Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High Pressure Liquid Hydrogen Pump

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Overview

Timeline and Budget

- Start date: January 2014
- End date: December 2016
- Total project budget: $5.7M
- Total recipient share: $1.5M
- Total federal share: $4.2M
- Total DOE funds spent: $1.8M*

*As of 3/31/15

- Funded jointly by Technology Validation, Storage, and Delivery

Barriers

- C. Hydrogen storage
- D. Lack of hydrogen infrastructure performance and availability data

Partners

- Spencer Composites Corporation custom cryogenic pressure vessels
- Linde LH_2 pump operation & maintenance
- BMW thermal insulation, performance requirements, automotive perspective

Relevance: We are building a new generation of cryogenic pressure vessels and testing them with an innovative liquid hydrogen pump

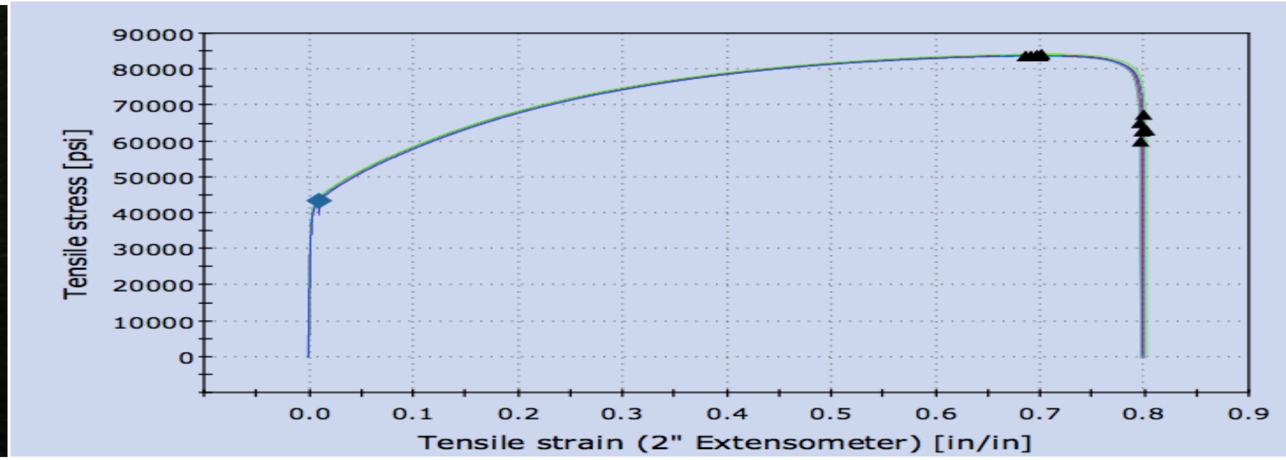
New generation cryogenic pressure vessel

- 65 liters, 34 cm diameter, 100 cm long
- 700 bar
- 50 g/L, 9% H_2 weight fraction
- Thin lined (<2 mm), high fiber fraction (up to 80%)
- 80+% volume ratio (inner vessel volume/outer vessel volume)
- Thin vacuum insulation (<1 cm)
- **Test strength (1600 bar new; 1300 bar cycled) and durability (1500 thermomechanical cycles)**

Liquid hydrogen pump

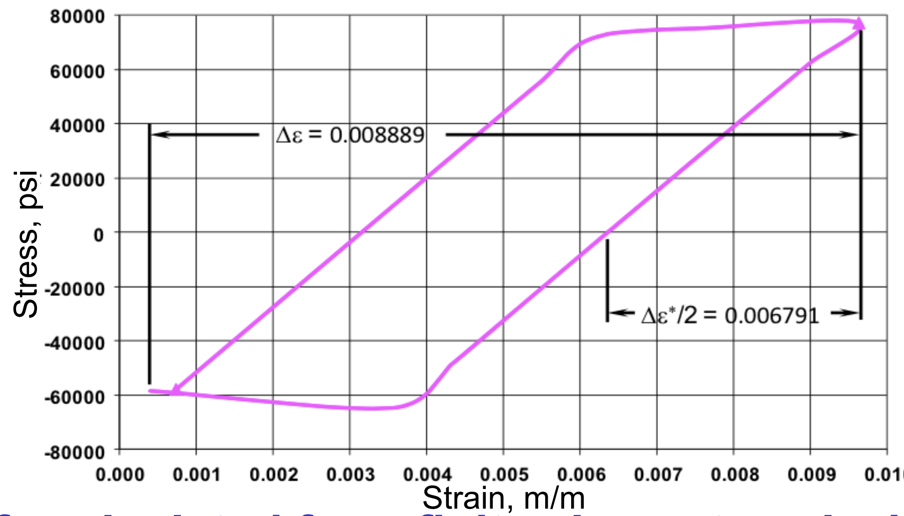
- Manufactured by Linde and installed at LLNL campus on FY13
- Rapid refuel of cryogenic vessels, even when warm and/or pressurized
- High fill density (80 g/L) and throughput (100 kg/h)
- LH_2 pump evaporation (1-3%) recycled into Dewar; not vented
- **Test pump degradation after dispensing 24 tonnes of LH_2**

Approach: design durable (1500 cycles) cryogenic compatible thin lined high volume ratio vessels



Liquid nitrogen tensile testing of candidate liner materials and welds

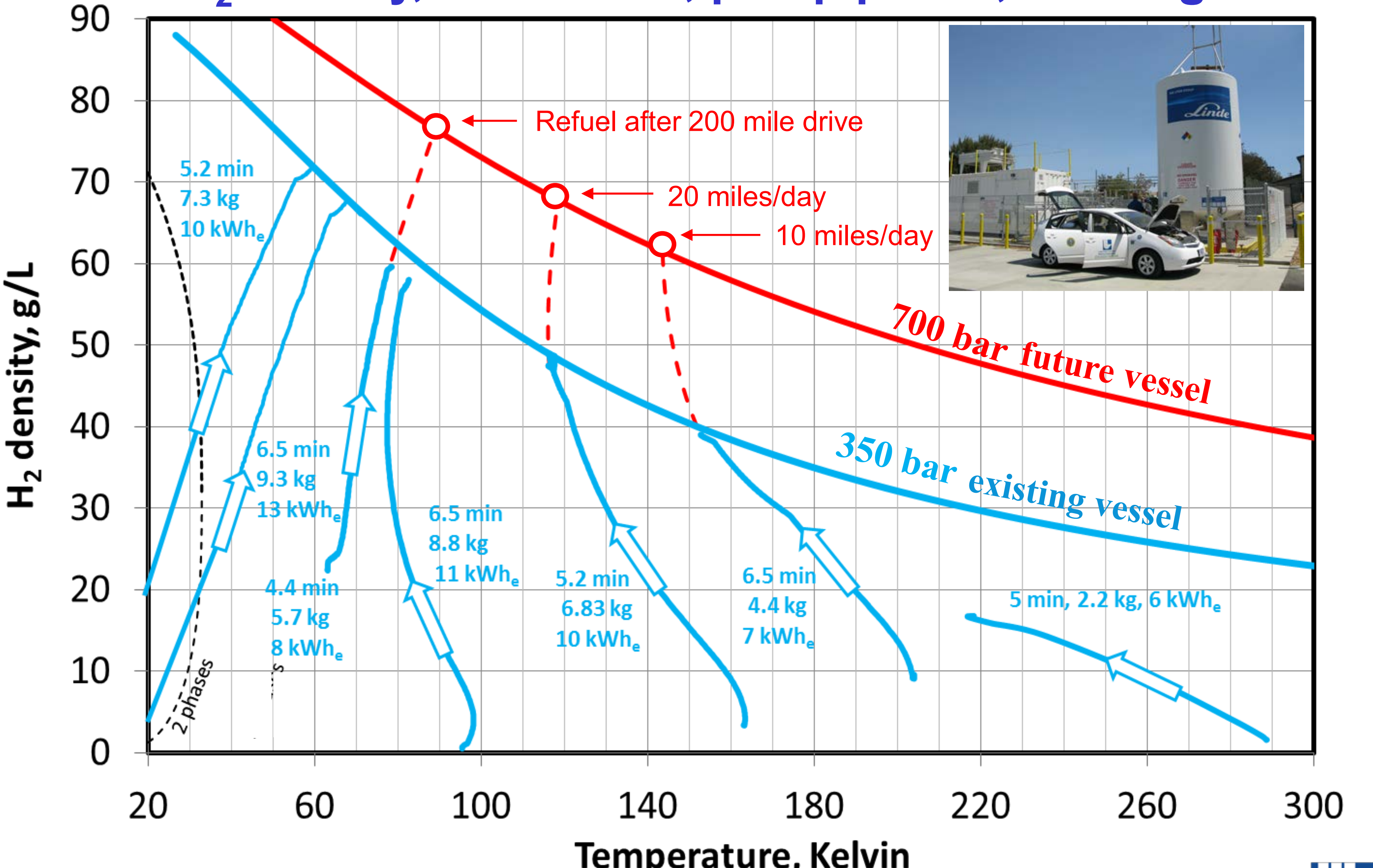
Ring tension tests determine minimum liner thickness and autofrettage pressure



Vessel cycle life calculated from finite element analysis

Guide vessel design with finite element analysis and cryogenic and ring tension experiments

Approach: Extend LH_2 refueling to 700 bar
Measure H_2 density, refuel time, pump power, and degradation

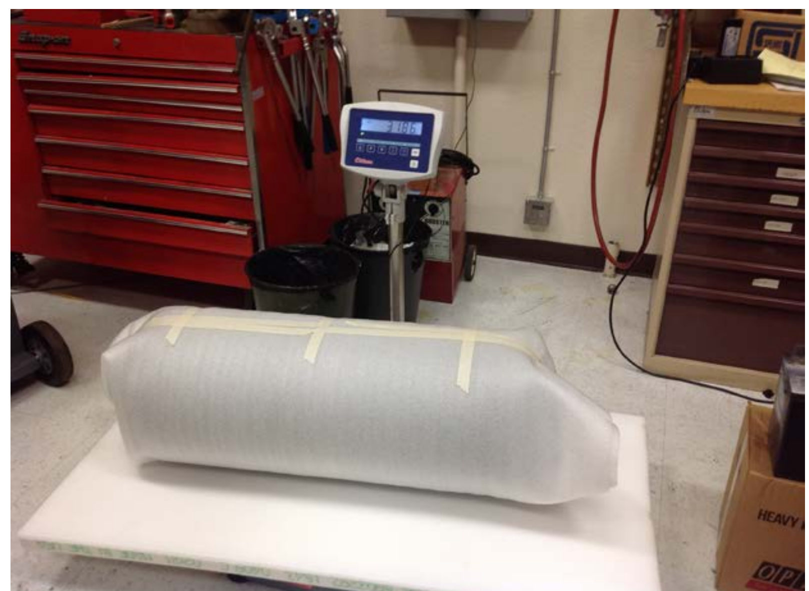


Up to 80g/L H_2 density possible at 700 bar

Accomplishments: We have built and tested the first cryogenic compatible, thin-lined (1.8 mm) pressure vessel

81% volume ratio at 700 bar (vs. 70% conventional vessels)

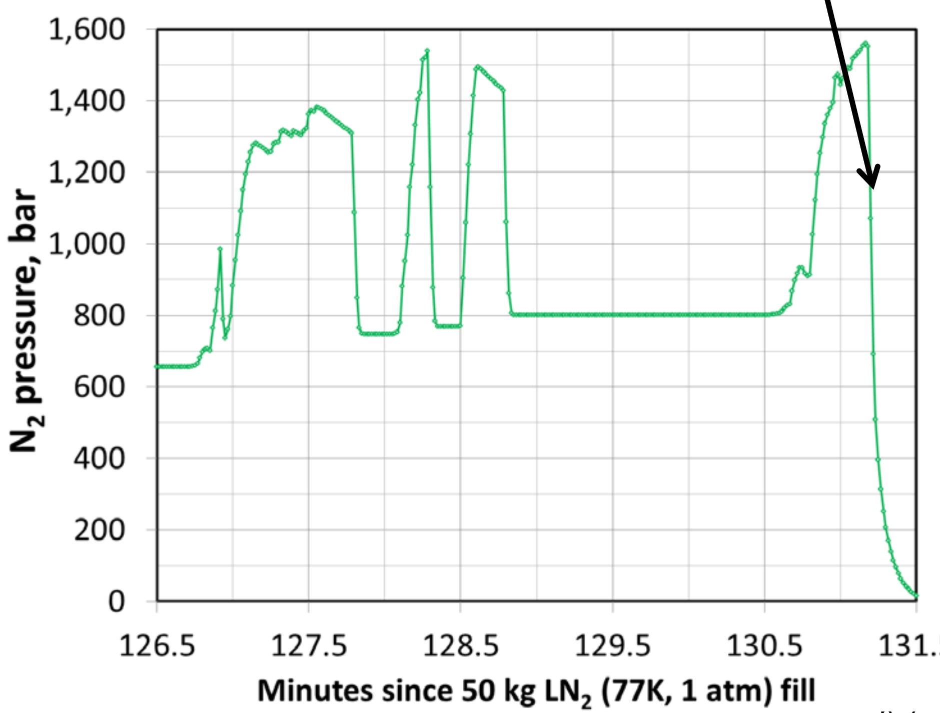
1.8 mm liner thickness
34 cm outer diameter
1 m long
32 kg weight
65 liter inner volume



Accomplishments: 65 L prototype vessel full of LN_2 withstood four pressure cycles to 1300+ bar before bursting at 1560 bar

Burst pressure 1560 bar vs.1600 bar target

Preferred failure mode:
hoop stress in cylindrical section
No failure in welds or domes



Accomplishment: instrumented pump with power analyzer, boil-off mass flow meter, and outlet temperature sensor

Power Analyzer

- 20 kHz sampling rate
- Precise power quality analysis (inductive, reactive, consumed active)

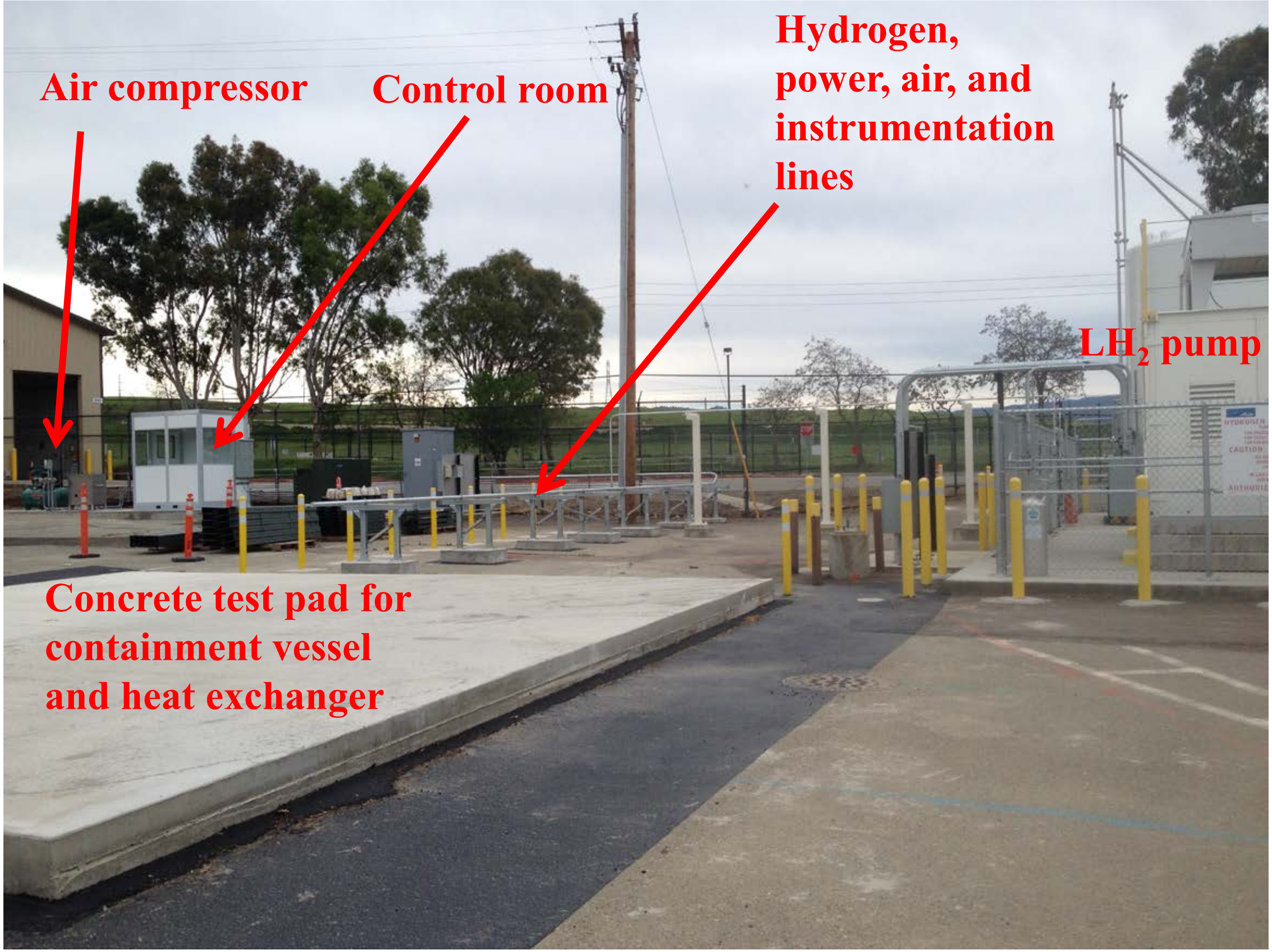
Boil-off Mass Flow Meter

- Explosion proof (Class 1 Division 1 Group B)
- Loop powered thermal mass technology
- 0-10 kg H_2/hour
- 1 Hz continuous acquisition

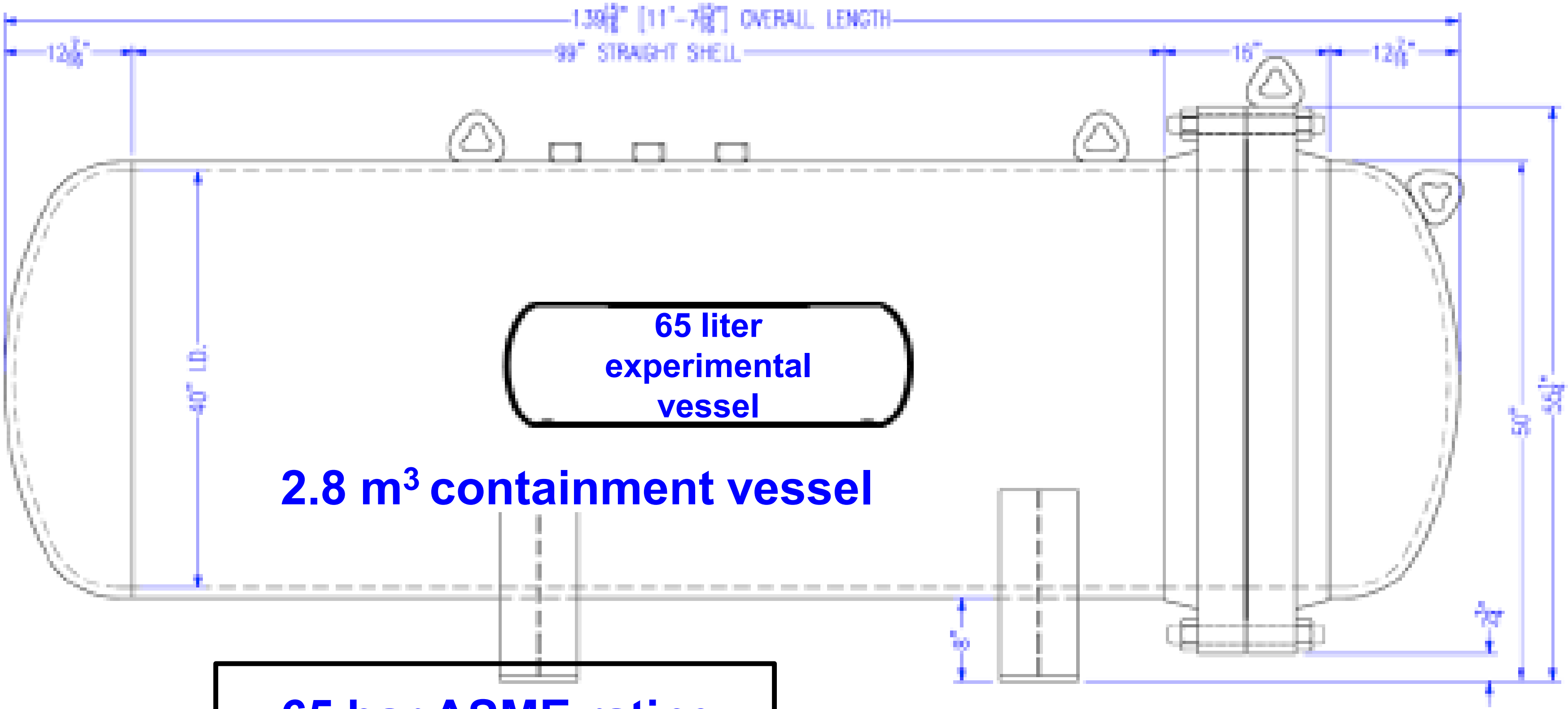
Temperature sensor at pump outlet

- Silicone diode
- Nearest location to pump outlet
- 1 Hz continuous acquisition

Accomplishment: Completed civil construction of cryogenic hydrogen pressure vessel test facility. Containment vessels and heat exchanger to follow in FY15



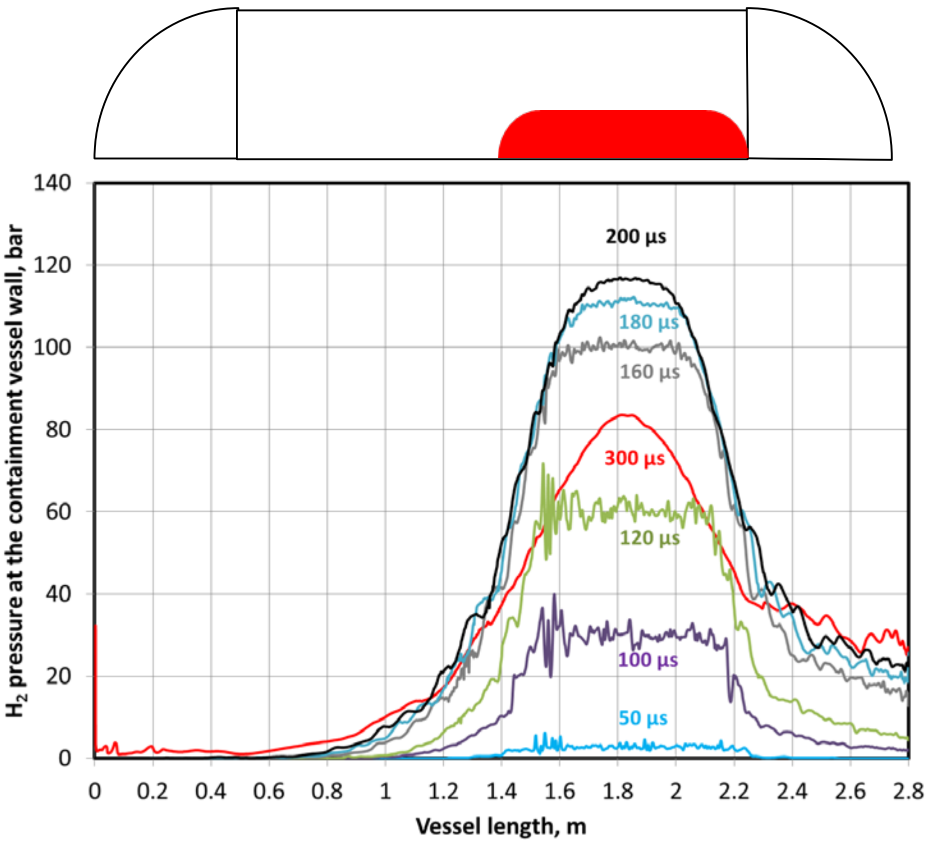
Accomplishment: Non (ASME, DOT, ISO) certified prototype vessels will be tested inside ASME-rated containment vessel

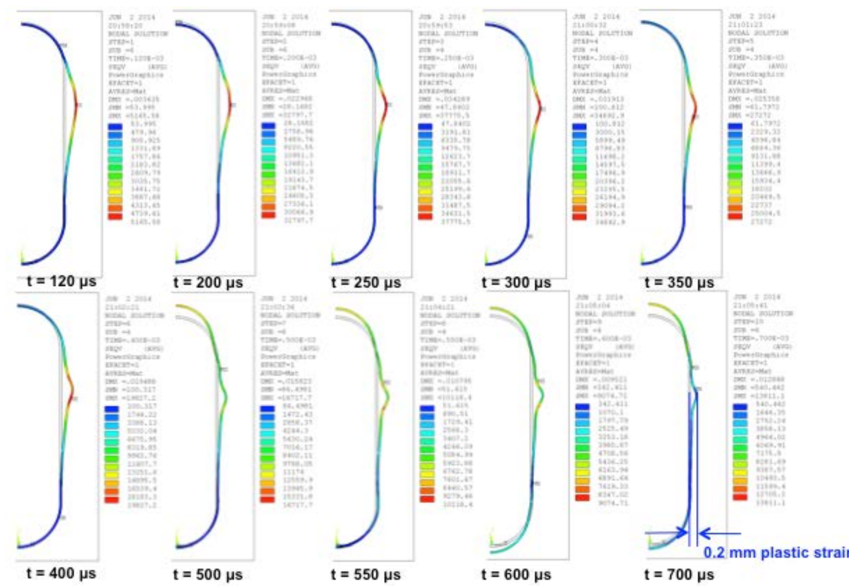


2.8 m^3 containment vessel

65 bar ASME rating
1 m diameter
3.7 m total length

Accomplishment: Obtained LLNL approval for installing 65 bar containment vessels for cycle and pressure testing of non (ASME, DOT, ISO) certified vessels



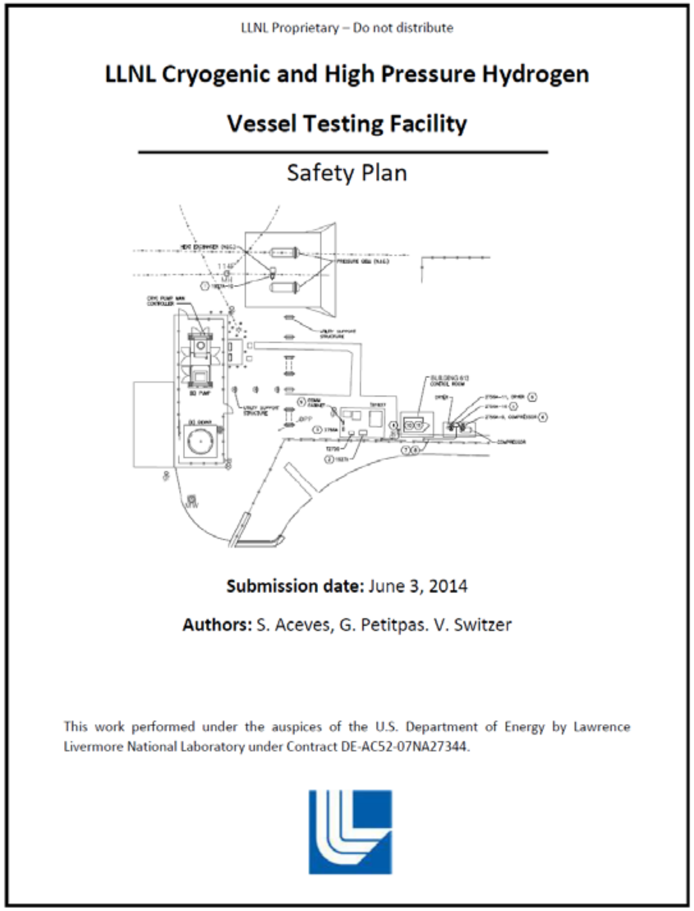


Von Mises stresses (psi), Initial conditions: 360 K, 875 bar, 40 gH_2/L, ANSYS®

Step 1. Fluid mechanics of sudden H_2 expansion upon vessel failure

Step 2. Dynamic structural analysis of blast wave impingement upon containment vessel wall

Accomplishment: 100+ page safety plan praised by DOE Safety Panel due to completeness and level of detail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LLNL Cryogenic and High Pressure Hydrogen Vessel Testing Facility

Safety Plan

Submission date: June 3, 2014

Authors: S. Aceves, G. Petitpas. V. Switzer

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Comprehensive plan includes key aspects of safe operation

- FMEA
- P&ID
- Site layout
- Safety distances for H_2
- Component specifications
- Design calculations

Plan was very well received by DOE hydrogen safety panel

- Requested authorization for using it as an example safety plan due to completeness and thoroughness

Responses to reviewers' comments

Project not reviewed last year

Long standing collaborations with Industry Leaders

- ***Spencer Composites (Sacramento, CA)*: Long expertise in custom composite pressure vessel development. Long-standing collaboration with LLNL on cryogenic vessels for H_2 storage and delivery**
- ***Linde:* World class cryogenics experience. Manufactures maximum efficiency LH_2 pump. Delivered first commercial LH_2 pump to BMW in 2009 (300 bar). Very cooperative, sharing detailed information throughout pump development, construction, and installation**
- ***BMW:* Long standing collaboration with LLNL through two cryogenic pressure vessel CRADAs. Contributing automotive perspective, technical information, and expertise. Advancing cryogenic pressure vessel technology & demonstration vehicles**

Remaining Challenges and barriers:

- ***Demonstrate cryogenic cyclability of thin-lined, high fiber fraction pressure vessels:*** **Next two prototypes will be cycled 1500 times in temperature and pressure, then pressure tested**
- ***Demonstrate high refuel density & durability of LH_2 pump:*** **Need 80+ gH_2/L cold refuel density and no degradation after pumping up to 24 tonnes LH_2 over 2 years**
- ***Demonstrate compact, lightweight system with adequate dormancy*****: thin (<1cm) vacuum insulation with volumetrically efficient vacuum jacket necessary for small diameter onboard storage**

Durability of vessel (1500 cycles) and pump (24 tonnes LH_2)
Light, compact insulated vessel with acceptable dormancy

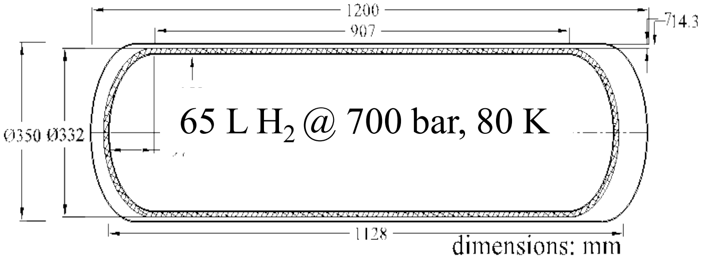
Proposed Future Work

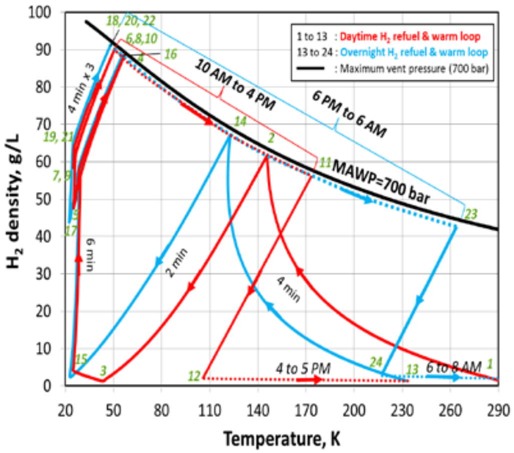
Future work includes:
- Installation of containment vessels and heat exchanger
- Manufacture and cycle testing of four thin-lined high fiber fraction vessels
- Vacuum insulation of top cryogenic vessel design

Second Go/No Go successful cryogenic 1300 bar strength test of prototype vessel after 1,500 pressure and temperature cycles

Milestones	Description
Q2/FY15	Determine pump performance at 700 bar using 163 L conventional vessel (40 gH_2/L_{sys}, 6 wt%H_2)
Q3/FY15	Demonstrate operation of hydrogen pressure vessel test facility by simultaneously cycle testing two 65 L vessels
Q4/FY15	Complete 1,500 accelerated thermomechanical cycles on two 65 L 700 bar, 80+% volume ratio vessels
Q1/FY16 *2nd Go/No-Go*	Demonstrate 1,300 bar minimum strength for at least one of the two cycled prototype vessels
Q2/FY16	Vacuum jacket prototype thin-lined high fiber fraction vessel and demonstrate 50 g/L, 9% H_2 weight fraction

Future work: 3 year project will demonstrate rapid refueling of 700 bar cryogenic H_2 vessels with high system density, small diameter (~35 cm), & cryogenic durability (1500 refuels)





Volumetric efficiency at 65 L capacity

- Up to 5.2 kg H_2 peak H_2 storage
- Thin metal liner (<2 mm)
- High fiber fraction (70+%)
- Thin vacuum insulation (<1 cm)
- Final system demo : 50 gH_2/L_{sys}, 9 wt%H_2
- Characterize heat transfer, vacuum, & dormancy

Rapid pressurized LH_2 refuel from any condition

- 100 kg/hr, up to 875 bar
- Refueled H_2 density 63-80 g /L (up to 700 bar)
- Low LH_2 evaporation (1-3%) returned to Dewar
- Test degradation after pumping 24 tonnes LH_2

700 bar vessel durability and cryogenic cycling

- Cryogenically cycle four 65 L vessels
  - 1500 thermomechanical cycles each
  - Spectrum of liner/composite combinations

Technology transfer activities: Technology jointly developed with BMW and Spencer composites Corporation

- BMW CRADA II signed July 2014: **Includes $1M cost share**

- Two recent patents:
  - Weisberg AH. **Methods for tape fabrication of continuous filament composite parts and articles of manufacture thereof**. United States Patent US 8545657 B2, November 2013.
  - Espinosa-Loza, F, Ross, TO, Switzer, V., Aceves, SM, Killingsworth, NJ, Ledesma-Orozco, E, **Threaded Insert for Compact Cryogenic Capable Pressure Vessels**, Granted March 12, 2015.

- A provisional patent and two records of invention

Project Summary

Relevance	Cryogenic pressurized storage has the potential to meet challenging DOE goals. Critical issues such as maximum system density, scalability, vessel and pump durability are being addressed
Approach	Demonstrate durability (1,500 cycles) of thin-lined, high fiber fraction vessels followed by pressure test (1,300 bar), test LH_2 pump degradation after 24 tonnes LH_2, and demonstrate compact vacuum insulation
Accomplishments	Manufactured thin-lined vessel with 81% vol. ratio Demonstrated cryogenic strength of thin lined vessel Instrumented LH_2 pump (electric, vent, temperature) Built pressure vessel test facility Obtained DOE/LLNL operational approvals
Future work	Complete pressure vessel test facility with heat exchanger and containment vessel Cycle test new 65 L thin lined vessel prototypes Vacuum jacket future 65 L vessel prototype