Predicting the Rupture of a Cryogenic Composite Pressure Vessel (COPV) Following a Hypervelocity Impact

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ABSTRACT

In some satellites the fuel tank or some other pressurized vessel is necessarily exposed to the hazards of space. A primary design consideration for such a spacecraft is the anticipation and mitigation of the possible damage that might occur in the event of an on-orbit micro-meteoroid or orbital debris (MMOD) particle impact. While considerable effort has been expended in the study of non-pressurized spacecraft components under room temperature conditions to MMOD impacts, technical and safety challenges have limited the number of tests that have been conducted on pressurized elements of such spacecraft, especially under cryogenic conditions. This paper presents the development of a data-driven equation for composite material pressure vessels (COPVs) under cryogenic operating conditions that differentiates between impact conditions that, given a tank wall perforation, would result in only a small hole or crack from those that would cause catastrophic tank failure. These equations would be useful to a spacecraft designer who might be able to tailor the design parameters and operating conditions of a tank so that if that tank were to be struck and perforated by the impact of an MMOD particle, then only a hole would occur and additional sizable debris would not be created as a result of that impact.

Key words: hypervelocity impact, cryogenic, COPV, rupture, orbital debris

1 INTRODUCTION

Most spacecraft have at least one pressurized vessel on board. For robotic spacecraft, it is usually a liquid propellant tank. In some satellite or spacecraft designs, the fuel tank or some other pressurized vessel is necessarily exposed to the hazards of space, including the micro-meteoroid and orbital debris (MMOD) environment. Because of the potential of serious mission-threatening damage that might result following an on-orbit MMOD impact, one of the primary design considerations of such spacecraft is the anticipation and mitigation of the possible damage that might occur in the event of such an impact. Considerable energy and effort has been expended in the study of the response of non-pressurized spacecraft components under room temperature conditions to MMOD impacts. However, fuel tanks are pressurized internally, and so their main walls will develop bi-axial stress fields because of that internal pressurization. Technical and safety challenges have limited the number of tests that have been conducted on the pressurized elements of such spacecraft, especially under cryogenic conditions.

This paper summarizes the results of initial efforts to address one aspect of this problem, namely, the development of general, data-driven equations for highly pressurized elements such as fuel tanks that differentiate between impact conditions that would result in only a small hole or crack from those that would cause catastrophic tank failure. This is an important consideration in the design of a pressurized tank – if possible, design parameters and operating conditions should be chosen such that additional sizable debris (such as that which would be created in the event of tank rupture or catastrophic failure) is not created as a result of an on-orbit MMOD particle impact. Furthermore, the analyses performed focus on composite material pressure vessels (COPVs) under cryogenic operating conditions.

2 MODELLING THE RUPTURE/NON-RUPTURE RESPONSE OF COPVS

There have been many high-speed impact test studies performed using tanks or pressure vessels over the past 50 years. These tests have been performed with varying amounts of internal pressure (including none); with internal fluids, air, or at a vacuum; using metallic tanks and composite material tanks; with spherical tanks as well as cylindrical tanks; using internal fluids at temperatures ranging from room temperature to cryogenic temperatures; and, with and without

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MMOD shielding. Reference [1] provides a breakdown of the high-speed impact testing that was done using pressurized tanks over the past 50 years. In this particular study, we focus on the high-speed impact tests performed on unshielded COPVs with internal cryogenic fluids [2,3].

The objective of the work performed was to develop an empirically-based equation that could be used to determine whether or not a particular set of impact parameters under a specified operation condition would result in the rupture of the tank. To render the equations as broadly applicable as possible, the operating conditions (x-axis) were parameterized as the hoop stress in the tank (normalized with respect to the temperature-adjusted ultimate tensile stress of the composite overwrap material). The impact conditions (y-axis) were parameterized in two ways: as impact energy, and as impact momentum, both normalized with respect to a number of appropriate tank wall material properties. Data from 24 impact tests were used in the development of these equation. Approx. 1/3 of the tests were performed using pressurized bottles; the remaining 2/3 were performed using so-called “pressure cylinders”. These cylindrical test articles consisted of one flexible endcap plate that made of the material of interest and which was impacted by the high-speed projectile.

Figs. 1 and 2 are plots of radially impacted, unshielded COPVs, showing which tests resulted in tank rupture (orange data points) and which did not (green data points). Fig. 1 shows the results when the data is plotted against normalized impact energy, while Fig. 2 shows the results when the data is plotted against impact momentum.

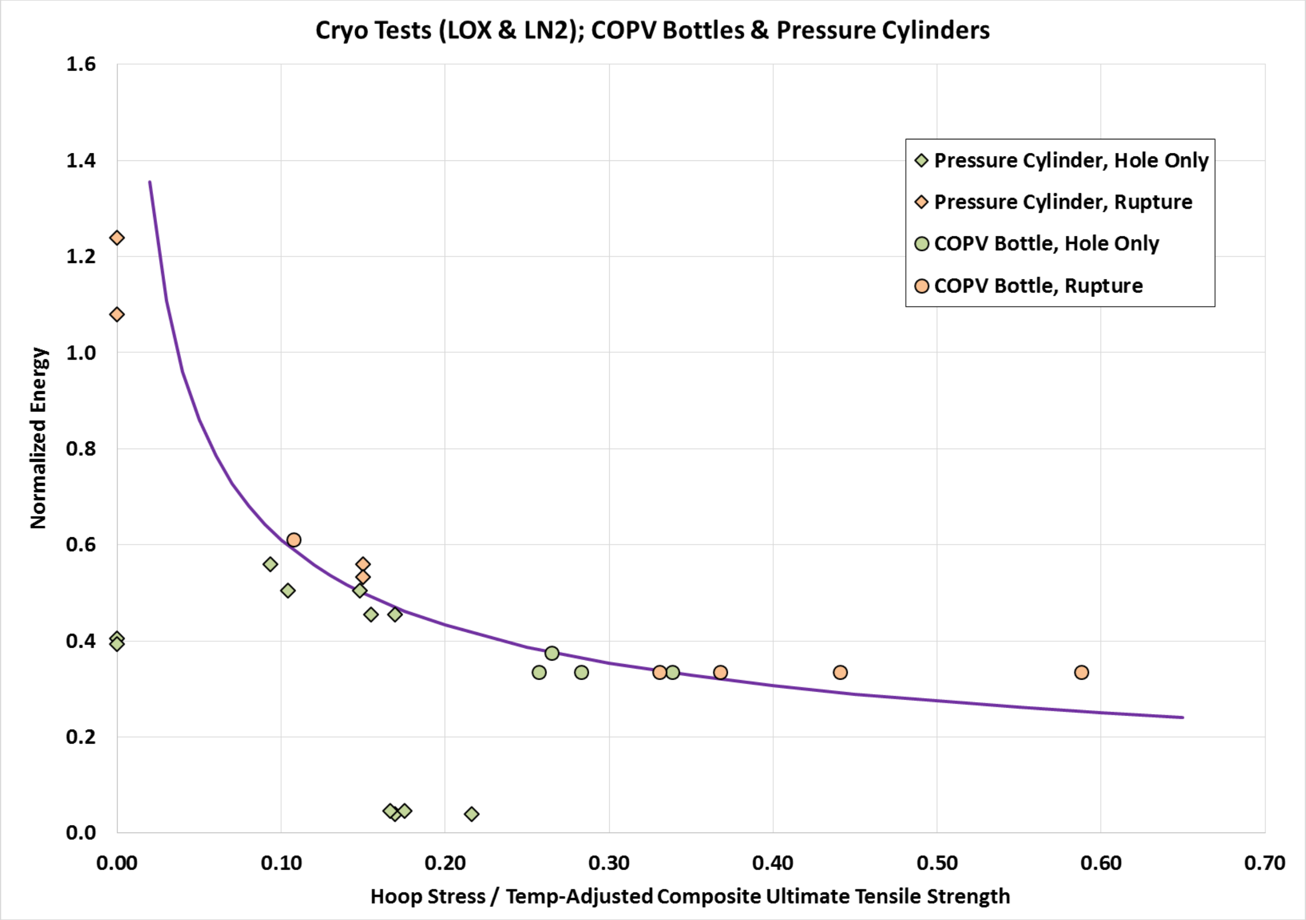

Figure 1. Impact Test Results and Energy-Based Demarcation Line

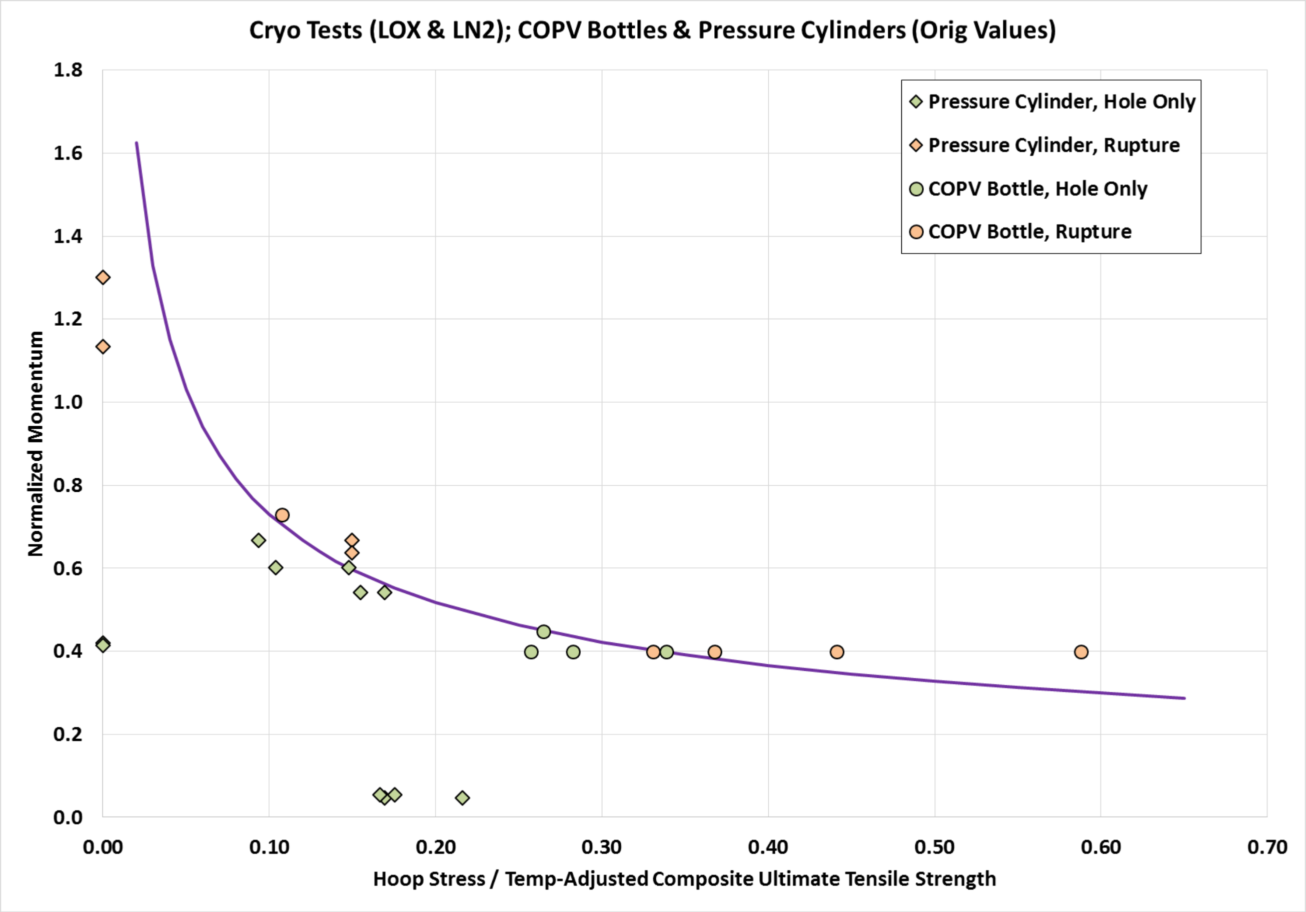

Figure 2. Impact Test Results and Momentum-Based Demarcation Line

Also plotted in Figs. 1 and 2 are some suggested forms of demarcation lines between tests that did not result in tank rupture (green data markers; should be mostly or all below any such line) and tests that did (red data markers; should be mostly or all above any such line). In order to maintain some consistency as well as simplicity, a power law form of the line was chosen for both the spherical and the cylindrical tank configurations. The power laws for the curves that separate the regions of rupture and non-rupture in Figs. 1 and 2 are given as follows:

$$\left\{\begin{matrix} \textit{Normalized Projectile Kinetic Energy} \\ \textit{Normalized Projectile Momentum} \end{matrix}\right\} = A\sigma_h^{-B} \qquad (1)$$

In Eq. (1), the $\overline{\qquad}$ refers to the non-dimensionalized hoop stress and where A and B are given for each normalized impact parameter in Table 1.

Table 1. Power Law Parameters for Energy-Based and Momentum-Based Demarcation Lines

	A	B
Energy-Based Line	0.195	-0.496
Momentum-Based Line	0.232	-0.498

Invoking the normalization scheme for kinetic energy and momentum that was used for the vertical axes in Figs. 1 and 2, we can solve for the critical kinetic energy and critical momentum of a penetrating impacting particle in terms of hoop stress using the following equation:

$$\left(\frac{X}{t_o^{0.75}\rho_t^{1.50}}\right)\left(\frac{460+T}{530}\right)^{4.4}\left(\frac{\rho_p}{\rho_t}\right)^{0.66} x$$

$$\left[\left(1+\frac{\sigma_{ut}^{l}}{100}\right)\left(1+\frac{\sigma_{us}^{l}}{100}\right)\right]^{0.10} = A\left(\frac{\sigma_h}{\sigma_{ut}^{c}}\right)^{B} \qquad (2)$$

where X is either the kinetic energy (in kJ) or the momentum (in kg-m/s) of the projectile, A and B are given in Table 1, t_o is the total thickness of the composite overwrap + liner (if any; in m), T is the temperature of the internal fluid (in ^{o}F), σ_h is the hoop stress (in MPa), σ_{ut} is the ultimate tensile stress of the composite overwrap and liner materials (super-script 'c' and 'l', respectively; in MPa), σ_{us} is the ultimate shear stress of the liner material (=0 if not present; in MPa), ρ_p is the density of the projectile (in gm/cm^3), and

$$\rho_t = \frac{\rho_c t_c + \rho_l t_l}{t_c + t_l} \qquad (3)$$

is (in gm/cm^3) the average or effective density of the composite overwrap-liner material combination, where ρ_c is the density of the composite overwrap material, ρ_l is the density of the COPV liner material (=0 if it is not present), t_c is the thickness of the composite overwrap material, and t_l is the thickness of the COPV liner (=0 if it is not present).

Then, in the event that tank penetration would occur, an impacting particle having a kinetic energy or momentum above the critical amount would likely result in tank rupture, while that with a kinetic energy or momentum below the critical amount (but still high enough to cause tank penetration) would likely not.

As can be seen from Figs.1 and 2, these equations predict the rupture / non-rupture response of pressurized composite overwrapped bottles at cryogenic temperatures fairly well. However, when test results from pressure cylinders are included, they appear to be a bit non-conservative. Some additional investigation into the details of the two ruptured pressure cylinder tests with zero internal pressure appears to be in order.

Since the demarcation lines shown in Figs. 1 and 2 are not curve-fits, and since the corresponding equations are not statistically based, it is not possible to obtain uncertainty bounds and/or confidence intervals in this particular case using traditional methods. However, it is still possible to develop a quantitative measure that would indicate, at least at some level, the accuracy of the demarcation lines when separating the region of impact conditions/operating conditions that would result in rupture from impact conditions/operating conditions that would not.

We can consider, for example, the use of **specificity** and **sensitivity ratios**, which are used in the medical world to distinguish between false positives and false negatives. For example, if we designate a rupture event as the event we are testing for, then a rupture might be considered as a "positive reading" and a non-rupture might be considered as a "negative reading". As such, the following definitions could be applied for any demarcation line equation:

Sensitivity ratio *= (Actual ruptures predicted as ruptures) / (Actual ruptures predicted as ruptures + Actual ruptures predicted as non-ruptures)* (4)

Specificity ratio *= (Actual non-ruptures predicted as non-ruptures)/ (Actual non-ruptures predicted as non-ruptures + Actual non-ruptures predicted as ruptures)* (5)

By using these ratios we would get a first-order quantitative assessment of whether or not a given demarcation line equation tends to be conservative or non-conservative (at least in the tested areas). For example, a low specificity value (i.e. more non-ruptures predicted as ruptures) and a high sensitivity value (i.e. fewer ruptures predicted as non-ruptures) would tend to demonstrate a conservatism in the demarcation line equation whereas a high specificity value and a low sensitivity value would tend to demonstrate non-conservatism. If both values were relatively high, that would indicate a fairly accurate curve, whereas if both values were fairly low, that might demonstrate a problem with the testing method or with test repeatability.

Table 2 presents the specificity and sensitivity ratios for the energy-based and momentum-based demarcation lines shown in Figs. 1 and 2. As expected, both types of equations are a bit non-conservative, again, primarily because they do not capture the two pressure cylinder ruptures.

Table 7. Sensitivity and Specificity Ratios

	Sensitivity Ratio	Specificity Ratio
Energy-Based	67%	87%
Momentum-Based	67%	87%

3 CONCLUDING THOUGHTS

This paper presented a summary of the work performed to address a key issue related to the design of pressurized vessels and tanks that are part of a spacecraft that would be built to operate in the MMOD environment. A set of empirical equations were developed that would differentiate between impact conditions that would result in only a small hole or crack in a COPV with an internal cryogenic fluid from those that would cause catastrophic tank failure. These equations predict fairly accurately the rupture / non-rupture response of pressurized COPV bottles at cryogenic temperatures. However, when test results from pressure cylinders are included, they appear to be a bit non-conservative. Based on the work performed, it would appear that the next step in this continually evolving task would be to develop similar equations for COPVs having internal contents that are kept at room temperature.

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5 REFERENCES

1. Schonberg, W.P., and Ratliff, M., “Hyper-velocity Impact of a Pressurized Vessel: Comparison of Ballistic Limit Equation Predictions with Test Data and Rupture Limit Equation Development”, *Acta Astronautica*, Vol. 115, 2015, pp. 400-406.

2. Dengler, R.P., *An Experimental Investigation of Chemical Reaction Between Propellant Tank Material and Rocket Fuels or Oxidizers When Impacted by Small High - Velocity Projectiles*, NASA TN-D-1882, NASA Lewis Research Center, Cleveland, OH, August 1963.

3. Stepka, F.S., *Projectile-Impact-Induced Fracture of Liquid-Filled, Filament-Reinforced Plastic or Aluminum Tanks*, NASA TN-D-3456, NASA Lewis Research Center, Cleveland, OH, June 1966.