NASA/TM—2012-217638

# Reliability of COPVs Accounting for Margin of Safety on Design Burst

*Pappu L.N. Murthy*
*Glenn Research Center, Cleveland, Ohio*

August 2012

# NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to *help@sti.nasa.gov*

- Fax your question to the NASA STI Information Desk at 443–757–5803

- Phone the NASA STI Information Desk at 443–757–5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2012-217638

# Reliability of COPVs Accounting for Margin of Safety on Design Burst

*Pappu L.N. Murthy*
*Glenn Research Center, Cleveland, Ohio*

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

August 2012

## Acknowledgments

The author wishes to acknowledge the sponsorship provided by the NASA Engineering Safety Center for the Independent Technical Assessment of safety of the Kevlar and Carbon COPVs onboard the orbiter and the International Space Station The author would also like to acknowledge the technical advice, review and support of Dr. Lorie Grimes-Ledesma the lead for the NESC CPV WG (Composite Pressure Vessel Working Group).



*Level of Review*: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

# Reliability of COPVs Accounting for Margin of Safety on Design Burst

Pappu L.N. Murthy
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Abstract

In this paper, the stress rupture reliability of Carbon/Epoxy Composite Overwrapped Pressure Vessels (COPVs) is examined utilizing the classic Phoenix model and accounting for the differences between the design and the actual burst pressure, and the liner contribution effects. Stress rupture life primarily depends upon the fiber stress ratio which is defined as the ratio of stress in fibers at the maximum expected operating pressure to actual delivered fiber strength. The actual delivered fiber strength is calculated using the actual burst pressures of vessels established through burst tests. However, during the design phase the actual burst pressure is generally not known and to estimate the reliability of the vessels calculations are usually performed based upon the design burst pressure only. Since the design burst is lower than the actual burst, this process yields a much higher value for the stress ratio and consequently a conservative estimate for the reliability. Other complications arise due to the fact that the actual burst pressure and the liner contributions have inherent variability and therefore must be treated as random variables in order to compute the stress rupture reliability. Furthermore, the model parameters, which have to be established based on stress rupture tests of subscale vessels or coupons, have significant variability as well due to limited available data and hence must be properly accounted for. In this work an assessment of reliability of COPVs including both parameter uncertainties and physical variability inherent in liner and overwrap material behavior is made and estimates are provided in terms of degree of uncertainty in the actual burst pressure and the liner load sharing.

### Nomenclature

| | |
|---|---|
| $F$ | lifetime distribution function |
| $DBP$ | design burst pressure |
| $ABP$ | actual burst pressure |
| $MEOP$ | maximum expected operating pressure |
| $BF$ | burst factor |
| $ABF$ | actual burst factor |
| $P_{ly}$ | liner share of pressure yield |
| $P_{lmeop}$ | liner share of pressure at MEOP |
| $s$ | stress ratio |
| $s_{BF}$ | stress ratio based on burst factor |
| $s_a$ | actual stress ratio |
| $\sigma$ | fiber stress |
| $\sigma_{ref}$ | fiber stress at burst pressure |
| $t$ | time in hours |
| $t_{ref}$ | characteristic time corresponding to $\sigma_{ref}$ |
| $\rho$ | power-law coefficient for stress |
| $\beta$ | lifetime shape parameter |
| $\eta$ | variable that captures uncertainty in burst pressure |
| $\lambda$ | variable that captures yield strength variability |
| $\Theta$ | ratio of liner support at MEOP to burst pressure |

# Introduction

Composite overwrapped pressure vessels are used for storing high pressure gases on board spacecraft such as the Orbiter, the International Space Station, and the Crew Exploration and Launch vehicles MPCV (multipurpose crew vehicle) and SLV (space launch vehicle) being developed under current NASA programs. The primary reason for using COPVs for these applications is due to the substantial weight savings they offer compared to all metallic pressure vessels. For example, on the Space Shuttle Orbiter, replacement of all metallic pressure vessels with Kevlar COPVs resulted in a total weight savings of about 30 percent of all metallic tanks weight. Mass critical space applications such as the Ares and Orion vehicles are currently being planned to use as many COPVs as possible in place of all-metallic pressure vessels to minimize the overall mass of the vehicle. Furthermore, robotic missions such as earth orbiting satellites or deep space missions to outer planets are usually much more mass critical, since any mass saved allows additional science instruments to be added. For these missions, mass savings of up to 50 percent can be realized through the use of COPVs.

COPVs are a mature technology, with a very successful use history at NASA. However, the stress rupture failure mode is not very well understood; therefore leading to significant conservatism and thus less weight savings. This composite failure mode is important to understand because the consequence of a failure is catastrophic. Since overwraps are subjected to sustained loads during long periods of a mission, the failure mode due to stress rupture is an added concern for the mission risk management.

Stress rupture life primarily depends upon the fiber stress ratio which is defined as the ratio of stress in fibers at the maximum expected operating pressure to actual delivered fiber strength. Since a COPV consists of a metallic liner (which minimizes permeability) overwrapped with composite, the delivered fiber strength is calculated analytically by removing the influence of the liner to provide the composite response at the pressure level of interest. Several other factors also influence the COPV stress rupture and detailed discussion of these can be found in References 1 and 2. The actual delivered fiber strength is calculated using the actual burst pressures of the vessels established through burst tests. These vessels are usually designed to a design burst factor of 2.0, however, launch vehicles and deep space mission vehicles sometimes use a more aggressive burst factor of 1.5. One reason to design with a higher burst factor is to minimize the stress rupture risk without unduly penalizing the mission performance. In general, the higher the burst factor, the lower the fiber stresses in the overwrap, thereby minimizing the stress rupture risk. COPV manufacturers however design the vessels such that the actual burst pressures are significantly higher than the design burst pressure, often as high as 5 to 10 percent.

In the current paper the stress rupture life reliability as a function of the burst factor and the margin of safety are computationally simulated utilizing the classic Phoenix model of stress rupture that was used for Orbiter reliability calculations. Furthermore, stress ratio dependency on several fundamental variables and their uncertainties in them are examined in detail. For this purpose the variability of burst strength, variability in liner yield strength and variability in operating pressure are considered as random variables.

# Methodology

Current carbon composite overwrapped pressure vessels are typically designed to operate with a safety factor equivalent to a Burst Factor of 2.0. The Burst Factor (BF) is defined as the ratio of the design burst pressure (DBP) to the maximum expected operating pressure (MEOP). The design burst is the pressure at which the manufacturer by actual test must demonstrate that the COPV is stable with no abnormal consequences during the qualification process. Following successful demonstration of the DBP, usually the test is continued by increasing the pressure until an actual burst occurs to demonstrate additional margin. It is not uncommon for the manufacturer to over design the vessel by 5 to 10 percent so that a successful qualification test is assured. According to the definition the burst factor is expressed as

$$BF = \frac{DBP}{MEOP} \tag{1}$$

At the maximum expected operating pressures (MEOP), an estimate of the fiber stress ratio in the overwrap based on design Burst Factor is given by

$$s_{BF} = \frac{1}{BF} \tag{2}$$

Two factors that contribute to the conservatism of Equation (2) must be considered to arrive at the actual fiber stress ratio. The first factor concerns with the actual burst pressure, *ABP* that must be used to calculate the fiber stress ratio as opposed to the design burst pressure (*DBP*). *ABP* is usually significantly higher than *DBP*. The actual burst strength may be expressed as

$$ABP = DBP(1+\eta) \tag{3}$$

η is the "margin of safety" on *DBP*. The actual burst factor is therefore given by

$$ABF = BF(1+\eta) \tag{4}$$

The actual burst strength of typical COPVs is a random variable with a mean value and a coefficient of variation. To account for this here η is considered as a random variable with a lognormal distribution. The mean value is usually around 0.1 to 0.15 (assuming that the actual burst strength is 10 to 15 percent higher than the design burst). The coefficient of variation is around 5 percent (typical for carbon). The actual stress ratio accounting only for the *ABP* is given by

$$\begin{gathered} s = \frac{1}{BF(1+\eta)} \\ \text{or} \\ s = s_{BF}/(1+\eta) \end{gathered} \tag{5}$$

From Equation (5) it can be seen that the stress ratio, $s$, is a random variable and is less than $s_{BF}$ since η is always a positive quantity. In reality, it is quite possible to have *ABP* less than *DBP*, for small η values with large scatter in burst strength however, in the current formulation using a lognormal distribution for η this possibility is eliminated.

The second factor affecting the stress ratio, concerns the load carrying contributions of the liner. It should be noted that in the above equation the liner contributions are neglected. Typically, the COPVs used for space applications are designed such that the liner carries 10 to 20 percent load at MEOP and therefore the fiber stress ratio needs to be adjusted to take this into account. For example if the liner support pressure at MEOP is $P_{lmeop}$ and the liner support pressure at yield is $P_{ly}$, then the actual stress ratio, $s_a$ at MEOP is given by

$$\begin{gathered} s_a = \frac{\left(MEOP - P_{lmeop}\right)}{\left(ABP - P_{ly}\right)} \\ \text{or} \\ s_a = \frac{\left(MEOP - P_{lmeop}\right)}{\left\{DBP(1+\eta) - P_{ly}\right\}} \end{gathered} \tag{6}$$

Equations (5) and (6) must be combined to calculate a more accurate value for the stress ratio. It should be noted that, the manufacturer's autofrettage cycle induces compressive and tensile residual stresses in the liner and overwrap, respectively, which introduce additional complications in the stress ratio estimation process. In the current work however, these issues are completely neglected and only the "margin of safety" on *DBP* included.

## Stress Rupture Life Reliability: Phoenix Classic Model

It is customary to utilize a Weibull statistics based approach to fit the stress rupture life data, in this case the original Lawrence Livermore National Laboratories (LLNL) test data (Ref. 1) were fitted with this approach. There are a number of models presented in the literature, with a comparison of advantages and disadvantages discussed in Reference 3. Herein the Phoenix Classic model is used. The so-called classic model was originally pioneered by Coleman (Ref. 4) in the late 1950s and further developed by Phoenix and colleagues (Refs. 5 to 9) over the past 27 years. More recently this model has undergone a thorough review during two independent technical reviews and assessments sponsored by the NASA NESC (NASA Engineering Safety Center) (Refs. 1 and 2). As mentioned above, the model is based on a Weibull distribution framework for strength and lifetime with the embodiment of a power law to describe damage in a composite versus stress level. Derivation of the model is available in references (Refs. 4 and 7) where the power-law in stress level (with temperature dependence) is derived from thermally-activated chain scission using a Morse potential as a model (Refs. 7). In the simplest setting of constant stress applied quickly and maintained over a long time period, the basic equation for the model is given by

$$F(t\,|\,s) = 1 - \exp\left[-\left\{\left(\frac{t}{t_{ref}}\right)(s)^{\rho}\right\}^{\beta}\right] \tag{7}$$

where $F(t\,|\,s)$ represents the probability of failure at time $t$. In the above equation the quantity ($s = \sigma_{op}/\sigma_{ref}$) is the ratio of fiber stress at operating pressure to fiber stress at burst pressure (stress ratio), $t$ is time, $t_{ref}$ is a reference time, $\rho$ is the power law exponent, and $\beta$ is the Weibull shape parameter for lifetime. The value for $\sigma_{ref}$ is determined from the flight COPV burst tests and stress analysis of the COPV. The model is shown for a single stress level over time, but for more general time histories a memory integral is used to accumulate damage (similar to Miner's rule for fatigue) at different stress levels.

## Illustrative Example

The Classic Model parameters that are appropriate for a representative carbon fiber, T1000G composite are given by (Ref. 2)

$$\begin{aligned} &\text{Classic Model} \\ &\rho = 114 \\ &\beta = 0.22 \\ &t_{ref} = 0.001 \text{ hr} \end{aligned} \tag{8}$$

The stress ratio used in the following calculations is based on Equation (5). The uncertainties associated with the model parameters are those for a "Hi-Variability" case. The "High variability" assumption means that the uncertainty associated with the model parameters used are those uncertainties that can be substantiated based on the small fiber strands database that currently exists. The associated coefficients of variation (cov) are given by

Classic Model Variabilities

$$\mathrm{cov}\,\rho = 25\%; \quad \mathrm{cov}\,t_{ref} = 30\% \qquad (9)$$

$$\mathrm{cov}\,\beta = 30\%;$$

For illustration purposes lognormal marginal distributions for all parameters are assumed. In addition to these, an additional random variable to account for the actual burst strength variability is introduced with the random variable $\eta$. It should be mentioned that since the stress ratio is assumed random (by virtue of the burst strength variability), this can complicate the uncertainty related to parameter distributions. Consequently, a Bayesian framework is employed although Bayes theorem is not relied on for computing a posterior distribution of the parameters. The distributions are all assumed to be independent with no correlations among them, even though it is acknowledged in reality they should be multivariate dependent variables. Ten thousand Monte-Carlo simulations of reliability using Equation (7) are performed and the results are shown in Figure 1. Here, the point estimate, mean and 95 percent confidence limit for reliability are plotted versus "margin of safety" varying from 0.01 to 0.2. Note, however, the simulation shows that although the margin of safety inherent in the simulation of a manufacturer's design does provide much higher point estimates of reliability, due to the high variability in model parameters, similar gains are not realized for the mean and 95 percent confidence reliability estimates; wherein no more than half a nine in reliability can be realized.

The actual stress ratio and the upper bound 95 percent confidence stress ratios are shown in Figure 2 versus margin of safety on DBP. If A-Basis values are required then the 99 percentile value has to be used instead of 95 percentile on stress ratio. Assuming that a typical range for the actual burst strength of COPVs have a margin of safety between 10 and 15 percent with a coefficient of variation of 5 percent, the actual stress ratio lies between 0.43 to 0.46 for a design burst factor of 2.0 as shown in the figure. Together Figure 1 and Figure 2 provide quick and useful estimates of operating stress ratio and preliminary reliability estimates for COPVs during the design stage, including typical uncertainties in various parameters.

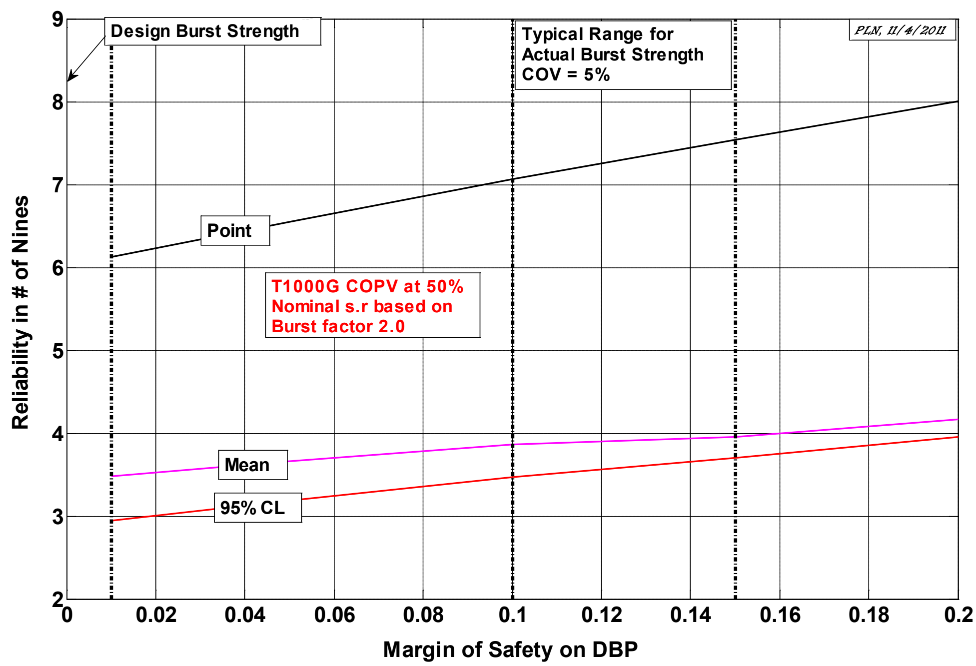


Figure 1.—Reliability measures for a typical carbon COPV as a function of margin of safety on design burst pressure (DBP). Almost two nines of reliability can be gained for point "margin of safety" equal to 0.2 as compared to 0.01 as seen in the figure.

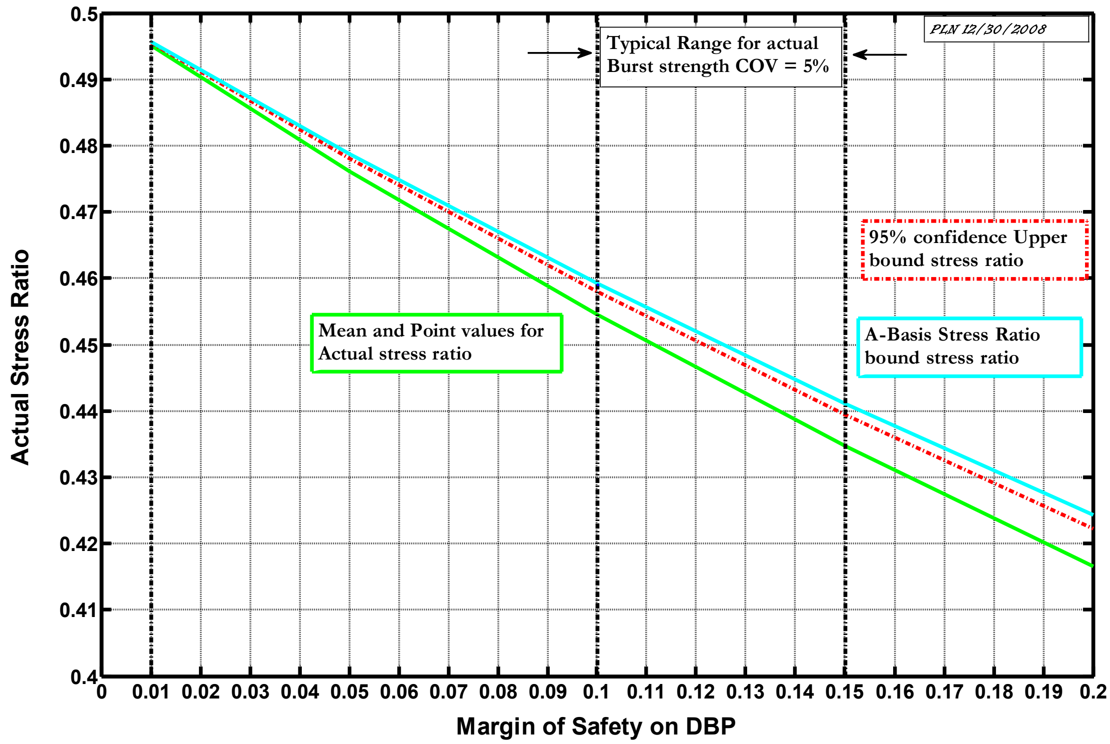


Figure 2.—Actual stress ratio estimates at MEOP for a typical carbon COPV as a function of margin of safety on design burst pressure (DBP).

# Sensitivity Analysis

The stress ratio used in the above calculations is based on Equation (5) which only has one random variable, the ABP of the vessel. However, as already mentioned, the stress ratio depends on other important variables where uncertainties do exist. Here an attempt is made to perform a sensitivity analysis on the stress ratio considering uncertainties in liner support at operating pressure and burst pressure. The results from such a sensitivity analysis can help quantify the uncertainty in the stress ratio which may arise due to its functional relationship to the aforementioned random variables and rank them in the order of importance. The steps to perform such an analysis involve, 1) formulating the stress ratio in terms of all the fundamental variables, 2) identifying the ones which are uncertain, and 3) provide information pertaining to their distribution statistics. Equation (6) for the stress ratio may be modified to include various independent variables in the following manner:

$$s_a = \frac{\left(\mu - P_{lmeop}\lambda\right)}{\left\{DBP(1+\eta) - P_{ly}\lambda\right\}} \tag{10}$$

where μ is the operating pressure, with a mean of MEOP and is assumed to be distributed normally. λ is a random variable that captures the variability in yield strength of the liner material which is also assumed to be normally distributed with a mean of 1. Thus we have the stress ratio expressed as a function of three fundamental random variables μ, λ and η. Variability in the geometry of the vessel, etc., are not considered explicitly in this preliminary analysis. However, these are indirectly accounted for in the variability of burst strength. Basically the aleatory variability in operating conditions (operating pressures), liner yield strength and the vessel burst, have been considered.

In Equation (10) it should be noted that $P_{ly}$ and $P_{lmeop}$ are related by the following inequality

$$P_{ly} \geq P_{lmeop} \tag{11}$$

Let us introduce a new parameter the liner participation factor, Θ, defined as the ratio of liner support at MEOP to liner support at burst; that is

$$\Theta = \left( \frac{P_{ly}}{P_{lmeop}} \right) \tag{12}$$

Furthermore, by substituting Equation (12) into Equation (10) the following expression for the stress ratio is obtained:

$$s_a = \frac{\left( \mu - \Theta P_{ly} \lambda \right)}{\left\{ DBP(1+\eta) - P_{ly} \lambda \right\}} \tag{13}$$

For plastically operating liners Θ is equal to 1 by definition and for all other cases is between 0 and 1, typically $0 << \Theta \leq 1$.

The above equation can be used to study the sensitivity of stress ratio to various fundamental variables.

## Trade Studies

The effect of liner support at MEOP and liner support at yield on the stress ratio has been studied for a range of liner supports at MEOP varying from 5 to 30 percent and for Θ = 0.8. For this exercise it has been assumed that the liner is elastic at MEOP and plastic at burst. Figure 3 shows the variability in stress ratio for a family of liner support values at MEOP varying from 5 to 30 percent and for a constant liner support at yield of 1.25 times the liner support at MEOP. The 99 percentile value (analogous to A-Basis) for stress ratio varies from 0.45 to 0.5 while the mean values range from 0.38 to 0.445.

Figure 4 shows the Point, 95 and 99 percentile values of stress ratio as a function of liner support at MEOP.

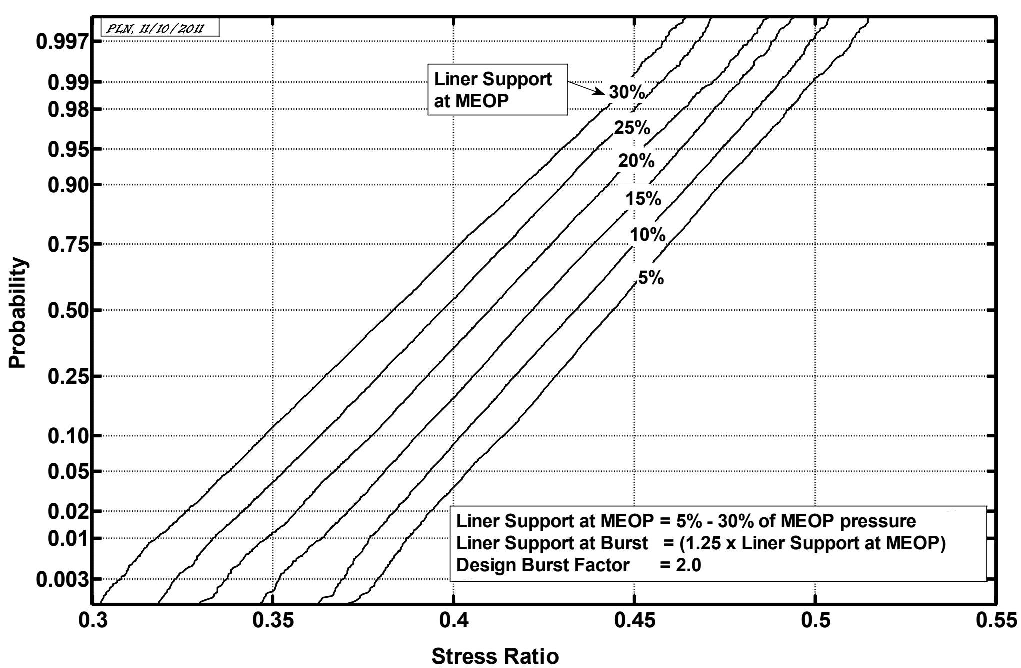


Figure 3.—Normal plots of stress ratios for a range of liner support at MEOP.

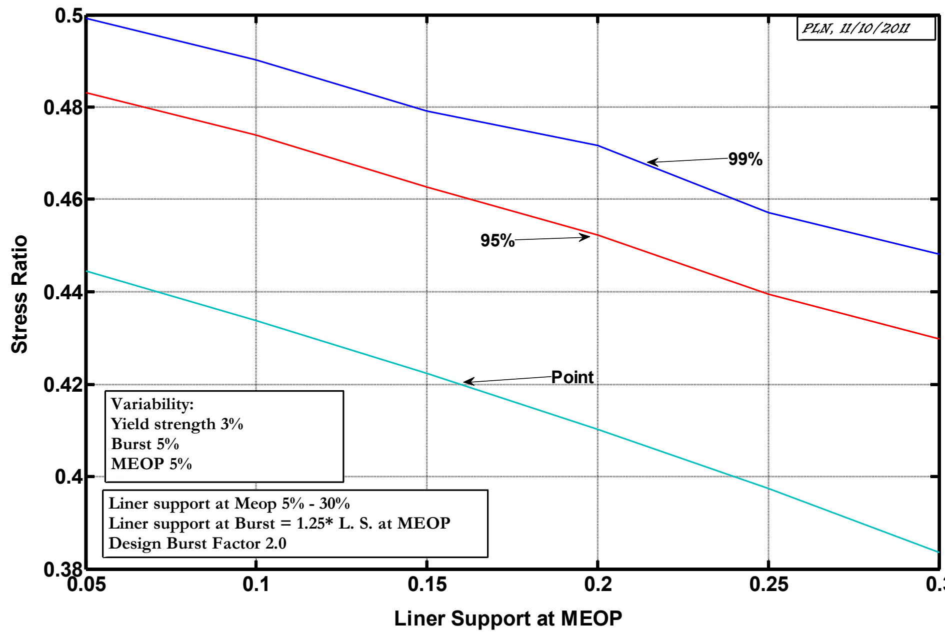


Figure 4.—Liner support versus stress ratio for a vessel designed for a burst factor of 2.0.

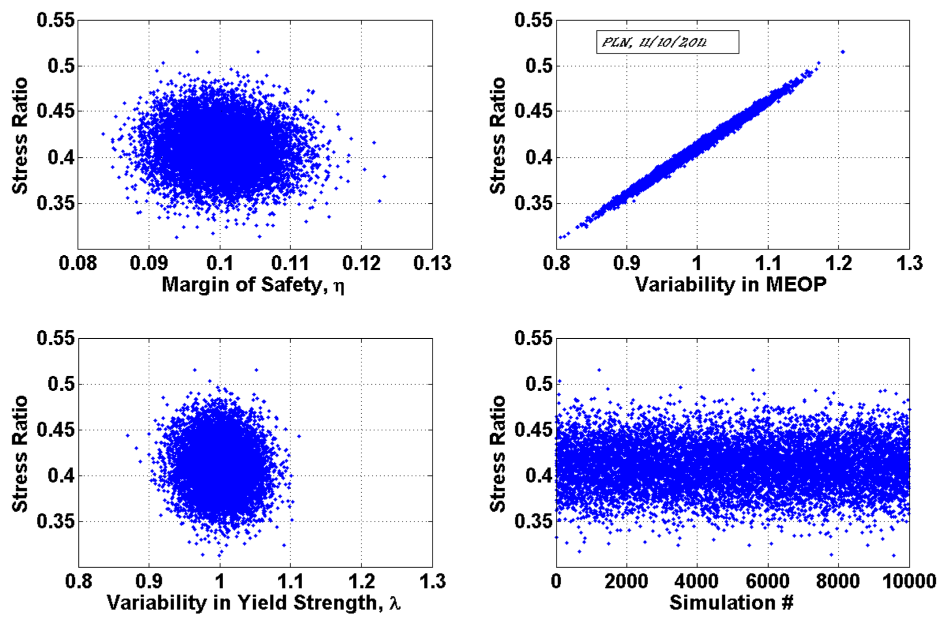


Figure 5.—Scatter plots showing the sensitivity of the fundamental variables on the stress ratio.

## Stress Ratio Sensitivities

As seen from Equation (10) the stress ratio is a function of three fundamental variables; the pressure at MEOP, the variability in liner yield strength and the variability in the actual burst strength. In Figure 5 plots of each fundamental variable versus the stress ratio are shown. As can be seen from the figure, the pressure at MEOP has a strong influence on the stress ratio, which is to be expected. The other two variables have minimal effect on the stress ratio. The magnitude of the correlation coefficient between the variable and stress ratio gives a measure of the sensitivity and is shown in a Bar plot in Figure 6.

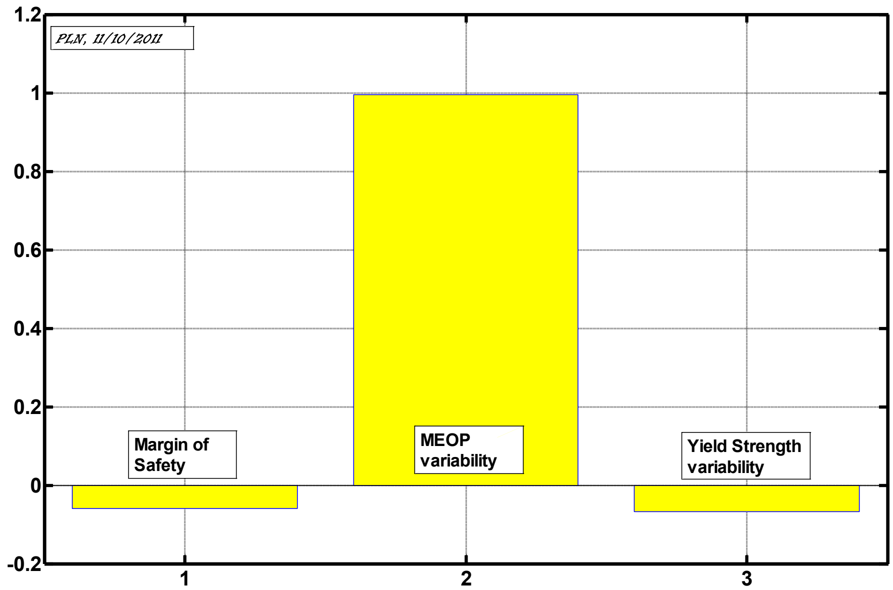


Figure 6.—Stress ratio sensitivities.

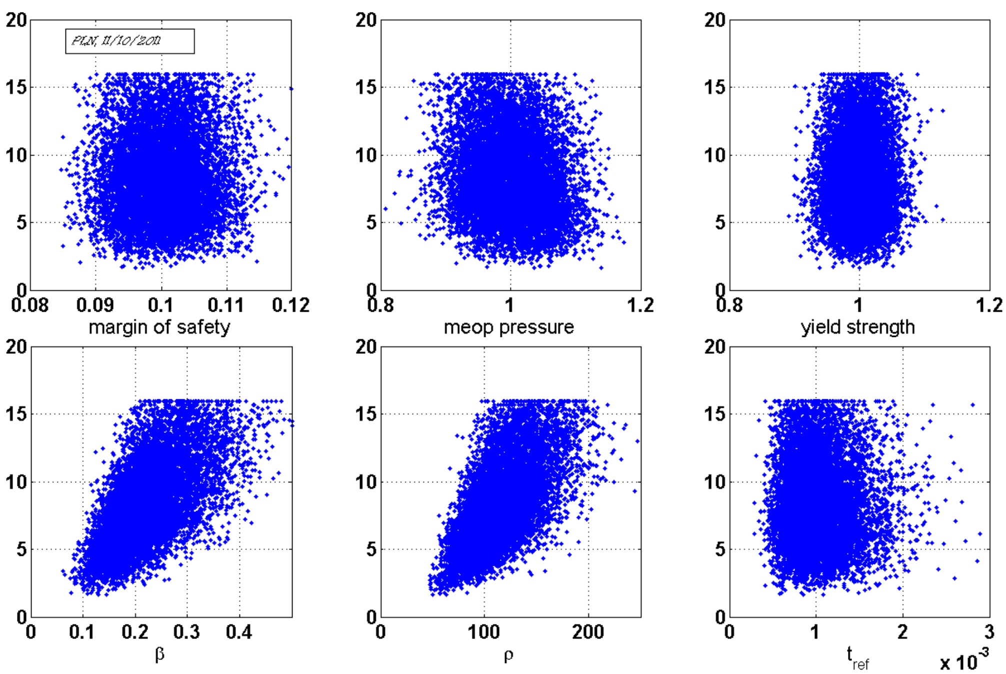


Figure 7.—Scatter plots showing the sensitivity of the fundamental variables on the stress rupture life reliability.

## Stress Rupture Life Reliability Sensitivities

With the aid of Equations (7) and (13) the influence of various random variables on stress rupture life reliability can be evaluated. The results are shown in Figure 7 and Figure 8.

As can be seen from Figure 7, the model parameters (β, ρ and $t_{ref}$) appear to be more strongly influencing the reliability compared to the other parameters like margin of safety, yield strength and MEOP. The magnitudes of these correlations can be seen more clearly in Figure 8 where the correlations are shown in bar chart format side by side. Among the non-model variables the MEOP appears to have the strongest

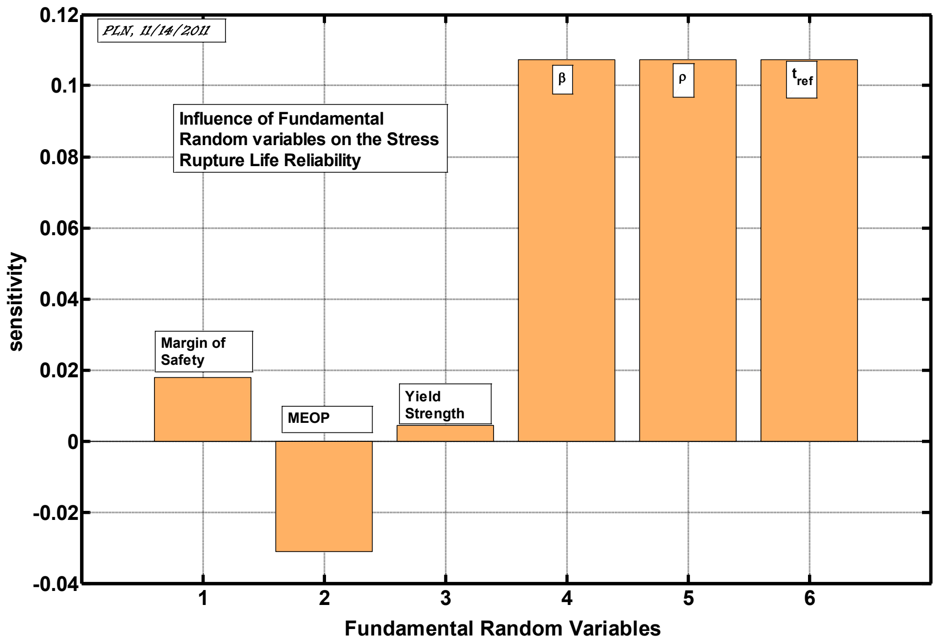


Figure 8.—Sensitivities of various fundamental random variables on the stress rupture life reliability.

influence on stress rupture life reliability. However, when comparing all variables, the model parameters by far have the most influence on the stress rupture life reliability. From these preliminary results it can be concluded that it is important to have a good set of data to establish model parameters with tight bounds, as these appear to control the reliability more significantly compared to the other parameters.

## Concluding Remarks

In this short paper the issue of unknown burst strength of a COPV during the design stage and how that affects the operating stress ratio and consequently the stress rupture life reliability evaluations of the vessel are addressed. Usually only the operating pressures and the design burst pressure are known during the preliminary COPV design stage. Herein we attempted to include randomness in the burst pressure and operating pressure along with variability in yield strength and a formal assessment of their influence on stress ratio and the stress rupture reliability were made. The sensitivity of various fundamental variables on the stress ratio as well as the stress rupture life reliability is assessed. As is expected the operating pressure has the greatest influence on stress ratio followed by the yield strength of the liner and burst strength margin of safety. The computations were made with the assumption that the liner is elastically responding at MEOP and its support at yield is about 25 percent higher than at MEOP. Furthermore, the sensitivity of the fundamental random variables on the stress rupture life reliability is also evaluated and the results show significantly more influence of stress rupture model parameters on the reliability as compared to the other parameters. Although, the simulations are performed for a single set of liner support, assessment for other combinations of liner support at MEOP and liner support at burst can be made with the given equations in a straight forward manner. The methodology developed herein can be of great use during the preliminary stages of COPV development for a specific mission.

# References

1. Orbiter Kevlar/Epoxy Composite Overwrapped Pressure Vessel Flight Rationale Technical Assessment Report, Vol. I and II, NASA NESC Report RP-07-34, April 12, 2007.
2. Shelf Life Phenomenon and Stress Rupture Life of Carbon/Epoxy Composite Overwrapped Pressure Vessels (COPVs) Technical Consultation Report, Vol. I and II, NASA NESC Report RP-06-83, September 14, 2006.
3. Lorie Grimes-Ledesma, Murthy, P.L.N., Phoenix, S.L., and Ronald Glaser, "A Comparison of Various Stress Rupture Life Models for Orbiter Composite Pressure vessels and Confidence Intervals", NASA/TM- 2007-214808.
4. Coleman, B.D. "Statistics and Time Dependence of Mechanical Breakdown in Fibers," *Journal of Applied Physics*, **29** (1958): 968.
5. Wu, H.F., S.L. Phoenix, and P. Schwartz, P. "Temperature Dependence of Lifetime Statistics for Single Kevlar49 Filaments in Creep-Rupture," *Journal of Materials Science*, **23** (1988):1851.
6. Phoenix, S.L., and E.M. Wu. "Statistics for the Time Dependent Failure of Kevlar-49/Epoxy Composites: Micromechanical Modeling and Data Interpretation." *IUTAM Symposium on Mechanics of Composite Materials,*
7. Phoenix, S.L. "Statistical Modeling of the Time and Temperature Dependent Failure of Fibrous Composites." *Proceedings of the 9th US National Congress of Applied Mechanics*, Book no. H00228, ASME, NY (1982): 219.
8. Phoenix, S.L. "The Asymptotic Time to Failure of a Mechanical System of Parallel Members," *SIAM Journal on Applied Mathematics*, **34** (1978): 227.
9. Phoenix, S.L. "Stochastic Strength and Fatigue of Fiber Bundles," *International Journal of Fracture*, **14** (1978): 327.

| REPORT DOCUMENTATION PAGE | *Form Approved OMB No. 0704-0188* |
|---|---|



| **1. REPORT DATE** *(DD-MM-YYYY)* 01-08-2012 | **2. REPORT TYPE** Technical Memorandum | **3. DATES COVERED** *(From - To)* |
|---|---|---|

**4. TITLE AND SUBTITLE**
Reliability of COPVs Accounting for Margin of Safety on Design Burst

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Murthy, Pappu, L., N.

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**
WBS 869021.03.03.02.01

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

**8. PERFORMING ORGANIZATION REPORT NUMBER**
E-18283

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSORING/MONITOR'S ACRONYM(S)**
NASA

**11. SPONSORING/MONITORING REPORT NUMBER**
NASA/TM-2012-217638

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified-Unlimited
Subject Category: 24
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
In this paper, the stress rupture reliability of Carbon/Epoxy Composite Overwrapped Pressure Vessels (COPVs) is examined utilizing the classic Phoenix model and accounting for the differences between the design and the actual burst pressure, and the liner contribution effects. Stress rupture life primarily depends upon the fiber stress ratio which is defined as the ratio of stress in fibers at the maximum expected operating pressure to actual delivered fiber strength. The actual delivered fiber strength is calculated using the actual burst pressures of vessels established through burst tests. However, during the design phase the actual burst pressure is generally not known and to estimate the reliability of the vessels calculations are usually performed based upon the design burst pressure only. Since the design burst is lower than the actual burst, this process yields a much higher value for the stress ratio and consequently a conservative estimate for the reliability. Other complications arise due to the fact that the actual burst pressure and the liner contributions have inherent variability and therefore must be treated as random variables in order to compute the stress rupture reliability. Furthermore, the model parameters, which have to be established based on stress rupture tests of subscale vessels or coupons, have significant variability as well due to limited available data and hence must be properly accounted for. In this work an assessment of reliability of COPVs including both parameter uncertainties and physical variability inherent in liner and overwrap material behavior is made and estimates are provided in terms of degree of uncertainty in the actual burst pressure and the liner load sharing.

**15. SUBJECT TERMS**
Composite overwrapped pressure vessels; Stress rupture; Weibull statistics; Stress rupture life; Liner load sharing; Burst pressure; Operating pressure; Fiber strength; Pressurization rate; Power law; Confidence intervals; Reliability statistics

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov) |
|---|---|---|---|---|---|
| **a. REPORT** U | **b. ABSTRACT** U | **c. THIS PAGE** U | UU | 18 | **19b. TELEPHONE NUMBER** ***(include area code)*** 443-757-5802 |

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18