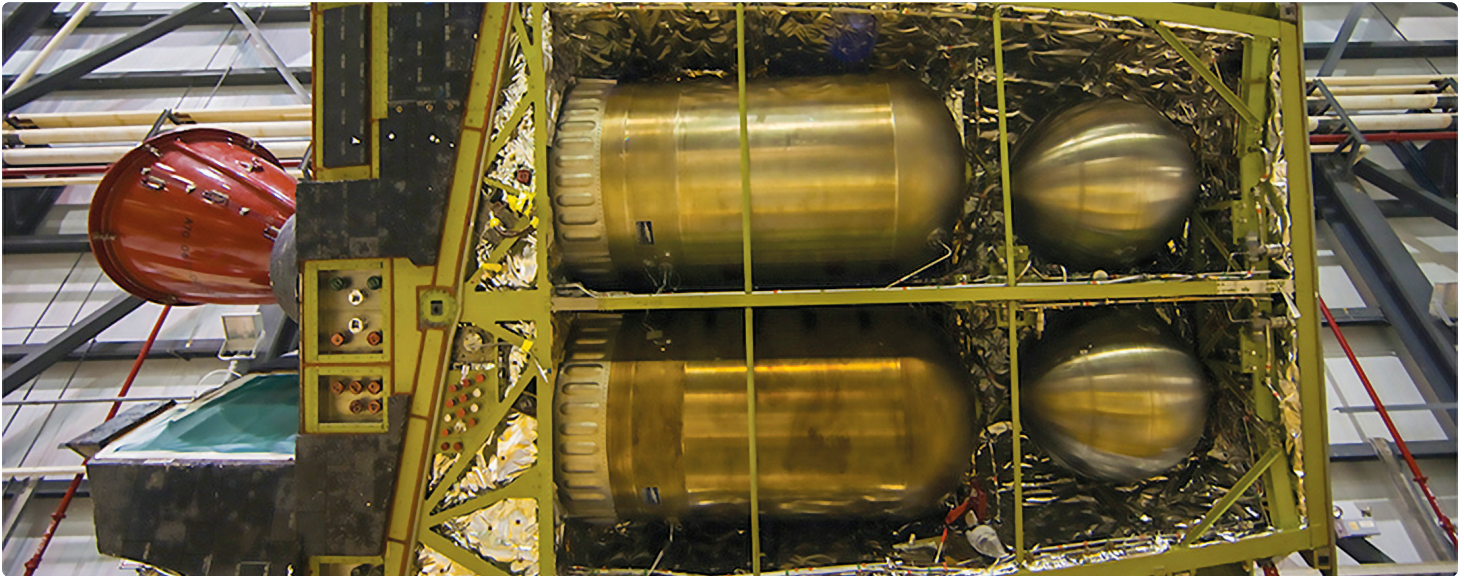


# DESIGN AND SAFE OPERATIONS OF COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPV): AEROSPACE AND AUTOMOTIVE APPLICATIONS

CODE 005



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.

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



High pressure resistant hydrogen storage tank for fuel cell vehicle.

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.

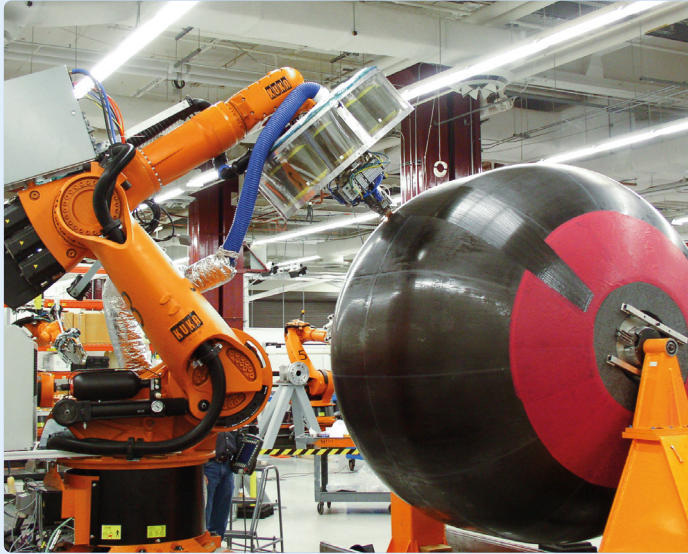
Autofrettage and proof-testing will be discussed in terms of plastic yielding of the liner that induces a significant compressive stress component beneficial to improving fatigue life. In this context, the Bauschinger effect on the final liner stress state and the potential for liner buckling will also 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 assess the thermal and mechanical response of the COPV.





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

## 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.

## 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

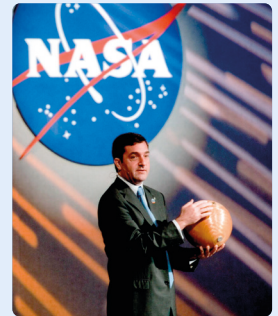
- Failure Modes and Controls for Safety: Overview of Standards
- Determining Operational Envelope
- Verification by Analysis: Modeling of Pressure Vessels with Finite Element Analysis Software: Abaqus and the WoundSIM Software Tool

- Verification by Test: Developing and Interpreting Certification Testing
- Composite Stress Rupture
- Preventing Mechanical and Impact Damage: Developing and Implementing a Damage Control Plan
- Non-Destructive Testing
- Liner Fatigue and Fracture: Analysis with the NASGRO Tool
- Operational Considerations

## 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.

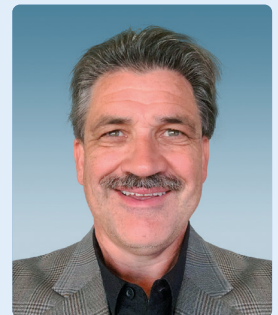
**Michael T. Kezirian** was an Associate Technical Fellow with the Boeing Company when he started his own company to apply space technology to the energy sector. He has brought extensive experience in composite materials, propulsion systems and system safety to address safety concerns for the Space Shuttle, International Space Station and Commercial Crew CST-100 Starliner Programs. As an Adjunct Professor of Astronautics Practice at the University of Southern



Michael T. Kezirian

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).

**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 Qus-tomApps and began development of WoundSim.



Mike Shubert