

# High pressure, low temperature hydrogen tube trailers

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Project ID #  
PD22



# Overview

## Timeline

- Start date: **October 2004**
- End date: **October 2011**
- Percent complete: **40%**

## Budget

- Total project funding
  - DOE: **\$950 k**
- Funding received in FY08:
  - **\$400 k (\$75 k to date)**
- Funding for FY07:
  - **400 k**

## Barriers

- **F. Gaseous hydrogen storage and tube trailer delivery cost**
- **G. Storage tank materials and costs**

## Targets

Meet DOE 2012 delivery targets:

- **Tube trailer delivery capacity: 700 kg**
- **Tube trailer operating pressure: 7000 psi**
- **Tube trailer capital cost: \$300 k**

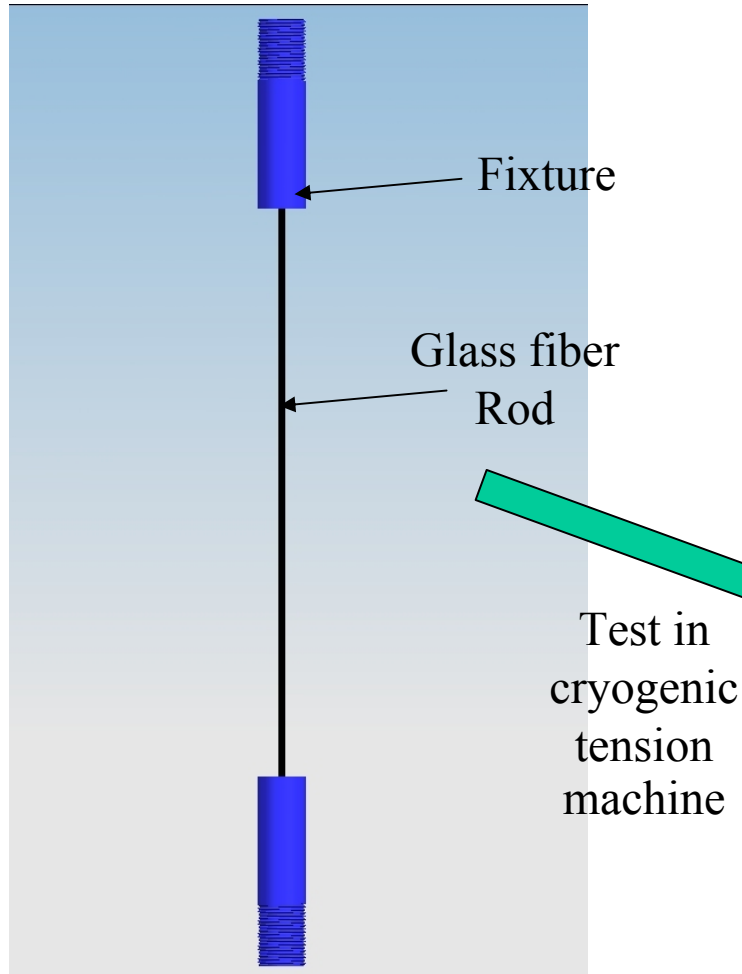
## Partners

Ongoing joint projects with composite/vessel manufacturers

- **Spencer Composites**
- **SCI**
- **Quantum**



**Glass fiber is weakened by water adsorbed into defects.  
Reducing water effect through vacuum and/or cold operation  
considerably strengthens glass fiber (50-100%)**

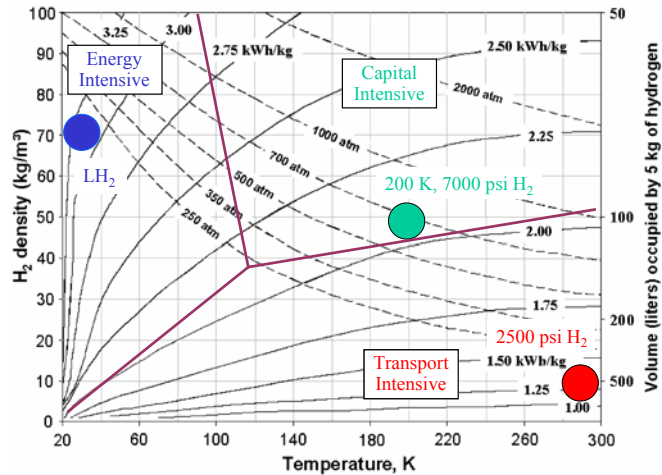


**Objective: Demonstrate inexpensive hydrogen delivery through synergy between low temperature (200 K) hydrogen densification and glass fiber strengthening**

- **Colder temperatures (~200 K) increase density ~35% with small increases in theoretical storage energy requirements**
- **Low temperatures are synergistic with glass fiber composites**
  - **higher glass fiber strength (by 50%?) at 200 Kelvin (vs. 300 K)**
  - **higher gH<sub>2</sub> density increases mass-limited trailer capacity**
- **glass composites (~\$1.50/kg) minimize material cost**
- **Increased pressure (7,000 psi) minimizes delivery costs**
- **Dispensing of cold hydrogen reduces vehicle vessel cost ~25%**

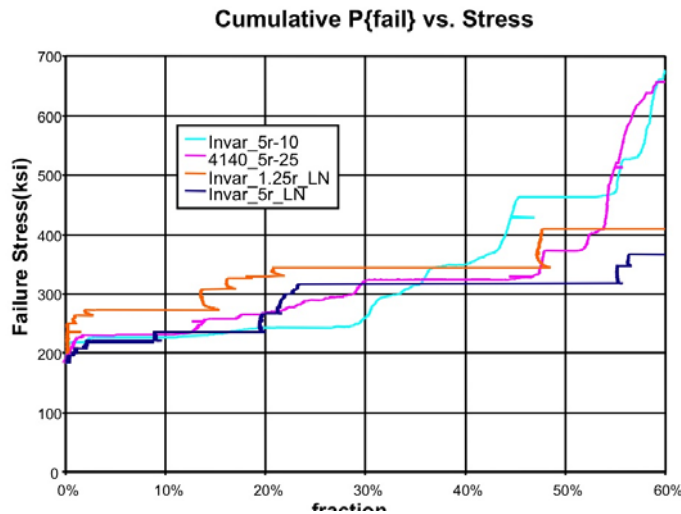


# Milestones: Conduct experiments and analysis to demonstrate high performance, inexpensive glass fiber at low temperature



**October 2006:** Discovered favorable P-T conditions for H<sub>2</sub> delivery

**January 2008:** Started cryogenic tension tests



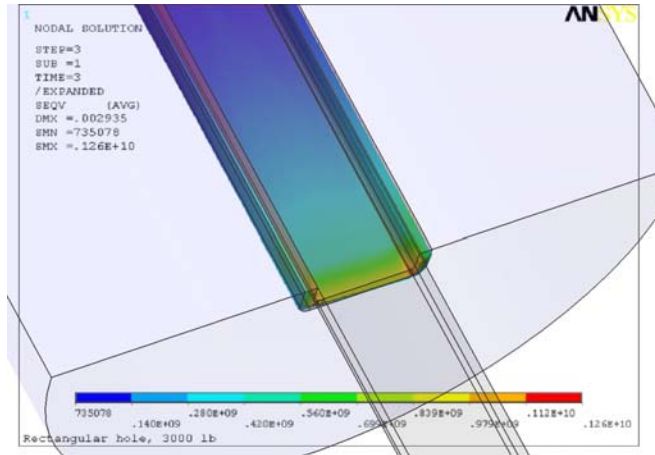
**March 2009:** Demonstrate cold strengthening of preferred glass fibers

**September 2011:** Build and test optimal macrolattice container





# Approach: Test glass fiber strength at cold/vacuum conditions enabling inexpensive, high performance vessels for H<sub>2</sub> delivery



**Stress analysis of fixtures**



**Prepare glass fiber samples**

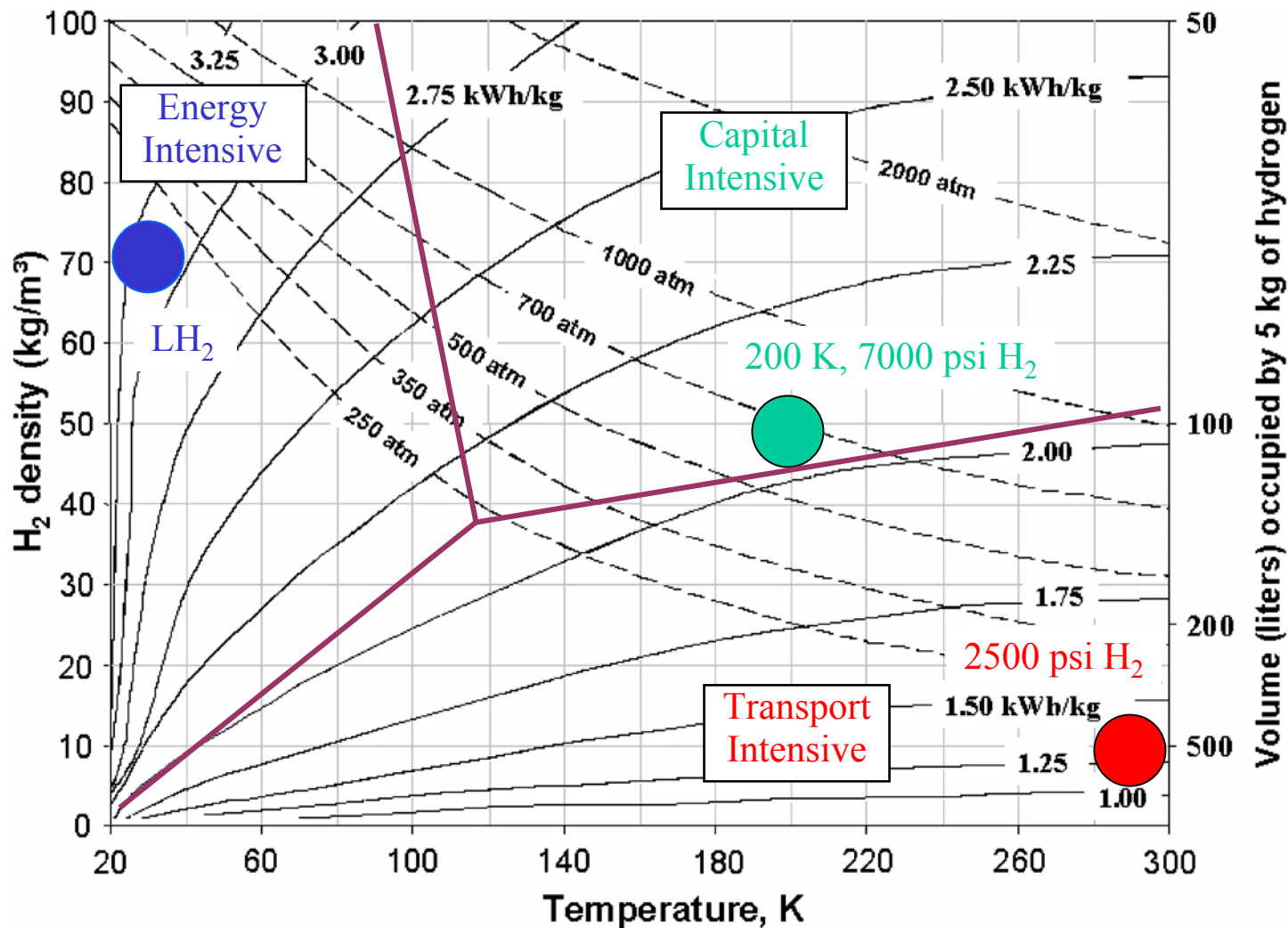


**Tension test at cryogenic conditions**

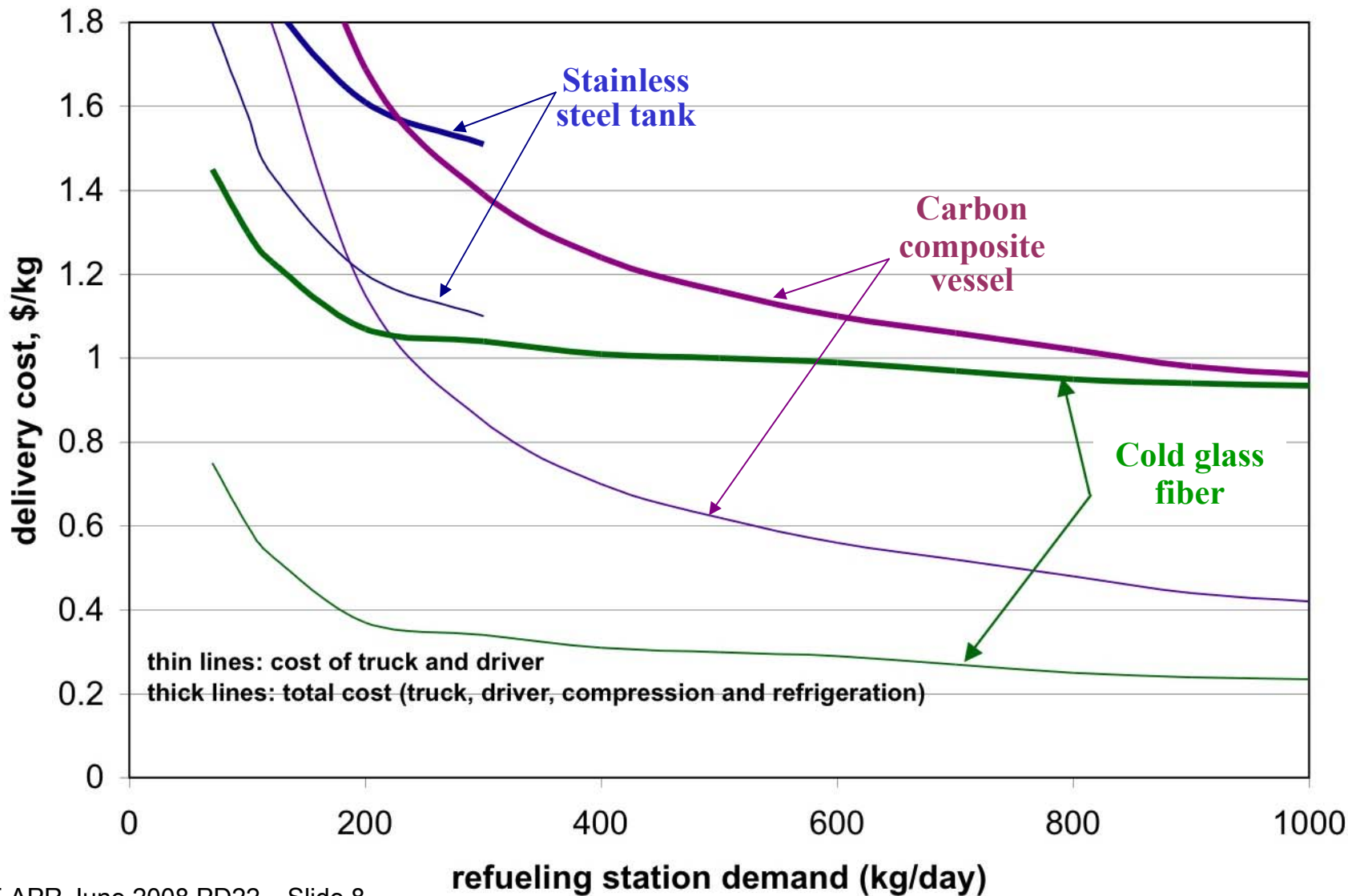


**Data analysis**

# Accomplishments: we have identified an operating regime (200 K, 7000 psi) that shows promise for minimizing delivery cost



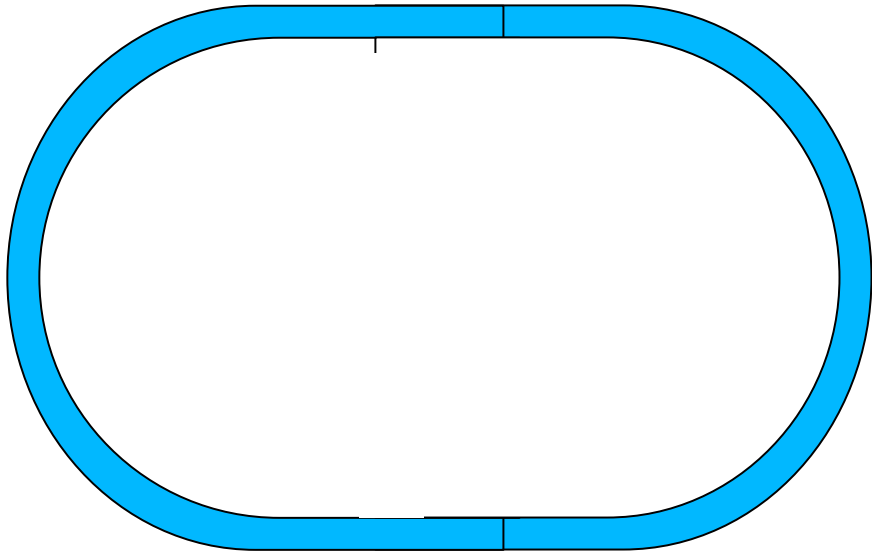
# Cold glass fiber pressure vessels minimize tanker truck cost, enabling inexpensive hydrogen delivery





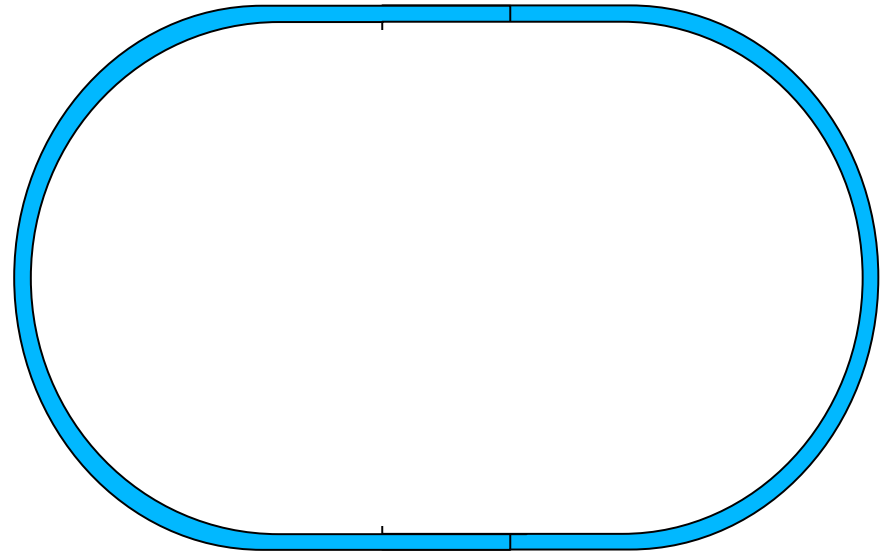
**Dispensing cold hydrogen avoids overpressure during fill,  
reducing vessel cost by 25%.**

**Reduced vessel cost saves a driver \$0.20/kg H<sub>2</sub>  
(assuming a vessel that meets the 2010 DOE goal of \$4/kWh)**



**Today's automotive vessel**

- Filled with warm hydrogen
- Service pressure: 5000 psi
- Fill pressure: 6250 psi
- Burst pressure: 11,250 psi
- Cost: \$ 1333 (2010 goal)

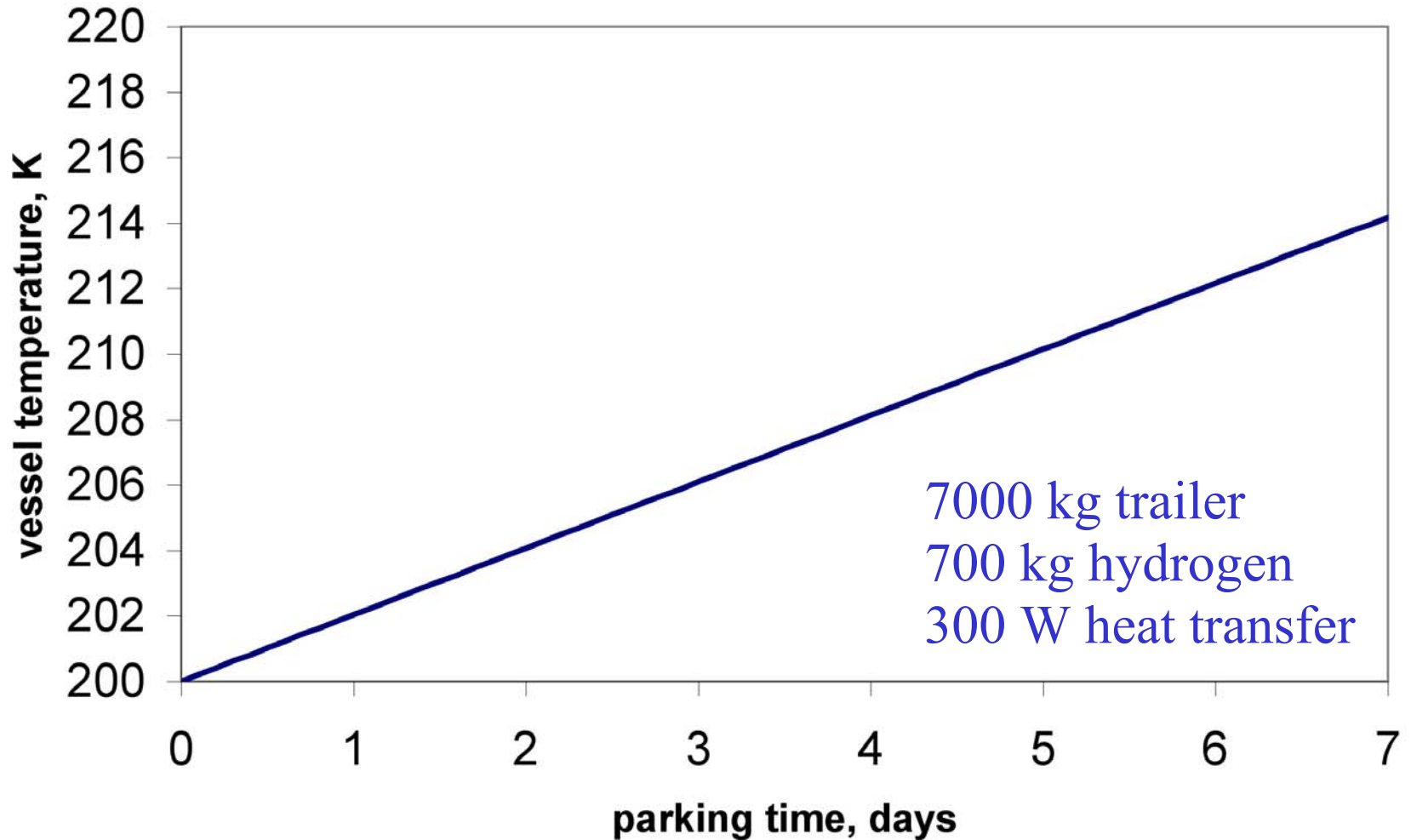


**Future automotive vessel**

- filled only with cold H<sub>2</sub>
- Service pressure: 5000 psi
- Fill pressure: 5000 psi
- Burst pressure: 9,000 psi
- Cost: \$ 1066



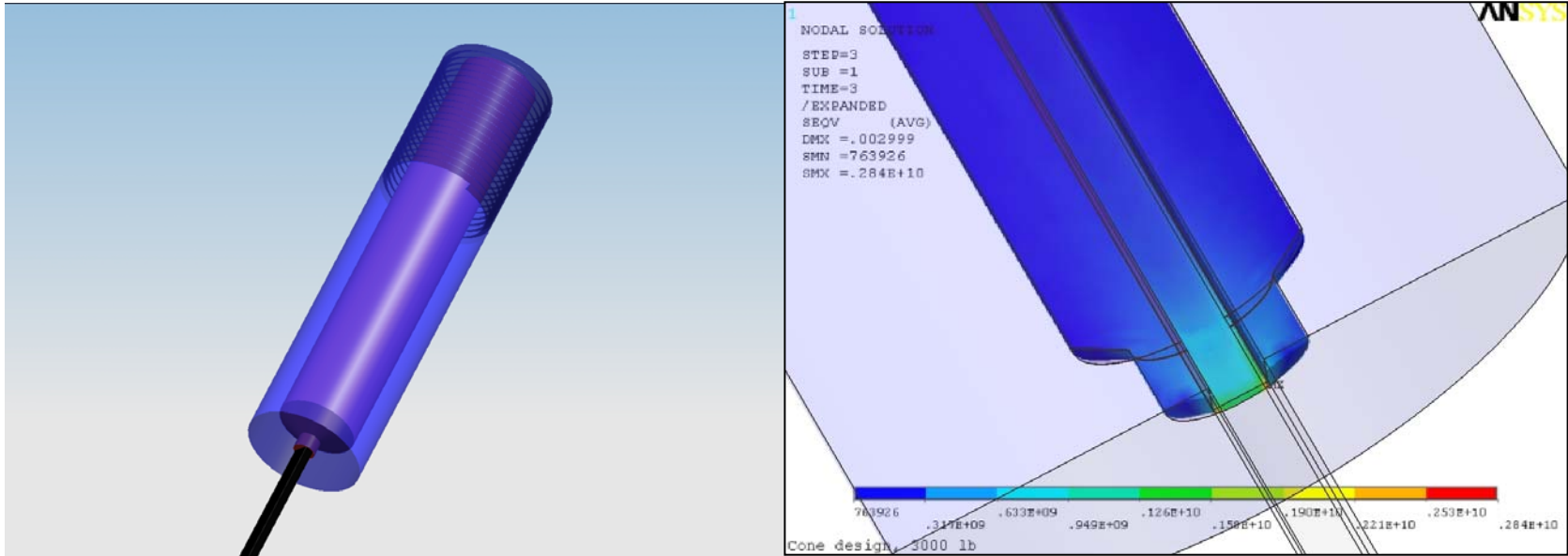
**A parked/stranded delivery truck  
heats up very slowly due to heat transfer from the environment,  
avoiding increased risk of failure due to lower safety factor**



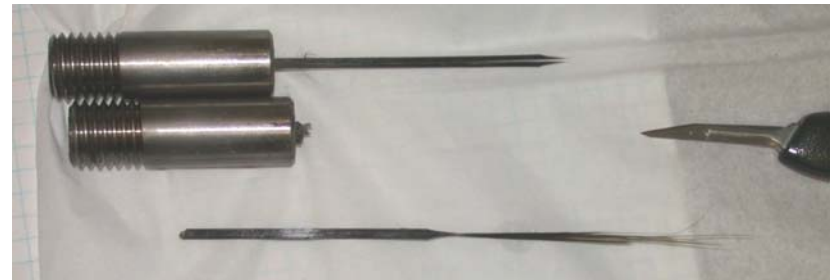
# Need to measure strength of manufactured composite as a function of temperature and immersion time



# Designing fixtures is not straightforward due to high fiber strength. Our advanced analysis enabled design of optimized fixtures allowing successful sample testing.



Conical cross section reduces stress concentration and allows higher tensile load

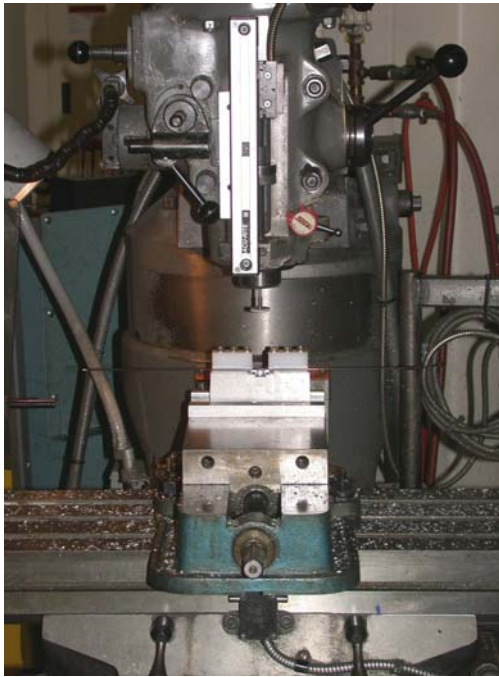


Conical design specimen holders  
after first cold tensile test success





# Photographs Showing Failed Composite in Reduced-Area Region

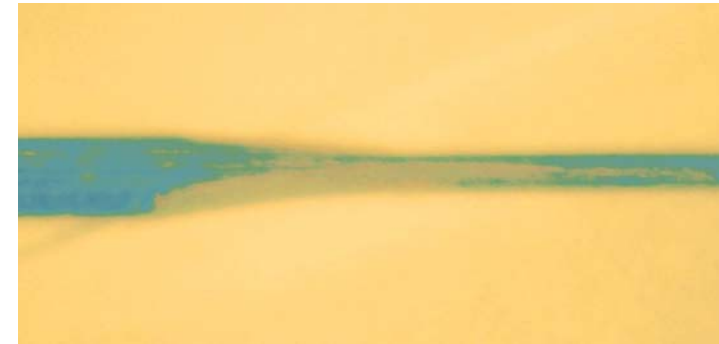


Grinding Mill allows area reduction (AR) of both glued-up + unglued specimens

Only splinters remain from AR tensile specimens that failed in LN



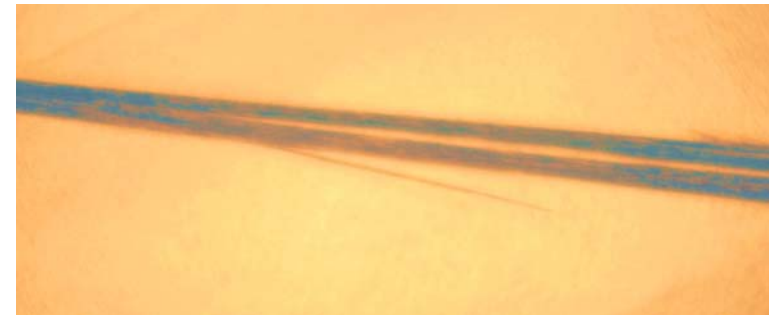
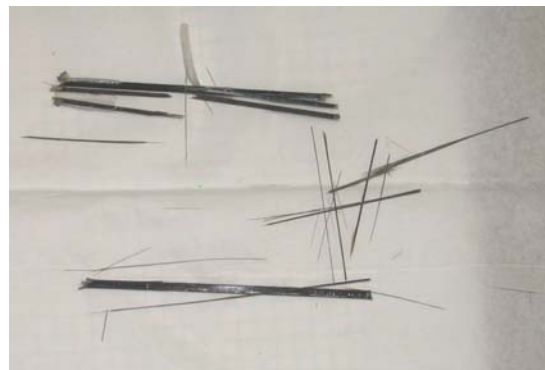
Earliest AR Section shows sheath of fibers damaged by grinding



'Tongue' pulls out inches long !



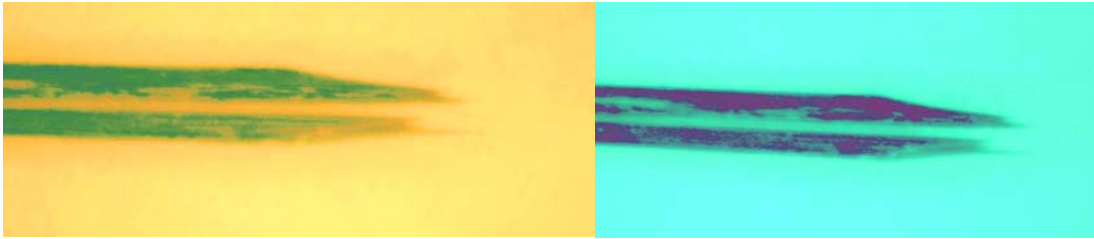
Can image fiber damage sites, but section areas are not possible to measure



What's left after AR fails



# More Close-Up Photographs Show Failed Composite Phenomena



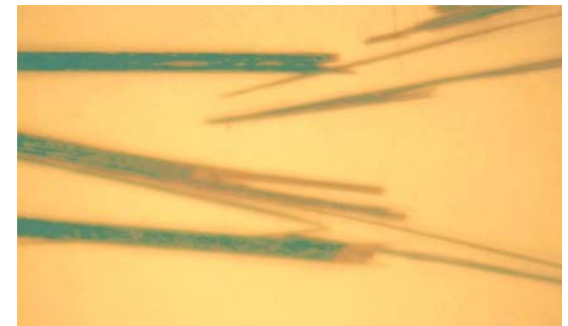
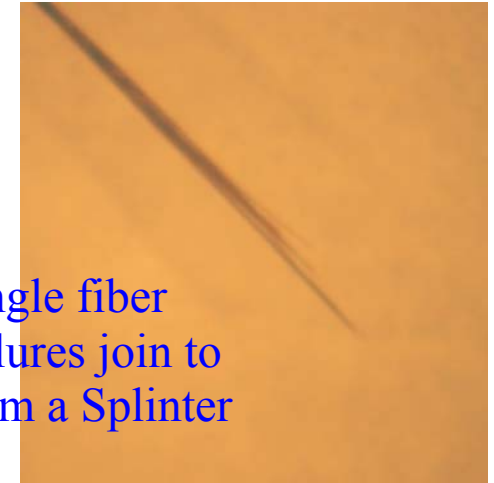
When failure occurs far from the AR section, a clean slot vacated of fiber is formed on the end opposite a 'Tongue' extending from the AR section to the defect where the highly loaded fibers that ran through the section are weakest

Only Splinters, no Tongue from fiber that failed near 0C



Ends of Tongues and Splinters show single and bundle fiber breakage, as well as possible defective manufacture (c.f. twisting)

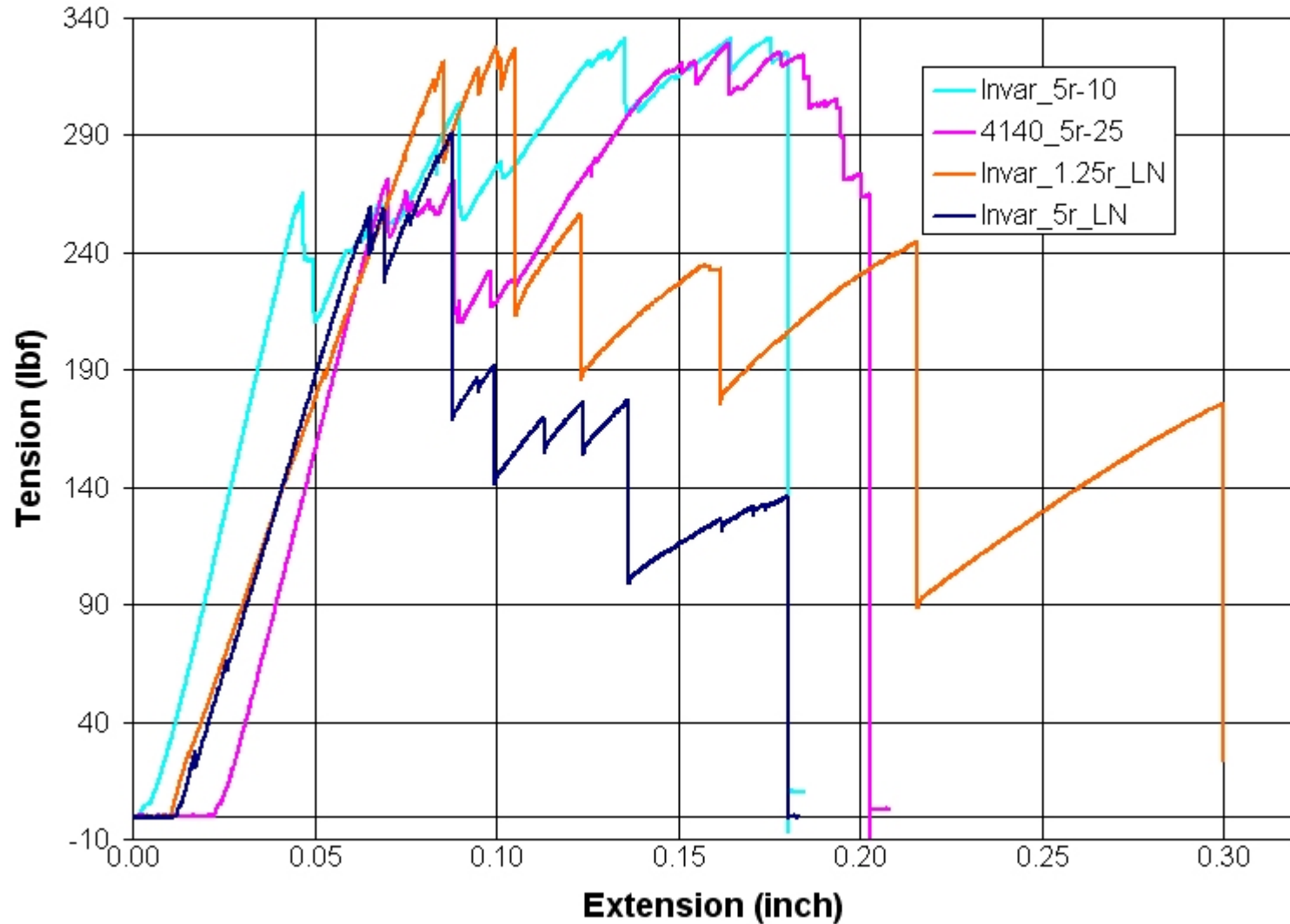
Single fiber failures join to form a Splinter





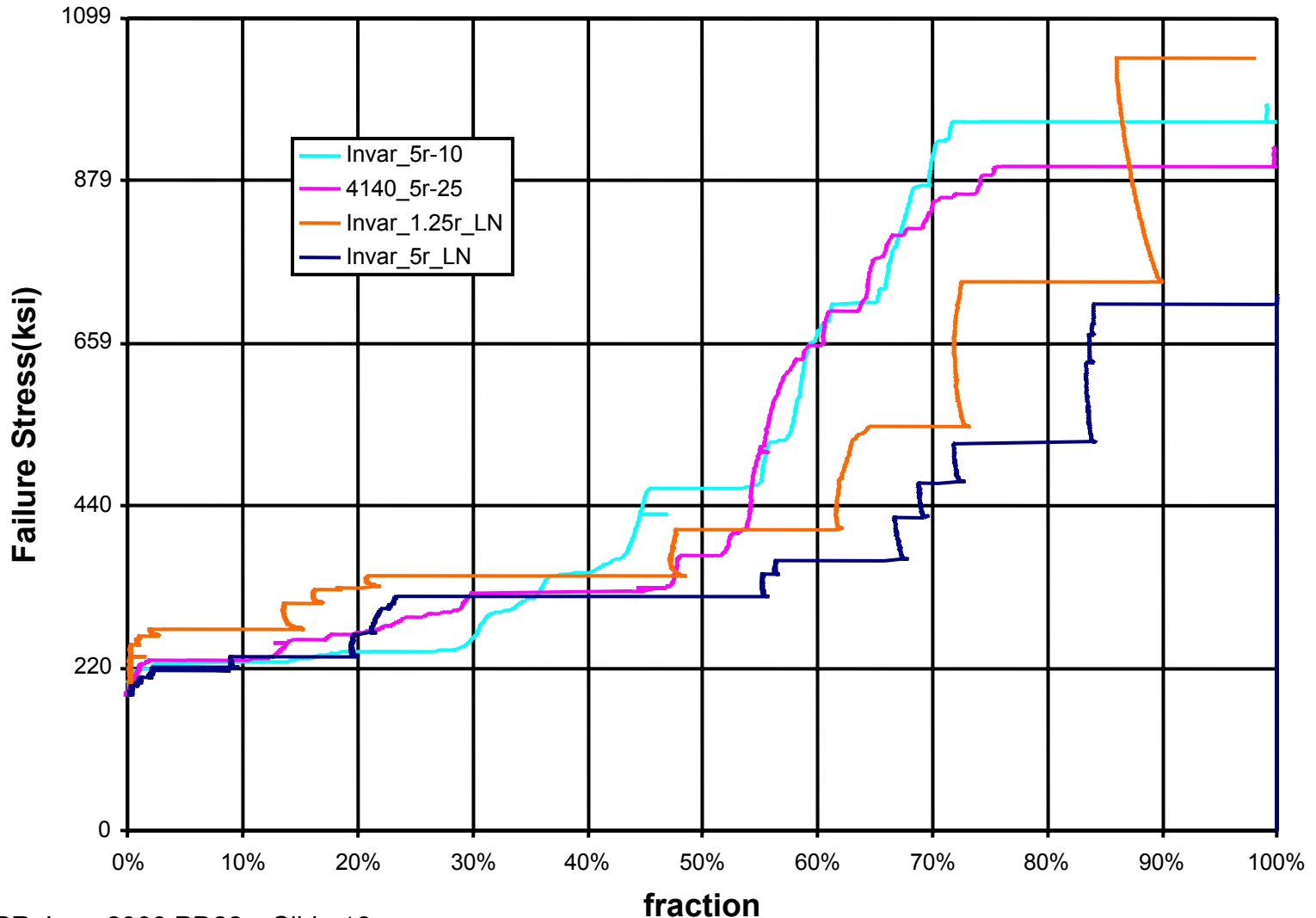
# Raw Data from Tensile Testing of Best Recent Specimens

## Tensile Load vs. Specimen Extension



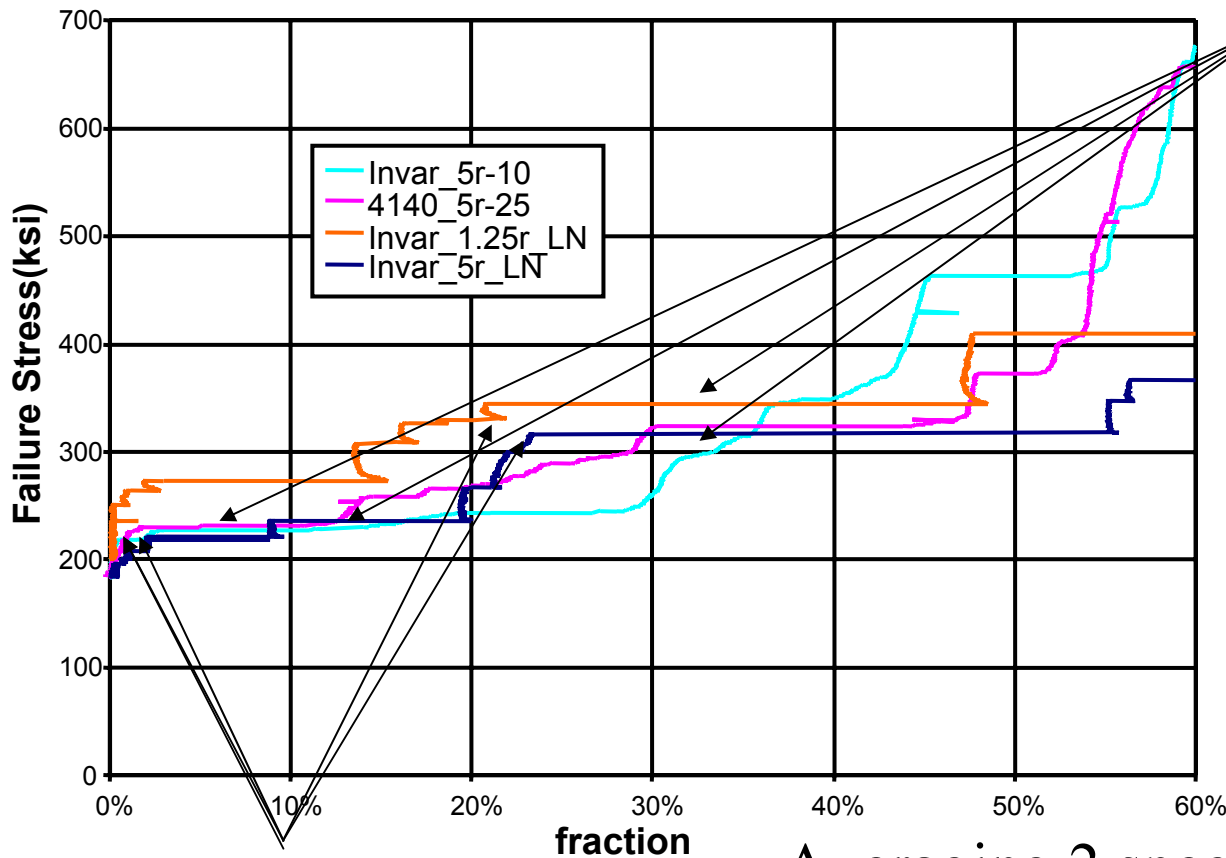
# Test Data Reduced into Cumulative Probability of Failure Using Weibull Distribution Procedure from 1950's

## Cumulative P{fail} vs. Stress



# Failure Stress for Core Fiber at Least 40% Higher at $-162^{\circ}\text{C}$ than at $-10^{\circ}\text{C}$ , and likely increases further with additional (diffusion) time spent at lower temperature

Cumulative P{fail} vs. Stress



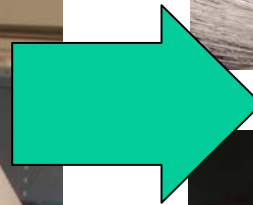
Plateaux in these curves occurs at nearly identical stresses for test specimens with same ambient and test section geometry despite fixture and epoxy differences

Damaged fiber fails early

Averaging 2 specimens/result  
yields  $1.41 = 335/238$



# Future work: Complete cryogenic characterization of glass fiber leading to improved, low cost delivery vessels



## Summary: Our synergistic approach to hydrogen delivery considerably reduces distribution cost



- *Hydrogen cooled to 200 K densifies by 35% at low energetic cost*

- *Inexpensive glass fiber strengthens by ~50% when cooled to 200 K*

- *Cryo-compressed vessels have considerably larger thermal endurance (~10x) than liquid hydrogen tanks*

- *Dispensing of cold (200 K) hydrogen reduces vehicle vessel cost by 25%*

Support Frames  
(not shown)



36 Wound Tanks

