COMPOSITE OVERWRAPPED PRESSURE VESSEL (COPV) STRESS RUPTURE TESTING

Nathanael J. Greene(1), Regor L. Saulsberry(2), Mark R. Leifeste(3), Tommy B. Yoder(4), Chris P. Keddy(5), Scott C. Forth(6), Rick W. Russell(7)

(1) NASA Johnson Space Center White Sands Test Facility, P.O. Box 20, Las Cruces, NM 88004, U.S.A., Email: Nathanael.J.Greene@nasa.gov
(2) NASA Johnson Space Center White Sands Test Facility, P.O. Box 20, Las Cruces, NM 88004, U.S.A, Email: Regor.L.Saulsberry@nasa.gov
(3) NASA Johnson Space Center White Sands Test Facility, NASA Test and Evaluation Contract, P.O. Box 20, Las Cruces, NM 88004, U.S.A., Email: Mark.R.Leifeste@nasa.gov
(4) NASA Johnson Space Center White Sands Test Facility, NASA Test and Evaluation Contract, P.O. Box 20, Las Cruces, NM 88004, U.S.A., Email: Tommy.B.Yoder@nasa.gov
(5) NASA Johnson Space Center White Sands Test Facility, NASA Test and Evaluation Contract, P.O. Box 20, Las Cruces, NM 88004, U.S.A., Email: Christopher.P.Keddy@nasa.gov
(6) NASA Johnson Space Center, 2101 NASA Road 1, Houston, TX 77058-3696, U.S.A, Email: Scott.C.Forth@nasa.gov
(7) NASA Kennedy Space Center, FL 32899-0001, U.S.A, Email: Richard.W.Russell@nasa.gov

ABSTRACT

This paper reports stress rupture testing of Kevlar® composite overwrapped pressure vessels (COPVs) at NASA White Sands Test Facility. This 6-year test program was part of the larger effort to predict and extend the lifetime of flight vessels. Tests were performed to characterize control parameters for stress rupture testing, and vessel life was predicted by statistical modeling. One highly instrumented 102-cm (40-in.) diameter Kevlar® COPV was tested to failure (burst) as a single-point model verification. Significant data were generated that will enhance development of improved NDE methods and predictive modeling techniques, and thus better address stress rupture and other composite durability concerns that affect pressure vessel safety, reliability and mission assurance.

1. INTRODUCTION

NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) has been involved since 1978 in an effort to develop test data for understanding failure mechanisms that affect composite pressure vessels and structures. WSTF has been actively working nationally and internationally to promote development of composite technology by filling data gaps that affect safety, reliability, and mission goals [1].

Much effort has recently been invested in developing data for safe use of Kevlar®[1] composite overwrapped pressure vessels (COPVs) because they have several failure mechanisms that must be controlled to ensure safe use from manufacturing to decommissioning. Failure mechanisms for COPVs include mechanical damage, stress rupture (composite damage progression), fluid attack, corrosion, fatigue crack growth, liner buckling, liner and overwrap manufacturing flaws, thermal environments, overstress, and micro-meteoroid and orbital debris impact [2].

This paper reports an investigation of the stress rupture failure mechanism as it occurs in Kevlar COPVs. Several COPVs were tested to determine parameters for a final stress rupture to failure test of one 102-cm (40-in.) vessel (S/N 007) to verify model predictions. Actual vessel behavior was compared to the model predictions, and significant data were generated. The stress rupture failure mechanism is characterized by damage progression with time in the composite under a sustained load. The damage evolution of stress rupture can degrade strength such that the burst of a pressure vessel occurs at operating pressure.

2. BACKGROUND

Investigation into the stress rupture failure mechanism for Kevlar in COPVs began during the development of the technology in the early 1970s. Kevlar overwrapped rubber-lined vessels were developed and tested in 1974 by Lawrence Livermore National Laboratories (LLL) on contract to NASA Lewis Research Center (now NASA Glenn Research Center (GRC)) [2]. Kevlar 10.80 cm (4.25 in.) diameter (Ø) spheres were developed and stress rupture tested at LLL in 1978 [3,4]. Also in 1978, Kevlar 8.6 cm (3.4 in.) Ø x 26.9 cm (10.6 in.) vessels (Fig.1) were stress-rupture tested at NASA WSTF [5], and 26.04 cm (10.25 in.) Ø spheres were stress rupture tested at JSC [6]. Time, temperature, and pressure data were collected on Kevlar COPVs so that predictions of a reliable lifetime under sustained load could be made. The test data collected demonstrated a large scatter in

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1 Kevlar® is a registered trademark of E.I. de Pont de Nemours, Wilmington, Delaware.

the time-to-failure data. Further testing, using the latest developments in nondestructive evaluation (NDE) and computerized predictive models, was needed to better understand Kevlar COPV stress rupture failure.

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Figure 1. The first flight-rated COPV stress rupture tests were at WSTF

3. EXPERIMENT DESIGN

Testing of Kevlar COPVs at NASA WSTF from 2004 to 2010 was a part of the effort to predict and extend the lifetime of flight vessels. The program included testing of five 102 cm (40 in.) Ø COPVs (S/N 002, 006, 007, 009, and 011), two 66 cm (26 in.) Ø COPVs (S/N 001 and 005), and three 56 cm (22 in.) Ø COPVs (S/N 014, 022, and 027).

Pressure cycling and burst tests were performed on the COPVs to characterize control parameters for stress rupture testing on flight articles. Upon completion of the control parameter tests, highly instrumented stress rupture testing of the 102 cm (40-in.) Ø COPV S/N 007 was performed to failure as a single-point model verification.

3.1. Stress Rupture Models

The large scatter in the time-to-failure data for pressure vessels requires statistical modeling to determine the mean time to failure at load and temperature. Models for estimation of stress rupture lifetime for Kevlar COPVs have been developed based on power law and Weibull and Pareto distributions, and result in differing predictions of vessel lifetime. Models reviewed in the experiment design for this test included those by Phoenix at Cornell University [7], Heydorn at NASA-JSC [8], Glaser at LLL [9], and Cavanaugh et al. [10] and Robinson [11] at The Aerospace Corporation.

The Phoenix model was used for life prediction and test parameter selection for the S/N 007 burst test. The Phoenix model is formulated with conditional reliability allowing the model to be re-baselined at various points. This approach for calculation of probability of failure provides different results than the straight reliability approach, as can be seen in Fig. 2. Equations 1 and 2 are simplified representations of the Phoenix Model II for the standard and conditional reliability life estimates, where:

- $F(t,\sigma)$ is reliability as a function of time at pressure and fiber stress level
- t_1 is the time at one stress level up to Δt where another stress level is applied
- $t_{c,ref}$ is a calculated reference time
- $\sigma_{op1/}\,\sigma_{ref}$ and $\sigma_{op2/}\,\sigma_{ref}$ are operating stress ratios
- ρ is the power law exponent
- β is the Weibull shape parameter

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

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

Equations. 1 and 2 have been used to generate the results in Fig. 2.

3.2. Model Verification

Because of the large scatter in data requiring statistical modeling, the standard "elephant test" approach was applied for comparing the model predictions to the test data. Elephant tests are also referred to as design limit tests or design margin tests. Allegorically, this testing approach is like having an elephant step on a product to see if it passes or fails a criteria [12].

The test success criteria for model verification were based on the Phoenix Model II lifetime predictions for the 95 percent confidence interval for low, mean, and high estimates for failure (burst) of the test vessel (Fig. 3).

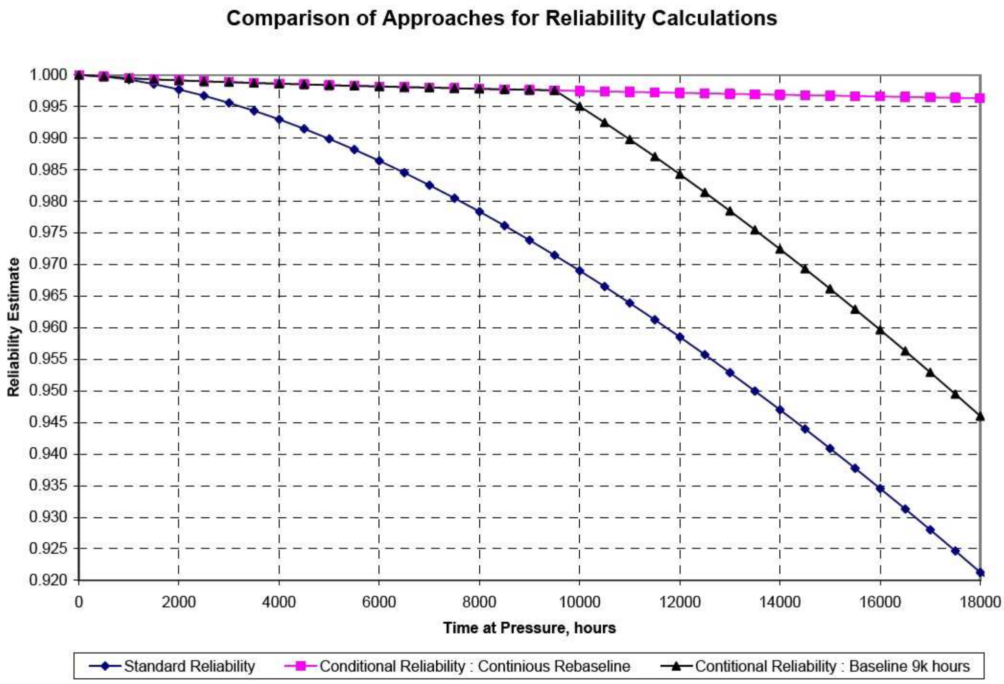

Figure 2. Straight reliability, conditional reliability at each pressurization and conditional reliability that re-baselines once and calculates future use relative to that baseline

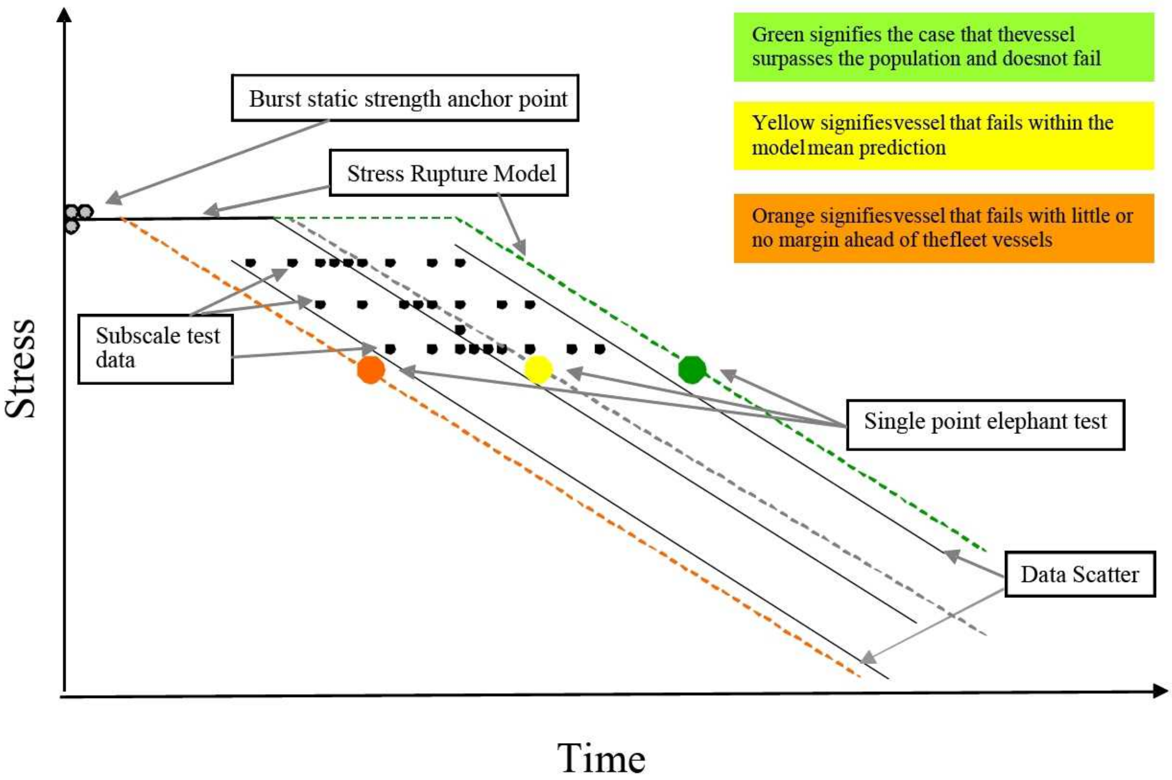

Figure 3. Single point stress rupture elephant test

4. TEST SYSTEM

Stress rupture testing of S/N 007 was conducted in the WSTF Hazardous Fluids Test Area in Test Cell 862. The test cell is 2.0 lb TNT blast-rated and has dual heating and cooling units to control the temperature of the vessel and test system to within ± 2.8 °C (5 °F). The instrumentation and pressure system is remotely controlled to protect personnel from stored energy. The test cell also provides dedicated power backup to ensure testing is not compromised. Fig. 4 is a photograph of the test cell and backup generator.

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Figure 4. Test Cell 862

The test system employs a high volume pump system (103 MPa (15,000 psig) rated) and a metering pump system for fine pressure adjustments.

A thermal control system inside the test vessel enclosure provides thermal stability to ± 1.1 °C (2 °F). Thermal gradients around the vessel were minimized to ensure known test conditions for the overwrap. Fig. 5 shows some thermal results from around a pressure vessel.

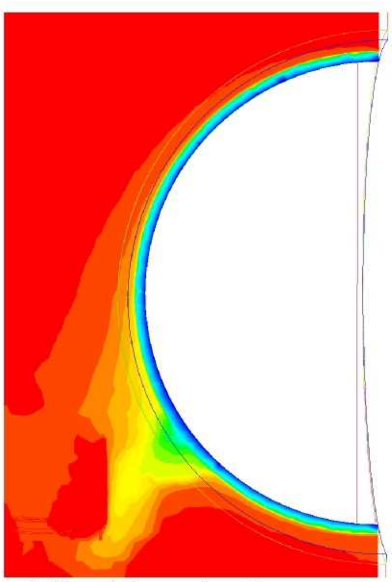

Figure 5. Vessel thermal environment (no fluid)

4.1. Nondestructive Evaluation

Multiple NDE methods were applied to determine the pre-test condition of S/N 007, including visual inspection per ANSI/AIAA S-081 [13], thermography, shearography, exterior laser profilometry and videoscope. Equipment and a methodology were developed at WSTF to perform internal laser profilometry for assessment of buckles and liner-to-overwrap bonding integrity. Fig. 6 shows a sample of laser profilometry results on a vessel, with 0 degrees indicating the weld. The internal laser profilometry data collected is traceable to National Institute of Standards and Technology (NIST) standards and has a sensitivity of ± 0.005 cm (0.002 in.). An example of liner ripple data detected with this technique is shown in Fig. 6.

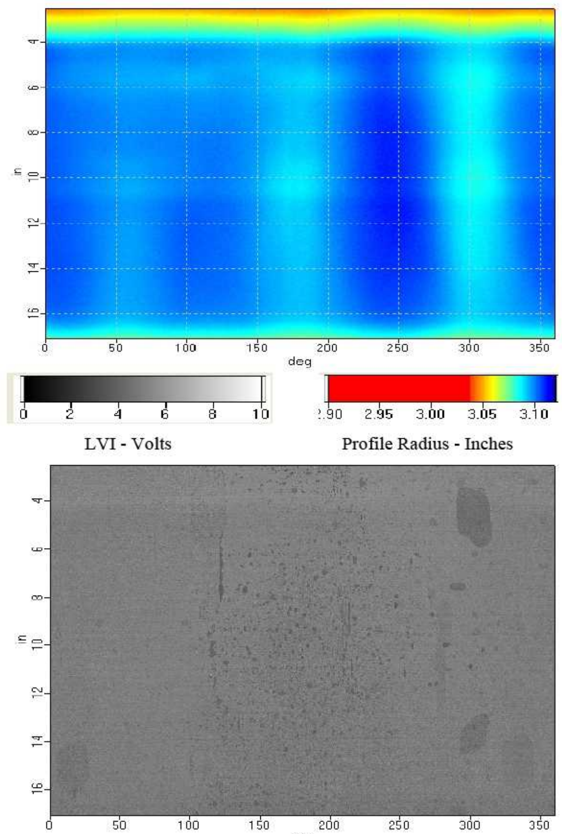

Figure 6. Laser profilometry liner ripples

4.2. Instrumentation

Test vessels used for parameter development were highly instrumented with strain gauges, fiber optic Bragg gratings (FOBG), linear variable displacement transducers, girth cables, Raman spectroscopy, pressurized thermograpy, overwrap and liner eddy current thickness monitors, internal volume, acoustic emission, audio, high speed and 30-frame/second video, and full field strain measurement. S/N 007 was instrumented with all these listed except FOBG.

WSTF partners from NASA JSC, GRC, Langley Research Center (LaRC) and Marshall Space Flight Center (MSFC) brought their expertise to the program and worked with WSTF to gather specialized test data. LaRC was responsible for analysis of acoustic emission and eddy current data; GRC was responsible for Raman spectroscopy full field strain; and MSFC was responsible for FOBG data. WSTF was responsible for analysis of all primary data including pressure, temperature, strain, boss linear displacement, volumetric growth, and diametrical changes.

A sample photo of a vessel with instrumentation installed prior to test is shown in Fig. 7.

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Figure 7. Typical Kevlar-epoxy vessel pre-test instrumentation

5. TEST RESULTS

The S/N 007 COPV, tested in stress rupture to failure, exhibited a burst failure mode after 0.9 years with a peak of 1.1 times maximum expected operating pressure and at a temperature of 79 °C (175 °F) (within temperature certification). The vessel exceeded the 95 percent confidence interval high prediction calculated by the stress rupture model. Figure 8 shows the S/N 007 vessel after hydraulic stress rupture testing.

All primary data were successfully collected, and data analysis from the test program is underway. Secondary data have been provided to team members for analysis. Final reports will be published on the results

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Figure 8. Kevlar vessel upon completion of stress rupture test

6. Breakthroughs in Testing

Several breakthroughs in NDE physical standards and test approach methodology for composite pressure vessel testing resulted from the COPV stress rupture testing program at WSTF.

NDE developments included:

- Raman spectroscopy for direct strain measurement
- Physical standards for laser shearography and thermography
- Laser profilometry for inspection of liner to overwrap interface

Test approach improvements included:

- Active pressure and temperature management control to ± 0.6 °C (1 °F) and ± -35 kPa (-5 psig)
- Stepped stress rupture test method for COPVs
- COPV health check recertification methodology

7. CONCLUSIONS

New techniques for NDE structural health monitoring are being developed as a result of the data collected from the methods employed during this test program. The S/N 007 vessel exceeded model predictions, resulting in a positive result for the elephant test. The variance in the test results from the model prediction indicates that further work is needed in order to improve model predictions for Kevlar epoxy vessels.

8. FUTURE WORK

Significant data exist on Kevlar epoxy in stress rupture; however, model improvements are needed. For other fiber types such as carbon and polybenzoxazole, less data are available. As a result, stress rupture model accuracy on COPVs and composite pressurized structures is unknown. However, in this program significant data were obtained as predictions were tested to compare vessel behaviour to the model. These data are available to feed back into all models for future predictions. WSTF is working with NASA, the U.S. Departments of Defense, Energy, and Transportation, the Federal Aviation Administration, and industry partners worldwide to answer questions about stress rupture and other composite durability concerns that affect safety, reliability and mission assurance.

9. REFERENCES

1. Greene, N. J. *WSTF Composite Pressure Vessel and Structure Summit* (2009): NASA White Sands Test Facility, Las Cruces, NM, http://www.nasa.gov/centers/wstf/news/safetysummit2009.html (accessed 5/3/2010).

2. Greene, N. J. (2009). "Composite Overwrapped Pressure Vessels." Chapter 17.5 in *Safety Design for Space Systems* (Eds. G. Musgrave, A. Larsen, T. Sgobba), Elsevier Publications (elsevier.com, accessed 4/28/10).

3. Chiao, T., E. Hamstad, E. Jessop, and R. Tolland (1978). *High-Performance Fiber/Epoxy Composite Pressure Vessels*. Report UCRL-52533, Lawrence Livermore National Laboratory, Livermore, CA.

4. Tolland, W., R. Sanchez, and D. Freeman (1978). *Stress-Rupture Life of Kevlar/Epoxy Spherical Pressure Vessels.* Report UCID-17755, Lawrence Livermore National Laboratory, Livermore, CA.

5. Luper, A., L. Linley, and D. Pippen (1982). *Portable Oxygen System Bottle Accelerated Aging*. TR-237-001, NASA Johnson Space Center White Sands Test Facility, Las Cruces, NM.

6. Schmidt, W. and G. Ecord (1983). *Static Fatigue Life of Kevlar Arimid/Epoxy Pressure Vessels at Room and Elevated Temperatures*. AIAA Paper number 83-1328, Propulsion Conference of the American Institute of Aeronautics and Astronautics, Reston, VA.

7. K. Cameron, L. Grimes-Ledesma, S. Phoenix, P. Murthy, J. Thesken, and R. Saulsberry. *Orbiter Kevlar/Epoxy Overwrapped Pressure Vessel Flight Rationale Technical Assessment Report.* RP-07-34 (restricted access), NASA Engineering Safety Center, http://www.nasa.gov/offices/nesc/home/index.html (accessed 5/3/2010).

8. R. P. Heydorn and T. English (2006). *Estimates of the Conditional Reliability of COPV's Based on DoE-Dupont and LLNL Time-to-Failure Data.* SAIC, Fairfax County, VA.

9. R.E. Glaser (1983). *Statistical Analysis of Kevlar 49/Epoxy Composite Stress-Rupture Data.* UCID-19849, Lawrence Livermore National Laboratories, Livermore, CA.

10. M. Cavanaugh, J. Chang, S. Ruth, and S. Sallam (2005). *Space Shuttle COPVs Life Extension Assessment Draft.* The Aerospace Corporation, El Segundo, CA.

11. E. Robinson (2005). *Reliability Analysis and Life Extension Forecast of Kevlar COPV in the STS-Orbiter - An Independent Assessment Draft.* The Aerospace Corporation, El Segundo, CA.

12. Nelson, W. (1990). *Accelerated Testing Statistical Models, Test Plans and Data Analyses.* Wiley Publishers, New York.

13. ANSI/AIAA S-081A (2006). *Space Systems - Composite Overwrapped Pressure Vessels (COPVs),* American Institute of Aeronautics and Astronautics, Reston, Virginia.

4th IAASS Conference - Making Safety Matter

Composite Overwrapped Pressure Vessel Stress Rupture Testing

NASA JSC White Sands Test Facility

Nathanael J. Greene

575-525-7601 nathanael.j.greene@nasa.gov

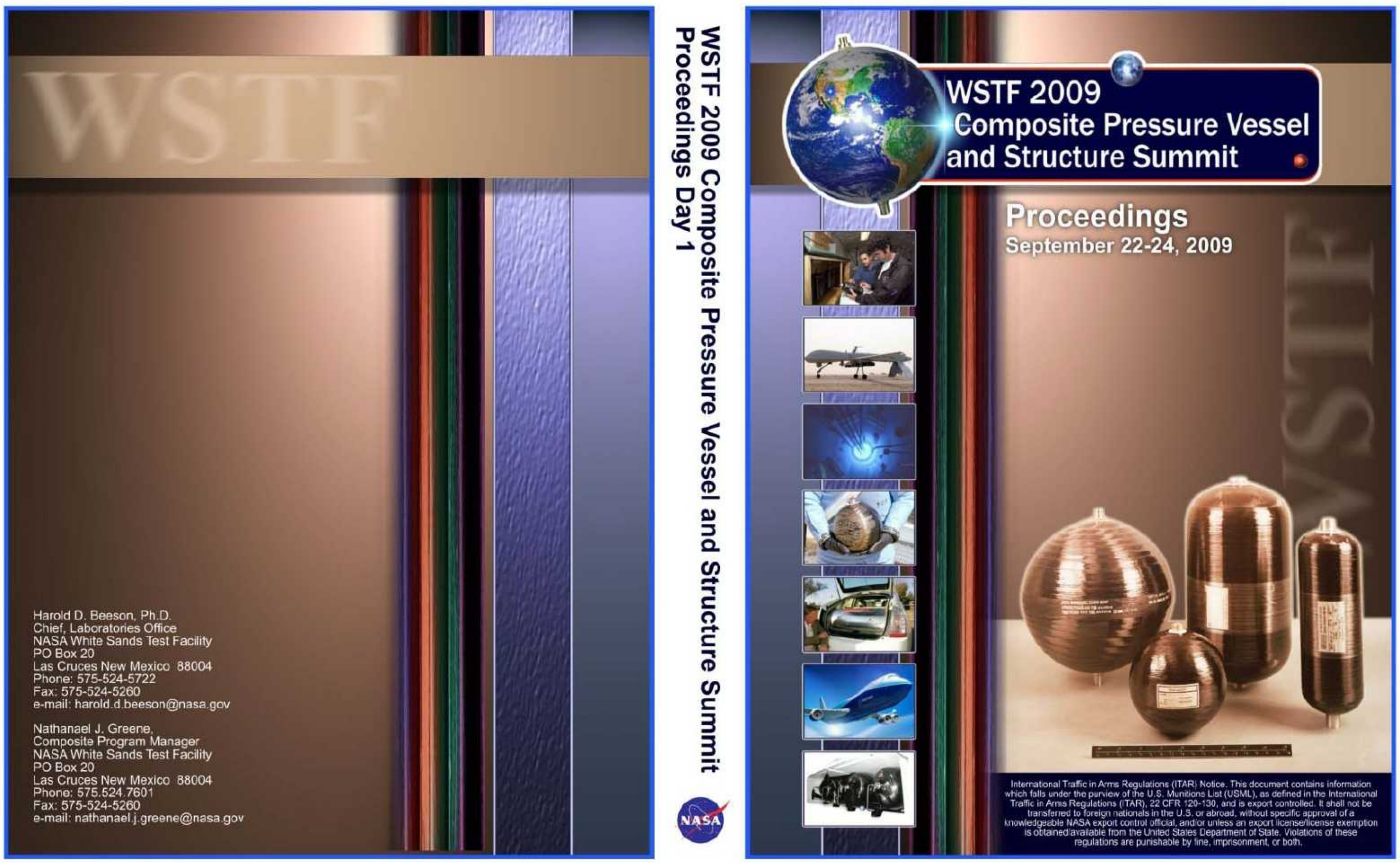
Overview

- NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) is a key leader in Composite Overwrapped Pressure Vessel (COPV) research
  - Since 1978, WSTF has been developing test data for understanding failure mechanisms that affect COPVs and structures
  - WSTF works with NASA, the U.S. Departments of Defense, Energy, and Transportation, the Federal Aviation Administration, and industry partners worldwide to investigate stress rupture and other composite durability concerns that affect safety, reliability, and mission assurance.

The first flight-rated COPV stress rupture tests were at WSTF

Overview (cont'd)

- In 2009, WSTF hosted the first Composite Pressure Vessel and Structure Summit



Fiber Reinforced Composite (FRC) 2009 Summit

The 9 central questions addressed at the Summit:

1. Should the design and quality assurance of hardware be regulated to ensure flight safety?
2. What current industry safety standards and operation protocols should be employed to guide the regulation and certification of FRC pressure vessels?
3. Are certification requirements detailed with sufficient information to assure safe use of FRC pressure vessels?
4. Should long-term strength testing (e.g., stress rupture testing) be considered in the design methodology ?
5. Do we know enough about the mechanical properties of FRC to establish a meaningful life factor on cyclic life or damage tolerance life?

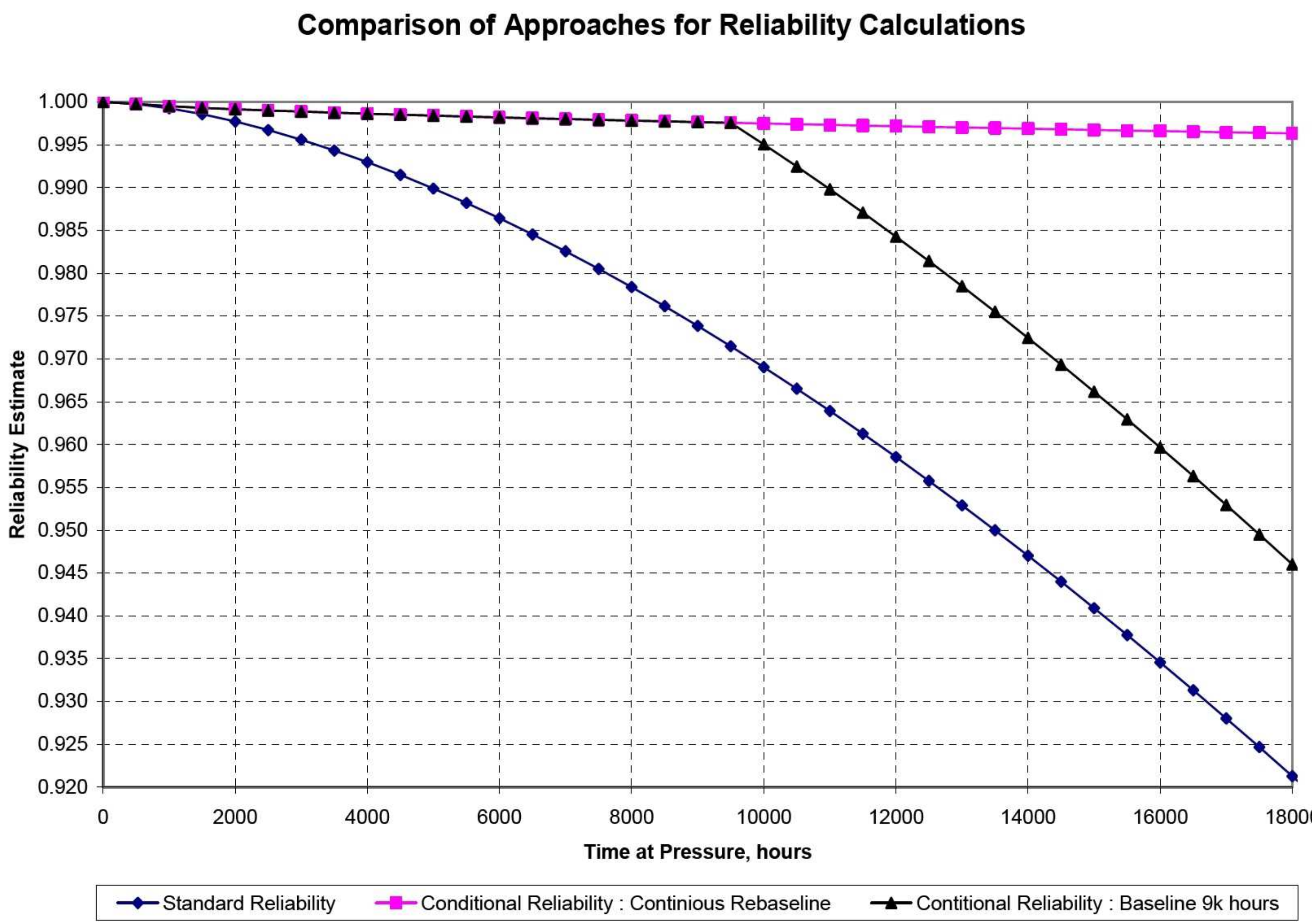
Fiber Reinforced Composite (FRC) 2009 Summit (cont'd)

6. Should we consider damage tolerance and fracture toughness of the FRC in the design criteria to establish safe life?
7. **Do we know enough about the potential failure mechanisms and coupling effects of composites for various ground and flight environments?**
8. Should there be different design requirements for constructing resin-based FRCs when different fluids are used (i.e., gas vs. liquid) to determine long-term stress or pressure rating?
9. Who should be responsible for modifying or developing standards that don't exist for new technology?

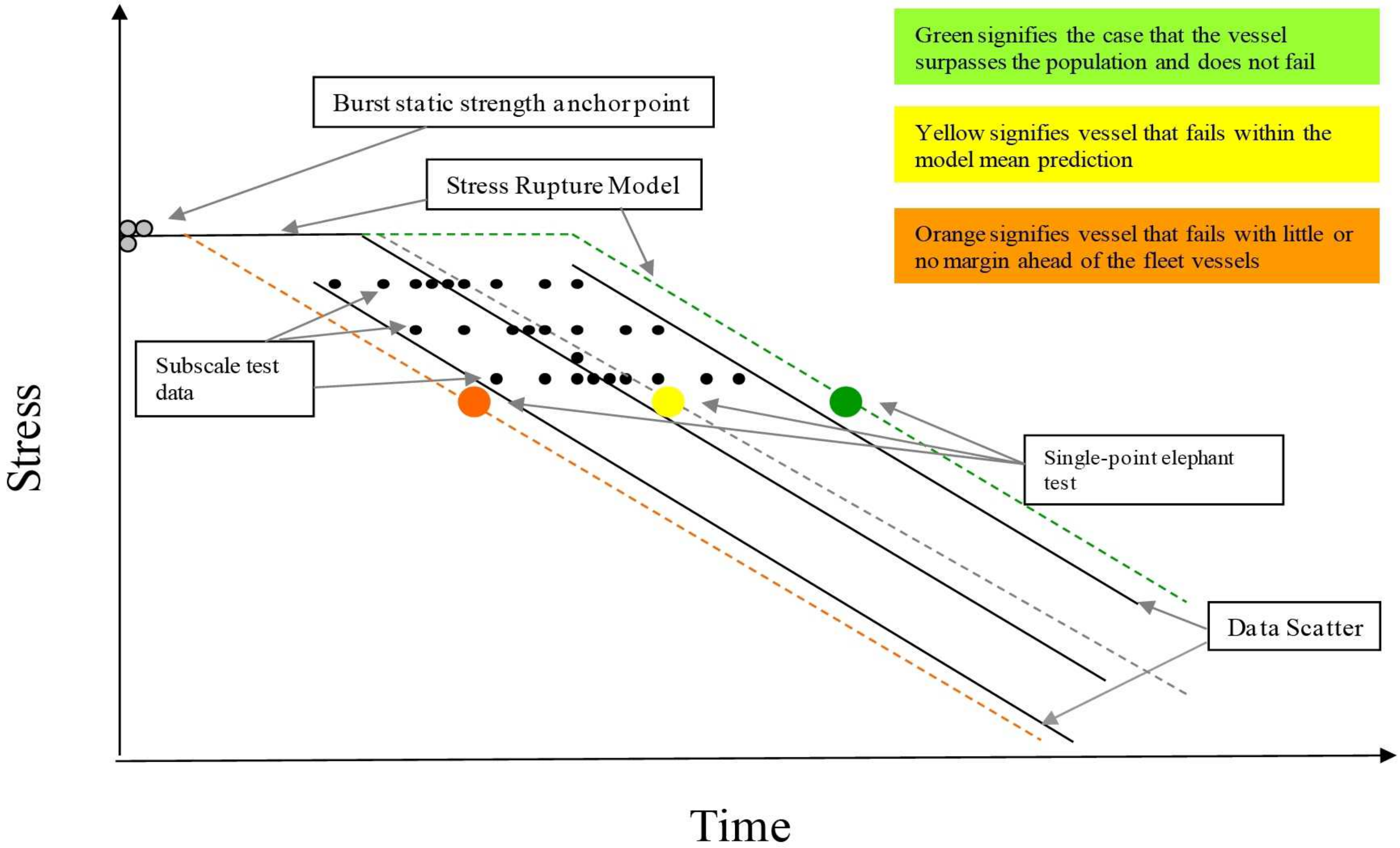
COPV Stress Rupture Testing Program

- A 6-year COPV testing program (2004-2010) at WSTF resulted in several breakthroughs for test approach and nondestructive evaluation (NDE) testing
- Previous tests yielded large scatter in time-to-failure data
- Further tests were needed with latest NDE techniques and predictive models for life extension
  - Pressure cycling and burst tests characterized control parameters for stress rupture tests on flight articles
  - Highly instrumented stress rupture testing of 102-cm (40-in.) COPV S/N 007
  - Stress Rupture Model
    - Phoenix Model II used for life prediction and test parameter selection
  - Model Verification
    - “Elephant test” approach

Phoenix Model II Approach Compared to the Straight Reliability Approach



Single-Point Stress Rupture Elephant Test



Stress Rupture Testing of S/N 007

- WSTF Hazardous Fluids Test Area
  - 2.0 lb TNT blast-rated
  - System temperature controlled to within ± 3 °C (5 °F)
  - Instrumentation and pressure remotely controlled
  - High volume pump system 103 MPa (15,000 psig) rated
  - Thermal control of 1 °C (2 °F) inside vessel enclosure

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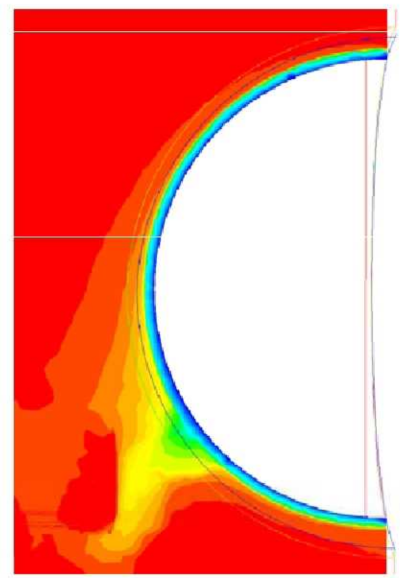
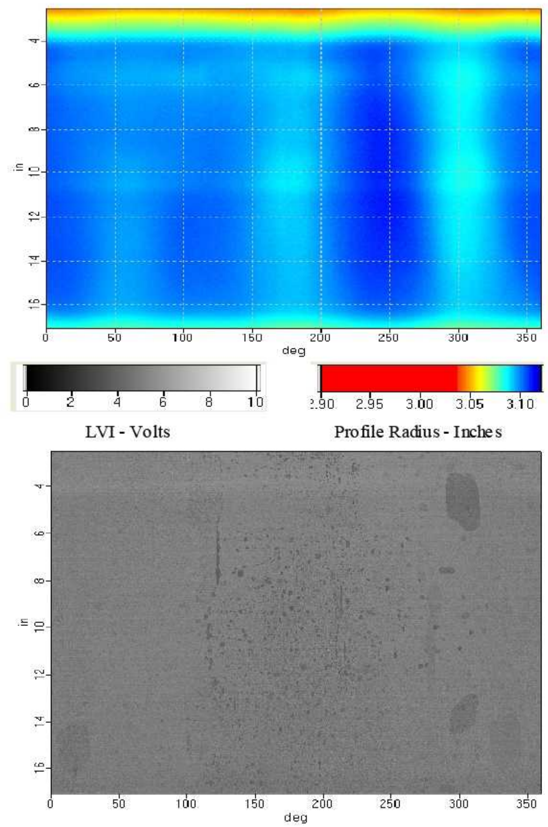
Test Cell 862 of the HFTA

Thermal gradients around the vessel minimized to ensure known test conditions for the overwrap



Nondestructive Evaluation

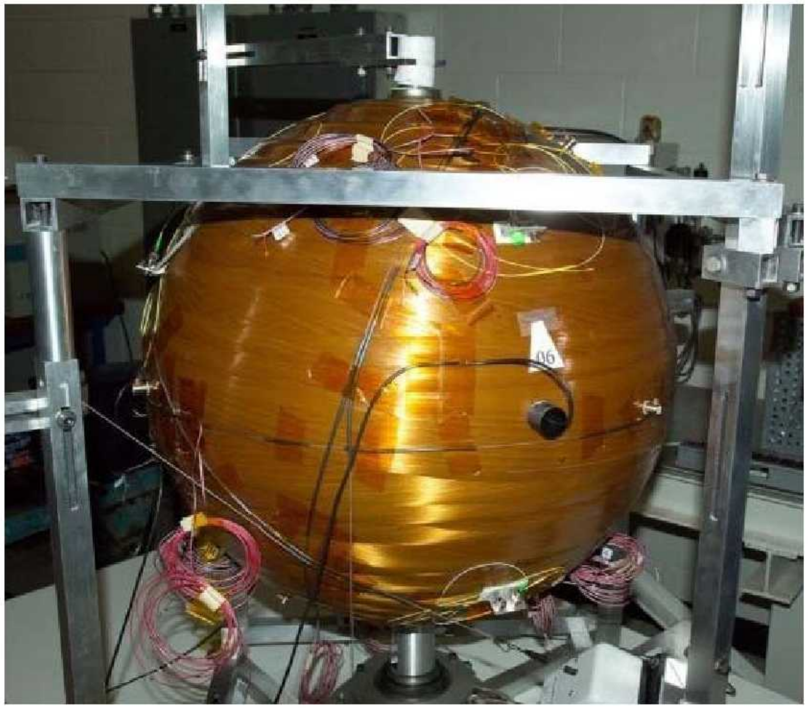
- Visual inspection per ANSI/AIAA S-081
- Thermography
- Shearography
- Exterior laser profilometry and videoscope
- Internal laser profilometry developed at WSTF
- Assessment of buckles and liner-to-overwrap bonding integrity



Laser profilometry liner ripples

Nondestructive Evaluation (cont'd)

- Instrumentation
  - Strain gauges
  - Fiber optic Bragg gratings (FOBG) (except S/N 007)
  - Linear variable displacement transducers
  - Girth cables
  - Raman spectroscopy
  - Pressurized thermography
  - Overwrap and liner eddy current thickness monitors
  - Internal volume
  - Acoustic emission
  - Audio
  - High-speed and 30 fps video
  - Full field strain measurement



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Typical Kevlar-epoxy vessel pre-test instrumentation

Test Team

- Expertise from various NASA Centers:
  - Data expertise:
    - NASA White Sands Test Facility
    - NASA Johnson Space Center
    - NASA Glenn Research Center
    - NASA Langley Research Center
    - NASA Marshall Space Flight Center
  - Acoustic emission and eddy current data
    - NASA Langley Research Center
  - Raman spectroscopy full field strain
    - NASA Glenn Research Center
  - FOBG data
    - NASA Marshall Space Flight Center

Test Results

- S/N 007 COPV tested in stress rupture to failure
  - Burst failure after 0.9 years
    - Peak of 1.1 times MEOP at 79 °C (175 °F) (within temperature certification)
    - Exceeded 95% confidence interval high prediction of stress rupture model

Kevlar vessel upon completion of stress rupture test

Breakthroughs for COPV Testing

- NDE developments included:
  - Raman spectroscopy for direct strain measurement
  - Physical standards for laser shearography and thermography
  - Laser profilometry for inspection of liner to overwrap interface

Breakthroughs for COPV Testing (cont'd)

- Test approach improvements included:
  - Active pressure and temperature management control to ± 0.6 °C (1 °F) and ± -35 kPa (-5 psig)
  - Stepped stress rupture test method for COPVs
  - COPV health check recertification methodology
- New techniques for NDE structural health monitoring are being developed as a result of data obtained from the methods used during this test program.

Future Work

- Significant data exist on Kevlar epoxy COPVs in stress rupture; however, model improvements are needed.
- Less data are available for other fiber types such as carbon and polybenzoxazole.
- Significant data from this stress rupture test program are available to feed back into all models for future predictions.
- WSTF works with partners worldwide to investigate composite durability concerns that affect safety, reliability, and mission assurance.

Point of Contact

NASA White Sands Test Facility

Nathanael J. Greene

575-525-7601

nathanael.j.greene@nasa.gov