

Title: Testing of Carbon Fiber Composite Overwrapped Pressure Vessel  
Stress-Rupture Lifetime

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## **ABSTRACT**

Carbon fiber overwrapped pressure vessels are known to fail from stress rupture, which is a catastrophic failure mode. Because this failure mode is a function of time and sustained load, composite overwrapped pressure vessels (COPVs) launch vehicles and spacecraft are particularly susceptible because missions can be of long duration and the operating loads on the composite overwrap are typically high. Mitigation of this failure mode requires appropriate characterization of this stress rupture lifetime. The current state-of-the-art for stress rupture characterization is the stochastic modeling of phenomenological data. Such models are then applied to COPVs to obtain an estimate of stress rupture lifetime in the future. Currently no standards exist for the development of data needed to characterize COPV stress rupture lifetime.

This paper contains summaries of testing procedures and analysis of stress rupture life testing for two stress rupture test programs, one for Kevlar COPVs performed at Lawrence Livermore National Laboratory, and the other a joint study between NASA JSC White Sands Test Facility and the Jet Propulsion Laboratory. These will be discussed in detail including test setup and issues encountered during testing. Lessons learned from testing in these two programs will be discussed.

## **INTRODUCTION**

There is a great need in the aerospace industry to find materials that minimize the mass of spacecraft, rocket, missiles and launch vehicle structures. In the last 25 years, the development of fiber-reinforced composite systems has led to the manufacture of such structures, but their development has presented new design challenges over traditional metallic structures. One design challenge is the determination of the stress-rupture life of the composite. This lifetime is the amount of time a composite can withstand a constant applied tensile load without breaking. Because stress-rupture failures occur in structures that are exposed to constant tensile stress for long periods of time, structures for use on long-term space missions are particularly susceptible to stress-rupture failures.

Composite tanks and composite overwrapped pressure vessels (COPVs) that are most susceptible to stress-rupture failure are regulated propellant tanks for long-term missions, pressurant tanks for missile propulsion systems that must be

pressurized in a state of readiness for many years, and tanks that are re-pressurized many times over many years.

To mitigate stress rupture failures in composite tanks, data is needed to allow model development for prediction of lifetime. Such models are based on the Weibull distribution and are primarily phenomenological because mechanisms which drive the phenomenon have not been identified. Unfortunately, data collection has been minimal, with limited composite strand and vessel data available. Usually data for the specific fiber and resin combination to be placed in service are not available and lifetime predictions must be inferred from existing data. Collection of new data has not been considered a priority for flight programs in the past and there is currently no standard method for development of new data.

## **PREVIOUS WORK**

In the 1970s, workers at Lawrence Livermore National Laboratory (LLNL) performed extensive lifetime testing on glass, aramid (Kevlar™), and carbon fiber composite strands and on Kevlar™ pressure vessels in order to develop models for stress-rupture lifetime for these materials [1,2,3,4]. Concurrently, other models based on Weibull statistics were developed based on these and other strand tests at Cornell. Follow-on work was performed throughout the 80s and 90s by Phoenix and Schaeffer to obtain data for various other types of single carbon fiber and composite strands and models based on the Weibull distribution have shown to be appropriate [5,6]. These fiber and strand tests have included S and E glass, aramid (Kevlar®) and several carbon types: Hercules IM6 [6], Union Carbide Thornel 50S [4], Hercules AS4 [3], and Toray T300 [7] carbon fibers. However, current designs for high-performance minimum weight COPVs typically use high strength carbon fibers such as Toray T-1000 or Hercules IM-7, for which limited strand data only exists for T-1000 [8, 9].

While insight into the lifetime of a complex composite structure such as a COPV can be gained from single fiber and strand data, issues such as the effects of stress concentrations, wrap pattern, and scaling cannot be resolved without COPV testing. Such tests have been very limited, with a few tests performed by the Department of Energy (DoE), Lawrence Livermore National Laboratory (LLNL), one at Boeing, and carbon COPV testing described here.[9,10]

## **STRESS RUPTURE ANALYSIS**

As previously mentioned, no mechanistic model exists for stress rupture lifetime and a phenomenological model must be used to describe stress rupture lifetime and to allow predictions for future life. The Phoenix model described here has been developed over the past 30 years and 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 elsewhere [14,15] , where the power-law in stress level (with temperature dependence) is derived from thermally activated chain scission using a Morse potential as a model.

In the simplest setting of constant stress applied quickly and maintained over a long time period, the basic equation for the model is below.

$$P(t, \sigma) = 1 - \exp \left[ - \left\{ \left( \frac{t}{t_{c,ref}} \right) \left( \frac{\sigma_{op}}{\sigma_{burst}} \right)^\rho \right\}^\beta \right] \quad (1)$$

The ratio of  $\sigma_{op}/\sigma_{burst}$  is the ratio of fiber stress at operating pressure to fiber stress at burst pressure (stress ratio),  $t$  is time,  $t_{c,ref}$  is a reference time,  $\rho$  is the power law exponent, and  $\beta$  is the Weibull shape parameter for lifetime. All parameters are determined based on the data obtained from stress rupture testing. Probability plots are created to determine these parameters and have the added advantage of pinpointing inconsistent data points within the data set for closer scrutiny. An example of this can be seen in Figure 4, where the data in the lower tail deviates significantly from the linear trend of the majority of the data. After determination of the parameters, the model allows for prediction of lifetime. A convenient way to view predicted stress rupture lifetime is through a set of quantile curves as shown in Figure 1. This Figure shows quantile predictions for Kevlar COPV data from the LLNL study as an example, and it provides a graphical method of determining stress rupture lifetime based on an appropriate stress ratio and reliability level for the design to be analyzed.

The equation above is for determination of lifetime 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. Also, at very high stress levels a second quantity within square brackets and of similar structure to the first must also be included. This second quantity has different parameter values, especially a much higher  $\rho$  value. If a more complex time history exists such that a successful past history for the vessels exists, the conditional probability approach can be used. In this approach, a reference time is chosen and all successful history prior to the reference is considered in the analysis. The conditional reliability equation for the Phoenix model is below.

$$F(t, \sigma) = 1 - \exp \left[ - \left\{ \left( \frac{t_1}{t_{c,ref}} \right) \left( \frac{\sigma_{op1}}{\sigma_{ref}} \right)^\rho + \frac{\Delta t}{t_{c,ref}} \left( \frac{\sigma_{op2}}{\sigma_{ref}} \right)^\rho \right\}^\beta + \left( \frac{t_1}{t_{c,ref}} \left( \frac{\sigma_{op1}}{\sigma_{ref}} \right)^\rho \right)^\beta \right] \quad (2)$$

In this equation, two new terms appear, one for a second stress level and another to account for past history. Determination of which form is appropriate for specific circumstances must be made on a case-by-case basis, but determination of parameters requires consistent data. Of note is the fact that while determining parameters for Kevlar COPVs from the LLNL tests, several data points appeared

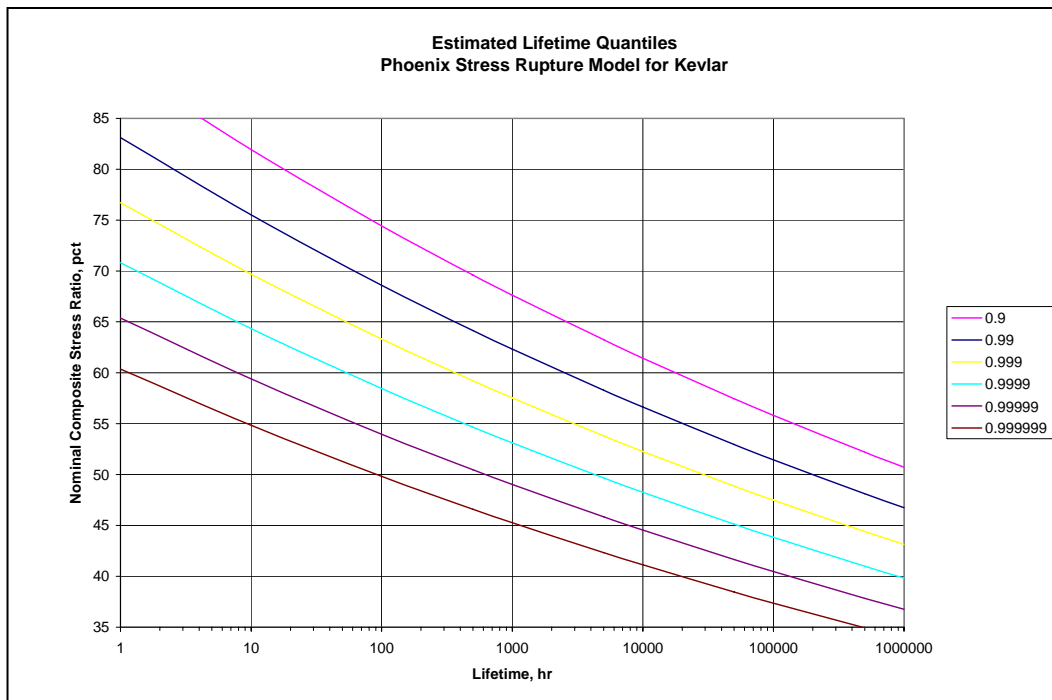


Figure 1. Stress-Rupture Curves for Kevlar COPV data.

that were inconsistent with the rest of the data. These testing artifacts had to be resolved using logbooks and interviews with test engineers more than 25 years after testing had been completed, which resulted in significant effort as discussed below [12]. A more complete description of the model is available in the paper by Phoenix et. al. in this session [16].

## EARLY COPV STRESS RUPTURE STUDIES

Early COPV lifetime tests were conducted at the DoE, Lawrence Livermore National Laboratory (LLNL) and at Boeing. The LLNL testing involved both strand and vessel specimen configurations for Kevlar and Thornel 50 Carbon fibers and the testing at Boeing involved the testing of cylindrical COPVs overwrapped with seven different carbon fiber types.

The Kevlar vessel testing at LLNL involved the manufacture of 240 COPVs that were approximately four-inches in diameter and were tested at five stress levels at the laboratory for 10 years. Similar testing using Thornel 50 fiber was also performed at LLNL [11]. The Kevlar data was recently examined by these authors and others as a part of an independent assessment performed by NASA. Data obtained during these tests were grouped into 6 test levels (instantaneous burst test, 86%, 80%, 74%, 68%, and 50% stress ratio) with approximately 30 vessels tested at each level. Vessels were pressurized within individual burst enclosures on individual manifolds inside a dedicated test facility at LLNL. Pressures and temperatures were recorded in written logbooks by technicians throughout the course of the testing and if pressure drops were noted, the pressure was increased back to the target. Over the 10 year period of test, pressure checks were not

consistently taken and after 7.5 years, the remaining test specimens were moved from one building to another at LLNL and testing was continued.

Upon review of the test record logbooks, inconsistencies in reporting, test facility, pressure level, stress ratio, temperature, assignment of test level by serial number, manufacturing and damage history, test history were noted. Testing was performed for almost 11 years and the data acquired at lower stress levels spanned the entire test period. In the first year of the test, pressure readings were consistently recorded every 3 days for each vessel, but as the test proceeded, pressure recordings were made every two to three months. At the end of testing, summary pages were written which contained more information than was available in the pressure records themselves. The summaries noted vessels that leaked, but these were not noted anywhere else in the lab notebooks. Presumably they were placed in test, but removed after they could not be brought to test pressure.

In December of 1984, the test setup was moved to another facility at LLNL. An intermediate location was used prior to the final test setup. Specific information on the move was not available, but internal LLNL records indicate that the move was made without support to the vessels within their blast shields (each vessel was enclosed in an individual blast shield, which made it difficult to directly observe a failure [either leak or burst]). After the move, several vessels were reported to have leaked (zero pressure) and needed stem replacement. These repairs were made and all of the remaining vessels were repressurized.

After initial filling, the test setup and pressurization procedures specified a +1% to -3% pressure envelope on the nominal test pressure, but violation of this by several percent was noted in the lab notebooks with pressure adjustments required on many vessels. Temperature was not constant during the testing, higher test temperatures were observed after the move to the new facility but low temperatures were also noted. These temperature excursions are probably linked to the pressure level changes noted in the lab notebooks, but specific notes were not made (but in one case a low temperature was noted as having caused a significant pressure drop in the vessels). In several cases, changes in pressure were accompanied by the failure of vessels by the next pressure check. It is suspected that the behavior of the COPVs was changed after the temperature spikes because increases in pressure result in additional yield of the liner. The effect of these pressure changes on the failure of the vessels is suspicious, but inconclusive.

A substantial effect overlooked by LLNL was the mechanical contribution of the 1100 aluminum liner. Initially the load carrying contribution of the liner was incorrectly assumed to be negligible and stress ratios calculated accordingly. However, recent close examination, as discussed in detail in Thesken et. al., illustrates that the stress ratios were between 2 and 6% lower than initially reported [17] due to the mechanical contribution of the liner.

Vessel serial number and test level assignments were made at the outset of testing, but changes in the test level were noted in the lab notebooks after the apparent completion of burst testing (the completion of 18 of the reported 29 burst data points). Eleven vessels were moved out of the burst level and into various stress-rupture pressure levels, and eleven were moved back into the burst level to obtain the 29 burst data points later. Of those moved out of the burst level and into the test levels, the vessels moved to the higher pressure levels were withheld (not tested) but the ones moved to the lower stress levels were tested. The implication is

that these vessels were problematic in the burst test and moved to other test levels where they could only be successfully loaded to test pressure at the lower pressure levels. There were no notes in the lab notebooks to confirm this. This finding is important because it establishes a more reasonable pattern of failure behavior in the distribution tails that is consistent with the pattern of noted “failures” (either leakers or bursts) seen at the other stress levels. Had the vessels been proof tested, it is likely that any low performing vessels would have been found before being placed in test. It is interesting to note that no vessels among the 29 burst tested were recorded as leaking on pressurization, yet a significant fraction leaked on loading in all stress rupture tests. Probability calculations show that the likelihood of having no leaking vessels during the burst tests is extremely small.

All of the winding records for the vessels were available with two vessels (53 and 108) having winding anomalies (only 108 was placed in test). Vessel 80 was noted as dropped prior to placement on test. It is not clear if either of these anomalies affected the resulting lifetime, but these findings indicate that vessels with prior damage history were placed on test.

All of the vessels placed in test at the reported 74% pressure level were previously cycled during an acoustic emission test. A disproportionately large number of vessels tested at this level leaked on pressurization as compared to the other test levels. No additional information was found in the lab notebooks to explain this, but these vessels had a very different past history than those tested at other levels.

Despite these inconsistencies found in the logbooks, the majority of the LLNL stress-rupture data follows trends observed in other stress-rupture data (strand), so the utility of the data set as a whole is not in question [12].

Although more detailed discussion of these tests can be found elsewhere [12, 13], the outcome of these test programs provided lifetime data to older space and missile systems and the Kevlar fiber and resin systems used are not as relevant for future COPV designs. However, lessons learned from this test program can be generally applied to carbon fiber COPV testing.

More relevant testing on carbon fiber COPVs was completed by Boeing, but due to very small sample sizes, predictions based on this data are difficult [9]. This study will not be discussed in detail, except to mention that due to the large scatter observed in stress rupture data, sample sizes larger than 5 are recommended.

## **STRESS RUPTURE TESTING AT WSTF**

As part of a joint program between the Jet Propulsion Laboratory (JPL) and NASA White Sands Test Facility (WSTF), vessel stress rupture testing was performed on small COPVs manufactured by Luxfer<sup>®</sup>.<sup>1</sup> The 120 COPVs procured for this program were delivered from Luxfer Gas Cylinders (Riverside, California) in August of 1998 to WSTF for stress rupture testing. Twenty COPVs were burst to establish the burst pressure of the design and to determine the fiber stress at burst. This fiber stress at burst and the results of a finite element analysis were used to determine the stress ratio,  $\sigma_{op}/\sigma_{burst}$ .

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<sup>1</sup> Luxfer<sup>®</sup> is a registered trademark of Luxfer, Inc., Riverside, CA.

## **COPV Design**

The cylindrical vessels measured 4.23 inches in diameter with a length of 11.4 inches and a weight of 1.6 pounds. Liners were 0.078-inch thick spun formed 6061-T6 aluminum. Because this special COPV design was intended for stress rupture testing only, the composite overwrap consisted of two helicals and one hoop wrap, making the composite substantially thinner than the majority of in-service high pressure COPVs. These COPVs were not proof tested prior to placement in stress rupture test. The thickness of the overwrap was minimized to force stress rupture failure to occur in the single hoop wrap layer, which was chosen to be the outermost layer to reduce the influence of “ply averaging” and allow hoop wrap failures to be observed immediately [12].

## **Test Facility**

To accommodate the testing of large numbers of small COPVs, a 12'x24' Morgan portable building was dedicated to the testing. To minimize environmental effects, the building had additional insulation added, all thermal leaks were sealed and the building was equipped with two window mounted HVAC units. Independent thermostats maintained blast enclosure temperatures to  $70 \pm 4^\circ \text{F}$  tolerance (during pre-accumulator short duration testing, temperature was actually within  $1^\circ \text{F}$ ). One group of vessels saw a larger temperature tolerance of  $70 \pm 8^\circ \text{F}$  over the 7301 to 8981 hours of test. These vessels had accumulators to reduce the magnitude of pressure swings. Access to the building was minimal and hazardous conditions are relayed to authorized personnel by area and test cell warning lights. The test system and Morgan buildings exterior are shown in Figure 2.

The interior of the building was outfitted with blast enclosures for the individual pressure test banks. Each bank pressurized 9 pressure vessels. The blast enclosures were designed to withstand a COPV rupture and were constructed with plywood and quarter inch ballistic grade Lexan®. Drip pans lined with craft paper were installed on the bottom of the blast enclosure to contain the pressurant in the event of a vessel failure. The craft paper is readily stained by pressurant, indicating a leak in the COPV or pressure system. Because of the uncertain effect of UV light exposure, the Lexan® windows were covered with welding screens during test.

The test systems were hard-line manifolds that contained hydraulic locked pressure and 9 COPVs were pressurized together on a single manifold. The pressurant used for testing was Chevron® Technical White Mineral oil. Thermally induced pressure deviations were minimized for longer duration tests by bladder-type gas accumulators as seen in the left side of Figure 2. System bleeding and pressurization was accomplished by a mobile hand pump. The pump was connected and disconnected to the various test systems as required [12].

## **Issues with Design and Test**

As previously mentioned, the design of these test articles differed significantly from that typically applied to COPVs manufactured for space flight. Further detailed analysis of the COPV structural design showed that the design intent was



not achieved as conceptualized and the failure process in the test articles proved to be distinctly different from that which occurs in flight hardware. At the higher pressure ratios in stress rupture testing, tow and band failures in the outer hoop wrap were frequently observed to evolve as progressive unwrapping of single and multiple tows, which typically occurred over a period of hours to days after

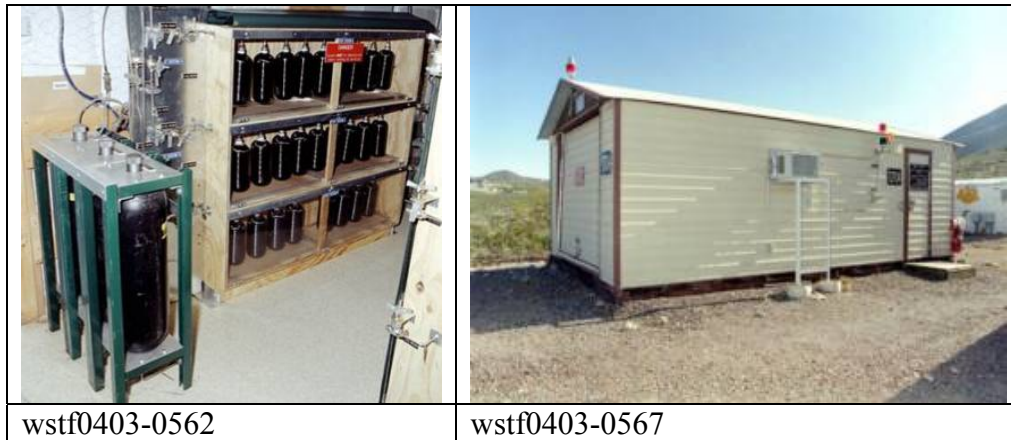


Figure 2: Carbon epoxy three-bank test system with accumulator, and stress rupture test facility



Figure 3. Fiber tow failure on test vessel.

pressurization as shown in Figure 3. This unraveling over time eventually led to a loss of hoop support over relatively large cylindrical regions (typically 0.5 inch or greater along the axial direction) and eventually to burst failure. In a burst test under rapid pressurization, such tow failures did not typically cause immediate burst failure since unraveling did not have time to occur. On the other hand, initial pressurization for the stress rupture tests occurred at rates of two orders of magnitude slower than for the burst tests as discussed below. Thus, if such tow or

band failure occurred during slow pressurization of a group of nine vessels up to a specific but relatively high target stress rupture pressure, failure of tows or bands in one of the vessels could occur well before reaching the target pressure. This could result in unraveling of the tow and possibly a reduced burst pressure on continued pressurization or very early failure in stress rupture. In a typical flight-like design, interleaving of overwraps would suppress this type of progressive unwinding following tow or band failure, and the load carrying disturbance would be highly localized and typically benign. Furthermore, in flight hardware, the composite overwrap is much thicker, and the liner is thinner than for the COPV used in the test program. The failure of a tow or band does not represent such a large fraction of the hoop support as in the test specimen design [12].

Qualification and acceptance test methodology that is required for flight COPVs was not applied to this special test specimen design. Of particular importance was the lack of a proof test, which would have altered the behavior of the COPVs. A proof test may have eliminated some vessels once tow failure or band failure was observed, but the proof pressure would need to have been well above 75 percent of the mean qualification burst pressure to eliminate any of the vessels from the current population.

As mentioned earlier, the four low values shown in Figure 4 (red dots) were observed during (or very shortly after) pressurization in the stress rupture tests at a much lower pressure rate (by two orders of magnitude) than used in the actual burst tests of the other 30 vessels. Any failed tows during the initial pressurization of the stress rupture tests would have considerably more time than in a rapid burst test to unravel and shed load onto neighboring tows. This could overstress neighboring tows over long lengths possibly failing them and accelerating the failure process.

Pursuing the cause for the four low burst values required advanced statistical and mechanical modeling as well as a deeper understanding of the results from the successful NDE inspection and burst testing of the ten selected test specimen COPVs. Four types of vessels were selected. The first type consisted of vessels that had been previously tested. The second vessel type consisted of three pristine or “green” samples that had not previously been pressurized or proof tested in any way. These three vessels had been stored in containers at WSTF since 1998. The third group of COPVs had been previously pressurized during stress rupture testing at a lower level than the first group and exhibited a hoop tow failure sometime in the first four hours of testing. The fourth groups of COPVs were also previously tested in stress rupture and were in the same bank with vessel S/N 2117 which burst in 15 hours, and another vessel which had a tow failure by 15 hours [12].

Based on the outcome of the burst testing of these four groups of vessels and pressure-strain response from Fiber Optic Bragg Grating strain gages during the tests, the delivered fiber strength had to be recalculated from the fiber stress ratios actually used in the stress rupture tests. According to the manufacturer’s FEA calculations, the target pressure for Group 1 would correspond to a fiber stress ratio of 87.5 percent, (i.e. a fiber stress of 87.5 percent of the mean delivered fiber strength as calculated from the mean burst strength). Structural analysis, however; shows that the effective fiber stress is actually about 90 percent of that occurring at 4288 psi - the mean of the burst tests performed at the beginning of testing. The reason for the difference is thought to be incorrect liner yield properties assumed in the initial FEA, thus leading to more liner contribution to pressure support than

actually occurred. Figure 5 illustrates the differences in the new stress ratios and those from the FEA. An important aspect of this recalculation of the stress ratios is that vessel S/N 2141, which burst at the lowest pressure actually

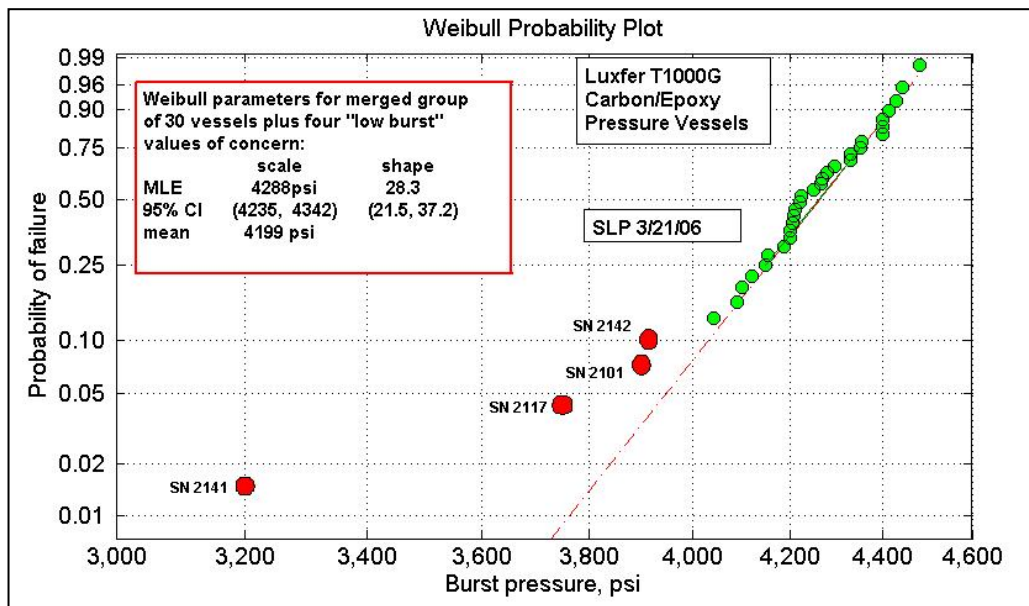


Figure 4. Weibull Plot of Burst Pressure Data from Three Burst Test Groups (●), and the Four Low Burst Values (●).

burst at a fiber stress ratio of about 58 percent, not the 52 percent as originally thought [12].

A statistical bundle failure analysis for these thin overwrapped vessels with no ply overlapping at different angles showed that strands would begin to fail at about 75 percent of the burst pressure under rapid loading. Such strand failures would not result in vessel failure under rapid pressurization due to the type of strand load-sharing involved. However, in a stress rupture situation, such strands could be expected to slowly debond and unravel over a period of just hours, causing stress concentration and premature failure [12].

Although the team was able to explain nearly all of the early failures, several lessons learned were gleaned from difficulties encountered during this testing.

## LESSONS LEARNED FROM STRESS-RUPTURE TESTS

### LLNL Kevlar COPV Testing

As a part of the review of the LLNL Kevlar COPV logbooks and subsequent analysis of the data, several key testing issues were identified as lessons learned. These were the importance of consistent pressure recordings, accurate stress ratios, sufficient temperature control, clear reporting of all failure times, consistent test facility, and the use of pristine vessels only for test.

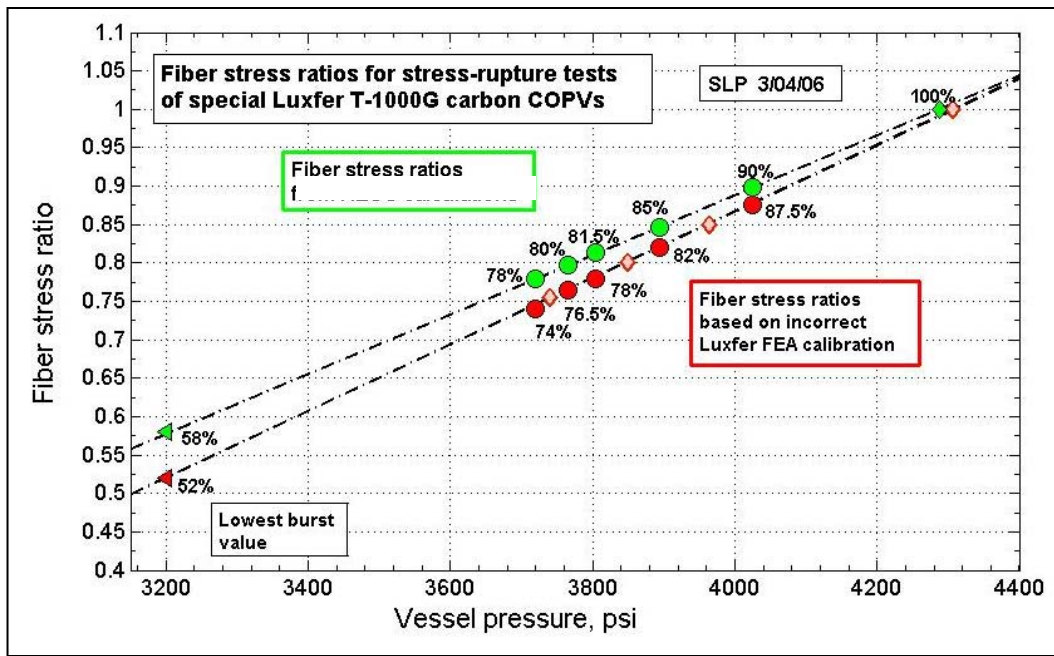


Figure 5. Stress Rupture Chart for specimen COPV.

The LLNL test was plagued with inconsistent pressure recordings and adjustments. As a consequence, pressure decay during testing was not carefully managed (i.e. increases in pressure were not timely, nor were they rigorously determined based on the mechanical behavior of COPVs). Also, the facility was moved during the test with reductions in pressure in the vessels noted. Since stress rupture is a strong function of stress ratio, such pressure drops altered the stress ratio for short periods of time, leading to unquantified effects on lifetime. Any future testing must have consistent pressure recording (preferably a computer-based data acquisition system) and any necessary pressure adjustments must be substantiated by detailed mechanical analysis of the test vessels to ensure that stress ratio is not altered. Clearly, a facility move during testing is not ideal.

The lack of temperature control is critical for fibers such as Kevlar, because increase in stress ratios were not accurately determined at the outset of the testing, resulting in data that was not accurately tied to stress level. This led to an overly-optimistic view of the stress rupture lifetime of Kevlar fibers because the lifetimes actually corresponded to stress ratios that were lower than reported.

In addition, the lack of temperature control is critical for fibers such as Kevlar, because temperature has been shown to dramatically reduce the stress rupture lifetime of Kevlar fibers [12]. This is also likely to be important for carbon vessels because temperature could change the behavior of the matrix resin in those vessels [13]. In addition, even small increases in the temperature of the testing fluid (even a few degrees) could result in pressure increases substantial enough to change the stress ratio of the vessel, changing the outcome of the test. Temperature must be as tightly controlled during stress rupture testing as possible and the effects of temperature range must be analyzed prior to the start of the test to determine if they are adequate.

For the vessels that survived the longest, those lasting more than 5 years, failure time recordings were sparse and the failure times of some had to be placed in an interval between reporting periods of up to several weeks. Because of this, the analysis required early censor times or an interval technique [10,12] for these data points, likely reducing the stress rupture lifetimes. Clearly, any long term test program needs consistent reporting and as has been mentioned already, an automated data acquisition system would resolve this issue.

The load history and damage state was not well recorded for the LLNL vessels. The pressure cycle required for acoustic emission testing changed the behavior of the vessels, leading to larger numbers of leaking vessels in that group and no special accounting of this fact was made in the testing (i.e. modifying pressures to account for the change in stress ratio or elimination of these vessels from the test). In addition, some vessels experienced mechanical damage prior to being placed in test. Because such histories could affect the stress rupture lifetime of these vessels, they must be well documented and although it may be possible to accommodate such events in the test plan to avoid spurious data, vessels with such prior load history and damage states are not recommended for use in testing.

### **WSTF/JPL COPV Testing**

Like the LLNL test program, several avoidable testing issues can be identified. These are the test specimen design, inconsistent stress ratio, and pressurization rate.

The initial reasoning behind the overwrap design for the WSTF/JPL test vessel was to allow determination of the earliest possible stress rupture failure. Unfortunately, the design resulted in more variability than was expected since failures occurred on loading and also at very short time periods due to the unexpected failure mode of strand failures. While the wrap pattern used in the testing could be used for flight, it is not representative of a standard COPV design, and therefore the damage progression through the composite during failure is also not representative of the majority of COPVs in service. A representative design would include interleaving wraps and a thicker overwrap. Development of an appropriate stress rupture design for test would include an involved study of damage progression and modeling.

Similarly, the FEA results from the manufacturer were found to be in error based on the pressure/strain response of the vessels. Appropriate mechanical characterization is required prior to start of test to ensure that stress ratios are correct; otherwise the resulting stress rupture lifetimes will not be accurate.

The WSTF/JPL testing was conducted without a proof test on each COPV in test being performed prior to start of test. While this alone is not necessarily a cause for concern, this in conjunction with the test procedure could have resulted in changes to the behavior of the COPVs that were not compensated for in test. Without proof test, the test pressure would have been the highest pressure the tanks had seen. When one tank in the bank failed, the other 8 tanks depressurized as well, serving as an in-situ proof test for those that did not fail. The procedure allowed for the remaining 8 tanks to be repressurized to the same pressure after the failure of one. However, the procedure did not account for the fact that upon reloading of the remaining tanks the liner contribution had changed, resulting in an increase in stress ratio. This change in stress ratio was not compensated for in the testing. In all, two

banks of COPVs were affected by this oversight. Future testing should require either initial proof testing to a pressure higher than that used in test or a pre-test pressure cycle should be applied to all vessels on test to a level equivalent to the highest test pressure. Alternatively, the test system could be modified such that each COPV is on a single manifold. In this way, the pressure in each tank could be controlled separate from the events of the others (the spherical Kevlar COPVs tested at LLNL were pressurized this way [12]).

In addition to separate manifolds, faster pressurization rate would have increased the number of survivors on loading. The pressurization rate was very slow and was accomplished using a hand pump with pressurized holds. Stress rupture testing must be accomplished using the same, or nearly the same pressurization rate as used during burst. Although the data available is inconclusive, it is suspected that the pressurization rate will substantially affect the resulting numbers of survivors during loading due to a large  $\rho$  value.

## CONCLUSIONS

In summary, several suggestions for future COPV stress rupture testing stem from an examination of the lessons learned from these two vessel stress rupture test programs:

1. Judicious reporting of pressure levels, temperatures, and failure times are paramount in stress rupture testing.
2. Tight temperature and pressure controls are required, and a mechanical analysis must be performed to justify control limits.
3. Load history and damage state must be characterized and accounted for during testing.
4. Test specimen design must be determined based on rigorous study of the vessel to which the data will be applied (i.e. progressive damage mechanisms must be considered in design).
5. Mechanical behavior must be well understood prior to testing and analysis must be reviewed carefully prior to testing to ensure correct stress ratios.
6. Ramifications of proof testing on stress ratio must be controlled.
7. Consistency in pressurization rate should be considered.

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