SAFETY FOR DESIGN AND OPERATIONS OF COMPOSITE OVERWRAPPED PRESSURE VESSELS: AEROSPACE AND AUTOMOTIVE APPLICATIONS

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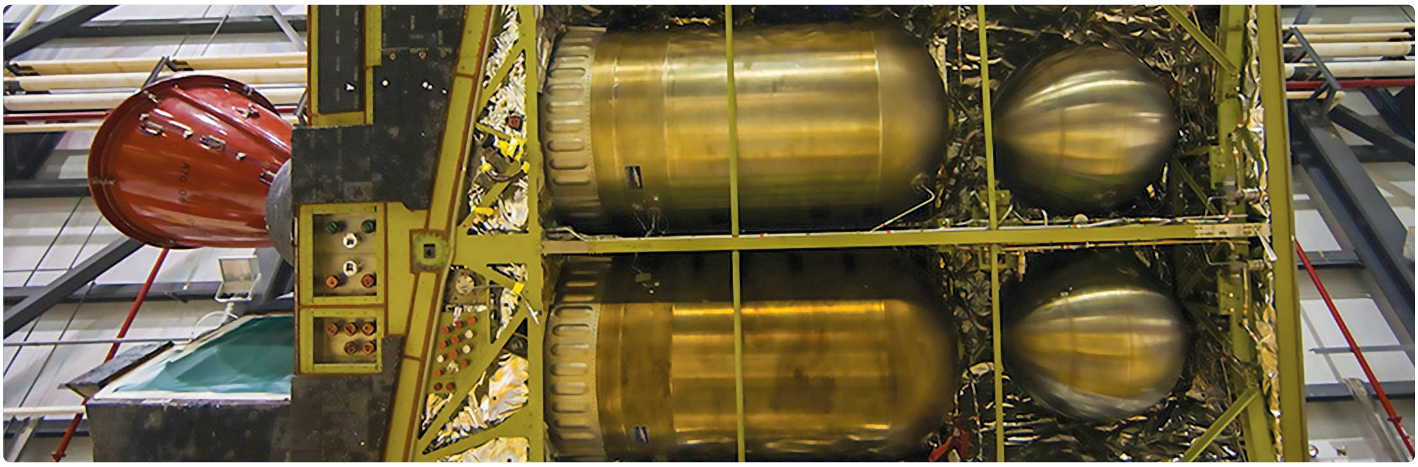


The Space Shuttle Orbiter Maneuvering System incorporated metallic and composite overwrapped pressure vessels (COPVs) to store propellant fluids. - Photo: NASA

The Challenge

High performance Composite Overwrapped Pressure Vessels (COPVs) have been utilized in the aerospace and automotive industries for many years, providing for inherently safe, lightweight and cost-effective storage for pressurized fluids. COPVs are commonly used for the storage of fluids for propellants in spacecraft and launch vehicles. They are also used for the storage of nitrogen and oxygen in environmental and life support systems. Typically, the stored energy for pressurized systems in aerospace applications is equivalent to several pounds of trinitrotoluene (TNT) with the magnitude depending on the quantity, pressure and fluid contained. In addition to the release of this energy, the consequences of a COPV failure contain the fluid include the release of potentially hazardous fluids. In the event that any flight hardware survives the explosion, the contained fluids are no longer available for its intended purpose.
In the aerospace sector, the emergence of a commercial space industry has reinforced the need for efficient and safe pressure vessels.
The aerospace and automotive sectors have taken somewhat different approaches to certification. The aerospace sector, as identified in standards developed by the AIAA, establishes performance-based requirements verified through a combination of analyses and tests. The automotive sector has developed prescriptive requirements through the CGA and ISO.
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 introduces 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.

While the course will consider the broad array of standards in the aerospace and automotive sectors, the course focus on the implementation of the following aerospace industry consensus standards:

ANSI/AIAA S-080A-2018 Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

ANSI/AIAA S-081B-2018 Space Systems—Composite Overwrapped Pressure Vessels

Currently, the aerospace industry is beginning to introduce COPVs with a plastic liner and linerless Composite Pressure Vessels. The AIAA is developing a Guide,

This course will discuss the critical issues with the certification of these classes of pressure vessels and the open issues in the development of the Guide and eventual standard.

ANSI/AIAA G-082 Space Systems—Composite Overwrapped Pressure Vessels with a Plastic Liner (in preparation)

For Automotive applications:

- CSA/ANSI NGV2 Compressed natural gas vehicle fuel containers
- CSA/ANSI HGV2 Compressed hydrogen gas vehicle fuel containers

The course will also provide the context of current and future standards from the heritage standards:
- DOT FRP-1 Basic Requirements for Type 3FC Cylinders
- DOT FRP-2 Basic Requirements for Type 3HW Cylinders
- UN GTR 13 Global technical regulation on hydrogen and fuel cell vehicles

In 2020, QustomApp and SVertical, though a joint-partnership, introduced WoundSim, an add-on to the Abaqus software tool to evaluate structural loads in composite pressure vessels. Concurrently, the Dassault Wound Composite Modeler (WCM) has been phased out by the company for the Abaqus environment. This IAASS course will introduce WoundSim capabilities necessary for analyzing candidate COPV designs. It can also be used to assess a range of operational conditions for compliance with performance standards, necessary for certification through aerospace standards.

AUTOMOTIVE APPLICATIONS

The section describes the development of the CSA/ANSI NGV2 standard and CSA/ANSI HGV2 standard for fuel cylinders used on-board vehicles powered using compressed natural gas, and compressed hydrogen, respectively. The automotive industry is driven by the need to have cylinders that are light-weight, lower cost, and safer, thus requiring a complex balance of design considerations. This section will outline the philosophy used in the design of cylinders for automotive use, and the rationale used to apply certain performance-based design qualification requirements.

Course Description

Safely using COPVs in all applications (but particularly in aerospace and astronautics) requires understanding hazards and their corresponding failure modes. Once the risk is identified, then the corresponding design and operational controls can be established. Flight safety can only be achieved through rigorous process control throughout the vessel lifecycle: design, manufacture, qualification and acceptance testing, handling, and operation. There are unique safety considerations in each of these lifecycle phases.

This course focuses on the requirements developed for space applications. The requirements are documented in industry consensus standards and tailored for use in NASA programs. The International Space Station Program, NASA exploration programs and NASA Commercial Cargo and Crew programs each have unique customization of these requirements.

Participants in this workshop will gain appreciation of a wide range of pressure vessels with a variety of materials aramids (e.g., Kevlar®49) and carbon (e.g., T1000), and liner materials including metals such as aluminum, stainless steel, titanium and Inconel. 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).

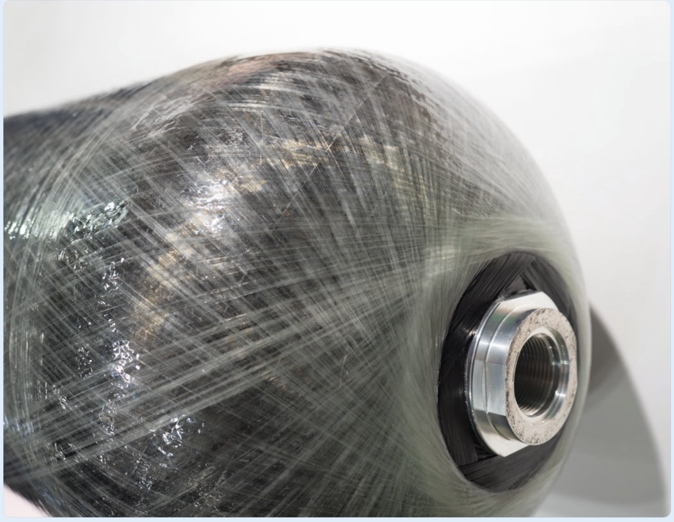
Another topic discussed will be the potential for liner distortion and buckling during winding, the consequences and candidate countermeasures to protect this phenomenon from occurring.

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 with the commercially available Abaqus FEA (from Dassault Systemes) product suite and the newly developed WoundSim (from QustomApps) The Wound Composite Module from Dassault is being discontinued in 2021. 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.

WoundSim is a next-generation tool used to design and simulate composite overwrap pressure vessels (COPVs). A graphical interface is used to instantly view the composite layup as the table of the composite layers is defined. Layers thickness buildup is automatically calculated, along with the continuously varying wind angles. Smeared material properties are computed and assigned throughout the COPV. An integrated FEA software translator produces a run-ready FEA model to asses the thermal and mechanical response of the COPV.

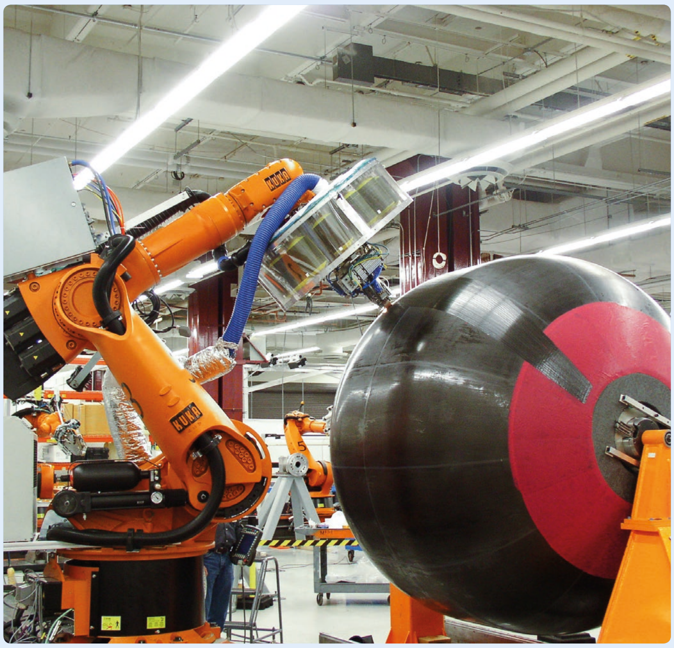


High pressure resistant hydrogen storage tank for fuel cell vehicle.

Target Audience

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

- 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.



A robot places composite fibers on cryogenic propellant tank. - Credits: Boeing

What You Will Learn

- Failure modes in COPVs and requirements for safe operation in space environments
- Tools used to develop Finite Element Models of COPVs
- Designing for Maximum Expected 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 Outline

The course is organized into the following ten sections.

Day 1

Section A: Introduction and Standards

This section introduces basic concepts relevant to pressure vessels and the inherent failure modes associated with the storage of pressurized fluids. Various government and industry standards have been developed to help ensure the safety and facilitate their use in numerous industries. This course describes the different approaches that aerospace and automotive sectors have used to certify pressure vessels, with a mixture of both prescriptive and performance requirements. The section will present the historical perspectives on the evolution of these standards and the direction the industry is taking to incorporate new technologies. These requirements are established to serve as controls for hazards.

Section B: Introduction to Analysis

This section introduces how the commercially-available Finite Element Analysis (FEA) software tool can analyze candidate pressure vessel designs. In this introduction section, we will explain how WoundSim capabilities enables the analyst to properly account for the presence of the composite overwrapped fiber layers and their contribution to the response of the pressure vessel to various conditions, including pressure, temperature, and external loads.

Day 2

Section C: Advanced Analysis Techniques

This section presents more advanced topics of the interpretation of FEA simulations of pressure vessel designs. It presents some lessons learned from experience from NASA programs. It considers the difficulties in scaling with thickness and considerations for various winding pattern design options.

Section D: Verification by Test

This section describes the various test programs required for qualification of new designs and acceptance of hardware. It reviews examples from past NASA programs and explores the lessons learned from successes and failures of such test programs.

Day 3

Section E: Autofrettage, Stability and Potential for Liner Buckling

Autofrettage is a metal cold forming technique in which a pressure vessel is subjected to a large internal pressure, higher than it would be experience during the operational service life. This technique causes internal metal liner to yield plastically, resulting in internal compressive residual stresses once the pressure is released. This section explores the opportunities and risks associated with this technique and the associated risk of liner buckling. The course will review the requirements on liner stability designed to address this failure mode.

Section F: Overwrap Stress Rupture

Stress rupture is the sudden and complete failure of a material under stress. It is a stochastic process and likelihood of failure depends on the combined effects of stress levels and time. The section addresses testing performed to understand this failure mode and the quantitative methods to determine the probability of occurrence. The section will also address how NASA programs address this risk on major programs.

Day 4

Section G: Liner Fatigue Fracture

This section describes how NASA establishes design life to fatigue and fracture. Typically, such estimates are performed numerically using the Nasgro® fracture mechanics and fatigue growth software program, developed jointly by Southwest Research Institute and NASA. The section describes the basic functionality of this software and how experimental data is used as the basis of these calculations.

Section H: Damage Control

This section describes the exhaustive test program performed at the NASA White Sands Test Facility associated with the Johnson Space Center to understand the effects of mechanical impacts on COPVs. For integrity of pressure vessels, it is necessary to establish a comprehensive approach to prevent mechanical impacts to flight hardware. Such approaches are documented in a Damage Control Plan, the elements of which are described here.

Day 5

Section I: Non-Destructive Test

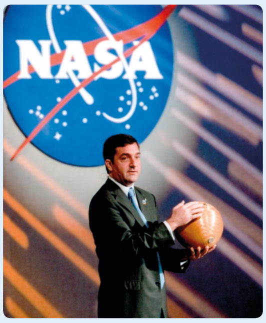
This section describes the theory and shows results from the latest non-destructive testing techniques of pressure vessels in space applications. Various methods apply to interior and exterior inspections, focusing on liner and overwrap, often separately. The section also discusses some of the latest research in the development of new methods.

Section J: Operations

This section addresses three topics critical to the operations of pressure vessels used in space applications. First, it describes opportunities to reduce the cumulative time under pressure, applying lessons learned from the Space Shuttle program in which controls were instituted to reduce the risk to composite stress rupture. Second, it addresses the risk to the uninvolved public, particularly during the processing of pressurized hardware during ground processing. Third, it presents the risk of Micrometeoroid and Orbital Debris (MMOD) and establishes protections for operating in the space environment and maintaining the integrity of this environment.

Instructors

The course instructors are internationally recognized experts in the field of COPV Design and Operations. Note that other industry experts may present lectures on relevant specialized topics.



Michael T. Kezirian

Michael T. Kezirian was an Associate Technical Fellow with the Boeing Company when he started his own company to apply space technology to the energy sector. 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 Professor of Astronautics Practice 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 has a bachelor's degree from Brown University and master's and doctoral degrees from MIT. 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 IAASS. Dr. Kezirian chairs the AIAA Aerospace Pressure Vessel Committee on Standards which issued ANSI/AIAA S-080A-2018 Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components and ANSI/AIAA S-081B-2018 Space Systems—Composite Overwrapped Pressure Vessels. He is a member of the AIAA Standards Executive Committee. In 2009 he was awarded the NASA Astronaut Personal Achievement Award (Silver Snoopy).

Rick Willardson

Rick Willardson has 25-years of experience in the aerospace and defense industry. He has been involved in the design, analysis, manufacture, and testing of a variety of composite structures throughout his career. He has a bachelor's degree in mechanical engineering and a master's degree in civil engineering from Brigham Young University. Some career highlights are work on the X-33 composite liquid oxygen tank team at Lockheed Martin Manned Space Systems; development of polymer lined COPV's at Beal Aerospace Technologies, including propellant tanks (up to 6.2-meter diameter) and pressurant tanks (3250-psi MEOP); leading the MALD (miniature air-launched decoy) composite airframe design and analysis team at Raytheon Space and Airborne Systems; leading a team of Dell Services engineers that supported the structural analysis of the James Webb Space Telescope (JWST) for ATK; development of liner-less composite propellant tanks for Firefly Space Systems (awarded a DARPA SBIR) and flight loads development for Raytheon's Next Generation Jammer pod. Additionally, he has served in the leadership of the Society for the Advancement of Materials and Process Engineering (SAMPE) for the last 10 years. Including North America President and SAMPE Global Board of Directors.

Craig Webster

Craig Webster has some 35 years of experience in the high pressure testing of CNG and compressed hydrogen tanks for the automotive industry. A graduate of the University of Toronto with a Bachelor of Applied Science degree in Metallurgy and Materials Science, Craig has been a leader in the development of standards for high pressure natural gas and hydrogen vehicle fuel cylinders. In addition to actively participating in the development of North American standards for CNG and hydrogen fuel cylinders, Craig has chaired the ISO working group for hydrogen fuel cylinders (ISO TR 15869/EC-79). Since 1995 he has been, and remains, the Chair of the ISO 11439 standard for CNG fuel cylinders. Craig has designed, constructed, and operated high pressure test facilities at Powertech Labs, and at CSA Group. He is currently Director of Technology at TesTneT Canada.

Mike Shubert

Mike Shubert has 30 years of experience working in the software industry. For 28 years, he worked as a developer at Hibbitt, Karlsson, & Sorensen before it became part of Dassault Systemes. He has a bachelor's and master's degree from the University of Colorado, Boulder in Civil Engineering. While as Dassault Systemes, he developed in the Abaqus solvers group, as well as, the Abaqus/CAE interface. In 2003, he moved to the local office in Texas where he developed Abaqus/CAE customization such as the PCB Modeler, the Abaqus Welding Interface, and the Wound Composite Modeler which became the defacto industry standard for FEA analysis tool for COPVs. In 2019, he started the company QustomApps and began development of WoundSim.

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Day	Morning	Afternoon
1	**A** - Pressure Vessel General Discussion Failure Modes Government/Industry Standards in the Automotive and Aerospace Sectors	**A2** - Overview of Pressure Vessel Manufacturing Techniques **B** - Verification by Analysis Introduction to Finite Element Analysis, ABAQUS and WoundSIM
2	**C** - Verification by Analysis Advanced Techniques Interpreting FEA Results Overwrap Design Winding Pattern Considerations	**D** - Verification by Test Material Property Testing Qualification and Acceptance Test Programs
3	**E** - Autofrettage, Stability and Potential for Liner Buckling Autofrettage and Proof Testing Stability Design Requirements Liner Buckling	**F** - Composite Stress Rupture Phenomenon Difficulties in Performing Experiments Experimental Test Results: Kevlar, carbon Reliability Modeling Impact to NASA Programs
4	**G** - Fatigue and Fracture, Liner Cycle Life Leak Before Burst and Damage Tolerance Life NASGRO and NASA developed software resources	**G2** - Fatigue and Fracture, for plastic liner and liner lines Pressure vessels **H** - Damage Control Test Basis for Flight Rationale Damage Control Plan
5	**I** - Non-Destructive Test Methods Acoustic Emission Shearography Laser-based Profilometry	**J** - Operational Constraints Minimizing Time Under Pressure Ground Operations: Risk to the Public Micrometeoroid and Orbital Debris, MMOD