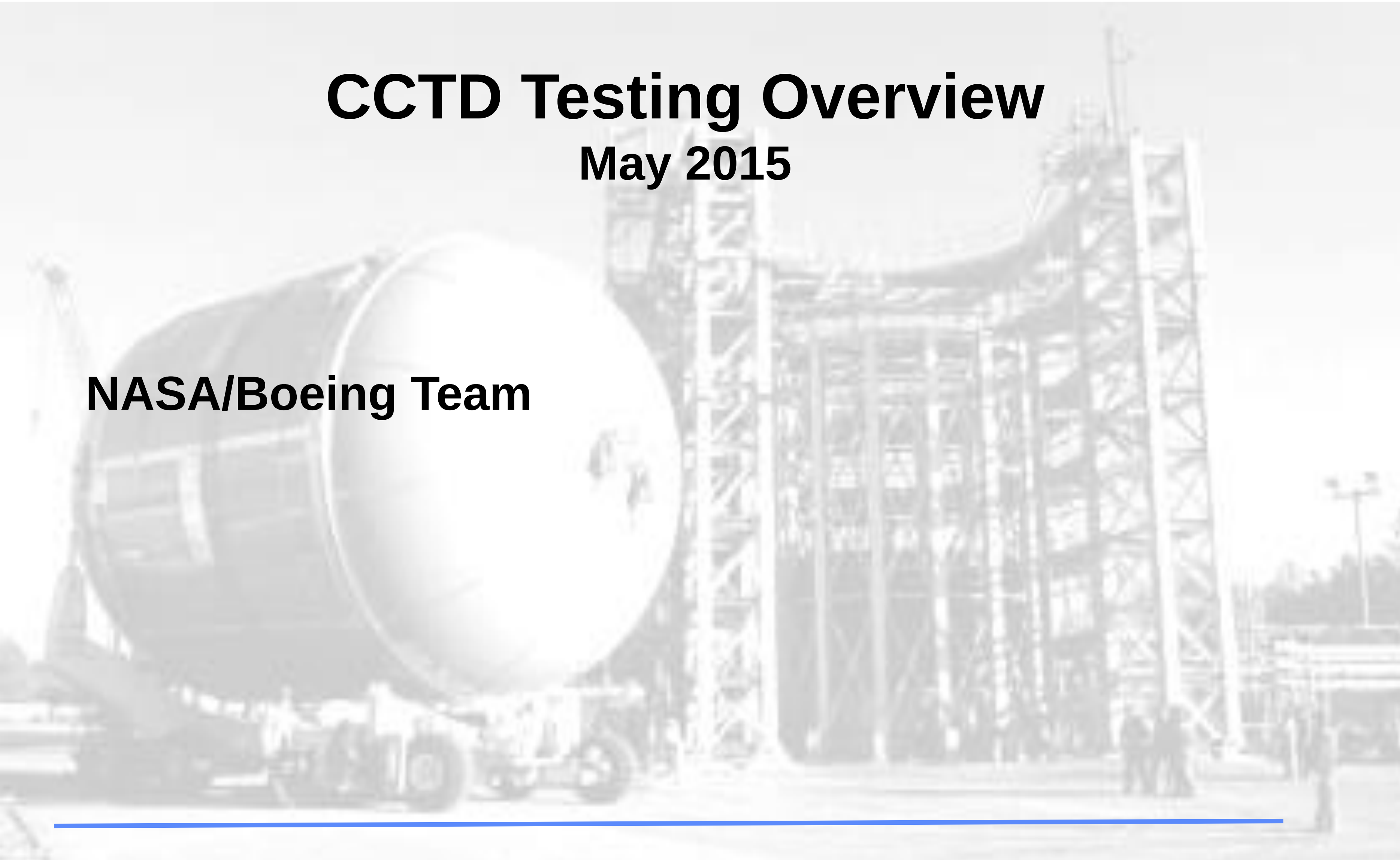
CCTD Testing Overview

May 2015

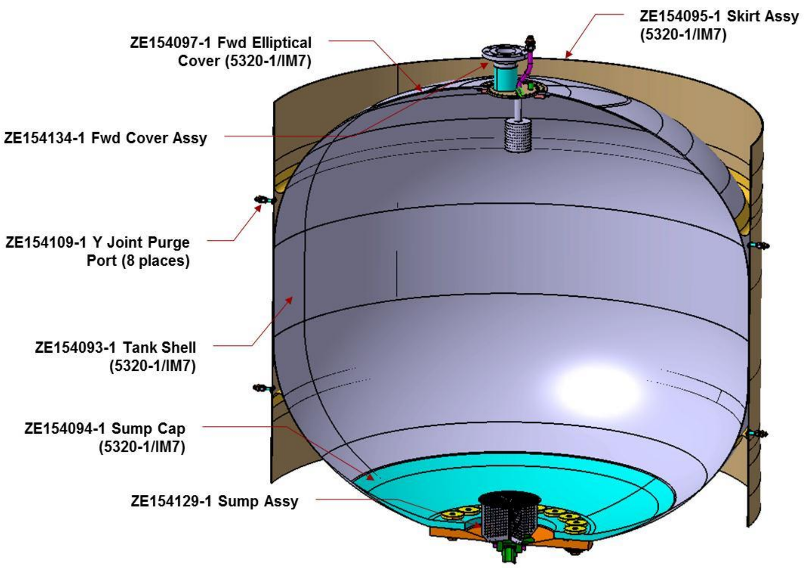


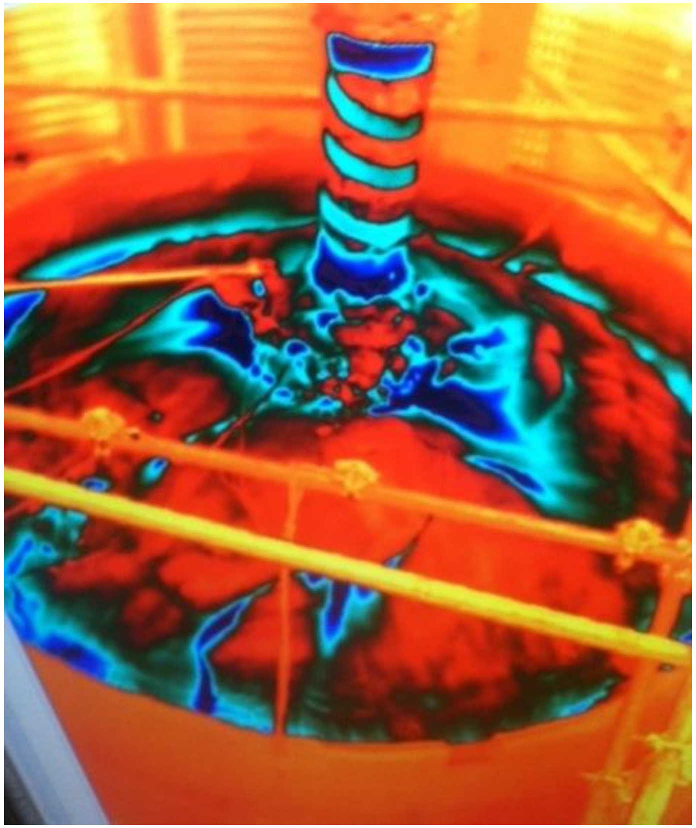
NASA/Boeing Team

2.4m Test Summary

6/25/2013:

- **135 psi achieved with tank filled with LH2**
- **20 press./de-press. cycles between 20 psi & 100 psi conducted**
- **Permeation measurements conducted at multiple test conditions:**





2.4m Thermal Image During LH2 Testing

Results Previously Presented NSMMS 2014

5.5m Test Overview

Ground Test Program

1. Ambient Pressure
2. Cryogenic Pressure
3. Ambient Pressure & Mechanical
4. Cryogenic Cyclic Pressure

Ground Test Summary

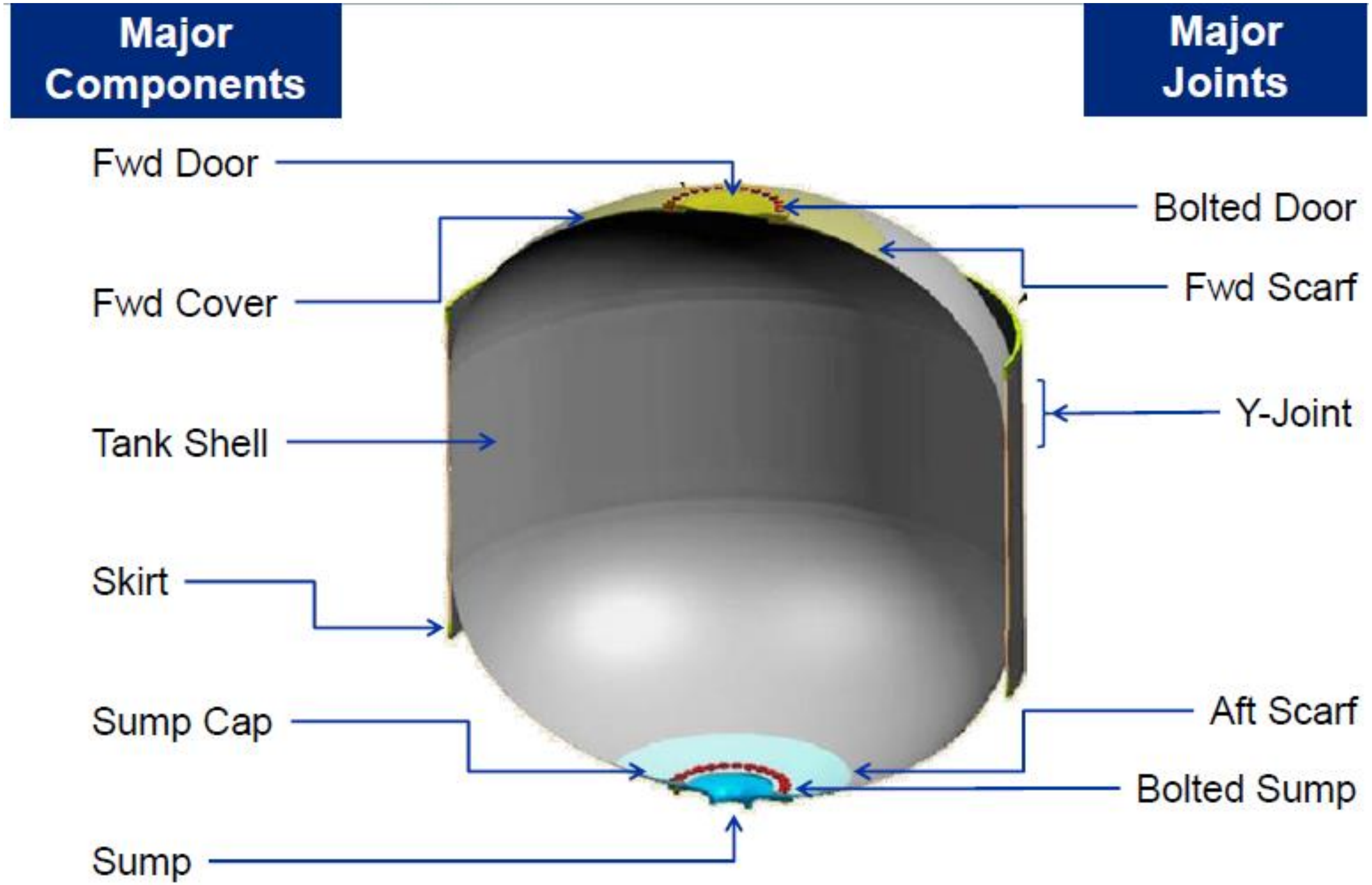
- ✓ 83 pressure cycles
- ✓ 2 thermal cycles
- ✓ 2 max pressure cases
- ✓ 1 combined load cycle

Data Acquired

- Load/strain response
- Thermal response
- Laminate permeation rate
- Bolted joint performance

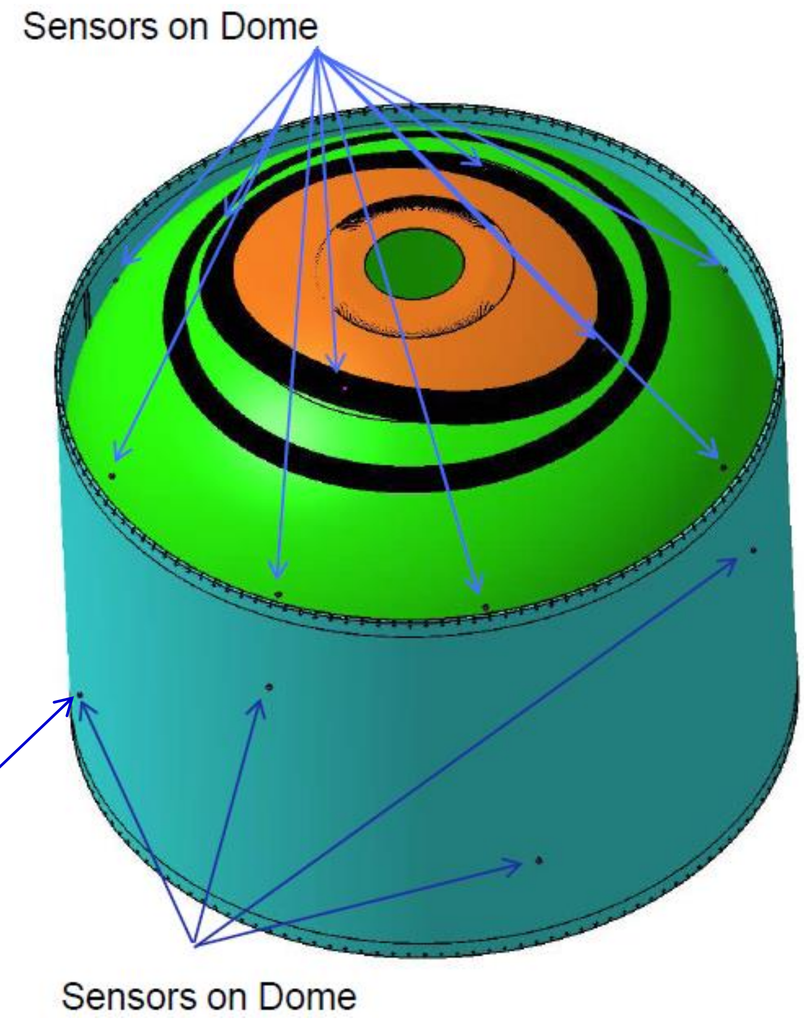
Instrumentation Reference

NASA Game Changing Development Program — Composite Cryotank Project

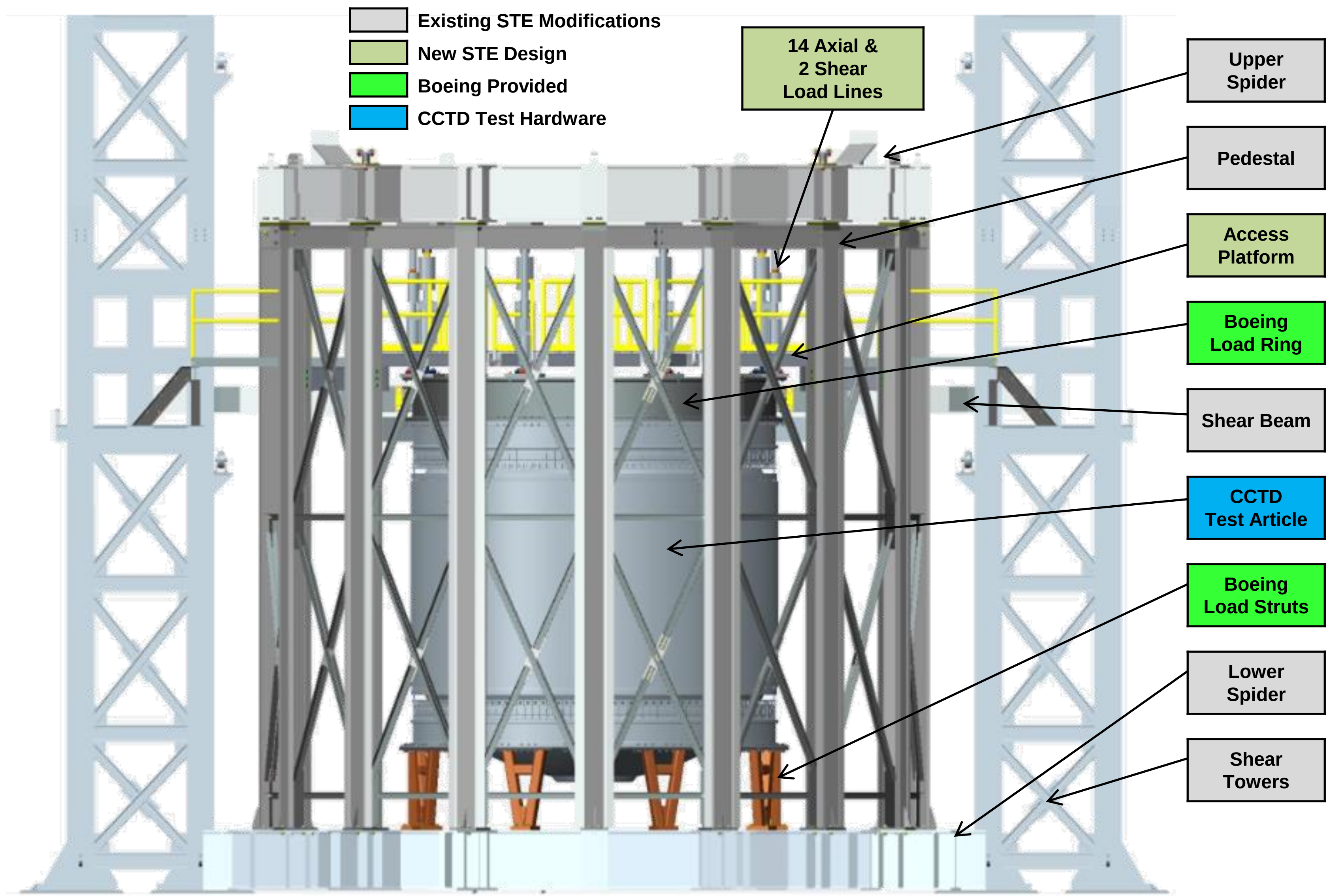


5.5m SHM Arrangement

- **AE Sensors:**
  - Thirty-two (32) acoustic emission sensors uniformly spaced around the circumference of the tank barrel and on both domes
  - Identified on Boeing SHM Instrumentation drawing, ZE154071
  - Tank barrel – four sensors evenly spaced (at 90 degrees) in forward section of tank; four evenly spaced sensors in aft section of tank offset by 45 degrees from forward sensors



5.5m Structural Test Arrangement



4699 CCTD Test Stand

NASA Game Changing Development Program

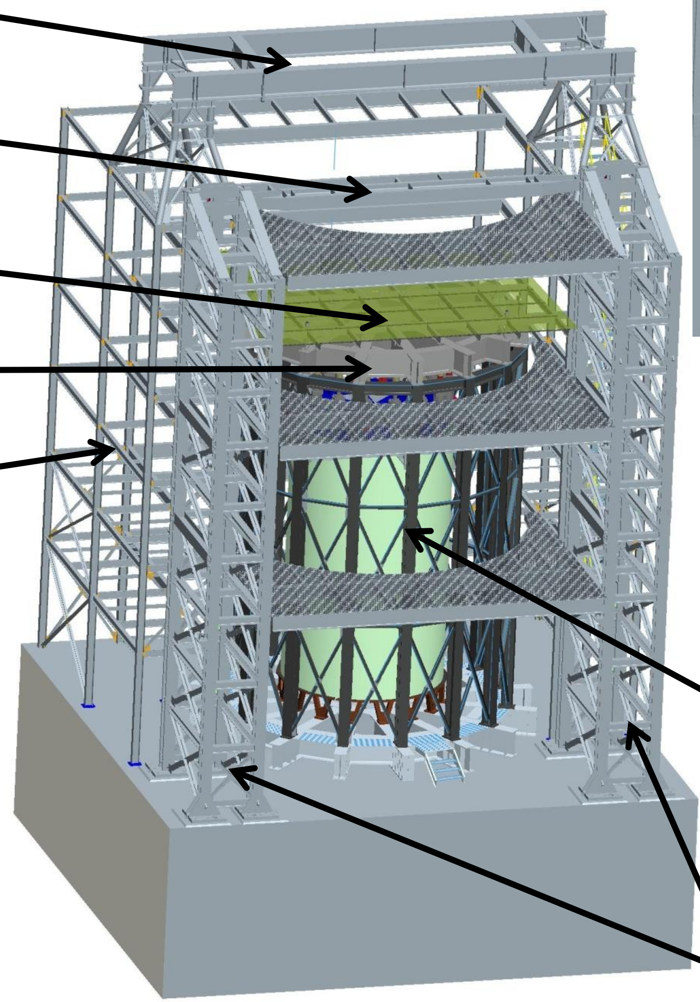
90M10449 ALTA Failure Recovery System (not used in this concept)

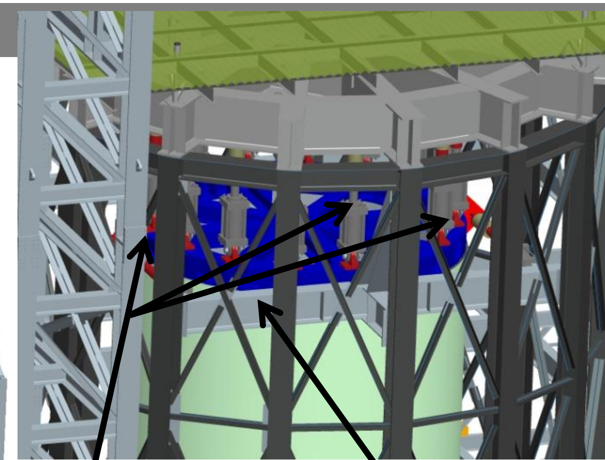
90M10553 ALTA Thrust Beam
90M10554 Thrust Fitting (not used in this concept)

90M11140 X-33 Environmental Cover Roof

90M10509 ALTA Upper Spider

90M03833 Access Tower and 3 ea removable platforms



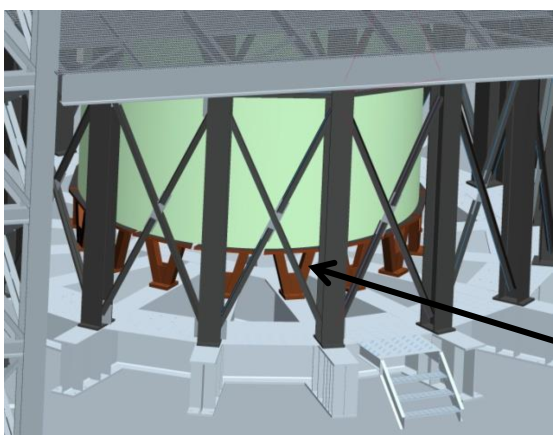


2 Shear Load Lines and 16 Axial Load Lines

90M11092 Reaction Beam

ALTA 90M10508 Pedestal (also used as environmental enclosure for X-33)

90M10503 Shear Towers



90M12374 Load Struts (16 ea.)

5.5m Test Summary

Testing Summary	Date	Type	Details
Ambient pressure test (nitrogen) was successfully conducted	5/22/2014	Ambient (Nitrogen)	Achieved target pressure and reached 80% of target strain
Liquid hydrogen cryogenic pressure test was successfully conducted	7/20/2014	Cryogenic (Liquid Hydrogen)	Achieved pressure and 100% of strain in the forward dome acreage. (Permeation samples taken)
Combined ambient pressure (nitrogen) and load test was successfully conducted	7/30/2014	Ambient (Nitrogen)	Achieved 100% desired pressure with 100% load on the tank
Liquid hydrogen combined cryogenic pressure and load test was performed	8/16/2014	Cryogenic (Liquid Hydrogen)	The test was prematurely stopped at 20% mechanical loads due to mechanical issues with applying the loads in the test facility (Permeation samples taken)
Liquid hydrogen cryogenic pressure cycle test was successfully conducted	8/17/2014	Cryogenic (Liquid Hydrogen)	Achieved our goal of 80 pressure cycles (20% to 90% max pressure) on the tank. (Permeation samples taken)
Permeation with gaseous hydrogen test was conducted	8/22/2014	Ambient (Gaseous Hydrogen)	Achieved desired pressure. Issues with a leak in facility piping and a leak in the bag prevented any useful permeation data.
Permeation with gaseous hydrogen test was conducted	8/28/2014	Ambient (Gaseous Hydrogen)	Achieved desired pressure. Obtained permeation data.

Critical Safety Factors

	Ambient	
Location	**Demonstrated** 100% target Pressure	**Demonstrated** Pressure + 100% Flight Load
Fwd Scarf	2.06	2.16
Aft Scarf	2.79	2.76
Y-Joint	6.21	4.64
Acreage	90% max allowable	92% max allowable
Local Buckling (67% of max pressure)		3.70

- Most critical areas are dominated by pressure loads
- At ambient, Y-joint is dominated by combined load case
  - Increased shear across joint

Critical Safety Factors

	Cryo	
Location	**Demonstrated** LH2 Pressure 100% achieved	Predicted / Not Tested LH2 Pressure + 20% Flight Loads*
Fwd Scarf	1.49	1.68
Aft Scarf	2.16	2.34
Y-Joint	0.53	0.52
Acreage	102% max allowable	94% max allowable
Local Buckling (67% of max pressure)		4.42

- Pressure test limited by acreage strain design limit.
- Not all Joint S.F. are above 2.0
- Buckling is above 1.5 requirement
- Y-joint strength is dominated by thermal load, not pressure or flight loads.

* Achieved 20% due to facility issues

Critical Safety Factors

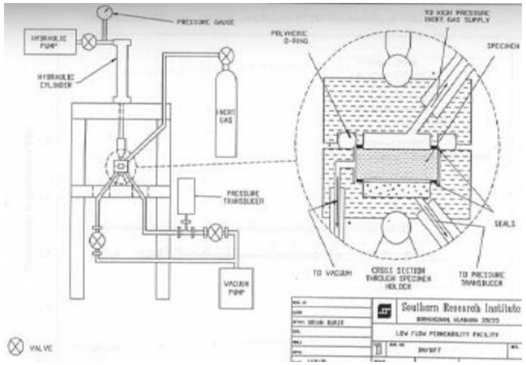
	Cryo	
Location	Demonstrated LH2 Pressure	Predicted / Not Tested LH2 Pressure + 100% Flight Loads*
Fwd Scarf	1.49 1.63(93% target pressure)	1.68
Aft Scarf	2.16 2.37(93% target pressure)	2.34
Y-Joint	0.53 0.53(93% target pressure)	0.52
Acreage	94% max strain allowable	94% max strain allowable
Local Buckling (30psi)		4.42

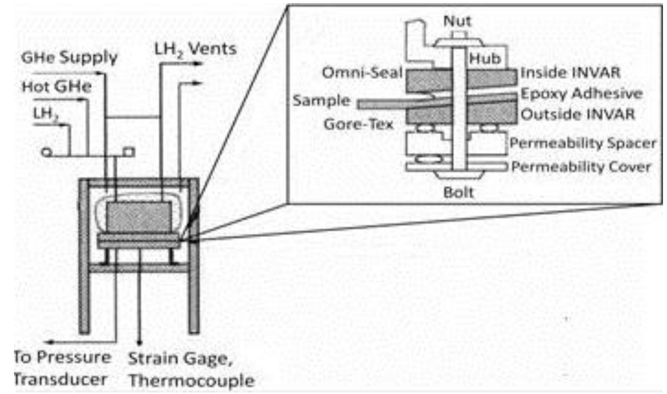
- Pressure test limited by acreage strain design limit.
- Not all Joint S.F. are above 2.0
- Buckling is above 1.5 requirement
- Y-joint strength is dominated by thermal load, not pressure or flight loads.
- **By analysis, the addition of Flight Loads do not significantly impact critical safety factors**

* Achieved 20% due to facility issues

Coupon Level Measurements

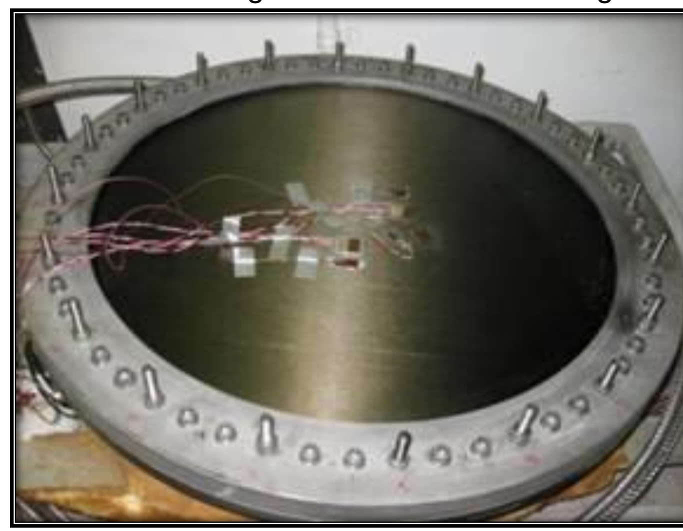
NASA Game Changing Development Program | **Composite Cryotank Project**





SRI Permeation Rig 100% In plane Loading

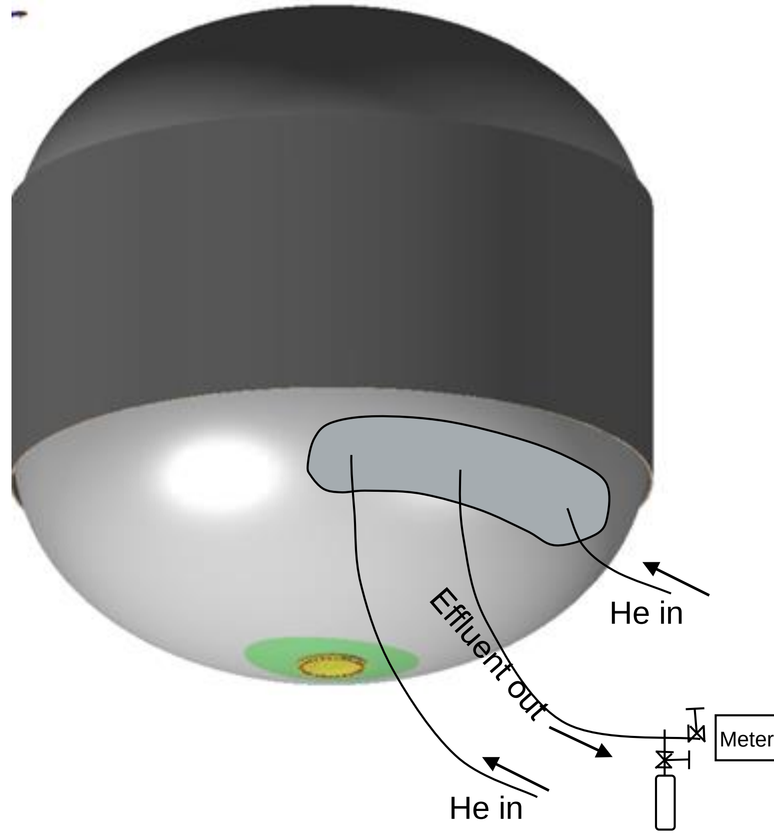
MSFC Permeation Rig 10% Mid Plane Bending Induced

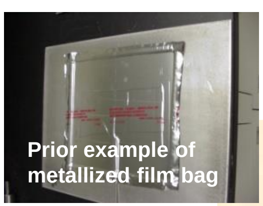


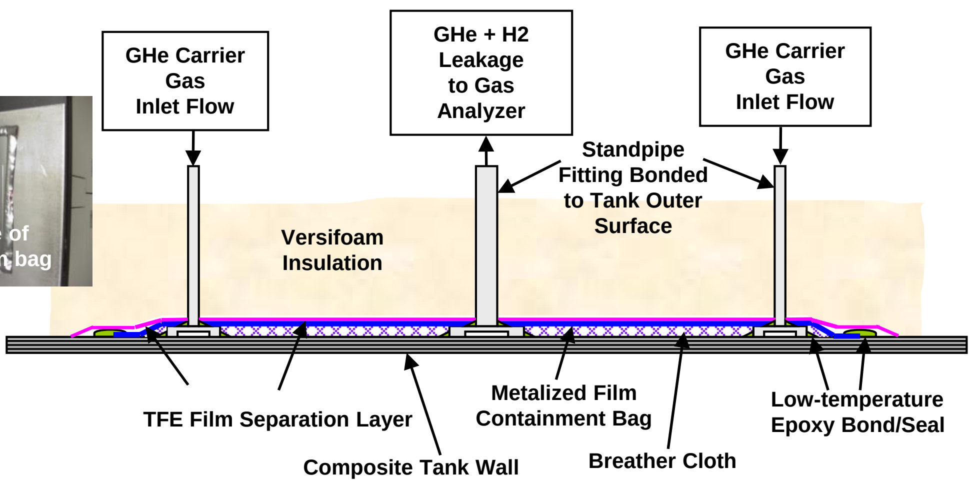
Multiple tests performed using both setups with coupons cut from same parent panel, SRI exhibited no detectable permeation on all tests. MSFC rig detected excessive permeation on all OOA cured hybrid laminates. 100% of autoclave cured laminated had 0% permeation on both tests, and all OOA cured, all thin ply laminates had 0% permeation on both tests.

CCTD In-Situ Permeability Measurement

- **Metallized film bag/Composite bag underneath foam insulation collects permeated hydrogen and helium carrier gas**
- **Bag effluent gas is collected in bottles at specified times; bottles taken to MSFC chem labs for gc-ms analysis. Measured total effluent flow rate at test site and composition from gas analysis gives permeation rate.**
- **Same equipment and procedure for 2.4-m and 5.5-m tanks**
- **Accurate permeability measurements are difficult under ideal conditions. Performing the measurement on an industrial scale offers a unique set of challenges.**







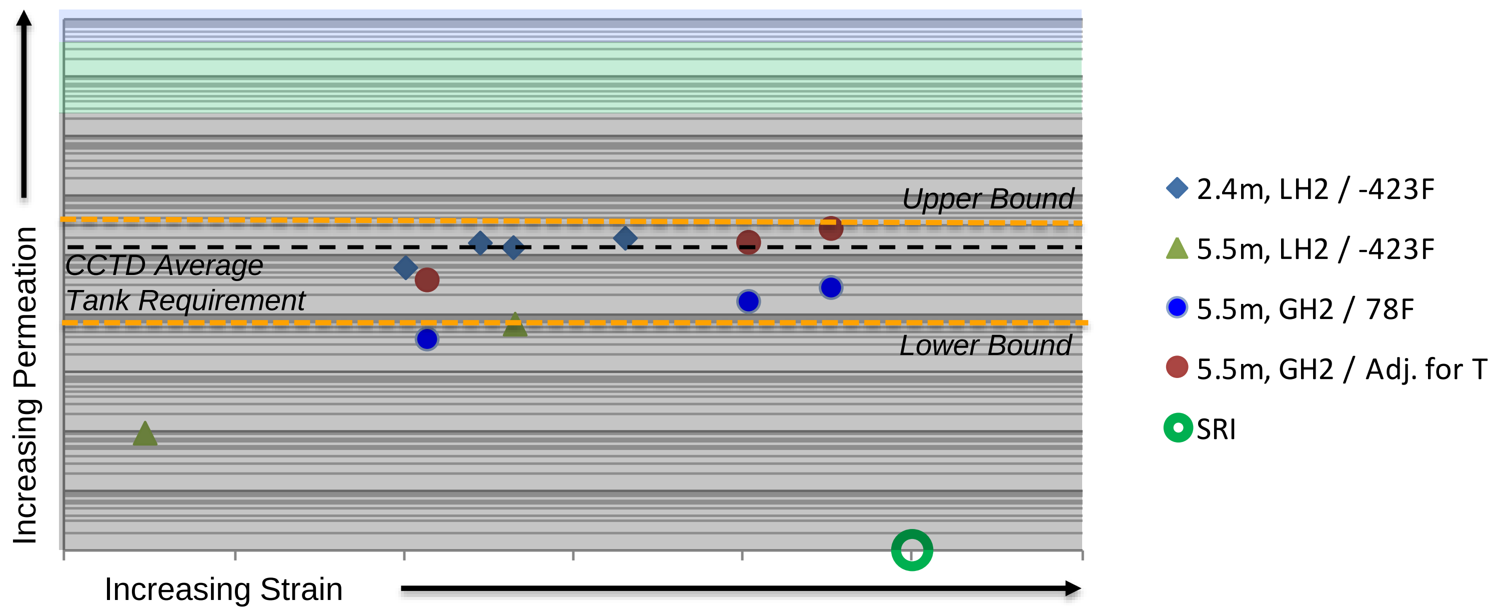
Permeation Results

NASA Game Changing Development Program | Composite Cryotank Project

Max. Allowables:

Boost Stage	Upper Stage / Earth Orbits	Long Duration (i.e. Lunar Lander)
4 - 6minutes	49min – 7.5hrs	*8-25days*

Permeation vs Strain

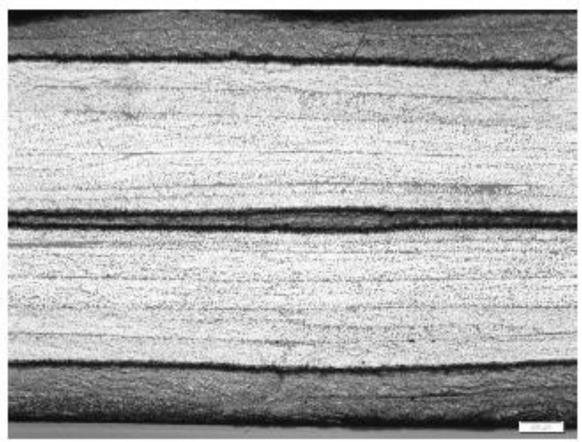


<u>Allowables depend on:</u>
- Boil off
- Draw off
- Total Allowable Losses
- Leakage through penetrations
- Residuals
- Mission Duration
- Explosive mixture limits

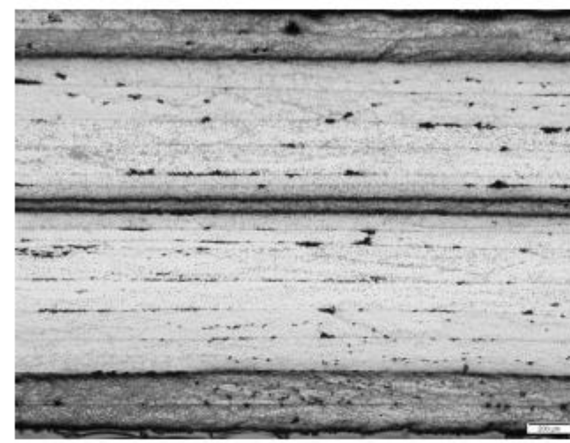
Implication of OOA on Hybrid Laminate

- **Objective: Determine Effects of OOA vs. Autoclave Cures**
- **Approach: Hybrid laminates fiber-placed panels produced at Boeing and LH2 tested at MSFC**
  - **Hybrid laminate 12 plies of 5.4mil with 5 plies of 2.5 mil material**
  - **OOA cured laminates exhibit ~4% porosity**

17 ply IM7/5320-1			
Ply ID	Orientation	Thickness	
1	12	0.00545	Thick
2	-12	0.00545	
3	-45	0.00545	
4	45	0.00545	
5	65	0.00545	
6	-65	0.00545	
7	*60*	*0.0025*	Thin
8	*-60*	*0.0025*	
9	*0*	*0.0025*	
10	*-60*	*0.0025*	
11	*60*	*0.0025*	
12	-65	0.00545	Thick
13	65	0.00545	
14	45	0.00545	
15	-45	0.00545	
16	-12	0.00545	
17	12	0.00545	
	Total	0.0779	

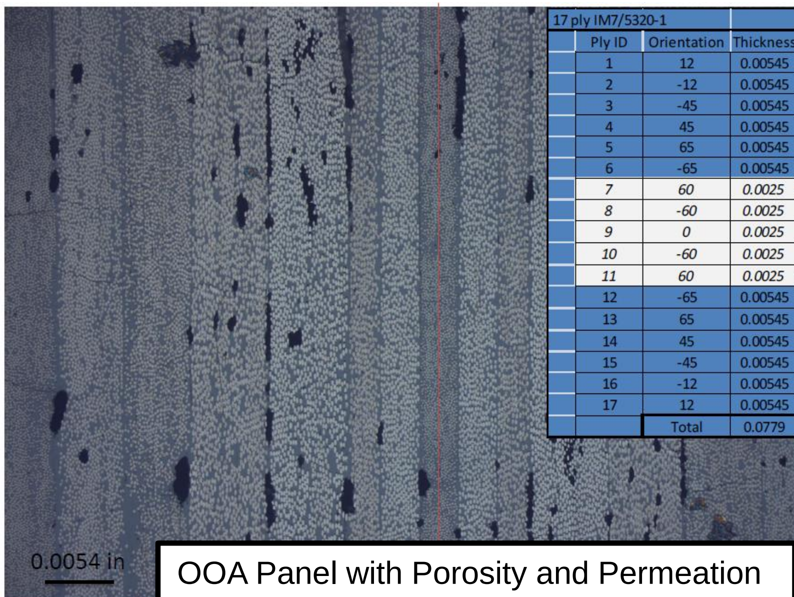


Autoclave Cure



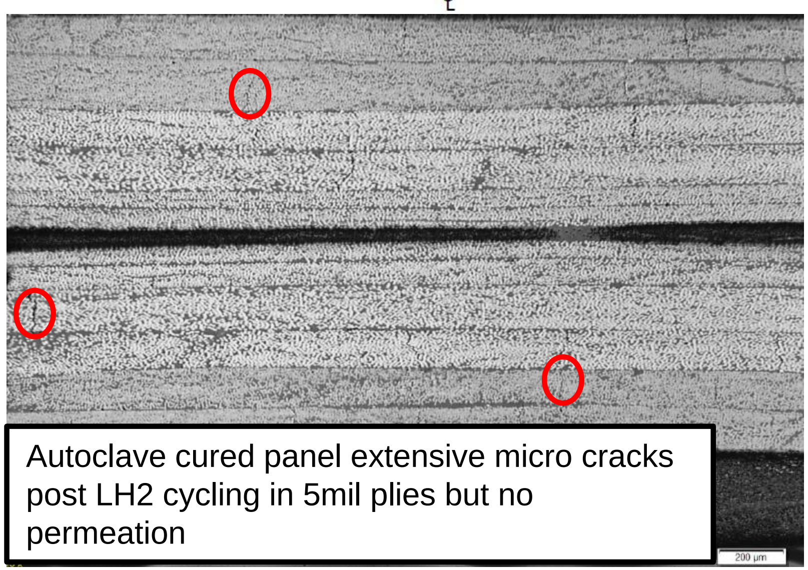
Out-of-Autoclave Cure

Why CCTD Laminate Leaked



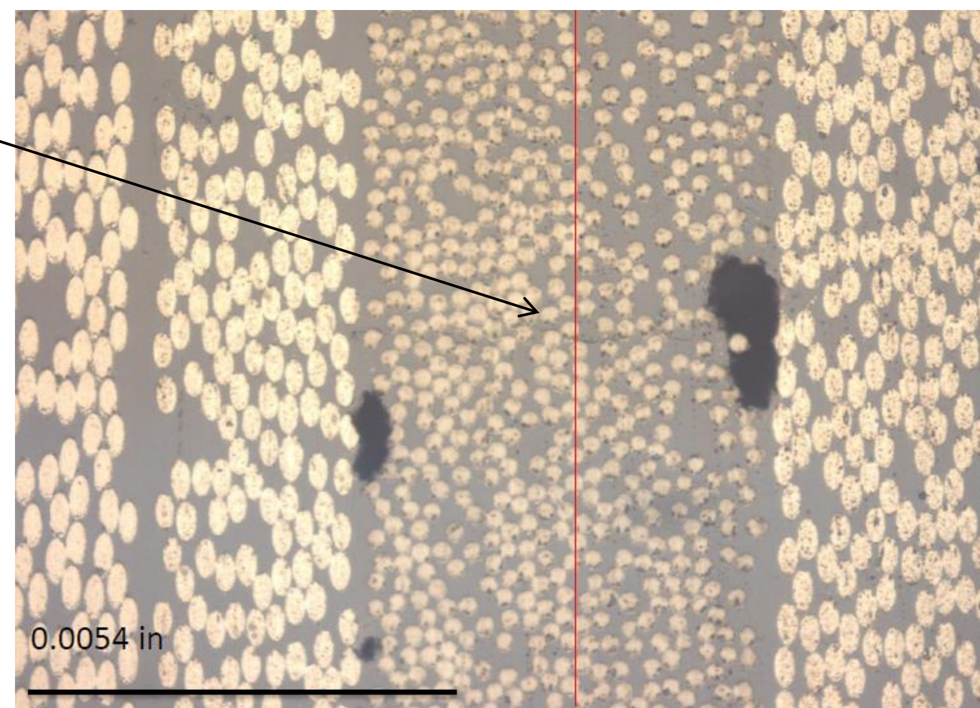
17 ply IM7/5320-1		
Ply ID	Orientation	Thickness
1	12	0.00545
2	-12	0.00545
3	-45	0.00545
4	45	0.00545
5	65	0.00545
6	-65	0.00545
7	60	0.0025
8	-60	0.0025
9	0	0.0025
10	-60	0.0025
11	60	0.0025
12	-65	0.00545
13	65	0.00545
14	45	0.00545
15	-45	0.00545
16	-12	0.00545
17	12	0.00545
	Total	0.0779

OOA Panel with Porosity and Permeation



Autoclave cured panel extensive micro cracks post LH2 cycling in 5mil plies but no permeation

- **Micro cracks formed in thin plies primarily due to presence of porosity**
- **To eliminate permeation**
  - Increase number of thin plies
  - Reduce porosity
    - Autoclave cure
    - Improved OoA AFP processes



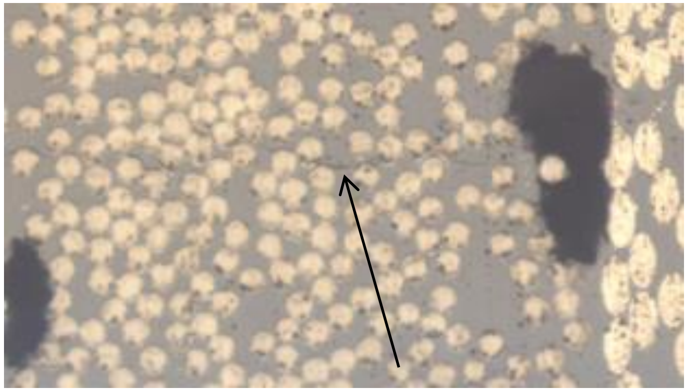
Conclusions

Tank level permeation measurements

- Meet upper stage and booster stage allowable
- Exceed CCTD, lunar lander based, requirement

Permeation is sensitive to

- Laminate quality
- Number of thin plies



Microcracks formed in thin plies primarily due to presence of porosity

To eliminate permeation

- Increase number of thin plies
- Reduce porosity
  - **Autoclave cure**
  - **Improved OoA Material Architecture and AFP processes**

Back Up

Boeing Installed Strain Gages

- **Strain gage type:**
  - 50 bi-axial strain gages, PN WK-03-250WR-350/W (Note: two legs of the rosette gage were used for measurement of biaxial strains)
  - 8 uniaxial strain gages, PN WK-03-250BG-350/W
- **Strain gage distribution:**
  - All Boeing strain gages located external to the tank shell
  - 4 biaxial strain gages (8 channels) on tank aft dome acreage
  - 4 biaxial strain gages (8 channels) on tank aft dome adjacent to aft scarf joint
  - 4 biaxial strain gages (8 channels) on tank fwd dome acreage
  - 12 biaxial strain gages (24 channels) on tank fwd dome adjacent to fwd scarf joint
  - 4 biaxial strain gages (8 channels) on tank fwd dome above forward y-joint
  - 8 biaxial strain gages (16 channels) on tank fwd dome near fwd y-joint – includes 8 redundant gages
  - 8 biaxial strain gages (16 channels) on tank aft dome near aft y-joint – includes 8 redundant gages
  - 6 biaxial strain gages (12 channel) on fluted core skirt exterior
  - 8 uniaxial strain gages (8 channels) on fluted core skirt exterior

NASA Installed Gages

- **Strain gage type:**
  - 48 bi-axial strain gages, PN WK-03-250RA-350 (Note: two legs of the rosette gage were used for measurement of biaxial strains)
- **Strain gage distribution:**
  - 4 biaxial strain gages (8 channels) on external tank skirt surface
  - 2 biaxial strain gages (4 channels) on internal tank forward dome near forward y-joint
  - 9 biaxial strain gages (18 channels) on external tank forward dome near forward scarf joint
  - 6 biaxial strain gages (12 channels) on internal tank forward dome near forward scarf joint – includes redundant strains
  - 8 biaxial strain gages (16 channels) on external tank forward dome surface
  - 9 biaxial back-to-back strain gages (18 channels) on tank aft dome surface – includes redundant strains
  - 8 biaxial strain gages (16 channels) on internal tank forward dome surface – includes redundant strains
  - 2 biaxial strain gages (4 channels) on internal tank barrel surface

Ambient Pressure Test

Success Criteria:

1. No evidence of catastrophic failure through the completion of the ambient pressure test.
2. No detrimental deformation (defined as excessive leakage or tank rupture) at or below the defined internal pressure level.
3. Data acquisition of a minimum amount of strain data to allow for post-test model correlation.

Test Goals:

1. Distinct from Success Criteria in that they are not considered when determining if a test is successful.
2. Correlation of Pressure Test strain data with predicted strains from Finite Element Models (FEMs) of the 5.5m Composite Tank design.

LH2 Pressure Test

Success Criteria:

1. No structural failure, defined as tank rupture or excessive leakage, that prevents achieving maximum test pressure.
2. Measure a maximum LH2 permeation rate of 1×10^{-3} at maximum test pressure and at a minimum strain of the permeation measurement location.

Test Goals:

1. Demonstrate the integrity of the LH2 filled 5.5m Cryotank at pressure loads of 58 psi.
2. Demonstrate a maximum LH2 permeation rate of 1×10^{-3} at maximum test pressure and at a minimum strain of the permeation measurement location.

Success Criteria

1. No evidence of catastrophic failure through the completion of the test.
2. No tank failure (defined as excessive leakage, tank rupture, or skirt buckling) at or below the defined internal pressure level and 100% mechanical loads.
3. Data acquisition of a minimum amount of strain data to allow for post-test model correlation, and to develop confidence for the upcoming Cryotank Combined Cryogenic Pressure and Mechanical Loads Test.

Test Objectives

1. Demonstrate structural integrity of the Composite Cryotank design (defined as excessive leakage or tank rupture) at or below the defined internal pressure level and with 100% of mechanical loads applied.

Success Criteria:

1. No structural failure, defined as tank rupture or excessive leakage, that prevents the planned thermal and pressure cycles.
2. Measure a maximum LH2 permeation rate of 1×10^{-3} at maximum test pressure at the permeation measurement location after an additional thermal and multiple mechanical pressure cycles.

Test Goals:

1. Demonstrate the integrity of the LH2 filled 5.5m Cryotank during one additional thermal and multiple pressure cycles to the max pressure demonstrated during the Cryogenic Pressure Test.
2. Demonstrate a maximum LH2 permeation rate of 1×10^{-3} at maximum test pressure after an additional thermal and multiple mechanical pressure cycles at the permeation measurement location.