The Challenge: High performance Composite Overwrapped Pressure Vessels (COPVs) have been utilized in the aerospace and automotive industries for many years, providing an inherently safe, lightweight and cost effective storage source for pressurized fluids. COPVs are commonly used for gas and propellant storage in spacecraft and launch vehicles. The consequence of a COPV rupture can be the release of caustic fluids, loss of necessary fluids and the release of stored energy equivalent to several pounds of trinitrotoluene (TNT) depending on the quantity, pressure and fluid contained in the COPV.

In the aerospace sector, the development of a commercial space industry has reinforced the need for light and low cost yet safe and reliable pressure vessels. In the automotive sector, new demands for alternative fuel vehicles driven by changes in the energy sector have given rise to opportunities for durable and low cost, and also safe and reliable pressure vessels, particularly for hydrogen and compressed natural gas.

Safety and high reliability are achieved by adhering to rigorous processes throughout the life cycle of a pressure vessel, including the design, manufacture, testing, handling, and operation phases.

Scope of the course: This course will provide an introduction to the basic principles governing the design and operation of Composite Overwrapped Pressure Vessels (COPV). The comprehensive overview of current technological understanding will provide both engineering mechanics fundamentals and practical applications drawn from experience to educate program managers, design engineers, ground and flight operators, safety analysts, quality inspectors and users/customers.

Fundamental to the use of COPVs in space applications is the relevant failure modes and the design techniques introduced to ensure safe operation. Flight safety can only be properly understood through appropriate engineering design and quality throughout the vessel lifecycle from design, qualification, manufacturing, acceptance testing, handling and finally operational use. Each step of the product lifecycle has relevant safety considerations, which will ultimately affect the likelihood for catastrophic failure resulting in loss of life during operations.

This course has been developed based on requirements developed for space applications for COPVs. The relative requirements are documented in NASA-developed standards applicable to US and international partners for use on the International Space Station, as well as for future programs such as the NASA Commercial Requirements. These various standards reference the appropriate AIAA requirements and these will be directly addressed in this course. The course is directly relevant to individuals concerned with COPVs in automotive applications. The failure modes are common across these industries. However, there is a difference in usage and need for robustness of typical pressure vessels and a difference in materials commonly selected for these products. Consequently, there are different standards and
approaches to certification. The class will explore these differences.

Participants in this workshop will gain appreciation of a wide range of epoxy-matrix composites that are used in overwraps based on fibers such as: S-glass, aramids (e.g., Kevlar®49) and carbon (e.g., T1000), and also various current liner materials including metals such as aluminum, stainless steel, titanium and Inconel, and polymers such as high density polyethylene. Attention will be paid to the potential effects of processing variables (e.g., heat treatment, welding, annealing) on ultimate liner performance as influenced also by the fiber used in the overwrap.

Various steps in the COPV design and manufacturing processes will be discussed, particularly aspects strongly influenced by end-use requirements and vessel geometry (cylindrical vs. spherical). To manufacture the overwrap, both wet filament winding and prepreg winding methods will be discussed, including their respective pros and cons and their relative importance in various designs. Another topic discussed will be the potential for liner distortion and buckling during winding, the consequences and candidate countermeasures to protect this phenomenon from occurring. Advantages and risks in bonding the overwrap to the liner will be discussed with respect to the overall design and potential failure mechanisms. Autofrettage and proof-testing will be discussed in terms of plastic yielding of the liner that induces a significant compressive stress component beneficial to improving fatigue life. In this context, the Bauschinger effect on the final liner stress state and the potential for liner buckling will also be discussed.

The relevant analysis and test methods used to demonstrate compliance to appropriate certification standards are presented. These include factors of safety set to mitigate against stress rupture failure modes of the overwrap and Leak-Before-Burst liner/overwrap concepts and demonstration, and finally FEA/NDE approaches to establish Safe Life with respect to risk of liner fatigue failure from crack initiation and growth.

Current non-destructive evaluation (NDE) techniques will be discussed as are used to detect flaws and damage in the liner and overwrap. NDE methods for detecting flaws and small cracks in liners include: visual, dye penetrant, X-ray, ultrasonic, eddy current, and borescope inspection. NDE methods for the overwrap include: Acoustic emission, Flash/Infrared thermography, laser shearography, digital image correlation of overwrap strains, and Raman spectroscopy to measure residual fiber stress.

Students will gain familiarity with the computational design tools that are used to analyze COPV. The majority of the examples in the course are created using the commercially available Abaqus FEA product suite and associated Wound Composite Module (from Dassault Systems). Computational results with this tool will be discussed to underscore the importance of proper design, manufacture, and operations to prevent the occurrence of various failure modes. Through these structured learning examples, users will gain an appreciation for the complexities of modeling these vessels.

The AIAA is currently updating the national standards which are used to certify metallic and composite overwrapped pressure vessels. The course will also review the updates to these standards which will be released by the time of the teaching of the course.

Target Audience:

- Engineers and Managers who are interested in the latest techniques for COPV design, development, manufacture and test
• System engineers who develop requirements for systems which incorporate the use of pressure vessels
• Safety, reliability and quality engineers who want to understand the approach to safety and mission assurance of systems which incorporate the use of pressure vessels
• Ground Operators and test engineers who performed non-destructive evaluation of pressure vessels.

The course would be beneficial to both seasoned experts in the field and new engineers to the technology.

What You Will Learn:
• Failure modes in COPVs and requirements for safe operation in space environments
• Designing for Maximum Operational Pressure and Relevant Factors of Safety
• Approaches to Liner Fatigue Modeling under Pressure Cycling
• Liner Buckling: Models, Trigger and Methods of Prevention
• Composite Stress-Rupture Phenomenon and Reliability Modeling
• Nondestructive Evaluation (NDE)
• Considerations for Ground Operations and Damage Control Mitigation Techniques.

Course Duration:
5.0 days

Instructors:
The course instructors are internationally recognized experts in the field of COPV Design and Operations:

S. Leigh Phoenix (PhD Cornell) is professor of Mechanical and Aerospace Engineering at Cornell University, where he has been on the faculty since 1974, and teaches courses in composite materials, solid mechanics and applied mathematics. Much of his research involves micromechanically–based statistical modeling and experiments on long-term reliability of fibrous composites (e.g., aramids, carbon, S-glass, PBO) under high stress in difficult environments. Examples include composite-overwrapped pressure vessels, pressurized hydraulic lines and wind turbine blades. He also models ballistic impact into fibrous materials in support of developing improved materials and architectures for soft body armor and flexible composite panels.

In 1983 Phoenix received the Fiber Society Award for Distinguished Achievement in Basic or Applied Fiber Science, and in 1992 he won the ASTM Harold DeWitt Smith Award in fiber mechanics. In 2005 he was awarded the NASA-NESC Engineering Excellence Award for his pressure vessel work in support of the Shuttle’s Return to Flight.

Michael T. Kezirian (PhD MIT) is an Associate Technical Fellow with the Boeing Company. He has brought extensive experience in composite materials, propulsion systems and system safety to address safety concerns for the Space Shuttle, International Space Station and Commercial Crew CST-100 Starliner Programs. As an Adjunct Associate Professor of Astronautical Engineering at the University of Southern California, he has taught undergraduate and graduate classes in Polymer Science, Spacecraft Dynamics and Safety of Space Systems and Space Missions. He is the founding Editor-in-Chief of the Journal of Space Safety Engineering. Dr. Kezirian is an Associate Fellow of the AIAA and Fellow Member of IAAASS. In 2009 he was awarded the NASA Astronaut Personal Achievement Award (Silver Snoopy).