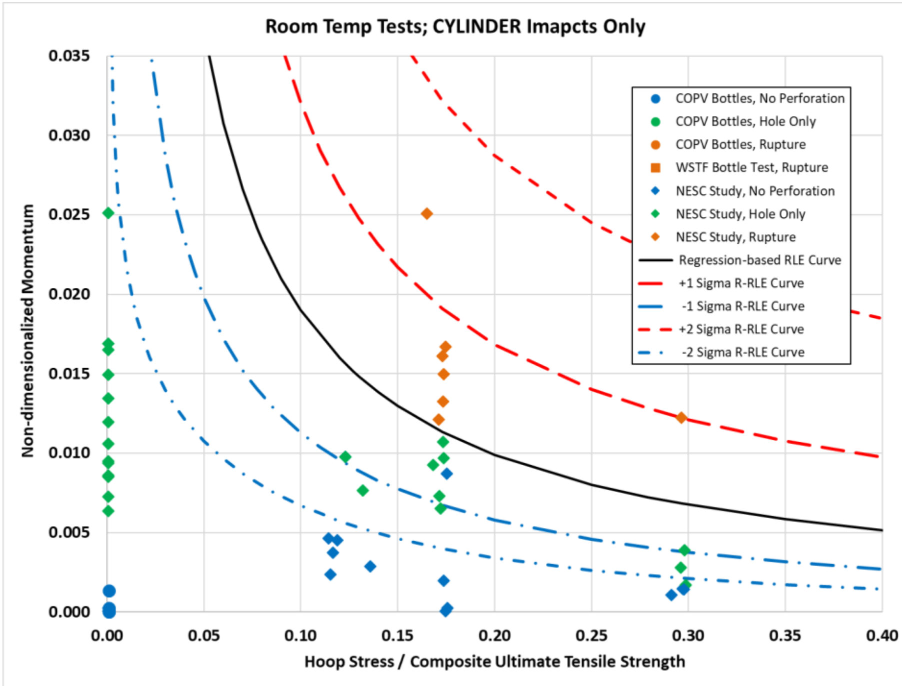

Fig. 2. Zoomed in Plots of Regression-based RLE Curve, Standard Deviation Curves, and Experimental Rupture/Non-rupture Data

1. The RLE shown in Fig. 1 as well as in Fig. 2 appears to make a clean cut between the green (non-rupture) and orange (rupture) data points. Thus, the RLE curve developed using this approach is 100% accurate in discriminating between COPV ruptures and non-ruptures as indicated by the data obtained thus far.

2. The RLE curve appears to be “skewed” to lie closer to the NR (green) data points near an ordinate value of ~0.30. However, this is merely an artifact of the regression process which was performed using log values of actual non-dimensionalized hoop stress and projectile momentum.

3. The confidence bounds on the RLE shown in Figs. 1 and 2 appear to be a bit wide. However, this is not unexpected for the following reasons.

    a. As can be seen in these figures, the data are grouped in four clusters: horizontally near a non-dimensional momentum value of ~0.3, and vertically about the non-dimensional hoop stress values of ~0, ~0.125, ~0.175, and ~0.30. Wide confidence bounds such as those shown in Figs. 1 and 2 are to be expected considering the distribution of the test data that were used in the development of this preliminary RLE.

    b. The validity of any regression analysis is predicated on the assumption of relatively continuous changes in dependent variable values with respect to corresponding changes in the values of the independent variables. In this exercise, values of +1 or -1 were assigned to the dependent variable function, depending on whether a particular test resulted in either a rupture or a not-rupture. This approach, while certainly capable of producing a curve fit for this type of non-continuous dependent variable data, is well-known to produce highly conservative error bounds, which are clearly evident in Figs. 1 and 2.

4. While this RLE is satisfactory as a preliminary attempt, the wide confidence bounds in Figs. 1 and 2 indicate that the RLE could be anywhere in the confidence region, and that it contains sensitive parameters whose slight variation could possibly significantly change the location and shape of the curve. Until and unless additional

tests are performed to generate data points in other regions of the plots shown in these figures, it is unlikely that best fit curves with "tighter" confidence bounds can be developed using this approach. If a reduction in the uncertainty bounds shown in Figs. 1 and 2 is desired, a more sophisticated or robust approach for determining alternative curves that discriminate between rupture and non-rupture data points is required.

5. The decided lack of overlapping of the rupture/non-rupture test data is primarily due to the judicious selection of the values of the exponents Q,S, and T. However, this lack of overlap is admittedly rather unusual, especially in hypervelocity impact test programs (see, e.g. the overlap and scatter in such testing of metallic dual-wall systems [9]). It is indeed possible that additional testing of similar COPVs could yield test results that cannot be so cleanly separated. In this case, there might be quite a bit of overlap and engineering judgement will be needed regarding where to best place the RLE (as well as the associate BLE) so as to best meet program needs and requirements. For example, in a program where a more conservative curve is required (e.g. one in which crew safety is paramount), the RLE can be shifted "downward" amongst any overlapping data. However, if a higher element of risk is acceptable in a particular program, then it can be shifted "upward" amongst the overlapping R/NR data.

4 BALLISTIC LIMIT EQUATION DEVELOPMENT

During the test programs that generated the data used in the development of the RLE, as projectile diameter was increased while impact velocity was kept (relatively) constant, it was observed that before projectiles were large enough to cause rupture there were impact conditions that resulted in merely front side perforation of the COPV (even under highly pressurized conditions). While catastrophic failure (i.e. a rupture) as a result of a high-speed MMOD particle impact would be disastrous to a mission and to the spacecraft occupants (if any), a perforation or puncture and the resulting thrust caused by the expulsion of fluids or gas from the perforated tank could result in the de-stabilization of the spacecraft's orbit (see, e.g. [10]). This, in turn, could also lead to loss of the spacecraft and quite possibly, for human missions, loss of life. As a result, an equation is needed that would distinguish between combinations of impact parameters and operating conditions that would result in a puncture (without rupture) of the front side of an impacted pressure vessel from those that would not.

4.1 Comments on the Data

Except for a single blue (or non-perforation) data point in Figs. 1 and 2, all of the green (perforation or venting, but non-rupture) data points appear to be grouped separately from the blue (non-perforation) tests. This should allow for the fairly straightforward development of a simple ballistic limit equation, or BLE, for the COPVs considered in this study, based on the test data obtained thus far.

With regard to the apparent "errant" non-perforation data point noted above, a review of the results for this test as well as for another test of the same kind of COPV and under similar operating (i.e. internal pressure) conditions reveals that liner thickness at its thinnest point (i.e. the crater floor) in the "errant test" was less than 50% of its original thickness, while the liner thickness at its thinnest point in the other "similar" test was just over 80% of its original thickness.

Subsequent pressurization of both test articles resulted in a burst pressure for the "errant test" to be only slightly above the internal pressure at testing, while the burst pressure for the other "similar" test was closer to the maximum expected operating pressure of the COPV. Based on this information, it would appear that the "errant test" was on the verge of being penetrated, but was not, possibly due to some variations in the materials from which that particular test article was made.

4.2 Equation Development

Considering, then, the rather clean separation of the liner penetration (green) and liner non-penetration (blue) data points seen in Figs. 2 and 4, we now construct a ballistic limit equation (BLE) for the COPVs considered in this study, which can be used to predict the onset of "front face" liner perforation of these and similar COPVs. In this particular case, the coefficients of a relatively simple function were adjusted subject to the following conditions with regard to the blue and green data points in Fig. 2:

1. the resulting curve should lie between the highest blue and lowest green data points when the non-dimensional hoop stress was ~0, ~0.125, ~0.175, and ~0.30; and,

2. the resulting curve should approach zero as the non-dimensional hoop stress approached unity.

After several iterations, the final form of the BLE was found to be given as follows:

$$\textit{Non-dimensional Projectile Momentum} = P_O \frac{1-e^{-C(1-\sigma_{hoop}/\sigma_{ult}^{comp})^E}}{1-e^{-C}} \qquad (21)$$

where values of the constants in Eqn (21) are $P_0 = 6.0\text{x}10^{-3}$, C = 4.0, E = 7.25.

These values of P_0, C, and E are again updated values from Ref. [7]. This update was required following new information that was received regarding composite overwrap and liner thickness values at the impact site for several of the tests conducted with internal pressures having non-dimensional hoop stress values between 0.10 and 0.15.

4.3 Comparison of the BLE against Empirical P/NP Results

Figure 6 shows a plot of the proposed BLE amid the pertinent data. As can be seen from Fig. 6, the BLE developed in this fashion, with the exception of the single "errant" point noted above, correctly discriminates between regions of liner perforation and non-perforation.

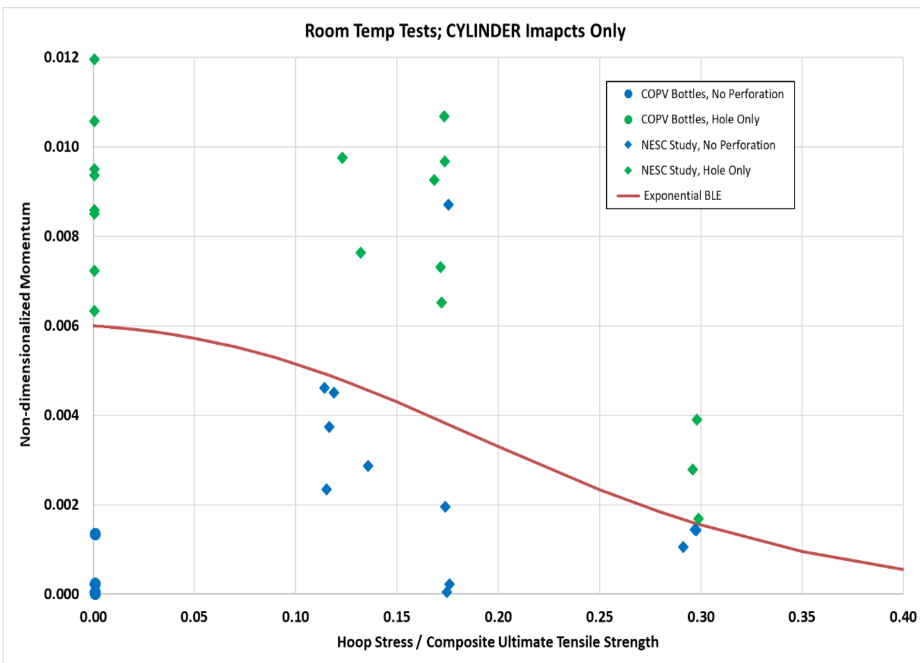

Fig. 6. Plot of Exponential BLE Curve and Experimental Perforation/Non-Perforation Data

5 SUMMARY AND CONCLUSIONS

A preliminary rupture limit equation (RLE) was successfully developed that can be used to discriminate between combinations of projectile momentum and COPV hoop stress that likely will or will not result in an impact-induced rupture of a COPV similar to the ones considered in this study. Similarly, a preliminary ballistic limit equation (BLE) was successfully developed that can be used to discriminate between combinations of projectile momentum and COPV hoop stress that likely will or will not result in an impact-induced puncture (without rupture) of a COPV similar to the ones considered in this study. In both cases, the RLE and BLE developed were able to correctly discriminate between regions of COPV rupture and non-rupture, and liner perforation and non-perforation, respectively. Further testing is needed, particularly for impact momentum and hoop stress combinations for which it appears to have not yet been done, and for other COPV configurations and constructions, in order to further refine the RLE and BLE and to render them applicable under a wider range of impact scenarios and operating conditions.

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