Inexpensive Delivery of Cold Hydrogen in High Performance Glass Fiber Composite Pressure Vessels

Andrew Weisberg, Salvador Aceves, Blake Myers, Tim Ross

Lawrence Livermore National Laboratory

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This presentation does not contain any proprietary or confidential information

Overview

Timeline

- Start date: **October 2004**
- End date: **October 2011**
- Percent complete: **60%**

Budget

- Total project funding
  - DOE: **$1.5 M**
  - Spencer: **$125 k/yr**
- Funding received in FY08:
  - **$900 k**
- Funding for FY09:
  - **$0**

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

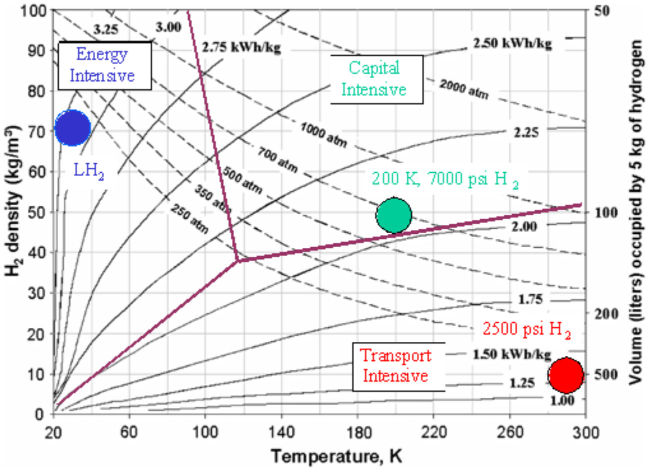
Ongoing joint projects with composite/vessel manufacturers

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

Objective: Demonstrate inexpensive hydrogen delivery through synergy between low temperature (140 K) hydrogen densification and glass fiber strengthening

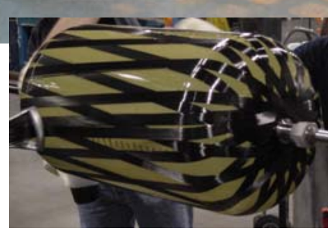
- **Colder temperatures (~140 K) increase density ~35% with small increases in theoretical storage energy requirements**
- **Low temperatures are synergistic with glass fiber composites**
  - **higher glass fiber strength (by > 80%) at 140 Kelvin (compared to 300 K)**
  - **higher gH_2 density increases mass-limited trailer capacity**
- **glass fiber (~$6/kg vs. ~$23/kg for carbon fiber) minimizes material cost**
- **Increased pressure (7,000 psi) minimizes delivery costs**
- **Dispensing of cold hydrogen reduces *vehicle* vessel cost ~25% by avoiding overpressurization during fast fill**

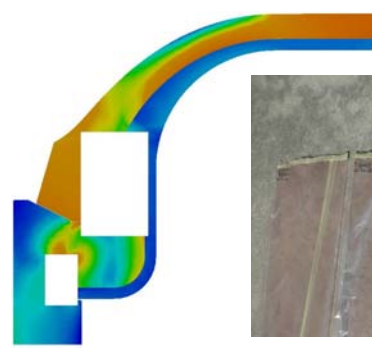
Milestones: Conduct experiments and analysis to demonstrate high performance inexpensive glass fiber at low temperature



October 2006: Discovered favorable P-T conditions for H_2 delivery

January 2008: Proved > 40% strengthening due to cold operation

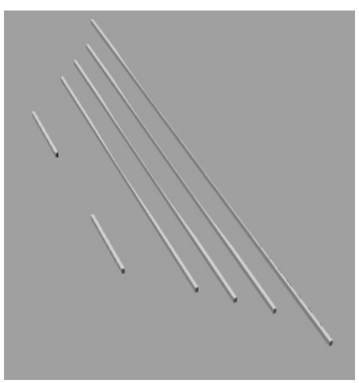


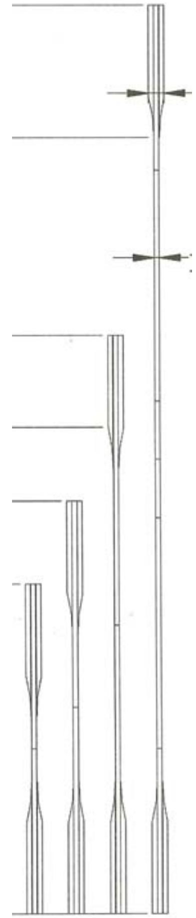


March 2009: Built and tested over 15 3” pressure vessels, designed 24” 8ksi end dome, both with new matrix and liner plastic qualified 77 K to ~335 K

Approach: We are studying low temperature glass fiber strengthening and applying it to design inexpensive vessels

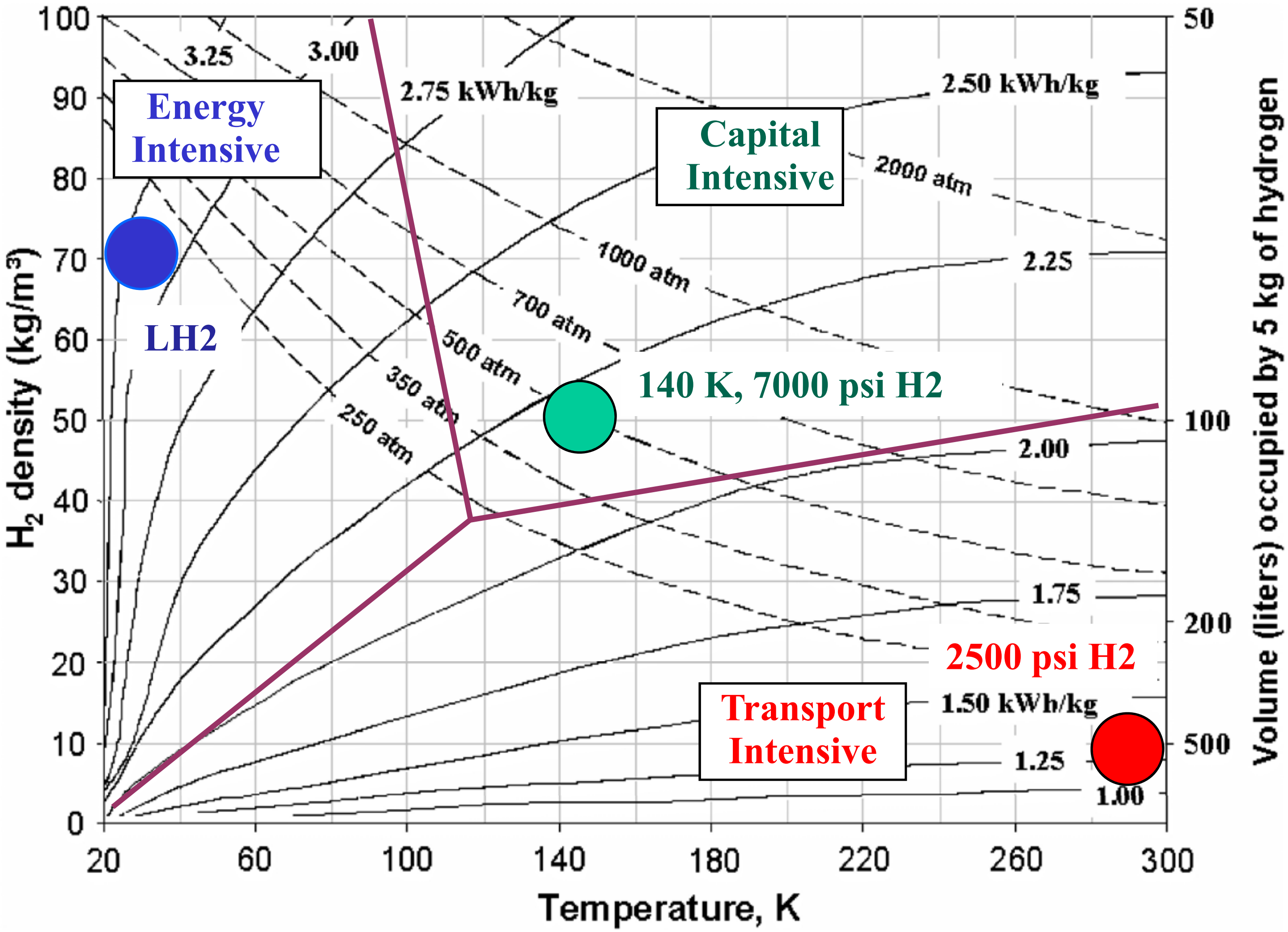
How does glass fiber strengthen through residence at low temperature or in a vacuum?



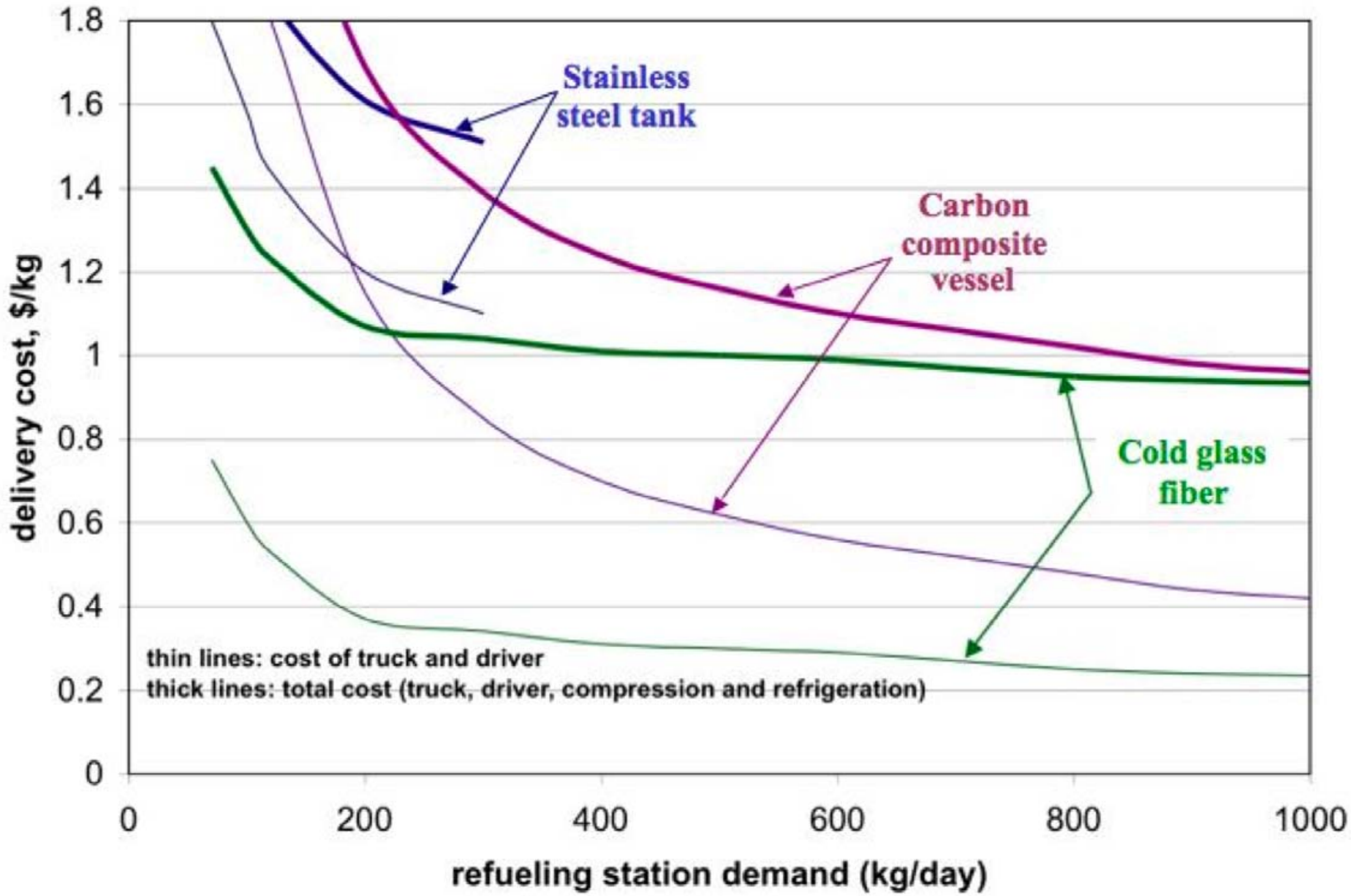


How can we best design inexpensive delivery vessels for low temperature operation?

Accomplishments: we have selected an operating regime (140 K, 7000 psi) that minimizes delivery cost

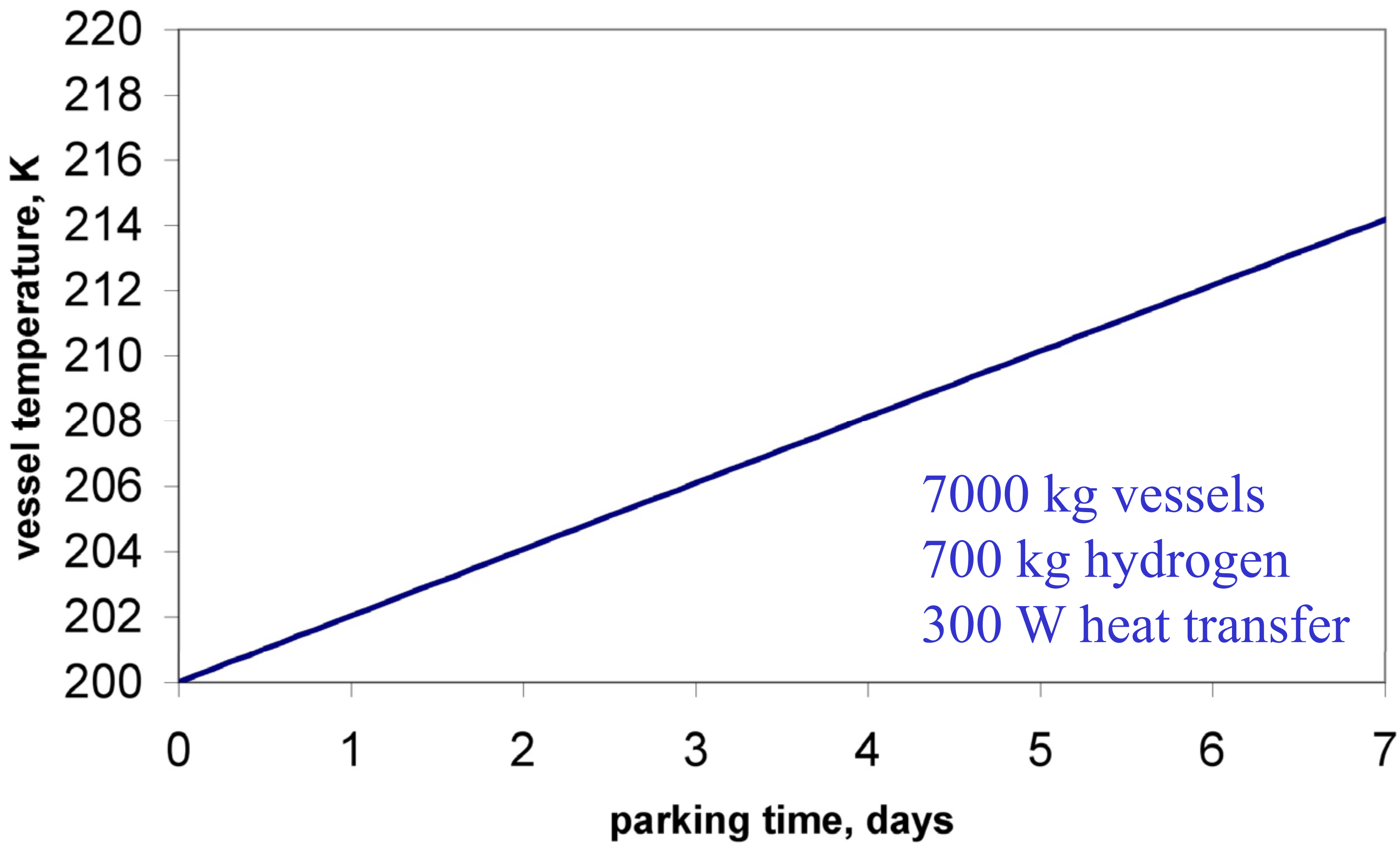


H2A-based modeling predicts that cold glass fiber pressure vessels minimize delivery cost

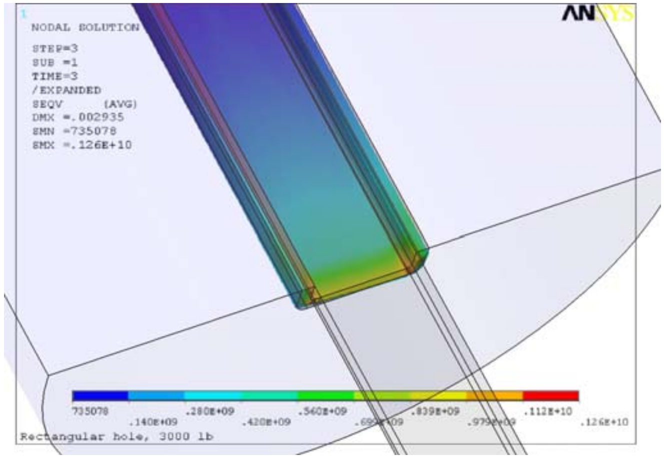


Cryogenic delivery trucks do not risk weakening due to warming unless stranded for *weeks*

H_2 losses avoided through large size and high pressure capability



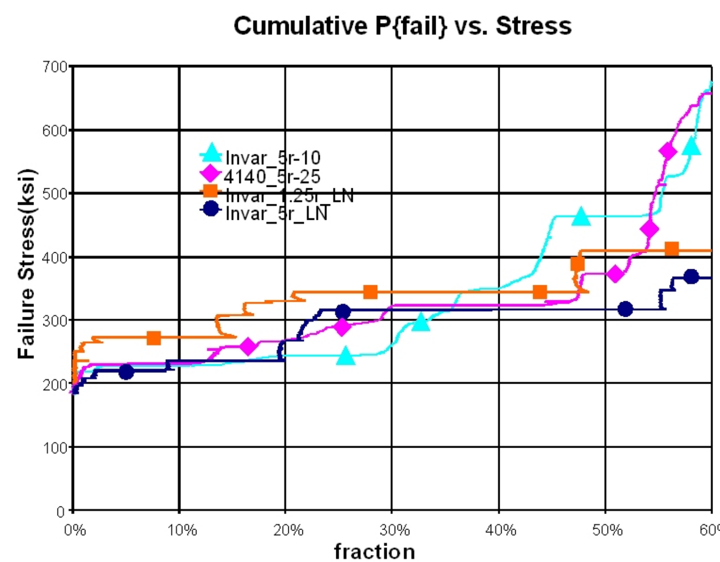
Last year we demonstrated ~40% glass fiber strengthening through short-term immersion in liquid nitrogen



Stress analysis of fixtures

Prepare glass fiber specimens

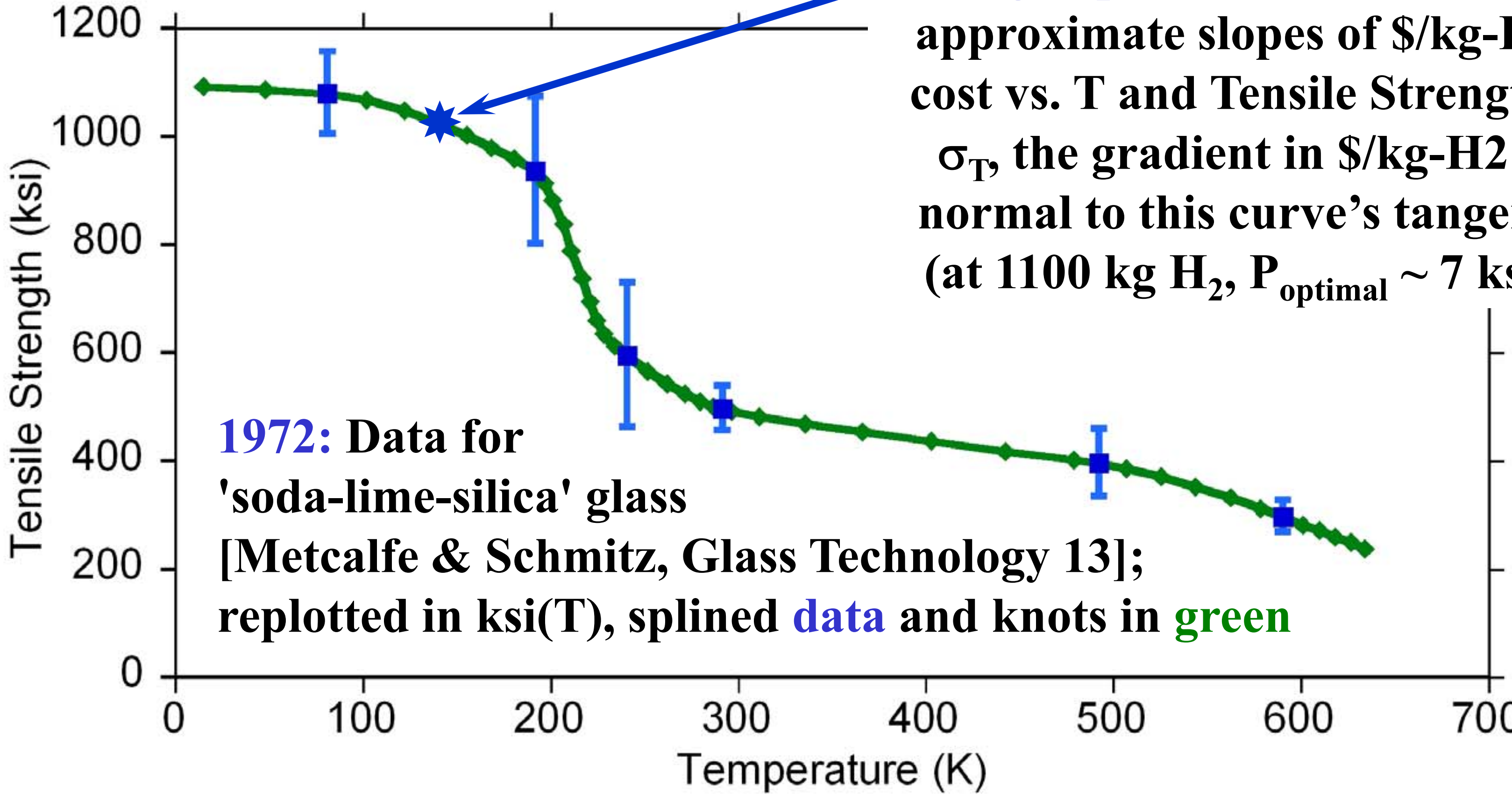
Tension test at cryogenic conditions



Data analysis

Literature survey has revealed considerably higher potential (>1.8x) for low temperature glass fiber strengthening

- **Sufficient to enable improved optimization of capital+energy costs, and specify preliminary operating T's for mobile H_2**

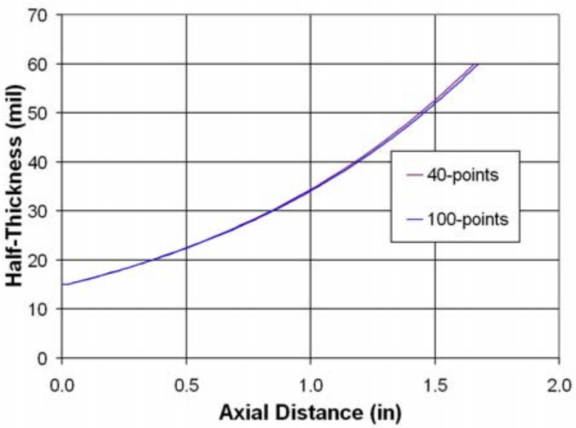


Rough optimum derived from approximate slopes of \$/kg-H_2 cost vs. T and Tensile Strength σ_T, the gradient in \$/kg-H2 is normal to this curve's tangent (at 1100 kg H_2, $P_{optimal}$ ~ 7 ksi)

1972: Data for 'soda-lime-silica' glass [Metcalfe & Schmitz, Glass Technology 13]; replotted in ksi(T), splined data and knots in green

Trying to reach full strengthening potential, we continue researching the effect of low temperature & vacuum operation on vessel performance

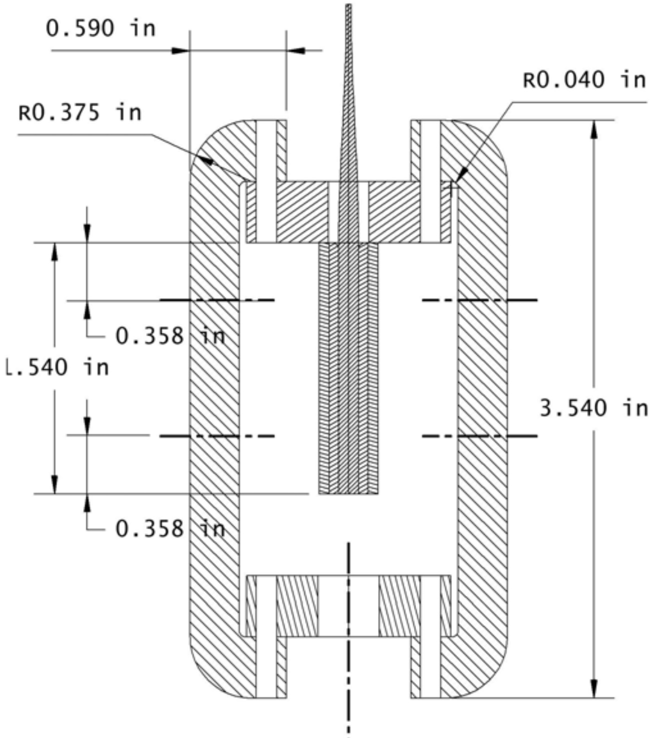
- **Stock for tensile specimens is protected from adsorbing water by bagging in Argon, storing in freezer, and vacuum bakeout**

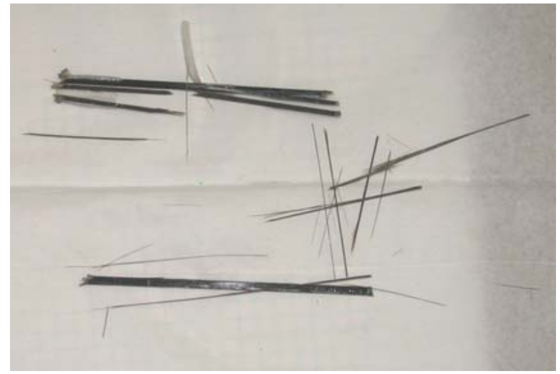


June 2008: **Multiple fiber types pultruded into epoxy matrix rectangular bar specimens of every type of near-term interesting glass fiber (basalt, 2 E-Glasses, S-Glass)**

March 2009: **New pultruded rod specimen neck design and machining method avoids grinding, gluing, and splintering during failure**

Cryogenic tension tests are a challenge due to high fiber strength We have designed an improved fixture that enables accurate tension test results without fiber splintering



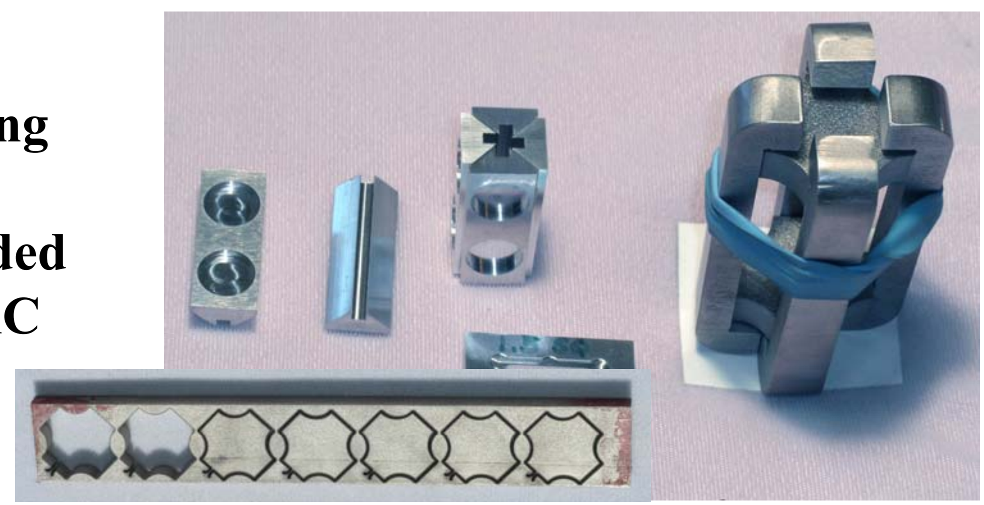


Only splinters remained from reduced area tensile specimens that failed in LN in March 2008

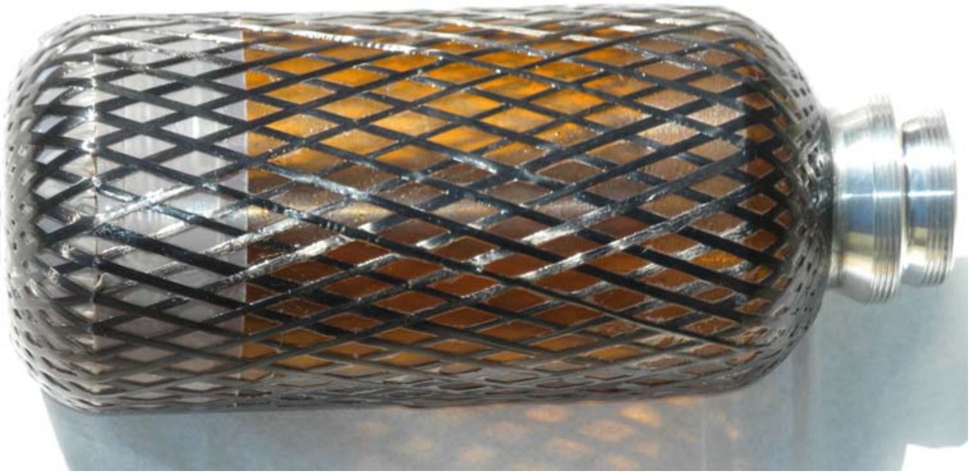
Reduced area sections showed a sheath of fibers damaged by grinding in March 2008

No More Grinding → Single-Point SiC mill

March 2009: New design being rapidly prototyped using WaterJet-cut 303 SS, pultruded rod specimens undergoing SiC cutting trials, enabling max-shear-stress anti-splintering



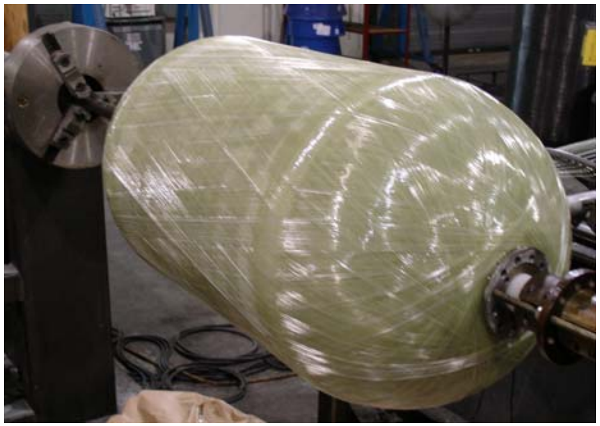
We are building and burst testing 3" vessels with improved liner plastic tooling and process



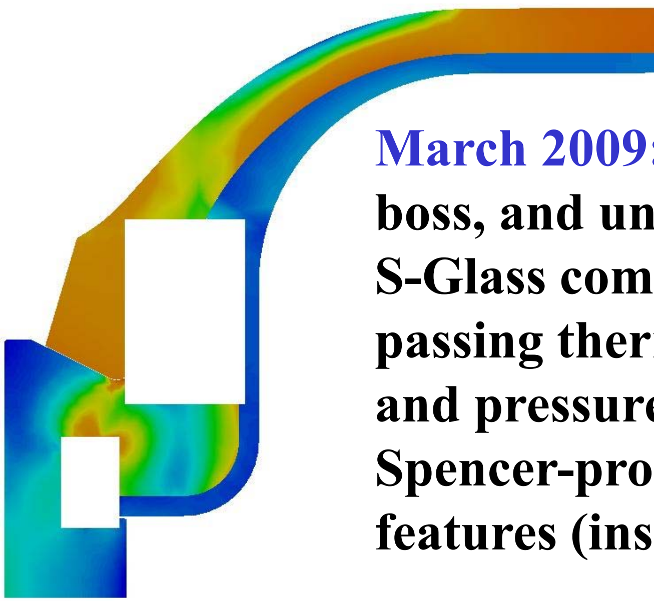
February 2009: Early liner production tooling dialed in, first pressure tests with a low-P boss

November 2008: Low cost and fast alteration tool built to mold liners

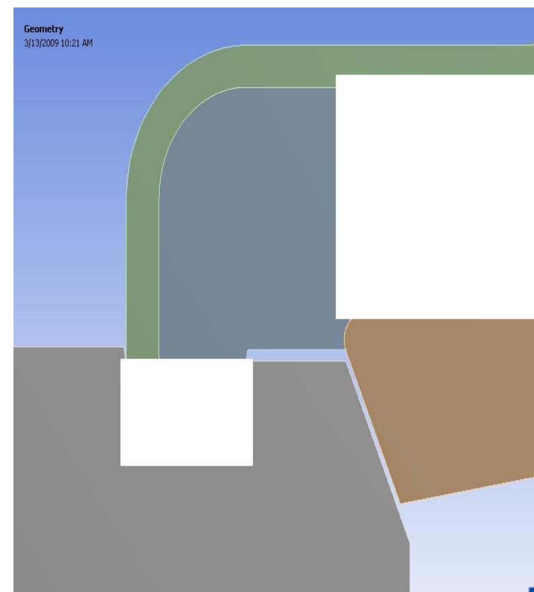
We are building full scale 24” diameter, 112” length vessel, rated for 8,000 psi service pressure, safety factor 2.25 including liner tooling and deep-cryo-compatible boss design



New liner plastic and glass composite overwrap matrix material are being developed (poster MFP01)

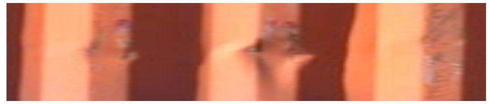


March 2009: FEA design of liner, boss, and un-cold-strengthened S-Glass composite overwrap is passing thermal cycling to 77K and pressure cycling to 18 ksi via Spencer-proprietary conical boss features (inside white rectangles)



We are designing vessels to fit inside ISO intermodal containers for permitted transportation and storage of hydrogen at any T

- Crashworthy shell is worth its weight !



  - Routinely stronger than road hazards, vandalism, pickup trucks...
  - Preserves shape in collisions with most trucks, concrete pillars
- Triple Containment (compared to 'naked')

  - Wrapper around container ➔ leak control
  - Clean conditions preserves function of planar insulation on walls
  - Vent or isolate part of Hydrogen payload: 1/12th, 1/6th ,¼, or ½
- Designed to be Stackable

  - Saves real estate at filling stations, 'gas' terminals, and in storage "tank farms"
  - Stack to > 7 high, can pick up from above
- Generic Solution (already widely supported)

  - Metal much more rugged, able to withstand T excursions
  - Head start on presumption of safety – nothing unusual visible

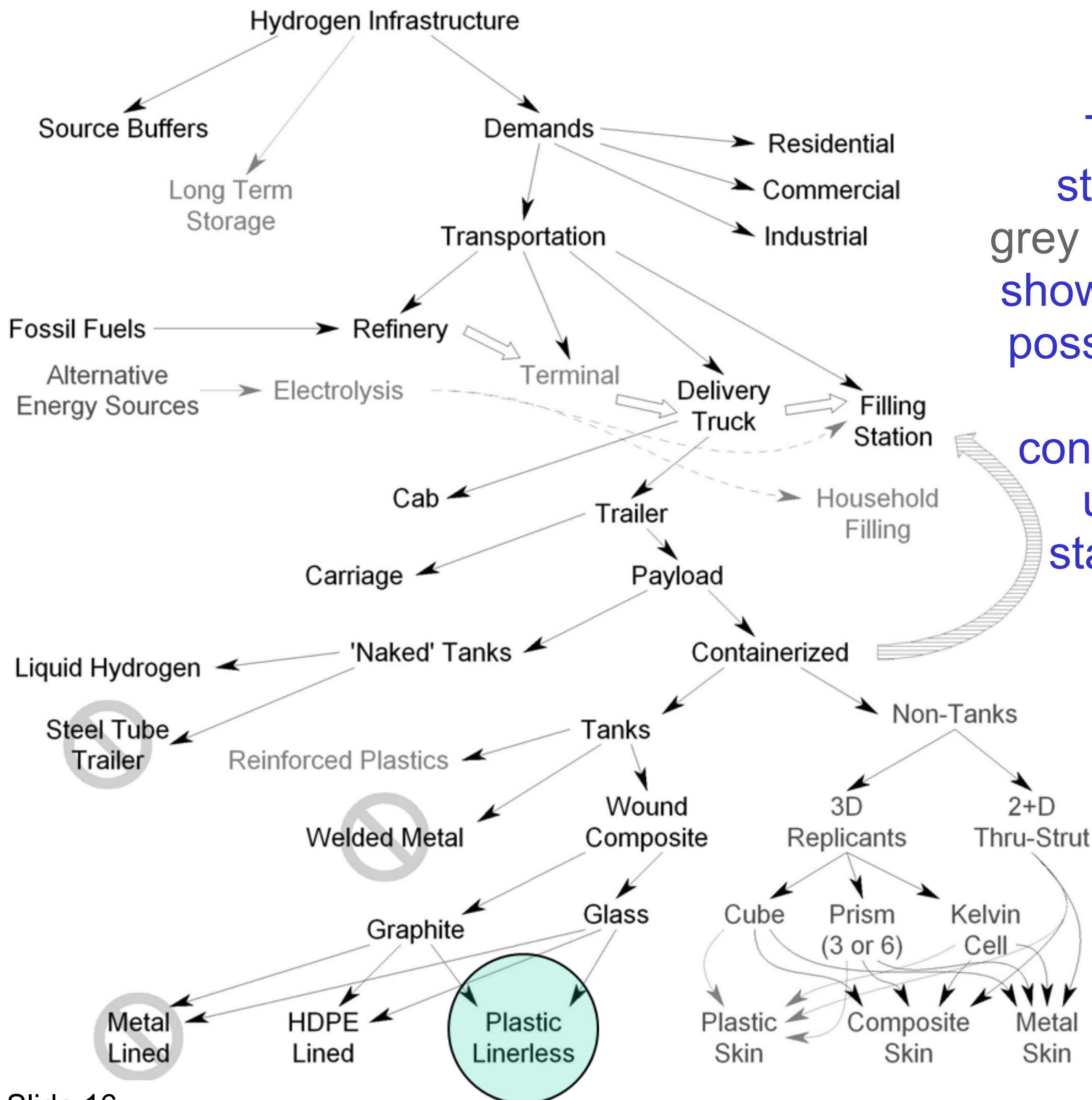
LLNL delivery studies considered infrastructure alternatives and indicate applicability for stationary applications

Thin arrows represent choices

Choices and Alternatives shown in grey are not options available in the next few years

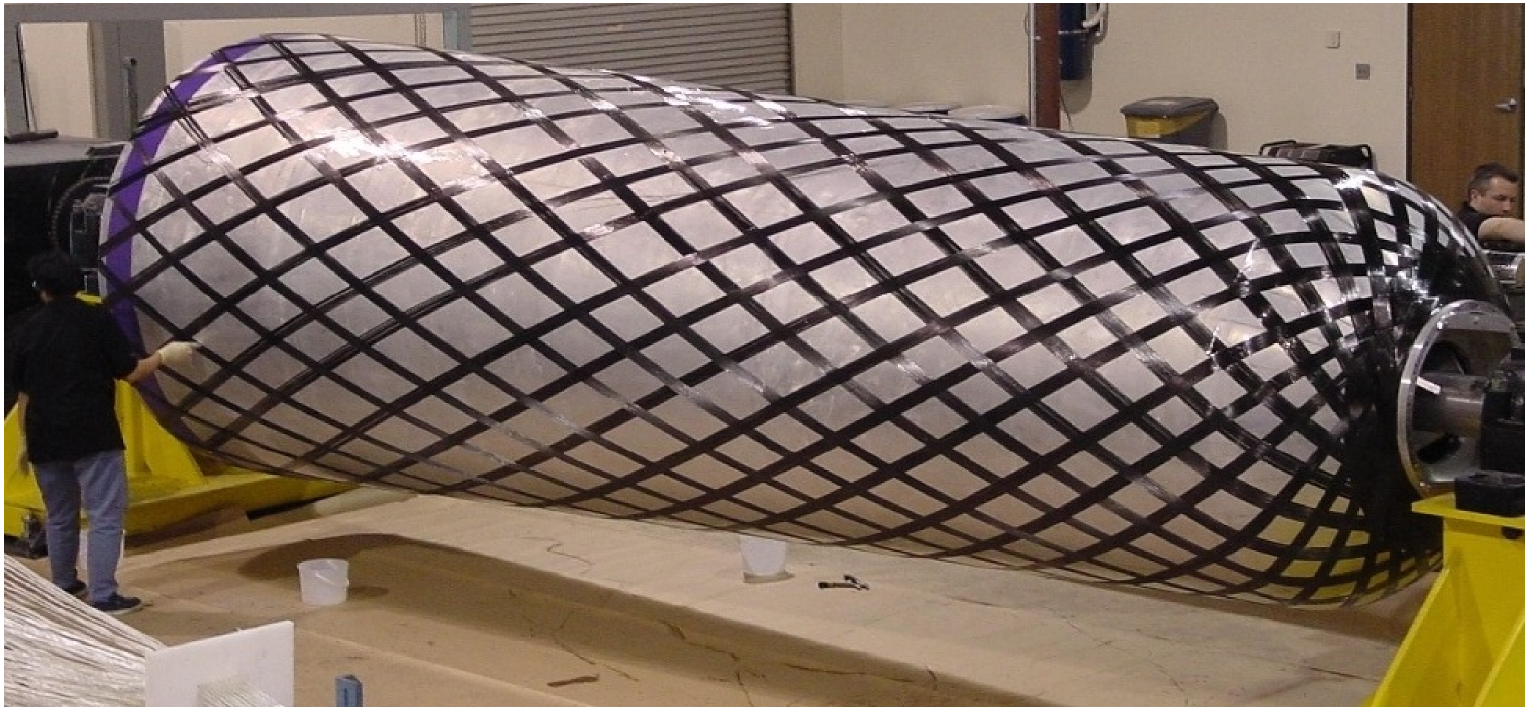
Thick, hollow, white arrows show Delivery to fuel vehicles

Alternatives with crossed circle through them have lost out in cost models



Thick, striped, grey arrow shows the possibility of container use at stations

Collaborations: Team with an Innovator with the proven ability to develop new, large composite parts

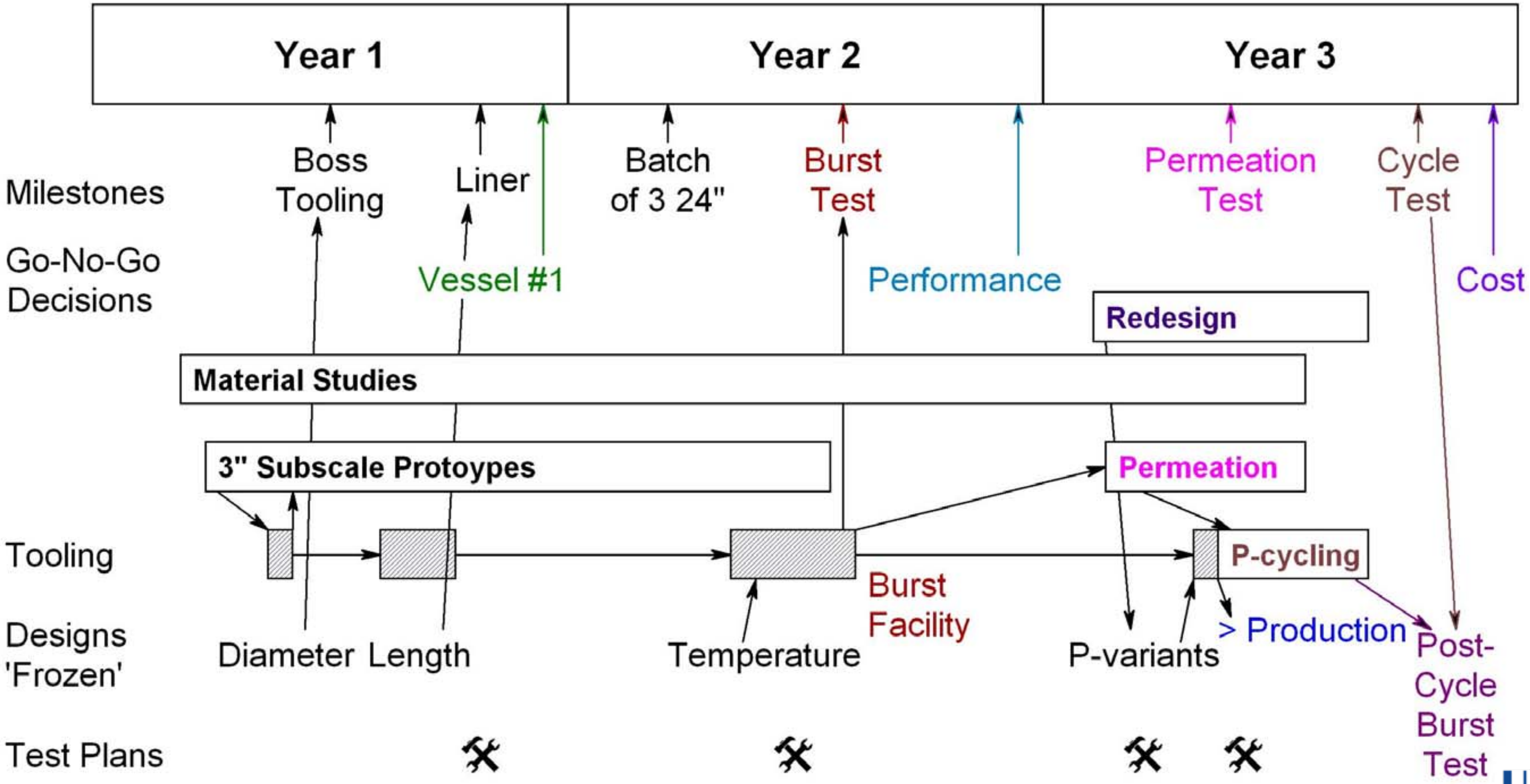


Spencer Composites

- **Adopt Spencer's development of ultra-low-cost matrix plastic**
  - **Unproven in large scale pressure vessels – but tested H_2 + cryogenic**
- **Affordable aerospace quality**
- **Contributing cost share**

Future plans: 3 Phases of 1 year each
Leading to large inexpensive delivery vessels at the end of year 3

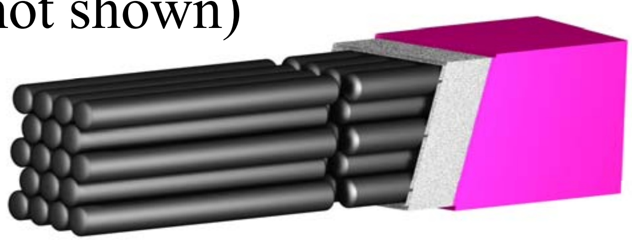
- **Technical risk reduction for all key unknowns**
  - **Design, permeation, and cycling of new plastic, + design errors**



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

Planar Insulation inside shell (shown in white)

Support Frames (not shown)



- ***Hydrogen cooled to 140 K densifies by 45% at low energetic cost***
- ***Inexpensive glass fiber strengthens by ~70% when cooled to 140 K***
- ***Cryo-compressed vessels have considerably larger thermal endurance (~10x) than liquid hydrogen tanks***
- ***Dispensing of cold (200 K) hydrogen reduces automobile vessel cost by 25%***

36 vessels per 20’ trailer hold up to 12 ksi, 72 per 40’ trailer at 8 ksi optimal