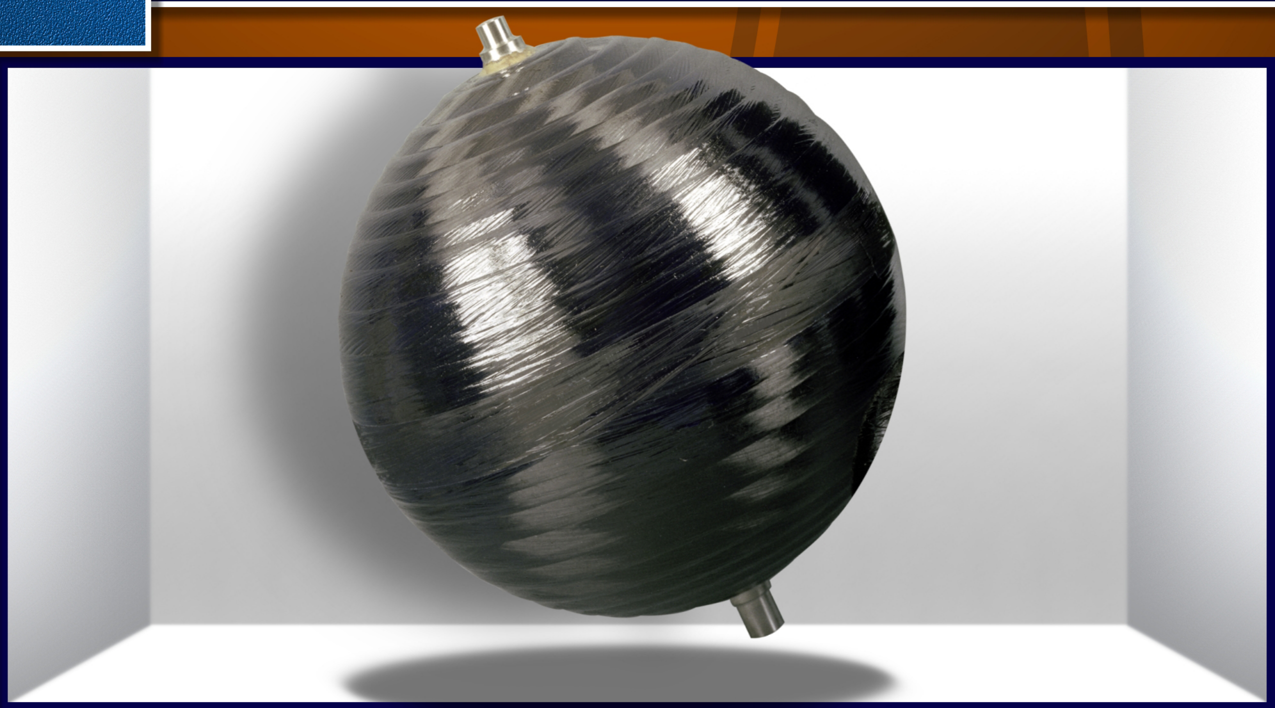
WSTF-RD-1198-001-13

Composite Conference

2012 Proceedings

Day 3



August 13-16, 2012, Las Cruces, NM

Composite Conference 2012

Thursday, August 16, 2012

7:30 – 8:00 a.m.	Continental Breakfast and Exhibition
8:00 – 10:00 a.m.	**Session 7: Failure** (Blast Data, Blast Modeling, Safety Clears) *Harold Beeson, NASA/WSTF Chair* *S. Stover, NASA/KSC Chair*
8:30 – 9:00 a.m.	**Blast Analysis** *C. P. Keddy*
9:00 – 9:30 a.m.	**COPV Ground Processing Hazards** *J. Hamilton*
9:30 – 10:00 a.m.	**Blast, Fragmentation, Quantity and Distance Panel** *C. Keddy, NASA/WSTF* *S. Stover, NASA/KSC* *B. Webb, E&S Technologies* *S. Woods, NASA/WSTF* **Moderator** *H. Beeson, NASA/WSTF*
10:00 – 10:30 a.m.	*Break*
10:30 – 12:00 a.m.	**Session 8: Standards, Design of Experiments** *J. Jackson, MKF Chair*
10:30 – 11:00 a.m.	**Part B. Application of Modal Acoustic Emission (MAE) for Assessing Structural Damage in Composite Overwrapped Pressure Vessel** *M. Toughiry*
11:00 – 11:20 a.m.	**Compressive Strength of Concrete Retrofitted with Kevlar/Carbon, Carbon/Basalt and T700 Unidirectional Fabrics** *S. Bondi , Z. Razzaq*
11:20 – 11:40 a.m.	**Fiber-Optic-Based Structural Health Monitoring of Aerospace Vehicles** *W. Richards, A. Parker, A. Piazza, and P. Chan*
11:40 – 12:00 p.m.	**High Fidelity Durability And Damage Tolerance Of Composite Overwrapped Pressure Vessels** *F. Abdi, M. Garg, G. Abumeri, AlphaSTAR Corporation, Long Beach, CA*
12:00 – 1:00 p.m.	***Lunch (Lunch speaker)***
1:00 – 3:00 p.m.	**Session 9: Standards, Codes, and Regulations** (AIAA/ASME/ASTM/NIST Working Group Session)
1:00 – 1:15 p.m.	**AIAA Standards Program Overview** *A. Barrett*
1:15 – 1:30 p.m.	**ISO Composite Pressure Vessel Codes and Standard** N. Newhouse Lincoln Composites

1:30 – 2:00 p.m.	**Status of AFSPCMAN 91-710 revision** *R. Geuther, U.S. Air Force 45th Space Wing/SEAN* **NASA ELV Payloads Safety** *C. Staulbus*
2:00 – 2:30 p.m.	**NASA Stakeholders meeting standards meeting summary** *N. Greene* **Summary of AIAA S-081B** *L. Grimes-Ledesma, N. Greene*
2:30 – 3:15 p.m.	**Automotive and DOE Panel: Assessing knowledge gaps for hydrogen vehicle and infrastructure codes and standards** *C. Moen and D. McColskey*
3:15 – 3:30 p.m.	*Break*
3:30 – 4:30 p.m.	**Working Group and Discussion**
4:30 – 5:00 p.m.	**Closing Speaker & Wrap Up** ***Conference Study of Research Needs*** Nathanael Greene, NASA/WSTF
5:30 – 8:00 p.m.	***Conference Reception and Banquet – Farm and Ranch Museum!***

Friday, August 17, 2012

Proceedings for Friday August 17, 2012 not placed in E-Book due to distribution limitations. Contact NASA/WSTF Publications for additional information

8:00 a.m. – 4:00 p.m.	**AIAA Composite Pressure Vessel Working Group Meeting –** **AIAA Coordinator Amy Barrett (AmyB@aiaa.org), U.S. Citizens Only** Location: NASA White Sands Test Facility, Las Cruces NM
	AIAA S-089 Composite Pressurized Structure (Draft) –Nathanael Greene, AIAA Chair
8:30-10:00	**Composite Pressurized Structures Qualification Testing Data Review and Status** *M. Rufer, N. Greene, R. Saulsberry*
10:00-10:30	**Review draft AIAA S-089 draft** *N. Greene*
10:30-10:45	**Break**
10:45-11:30	**Continue review of draft AIAA S-089 draft** *N. Greene*
11:30-12:30	**(Working Lunch) Status of AIAA S-089 literature review** *B. Webb*
12:30-12:45	**Review draft ground safety section for CPS** *J. Hamilton*
	AIAA S-081 Composite Overwrapped Pressure Vessels Lorie Grimes Ledesma, AIAA Chair
1:00-2:00	Review of work in FY 10 and FY11 and discuss the proposed updates and future work plan

	L. Grimes-Ledesma
	AIAA S-080 Metallic Pressure Vessels James Chang, AIAA Chair
2:15-2:45	**Break**
2:15-3:30	**Discuss comments for the next revision** *J. Chang, L. Grimes-Ledesma, or AIAA Representative*
3:30-3:45	**Summary of draft ground and range safety requirements for Metallic pressure vessels** *J. Hamilton*
4:00-4:30	**Wrap-up and action items** *A. Barrett*
8 a.m. – 5:30 p.m.	**Tours and Meetings at NASA White Sands Test Facility** **Spaceport America Tours** **Tours are on Friday, Saturday and Sundays** **Times: 9am and 1pm (9am only on Sunday)** **Tour Length: ~3.5 hours** Pick up locations: Elephant Butte Inn, 401 New Mexico 195, and Elephant Butte, NM and across from Sunset Grill on 306 S. Pershing St., Truth or Consequences, NM. Cost: $59 for Adults and $29 for Children under 12 **Reservations are required and minimum of two guests per tour.** For more information call Follow the Sun Inc. 1-505-897-2886 | Toll Free: 1-866-428-4SUN(786)

Composite Conference 2012

Methodology for Assessing a Boiling Liquid Expanding Vapor Explosion (BLEVE) Blast Potential

Chris P. Keddy
NASA Test and Evaluation Contract
NASA White Sands Test Facility
Las Cruces, New Mexico

Introduction

- Composite Vessels are now used to store a variety of fluids or gases including cryogenic fluids under pressure
- Sudden failure of these vessels under certain conditions can lead to a potentially catastrophic vapor expansion if thermal control is not maintained prior to failure
- This can lead to a "Boiling Liquid Expanding Vapor Explosion" or BLEVE

Scope

- BLEVEs
  - Definition
  - “Superheat Energy” and “Superheat Limit”
  - Thermodynamics of BLEVEs
  - Work Available for Blast
    - Isentropic(Reversible)
    - Adiabatic (Irreversible)
  - Step-by-step methodology for estimation
- Cryogenic BLEVES
  - Nitrogen Example (Comparison of Blast Potentials)
    - Hydrostatic
    - Pneumatic
    - BLEVE
  - Other Cryogens, Current Work, and Safety

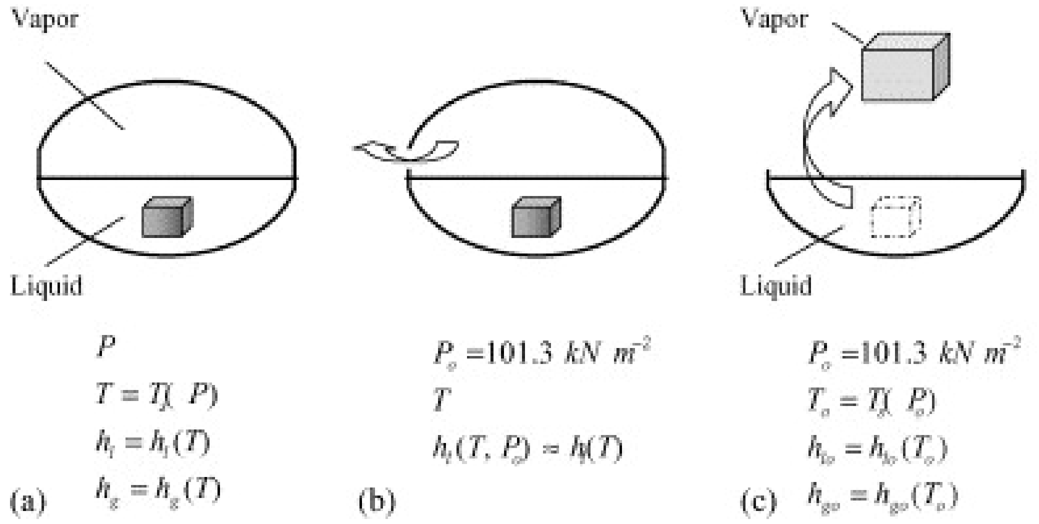
BLEVE

- Boiling Liquid Expanding Vapor Explosion (BLEVE)
  - Any heated fluid under sufficient pressure that is suddenly exposed to lower pressures (ex. ambient) can ‘flash’ to vapor if the fluid temperature is above a certain value known as the ‘superheat limit’ temperature (T_{sl})
  - The mechanism at or above T_{sl} is a homogeneous nucleation process throughout the entire liquid mass and vaporization proceeds in the millisecond timeframe. This process is similar to rapid combustion in solids that convert solids to gas in the sub-millisecond domain (i.e. explosives).
  - The process creates a co-volume of liquid and a gas near the density of the original liquid acting like a highly pressurized gas volume within the vessel at a pressure typically well in excess of the original design burst pressure.
  - The end result is a blast that is very similar to a non-ideal gas pneumatic burst event and can create significant overpressures posing a risk to life and property.

Typically the T_{sl} for a wide range of compounds has been found to be:

T_{sl} ~ 0.89Tc to 0.90Tc

Tc = Critical Temperature of Fluid



Properties of Interest

- Variables
  - T = Temperature (K)
  - P = Pressure (N/m^2)
  - M = Mass (kg)
  - U, u = Internal energy (kJ), Specific internal energy (kJ/kg)
  - H, h = Enthalpy (kJ), Specific enthalpy (kJ/kg)
  - V, ν = volume (m^3). Specific volume (m^3/kg)
  - S, s = entropy (kJ/K), specific entropy (kJ/kg·K)
- Subscripts
  - Subscript 1 refers to the initial state
  - Subscript 2 refers to the expanded state (ambient)
  - Subscript g refers to state of saturated vapor at ambient conditions (state 2)
  - Subscript f refers to state of saturated liquid at ambient pressure (state 2)

Thermodynamics

- State calculations can be used to estimate the available energy (work) to generate a blast wave
- Two bounding values bracket the range of available work
  - Maximum : Reversible Expansion (isentropic work) = $W_i = U_1 - U_2$
  - Minimum: Irreversible Expansion work against atmospheric pressure ($W_o = P_o \Delta V$)
- Typically the maximum isentropic work value is used to bound the 'worse' case scenario for hazard assessment ($W_i = \Delta U$)
- The liquid's initial internal energy, U_1, can be found for the initial state using tables or graphs. Since most tables or graphs only supply h, ν, and s the value of U_1 can be found from $u = h - p\nu$ and the system mass

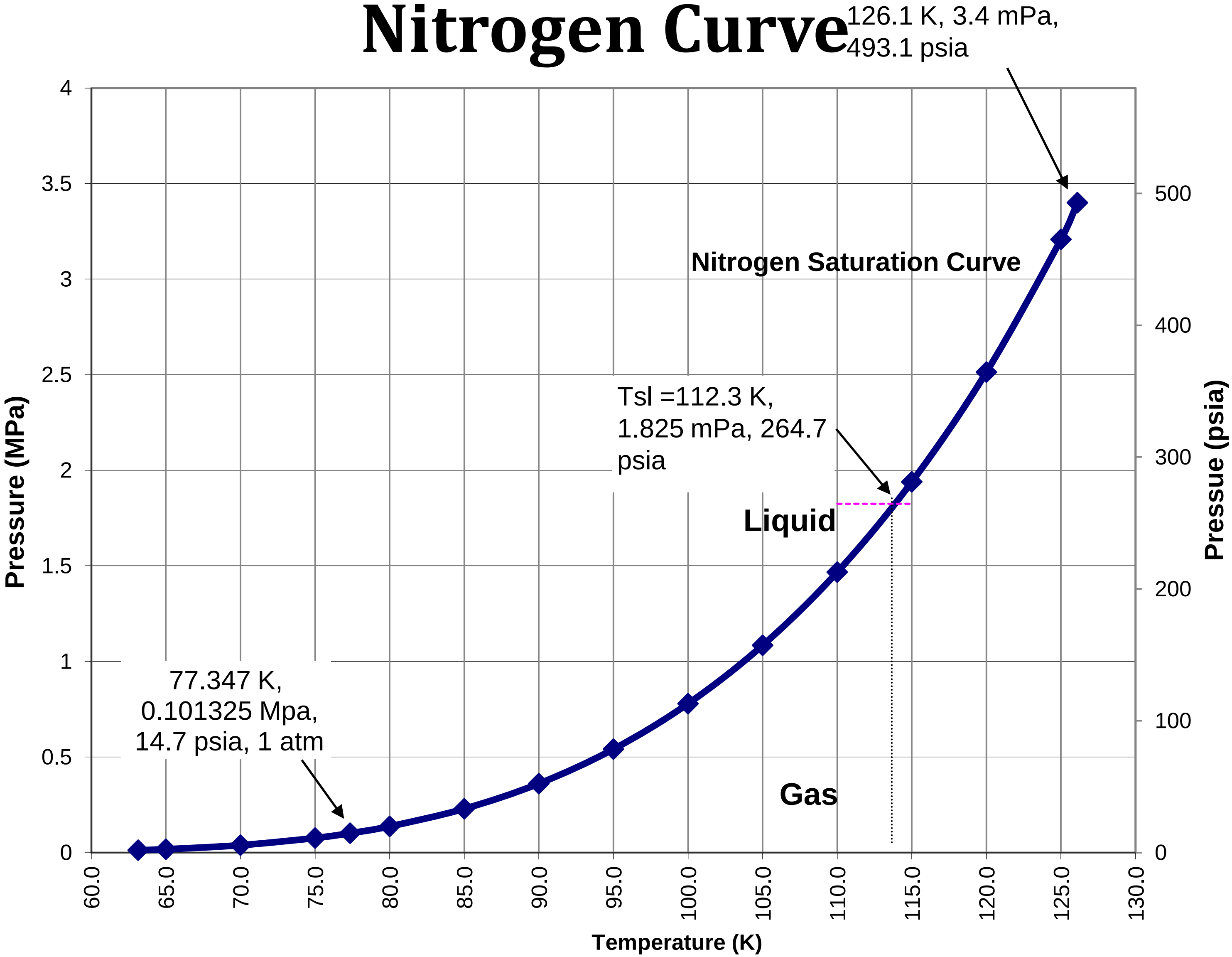
Step-by-Step Methodology

- First determine the initial state
  - Ideally the exact temperature of the fluid is desirable
  - Alternatively the pressure just prior to BLEVE can be use to determine the maximum temperature of the fluid by assuming saturated conditions

Example: Liquid Nitrogen

- Find Initial state
- Determine if at or above T_{sl}
- Solve for initial and final states

Nitrogen Curve



Primary Method

Reversible Adiabatic Expansion (Isentropic)

(Isentropic Work, Δu) (Subscript 1 indicates initial state)

- Find u_1 (find h_1 and ν_1 at P_1 and T_1)
  Where
  $u_1 = h_1 - p_1\nu_1$ (eq. 1)

- Find u_2 based on:

  $u_2 = (1-X)h_f + Xh_g - (1-X)p_2\nu_f - Xp_2\nu_g$ (eq. 2)

  where

  $X =$ Vapor Ratio $= (s_1-s_f)/(s_g-s_f)$ (eq. 3)

  - Subscript 1 refers to the initial state
  - Subscript 2 refers to the expanded state (ambient)
  - Subscript g refers to state of saturated vapor at ambient conditions (state 2)
  - Subscript f refers to state of saturated liquid at ambient pressure (state 2)

Isentropic Work

Calculated Values are readily available for various compounds

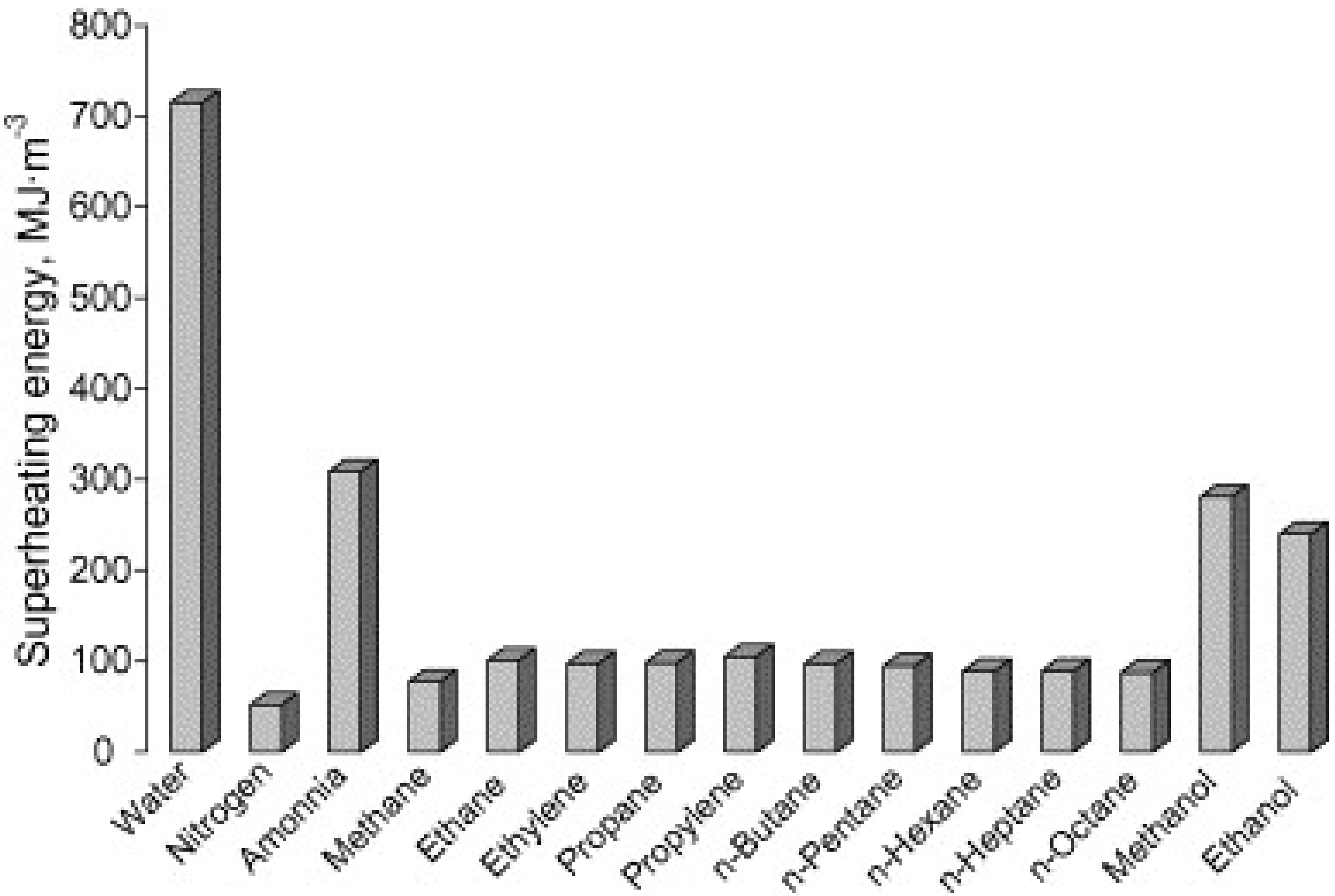
(Table Right)
Table 6.12 Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVES, Center for Chemical Process and Safety, American Institute of Chemical Engineers, 1994
Shows values of isentropic work W_i expressed as E_{ex} (Energy of Explosion) for a range of temperatures

(Table below)
Table 1: Casal, J. and Salla B., "Using Liquid Superheating Energy for the a Quick Estimation of Overpressure in BLEVEs and Similar Explosions", Journal of Hazardous Materials, Vol. 137, Issue 3, 10-2006, pg 1321-1327
SE = Total Superheat Energy of System

TABLE 6.12. Expansion Work of NH_3, CO_2, N_2, O_2

			Liquid	
Fluid	T_1(K)	p_1 (10^5 Pa)	e_{ex} (kJ/kg)	e_{ex}/V_l (MJ/m^3)
Ammonia, T_{sl} = 361.0 K				
	324.8	21.2	82.5	46.2
	360.0	48.0	152.5	74.7
	400.0	102.8	278.5	95.7
Carbon dioxide, T_{sl} = 270.8 K				
	244.3	14.8	54.4	58.2
	255.4	21.1	60.9	62.1
	266.5	29.1	68.1	65.6
Nitrogen, T_{sl} = 112.3 K				
	104.0	10.0	13.2	8.78
	110.0	14.5	18.2	11.3
	120.0	24.8	28.6	15.0
Oxygen, T_{sl} = 137.7 K				
	120.0	10.1	12.8	12.5
	130.0	17.3	18.7	16.8
	140.0	27.5	27.2	22.1

	$T_{\text{sl-E}}$ (K)	$P_{T_{\text{sl-E}}}$ (kPa)	$\rho_{1,T_{\text{sl-E}}}$ (kg m^{-3})	$SE_{m,T_{\text{sl-E}}}$ (kJ kg^{-1})	$SE_{V,T_{\text{sl-E}}}$ (MJ m^{-3})	W_i (kJ kg^{-1})	W_o (kJ kg^{-1})
Water	606.4	13357.0	632.5	1131.0	715.4	319.9	83.0
Nitrogen	118.6	2389.0	533.3	97.0	51.7	28.4	10.6
Ammonia	375.2	6507.0	450.9	684.1	308.4	187.0	55.7
Methane	174.7	2696.0	297.8	258.3	76.9	72.3	26.4



Casal, J. and Salla B., Using Liquid Superheating Energy for the a Quick Estimation of Overpressure in BLEVEs and Similar Explosions, Journal of Hazardous Materials, Vol. 137, Issue 3, 10-2006, pg 1321-1327

Comparison of relative isentropic work (W_i) potential for various fluids near T_{sl}

Basic Method

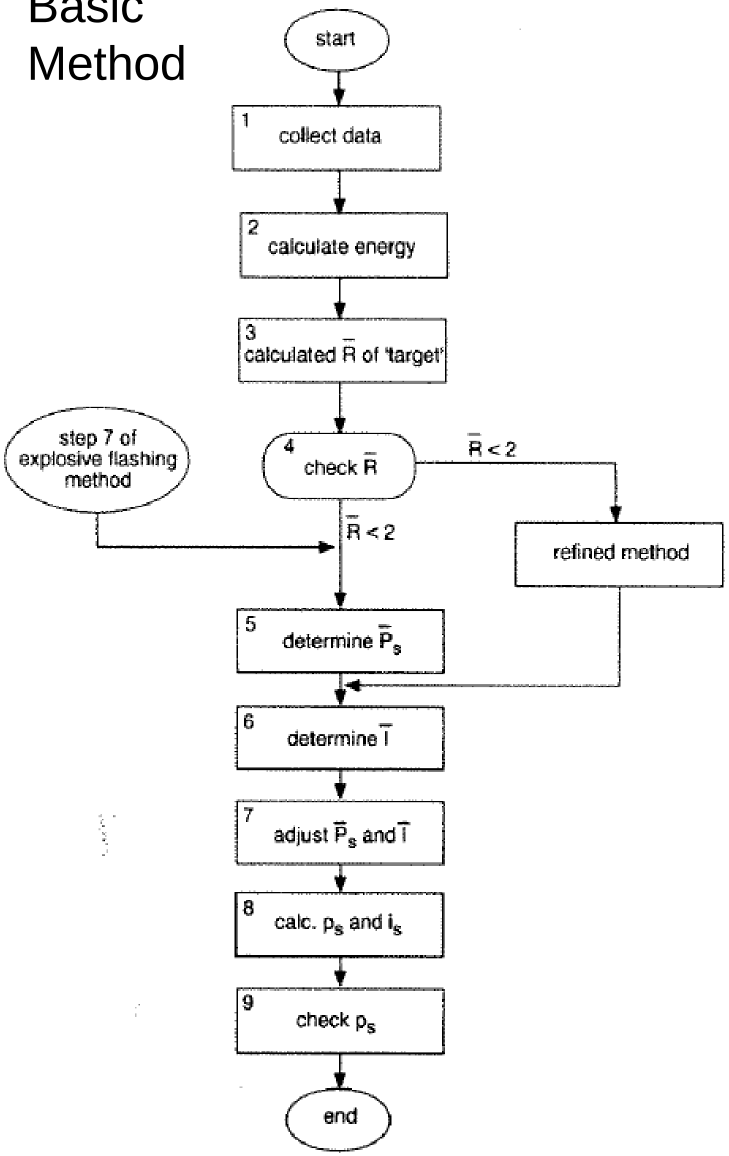


Figure 6.20. Basic method.

BLEVE

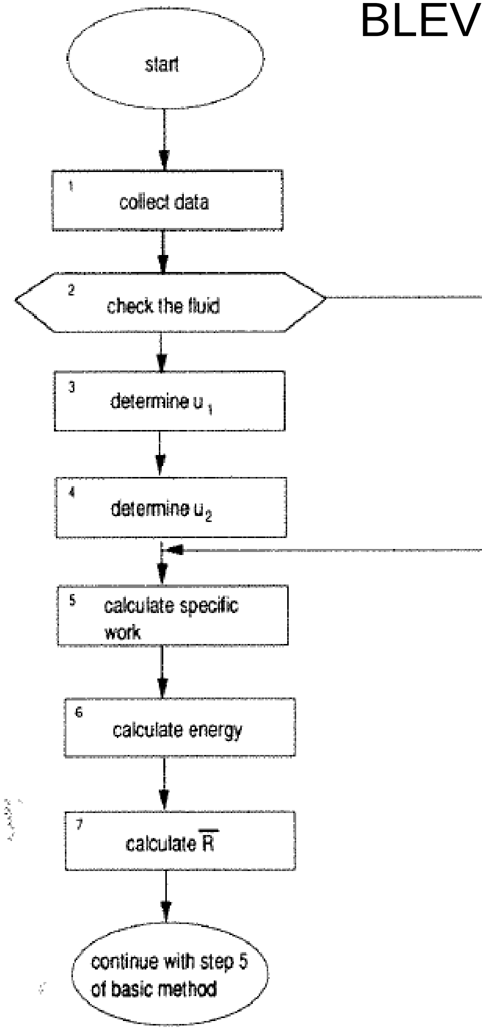


Figure 6.29. Calculation of energy of flashing liquids and pressure vessel bursts filled with vapor or nonideal gas.

Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVES, Center for Chemical Process and Safety, American Institute of Chemical Engineers, 1994

Comparison of Blast Potential (Nitrogen)

- Example: 1 liter (0.001 m^3) of Nitrogen, P_1 = 500 psi (3.45 MPa)
- Stored Energy Comparison
  - Hydrostatic: The approximate stored energy in pressurized liquids is relatively small, (based on a bulk modulus of liquid nitrogen of ~13 Gpa) 1 liter of nitrogen at 500 psi stores
    - ~0.5 J
  - Pneumatic: Nitrogen gas (assumed ideal) at 500 psi and 1 liter can store
    - ~5.5 kJ

$$U = \frac{P_1 \cdot V_1}{\gamma - 1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right], \gamma = 1.4, P_1 = 3.45 MPa, P_2 = 0.1014 MPa$$

  - BLEVE: 1 liter Superheated Liquid Nitrogen at 500 psi (T= 126 K) can store up to
    - ~30 kJ

Equivalent Pneumatic System

- The previous calculations showed the 'work' available to a BLEVE can be several times that of relatively low pressure (500 psi) gaseous pressure vessel or hydrostatic case
  - BLEVE vs. Pneumatic up to ~6 times greater (in this case)
  - BLEVE vs. Hydrostatic up to ~60,000 times greater (in this case)
- To 'match' pneumatic and BLEVE potentials a pneumatically charged nitrogen vessel would be at ~2,250 psi
- Finally it should be noted that nitrogen BLEVEs (or pneumatic releases) generate a local asphyxiation hazard and cryogenic burn hazard

Other Cryogens

- Liquid Oxygen (LOX) is very similar to liquid nitrogen (LN2) in its BLEVE behavior but has the added hazard of an oxidizer and promoted combustion risks
- Liquid Hydrogen (LH2)
  - Examination of Characteristics
  - Boiling Point (1 atm) = 20.37 K
  - Critical Point = 32.97 K
  - T_{sl} (estimate Redlich-Kwong equation of state) = 29.51 K
  - The final result is LH2 BLEVEs have an estimated blast potential less than LN2 (based on mass) but can still be catastrophic and have an additional vapor cloud explosion hazard in air (combustion, deflagration, or deflagration to detonation)
- Current WSTF efforts include:
  - Verifying BLEVE threshold (T_{sl}) value for Nitrous Oxide (N2O)
  - Determining Blast Potential of Nitrous Oxide BLEVEs

Other Hazards

- Additional Safety Notes
  - Cryogenic systems (LN2) can condense ‘Air’ and form a liquid consisting of ~50% liquid oxygen and ~50% liquid nitrogen as it drips off the cold surfaces
  - Liquid oxygen when in contact with hydrocarbons or products containing hydrocarbons (ex. oil, grease, asphalt, leather goods, etc.) can form impact or shock sensitive explosive compounds rivaling the strength of similar solid high explosives

- Questions?

Composite Pressure Vessel Ground Processing Hazards and Risk Management at KSC

Joseph Hamilton 2012

KSC S&MA Directorate/SMASS/MEI

Topics and Background

- **Major Topics**
  - **COPV safety documentation (only Leak Before Burst (LBB) failure mode vs. current COPV failure modes/hazard causes)**
  - **Brief overview of the KSC Cryogenic Composite Tank Rupture Incident**
  - **KSC COPV ground processing hazards**
    - **How they were managed for the Shuttle Program**
    - **How they are being controlled for the International Space Station (ISS) Program**
  - **NASA, Air Force , and industry standards for composite pressure vessels**

NASA Safety Documentation of COPV risks and LBB

- Safety documentation for Shuttle and International Space Station originally stated COPVs were "designed to have a leak before burst failure mode".
  - The safety documentation did not address other possible COPV failure modes. COPV burst due to stress rupture or impact damage of the composite was not addressed

- Per AIAA S-081, Leak-Before-Burst (LBB) is a design approach in which pre-existing flaws in the metallic liner may grow through the liner and result in pressure-relieving leakage rather than burst or rupture
  - LBB does not apply to the composite overwrap.

- Following a NASA Engineering and Safety Center (NESC) review that showed a significant risk of COPV composite stress rupture, the Shuttle program updated their flight COPV Hazard Reports and CILs to address COPV stress rupture.

- Shuttle Hazard Report "Stress Rupture of an Orbiter ECLSS, OMS/RCS, or MPS Composite Overwrapped Pressure Vessel (COPV) during Ground Processing" documented the COPV ground processing risks, mitigations, and controls.

COPV Failure Modes

- To correct this for ISS COPVs, Scott Forth/ NASA Pressure Vessel & Fracture Control Technical Monitor, issued Technical Memo ES4-08-043 Composite Overwrapped Pressure Vessel (COPV) Risks which states:

"Failure of a COPV may be catastrophic, leading to loss of the vehicle, ground personnel, or crew, and is therefore fracture critical."

- The memo identified four failure modes associated with COPVs:
  - Burst from over-pressurization
    - Operationally controlled
  - Fatigue failure of the metallic liner
    - Test data shows this risk to be low for KSC operations for most ISS COPVs.
    - This risk may be higher for NORS COPVs due to Inconel welded liner.
  - Burst resulting from damage to the metallic or composite
    - Failure of the COPV from damage to the composite is mitigated by the Damage Control Plan and damage tolerance testing.
  - Stress rupture of the composite overwrap
    - To date, the composite stress rupture failure mode of the ISS COPVs has not been adequately mitigated. COPV stress rupture is a sudden failure mode that can occur at normal operating pressures and temperatures, while at stress levels below ultimate strength. It can produce significant overpressure/ blast wave and fragmentation/shrapnel.

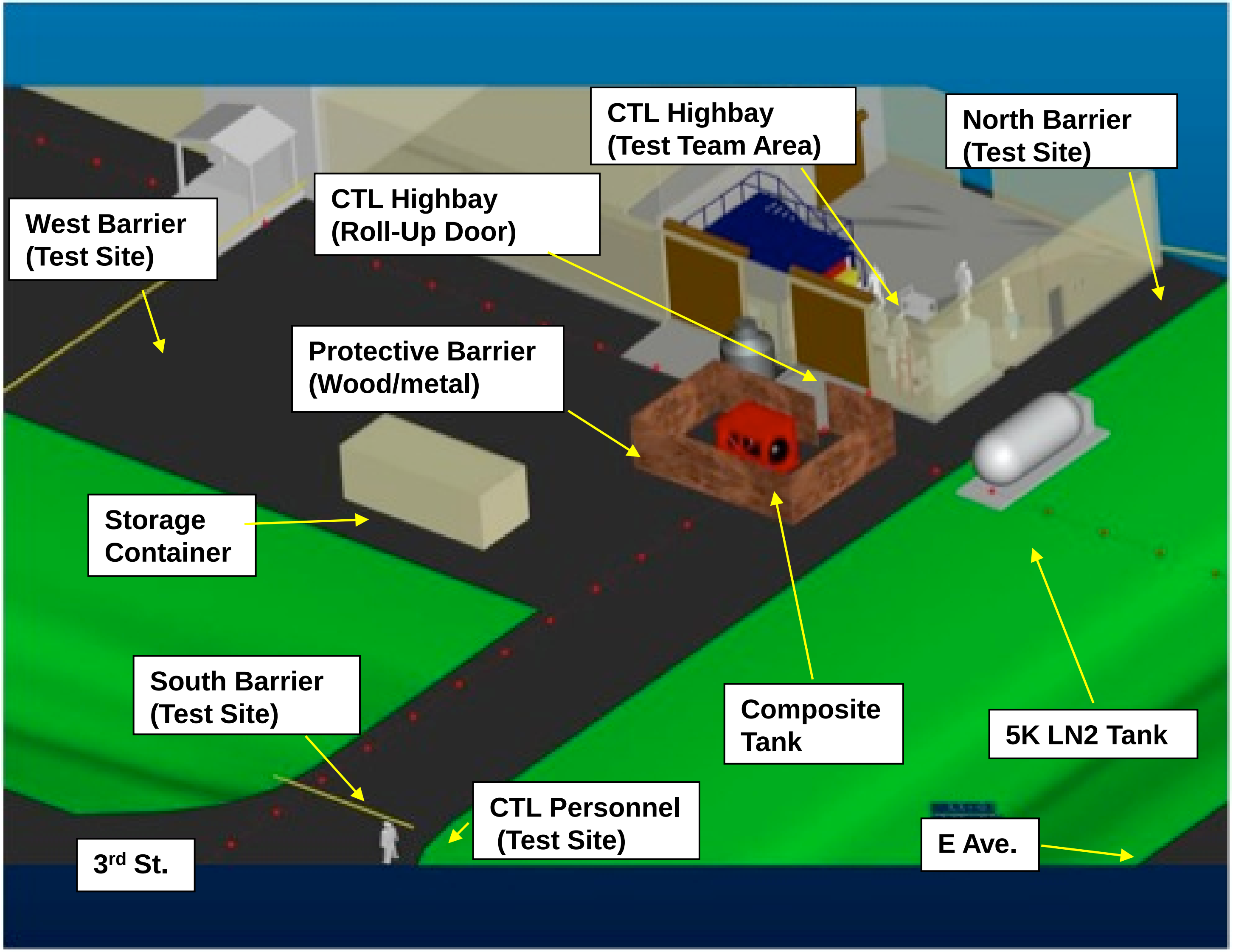
Cryogenic Composite Tank Rupture Incident at KSC

- On December 23, 2008 a composite pressure vessel (no liner) burst during pressure testing while filled with LN2 (~900 gal.) and pressurized with GN2. The test team expected a **leak-before-burst** failure and failed to take into account additional energy potential including BLEVE (Boiling Liquid Expanding Vapor Explosion).
- The test team thought they were protected by plywood barriers and a roll-up door. However a high velocity jet of LN2 impacted and opened the door, directly contacting 4 team members and filling the room with N2. Several team members received mild cryo burns, one member received a cracked rib, 2nd degree cryo burns and other injuries. The test team was fortunate, they could have suffered much worse consequences.

Test Unit Plywood Protective Barrier Under Construction

Area surrounding test unit following tank rupture. Test team location was behind roll-up door at top of image.

Cryo Tank Pre-Test Set-up



Post-Rupture

CTL Exterior

Cryo Tank

Figure 2-2. Composite Tank in Support Structure

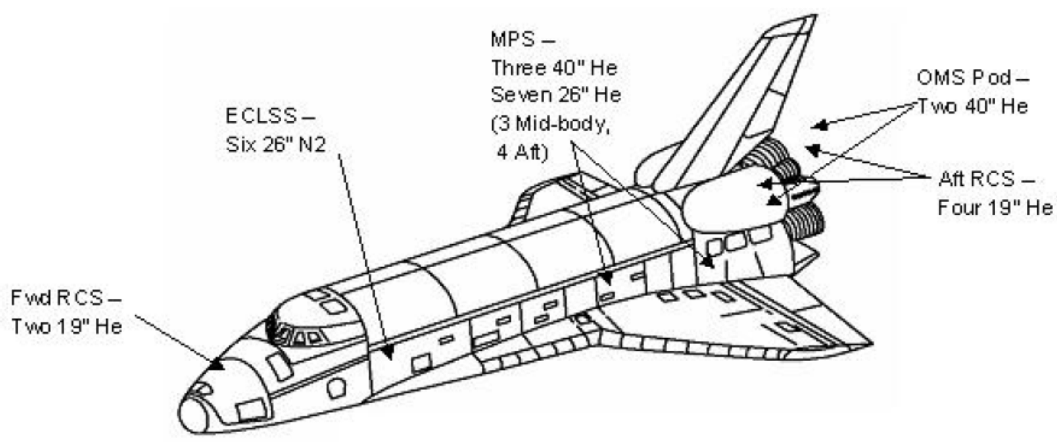
Cryogenic Composite Tank Rupture

Mishap Investigation Report Findings:

- The pretest analysis was in error regarding the total energy available during a failure; it only considered the pneumatic energy of the 10% by volume ullage space.
- There was no blast/fragmentation or QD siting analysis of barrier capabilities, plywood, or door.
- The Test Team accepted the manufacturer’s CPV structural analysis without sufficient review.
- The manufacturer of the tank maintained it would fail by a Leak Before Burst scenario without supporting evidence, as did the test team in its Test Readiness Review.

Orbiter COPV Processing Risk Management

- COPVs on the Shuttle Orbiter were Kevlar/Epoxy overwrapped, with one graphite Epoxy COPV.
- Based on the Orbiter COPV working group stress rupture risk calculations for Orbiter COPVs, COPV Stress Rupture became a top Shuttle program risk. Significant changes were made to reduce the ground processing risk to personnel :
  - Modified pressurization of COPVs to limit temperature and fiber stress
  - The pad was cleared during COPV pressurization
  - The KSC COPV Safety Bulletin limiting pad access to essential personnel from L-4 to launch was broadcast through out KSC
  - Several COPVs from Orbiters with highest stress rupture risk were replaced
  - Reduced OMS flight pressures for remaining flights
  - WSTF performed burst and stress rupture tests of existing Orbiter COPVs and blast analysis



Orbiter COPV risk from 10/18/2007 PRCB

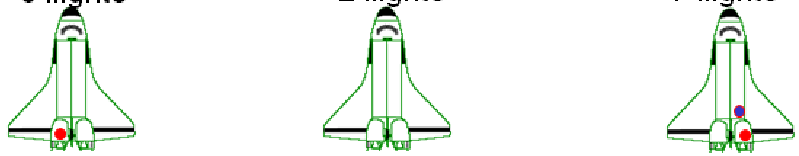
Life of Program Reliability Estimate

Two Day Launch Scrub - PRCB 10/18/2007

Presenter:	
MT Kezirian	
Date: 11/15/2010	Page: 1

From STS-118

	OV-103 6 flights		OV-104 2 flights		OV-105 7 flights		Life of Program COPV Reliability 15 Flights Combined	
Per Flight Reliability Numbers*	OMS Full	OMS Reduced	OMS Full	OMS Reduced	OMS Full	OMS Reduced		
Point	.999 66	.999 89	.999 994	.999 997	.999 85	.999 944	.998 6	1:710
Mean	.999 53	.999 84	.999 989	.999 995	.999 78	.999 918	.998 0	1:489
95% CL	.998 3	.999 42	.999 958	.999 978	.999 20	.999 69	.992 5	1:134



Life of Program, 15 flight Failure Likelihood

Cumulative Reliability (per vehicle) From # of Flights	1 Flight	5 Flight	1 Flight	1 Flight	1 Flight	6 Flight
Point	0.999 09	1:1,099	0.999 991	1:111,111	0.999 51	1:2,041
Mean	0.998 7	1:769	0.999 984	1:62,500	0.999 27	1:1,370
95% CL	0.995 3	1:213	0.999 936	1:15,625	0.997 3	1:370

- OMS tank s/n 020 in RP03 is the driver for OV-103 reliability numbers
- OMS tank s/n 018 in LP03 is the driver for OV-105 reliability numbers
- MPS tank s/n 021 in OV-105 is a large contributor to reliability numbers

* Note that reliability for each individual flight is virtually the same for all the individual flights through the end of the Program

BOEING

Note: OV-104 numbers based on replaced MPS Tanks.

USA United Space Alliance

- **COPVs used on the ISS Element and in ISS Experiments are primarily Graphite Epoxy Composite Overwrapped:**
  - **ISS Element COPVs include Nitrogen Tank Assembly (NTA), High Pressure Gas Tank (HPGT), and Plasma Contactor Unit (PCU)**
  - **ISS Experiment COPVs include Alpha Magnetic Spectrometer (AMS-2), SPACEDRUMS (Space Dynamically Responding Ultrasonic Matrix System), JAXA Gas Bottle Assembly (GBU), Verification Gas Assembly (VGA), and Vehicle Cabin Atmosphere Monitor (VCAM)**
- **COPVs for the Nitrogen Oxygen Recharge System (NORS) are in the qualification phase. They were designed to ISO requirements, and have received a DOT Special Permit for transportation of pressurized COPVs.**
- **At KSC, ISS COPVs were remotely pressurized in an offline blast resistant facility. The primary ground processing risk to personnel was during processing in the SSPF and pad once pressurized.**

Carbon COPV Reliability

- The NESC COPV Working Group was asked to determine the probability of COPV stress rupture for ISS ground processing and ISS flight operations, but due to the limited Graphite strand and vessel test data available at the time, the results of this analysis were problematic.

  "All NASA programs that use COPVs have the same basic issue: We do not have a way to adequately quantify (graphite) COPV risk with current data and models. "

  "The failure mechanism associated with stress rupture is complex, not well understood, and is difficult to accurately predict or detect prior to failure"

- To address this problem, NASA currently has an extensive COPV test program underway at WSTF to determine carbon COPV reliability.

  300 Carbon subscale COPVs manufactured by General Dynamics

  Burst Testing complete

  Sub-scale test program is on-schedule to meet ISS flight needs

  A full scale COPV testing program is being evaluated which will reduce conservatism in reliability calculations and verify modeling assumptions

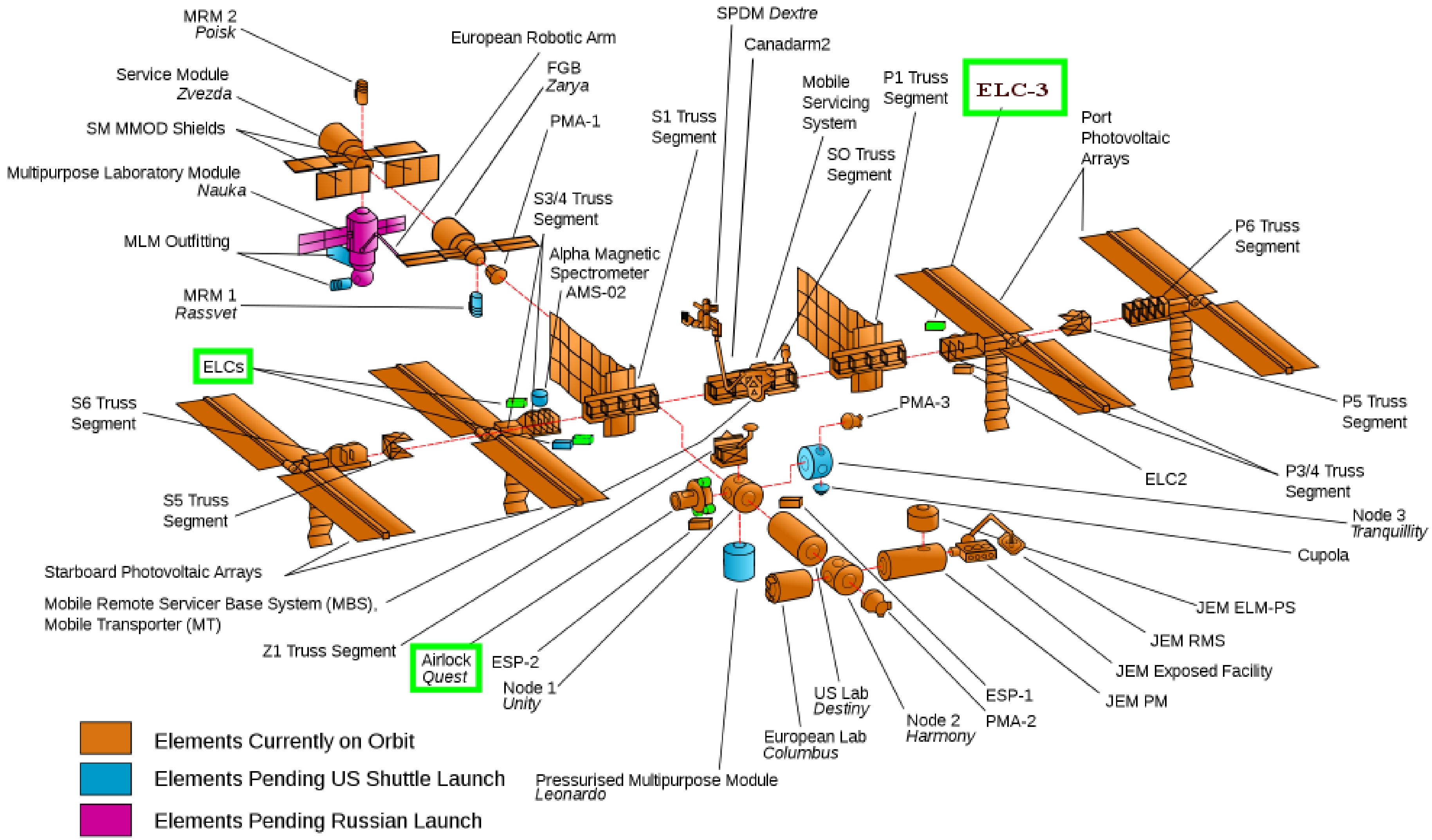
  – Flight-quality COPVs have better manufacturing process

ISS Vehicle COPVs

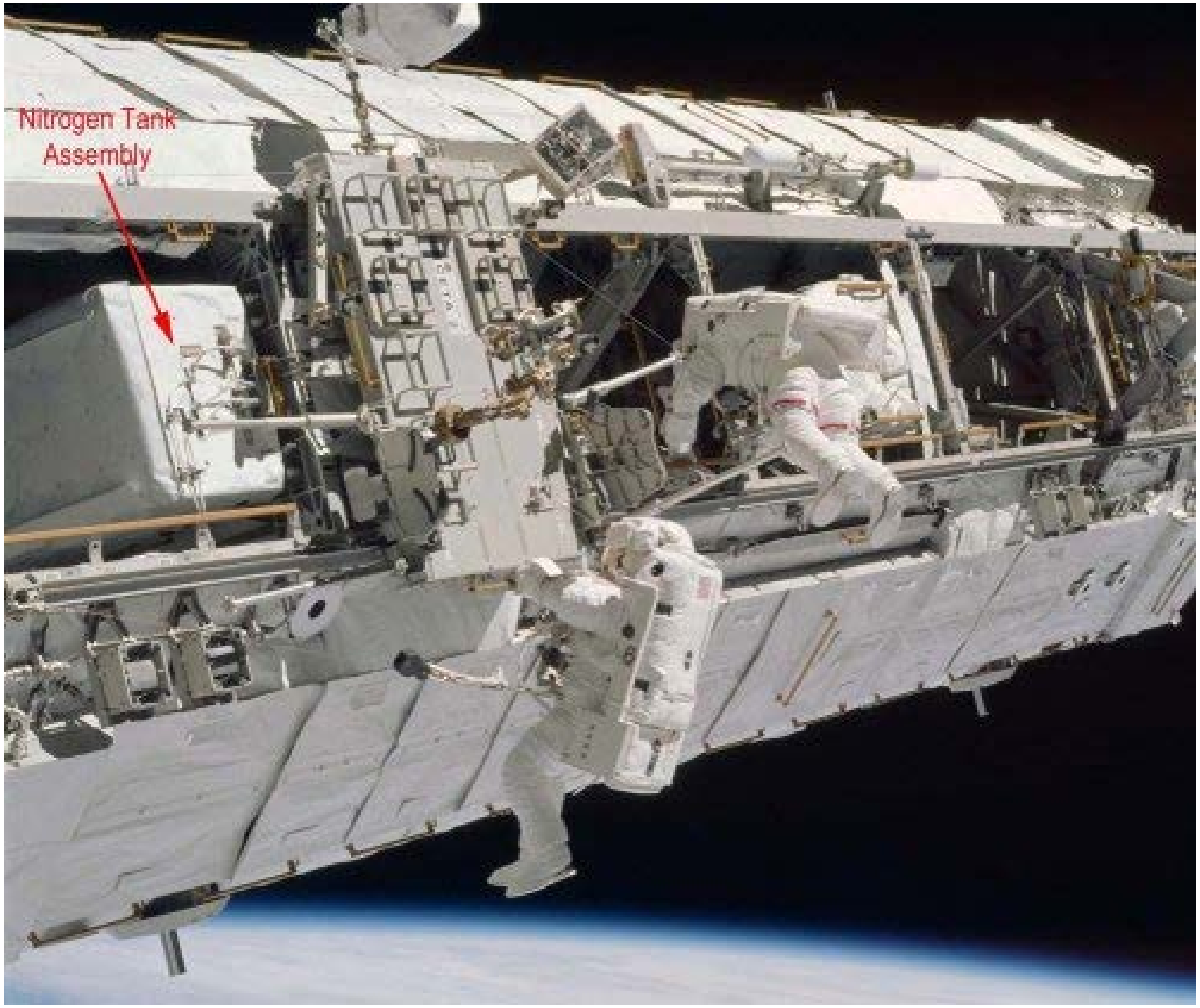
ISS Configuration

As of November 2009 (ULF3)

HPGT Locations



Nitrogen Tank Assembly



ISS COPV Ground Processing Risk Reduction

- Risk Reduction for ISS COPV ground processing was accomplished through multiple steps:
  - Revised mission processing operations to minimize pressurized COPV exposure time
  - ISS COPV Tracking Matrix
  - Generate ISS COPV Mechanical Damage Control Plans to control impact damage
  - ISS COPV Blast/fragmentation Damage Analysis by WSTF
  - Personnel COPV Risk Education and Imposing Access Restrictions for Pressurized COPVs in the SSPF and Pad based on the COPV blast analysis
  - Adherence to KNPR 8715.3 Safety requirements for ground processing of COPVs
  - Followed the guidelines in ES4-09-031 NASA Carbon Overwrapped Pressure Vessel (COPV) Pressure Restrictions
    - Maintain the operating strain in the fiber below 50 % of ultimate fiber strain during ground pressurization, integration and flight operations.
    - Pressurize the COPV as late in the flow as possible to minimize ground personnel exposure time.
    - Label the COPVs to prevent damage, report any inadvertent damage, maintain safety clears around pressurized COPVs (above 1/3 design burst) based on blast/fragmentation analysis.

COPV Tracking Matrix

- **To better understand and assess the safety risk of processing the various ISS COPVs, KSC Safety developed the ISS COPV Tracking Matrix .**
  - **It contains data on each ISS COPV at KSC such as COPV liner material, fiber, resin, fill pressure, MDP, minimum design burst, volume, max fill/burst pressure, dimensions, associated mission, last fill date, MDCP hyperlink, TNT equivalent, restricted access radius, etc.**
- **Data in the ISS COPV Tracking Matrix was used for risk assessments and as a decision making tool.**

ISS COPV Mechanical Damage Control Plans

- To address the COPV impact damage failure mode, Mechanical Damage Control Plans were written and implemented for all ISS COPVs.
- The NASA Fracture Control Board Chairman issued a COPV Damage Control Plan template document to **supplement the requirements in ANSI/AIAA S-081 and KNPR 8715.3**.
- ISS COPV Mechanical Damage Control Plans established procedures to prevent impact damage to COPVs during manufacturing, shipping, KSC processing and handling, and installation into ISS systems.
- ISS COPV Mechanical Damage Control Plans are now reviewed and approved as part of the ISS Ground Safety Review Panel process and by the NASA Pressure Vessel & Fracture Control Technical Monitor.

COPV Inspection at KSC

- Per KNPR 8715.3 section 13.18.1 GRAPHITE/EPOXY (Gr/Ep)COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPVs)

  c. Prior to the first pressurization of Gr/Ep COPVs at the KSC, CCAFS, VAFB or Dryden, an inspection of the vessel for visible damage shall be performed by a trained inspector.

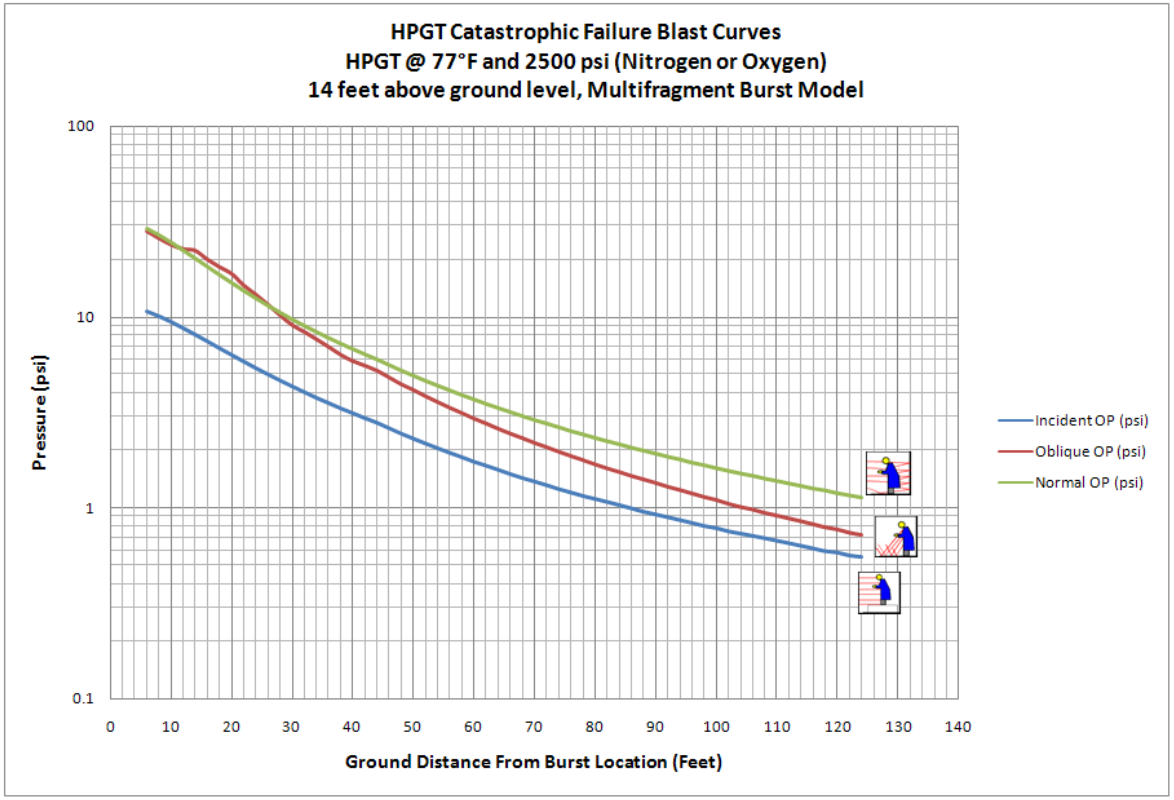
  Trained Inspector: (COPV) A person trained specifically in the detection of visual damage of COPVs and familiarized with the NDE methods and results that could be used to aid in the interpretation of visual damage. White Sands Test Facility typically conducts this training as part of their COPV damage control and inspection course.

- At KSC for ISS COPV processing, COPV inspection is provided by NASA QA personnel with WSTF COPV inspection training.

COPV Rupture Consequence

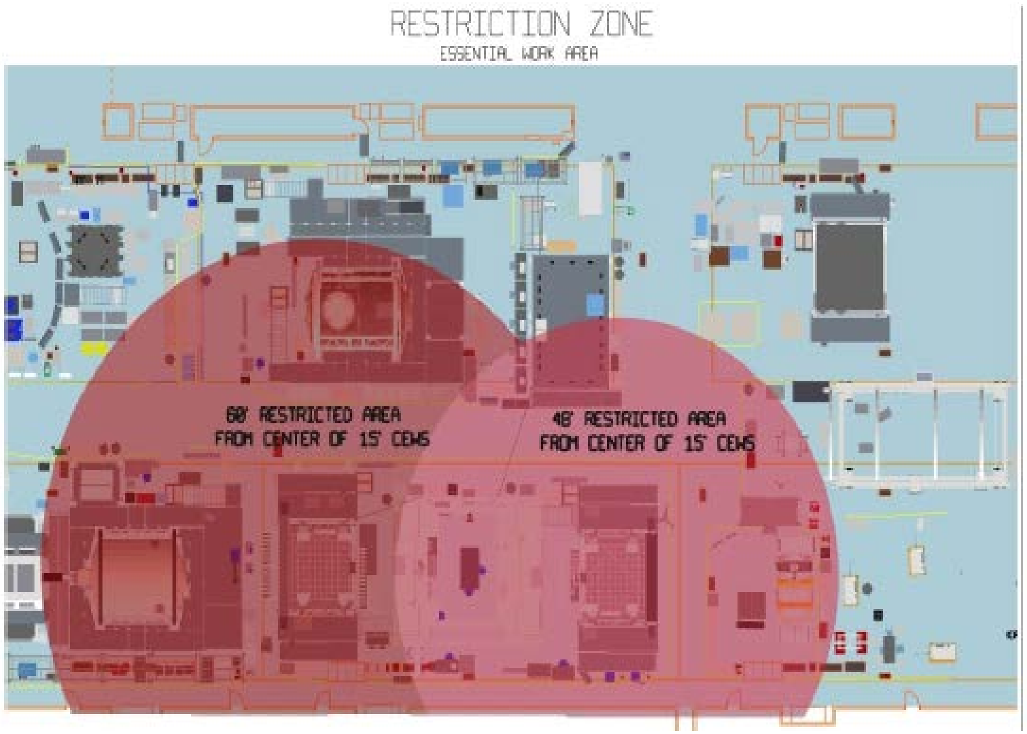
WSTF Blast/Fragmentation Analysis

- KSC assessed the COPV stress rupture consequence based on the Chris Keddy WSTF ISS COPV blast/fragmentation analysis report (Examination of Catastrophic Failure of COPVs During Ground Operations: KSC SSPF Flight ULF-3 2009)
  - Primary COPV rupture effects as well as some secondary effects were considered
- Below is a ISS COPV blast overpressure result using the PV HAZARD software



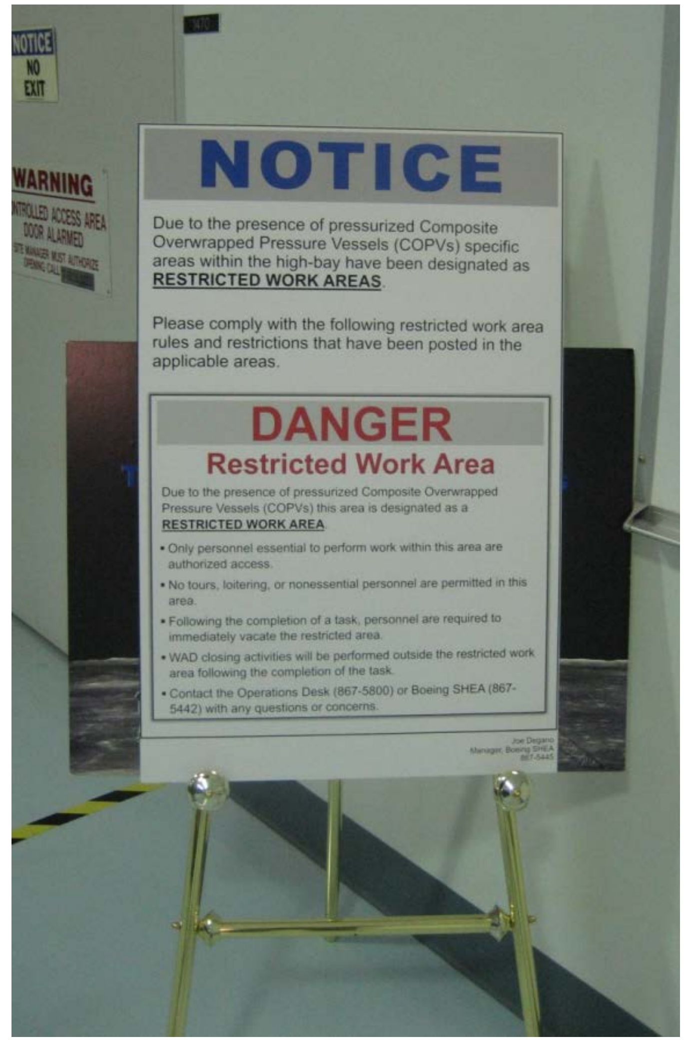
Personnel Education and Access Restrictions for Pressurized ISS COPVs

- All Space Station Processing Facility (SSPF) residents are notified of the presence of pressurized COPVs and the associated hazards.
- Personnel access restrictions around pressurized COPVs in the SSPF were based on the WSTF ISS COPV blast fragmentation analysis report overpressure curves at 3psi.
- Personnel access restricted zones in the SSPF for pressurized HPGT and NTA are shown below

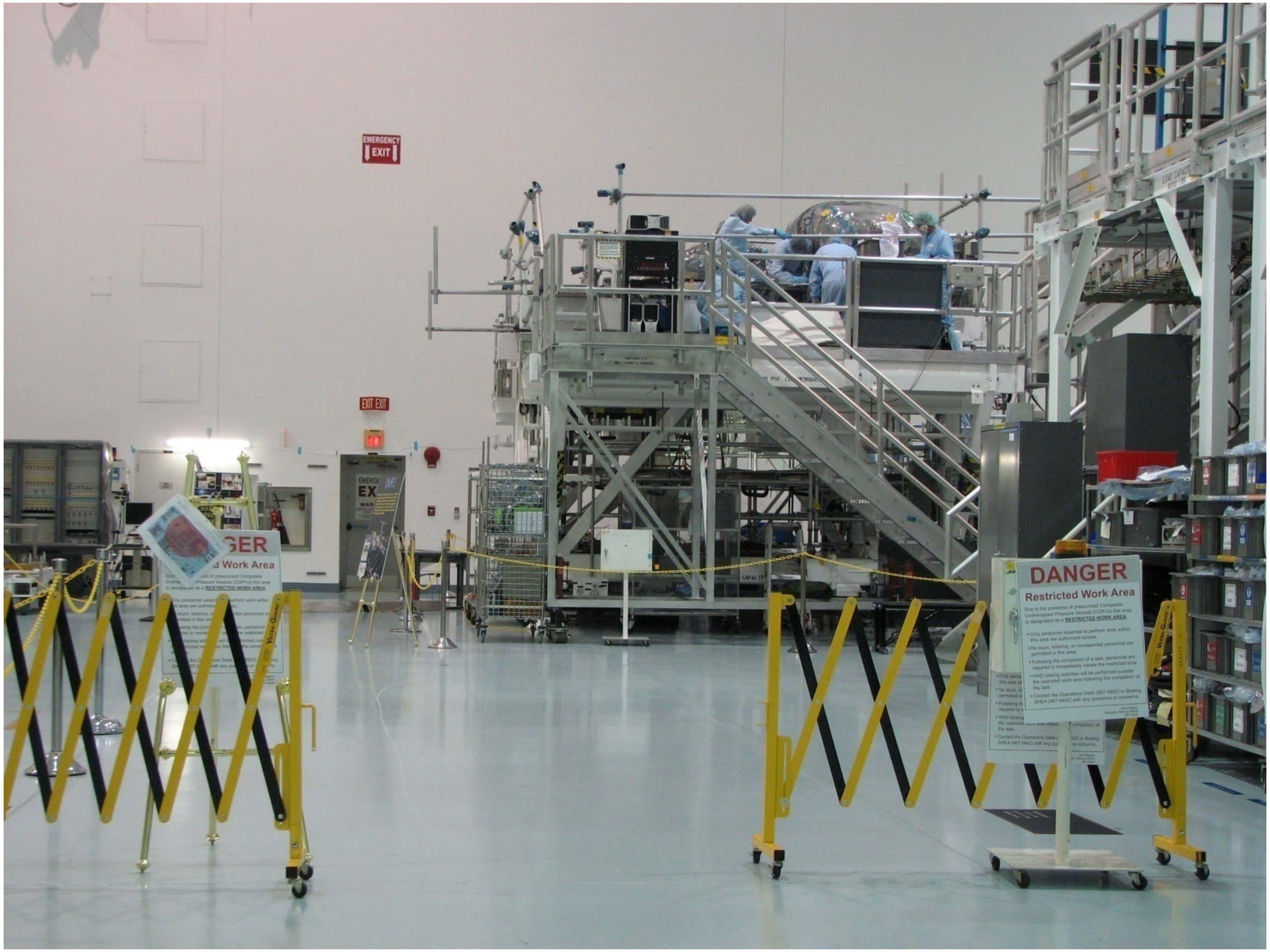


SSPF Access Restrictions around Pressurized COPVs

- **COPV restricted areas in SSPF processing area with warning signage**



SSPF Access Restrictions around Pressurized COPVs



KNPR 8715.3 COPV processing requirements

- 13.18 SAFETY REQUIREMENTS FOR DESIGN, TEST, AND GROUND PROCESSING OF FLIGHT COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPVS) AT THE KENNEDY SPACE CENTER (KSC), CAPE CANAVERAL AIR FORCE STATION (CCAFS), AND THE VANDENBERG AIR FORCE BASE (VAFB)

Summarizing

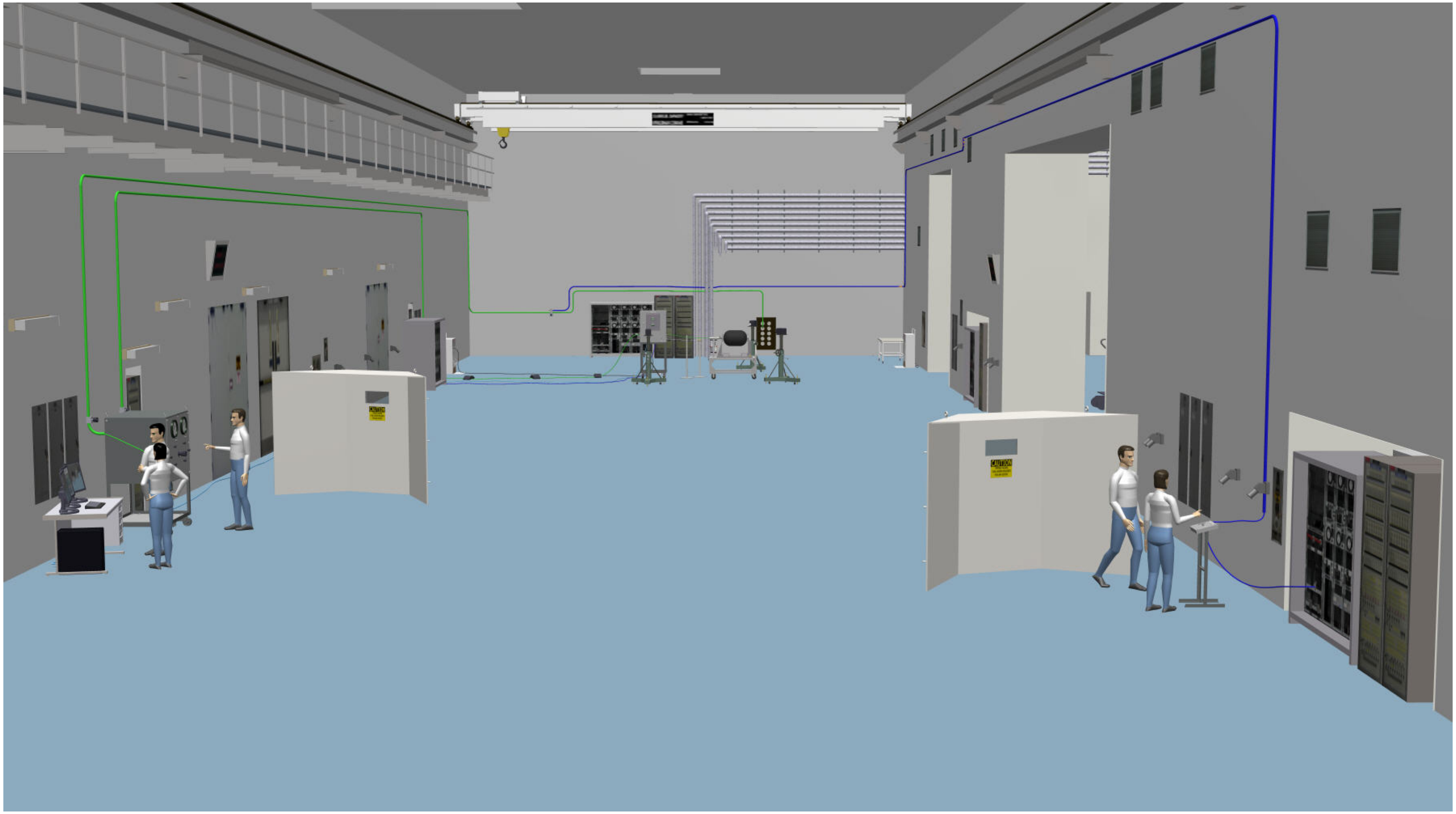
- Prior to the first pressurization of COPVs at KSC (or last time COPV was accessible), an inspection of the vessel for visible damage shall be performed by a trained inspector.
- Following visual inspection, COPV shall be pressure tested to 1.1 times the ground maximum operating pressure. (If the COPV is shipped pressurized to KSC, this requirement is usually waived.). (This requirement is being considered for deletion)
- The 1.1 test or any pressurization above 1/3 design burst pressure shall be performed remotely or a blast shield shall be used to protect personnel
- Personnel limits for operations around COPVs above 1/3 design burst pressure shall be established (based on a COPV blast effects analysis).
- The transport of pressurized COPVs at pressures greater than 1/3 design burst pressure shall be along routes that minimize exposure to personnel and facilities with escort during designated “off-shift” time periods.
- A Mechanical Damage Control Plan (MDCP) for each COPV shall be provided by the design agency and made available for review by the Ground Safety Review Panel, the NASA Pressure Vessel Technical Monitor, and the KSC ISS operations and engineering department prior to operations.

Future ISS Program COPVs

Nitrogen Oxygen Recharge System (NORS)

- **NORS COPVs (Qty: 35-150) will supply oxygen and nitrogen to ISS for:**
  - Maintaining normal atmospheric pressure
  - Crew metabolic needs & emergency medical usage
  - Extravehicular Activity (EVA)
  - Contingency module repressurization
  - Payload usage
  - Thermal Control System
- **COPV design requirements were intended to envelope NASA SSP 30558 & 30559, AIAA S-081a and ISO/DOT (to enable ship fully pressurized).**
  - ISO/DOT Fatigue Testing (supersedes NASA SafeLife Analysis)
  - Design FOS=3.4; (Actual Design Burst Pressure corresponds to a higher FOS)
  - Reduced Qualification Test Program (focus on essential requirements)
  - Obtained DOT Special Permit for shipping fully pressurized.
  - NORS COPV Mechanical Damage Control Plan has been developed and implemented throughout the lifecycle of the NORS
- **Concept of Operations**
  - NORS COPV will be pressurized to flight pressures at KSC
  - NORS COPV will be shipped fully pressurized from KSC to launch sites (CCAFS, Wallops, and Tanegashima) for SPACEX, Orbital Cygnus, and HTV.

NORS COPV Pressurization at KSC



- **AIAA S-080 Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components**
- **ANSI/AIAA S-081 Space Systems – Composite Overwrapped Pressure Vessels (COPVs)**
- **Proposed Draft AIAA- S-082 –Composite Pressure Vessels (no liner)**
- **Draft BSR/AIAA S-089 American National Standard Space Systems – Composite Pressurized Structure (CPS)**
- **Note we are proposing adding ground processing requirements to the above AIAA standards, which will be discussed at the AIAA working group meeting.**
- **The KSC Safety Practices Procedural Requirements KNPR 8715.3 COPV ground processing requirements section will be revised to address the 4 types of flight pressure vessels listed above.**
- ***AIR FORCE SPACE COMMAND MANUAL (*AFSPCMAN) 91-710, Range Safety User Requirements**
- **NASA-STD 8719.24 NASA EXPENDABLE LAUNCH VEHICLE PAYLOAD SAFETY REQUIREMENTS**

Summary

- COPVs are used in NASA and Air Force spaceflight programs .
- All COPV failure modes/ Hazard causes should be addressed in the associated COPV safety analysis with recommended mitigations and controls.
- The Shuttle Program addressed the risks associated with COPVs and put practical mitigations in place to significantly reduce the ground risk.
- The ISS Program assessed COPV ground processing risks and KSC has implemented procedures to reduce ground processing risk in accordance with the NASA guidelines.
- Ground processing safety requirements for all types of Composite Pressure Vessels should be incorporated in NASA and industry standards. (This topic will be discussed in the AIAA working Group meeting later this week)

Backup

Definition of BLEVE

- BLEVE definition from Wikipedia, the free encyclopedia
- BLEVE (pronounced /*BLEV-ee*), is an acronym for Boiling Liquid Expanding Vapor Explosion.
- Mechanism
  - If a vessel partly filled with liquid with vapor above filling the remainder of the container, is ruptured, the vapor portion may rapidly leak, lowering the pressure inside the container. This sudden drop in pressure inside the container causes violent boiling of the liquid, which rapidly liberates large amounts of vapor. The pressure of this vapor can be extremely high, causing a significant wave of overpressure (an explosion) which may completely destroy the storage vessel and project fragments over the surrounding area.

Definition of Stress Rupture

- Dr. Leigh Phoenix / Cornell University provided this definition of COPV stress rupture
- Stress rupture is a sudden failure mode for Composite Overwrapped Pressure Vessels (COPVs) that can occur at normal operating pressures and temperatures. This failure mode can occur while at stress levels below ultimate strength for extended time. The failure mechanism is complex, not well understood, and is difficult to accurately predict or detect prior to failure. The location and mechanism of triggering damage causing sudden failure is highly localized, but at a random location. This location and extent of local damage has not been able to be detected by current Nondestructive Evaluation (NDE) techniques prior to catastrophic failure. Pressure, duration of time at pressure, and temperature experienced contribute to the degradation of the fiber and/or the fiber-matrix interface, particularly around accumulations of fiber breaks, and these increase the probability of COPV stress rupture.

Composite Conference 2012

Compressive Strength of Concrete Retrofitted with Kevlar/Carbon, Carbon/Basalt and T700 Unidirectional Fabrics

Stella B. Bondi, PhD and Zia Razzaq, PhD
Old Dominion University, Norfolk, VA

Overview

- Introduction
- Fiber Reinforced Polymers (FRP)
- Materials – Background
- Testing Procedures
- FRP Application
- Fabrics Used
- A Composite Example
- Advantages on Retrofitting with FRP
- Comparison of Results
- Conclusion

Introduction

- Coastal areas cause environmental damages to concrete columns.
- A method of retrofitting suspected impaired short columns is through the use of composite fibers.
- The increased availability, high strength and high modulus of elasticity of various types of composite materials make them great candidates.
- It is the goal of the authors to test and find the most beneficial application of the right fabric that will enable more efficient applications for retrofitting purposes.

Fiber Reinforced Polymers (FRP)

Fiber Reinforced Polymer (FRP) Composites are defined as:

“A matrix of polymeric material that is reinforced by fibers or other reinforcing material”

FRP’s PRIMARY FUNCTION:

- To provide STRENGTH and/or STIFFNESS in ONE DIRECTION!
- TO CARRY LOAD ALONG THE LENGTH OF THE FIBER

Materials - Background

- The strength of FRP Reinforcing fibers provide the mechanical strength components of the composite. The strength is dependent on:
  - The type of fiber
  - The amount of fiber
  - The orientation of the fiber
- Changing these parameters, a change of mechanical properties is possible.

Testing Procedures

- 24 cylinders were made
- Strength of concrete was approx. 4,000 psi
- Curing time: 28 days in a controlled space
- Fabric was cut to fit cylinders
- Epoxy used was made of two part system: Resin and Hardener
- A thin layer of epoxy was applied to the cylinder
- FRP material was applied directly on the surface
- Specimen was let to cure for seven days prior to testing

Producing Concrete Speciments

- Mixing
- Pouring
- Curing

FRP Application

- After 28 days of concrete curing…
- Mixed the epoxy, prepared the putty, etc.
- Measured and prepared the FRP fabrics
- Applied of the FRP Resin and Hardener mix
- Cured the wrapped with FRP cylinders
- Prepared for testing

Fabrics Used

- Three different types of fabrics were tested during this study:
  - Kevlar/Carbon ® (50/50 percent)
  - Carbon/Basalt and
  - T700 Unidirectional Aerospace Grade – A high strength composite having parallel fibers

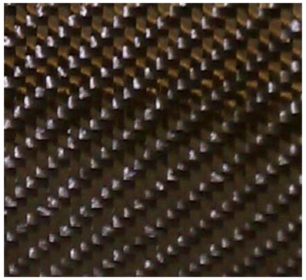
A Composite Example:

- Column wrapped with a composite which has all the fibers aligned in one direction, it is stiff and strong in that direction, but in the transverse direction, it will have a lower modulus and low strength.
- Also, the fiber volume fraction heavily depends on the method of manufacture.
- Generally, The higher the fiber content the stronger the composite.

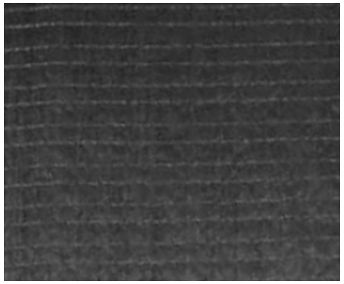
Material Tested

Kevlar/Carbon

Carbon/Basalt



Carbon Fiber
Uni-Directional



Some Advantages on Retrofitting Short Columns with FRP

- Low Maintenance
- Increased Strength
- Low Weight
- Reduced Construction Time

Comparison of Results

Cylinders Retrofitted with Composite Material		
Material/Fabric Type	Ratio Between Concrete and Fabric	Increase in Strength (Percent)
Carbon/Kevlar®	1.22	22%
Carbon/Basalt	1.23	23%
T700 Unidirectional Aerospace Grade	25.22	252%

Conclusion

- Comparing unreinforced concrete cylinder with Carbon/Kevlar® produced a 22% increase in strength
- Comparing unreinforced concrete cylinder with Carbon/Basalt produced a 23% increase in strength – Because the orientation of the fiber fabric was changed!
- Comparing unreinforced concrete cylinder with T700 Unidirectional Aerospace Grade fibers produced a 252% increase in strength or 2.5 times increase the concrete's strength

Thank you!

National Aeronautics and Space Administration

Fiber-optic-based Structural Health Monitoring of Aerospace Vehicles

Dr. Lance Richards, Allen. R. Parker, Jr., Anthony Piazza,

Dr. William L. Ko, and Dr. Patrick Chan

NASA Dryden Flight Research Center
Edwards, CA

2012 Composites Conference
Las Cruces, NM
August 16, 2012

Topics

- **Structural Health Monitoring**
  - Definition
  - SHM, NDE, Materials, & Structures
- **Background and Inspiration**
- **Strain-based Parameter Development**
  - Shape sensing
  - Externally Applied Loads
  - LH_2 Liquid Level Sensing
- **Sensor and System Development**
- **Sensor Attachment / Embedment**
- **Ground Applications**
- **Flight Applications**

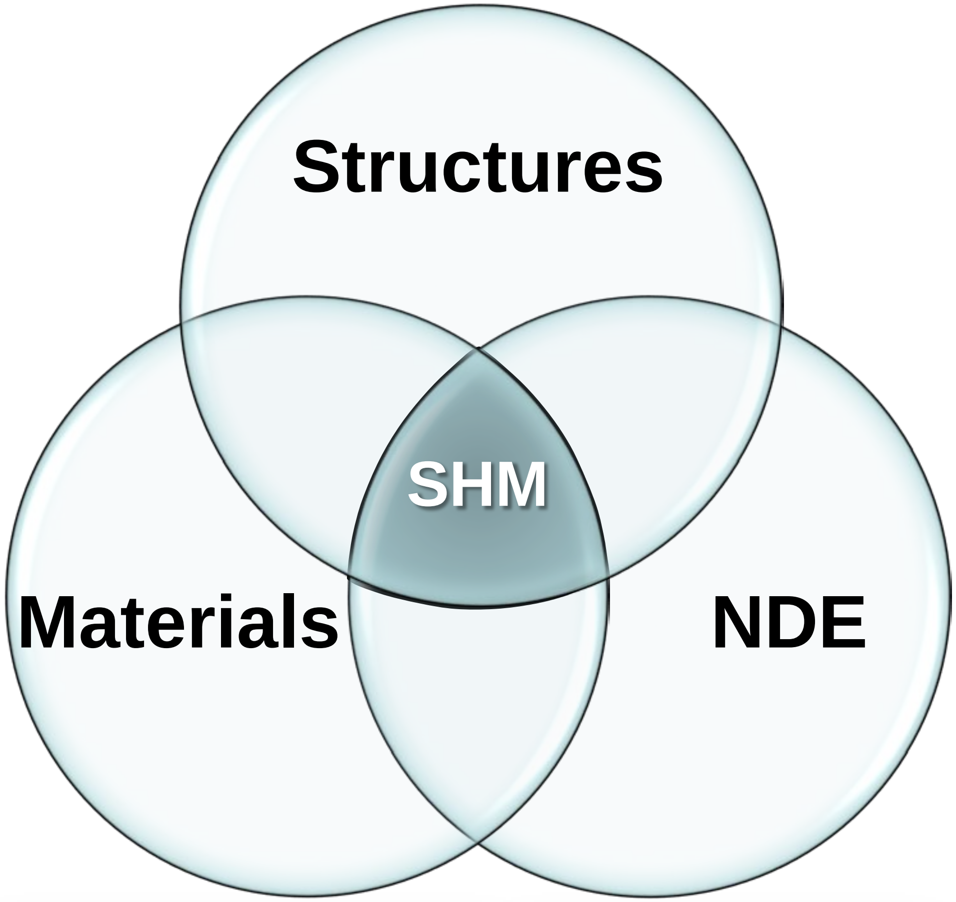
What is Structural Health Monitoring?

- **SHM combines advanced sensing technology with a knowledge of material/structural damage characteristics to monitor the condition of structures in real time while in service. (Chang, 1999)**
- **An emerging technology dealing with the development of techniques and systems for the continuous monitoring, inspection, and damage detection of structures, with minimum labor involvement (Guemes et. al., 2001)**
- **Allows for the optimal use of structures (minimizing their downtime, avoiding catastrophic failures, etc) while manufacturers can improve their products, reduce inventory and minimize their life-cycle costs**
- **Involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. (Farrar et. al., 2001)**
- **The goal of SHM is not to detect failure (as with conventional fault detection methods), but to identify physical damage and define remediation strategies for decision-makers before structural failure occurs.**

NASA Focused Structural Health Monitoring

<u>Key Drivers</u>

Vehicle-focused
Real-time, decision-making
Online processing
Onboard systems
Lightweight, Small size, Low power, System solutions

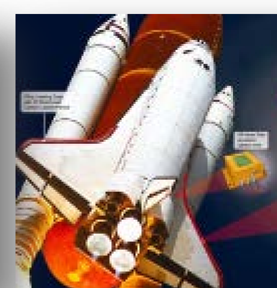


<u>Enabling Technologies</u>

Advanced Sensing
- Multi-parameter
- Sensor arrays

Advanced Systems and Processing
- Solid state
- Rugged
- High Speed

Ultra-Efficient Algorithms



Fiber Optic Sensors - Benefits & Challenges

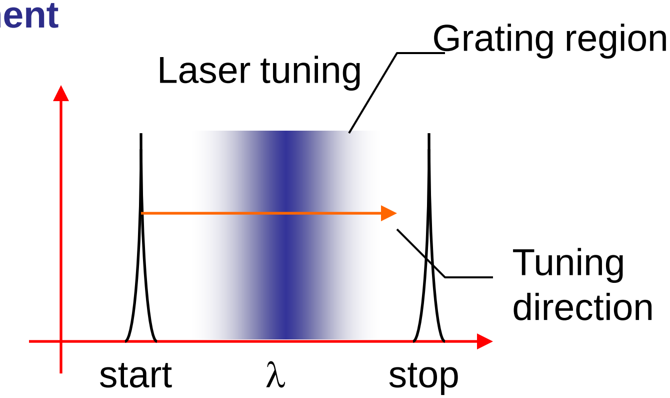
National Aeronautics and Space Administration

- **Benefits**
  - **Direct weight savings**
    - Fiber optic sensors are ~***100x*** lighter than conventional strain gage wiring based on a projected application
    - Fiber optic sensors ~***1000x*** lighter than conventional strain gage wiring for ARMD SFW application
  - **Indirect weight savings**
    - Improved designed tool / model validation
      - Increased data enables improved model and system verification and validation for a wider range of circumstances
      - Highly multiplexed fiber optic sensors provide “finite-element-like” spatial resolution in real-time
  - **Increased channel counts**
    - Fiber optic sensors system can also provide >***100x*** the number of conventional strain/temperature measurements at ***1/100*** the total sensor weight
- **Challenges**
  - Fiber optic systems, which can measure strain, temperature, structural shape, and loads, are currently limited to data rates of ~100 samples/sec
  - Acceptance of FOSS limited by conventional thinking

Fiber Optic System Operation Overview

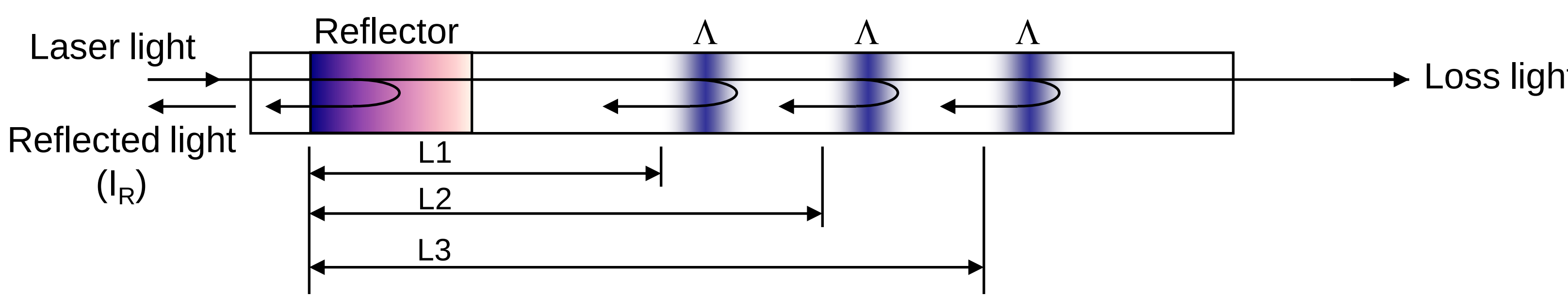
Fiber Optic Sensing with Fiber Bragg Gratings

- **Immune to electromagnetic / radio-frequency interference and radiation**
- **Lightweight fiber-optic sensors are amenable for embedment within composite structures**
- **Multiplex 100s of sensors onto one optical fiber**
- **Fiber gratings are written at the same wavelength**
- **Uses a narrowband wavelength tunable laser source to interrogate sensors**
- **Typically easier to install than conventional strain sensors**
- **In addition to measuring strain and temperature these sensors can be use to determine shape**

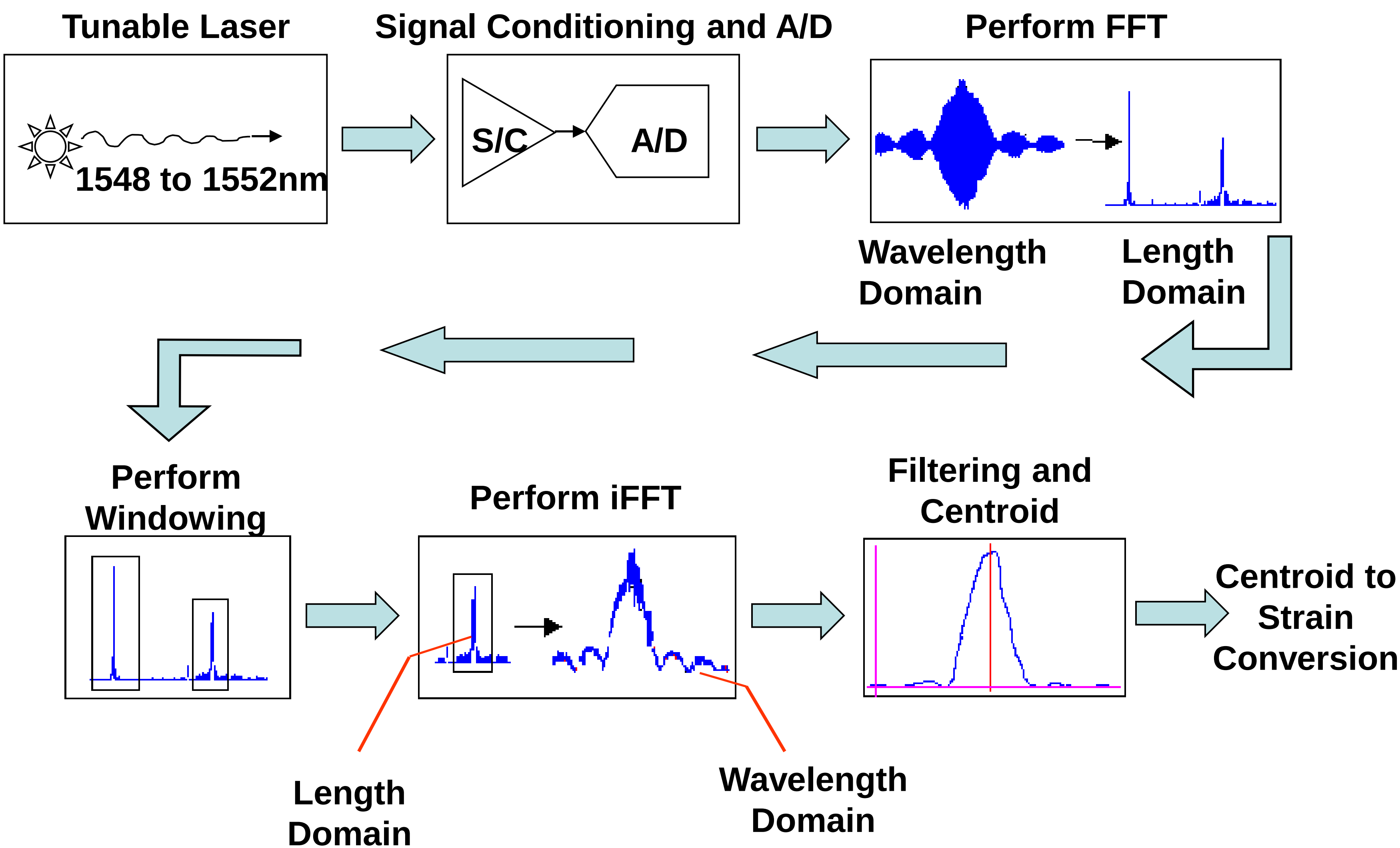


$$I_R = \sum_i R_i Cos(k2nL_i) \qquad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i^{th} grating
n – effective index
L – path difference
k – wavenumber



Interrogation Process



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Derived Parameter Development

Shape Sensing

Helios wing dihedral on takeoff

In-flight breakup

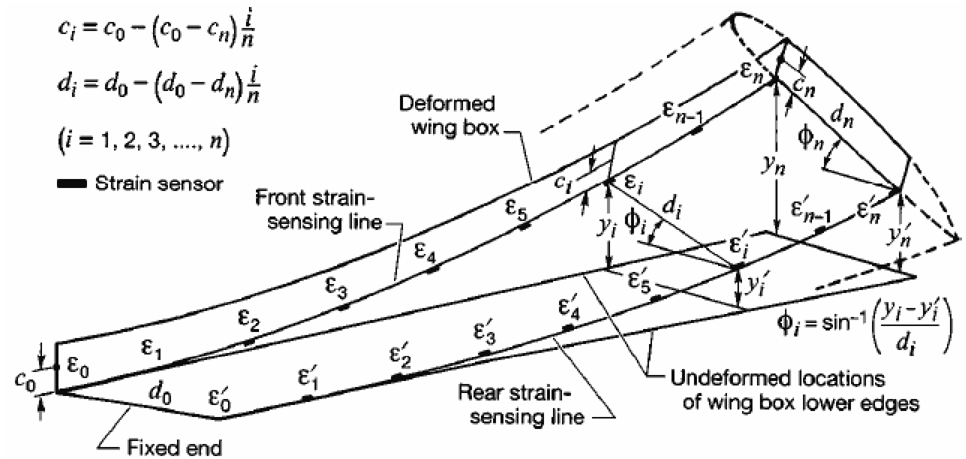
Helios Mishap Report – Lessons Learned

- **Measurement of wing dihedral in *real-time* should be accomplished with a visual display of results available to the test crew during flight**
- **Procedure to control wing dihedral in flight is necessary for the Helios class of vehicle**

Derived Parameter Development

Shape Sensing Formulation

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI}$$



Deflection of a Single Fiber:

$$y_i = \frac{(\Delta l)_i^2}{6c_{i-1}}\left[\left(3 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + y_{i-1} + (\Delta l)_i \underbrace{\tan\theta_{i-1}}$$

Slope:

$$\overbrace{\tan\theta_i} = \frac{(\Delta l)_i}{2c_{i-1}}\left[\left(2 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + \tan\theta_{i-1}$$

Typically the first station is at the root:

$$y_0 = \tan\theta_0 = 0$$

Derived Parameter Development

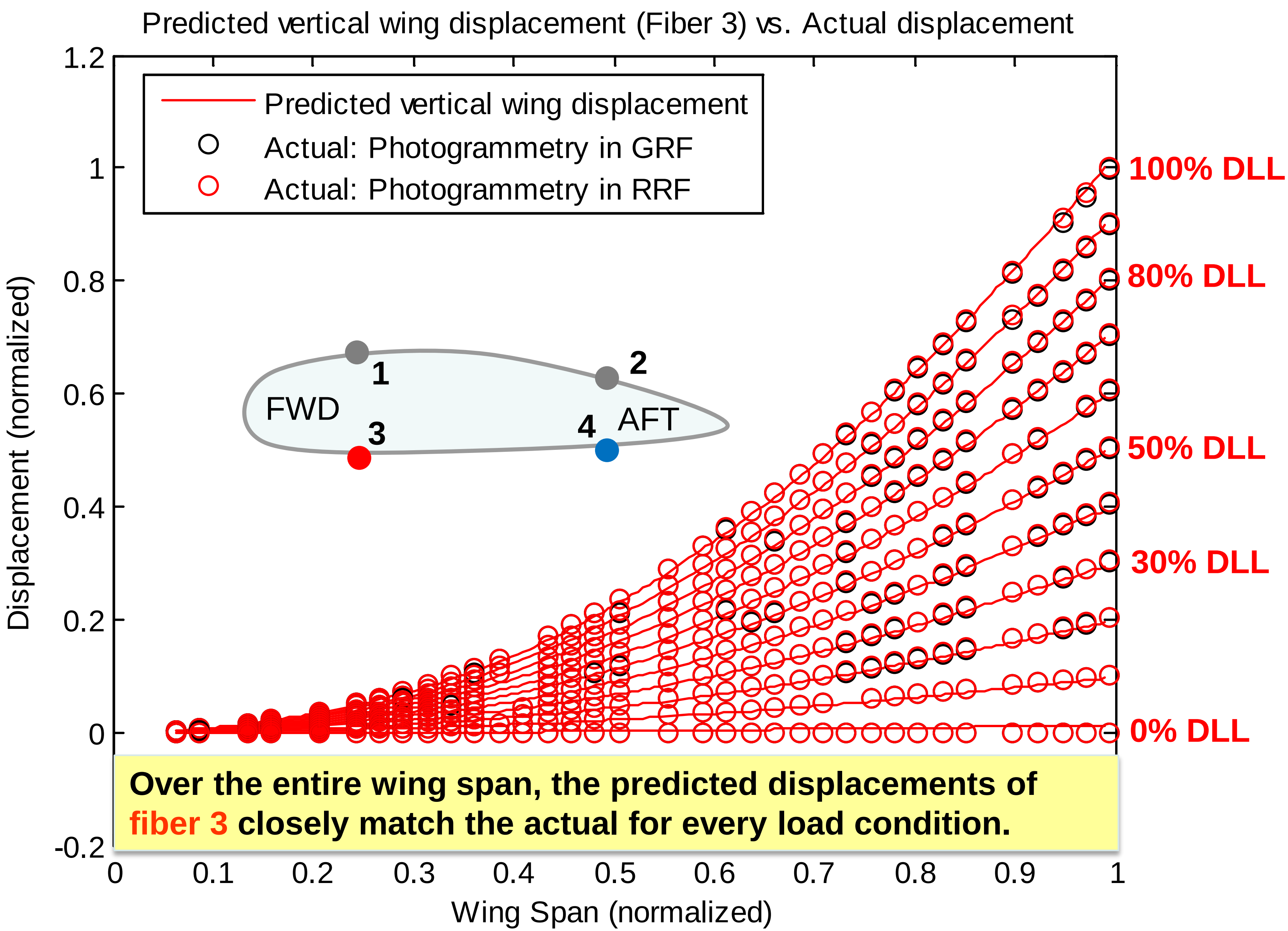
Shape Sensing Validation Testing

- **Strain gages**
  - Validate the FBGs
  - Not used for shape prediction, used for structural evaluation
- **Photogrammetry**
  - Provided validation information for wing shape prediction
  - Measures actual displacement vectors at target points
  - 10 photogrammetry images taken per load condition

175 ft all-composite UAV Wing

Derived Parameter Development

Shape Sensing Validation Test Results



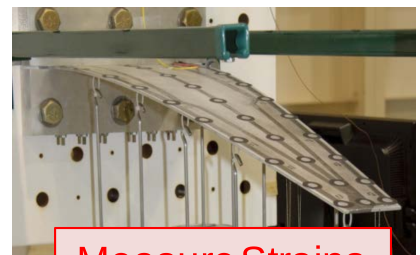
Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.

Derived Parameter Development

External Structural Loads

- **Bending moment calculated at each analysis station**
- **Cross-sectional properties calculated by applying known load**
  - EI/c term backed out at each evaluation station
- **With properties known, strain can be directly related to bending moment**

Operational Loads

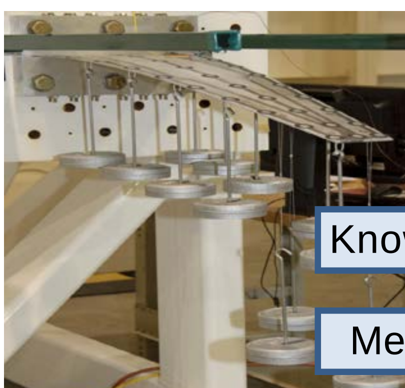


Measure Strains

$$\left(\frac{EI}{c}\right)\cdot\varepsilon=\underline{M}$$

Calculate moment at each station

Calibration Load



Known Moments

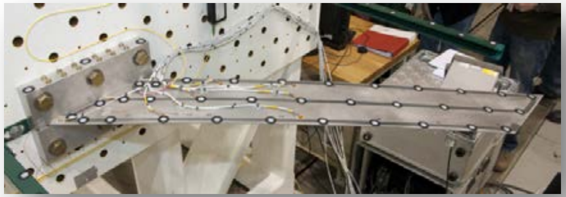
Measure Strains

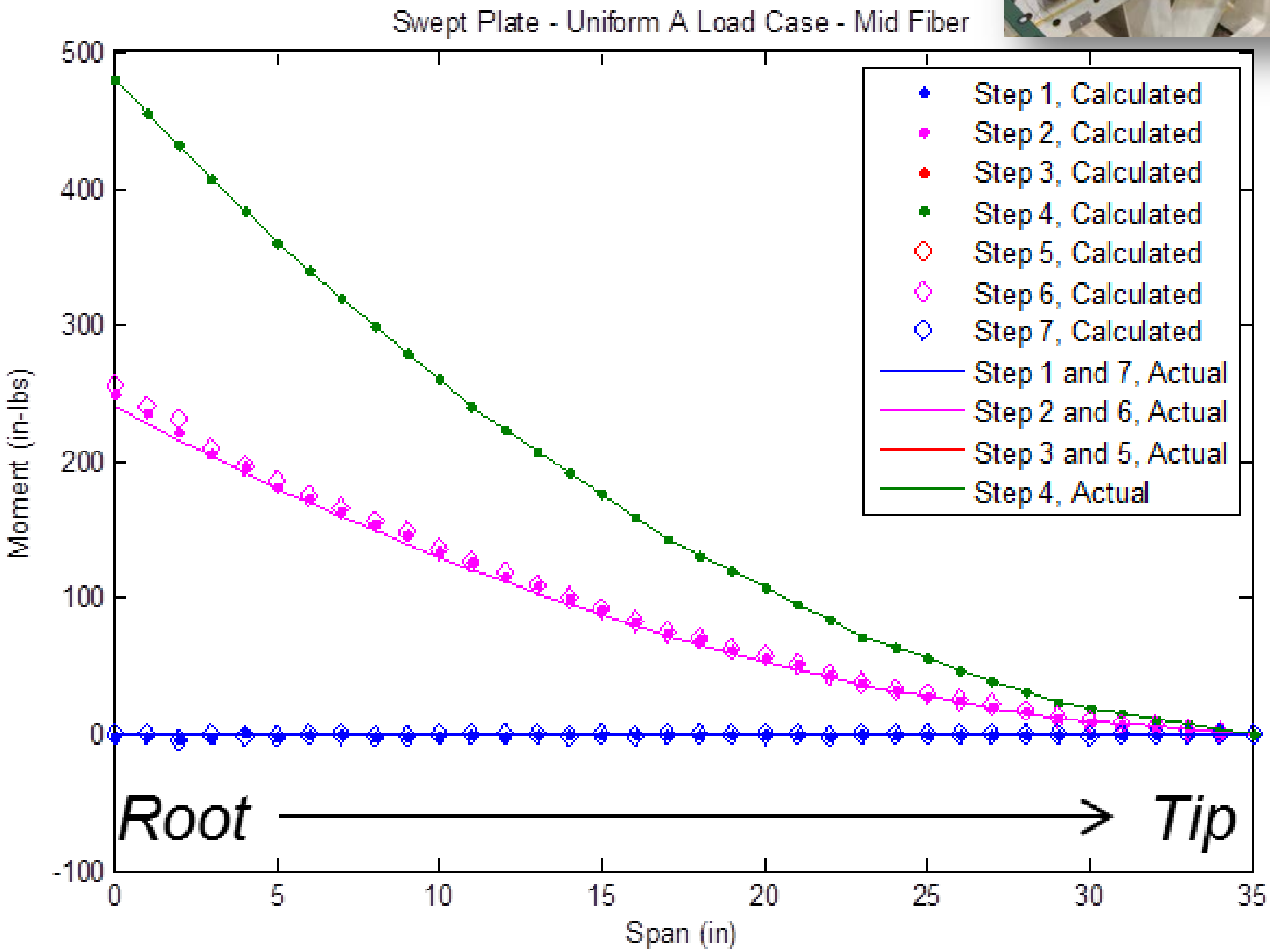
$$\frac{M}{\varepsilon}=\left(\frac{EI}{c}\right)$$

Properties at each station

Derived Parameter Development

Small Monolithic Flat Plate Validation Testing





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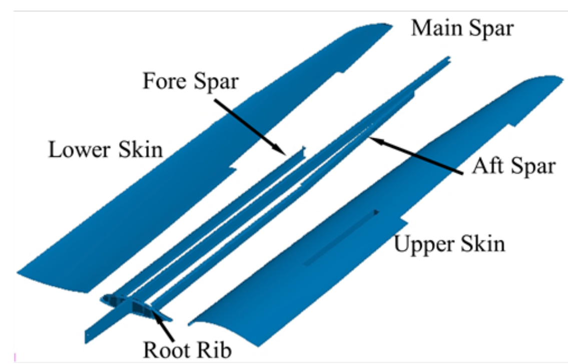
Derived Parameter Development
Large-Scale Composite Wings - Mississippi State Univ

ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.

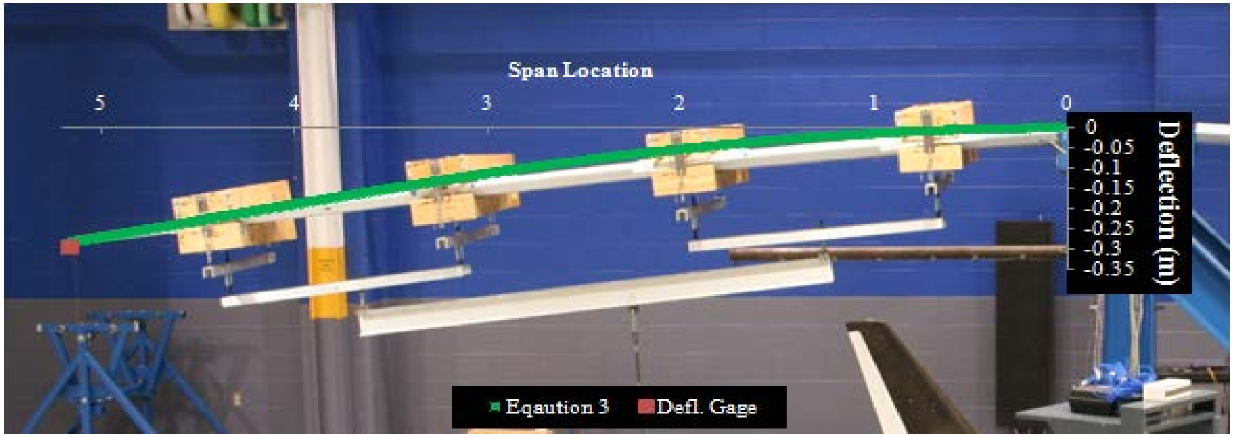
Material Properties	Woven fabric Toray-T700G	Unidirectional fabric Toray-T700S	Foam core DIAB Divinycell HT 50
E_{11}, GPa	5.54×10^{1}	1.19×10^{2}	8.50×10^{-2}
E_{22}, GPa	5.54×10^{1}	9.31×10^{0}	--
G_{12}, GPa	4.21×10^{0}	4.21×10^{0}	--
ν_{12}	3.00×10^{-2}	3.10×10^{-1}	3.20×10^{-1}
ρ, kg/m^3	1.49×10^{3}	1.52×10^{3}	4.95×10^{-1}



National Aeronautics and Space Administration

Derived Parameter Development

Large-Scale Composite Wings - Mississippi State Univ



MEASURED AND CALCULATED WING TIP DEFLECTIONS

F, N	Measured δ_L, m	Calculated δ_L, m	Error, %
1373	-0.184	-0.178	**3.02**
1592	-0.209	-0.205	**2.29**
1837	-0.241	-0.231	**4.08**
2036	-0.265	-0.257	**3.23**
2269	-0.295	-0.284	**3.75**

OUT-OF-PLANE APPLIED LOAD

Applied Load, N	Calculated Load, N	Error, %	Difference, N
-185.5	-178.8	**3.60**	6.7
-194.4	-210.0	**7.98**	15.5
-241.5	-252.0	**4.35**	10.5
-288.5	-291.5	**1.05**	3.0
-333.3	-332.9	**0.12**	0.4
-378.1	-381.1	**0.80**	3.0
-422.9	-435.9	**3.07**	13.0
-472.2	-486.4	**3.01**	14.2
Average EI=98728.2-N*m^2			

Test Procedure for displacement

- Collect FBG strain data
- Use displacement Eq. and Strain data to calculate deflection

Test procedure for out-of-plane loads

- Determine EI for the wing.
- Determine moment acting on wing.
- Determine Load applied.

$$EI = \frac{P * x * c}{\epsilon} \qquad M = \frac{\epsilon * EI}{c} \qquad P = \frac{M}{x}$$

Derived Shape and Load Parameters

Conclusions

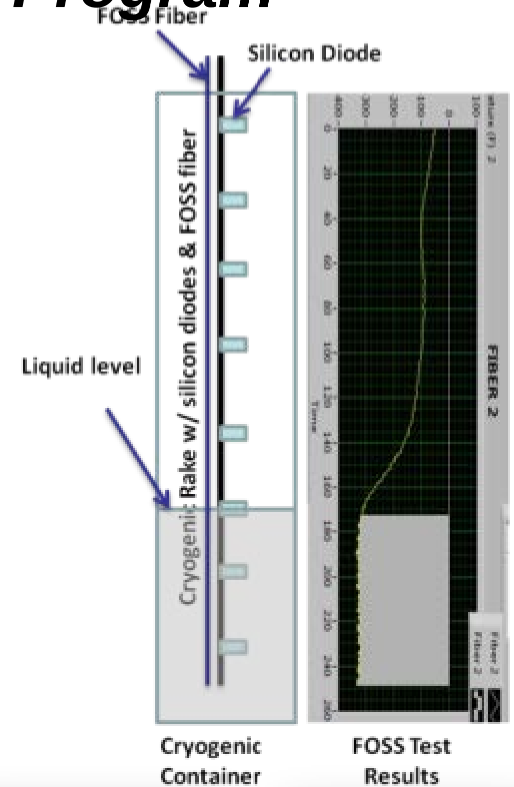
- **Deflection calculations are accurate for most cases**
  - Different test articles
  - Different load cases
  - Different load magnitudes
- **Load results will be improved**
  - Least-squares method
- **Developing methods to further use FOSS measurements**
  - Angle-of-twist
  - Improved deflection and load
  - Torque

National Aeronautics and Space Administration

Fiber Optic Cryogenic Liquid Level Sensing

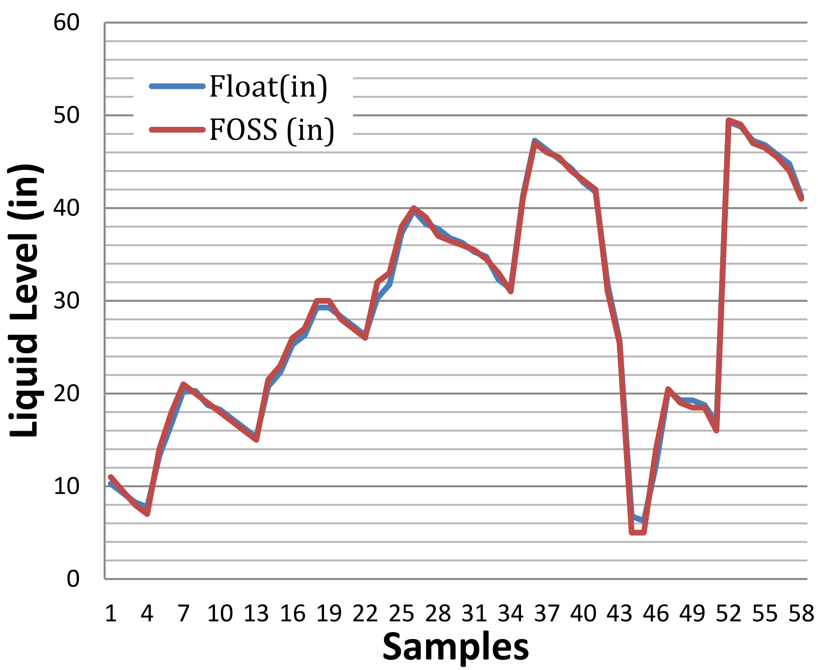
NASA KSC – Launch Services Program

- **The Challenge**
  - The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements
  - Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level ***and not suitable for flight***
- **FOSS Approach**
  - By exciting the fiber, the transitional phase can be mapped better
  - Using a single continuous grating fiber high spatial resolution can be achieved
  - In conjunction with the continuous grating fiber, Dryden's adaptive spatial density algorithm can resolve even higher spatial resolution targeting in the region where the actual level is located
- **Applications:**
  - Launch vehicles, Satellites, Space vehicles, Ground Testing, COPV bottles
- **Status: LN_2Testing Complete at MSFC, 8/2011**
  - Good correlation between fiber optic temperature sensor and conventional ground based system
  - Preparing for LH_2 Testing in May 2012



Cryogenic Container located at MSFC (above deck)

Cryogenic Container located at MSFC (below deck)


60
50
40
30
20
10
0
Float(in)
FOSS (in)
Liquid Level (in)
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Samples

LH_2 Liquid Level Sensor – CryoFOSS

NASA KSC / MSFC

Objective

- Experimentally validate Dryden-developed LH_2 liquid level sensor (cryo-FOSS) using Dryden's fiber optic strain system (FOSS) technology

Test Details

- Dewar dimensions: 13-in ID x 37.25-in
- Fill levels of ~20%, 43%, and 60% were performed
- Instrumentation systems
  - Video boroscope (validating standard)
  - Cyrotracker (ribbon of 1-in spaced silicon diodes)
  - MSFC Silicon diode rake
  - Fiber optic LH_2 liquid level sensor

Results

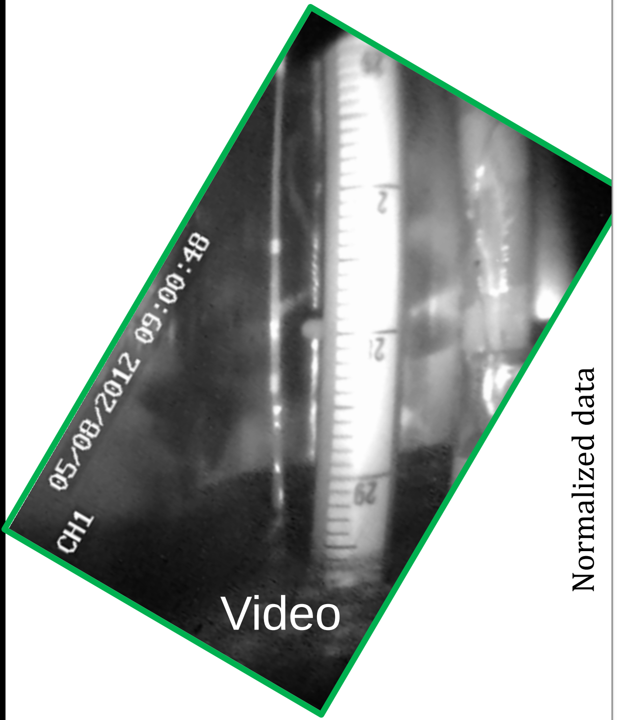
- Cryo-FOSS sensor discerned LH_2 level to approx. ¼-in in every case
- Excellent agreement achieved between cryo-FOSS, boroscope, and silicon diode cryotracker

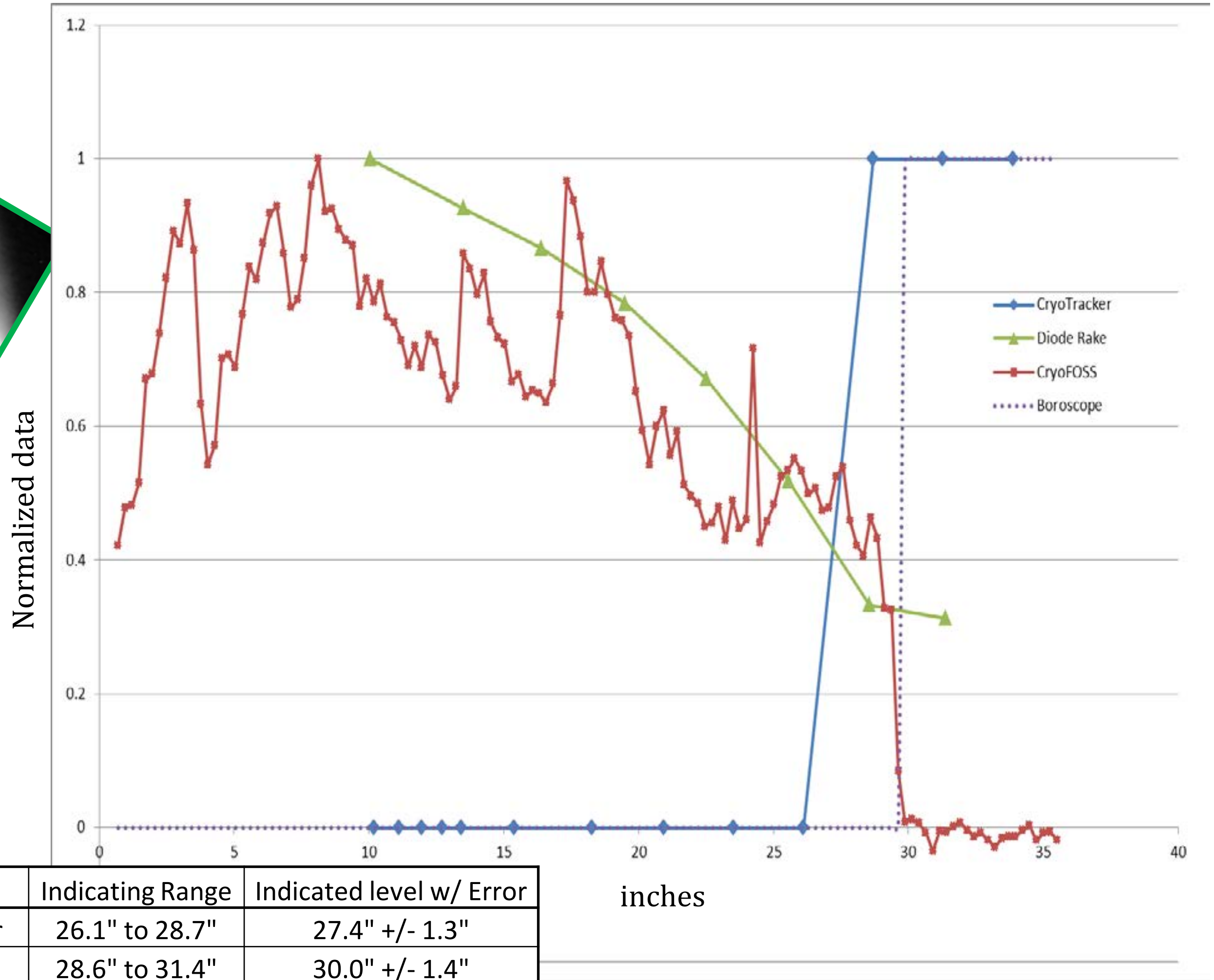
Bottom line

- Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for the ground- and in-flight cryogenic fluid management of launch vehicles in the future

A NASA New Technology Report (NTR) has been filed for the cryogenic liquid level measurement method described in this technical paper (or presentation) and are therefore protected. Those interested in using the method should contact the NASA Innovative Partnership Program Office at NASA Dryden Flight Research Center for more information

LH_2 20% Fill Level (29.6”)

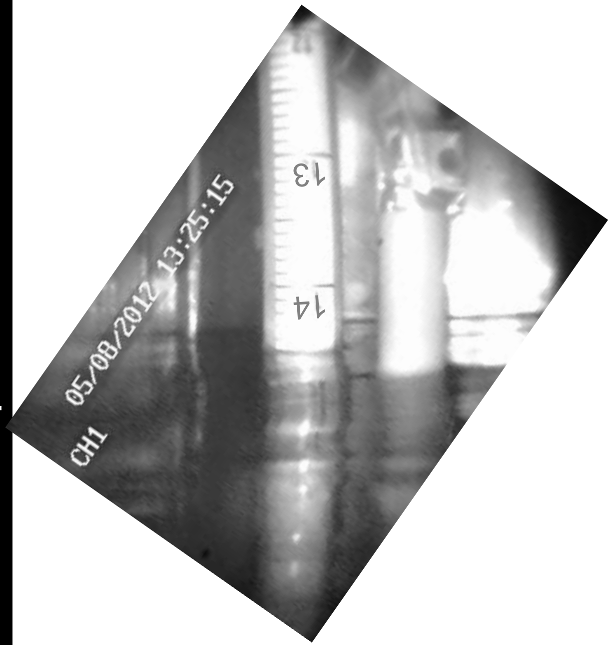




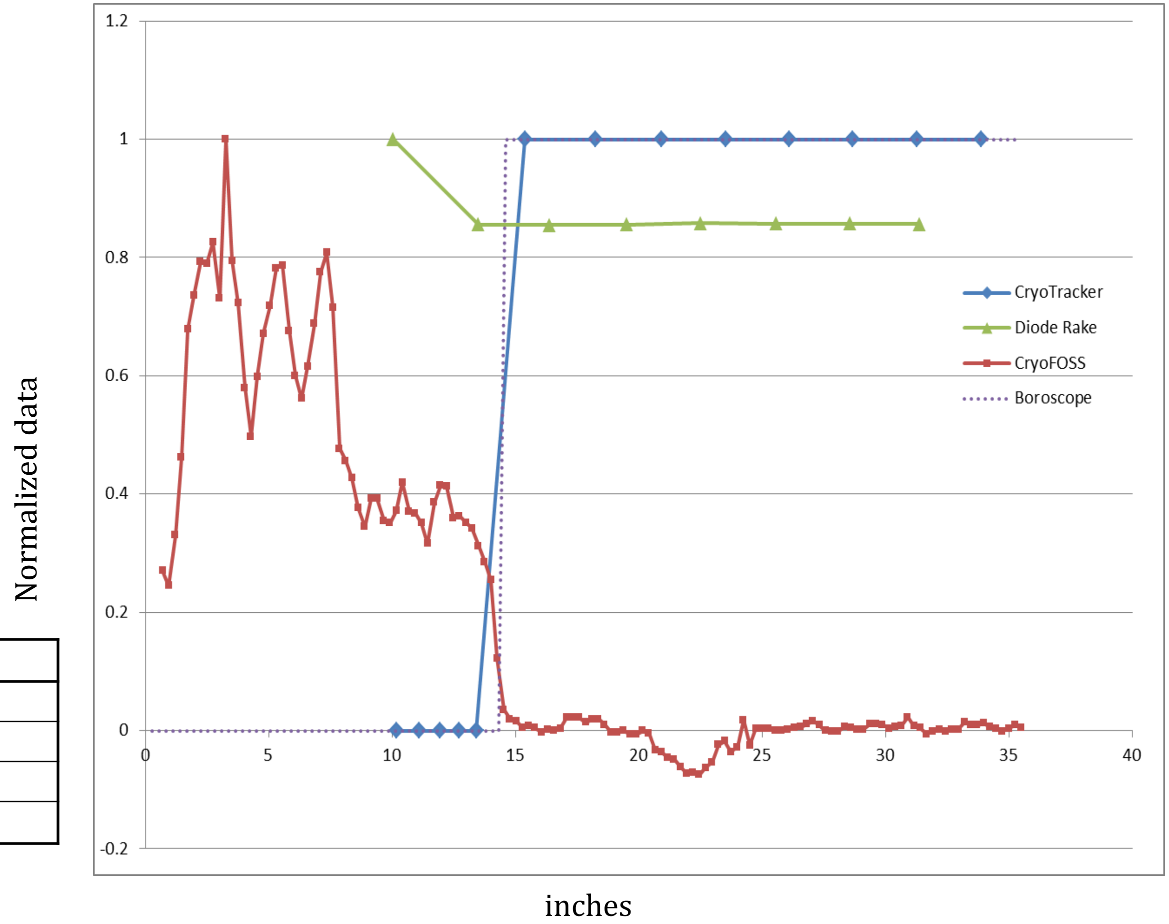
device	Indicating Range	Indicated level w/ Error
CryoTracker	26.1" to 28.7"	27.4" +/- 1.3"
Diode Rake	28.6" to 31.4"	30.0" +/- 1.4"
CryoFOSS	29.4" to 29.6"	29.5" +/- 0.13"
Boroscope	29.6"	29.6"

A NASA New Technology Report (NTR) has been filed for the cryogenic liquid level measurement method described in this technical paper (or presentation) and are therefore protected. Those interested in using the method should contact the NASA Innovative Partnership Program Office at NASA Dryden Flight Research Center for more information

LH_2 61% Fill Level (14.5”)

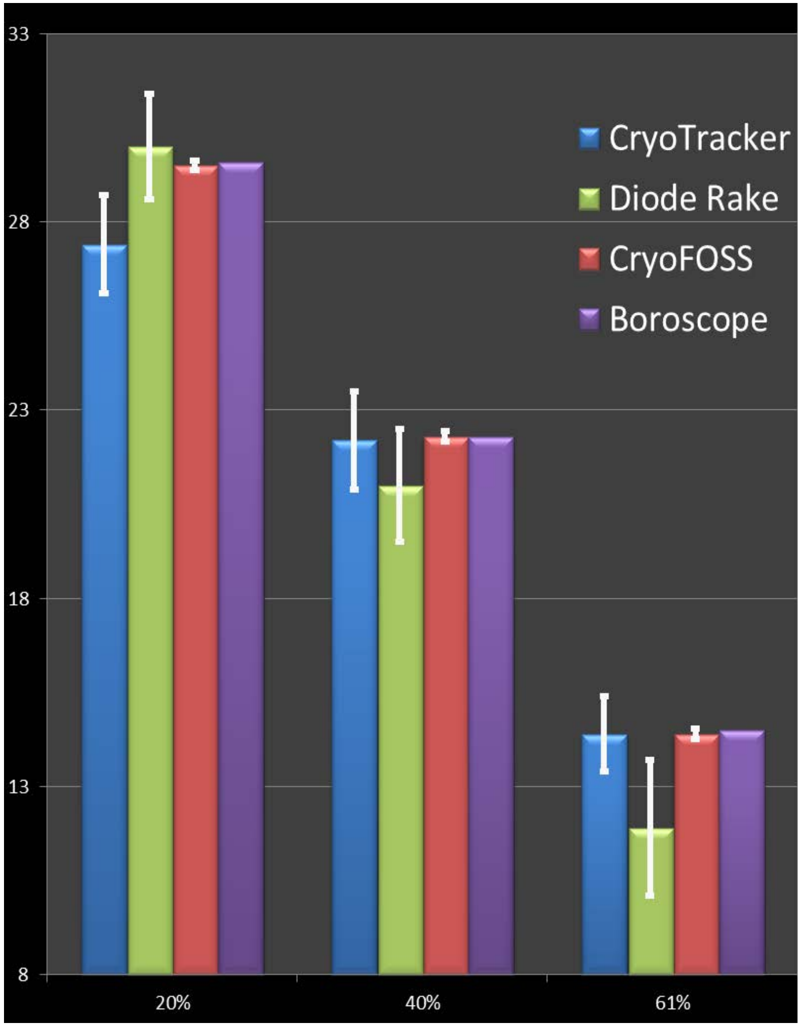


device	Indicating Range	Indicated level
CryoTracker	13.4" to 15.4"	14.4" +/- 1.0"
Diode Rake	10.1" to 13.5"	11.9" +/- 1.8"
CryoFOSS	14.3" to 14.5"	14.4" +/- 0.13"
Boroscope	14.5"	14.5"

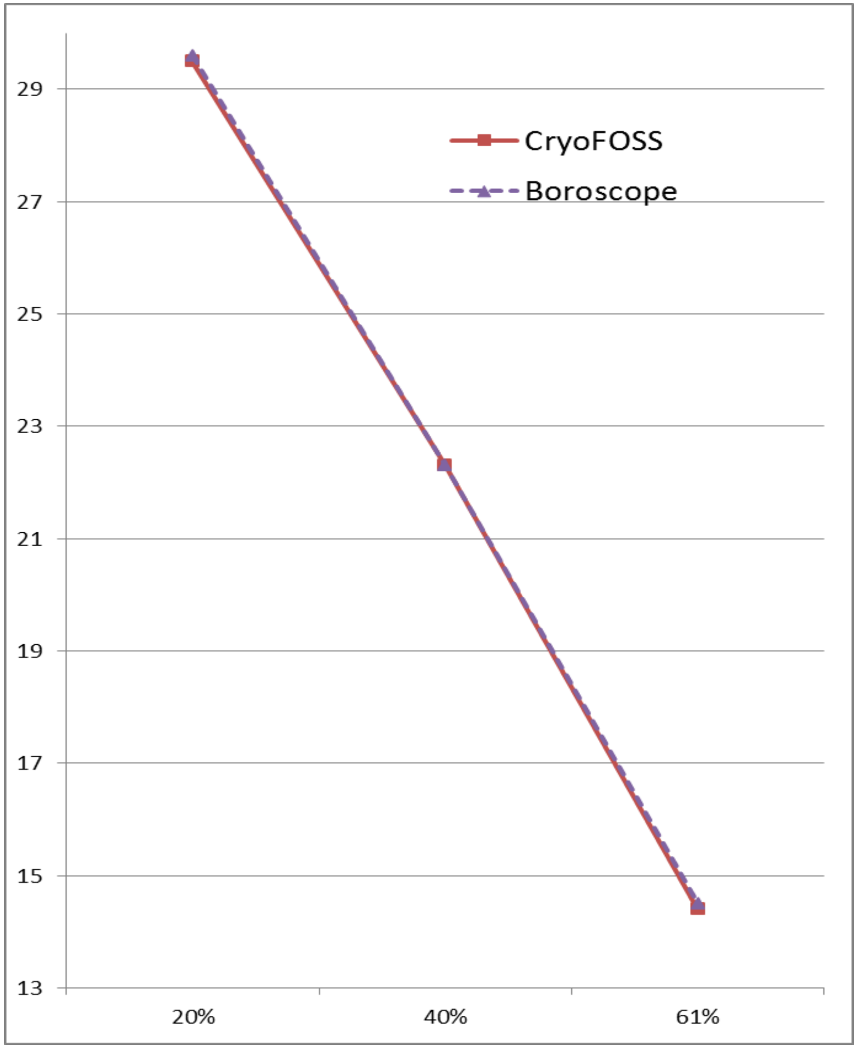


A NASA New Technology Report (NTR) has been filed for the cryogenic liquid level measurement method described in this technical paper (or presentation) and are therefore protected. Those interested in using the method should contact the NASA Innovative Partnership Program Office at NASA Dryden Flight Research Center for more information

LH_2 Overall Results



Combined Results



CryoFOSS compared to Boroscope

A NASA New Technology Report (NTR) has been filed for the cryogenic liquid level measurement method described in this technical paper (or presentation) and are therefore protected. Those interested in using the method should contact the NASA Innovative Partnership Program Office at NASA Dryden Flight Research Center for more information

Legacy Systems
4 Fiber Flight Interrogation System

- **Current flight system specifications**
  - Fiber count — 4
  - Max fiber length — 40 ft
  - Max sensing length — 20 ft
  - Max sensors / fiber — 480
  - Total sensors / system — 1920
  - Sample rate — 2 fibers @ 50 sps; 4 fibers @ 30 sps
  - Power (flight) — 28VDC @ 3 Amps
  - User Interface — Ethernet
  - Weight (flight, non-optimized) — 23 lbs
  - Size (flight, non-optimized) — 7.5 x 13 x 13 in
- **Environmental qualification specifications for flight system**
  - Shock — 8g
  - Vibration — 1.1 g-peak sinusoidal curve
  - Altitude — 60kft at -56C for 60 min
  - Temperature — -56 < T < 40C

Flight System

Ground System

Ikhana in Flight

Legacy Systems

8 Fiber Flight Interrogation System

- **Current flight system specifications**
  - Fiber count 8
  - Max fiber length 80 ft
  - Max sensing length 40 ft
  - Max sensors / fiber 960
  - Total sensors / system 7680
  - Sample rate 8 fibers @ 60 sps

  - Power (flight) 28VDC @ 5 Amps
  - User Interface Ethernet
  - Weight (flight, non-optimized) 29 lbs
  - Size (flight, non-optimized) 7.5 x 13 x 17 in
- **Environmental qualification specifications for flight system**
  - Shock 8g
  - Vibration 1.1 g-peak sinusoidal curve
  - Altitude 25kft at -56C for 60 min
  - Temperature -56 < T < 40C

Flight System

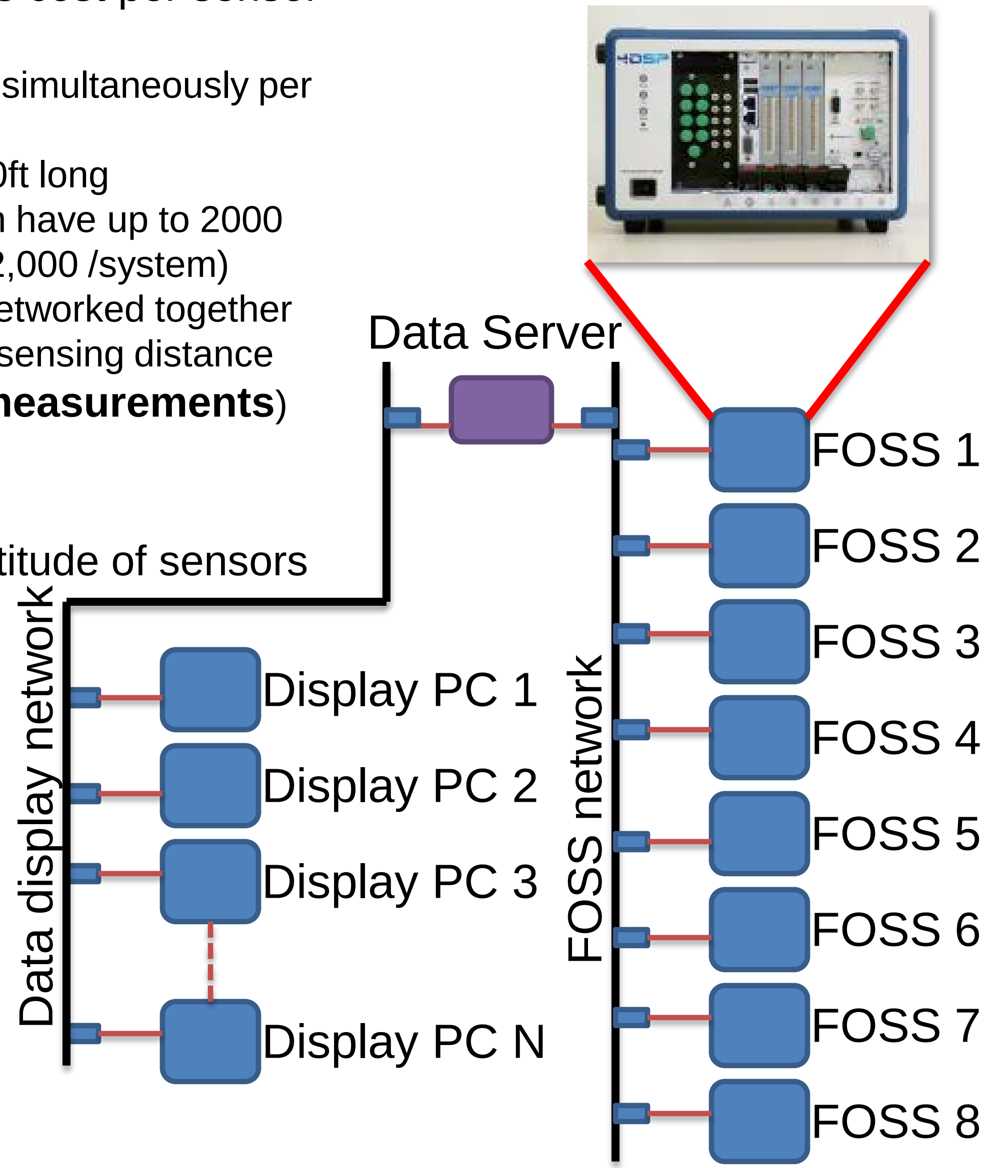
Ground System

National Aeronautics and Space Administration

Large Scale FOSS (LsFOSS) Technology

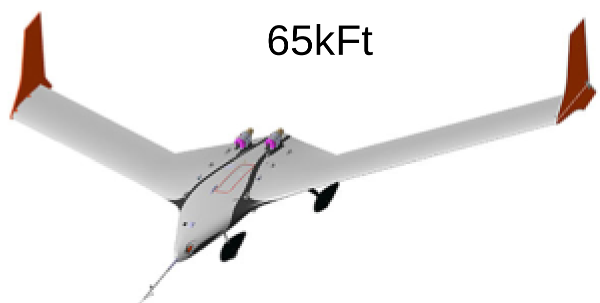
- **Technical Highlights**
  - Single laser greatly reduces cost per sensor
  - High fiber count systems
    - Up to 16 fibers monitored simultaneously per system
    - Each fiber can be up to 40ft long
    - Each fiber at 40ft long can have up to 2000 measurements (total of 32,000 /system)
    - Up to 8 systems can be networked together yielding approx. 1 mile of sensing distance (1/4" spacing, **256,000 measurements**)
  - 11" x 7" x 12"
  - 100 Hz max sample rate
  - Lightweight system for multitude of sensors

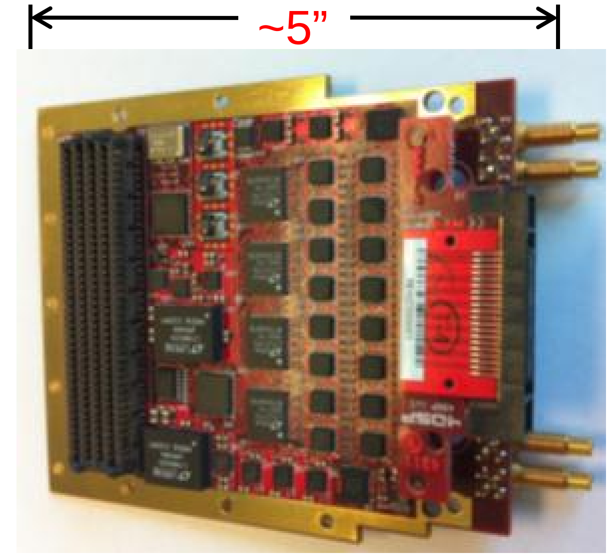
- **Applications:**
  - Transport Aircraft
  - Ships
  - Civil Structures
  - Ground Testing
  - Structures Laboratory



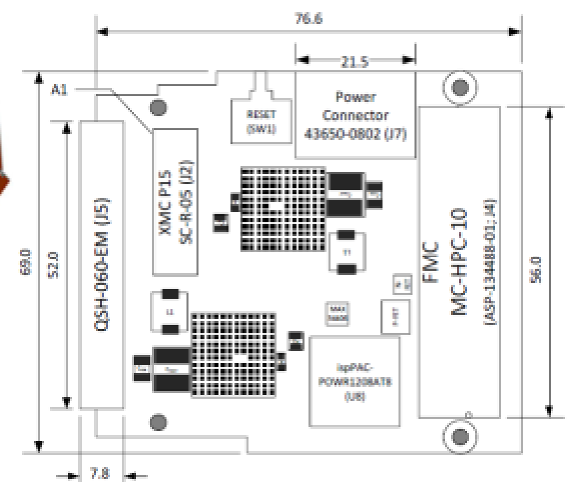
Current cFOSS Target System Specs.

- **Lightweight, ruggedized system**
  - Packaged within a 6” cube
- **Targeted specifications:**
  - Fiber count: 16
  - Max Fiber length: 80 ft
  - Max # sensors/system: 30,720
  - Max Sample rate: 100 Hz
  - Power: 50W @ 28Vdc
  - Weight: <10 lbs
  - Size: 5 x 6 x 6 in
  - Vibration and Shock: (DCP-O-018) NASA Curve B
  - Altitude: 65kFt
- **Applications:**
  - Launch vehicles
  - Fighter aircraft
  - UAVs
  - Spacecraft
- **Target system cost: $45K**
- **Availability: End of 2012**





16-Fiber A/D



Power Module

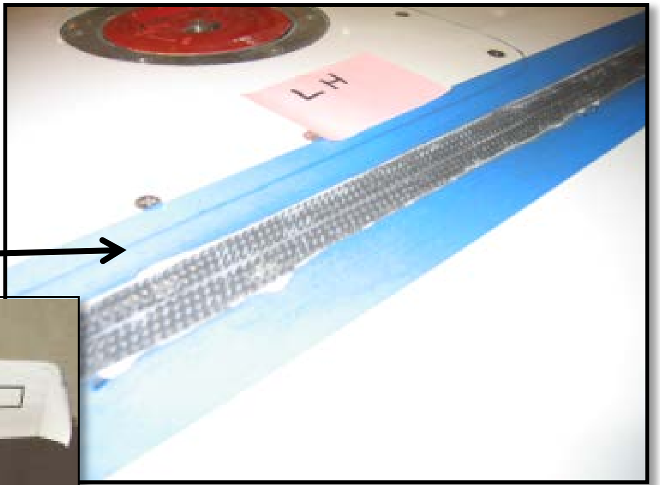
FBG Surface Attachment
Advantages and Challenges

Installation Advantages

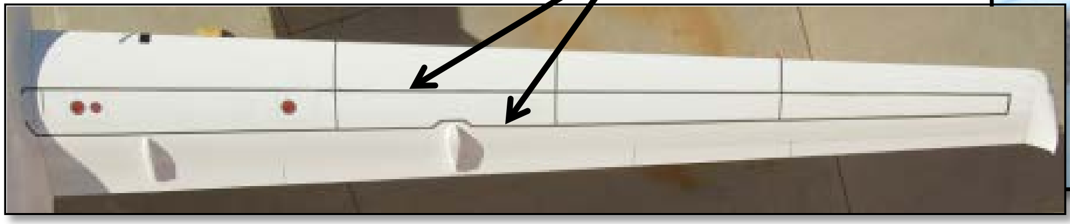
- **Greatly reduced installation time compared to conventional strain gages**
  - 2 man days for 40’ fiber (1000 strain sensors for a continuous surface run)
  - Multiple sensors installed simultaneously
  - Same surface preparation and adhesives as conventional strain gages
  - Minimal time spent working on vehicle
  - All connectors can be added prior to installation, away from part
  - No soldering, no clamping pressure required
  - Circular cross-section eliminates possibility of trapping air between sensor and part (eliminates repeat installations)
- **Can be installed with little or no impact to OML**

Installation Challenges

- **Optical fiber more fragile than conventional strain gages**
- **Some measurement locations not practical due to fiber minimum bend radius**
- **Not practical if only interested in spot measurements**



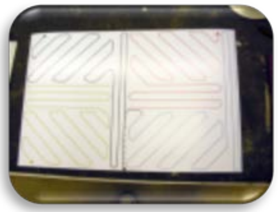
Optical Fiber

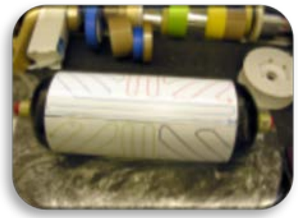
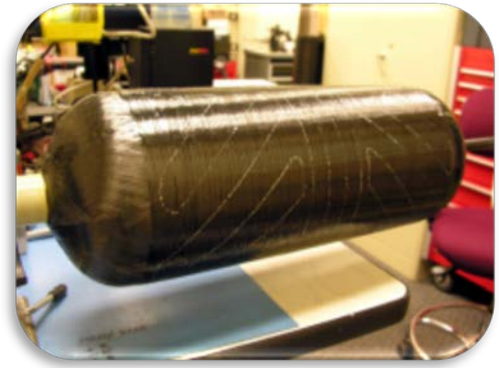


FBG Surface Attachment on COPVs

Installation methods developed

- Transfer pattern to bottle surface

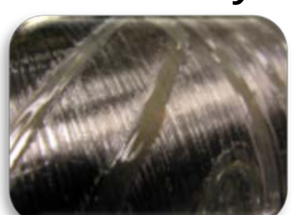


- Mask and fill basecoat paths




- Sand down close to surface layer

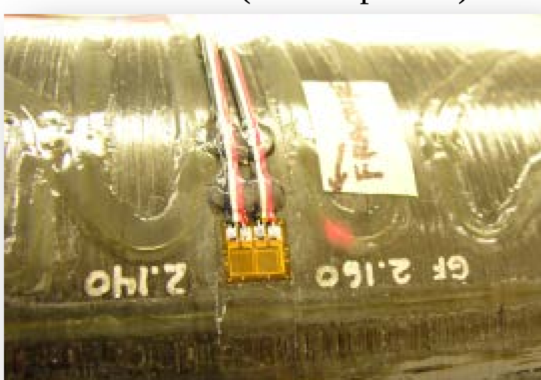
- Rout and attach FBGs

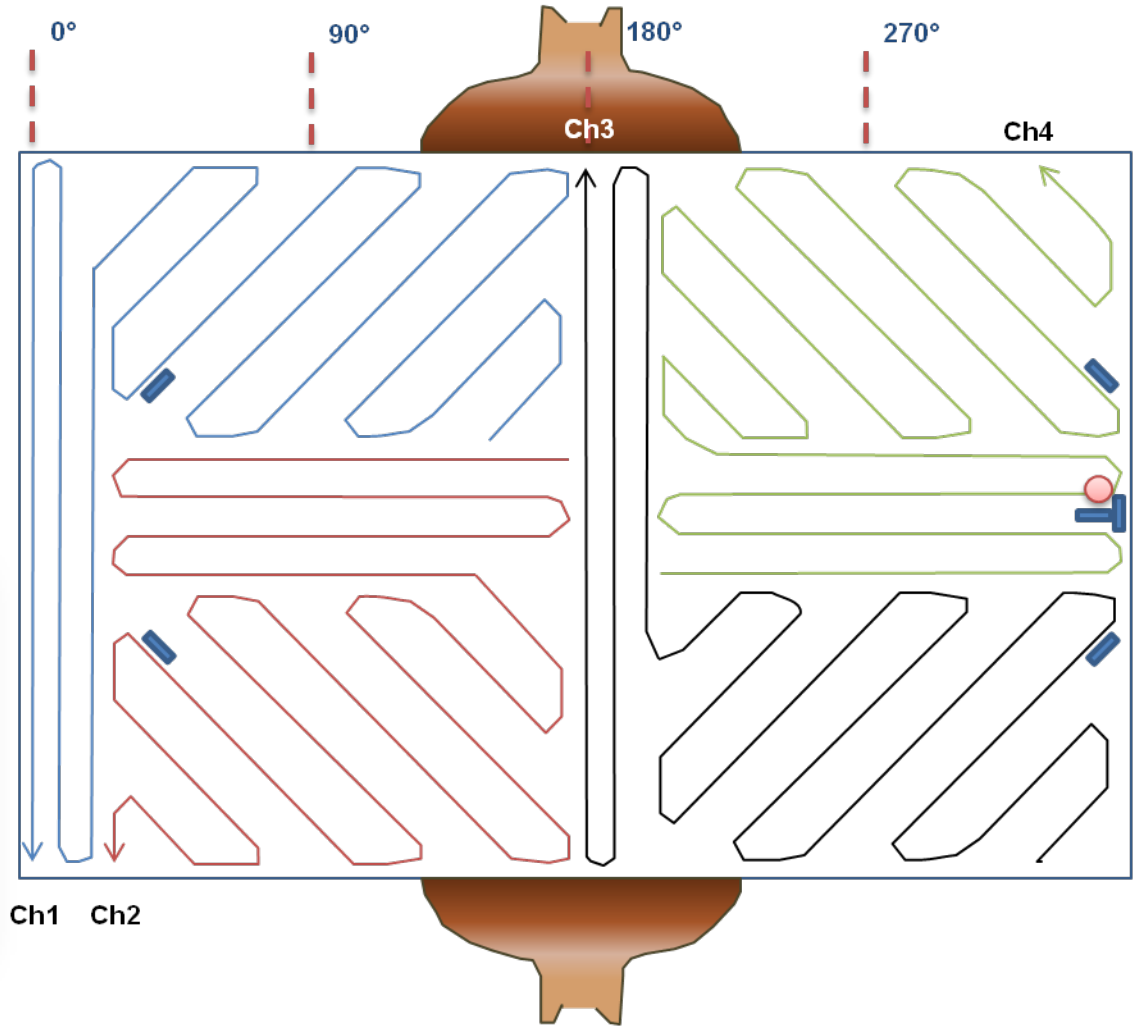
FBG Surface Attachment

GD T1000 Bottle Surface Instrumentation Map

- 4 FBG channels
  ≈ 8-ft (colored lines)
  sample rate = 1/sec
- 6 conventional SGs
  R = 350Ω
  GF = 2.14
  3-leadwire config

Ch4 fracture visible with red laser source (fiber replaced)





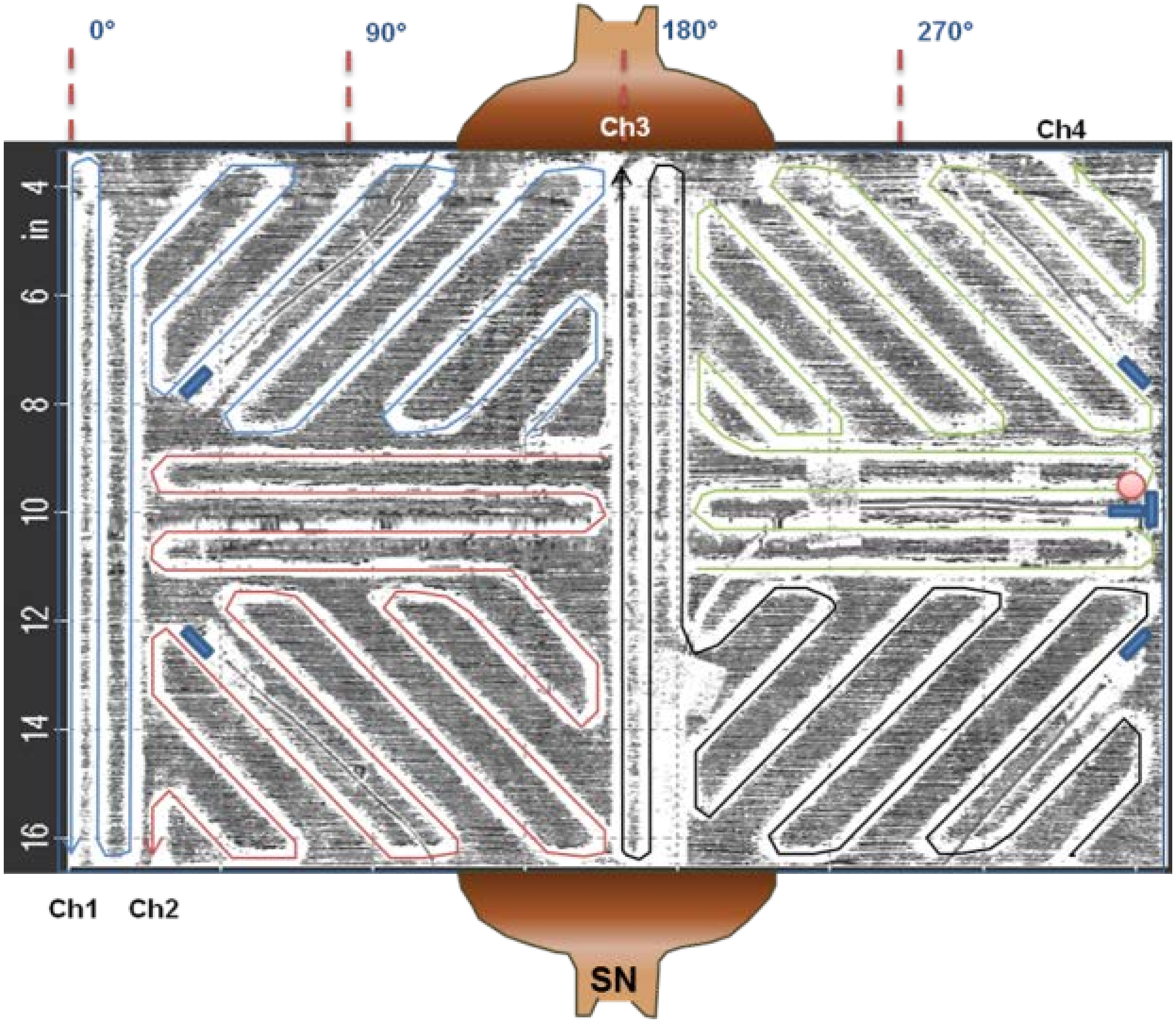
Profilometry Results
White Sands Test Facility

Origin

- SN is at bottom
- Depth axis zeroed at top boss face
- Rotary axis zeroed on left-most run of FBG Ch1 near equator

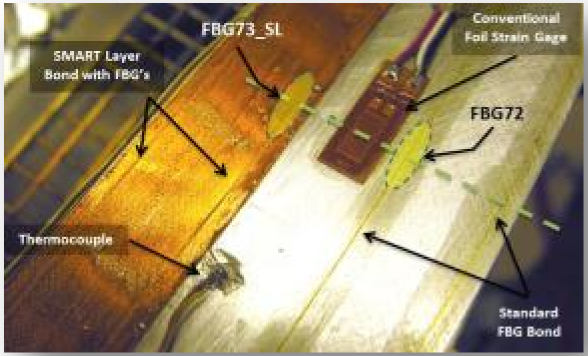
Scan Results:

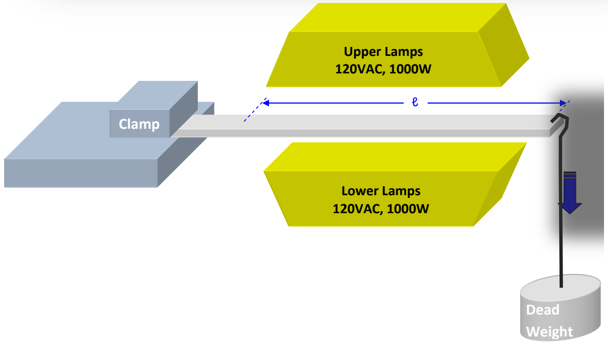
- LVI images were more effective for layout verification than LP
- DFRC's layout matches their instrumentation plan very well



Incorporation of FBGs with Polyimide SMART Layer
Acellent Technologies

- **The Goal**
  - Develop and evaluate techniques for the installation of FBG's in a more simplified and efficient manner than current direct surface bond with epoxy
- **FBG Approach**
  - Develop process to incorporate FBGs into Acellent SMART Layer technology
  - Evaluate methods for adhering SMART Layer to structure for distributed sensing
  - Evaluate any effect on strain transfer or sensitivity under combined thermal-mechanical loads
- **Results**
  - 2-3% agreement with strain gages
  - More robust, sturdy, and protected installation with SMART Layer
- **Applications:**
  - Structural health monitoring
  - Flight control feedback

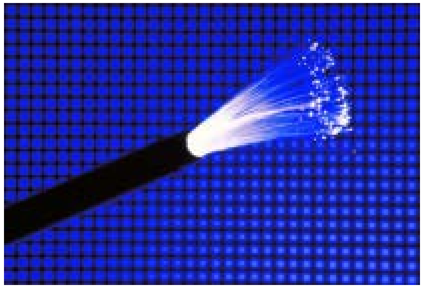


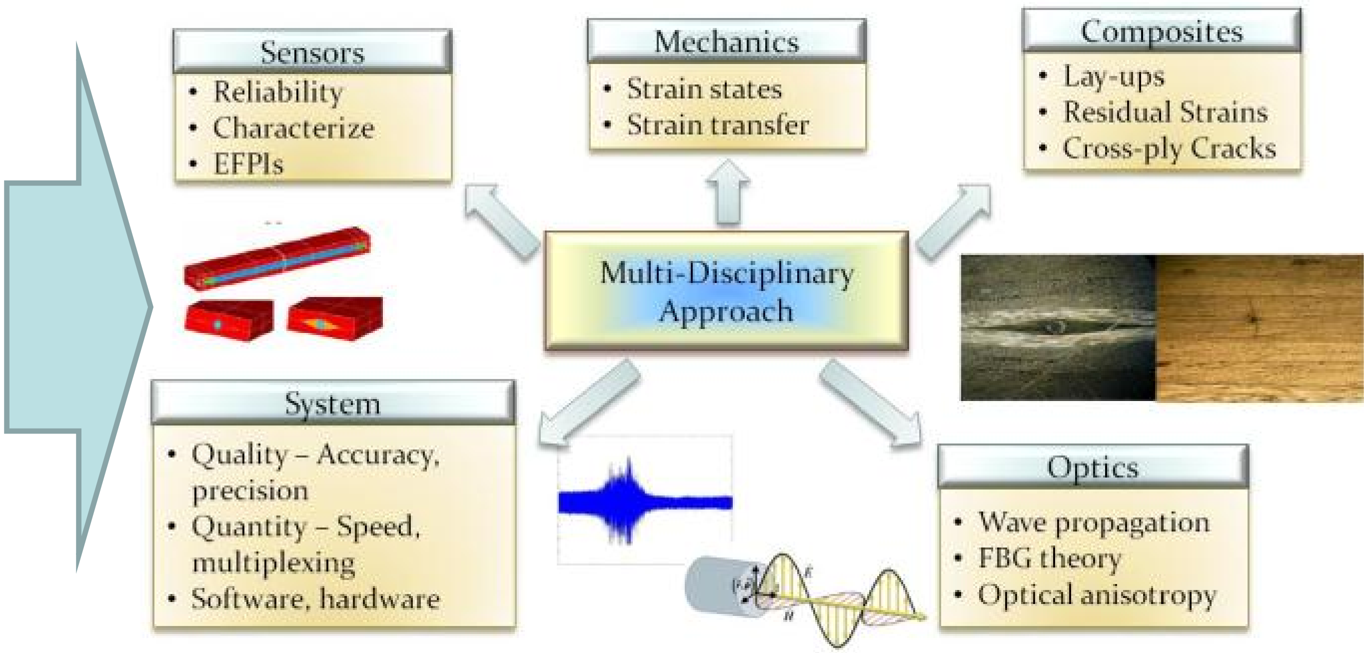


COPV Embedment: the Multidisciplinary Challenge
NASAs NNWG / WSTF / MSFC

- **Fiber Optic Sensors embedded within Composite Overwrapped Pressure Vessels**
- **Goal is to understand embedded FBG sensor response**
  - Requires comprehensive, multi-disciplinary approach

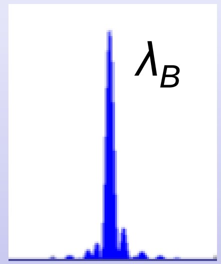
+



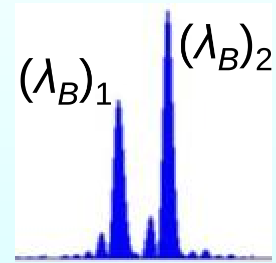


Identifying Birefringence in FBGs

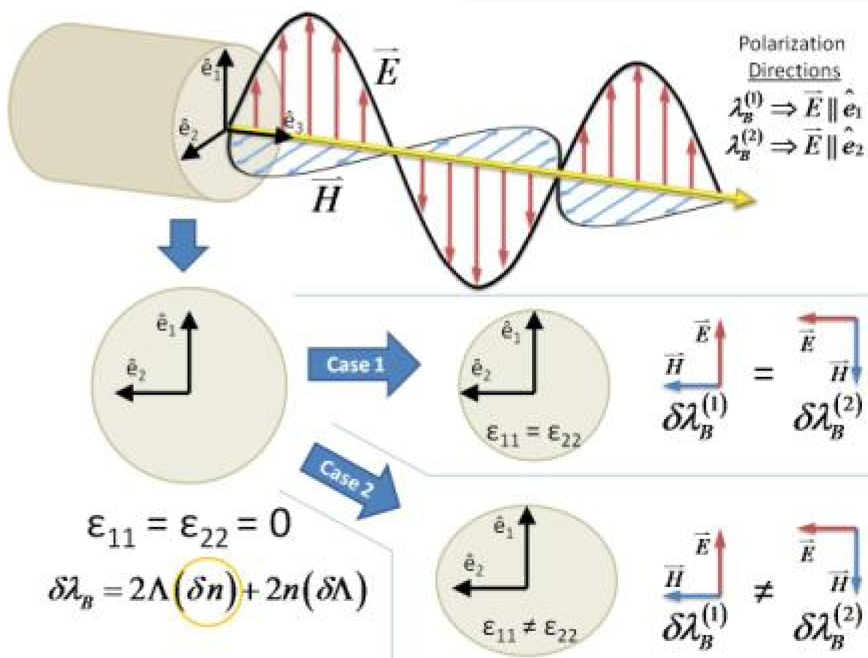
- **What is it?**
  - Splitting of single peak FBG reflection in two
- **What causes it?**
  - Complex strain state
  - Too many unknowns, not enough equations
- **When is it common?**
  - Embedded FBGs
- **How can we use it?**
  - Accuracy of uniaxial strain assumption
  - Signals damage

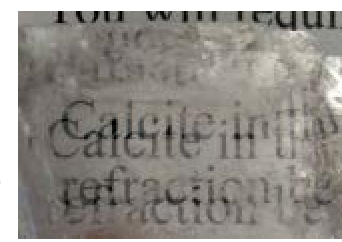


$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - p_e\right)\varepsilon$$



$$\begin{Bmatrix} \left(\dfrac{\Delta\lambda_B}{\lambda_B}\right)_1 \\ \left(\dfrac{\Delta\lambda_B}{\lambda_B}\right)_2 \end{Bmatrix} = \begin{bmatrix} -\dfrac{n^2}{2}p_{11} & -\dfrac{n^2}{2}p_{12} & 1-\dfrac{n^2}{2}p_{12} \\ -\dfrac{n^2}{2}p_{12} & -\dfrac{n^2}{2}p_{11} & 1-\dfrac{n^2}{2}p_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}$$

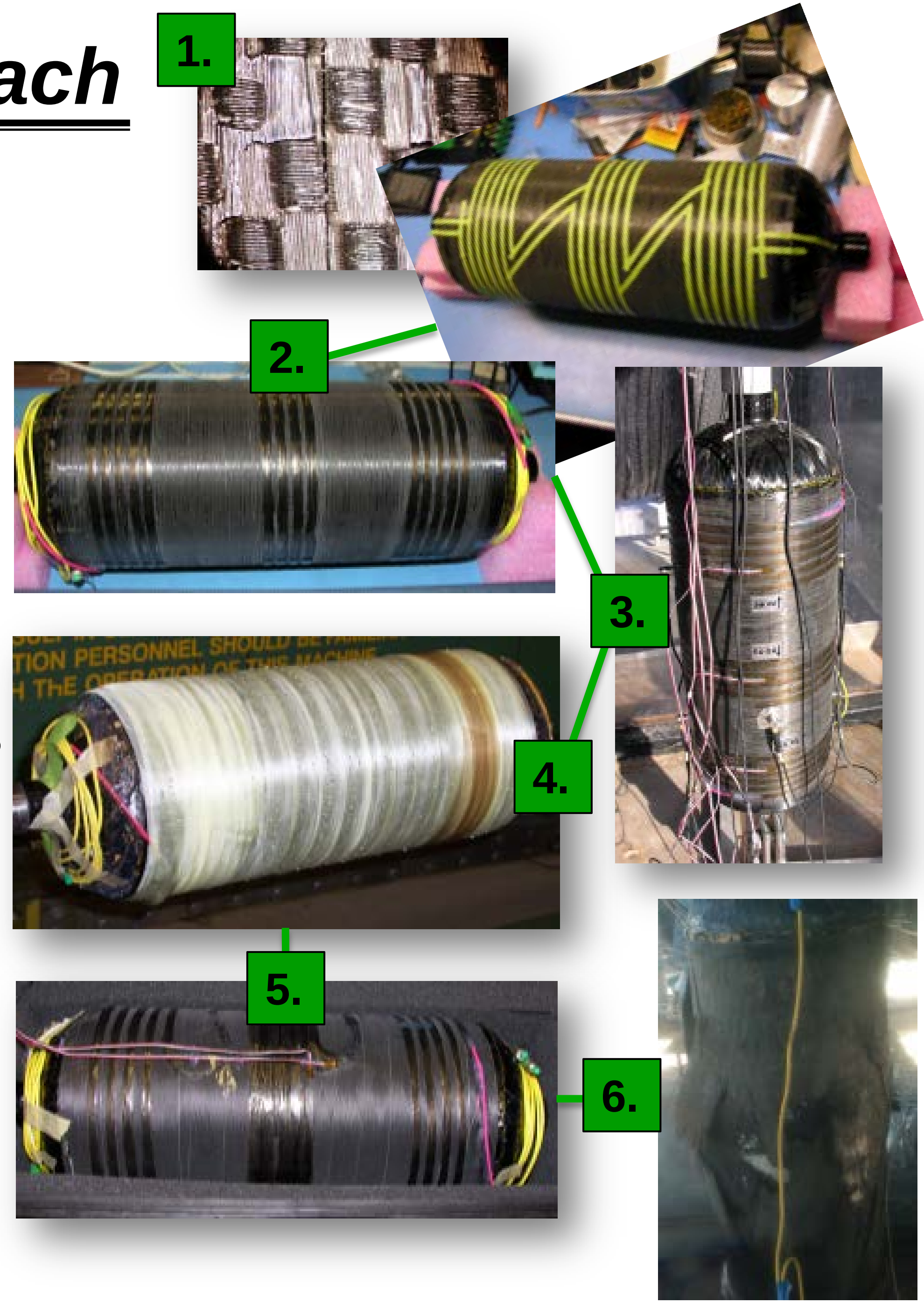




Calcite crystal

Experimental Approach

1. Develop and Test surface-attachment techniques
2. Install surface FBGs
3. Test (non failure)
4. Overwrap surface FBGs
5. Install new surface FBGs over “embedded” FBGs
6. Failure test



Bottle 1 Fiber Layout

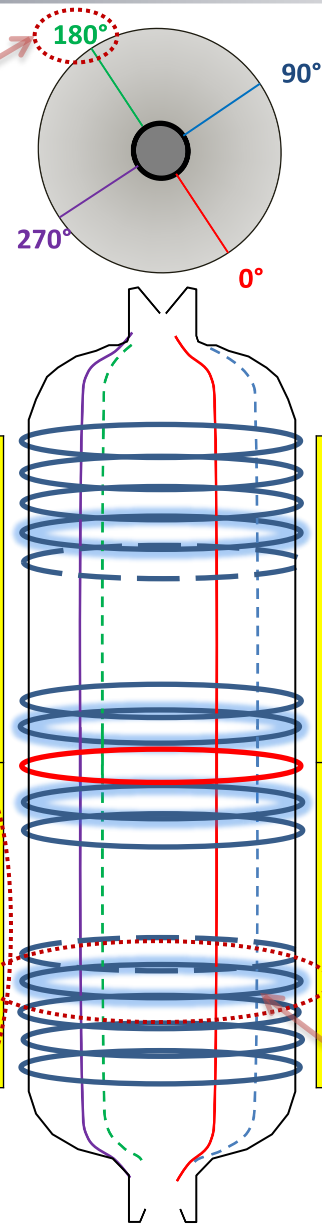
SY CH	File Name	Fiber
1	xx_F1	F1e
2	xx_F2	F2e
3	xx_F3	F1s
4	xx_F4	F2s

e = embedded

s = surface

Lateral / radial ref

Grating @ cross-section of hoop and lateral reference



Embedded Fiber Runns

Fiber ID Hoop No.	FBG @ θ (deg) 0	90	180	270	SY CH
F1e_H1	3	16	29	42	SY CH 1
F1e_H2	56	70	83	97	SY CH 1
F1e_H3	108	121	134	147	SY CH 1
F1e_H4	161	174	188	201	SY CH 1
F1e_H5	213	226	240	253	SY CH 1
	266				SY CH 1
					SY CH 1
					SY CH 1
F1e_H5	291	305	320	334	SY CH 1
F1e_H6	343	356	369	382	SY CH 1
	396				SY CH 1
	393				SY CH 2
F2e_H6	341	354	367	380	SY CH 2
F2e_H5	288	301	314	327	SY CH 2
					SY CH 2
					SY CH 2
	266				SY CH 2
F2e_H5	213	226	240	253	SY CH 2
F2e_H4	161	174	187	200	SY CH 2
F2e_H3	108	121	135	148	SY CH 2
F2e_H2	56	69	83	96	SY CH 2
F2e_H1	3	16	30	43	SY CH 2

Surface Fiber Runs

SY CH	Fiber ID Hoop No.	FBG @ θ (deg) 0	90	180	270
SY CH 3	F1s_H1	2	15	28	41
SY CH 3	F1s_H2	54	68	81	95
SY CH 3	F1s_H3	108	121	134	147
SY CH 3	F1s_H4	160	173	187	200
SY CH 3		213			
SY CH 3					
SY CH 3					
SY CH 3					
SY CH 3	F1s_H5	233	247	262	276
SY CH 3	F1s_H6	290	303	316	329
SY CH 3		342			
SY CH 4		342			
SY CH 4	F2s_H6	290	303	316	329
SY CH 4	F2s_H5	238	251	264	277
SY CH 4					
SY CH 4					
SY CH 4					
SY CH 4		214			
SY CH 4	F2s_H4	161	174	187	200
SY CH 4	F2s_H3	109	122	136	149
SY CH 4	F2s_H2	56	69	83	96
SY CH 4	F2s_H1	3	16	30	43

Fiber ID

RTV lateral transition

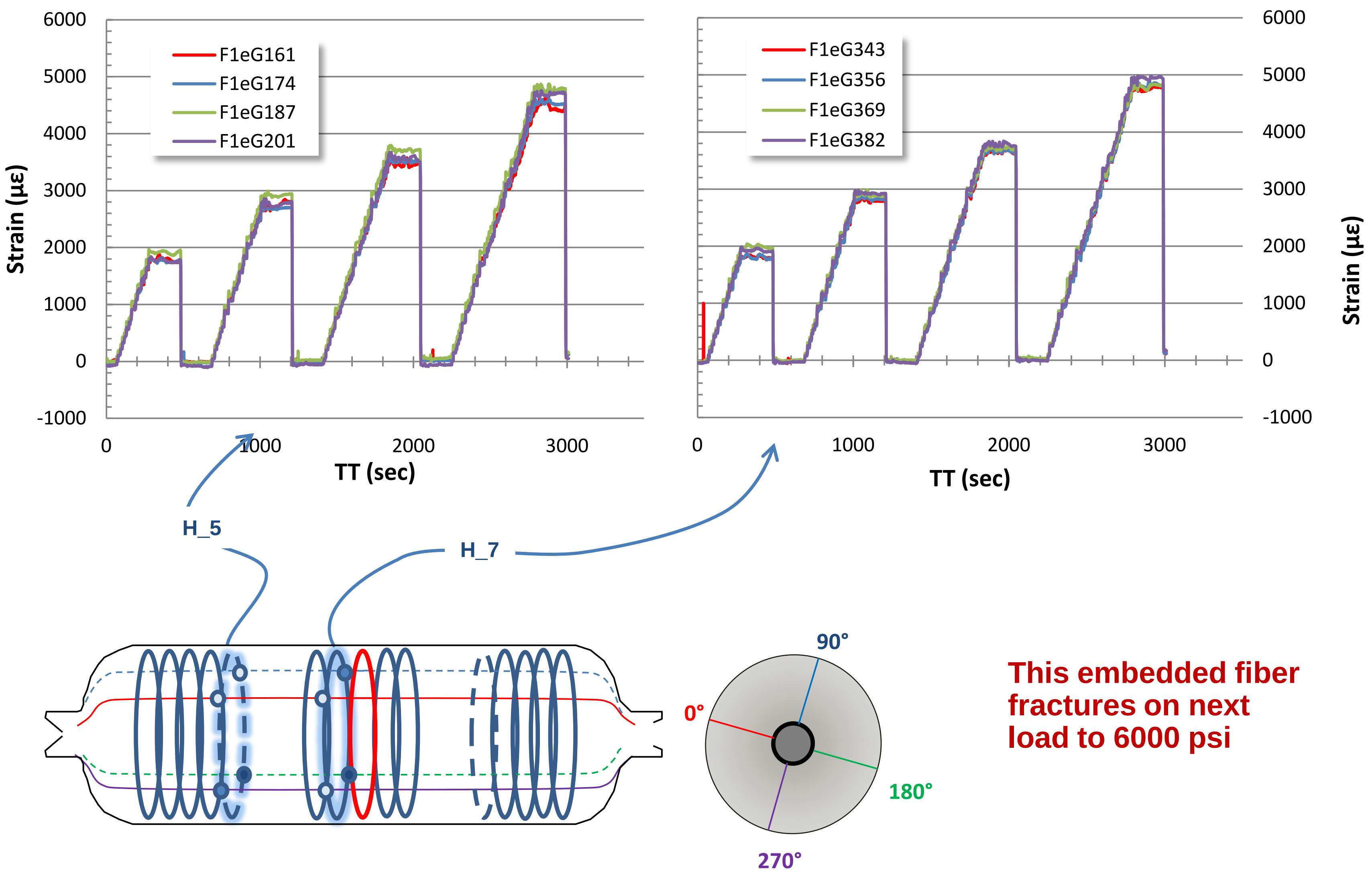
Hoop designation

FO System Chan #

Hoop of interest

Embedded Fiber to 5000 psi

F1e Hoops 5 & 7 Cross-Sections



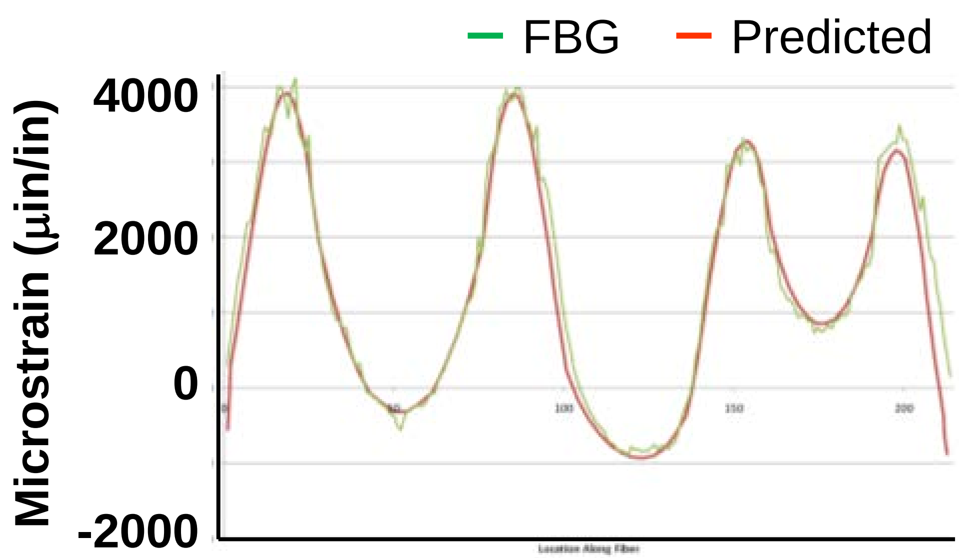
This embedded fiber fractures on next load to 6000 psi

NNWG / COPV

Full-Scale Composite Crew Module Testing

NASA Engineering and Safety Center (NESC)

- Four fibers were installed around the module's three windows and one hatch
- 3300 real-time strain measurements were collected as the module underwent 200%DLL pressurization testing
- Measured strains compared and matched well to predicted model results
- Project concluded:
    - "Fiber optics real time monitoring of test results against analytical predictions was essential in the success of the full-scale test program."
    - "In areas of high strain gradients these techniques were invaluable."

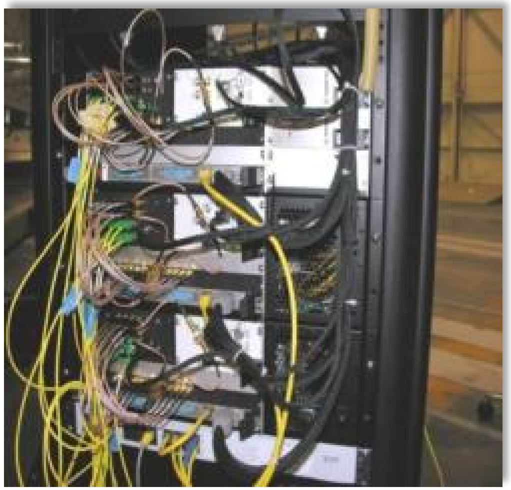


Inner Hatch FBG Strains, Max Pressure

Global Observer - Wing Loads Tests at Dryden

AeroVironment

- Validate strain predictions along the wingspan
- Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.
- FO Strain distribution measurements are being used to interpret shape using Dryden's single fiber shape algorithm
- A 24-fiber system was designed of which 18 fiber 40ft (~17,200 gratings) fibers were used to instrument this wing



Thermal Protection System Health Monitoring
CSIRO Australia / NNWG

- ***Combined AE/ Fiber Optic thermal monitoring of impact damage to TPS***
  - **Uses AE sensors to detect and locate impact location.**
  - **An external heat source (e.g. solar) and embedded thermal sensors then monitor local anomalies in the thermal conductivity of the TPS to evaluate functional effects of damage.**
  - **Fiber Bragg grating (FBG) sensors may be used for efficient high-density thermal measurement which is essential for TPS performance validation**
  - **A modular, distributed agent-based architecture is proposed for robust, scalable operation of the AE and FBG sensing modalities.**
  - **CSIRO Australia has worked with NASA LaRC to develop and demonstrate monitoring of impact damage with multi-agent architecture.**

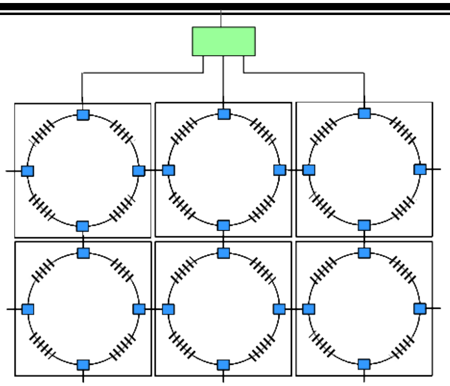
Vehicle Re-entry (conception)

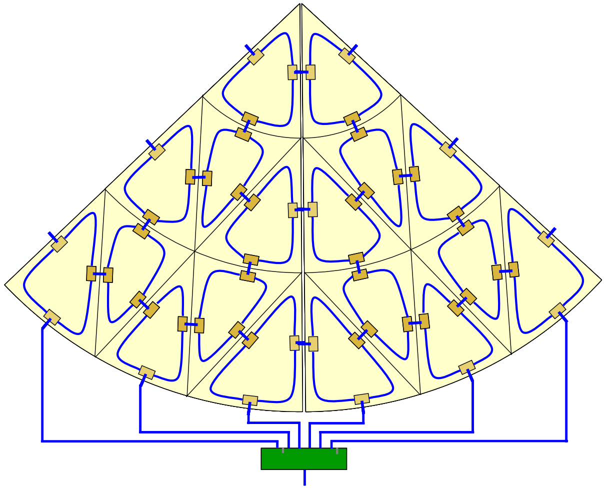
NASA / CSIRO
Concept Demonstrator

Large-scale testing at DFRC

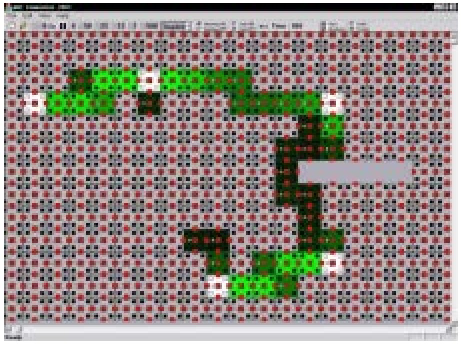
Technical Methodology / Approach
CSIRO / NNWG

- ***Robust reconfigurable optical fiber network***
  - Use modular agent-based (cellular) architecture, with electronically-switchable fiber segments.
  - Multiple routing configurations enable light to reach any local region.
  - Bench-top network will be set up and evaluated as first step, with central control of routing.
  - Cellular structure for segmented TPS.



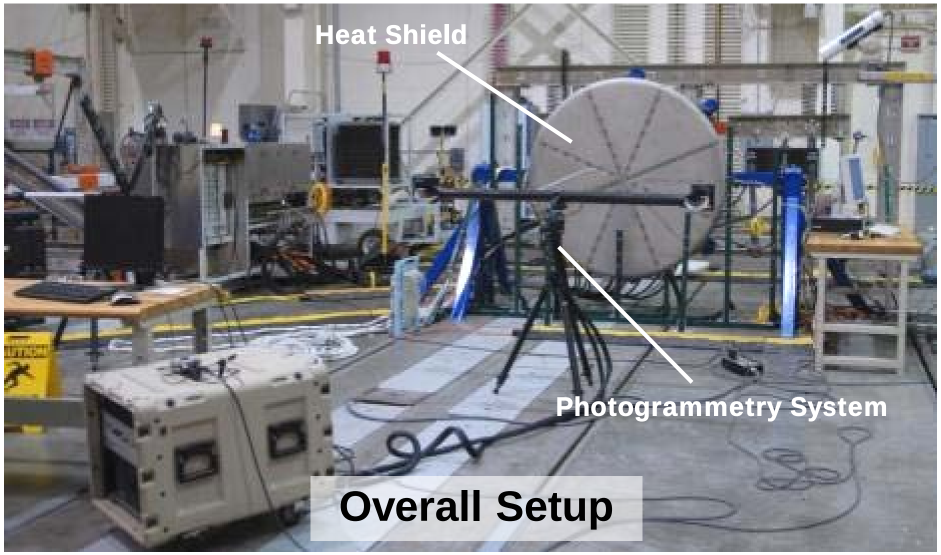


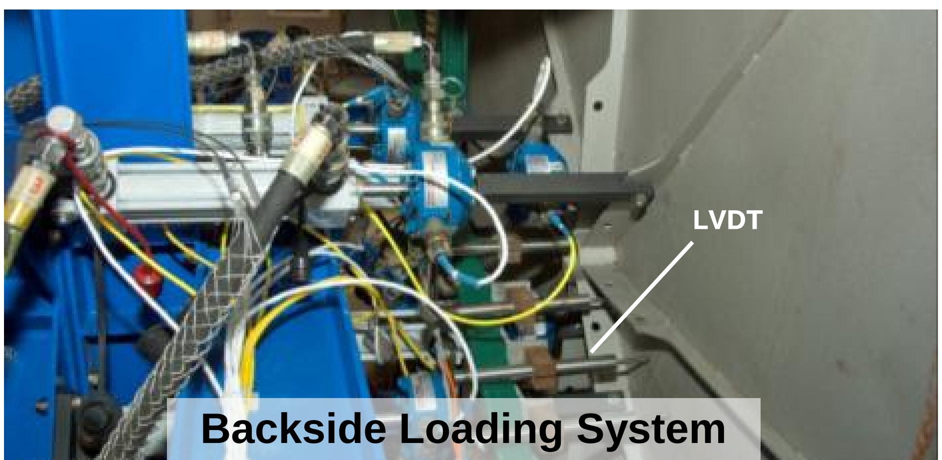
- ***Self-organized configuration control***
  - CSIRO technology for self-organized control (e.g. using ant colony optimization algorithm) to define shortest undamaged path to region of interest.
  - Demonstrate on segmented test structure.



National Aeronautics and Space Administration

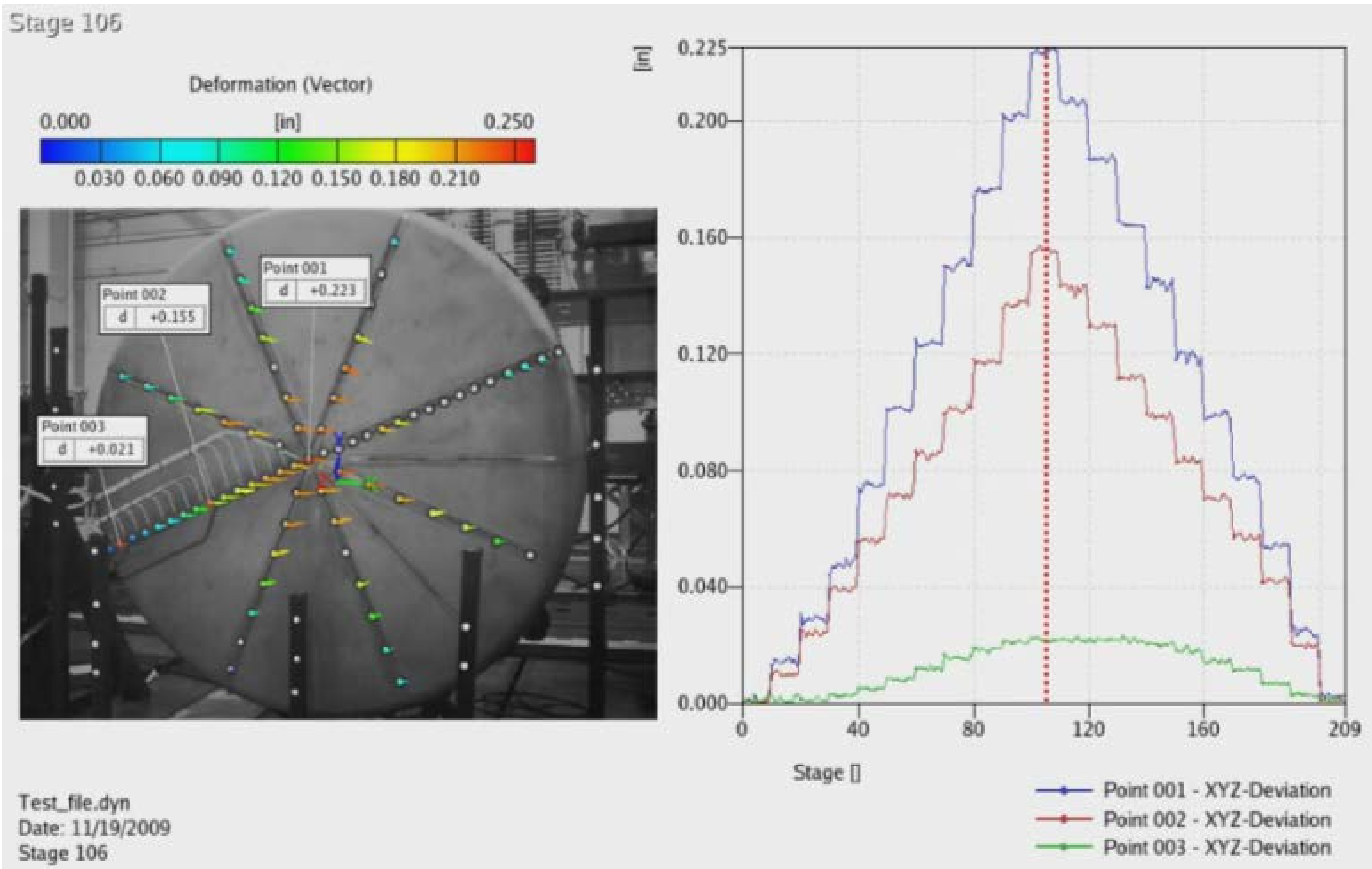
TPS Heat Shield Designed and Built





Shape Sensing Algorithms Validated

Photogrammetry Displacement Results



Flight Test Validation Results – Predator-B

- **Flight validation testing**
  - 18 flights tests conducted; 36 flight-hours logged
  - Conducted first flight validation testing April 28, 2008
  - Believed to be the first flight validation test of FBG strain and wing shape sensing
  - Multiple flight maneuvers performed
  - Two fiber configurations
  - Fiber optic and conventional strain gages show excellent agreement
  - FBG system performed well throughout entire flight – no issues

Video clip of flight data superimposed on Ikhana photograph

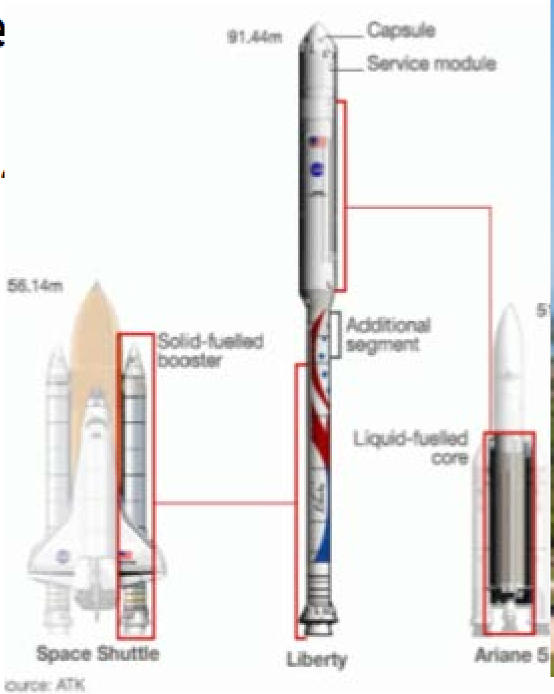
AeroVironment's Global Observer

Flight Testing

- **Validate strain predictions along the left wing using 8, 40ft fibers**
- **An aft fuselage surface fiber was installed to monitor fuselage and tail movement**
- **Strain distribution were measured along the left wing centerline top and bottom as well as along the trailing edge top and bottom.**
- **8 of the 9 total fibers are attached to the system at any give time**

Solving the Challenge of Flexible Dynamics

- Improved flight performance
- Stretching tanks?
- Improved launch availability?
- The ability to validate structural dynamics?
- Want to drop those expensive body bending sensors?
- FBG sensor technology:



- ✓ Large number of sensors
- ✓ Very small weight penalty
- ✓ Insensitive to EM noise
- ✓ High update rate (1 KHz non-multiplexed)

Opportunities for real time estimation and control created by novel FBG interrogation technology

Courtesy of KSC LSP and Florida Institute of Technolog

Anticipated Impact of Fiber Optic based SHM

- ***Potential to revolutionize aerospace design and performance throughout the vehicle life-cycle***
  - ***Design and development***
  - ***Fabrication***
  - ***Test and Evaluation***
  - ***In-flight operation***
  - ***Off-nominal flight***
  - ***End of life-cycle decisions***

Questions?

High fidelity Durability and Damage Tolerance of Composite Overwrapped Pressure Vessels

NASA Composite Conference 2012:

The Future of Composite Vessels and structures

New Mexico State University, Las Cruises New Mexico

August 13-17, 2012

F. Abdi (PhD), M. Garg, G. Abumeri

AlphaSTAR Corp., Long Beach, CA, USA

Outline

- Challenges Associated to COPV
- COPV Simulation Process
- Low Fidelity Model
- Low-to-High Fidelity FE Model
- High Fidelity Model

- Winding Process
- Durability and Damage Tolerance
- Reliability and sensitivity evaluation
- Conclusion and Lessons Learned

Challenges Associated to COPV

- Accurate description of the **tape schedule**, **defects**, **tape angles**, **tape pre-tension**, **Residual stress** is required for analysis of COPV and life prediction
- Manufacturing practice based on experience rather than design analysis
- Design of better product dependent on interaction between analytical tools and manufacturing techniques

COPV Product lines

A Reliable Computational Simulation Tool is Essential to Address

- Thickness distribution and bald spots due to winding
- Residual stress – strain predictions
- Ply angle orientation due to wrapping
- Leakage prediction
- Slippage of gas in the dome area where equipment are installed
- Rupture due to service load
- Sustained Fatigue (short, high cycles) pressurization,
- Unloading (**Auto-Frottage, Proof Pressure Testing**)
- Micro-crack formation
- Damage and failure multi-site locations

COPV Simulation Process

Manufacturing process & subsequent durability & damage tolerance/Reliability under service load

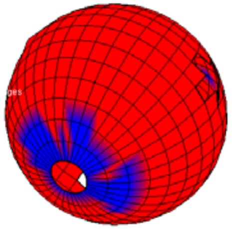
- **Multi-scale progressive failure analysis (MS-PFA).**
  - composite material characterization and qualification considering the manufacturing defects and scatter;
  - prediction of residual stresses due to manufacturing,
  - prediction of leakage/slippage, delamination initiation/growth between plies, location of burst,
- **Integration of manufacturing, progressive failure, and probabilistic analysis** into a robust software package of Low Fidelity and High Fidelity
  - that considers winding a) tape width, b) tape pre-tension, variable internal pressure, and tape/winding schedule

- **Low Fidelity**: use of FE layered shell element designed to achieve an overall durability, reliability and layup optimization to achieve a minimum weight minimum damage, and higher strength

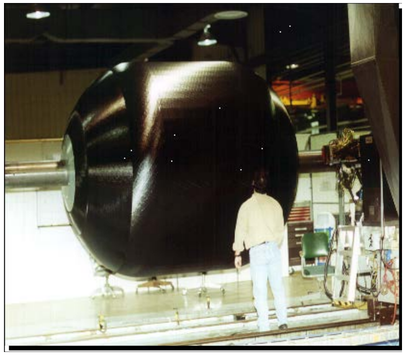
- **High Fidelity**: use of FE layered solid element designed to evaluate detailed damage initiation/progression in-and out-of-plane, and provide with information such as equipment boss contact stresses with composite layup and gas slippage. It determines damage mode, composite leakage.

COPV Simulation Process

Replicate Actual Complete Process

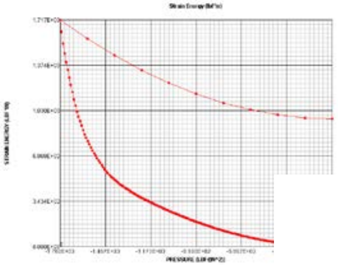


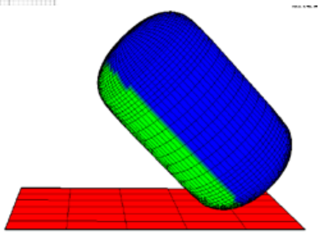
- ❑ **Filament Winding Optimization (Lo- & Hi-Fidelity Analysis)**
- ❑ **Tank Geometry**
- ❑ **Filament Winding (consider residual stresses due to curing & tape tension)**



Pressure	Cycle	Damaged ...	Fractured ...
-880	1000	0	0
-880	2000	0	0
-880	4000	0	0
-880	8000	8	0
-880	8000	9	0
-880	8000	9	0
-880	16000	40	0
-880	16000	40	0
-880	16000	40	0
-880	32000	60	0
-880	32000	60	0
-880	32000	60	0
-880	64000	103	0
-880	64000	104	0
-880	64000	104	0
-880	80000	115	0
-880	80000	115	0
-880	88000	131	0
-880	88000	131	0
-880	88000	131	0
-880	90000	135	0
-880	90000	135	0
-880	90000	135	0
-880	90500	136	0
-880	90500	136	0
-880	90500	136	0
-880	91000	136	0
-880	91000	137	4
-880	91000	293	46
-880	91000	564	367

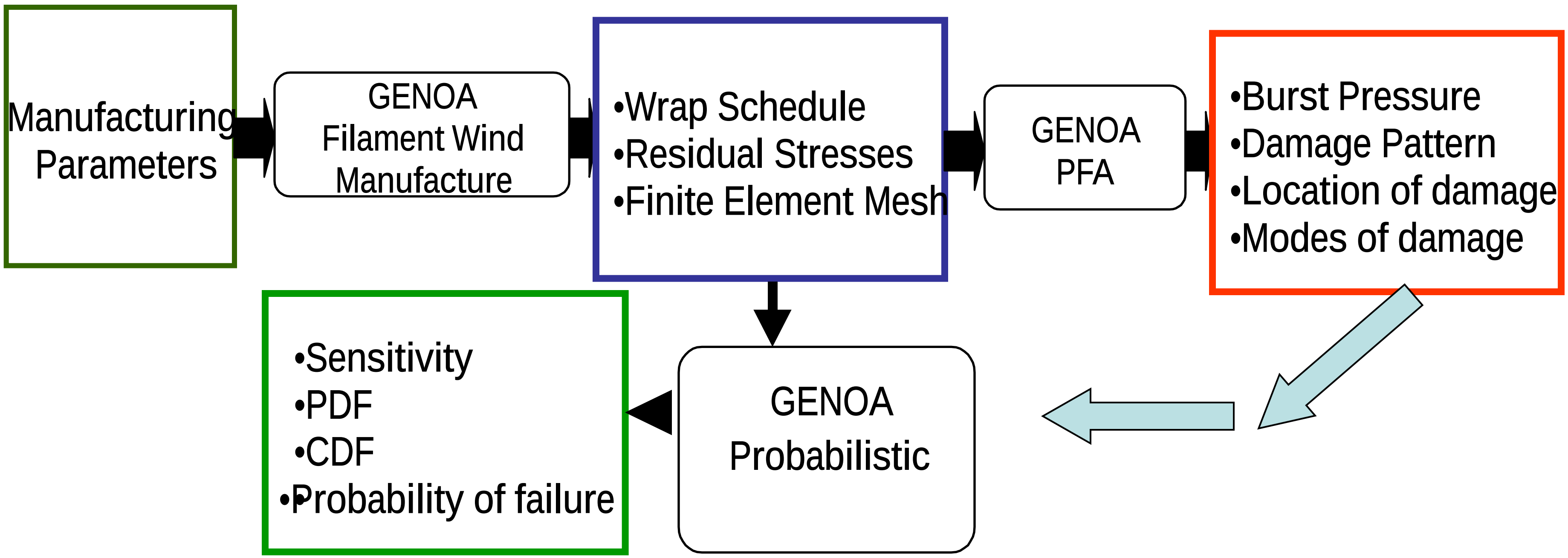
- ❑ **Burst Pressure Analysis**
- ❑ **Loading-Unloading Analysis (Autofrettage)**
- ❑ **Fatigue Loading Analysis (life Assessment)**
  - ❑ **Mechanical**
  - ❑ **Thermal (including Cryogenics)**
- ❑ **Skew-Impact Analysis**
- ❑ **Creep Analysis**





- ❑ **Probabilistic Analysis (PDF, CDF, Sensitivity)**
- ❑ **Reliability Analysis**

COPV Analysis and Design Process

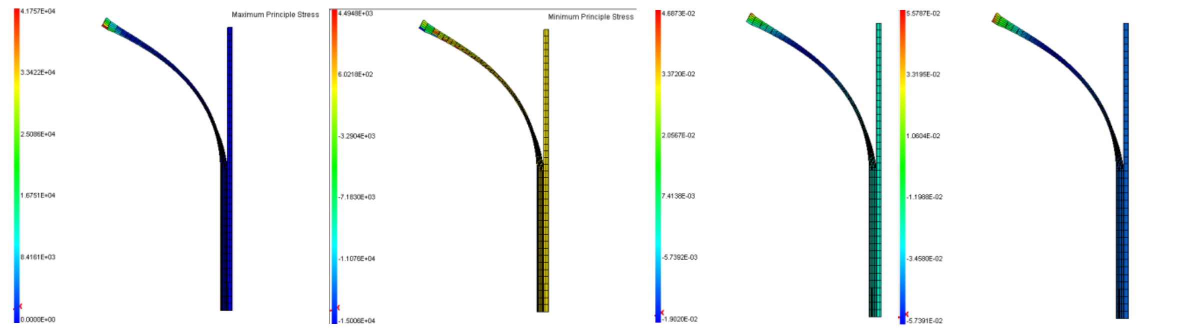


Low Fidelity Model: PFA-ABAQUS

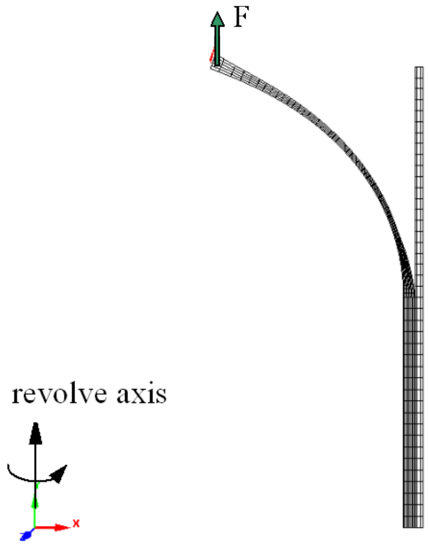
Axis-symmetric elements Verification Example

axis-symmetric elements

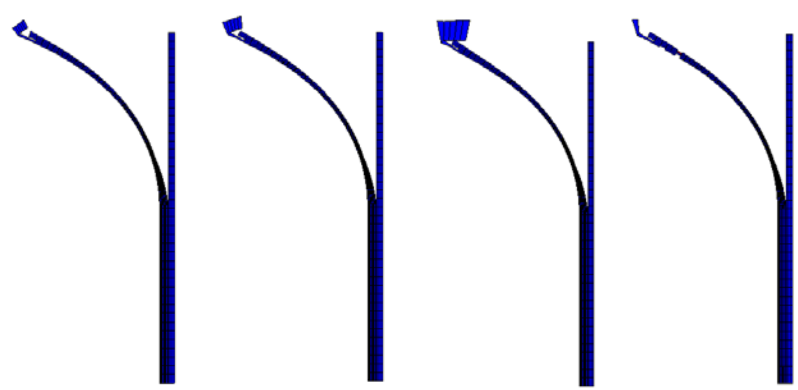
ELEMENT: 672 4-node axis-symmetric elements
NODES: 783
LOAD: 6
CONSTRAINTS: 6
PLY PROPERTIES: 2



(a) Max principle stress; (b) Min principle stress; (c) x displacement; (d) y displacement



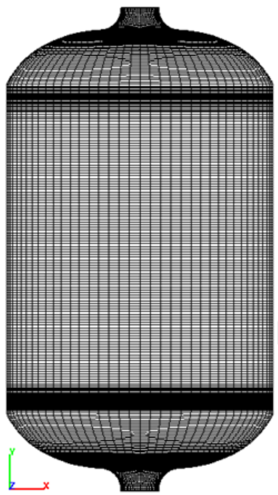
FEM model



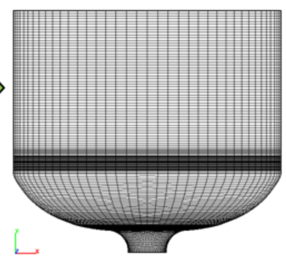
(a) 92436.75 lb; (b) 184873.5 lb; (c) 369747 lb; (d) 184900 lb
Damage propagation at different load levels

COPV Simulation Process

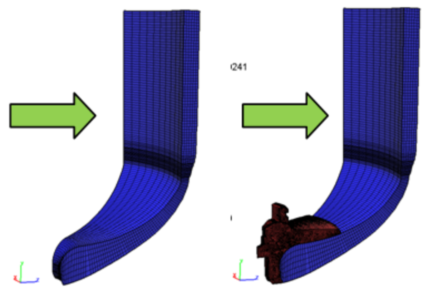
Low-to-High Fidelity FE Model

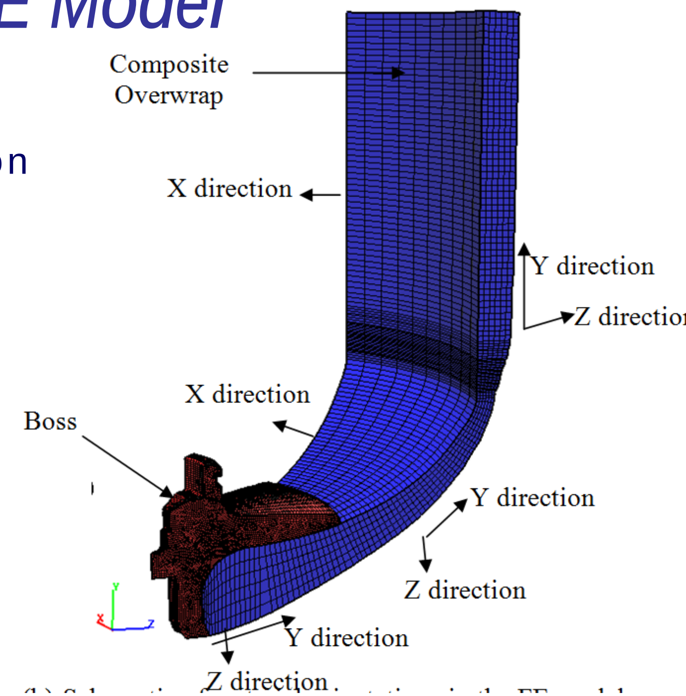


Shell Model
No Equipment

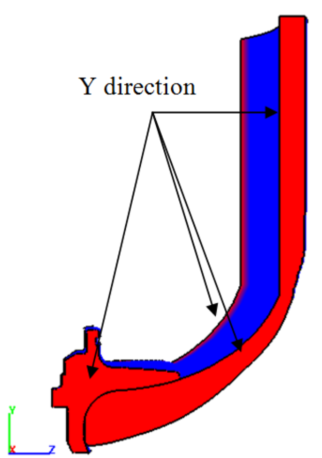


Solid Model
Equipment Insertion

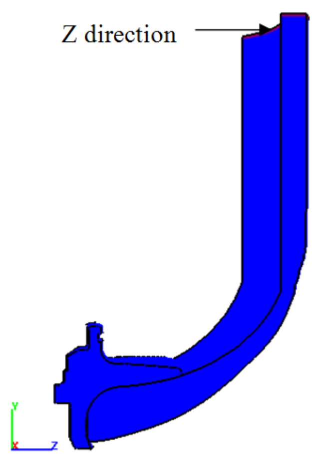




Boundary Condition

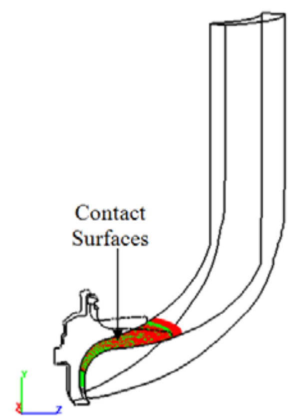


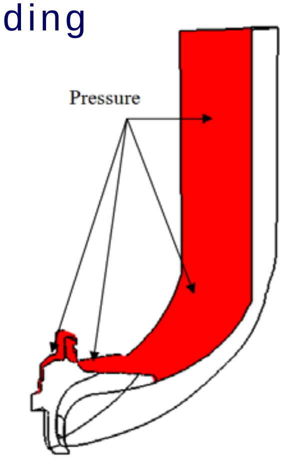
(b) tangential constraint



(c) axial constraint

Loading

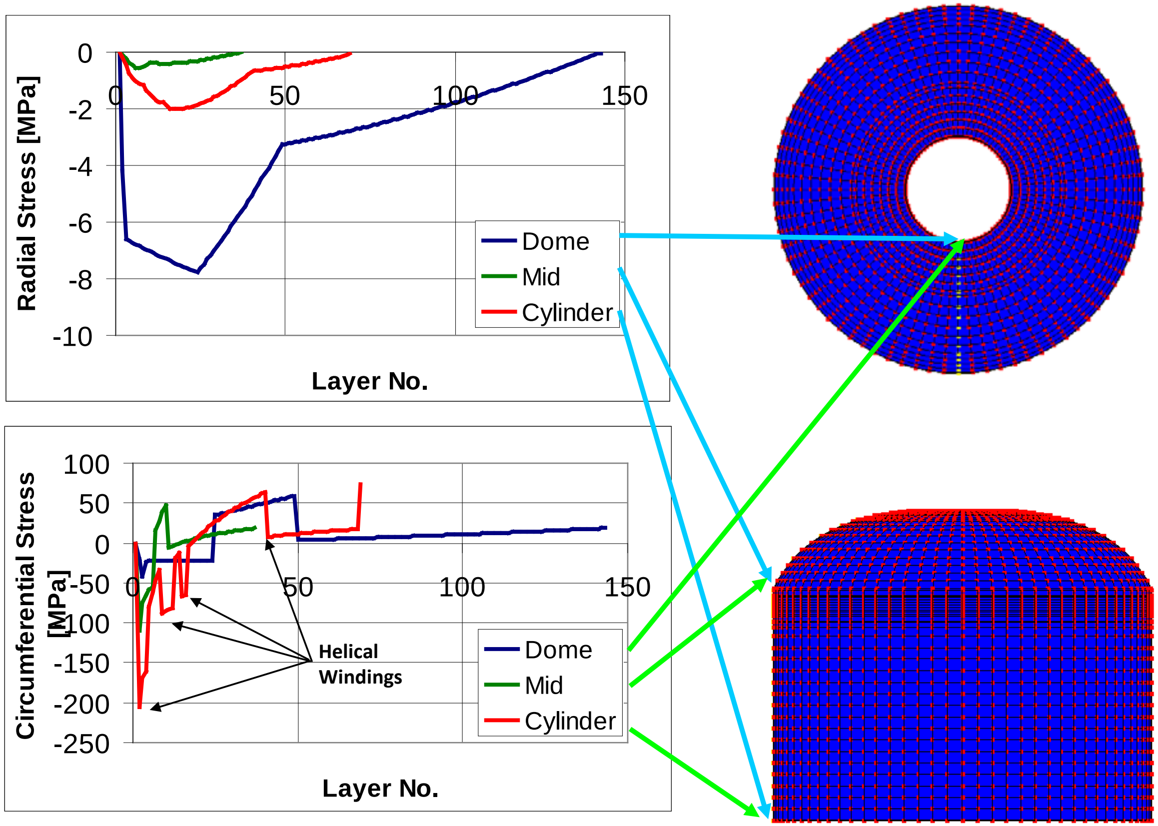




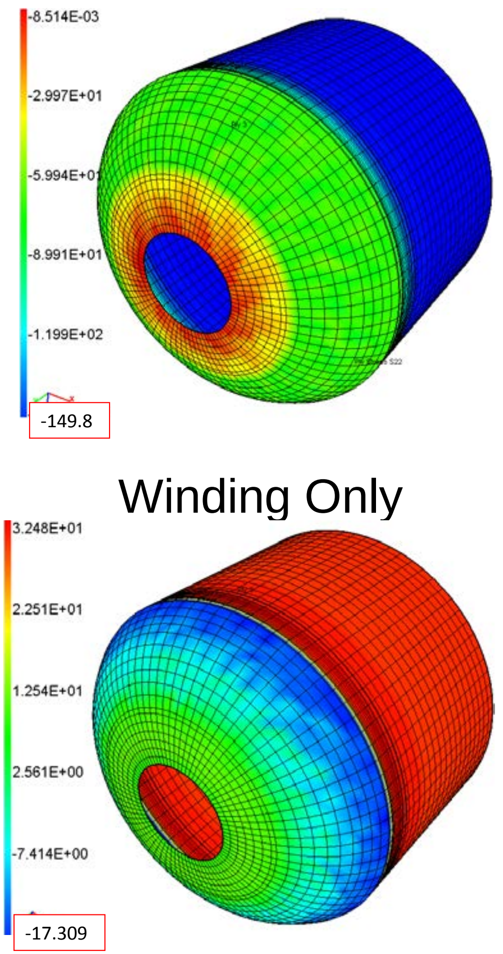
Residual stresses due to filament winding & Curing

hoop and radial directions: *at cylinder mid-section, cylinder to dome transition, and dome opening*

Residual stress Vs. tape Layer (through-the-thickness



Residual Ply Stresses

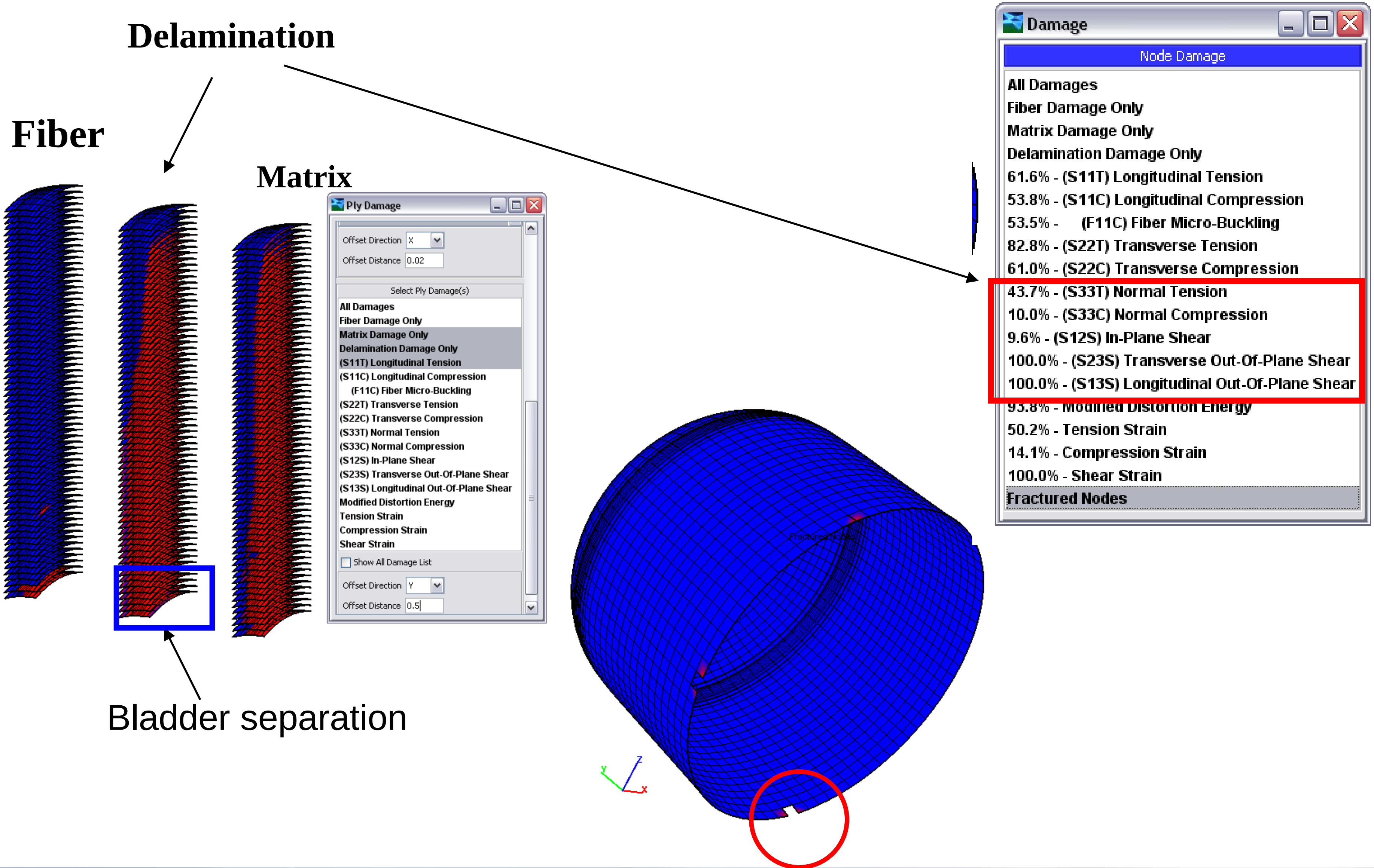


Winding Only

Curing Only

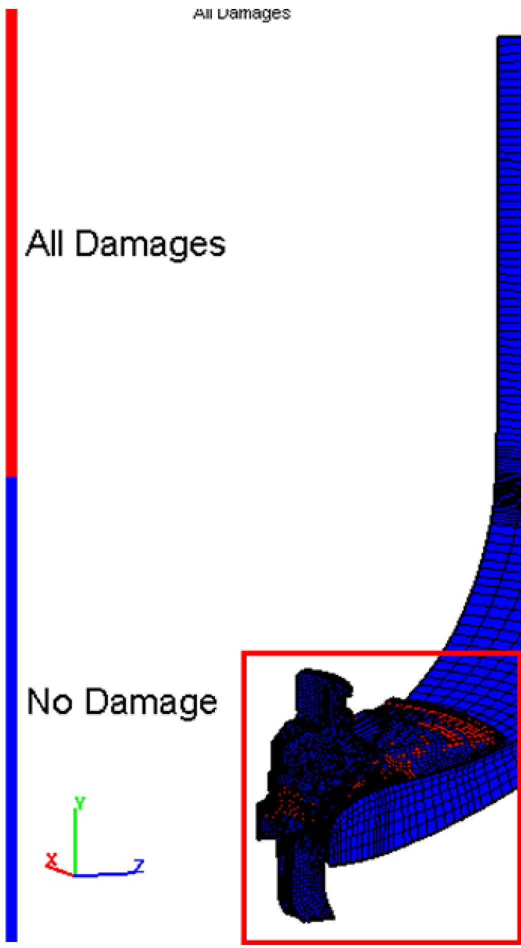
Damage Evolution in COPV

Micro-mechanics damage model

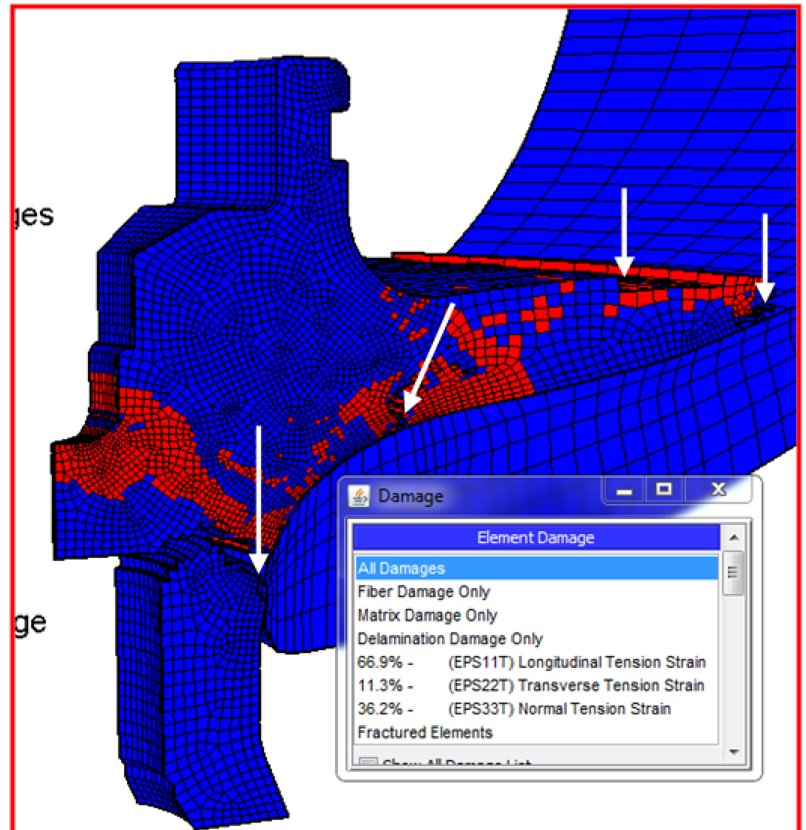


Composites Over-wrapped Pressure Vessels:

Metallic Equipment D&DT Analysis (Damage & Fracture)



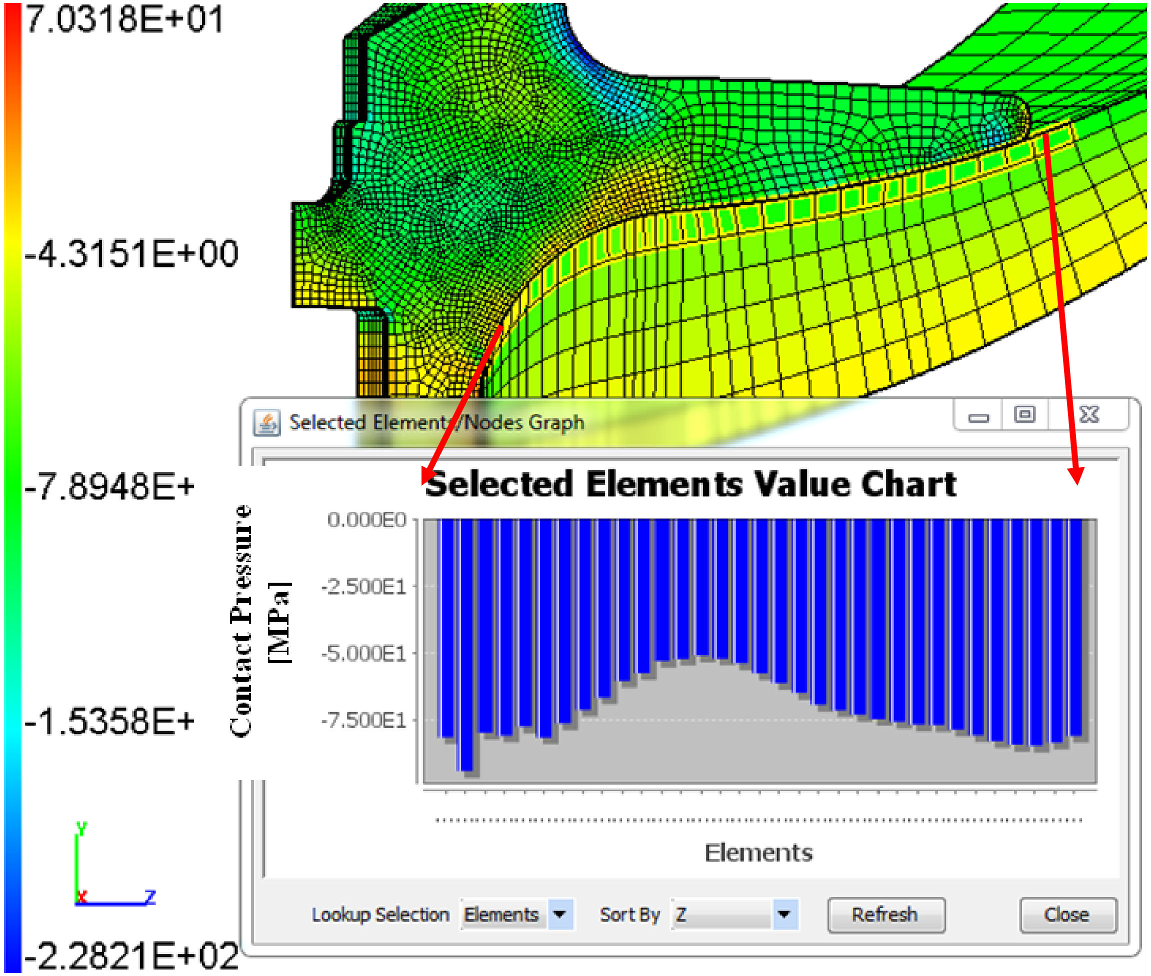
(a) Overall damage in the boss



(b) close-up view of the boss damage

Composites Over-wrapped Pressure Vessels:

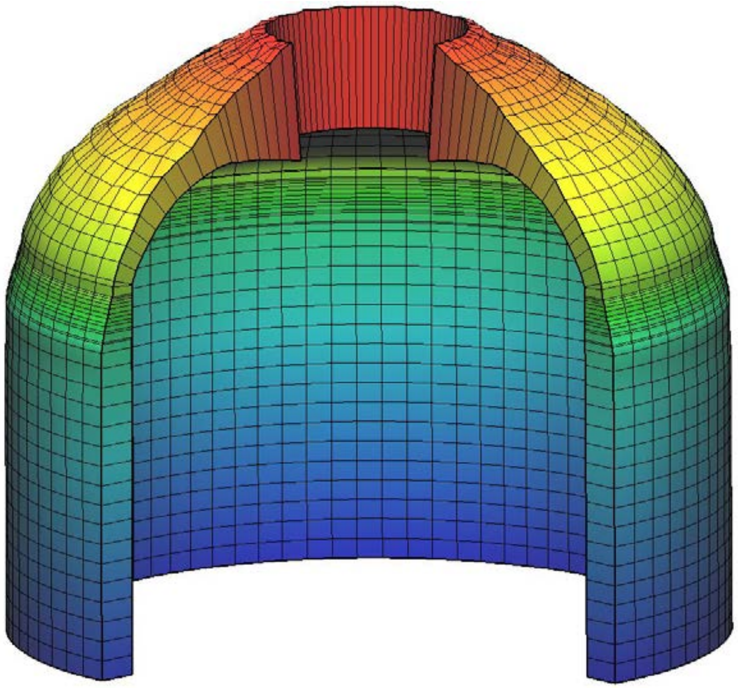
Contact Stresses: Boss & Composite Overwrap

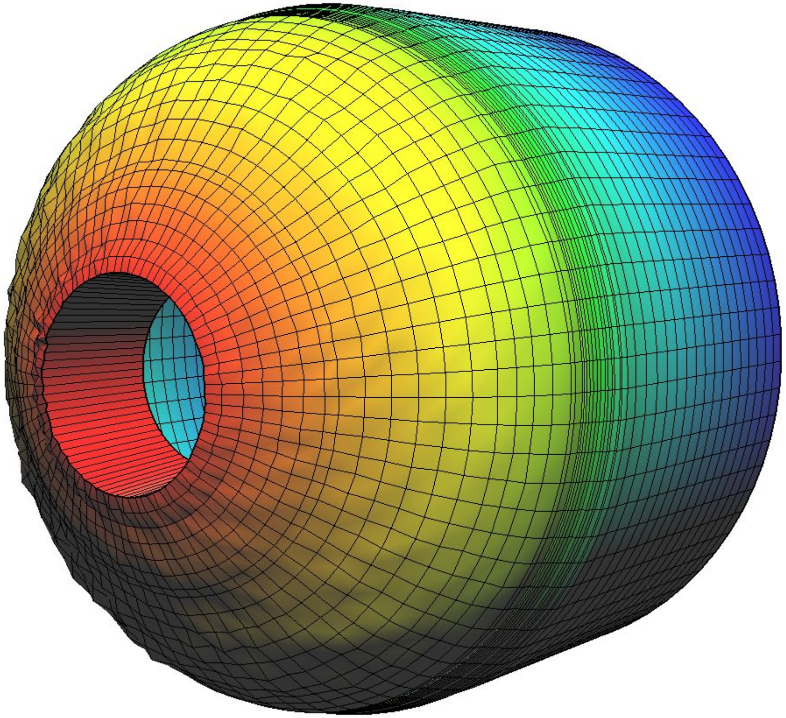


COPV High Fidelity Mesh

Solid FEM

- **Automated extrusion Process**
  1. **Element size Through Thickness**
  2. **Automatic Ply assignment between elements**
  3. **Contact between wall assembly and tank**
  4. **Account residual stress from shell filament wound model**

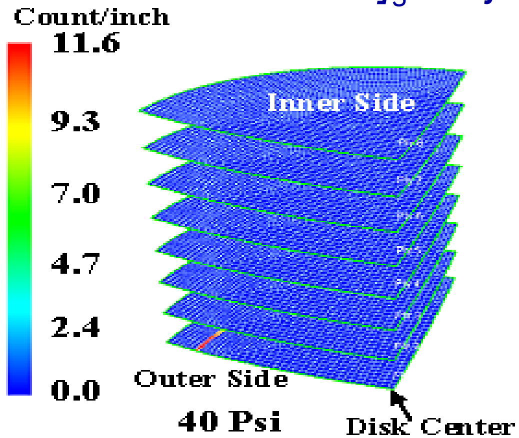




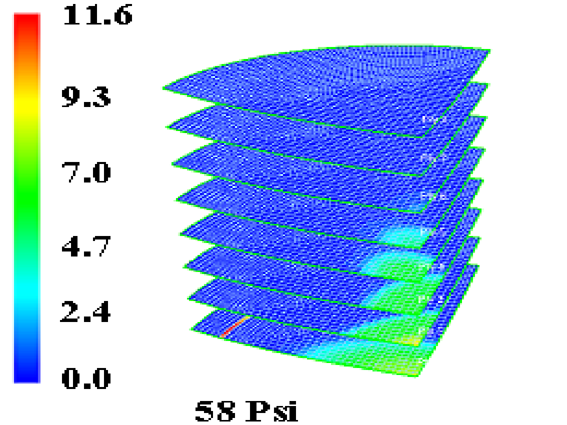
Micro-crack Formation Prediction Verification

Through-the-thickness crack density *cont'd*

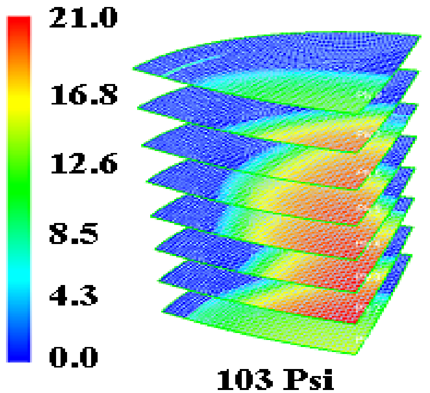
distributions in the layers of 25-inch composite disk made of quasi-isotropic laminate $[45/90/-45/0]_s$ subject to various levels of external pressure



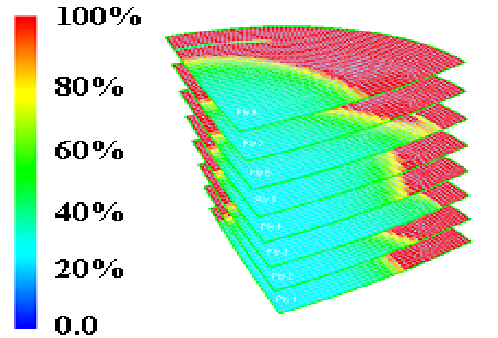
a) Crack Density Distribution at 40 psi



b) Crack Density Distribution at 58 psi



c) Crack Density Distribution at 103 psi



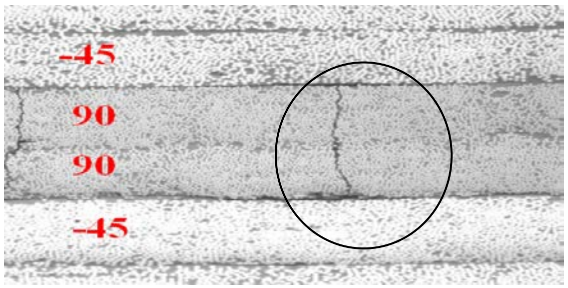
103 Psi – Ratio of the Matrix Residual Stiffness to Its Original Stiffness

d) Matrix Residual Stiffness at 103 psi

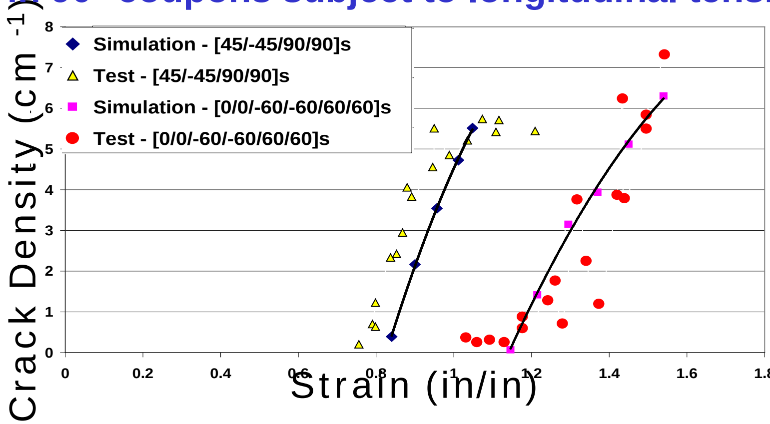
Reference: F. Abdi, L. Israeli, S. Johnson, P. Aggarwal, J. Rayburn, D. Fox "**Composite Tank Permeation Prediction And Verification**". **SDM 44 Conference Paper.**

Micro-crack Formation Prediction Verification *cont'd*

- Many composites failures initiate as a result of matrix cracking
- When matrix cracks
  - it releases energy that causes accumulation of additional cracks.
  - The process continues until reaching a saturation point
  - Residual Stiffness observed

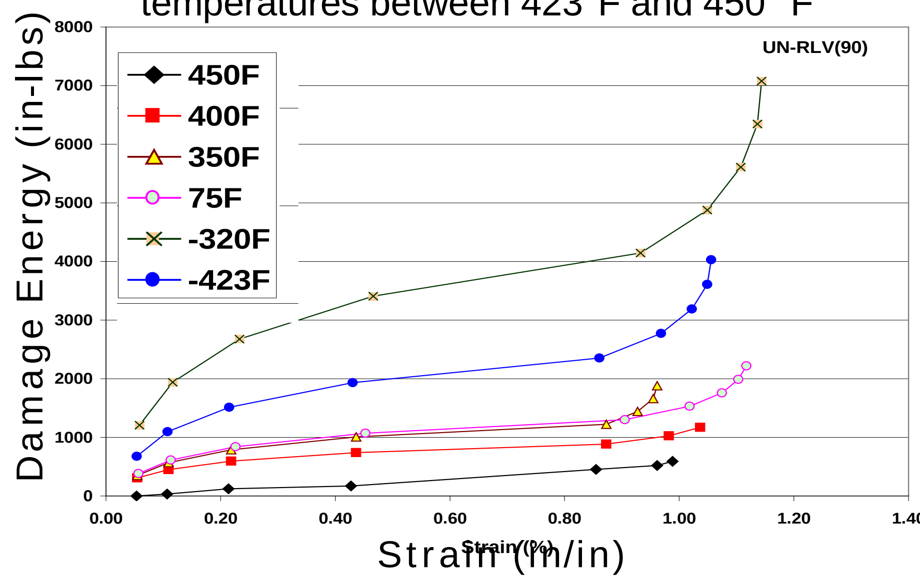


Prediction/Test verification of crack densities in 90 coupons subject to longitudinal tension



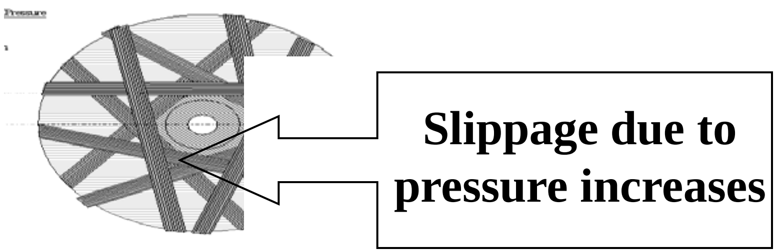
Leakage Study of Cryogenic Tank

[-45/0$_3$/45/90$_3$/45/0$_3$/-45] IM7-977-2 at the range of temperatures between 423 F and 450 F

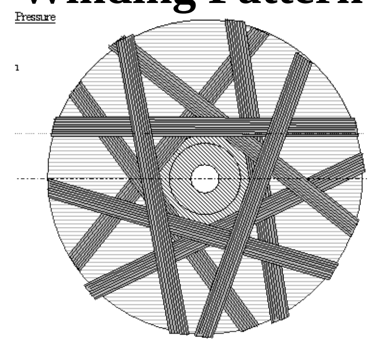


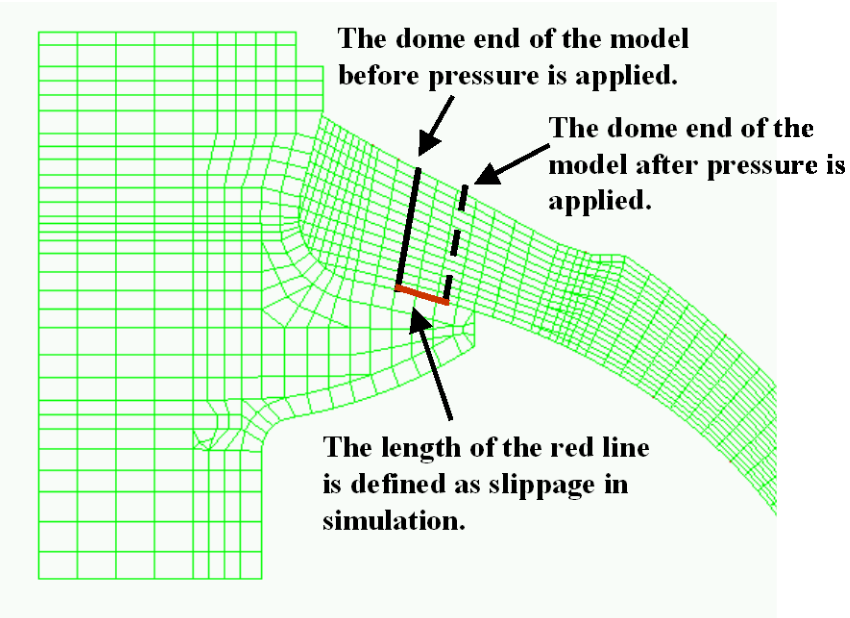
Reference: Frank Abdi, Xiaofeng Su "**Composite Tank Permeation and Crack Density Prediction an Verification**", ASME Paper No. IMECE2003-4439, November 2003.

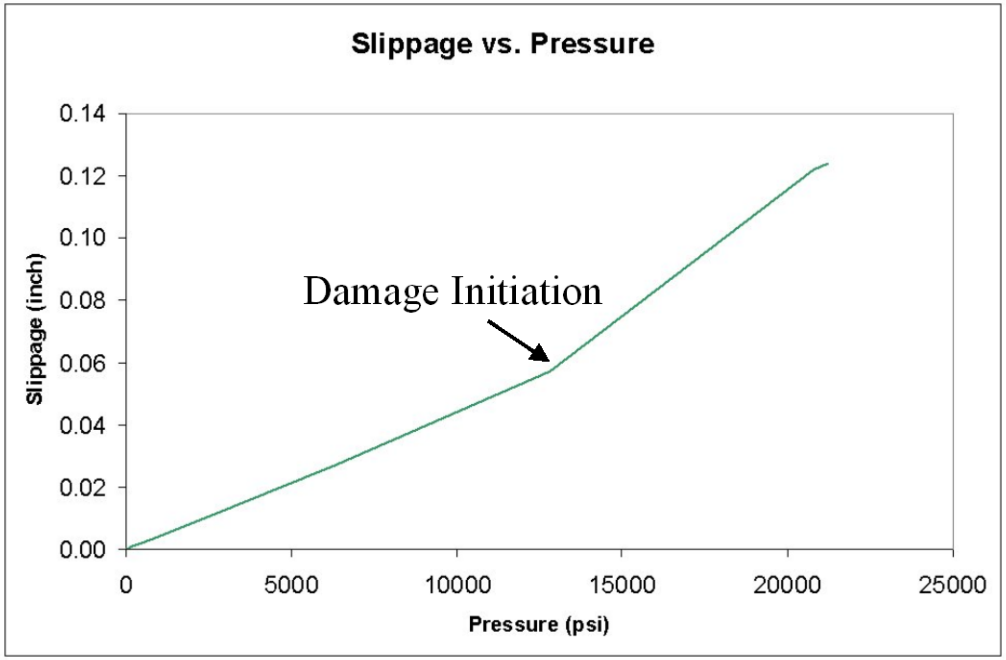
Slippage Definition and Simulation



Winding Pattern







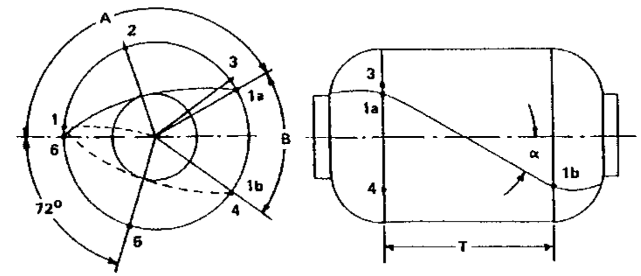
slippage increases as the pressure increases. It becomes faster after damage occurs

Composites Over-wrapped Pressure Vessels

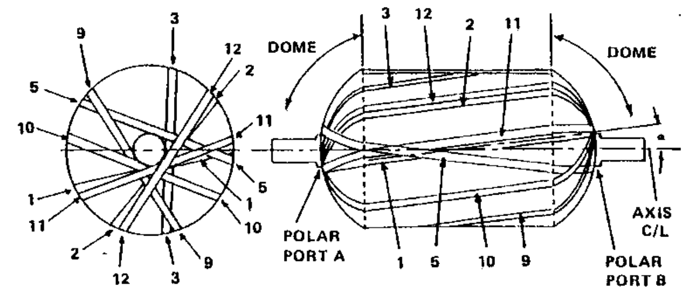
Winding Process

Tape Material						
Number	Fiber	Matrix	Thickness	Angle	FVR	VVR
1	ALT6	ALT6	0.025	0	0.0001	0
2	SCI-	EPOX	0.01	0	0.555	0

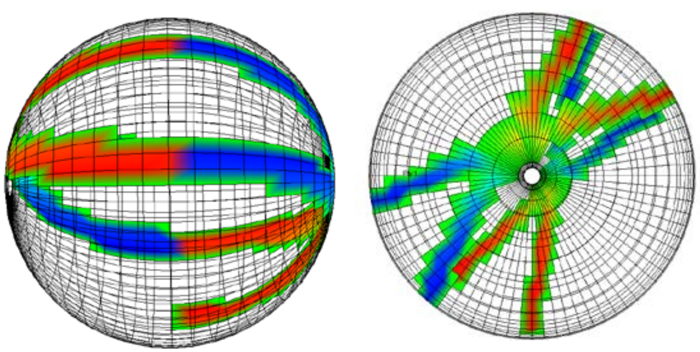
Tape Wrapping								
Wrap Type	Ply Material	Tape Width	Overlap	Start Angle	Winding Angle	Circuits	Hoop Over Dome	Tape Tension
HELICAL	2	0.5	0	0	10	2	N/A	20



- **Allows to define Helical and Hoop winding patterns**, along with number of circuits, tape width, tape thickness, winding angle, tape tension, etc.,



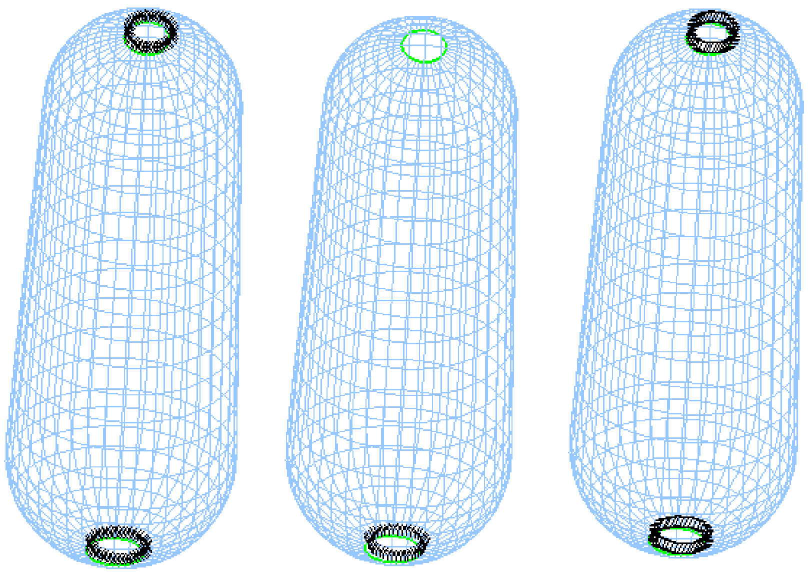
- **Liner tanks** (constant / variable thickness)
- **Liner + composite tanks** (accounts for the residual Stresses)
- **Liner-less tanks**
- **Contact of liner and the COPV**, and model friction/frictionless behavior
- **Allows to use different solver types** (NASTRAN, ABAQUS, LS-DYNA,
- Allows to account for **Hydrostatic Pressure** (fluid weight)



Composites Over-wrapped Pressure Vessels

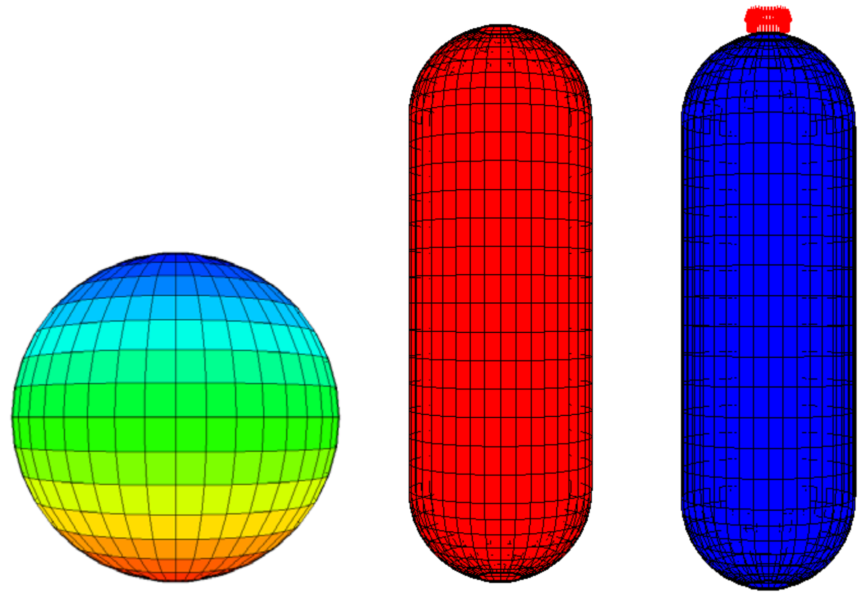
Input

Boundary Conditions



X Y Z

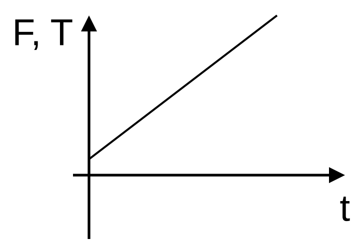
Loading Conditions

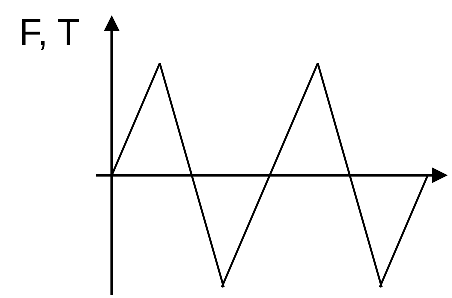


Fluid Weight

Internal Pressure

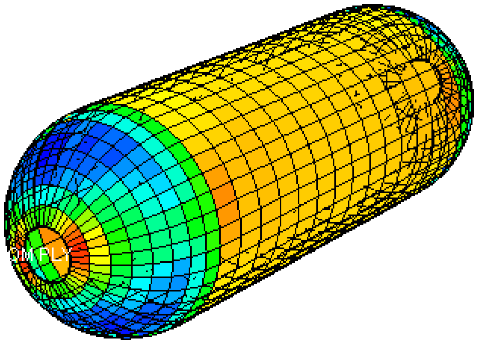
Force at the Boss



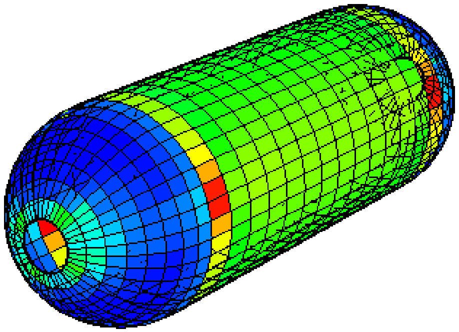


Composites Over-wrapped Pressure Vessels

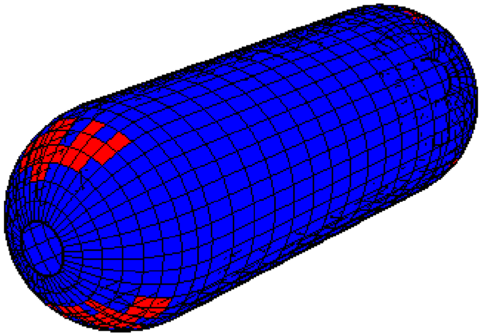
Output



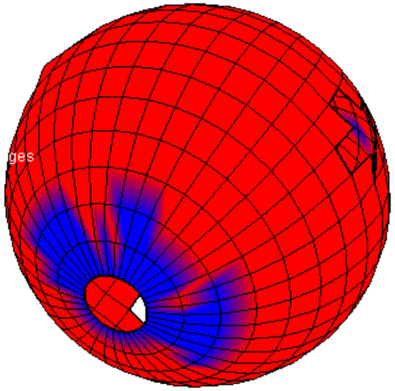
Monitor Stresses



Margin of Safety



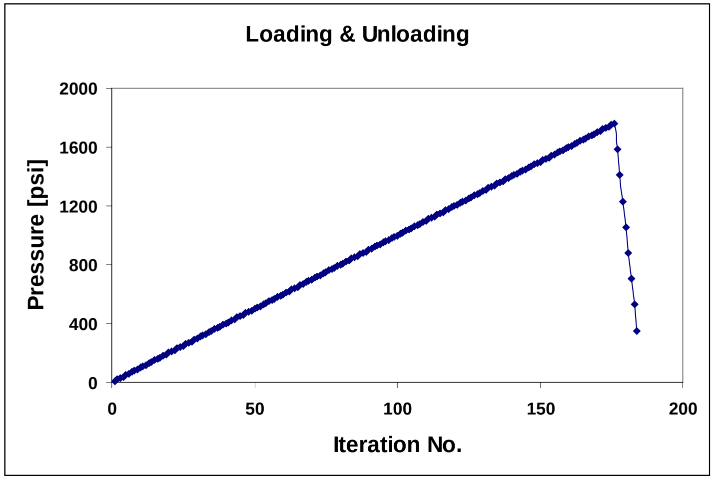
Track Damage Initiation

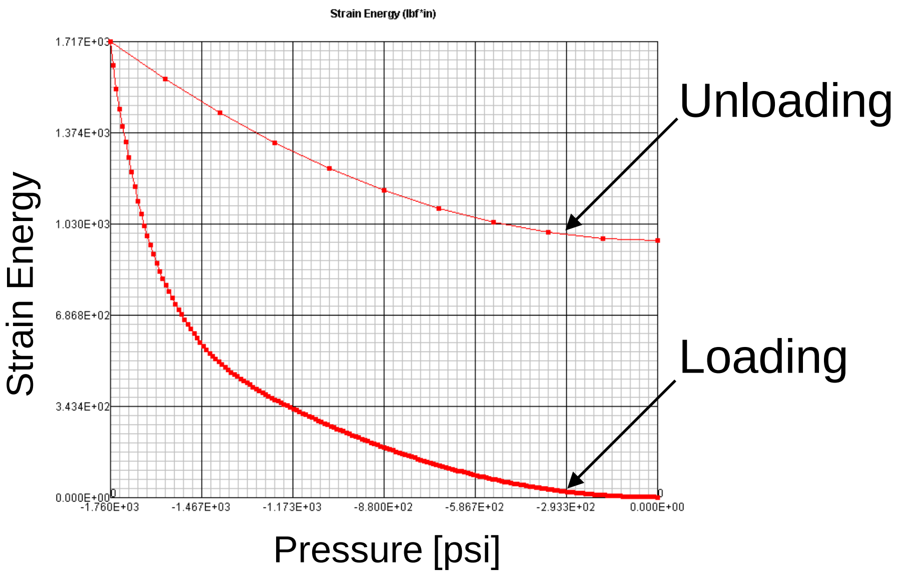


Predict Failure, Leakage, Burst pressure

Composites Over-wrapped Pressure Vessels:

Loading-Unloading Analysis (Autofrettage)



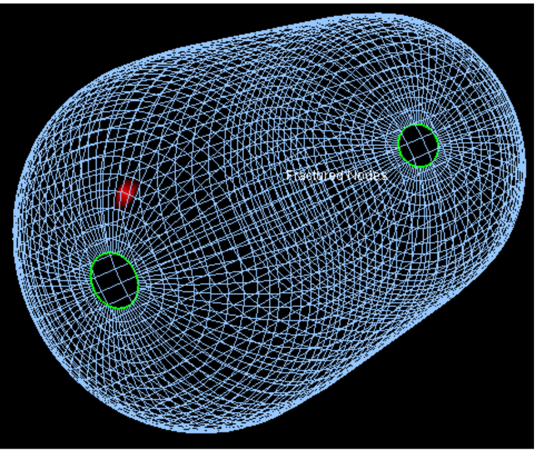


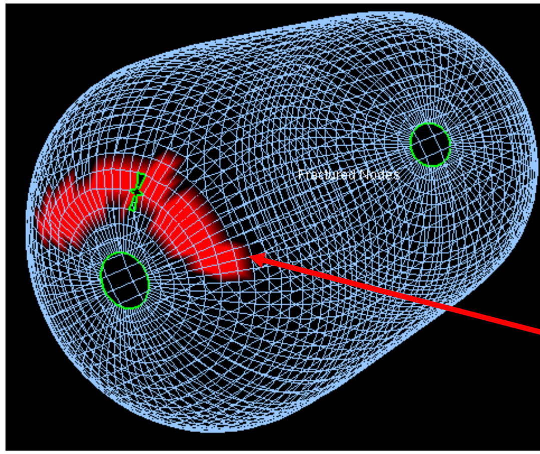
- Plastic deformation of the Metallic Liner
- Loaded before the composite over-wrap starts to damage
- Unloaded
- Account for accumulated residual stresses and mesh deformation

Composites Over-wrapped Pressure Vessels:

Fatigue Loading Analysis: Mechanical

Pressurized Composite Hydrogen Vessel





- **Predicted No. of Service Cycles: 33,750**
- **Experimental No. of Service Cycles: 25,000–37,000**

Fatigue rupture at the closed end

Input Data

- Calibrated data bank
- Residual stress from Impact
- Damage index from Impact
- Ply schedules
- FE mesh, Simple BC's
- * Strength Life curve (liner, matrix)
- 2 MPa <Cyclic pressure< 45 MPa)

Output Data

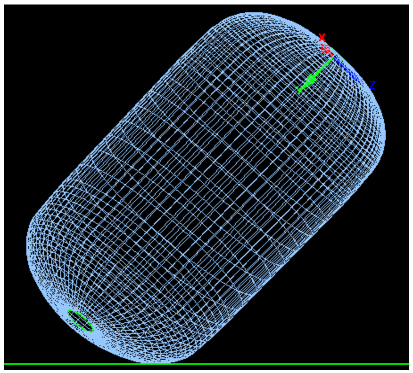
- Stress-strain fields at each node
- Damage index at each node
- Ply stresses and strains in the top and bottom layers
- Displacements
- Damage progression history
- Damage energy history

*__Ref__: Composite matrix degrades according to the experimental results in NASA/TM-2001-211035

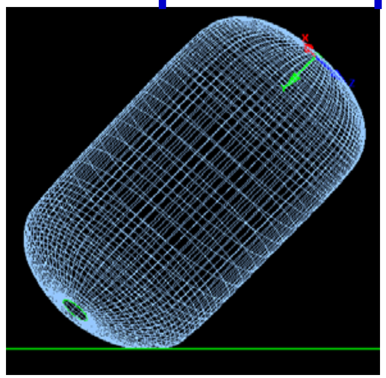
Composites Over-wrapped Pressure Vessels:

Skew Impact Analysis

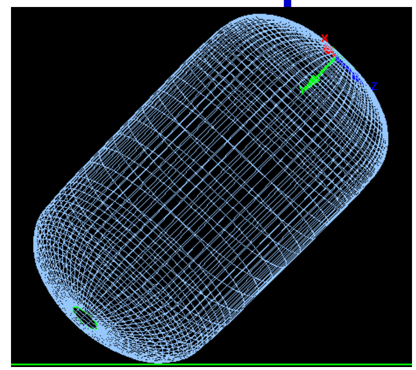
Impact Drop test time step



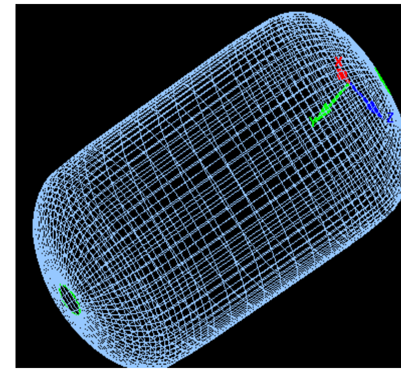
t = 6.0e-4 sec



t = 1.6e-3 sec



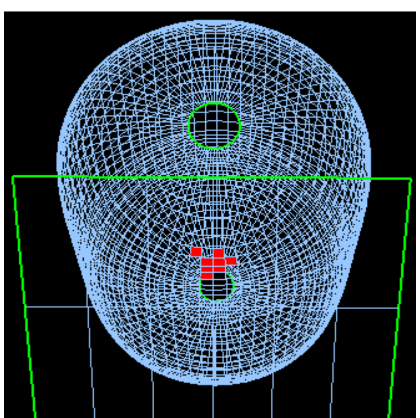
t = 3.4e-3 sec



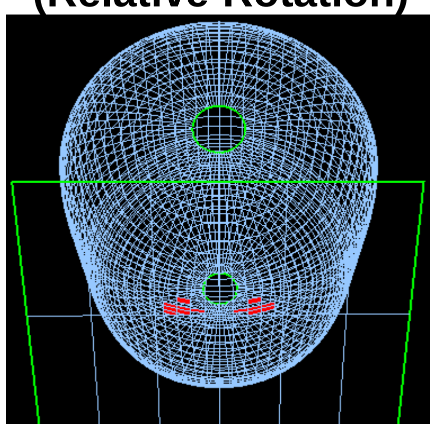
t = 2.0e-2 sec

Localized impact damage

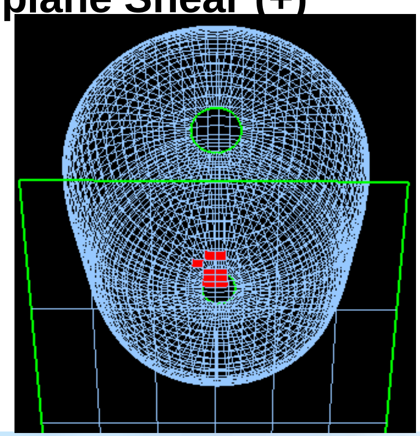
Fiber Micro-Buckling



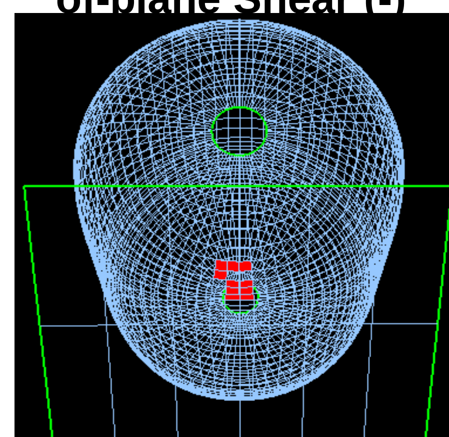
Delamination (Relative Rotation)



Transverse Out-of-plane Shear (+)

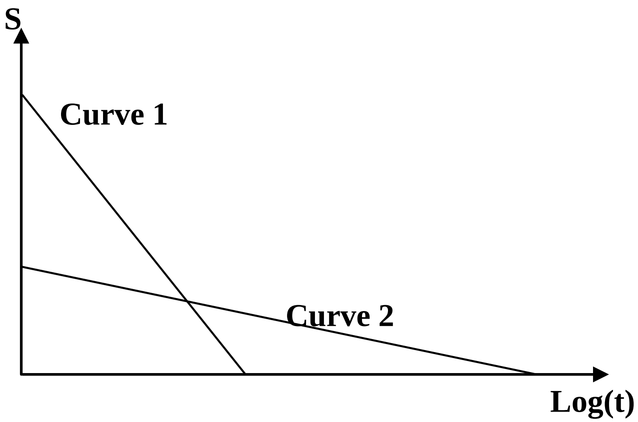


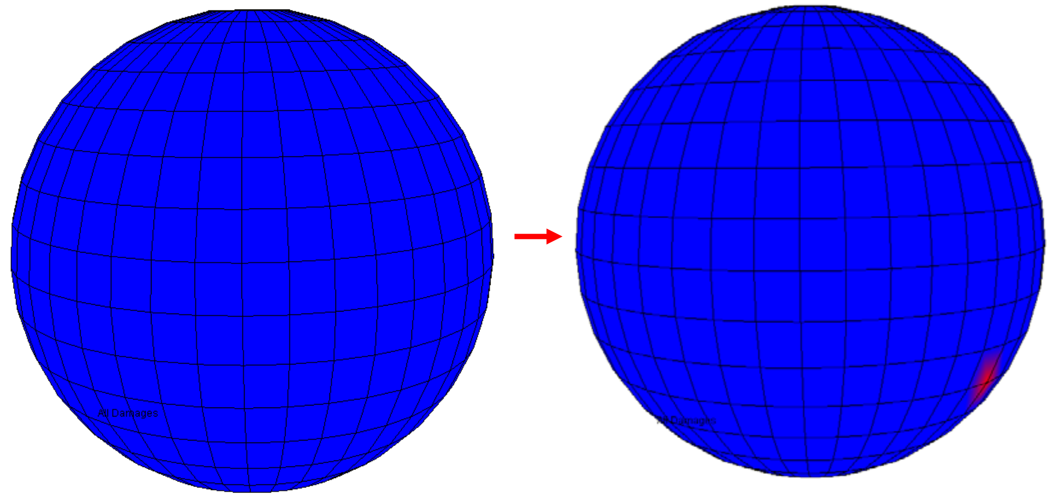
Transverse Out-of-plane Shear (-)



Composites Over-wrapped Pressure Vessels:

Demonstration of Creep Analysis





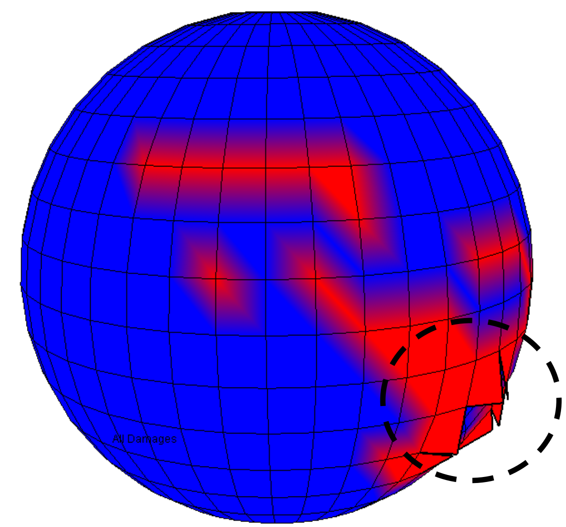
Damage Initiation ~3.82 years

Two-Stage Bilinear Degradation

- ❑ Curve 1 is defined as
  $S = a_1 - b_1 log(t)$
- ❑ Curve 2 is defined as
  $S = a_2 - b_2 log(t)$

All Damages

- 15.4% - Longitudinal Tensile
- 100.0% - Transverse Tensile
- 5.8% - In-Plane Shear (+)
- 7.7% - In-Plane Shear (-)
- 30.8% - Modified Distortion Energy
- 5.8% - Relative Rotation Criteria
- 15.4% - Tension Strain
- Fractured Nodes



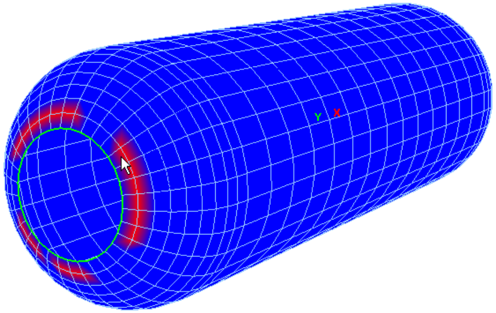
Creep Model Setup

- ❑ Liner-less Pressure Vessel
- ❑ Constant Pressure = -100 psi

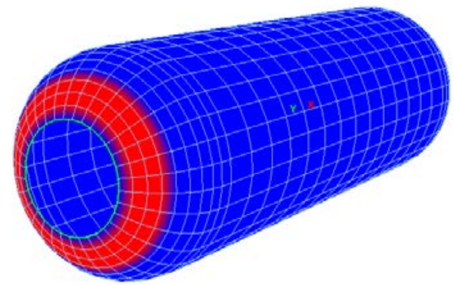
Tank Fails in ~3.85 years

Army Composites Over-wrapped Pressure Vessels
Probabilistic & Reliability Analysis *cont'd*

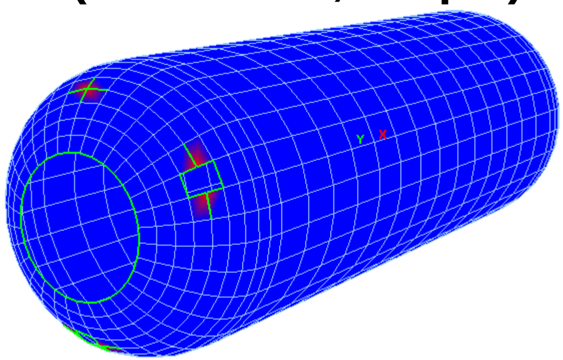
COPV Delamination Initiation / Progression and Fracture Simulation



Delamination Initiation in Tank 3
(Pressure 3,200 psi)



Delamination Progression in Tank 3
(Pressure 4,480 psi)



Fracture Initiation in Tank 3
(Pressure 5,040 psi)

Fracture Test/Prediction Comparison

Test: 4,890 to 5,303 psi
Test Average: 5,057 psi

GENOA: 5,040 psi

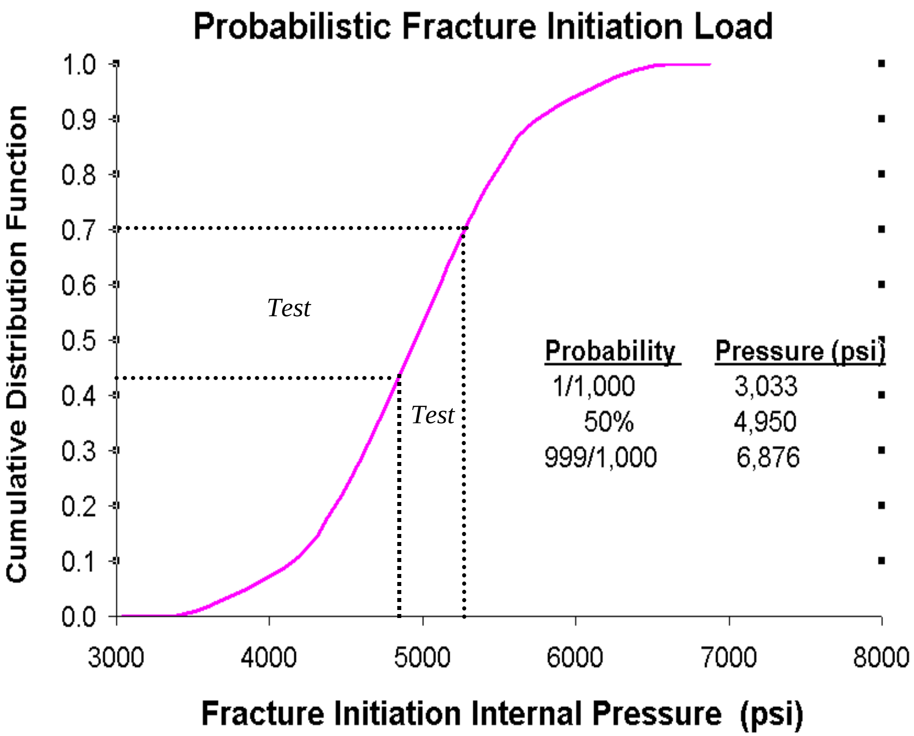
Prediction burst pressure is 0.33 % lower than the average test pressure

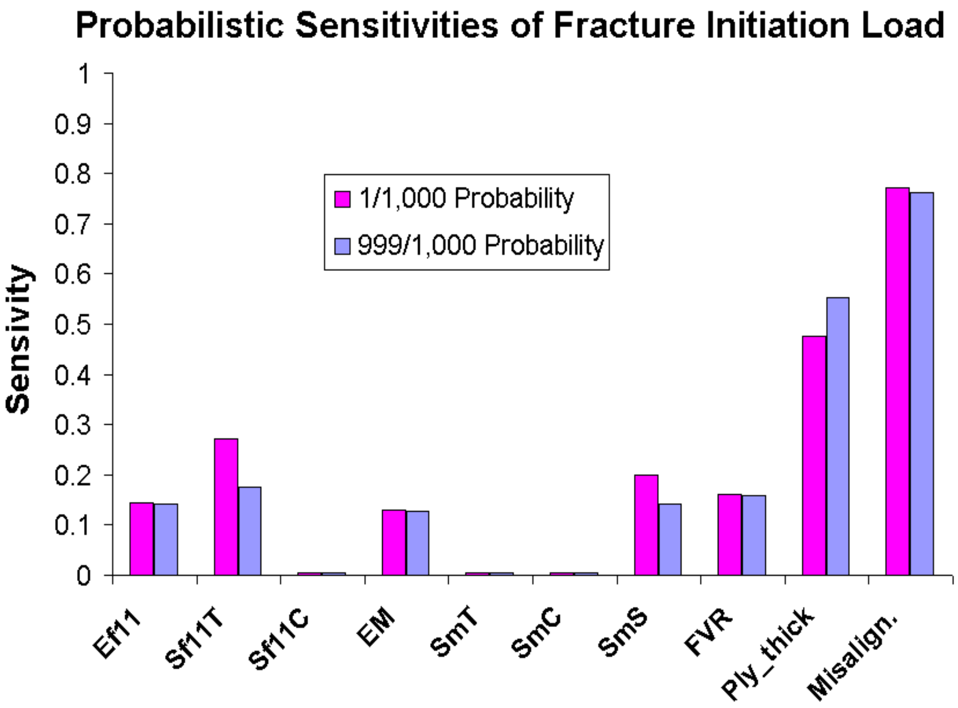
Reference: G. Abumeri, F. Abdi, M. Baker, M. Triplet and, J. Griffin **"Reliability Based Design of Composite Over-Wrapped Tanks".** SAE World Congress, 2007, 07M-312, Detroit Mi, April 2007

Probabilistic Evaluation

Fracture Initiation Load of Composite Tank

cont'd





<u>Test Fracture Internal Pressure</u>

4,890 to 5,303 psi corresponds to cumulative probability of 0.425 to 0.70;
Test Average: 5,057 psi GENOA 50% Probability Prediction: 4,950

Methodology is applicable to all types of materials and structures

<u>Reference:</u> G. Abumeri, F. Abdi, M. Baker, M. Triplet and, J. Griffin **"Reliability Based Design of Composite Over-Wrapped Tanks".** SAE World Congress, 2007, 07M-312, Detroit Mi, April 2007

Conclusion

- **Manufacturing process & subsequent durability & damage tolerance/Reliability under service load**

- **Multi-scale progressive failure analysis (MS-PFA).**
  - composite material characterization and qualification considering the manufacturing defects and scatter;
  - prediction of residual stresses due to manufacturing,
  - prediction of leakage/slippage, delamination initiation/growth between plies, location of burst,

- **Integration of manufacturing, progressive failure, and probabilistic analysis**

- **Low Fidelity**: use of FE layered shell element designed to achieve an overall durability, reliability and layup optimization to achieve a minimum damage,
  - higher strength/burst pressure

- **High Fidelity**: use of FE layered solid element designed to evaluate detailed damage initiation/progression in-and out-of-plane,
  - provide with information such as equipment boss contact stresses with composite layup and gas slippage. It determines damage mode, composite leakage.

AIAA Standards Program Overview

Composite Pressure Vessel Conference

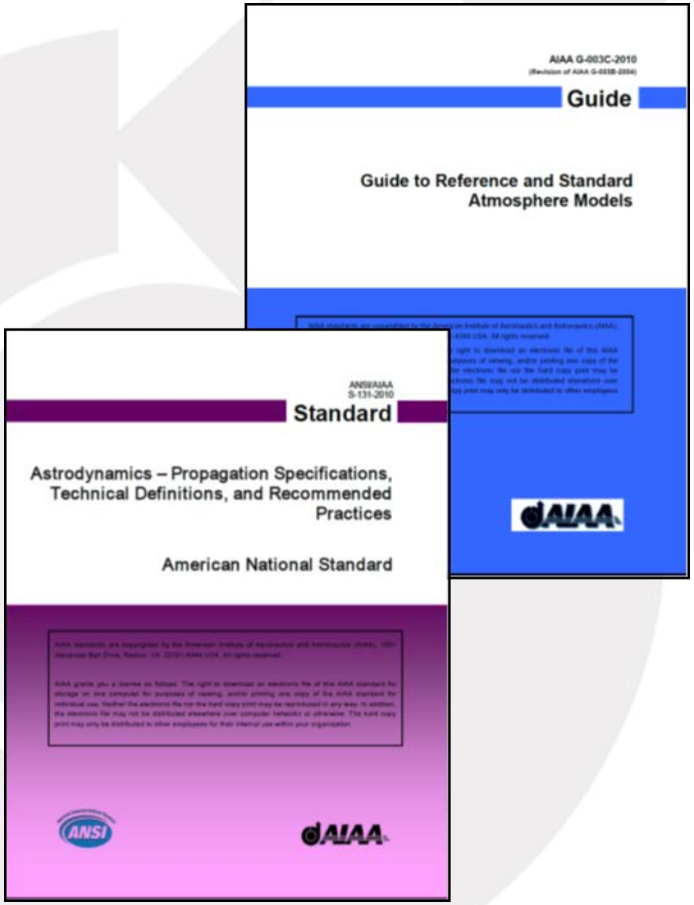
16 August 2012

Las Cruces, NM

The World's Forum for Aerospace Leadership

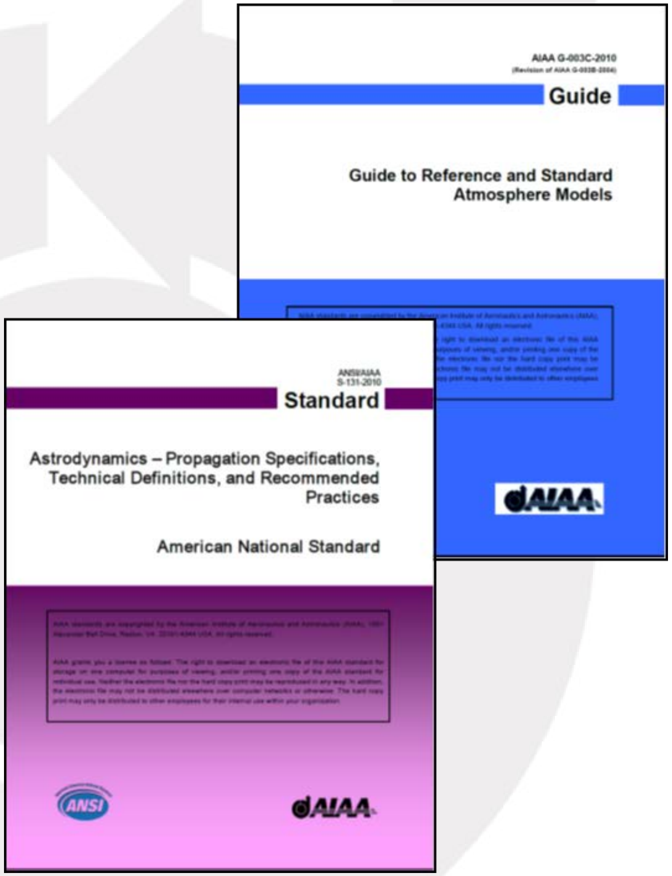
Overview

- Benefits and principles of standards
- International participation
- Who develops standards
- National participation
- AIAA Standards



Benefits of Standards

- Economies of scale
- Expanded trading possibilities
- Indirect network effects
- Establish a common technology base/technical integrity
- Support legislation and regulatory matters
- Support preparation of requirements for development of products
- Support preparation of operational procedures for systems
- See also www.standardsboostbusiness.org

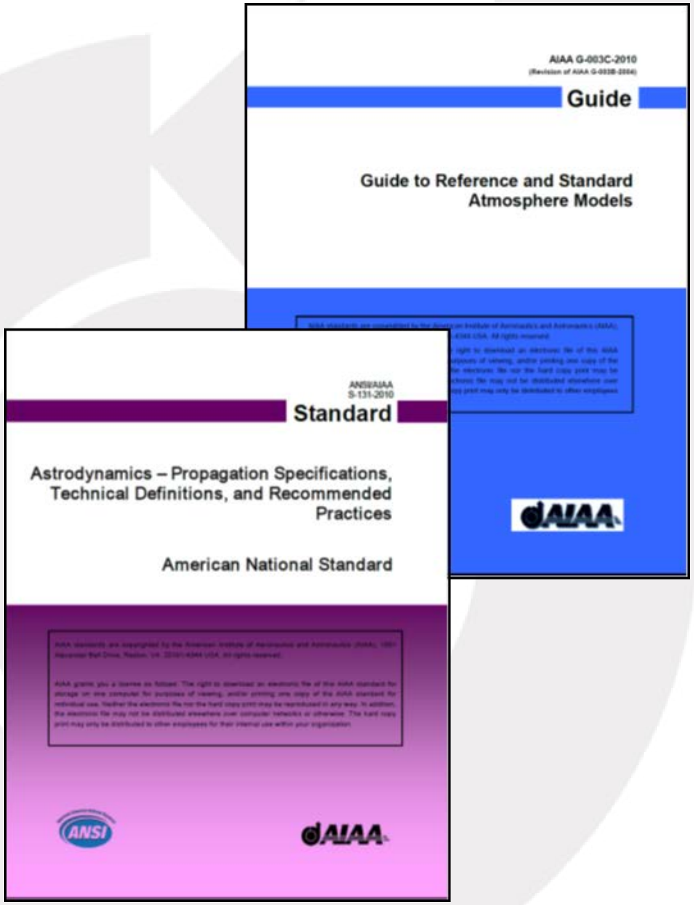


Principles of Standards

- Transparency
- Openness
- Impartiality
- Consensus
- Performance based
- Coherence
- Due process

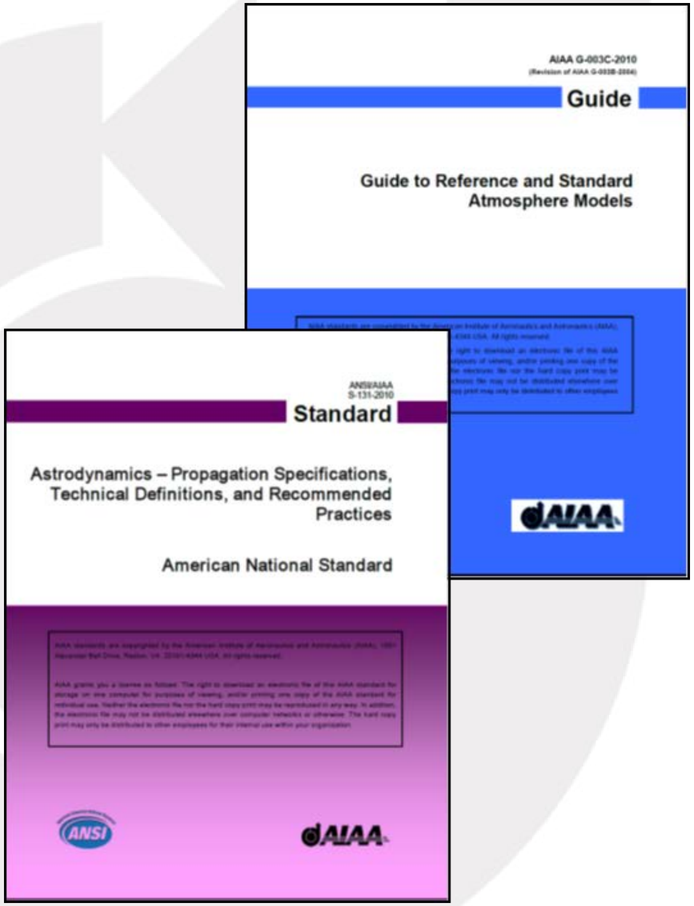
The process is

  – Flexible
  – Timely
  – Balanced



AIAA is an ANSI accredited Standards Development Organization (SDO)

- Reaffirmed by the American National Standards Institute in December 2010; will undergo the reaccreditation process in 2015
- Accreditation adds value to the standards process/development
- Ability to add the “American National Standard” moniker
- Required by certain government contracts (e.g., CCSDS)



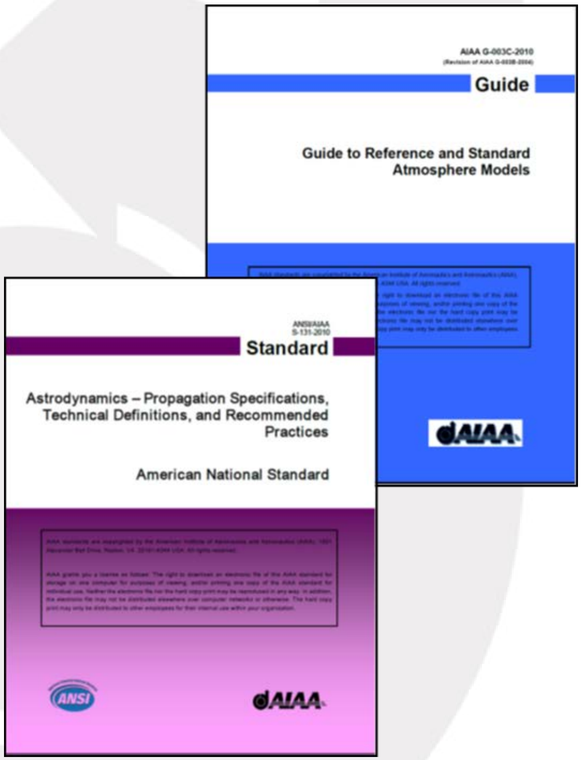
Standards Program at AIAA

- AIAA Secretariat for two sub-committees under ISO TC20 Aircraft and Space Vehicles
  - SC14 Space Systems and Operations
  - SC13 Space Data and Information Transfer Systems

- Administers the U. S. Technical Advisory Groups TAGs) for both Sub-Committees
  - SC14 has 7 working groups with corresponding sub-TAGs at the U.S. level
  - WG 1 Program Management
  - WG 2 Interface, Integration, and Test
  - WG 3 Ground Support
  - WG 4 Space Environment
  - WG 5 Program Management
  - WG 6 Materials and Processes
  - WG 7 Orbital Debris

Domestic Standards at AIAA

- Currently 58 standards, guides, recommended practices, and special projects are available on the AIAA Standards web site
- There are more than 40 documents being developed within various Committees on Standards



Oversight of the AIAA Domestic Standards Program

- AIAA Standing Committee, Standards Executive Council
  - 14 members of the SEC representing a balance of interests from a range of organizations
  - Laura McGill, Raytheon, VP Standards
  - Technical Activities Committee liaison serves to bridge information between the Standards Program developments and TC and PC standards activities
- Eleven Committees on Standards
  - CoS Chairperson required to be a member of AIAA
  - Participants not required to be AIAA member
- Approved by ANSI

Sampling of AIAA Committee on Standards

- Atmospheric and Space Environments
  - Guide to Reference and Standard Atmosphere Models (AIAA G-003C-2010)
  - Guide to Reference and Standard Ionosphere Models (ANSI/AIAA G-034A-201X)
  - Kent Tobiska, Lead
- Hydrogen
  - Guide for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation (AIAA G-095-201X)
  - Steve Woods, Lead with Steve McDougle, Co-Chair
- Systems Engineering
  - Space Systems Verification and Program Management Process (AIAA S-117-2010)
  - Guide for the Preparation of Operations Concept Documents (ANSI/AIAA G-043A-2012)
  - Systems Integration Assessment Guide (G-135-201X)
  - Satoshi Nagano, Lead

Sampling of AIAA Committee on Standards

- Aerospace Pressure Vessels
  - S-080 Space Systems—Metallic Pressure Vessels
  - S-081 Space Systems—Composite Overwrapped Pressure Vessels
  - S-089 Space Systems—Composite Pressurized Structures
  - SP-088 Special Project Report: COPV Damage Detection Handbook
  - Nathanael Green, Lead

Areas for Participation in AIAA Standards Program

- Serve on Committee on Standards currently under development
- Propose an AIAA Standard, Guide, or Recommended Practice for development
- Organize a Committee on Standards and provide leadership accordingly
- Serve as a reviewer of AIAA Standards, Guides, or Recommended Practices
- Serve on the Standards Executive Council
- Provide sponsorship support for the program

QUESTIONS?

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AIAA

The World's Forum for Aerospace Leadership

Composite Conference 2012

ISO Composite Pressure Vessel Codes and Standards

Norman L. Newhouse, Ph.D., P.E., Lincoln Composites

ISO Procedures

- ISO develops standards for international use
- ISO procedures for development of standards are available on-line
- ISO standards must be reviewed periodically, and either confirmed, revised, or withdrawn
- Technical Management Board (TMB) is highest level ISO group
- Technical Committees, and their Sub-Committees if needed, operate under the TMB

ISO Committees with Composite PV Standards

- ISO TC 58 – Gas Cylinders
  - SC2 Cylinder fittings
  - SC3 Cylinder design
  - SC4 Operational requirements
- ISO TC 197 – Hydrogen Technologies
- Other TCs/SCs also have some PV coverage
- Working Groups operate under each TC and SC

US Activity for ISO Standards

- ANSI represents the US in ISO, including on TMB
- US has a Technical Advisory Groups (TAG) for each ISO group (TC and SC)
- Compressed Gas Association is the secretariat for TC 58 and TC 197
- TAGs formulate US positions on issues, conduct votes as required on CD, DIS, and FDIS drafts
- TAGs may propose new work items through ANSI
- Experts serve independently on Working Groups developing standards

ISO 11119 Composite Cylinder Standards

- Transportable composite cylinders
- -1: Hoop wrapped cylinders
- -2: Full wrapped, load sharing liner
- -3: Full wrapped, non-load sharing liner
- Up to 450 L water capacity
- Up to 6280 psi service pressure
- Currently in revision, and in final approval process

ISO Fuel Container Standards

- ISO 11439
  - Natural Gas Vehicle Fuel Containers
  - Metal and composite construction
  - No limit on size or pressure
  - Currently in revision
- ISO/TS 15869
  - Hydrogen Gas Vehicle Fuel Containers
  - Metal and composite construction
  - No limit on size or pressure
  - Currently a technical specification
  - In development as an international standard

ISO Composite Tube Standards

- ISO 11515
  - Transportable composite tubes
  - Based on ISO 11119
  - Volumes from 450L to 3000L
  - Service pressure to 15,450 psi
  - Currently in development, in final approval voting
- ISO 17519
  - Composite cylinders for tube trailers
  - Based on ISO 11439
  - Volumes from 450L to 10,000L
  - No limit on service pressure
  - Currently in development

ISO Stationary Composite Tanks

- ISO 15399
  - Stationary tanks for hydrogen storage
  - Up to 10,000L water capacity
  - Up to 16,000 psi service pressure
  - 15 to 50 years service life
  - Currently in development

WG24 – Guidance for Composite Vessel Design

- Addressing underlying technical issues/foundations
- ISO TR 13086-1 published
  - Stress ratios of fibers
  - Burst ratios related to test pressure
- ISO TR 13086-2 in initial development
  - Calculation of stress ratios
  - Cyclic fatigue issues
  - Bonfire test issues

UN Adoption of ISO Standards

- United Nations Committee of Experts on the Transport of Dangerous Goods
  - Develops “Model Regulations” (aka “Orange Book”)
  - Generally adopts ISO Standards, may make some modification of requirements
- US DOT may adopt standards included in the UN Model Regulations into 49 CFR

Summary

- ISO develops standards in accordance with established procedures
- Gas cylinder and pressure vessel standards have been developed, and are being developed, under ISO
- ISO standards are periodically updated as appropriate
- ISO standards may be included in the UN Model Regulations
- UN Model Regulations may be incorporated into 49CFR by DOT

AFSPCMAN 91-710 Status

16 Aug 2012

Robert Geuther
45 SW/SEAN

Overview

- Purpose
- Update Status
- Alternatives
- Summary

Purpose

- Update the Status of AFSPCMAN 91-710

- Discuss Alternative Means of Incorporating Changes

AFSPCMAN 91-710 Status

- Current version approved 1 Jul 2004
- Calls for updates at least every four years
- Change Requests have been submitted and compiled
- Update in work, but slowed due to available manpower
  - Initial version (7 Volumes, 985 pages) employed several people to write in addition to the Safety Staffs at HQ AFSPC and the 30th and 45th Space Wings

Alternate Means of Changing

- **Tailoring of AFSPCMAN 91-710 Continues**
  - **Tailoring is program specific**
  - **As long as the tailoring is non-proprietary, it can be shared with other programs**
  - **Sharing would allow for consistency between programs**

Alternate Means of Changing (Cont.)

- **Policy Letters or Supplements to AFSPCMAN 91-710**
  - **Addresses new technologies or lessons learned not covered in the current safety requirements**
    - **Lithium-Ion Batteries an example**
  - **Can be used by any program**
  - **Coordinated with HQ AFSPC/SE, 45 SW/SE and 30 SW/SE**

Alternate Means of Changing (Cont.)

- NASA STD 8719.24
  - Tailored version of AFSPCMAN 91-710 for NASA ELV Payloads
  - May be used by any NASA ELV Payload program
  - Open for reviews and may have updates in addition to a revision when AFSPCMAN 91-710 is updated
  - Coordinated with 45 SW/SE and 30 SW/SE

Summary

- **While HQ AFSPC/SE is working on the next revision to AFSPCMAN 91-710, there are means of capturing requested changes and updates and sharing the changes with other programs**
- **45 SW/SEA is ready to assist**

Composite Conference 2012

Aerospace Composite Standards Update

Nathanael J. Greene
NASA White Sands Test Facility
Composite Pressure Vessel Core Capability Manager

Aerospace Composite Pressure Vessel Standards Harmonization Status

- Initiated an international effort to coordinate harmonize aerospace composite pressure vessel standards in October 20-21st, 2008 in Rome at the IAASS Space Safety COPV Workshop (http://www.congrex.nl/08a11/copv.asp)

Progress

- Three draft ground safety standards have been developed:
  - Requirements for processing composite overwrapped pressure vessels (COPVs) for space flight, proto-flight and aircraft payloads not meeting standard DOT/FAA certification criteria
- The three draft ground safety standards are for ground processing of:
  - Composite Pressure Vessels
  - Composite Pressurized Structures
  - Metallic Pressure Vessels
- Three standards to be implemented at KSC as a pathfinder
  - After KSC use propose use nationally and internationally
  - Will remove the 1.1 proof test outlined in the 1993 Interim Policy Letter if mechanical damage control plan is followed

Meetings

- Meetings
  - 3RD IAASS COPV Safety and Integrity Workshop, Oct. 21, 2008 (Rome, Italy)
  - NASA-Air Force KSC COPV Safety TIM, Dec. 8, 2008 (Cape Canaveral, Fl)
  - WSTF Composite Pressure Vessel and Structures Summit, Sept. 22-24th, 2009 (Las Cruces, NM)
  - ANSI/AIAA COPV Working Group, Dec. 8-9, 2009 (S-081B, S-082, S-089), (Norwood, NJ)
  - COPV Special Session of the 4th IAASS conference, May 19, 1010 (Huntsville, AL)
  - Composite Pressure Vessel Ground Processing Safety Requirements Review, February 8, 2011 (Cape Canaveral, FL)
  - Joint AIAA/ASME/ASTM and NIST Working Group Meeting at NASA WSTF, August 17 (Las Cruces)

Initial Focus

- The team has focused work on review of ground processing safety requirements including KNPR 8715.3, Air Force COPV ground safety requirements documents (1993 memo on Interim safety requirements for COPV processing, Air Force Space Command Manual (AFSPCMAN) 91-710, and (EWR 127-1), Mil-STD-1522, the aerospace industry COPV standards (ANSI/AIAA S-081& ANSI/AIAA S-081A), and the NASA PV Technical Monitor COPV memos (ES4-08-043, ES4-0-031).

Item	Topic	Item	Topic
1	Damage Control Plan	8	Chemical Compatibility (Exclude from G.S.)
2	Composite Visual Inspection	9	Emergency Response Plan
3	Safety Clears for Workaround	10	1.1 Proof Test (Remove if DCP followed)
4	Blast Analysis	11	Stress Rupture
5	Storage	12	Fatigue and Crack Growth Failure Mode
6	Transportation	13	Design Requirements (Exclude from G.S.)
7	Overpressure	14	Data Package

Path Forward

- Implement three ground safety standard sections at KSC
- Discuss ground safety updates to ANSI/AIAA S-081, NASA WSTF August 17th.
- Meeting with Air Force 45th and 30th Space Wing harmonize with AFSPCMAN 91-710 updates
- Meeting with international community
  - Propose deleting the 1.1 proof test if mechanical damage control plan is followed (6th IAASS Space Safety Conference?)

Composite Conference 2012

ANSI/AIAA S-081

Lorie Grimes-Ledesma
Jet Propulsion Laboratory
Nathanael Greene
NASA White Sands Test Facility

History and Participation

- Work started in 1998 to address COPV-specific needs for aerospace
- Intent to rework/update requirements in MIL-STD-1522A
- S-080 (all metal pressure vessels) started in 1996 followed by development of S-081-2000
- Requirements in S-081 for liners are based on requirements in S-080
- S-081A adopted in 2006
- Participation from NASA, DoD, FAA, commercial spacecraft/launch providers, COPV suppliers in the USA

S-081 Updates

- Addressed composite issues
  - Stress rupture
  - Impact damage
  - Material and process control requirements for composites
- Added verification requirements
  - Acceptance tests for flight tanks:
    - "transportation" proof (1.1x maximum expected operating pressure)
    - Exterior examination for visual impact sites
  - Qualification tests
    - Option to demonstrate LBB or safe-life demonstration via coupon or vessel test

Impact Damage

- USAF/NASA test program to support development of impact damage requirements
- Tests provided substantiation that impact damage reduces burst strength

Impact Damage Requirements

- Requirement to address via process control:
  - Damage control plan with risk assessment
  - Visual inspection

Or

- Requirement to address via impact damage tolerance demonstration
  - Barely visible impact damage (dependent on visual inspection)
  - Verification that a COPV with barely visible of strength requirements

Fracture Control Requirements

- ANSI-AIAA S-081 requires either leak-before-burst (LBB) or safe-life
  - Analysis or test location determined based on approach
  - Crack location and orientation must be considered

- LBB is about crack stability in the liner for an assumed crack of defined size

- Safe life is about crack depth and length growth of an NDE-defined initial crack during 4 mission duty life cycles

Review of LBB Requirements

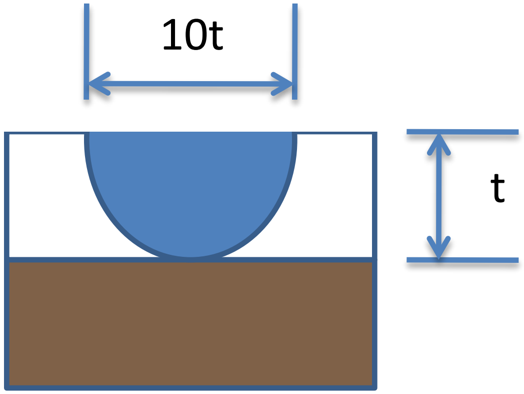
- Definition: a design approach in which, at and below MEOP, potentially pre-existing flaws in the metallic liner, should they grow, will grow through the liner and result in pressure-relieving leakage rather than burst or rupture

- Demonstrate that an initial part through crack results in K<Kc and when length is 10xthickness

- For elastically responding liner (elastic after autofrettage), LEFM approaches are acceptable

- Coupon and/or COPV testing are allowed. Coupon cracks must result in a crack with length 10xthickness. COPV tests must contain crack(s) in worst case location and LBB is demonstrated when one or more break through and result in leakage.

- Range of 0.1 to 0.5 a/2c must be used



Review of Safe-Life Requirements

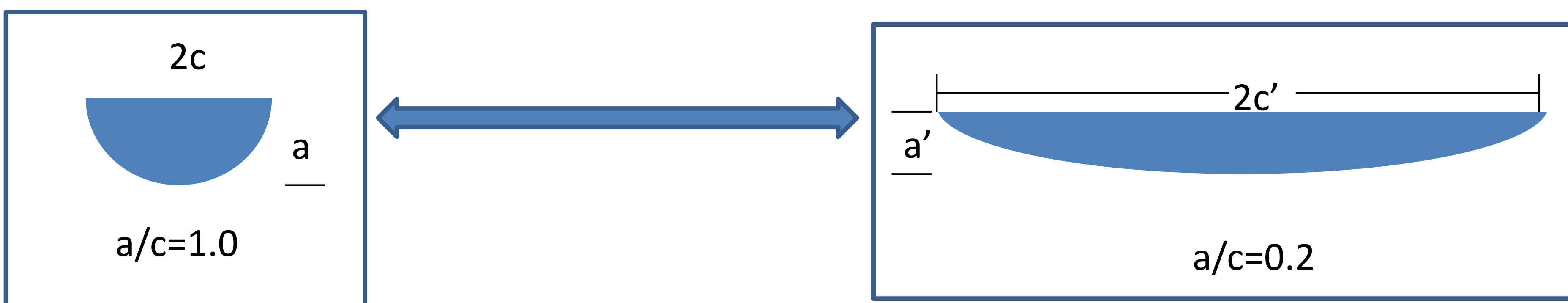
- Definition: the required period of time or number of cycles that the metallic liner of a COPV, containing the largest undetected crack shown by analysis or testing, will survive without leaking or failing catastrophically in the expected service load and environment

- Demonstrate 4 x service life with initial crack in the most critical and unfavorable orientation and defined by 90/95 POD

- For elastically responding liner (elastic after autofrettage), LEFM approaches are acceptable

- Coupon and/or COPV testing are allowed. Two surface cracks shall be tested.

- Range of 0.1 to 0.5 a/2c must be used



Stress Rupture

- The COPV shall be designed to meet the design life considering the time it is under sustained load. There shall be no credible stress rupture failure modes based on stress rupture data for a probability of survival of 0.999.
- To meet the stress rupture requirements, the lowest fiber reinforcement stress ratio at MEOP shall be: Carbon = 1.5, Aramid = 1.65, Glass = 2.25
- Other materials shall have stress rupture data and reliability analysis comparable to the materials listed above to support a given stress ratio at MEOP

Models typically used by industry to address this requirement and determine stress rupture threats for are not supported by an adequate set of experimental data

S-081A

- S-081A adopted in 2006
- Primary difference:
  - Requires demonstration by analysis or test of both LBB and safe-life

  -Smaller differences:

    -reliability requirement removed for stress rupture

    -service life definition, autofrettage definition

    -proof test hold time removed

Forward Work

- Revise S-081A to include changes in requirements for:
  - Fracture control demonstration
  - Impact damage
  - Stress rupture
  - Mechanical response verification (liner and composite)
  - Ground safety requirements

Assessing knowledge gaps for hydrogen vehicle and infrastructure codes and standards

Panelists: Norman Newhouse, Lincoln Composites
Mark Toughiry, DOT/PHMSA
John Koehr, ASME

Moderators: David McColskey, NIST
Chris Moen, Sandia National Laboratories

Hydrogen Compatible Materials Workshop 2010

- **Goals:** 1) Identify gaps in H2 compatible materials R&D
  2) Develop international R&D pathways to address gaps
- **Attendees:** ~30 people from research labs, government, industry, and standards development organizations

- **Output:** identification of high-priority gaps in data and phenomenology, technology, and codes and standards
  - Influence of welds on H_2 compatibility of structures
  - Testing protocols for materials evaluation
  - Measurements of mechanical properties of structural metals in high-pressure H_2, in particular fatigue properties
  - Database for properties of structural materials in H_2 gas
  - High-strength, low-cost materials for long-life H_2 service

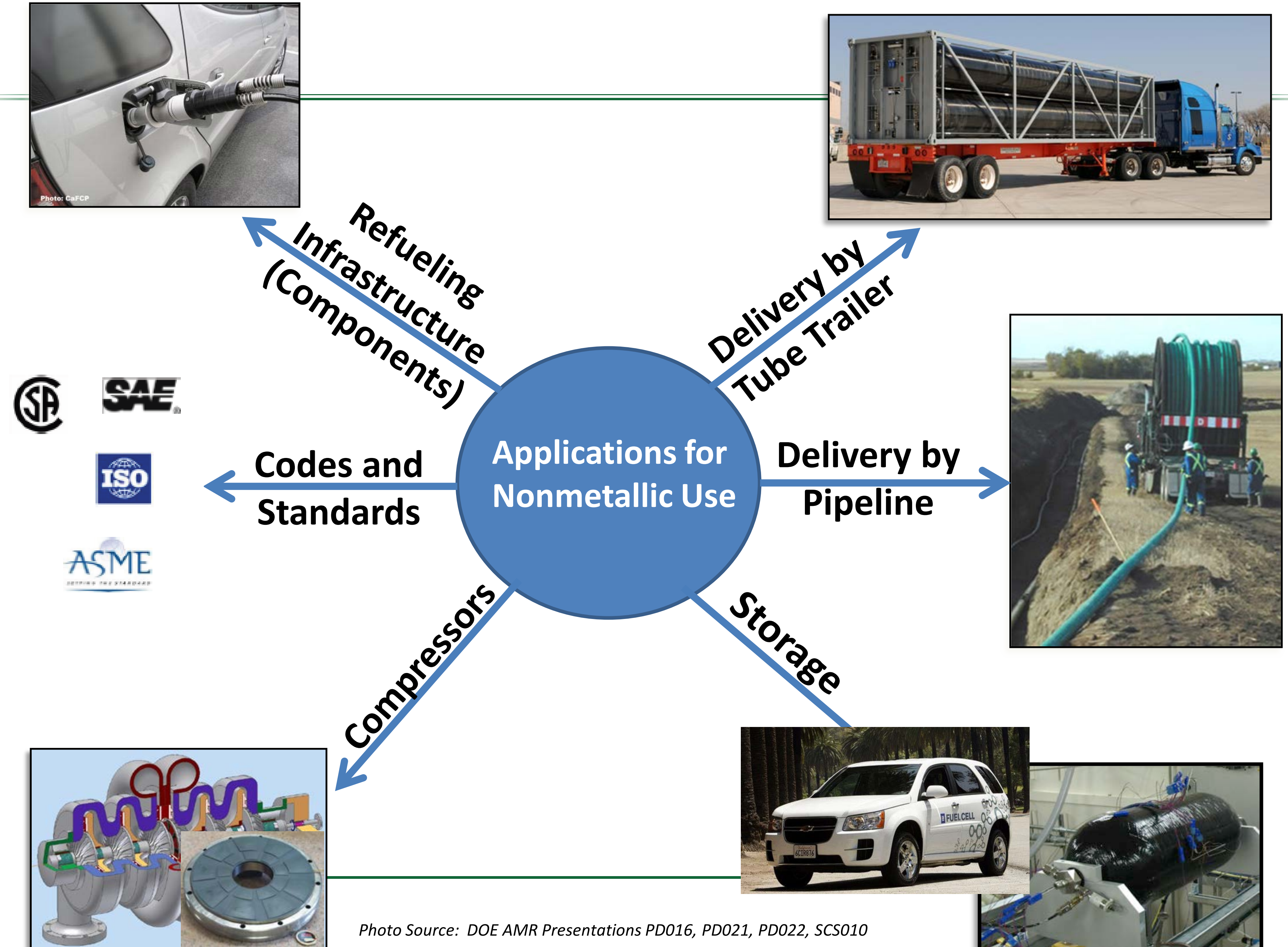


Photo Source: DOE AMR Presentations PD016, PD021, PD022, SCS010

PANELISTS:

- What are the critical knowledge gaps that may hinder the widespread application of composite material systems for automotive hydrogen service at high pressures and ambient and cryogenic temperatures?
- What sort of material characterization, test protocol validation, or lifecycle analysis research would be of value?

PANELISTS & AUDIENCE:

- What can the automotive vehicle/infrastructure industry learn from other industries?
- Are there any new or developmental C&S that can be adapted?
- Are there any partnerships that could be formed to better address needs?

Backup

Standards activities need material performance information

- **CSA CHMC1**
  - Materials testing and data application standard
  - Phase 2 beginning to look at polymers
- **SAE J2579**
  - Fuel systems in fuel cell and other hydrogen vehicles
  - Need material performance at temperature extremes
  - Validation of proposed performance-based verification of stress rupture
- **SAE J2601**
  - Fueling protocols for light duty gaseous hydrogen surface vehicles
  - Need material performance at temperature extremes
- **ASME B31.12**
  - Hydrogen piping and pipelines
- **ISO 11114-2**
  - Gas cylinders -- Compatibility of cylinder and valve materials with gas contents -- Part 2: Non-metallic materials

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Knowledge Gaps Hydrogen Cylinder Codes & Standards

Norman L. Newhouse, Ph.D., P.E.
Lincoln Composites

Materials of Construction

- Steel cylinders, liners, and bosses
- Stainless steel cylinders, liners, and bosses
- Aluminum alloy cylinders, liners, and bosses
- Polymer liners
  - HDPE is common
  - Other materials are being used
- Reinforcing fibers
  - Carbon
  - Glass
  - Aramid
  - Steel
- Resins
  - Epoxy
  - Vinyl Ester
- Other materials are found in o-rings, PRDs, valves, fittings, piping, and other components

Basic Considerations

- Cylinders, liners, and bosses are exposed to full hydrogen pressure
- Reinforcing fibers are exposed to hydrogen pressure only to the extent the composite is saturated with hydrogen
- Hydrogen saturation levels in components rise with pressure increase, fall with pressure decrease
- Temperatures rise during fill, fall during discharge
- Pressures increase with rising temperature

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Conference Study of Research Needs

Moderators
Nathanael Greene, NASA WSTF
and David McColskey, NIST

NDE/Structural Health Monitoring

- Shearograpy vs. MSC and other techniques
- Hyphenated MSG through thickness characterization
- Integration of experimental techniques and analytical modeling
- Accept reject criteria that ties back to quantitative NDE and a validated structural model
- Validated NDE for class of vessel
- Need to know the affect of defects on performance
- Quick and inexpensive NDE for broad use in industry
- Reliability of NDE/SHM measurements
- Definitive criteria for shearography
- Need NDE standards that result in probability of detection thresholds (POD)
- NDE accept reject criteria appropriate for the application
- NDE must be cost effective relative to the cost of the pressure vessel
- Identify opportunities for data sharing Inter-government, inter-industry and international
- Perform a risk analysis
- Minimize uncertainty
- Need a committee that will address the manufacturing issues related to the needs. We sometimes get stuck in codes and standards (not appropriate)

Structural Modeling

- Efficient modeling techniques. Possibly analytical solutions that could be used in real time. Validate with experimental measurements
- Better commonality in materials databases and methodology in the properties used
- No model that will go from fiber to lamina to component properties that will model mechanical damage and predict the failure point
- Vetting of statistical models and stochastic models
- Structural modeling should be focused on the performance of the as built composite pressure vessel

Fatigue/Fracture

- Effect of radiation on COPV
- Two stage fatigue (low vs. high cycle fatigue)
- Understand how design drives the failure modes of the COPVs
- Standards for fatigue and fracture (procedural standards)
- Dissemination of critical flaw size for all known liner materials and thicknesses (could be configurationally dependent)
- Elastic-Plastic liner fracture
- Modeling autofrettege from a fatigue perspective
- Affect of impact damage on stress rupture life
- Increased focus on fatigue testing (liners)

Testing/Qualification

- Pneumatic testing and effects of failure mode and fragmentation
- Effects of fast fill on composite pressure vessels
- Cryogenic environments and fluids
- Testing and qualification based on application (e.g. fast filling)
- Fluid media compatibility on liner materials
- Gap in measurement science for accurate mass flow during filling (better measurements needed)
- Hypervelocity testing for damage tolerance
- What is desired for processes for certification of new designs
- Coordinating with ASTM E08 on Fracture and fatigue
- Panel on what fatigue and fracture testing is required in different standards – Mark T.

Codes and Standards/Other

- Clear differentiation between AIAA/ASTM/ASME coverage

Other Gaps

- Vet fast fill proposals to make sure there are no adverse material affects

Future Action

- NASA White Sands Test Facility coordinating interagency and international research effort
- Composite Conference 2014
  - Point of Contact

NASA White Sands Test Facility
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Thank you to our Sponsors!

- New Mexico State University DACC
- ASME
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