National Aeronautics and
Space Administration

NASA Composite Cryotank Technology Project Game Changing Program

Presented by:
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NASA Marshall Space Flight Center
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Overall Project Objective

The fundamental goal of this project was to provide new and innovative cryotank technologies that enable human space exploration to destinations beyond low earth orbit such as the moon, near-earth asteroids, and Mars.

The goal … to mature technologies in preparation for potential system level flight demonstrations through significant ground-based testing and/or laboratory experimentation.

Composite Cryotank Project Goals

Objective: Advance technologies for lightweight cryotanks for heavy lift vehicles + spin-off capabilities for multiple stakeholders - NASA, DOD, and Industry

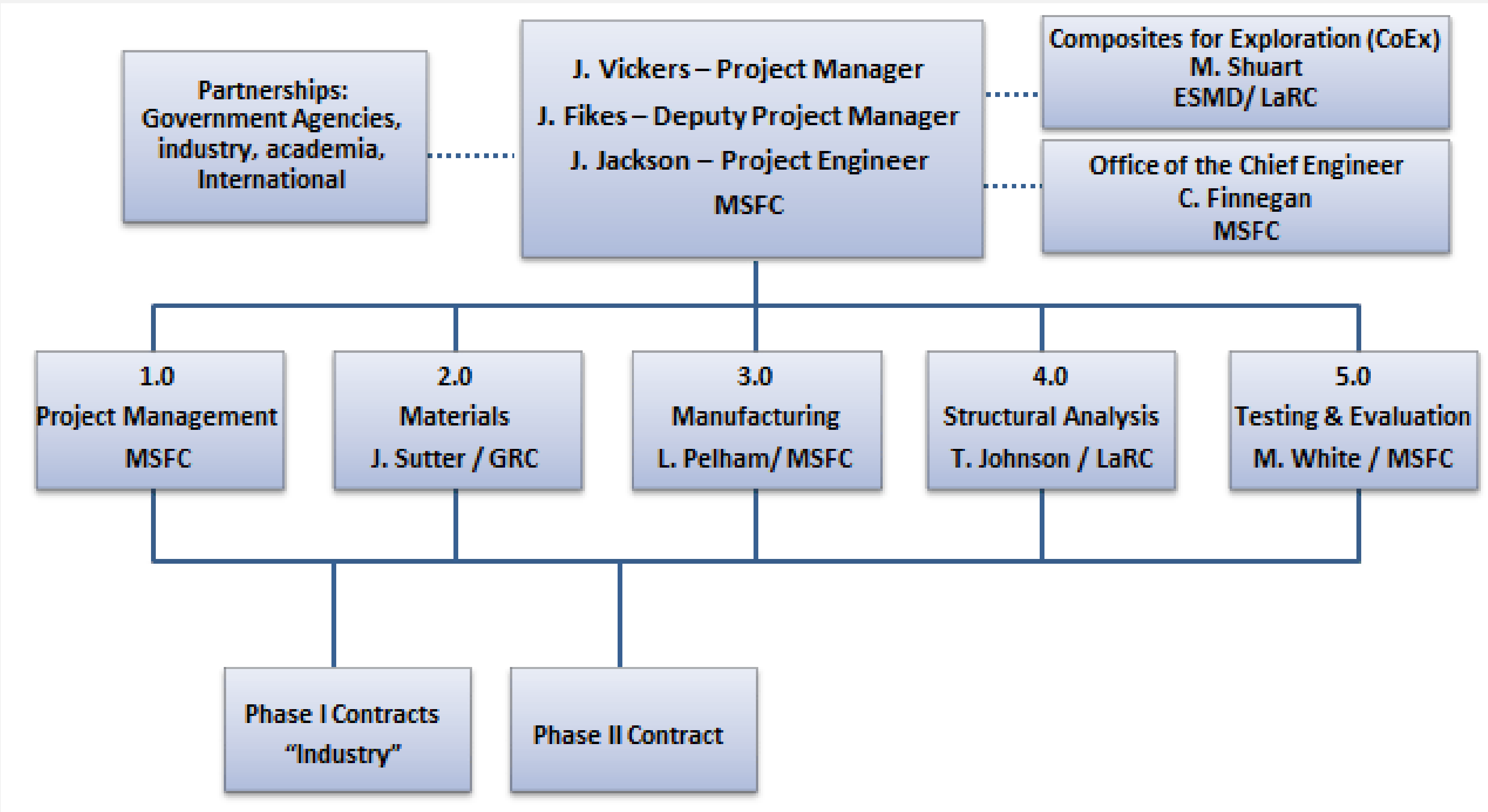
Concept: Develop and demonstrate composite tank critical technologies – **Materials, Structures, and Manufacturing - Out-of-Autoclave**

Approach: Focus on achieving affordability, technical performance, verified through agreement between experimental results and analysis predictions

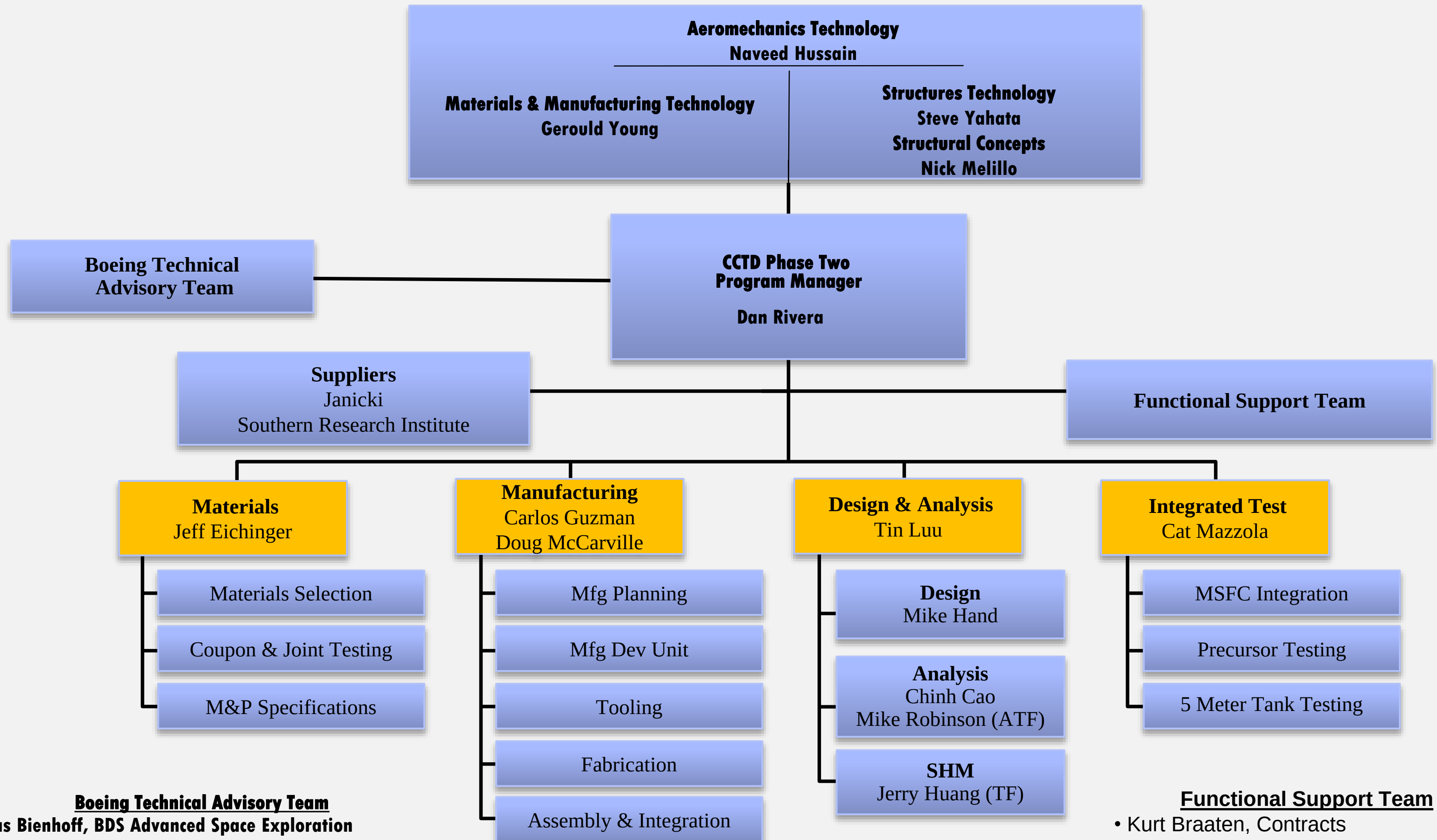
Goal: Produce a major advancement in technology readiness; successfully test a 5.5-meter diameter composite hydrogen fuel tank, achieve:

- **25-30% weight savings**
- **20-25% cost savings**

NASA Project Organization and Key Personnel



Boeing Organization



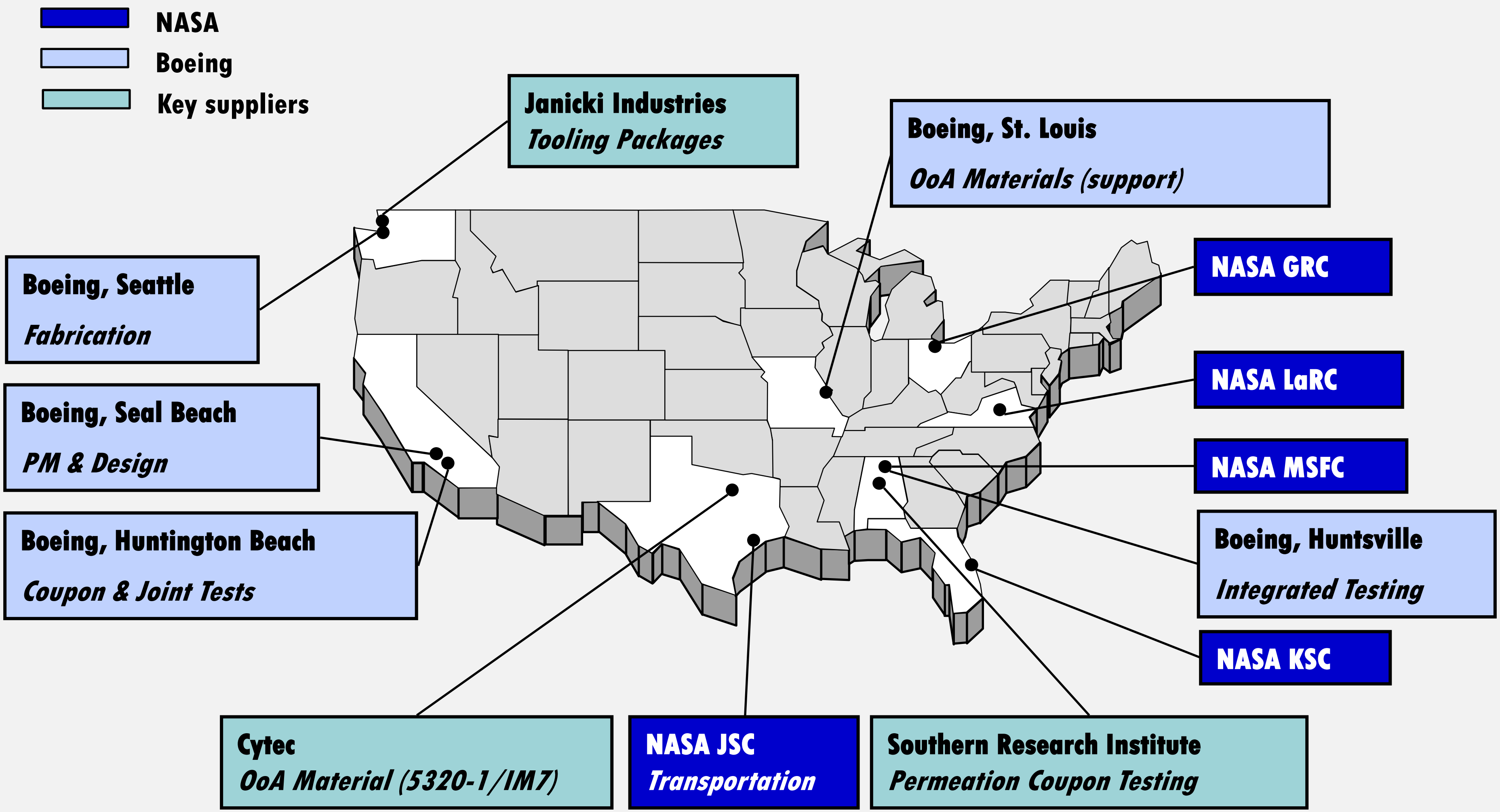
Boeing Technical Advisory Team

- Dallas Bienhoff, BDS Advanced Space Exploration
- Gail Hahn (TF), Next Gen Materials & Labs
- Brice Johnson (TF), Composites & Non-Metallics
- Don Barnes (ATF), BDS/Exploration Launch Sys
- Al Olsen, Propulsion Technology
- Marc Piehl (TF), Primary Structural Bonding
- Kurtis Willden (ATF), Composite Fabrication
- Richard Bossi (STF), Non-Destructive Evaluation

Functional Support Team

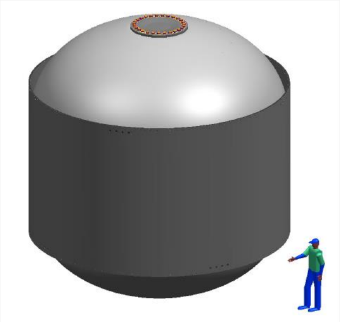
- Kurt Braaten, Contracts
- Ros Campbell, Schedule
- David Sanchez, Finance
- Mark Mihalco, Supplier Mgmt
- Denise Boss, Data Mgmt
- Roger Smith, Quality
- Charlie Conway, Safety
- Jeff Fukushima, ERB/MRB/CCB

NASA & Industry Team



Building Block Program Culminated With 5.5m Cryotank

Composite Cryotank | **STMD Game Changing Program**

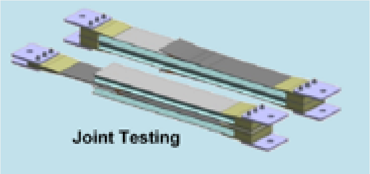


5.5 meter Tank

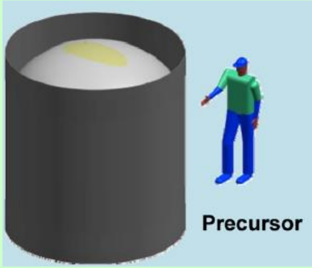
Available to support 5.5m Tank

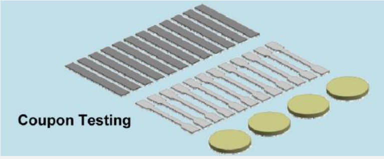
2.4 meter Precursor Tank

Manufacturing Demonstration Units



Joint Testing

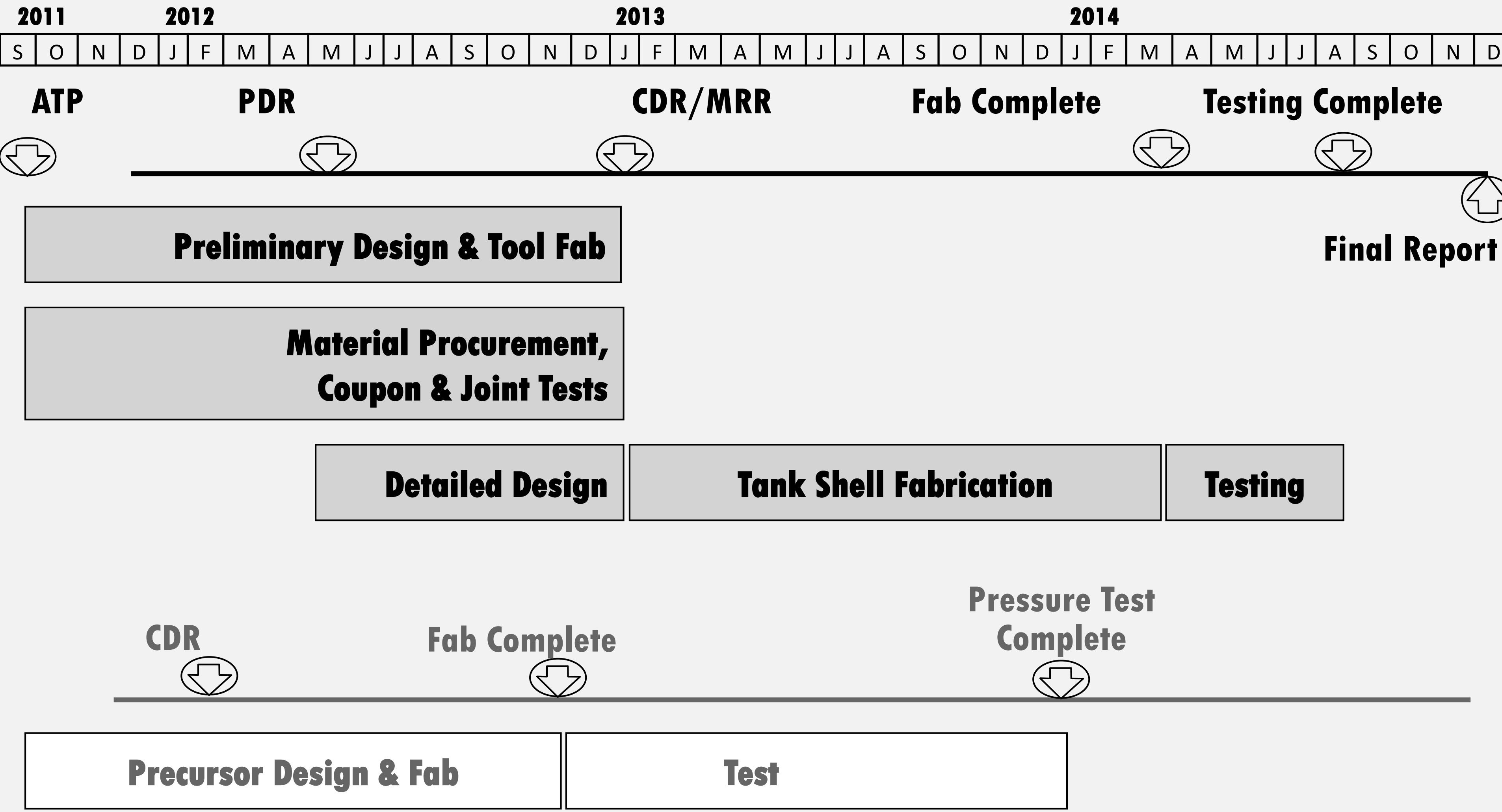




Coupon Testing

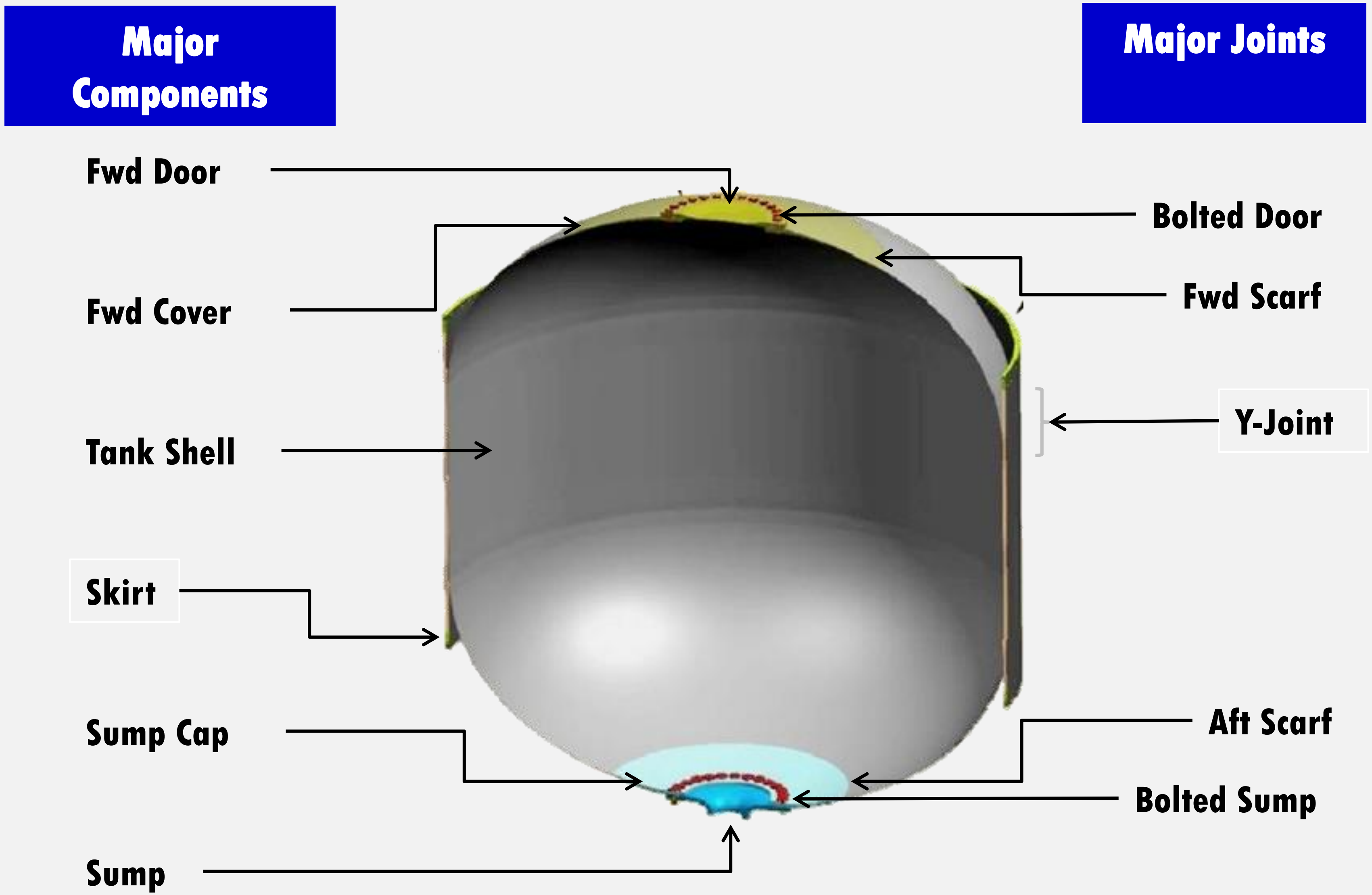
Building block approach essential to successful technology maturation

Schedule Overview

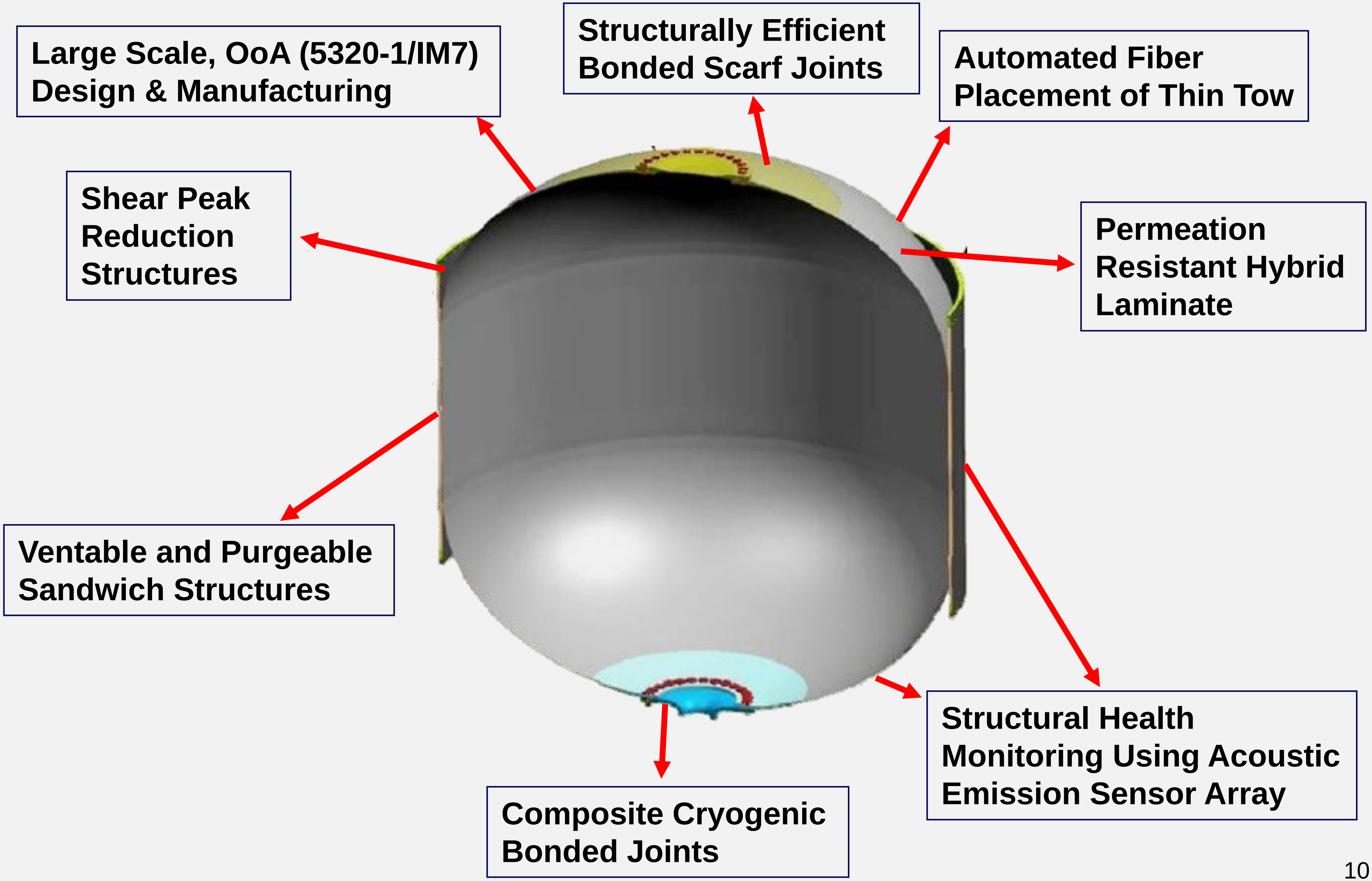


Saved 13 months in comparison to typical Serial Development

CCTD Key Terminology



Technologies Matured by CCTD



Major Accomplishments

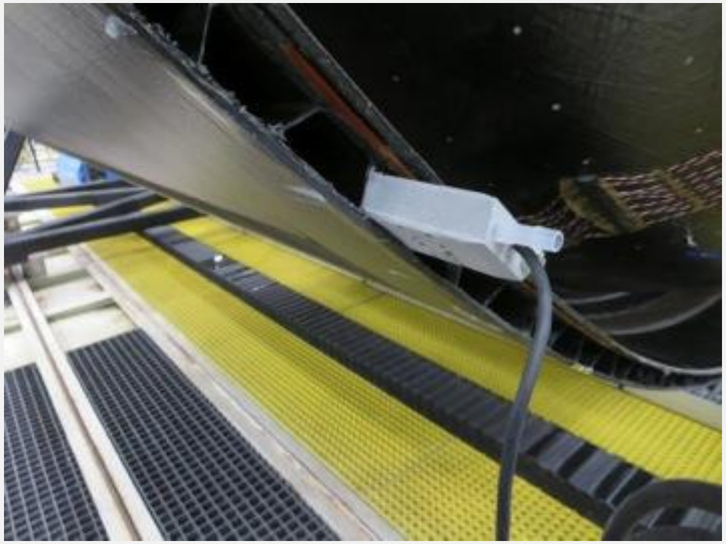
- Large AFP test article using 5320-1/IM7
- 70gsm fiber placed cryotank (hybrid laminate)
- Benefits:
  - Enables Out-of-Autoclave manufacturing
  - Meets material out time
  - Provides permeation barrier

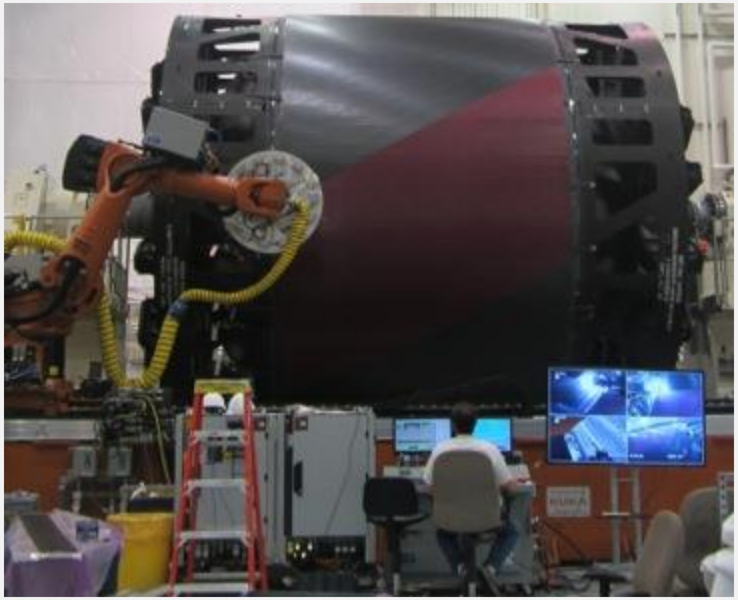
Major Accomplishments

- **Janicki - Large scale, spherical segmented tool**
  - **Enables lightweight, 1-piece tank shell**
  - **Successfully used to fabricate cryotank**
  - **Successfully extracted**

Major Accomplishments

- **Large scale, Gr/Ep fluted core sandwich & NDI**





Major Accomplishments

- **Cold temperature softening strip.**
- **All composite bolted cover joints.**

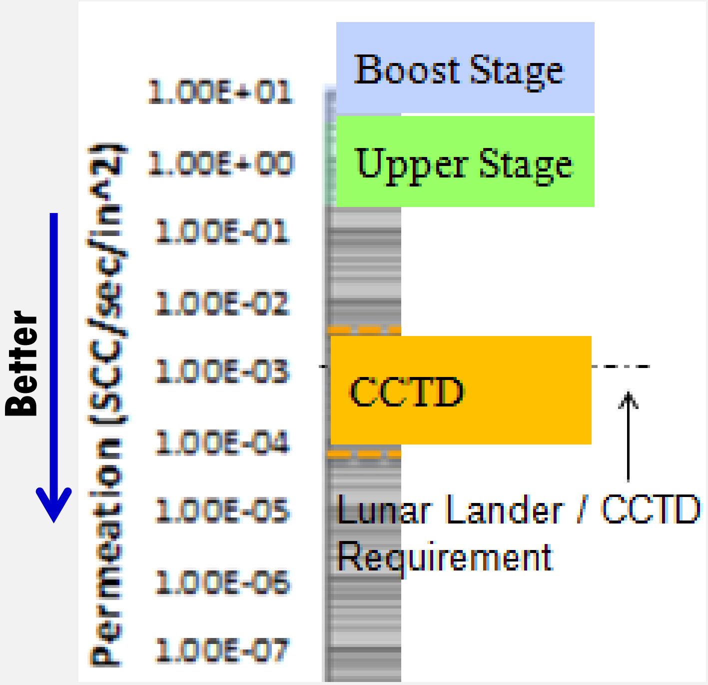
Major Accomplishments

Permeation Reduction:

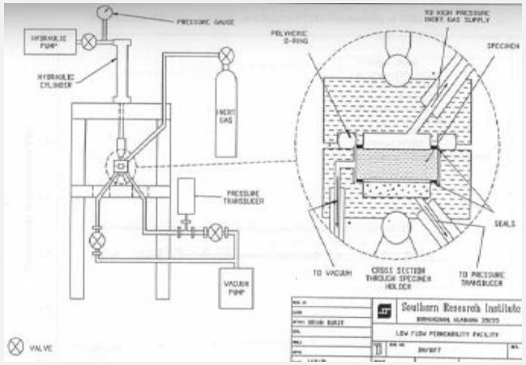
- Hybrid laminate with thin plies prevented microcracking and reduced permeation levels.

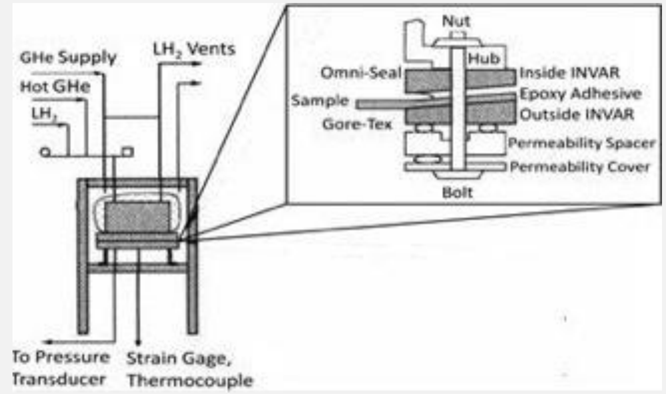
- Design meets upper stage & booster stage calculated permeation allowable.

- To improve performance further:
  - Improve OoA AFP materials & processes
  - Increase number of thin plies
  - Autoclave cure



Permeation Coupon Measurements





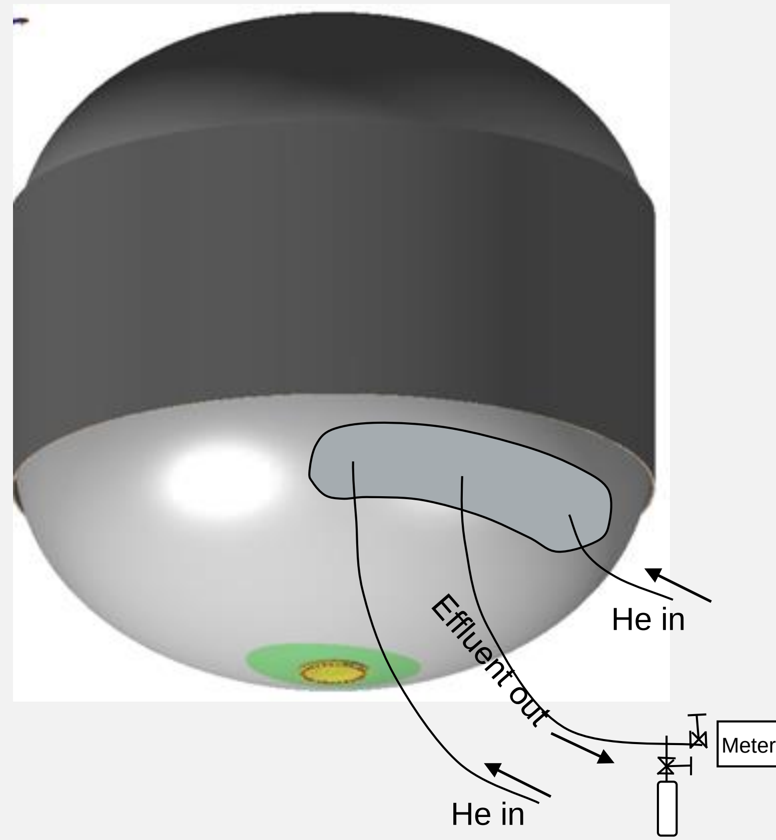
SRI Permeation Rig 100% In-plane Loading

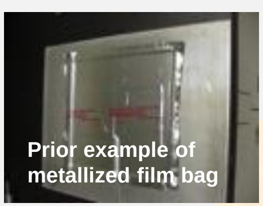
MSFC Permeation Rig 10% Mid-Plane Bending Induced

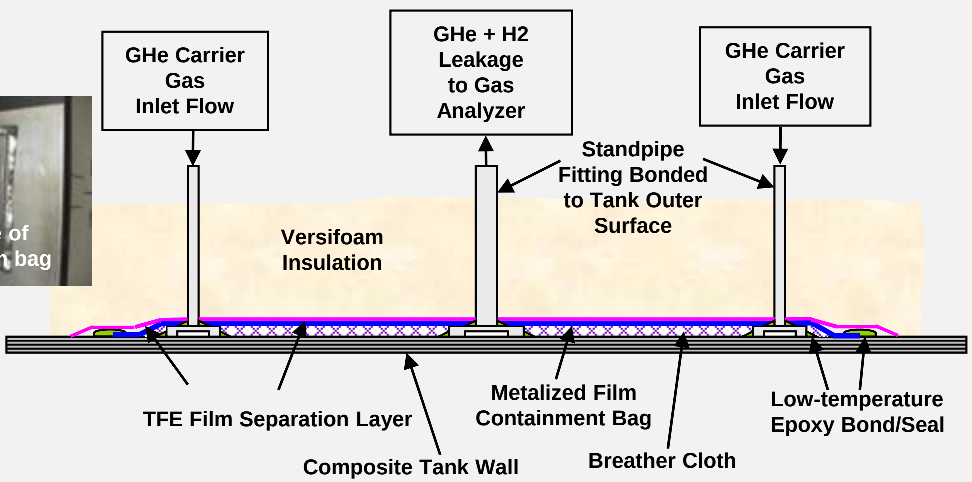
Multiple tests performed using both setups with coupons cut from same parent panel, SRI exhibited no detectable permeation on all tests. MSFC rig detected excessive permeation on all OOA cured hybrid laminates. 100% of autoclave cured laminated had 0% permeation on both tests, and all OOA cured, all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

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.



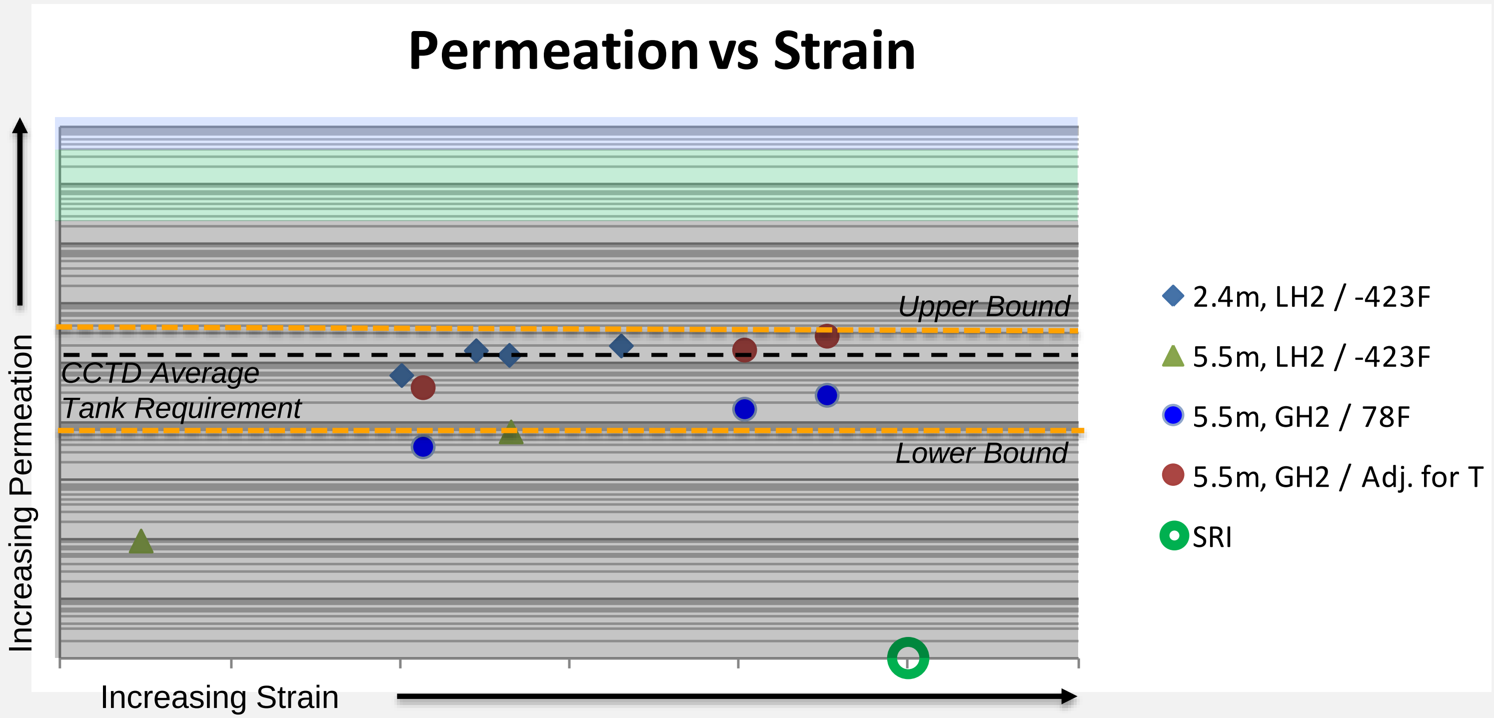




Permeation Results

Max. Allowables:

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



Allowables depend on:

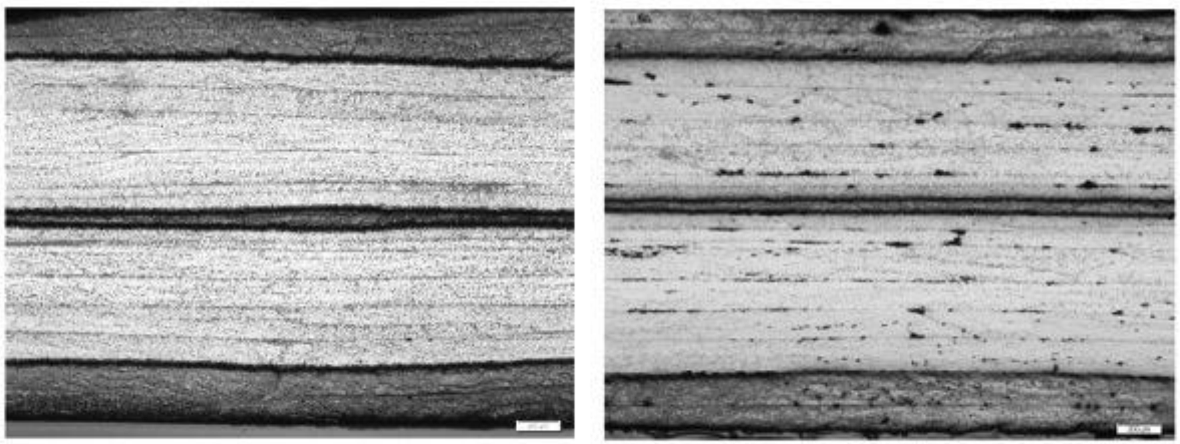
- Boil off
- Draw off
- Total Allowable Losses
- Leakage through penetrations
- Residuals
- Mission Duration
- Explosive mixture limits

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**

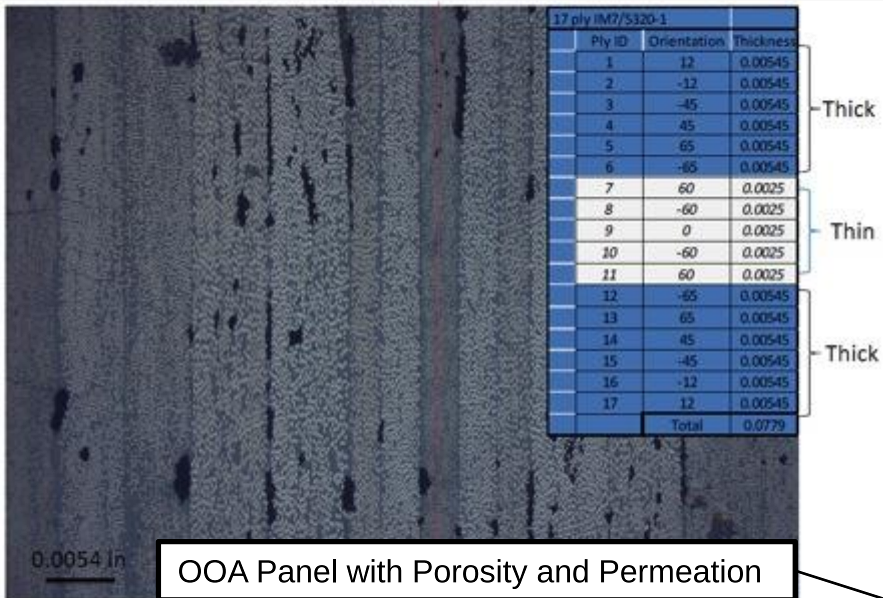
17 ply IM7/5320-1

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	



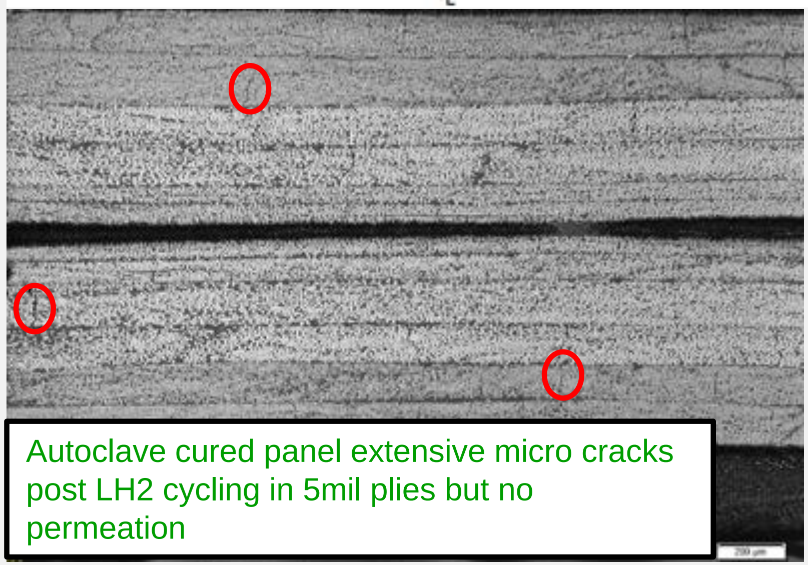
Autoclave Cure | Out-of-Autoclave Cure

Laminate Micro-Cracks



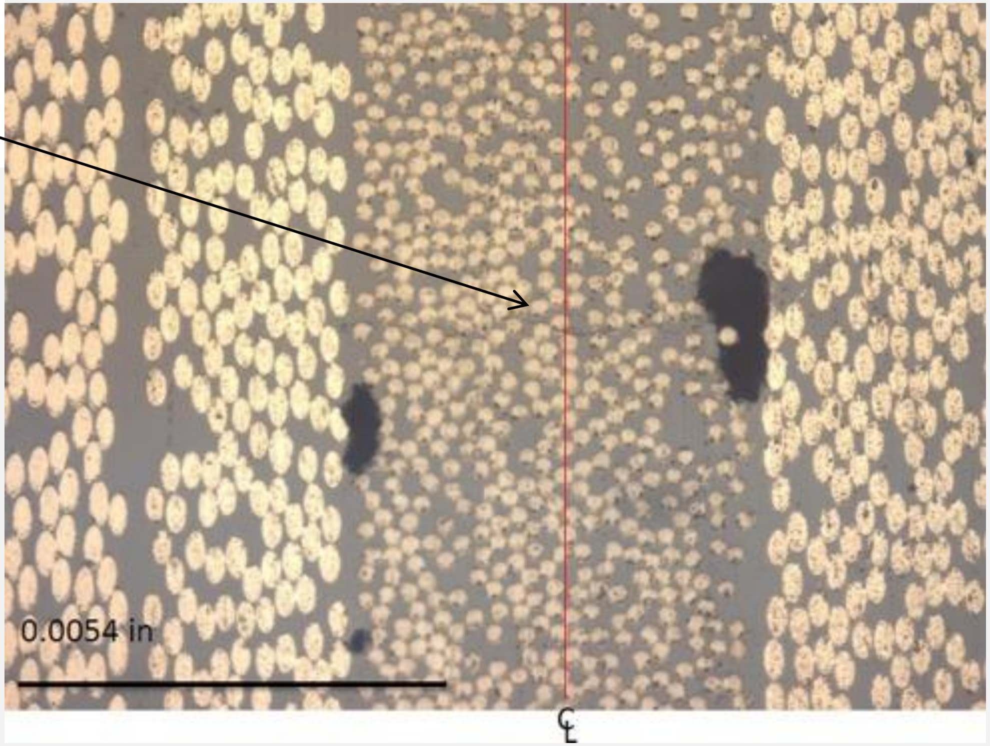
17 ply IM7/5320-1		
Ply ID	Orientation	Thickness
1	12	0.00545
2	-12	0.00545
3	-45	0.00545
4	45	0.00545
5	65	0.00545
6	-65	0.00545
7	60	0.0025
8	-60	0.0025
9	0	0.0025
10	-60	0.0025
11	60	0.0025
12	-65	0.00545
13	65	0.00545
14	45	0.00545
15	-45	0.00545
16	-12	0.00545
17	12	0.00545
	Total	0.0779

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



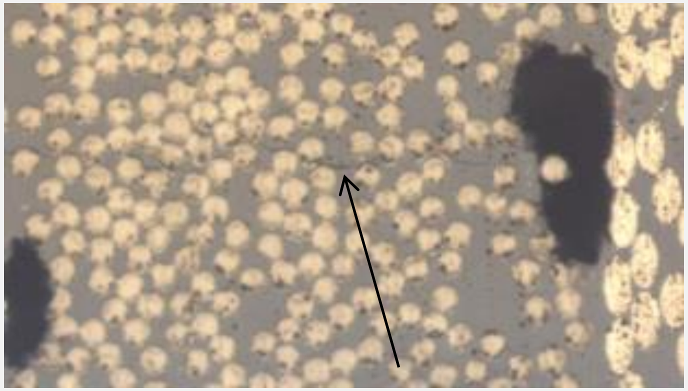
Permeation Conclusions

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

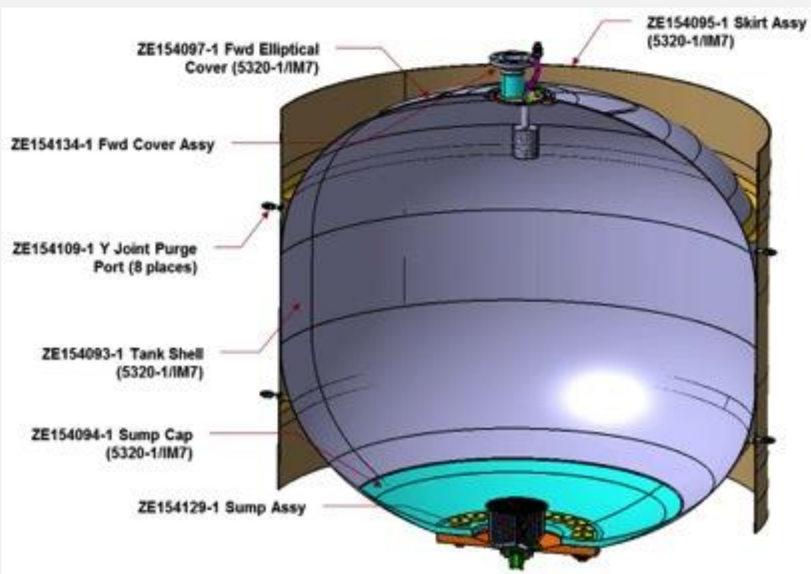
To eliminate permeation

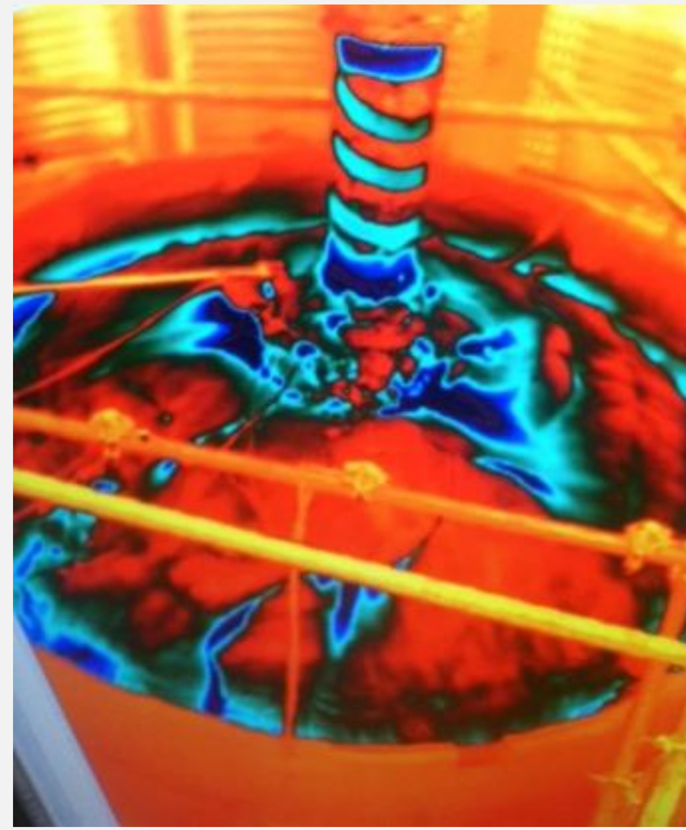
- Increase number of thin plies
- Reduce porosity
  - **Autoclave cure**
  - **Improved OoA Material Architecture and AFP processes**

2.4m Test Summary

Composite Cryotank | STMD Game Changing Program

- **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:**



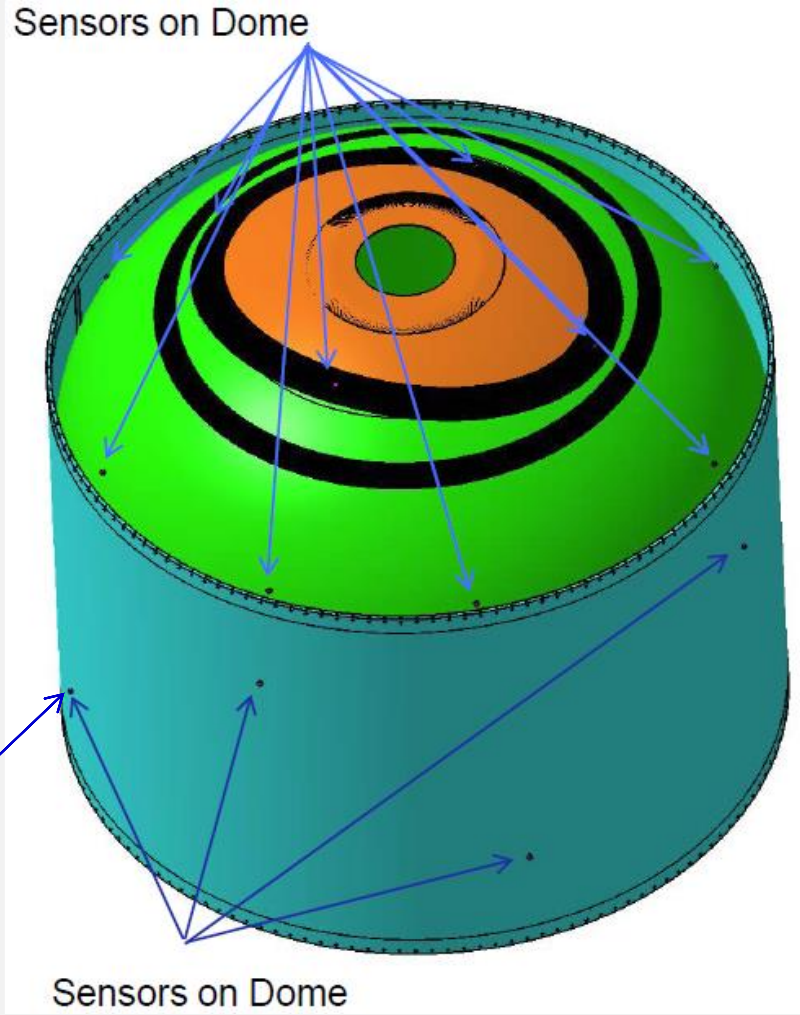


2.4m Thermal Image During LH2 Testing

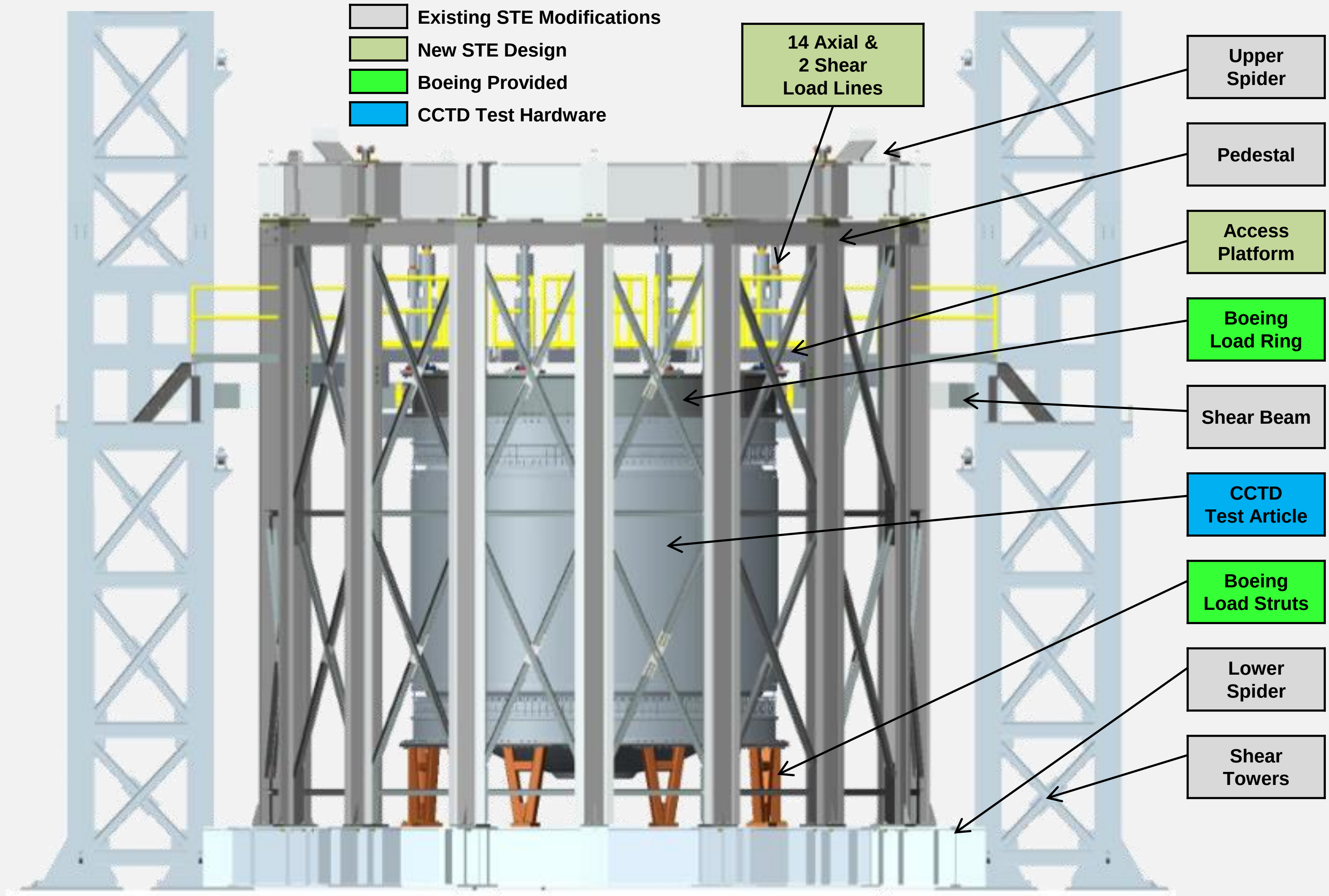
Results Previously Presented NSMMS 2014

5.5m 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



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.
- **By analysis, the addition of Flight Loads do not significantly impact critical safety factors**

* Achieved 20% due to facility issues

Major Accomplishments

Largest Successfully Ground Tested Composite Cryotank

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

Marshal Space Flight Center

Projected Composite Cryotank Benefits

	Reference	Composite	Weight Savings
10 meter (2011, Phase 1)	**NASA** **Al- LI** **11,000lbs**	**6,700lbs**	**39%** (4,200lbs)
10 meter (2014, Phase 2)	**NASA** **Al-Li** **11,000lbs**	**7319 lbs** **+ 619lbs for acreage & fwd joint**	**33%** (3,681lbs)
5 meter	Delta IV Al – 2219	CCTD Phase 2 Test Article	**33%**

CCTD Overview Summary

Prior Barriers
…. to Application of Large-Scale Composite LH2 Tanks

- **Manufacturability** – Scalable automated fiber placement & tooling.
- **Strain Limits** – Capable of 5,000με.
- **Y-Joint Strength** – Achieved 58psi at LH2 temp, despite low margins.
- **Bolted Joint Seals** – Demonstrated composite joint w/ furon omniseal.
- **Hydrogen Permeability**
  - Out-of-Autoclave – Thin plies significantly reduced permeation.
  - Autoclave – Hybrid laminate coupon did not permeate.

Summary

Successful culmination of a three-year effort to design and build a large high-performance tank with new materials and new processes and to test it under extreme conditions

Credit the NASA's Space Technology Mission Directorate, and Game Changing Development Program with goals for innovating, developing, testing and flying hardware for use in NASA's future missions.

This is a significant technology achievement for NASA, Boeing and industry. “We are looking at composite fuel tanks for many aerospace applications.”