TESTING OF FULL SCALE FLIGHT QUALIFIED KEVLAR COMPOSITE OVERWRAPPED PRESSURE VESSELS

for Special Session on Composite Overwrapped Pressure Vessels "Pappu LN Murthy, Chair"

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Many decades ago NASA identified a need for low-mass pressure vessels for carrying various fluids aboard rockets, spacecraft, and satellites. A pressure vessel design known as the composite overwrapped pressure vessel (COPV) was identified to provide a weight savings over traditional single-material pressure vessels typically made of metal and this technology has been in use for space flight applications since the 1970's[1]. A typical vessel design consisted of a thin liner material, typically a metal, overwrapped with a continuous fiber yarn impregnated with epoxy. Most designs were such that the overwrapped fiber would carry a majority of load at normal operating pressures. The weight advantage for a COPV versus a traditional single-material pressure vessel contributed to widespread use of COPVs by NASA, the military, and industry. This technology is currently used for personal breathing supply storage, fuel storage for auto and mass transport vehicles and for various space flight and aircraft applications.

The NASA Engineering and Safety Center (NESC) was recently asked to review the operation of Kevlar®[2] and carbon COPVs to ensure they are safely operated on NASA space flight vehicles. A request was made to evaluate the life remaining on the Kevlar COPVs used on the Space Shuttle for helium and nitrogen storage. This paper provides a review of Kevlar COPV testing relevant to the NESC assessment. Also discussed are some key findings, observations, and recommendations that may be applicable to the COPV user community. Questions raised during the investigations have revealed the need for testing to better understand the stress rupture life and age life of COPVs.

A NASA Engineering and Safety Center assessment of COPVs being utilized on the Space Shuttle and International Space Station (ISS) has been completed. The team assembled by the NESC observed that the operating stress ratios on the Space Shuttle Kevlar® 49 COPVs were higher than they were originally thought to be. This raised concerns about the possibility of composite stress rupture, an unpredictable and catastrophic event. Assessments of the likelihood of stress rupture in future missions has relied largely on a database of small spherical COPVs and epoxy-impregnated strands generated at Lawrence Livermore National Laboratory (LLNL) (University of California, Livermore, California). While the LLNL database has been very

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[1] Chiao, T. T., Wells, J. E., Moore, R. L., and Hamstad, M. A., "Stress Rupture of Strands of and Organic Fiber/Epoxy Matrix," Composite Materials: Testing and Design (Third Conference), ASTM STP 546, American Society of Testing and Materials, Philadelphia, 1974, pp. 209-224.

[2] Kevlar® is a registered trademark of E. I. du Pont de Nemours and Company, Wilmington, DE.

valuable, the vessels used in those tests differ in the amount of Kevlar 49 overwrap by three orders of magnitude as compared to the Space Shuttle vessels; the yarn denier and epoxies used were very different as well. This has led to the need for additional testing on Kevlar-epoxy COPVs that are more representative of flight configuration. The objective of the Kevlar-epoxy COPV testing is to provide additional data that could be used in reliability and mechanics models to predict stress rupture life on Space Shuttle COPVs. This could potentially extend estimates of Space Shuttle COPV useful life on the basis of more refined and less conservative estimates than have been developed so far. Current procedures used to repair damaged COPVs have also been included as part of the Kevlar-epoxy COPV evaluation effort. Adjustments to the parameters of the model used to predict Kevlar-epoxy COPV stress rupture lifetime are anticipated from test results of several available Kevlar-epoxy COPVs. COPV articles for testing include flight qualified COPVs and subscale COPVs. A long-term test program has been underway for 8 years at NASA Johnson Space Center White Sands Test Facility (WSTF) to investigate the effects of impact damage on carbon-epoxy COPV stress rupture life and to provide carbon-epoxy COPV fleet leader data for the ISS. Carbon-epoxy special test COPVs have been burst-tested with strain gauge and fiber Bragg grating instrumentation to evaluate a theorized carbon-epoxy shelf life effect. While Kevlar-epoxy COPVs were found to be more susceptible to stress rupture than carbon-epoxy COPVs, several concerns have risen from the data on carbon-epoxy COPVs that point to a less-than-adequate understanding of long-term risks. From this perspective, the investigation on the stress rupture behavior and reliability of Kevlar-epoxy COPVs has proven to be a very valuable "case study" of the methodology, modeling, and efficient testing that is necessary.

The focus of this paper is to describe burst testing of Kevlar COPVs that has been completed as a part of an the effort to evaluate the effects of ageing and shelf life on full scale COPVs. The test articles evaluated in this discussion had a diameter of 22 inches for S/N 014 and 40 inches for S/N 011. The time between manufacture and burst was 28 and 22 years. Visual inspection, shearography, heat soak thermography and borescope inspection were performed on vessel S/N 011 and all but shearography was performed on S/N 014 before they were tested and details of this work can be found in a companion paper titled, "Nondestructive Methods and Special Test Instrumentation Supporting NASA Composite Overwrapped Pressure Vessel Assessments.[3]" The vessels were instrumented so that measurements could be made to aid in the understanding of vessel response. Measurements made on the test articles included girth, boss displacement, internal volume, multiple point strain, full field strain, eddy current, acoustic emission (AE) pressure and temperature. The test article before and during burst is shown with the pattern used for digital image correlation full field strain measurement blurring as the vessel fails.

[3] Saulsberry, R. Nondestructive Methods and Special Test Instrumentation Supporting NASA Composite Overwrapped Pressure Vessel Assessments. Proceedings of the AIAA SDM conference at Hawaii, April 23-26, 2006.

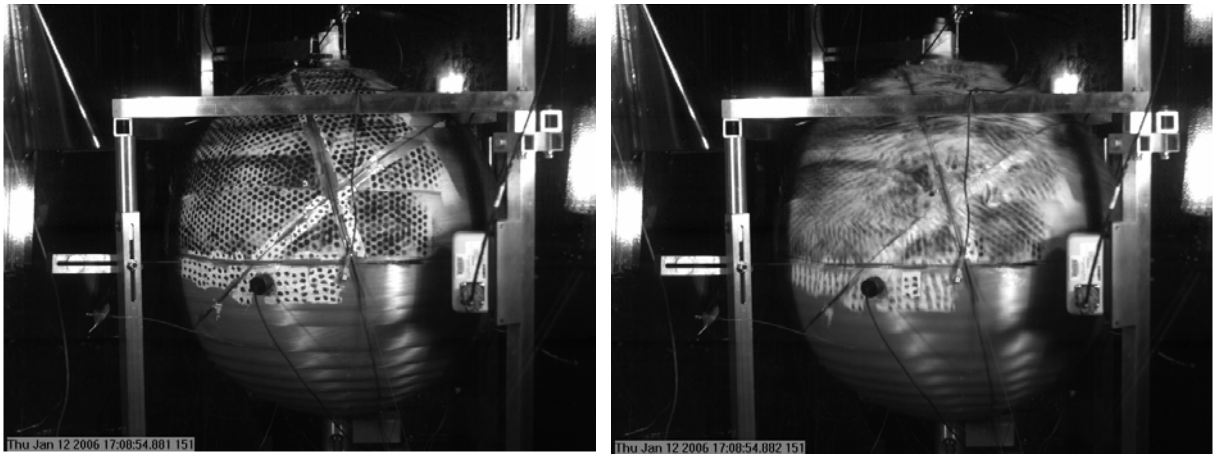

Figure 9. COPV S/N 014 burst test photographs.

Cycle testing was performed prior to burst and the yield point of liner could be identified from multiple measurement techniques. The vessels both burst above the manufacturers minimum design burst requirement. Strands have also been extracted from the vessels for testing to determine if there is deterioration of the materials of the components with age and pressurized time. Figure 2 demonstrates the volumetric growth that S/N 014 experienced up to burst pressure.

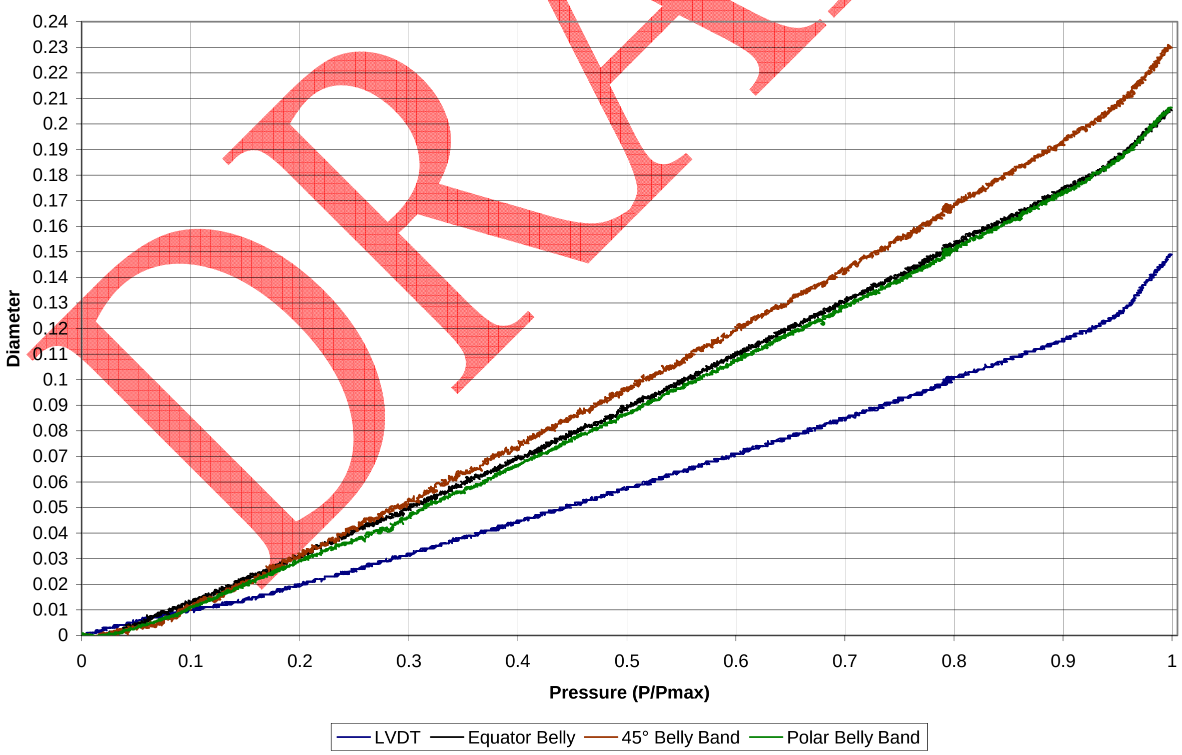

Figure 2. COPV S/N 014 burst test composite diameter change measurement.

Mechanical response formulation will be discussed for comparison with test data. Results agreed well with theoretical calculation except for through the composite thickness measurements. Larger through the composite thickness compression than was expected from calculation than was observed in the test data. Measurements were made using the difference between the internal and external diameters of the vessel and Eddy current multiple point Eddy current measurements.

Results from this testing will be used to evaluate stress rupture test plans on full scale test articles and will contribute to the safe operation of Kevlar COPVs.