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

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Project ID # TV029

Overview

Timeline and Budget

- Start date: January 2014
- End date: December 2016
- Total project budget: $5.5M
- Total recipient share: $1.5M
- Total federal share: $4M
- Total DOE funds spent: $2.7M*

*As of 3/31/16

- Funded jointly by Storage, Delivery, and Technology Validation
- Also presented as ST-111 Thursday AM in storage session

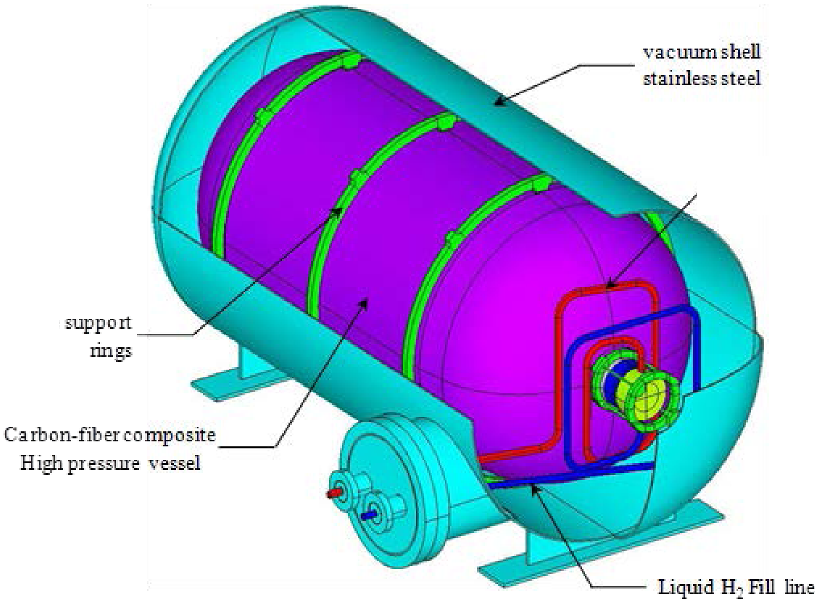
Barriers

- 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 & HAZOP
- BMW thermomechanical stress modeling, performance requirements, automotive perspective

Relevance: Cryogenic pressurized H_2 storage and delivery provide safety, cost and weight advantages over alternative approaches to long-range (500+ km) zero emissions transportation



Cryogenic pressure vessels have the best performance:

- Highest system storage density (43 g/L)
- Highest hydrogen weight fraction (7.5%)
- Lowest cost of ownership (Argonne [1])
- Compelling safety advantages:
  - 20X less expansion energy vs. 300 K gas
  - Inner vessel protected by vacuum jacket
  - Gas expansion into vacuum jacket reduces thrust by 10X

Outstanding issues:

- Scalability to smaller diameters (35 cm)
- Vacuum stability
- Manufacturability

[1] Paster, M. D., Ahluwalia, R. K., Berry, G., Elgowainy, A., Lasher, S., McKenney K., and Gardiner, M., "Hydrogen Storage Technology Options for Fuel Cell Vehicles: Well-to-Wheel Costs, Energy Efficiencies, and Greenhouse Gas Emissions," International Journal of Hydrogen Energy, Vol. 36 (22), 14534-14551, Nov. 2011.

Relevance: Demonstrate performance limits (50 g/L, 9% H_2wt) of cryo-compressed technology by combining thin-walled vessels, thin insulation, and high density H_2 from LH_2 pump

New generation cryogenic pressure vessel

- 65 liters, 34 cm diameter, 100 cm long
- 700 bar
- 50 g/L, 9% H_2 weight fraction (3X and 2X better than 700 bar CGH_2)
- Thin lined (<2 mm), high fiber fraction (up to 80%)
- 80+% volumetric efficiency (inner vessel volume/outer vessel volume)
- Thin vacuum insulation (<1 cm)
- **Test strength (1600 bar new; 1300 bar cycled) and durability (1000 thermomechanical cycles)**

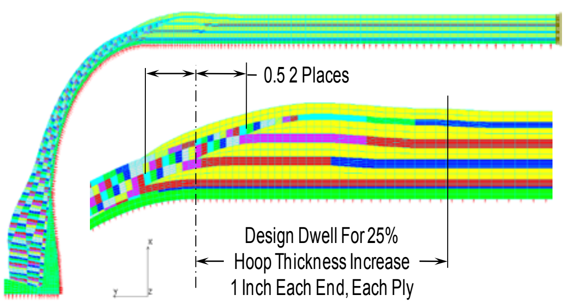
Liquid hydrogen pump

- 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 by pumping 24 tonnes of LH_2**

Approach: Combine finite element modeling and design expertise to demonstrate durable (1000 cycle) thin-lined (<2 mm) volumetrically efficient (80+%) 700 bar vessels

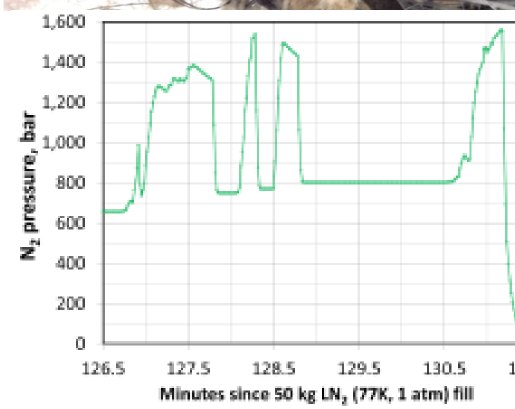
FY15: static pressure vessel strength test

Cold strength test of candidate liner materials



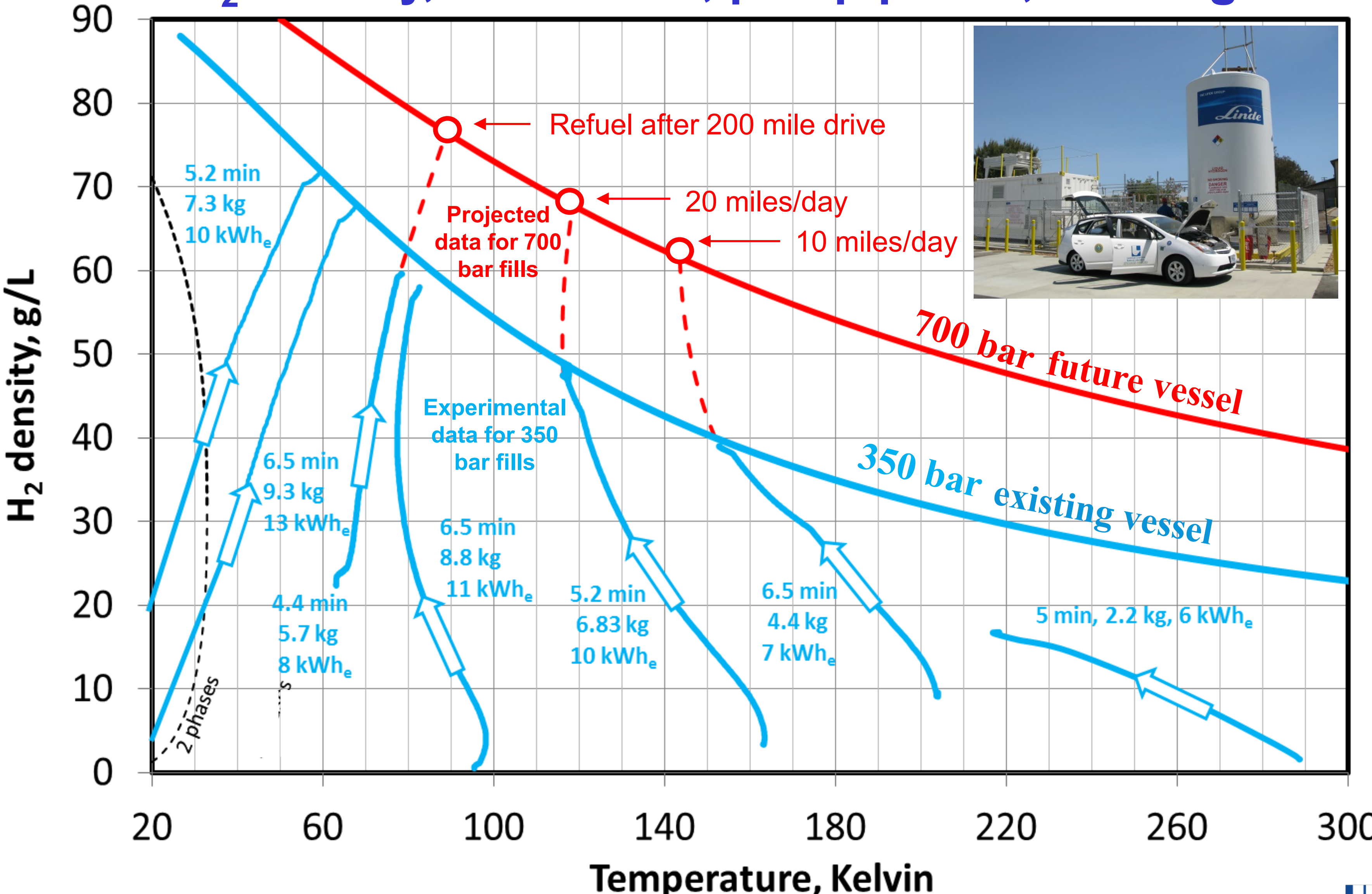
Finite element modeling of thin-lined vessel

First thin-lined (1.8 mm) vessel, 81% volumetric efficiency (vs. 70% conventional vessels)



Vessel pressure tested to 1560 bar
Preferred failure mode:
Hoop stress in cylindrical section
No failure in welds or domes

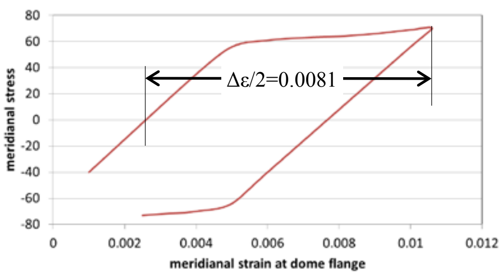
Approach: Extend LH_2 refueling to 700 bar
Measure H_2 density, refuel time, pump power, and degradation



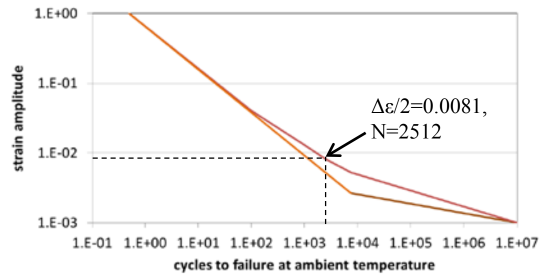
Up to 80g/L H_2 density possible at 700 bar

Accomplishment: Use finite element and fatigue analysis to design durable (1000 cycle) thin-lined (<2 mm) volumetrically efficient (80+%) pressure vessels

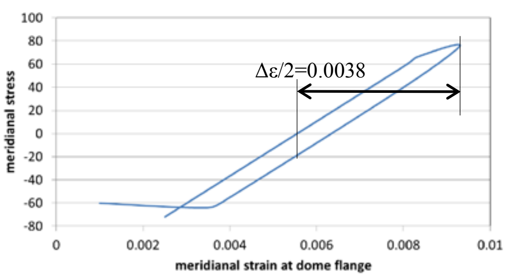
FY16: fatigue analysis of dynamically cycled vessel



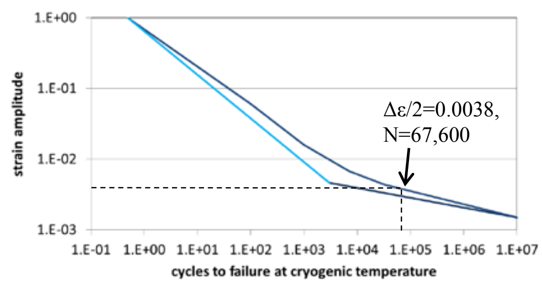
Cool-down cycle from 300 K to 80 K



Ambient temperature strain vs. cycle life



Cold fill cycle between 80 and 20 K



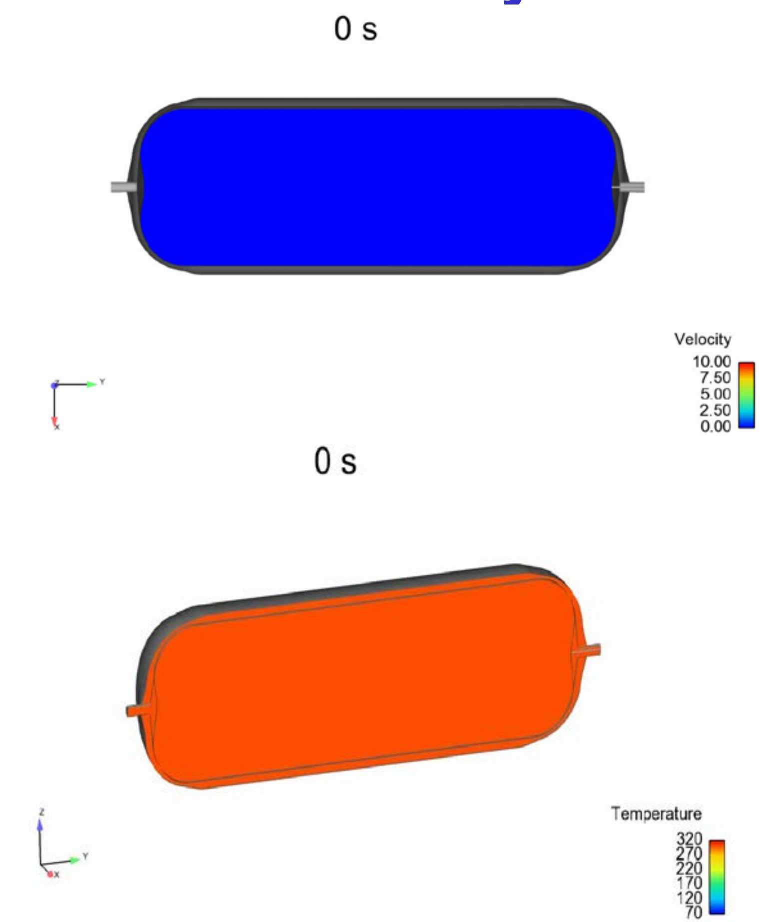
Cold (80 K) strain vs. cycle life

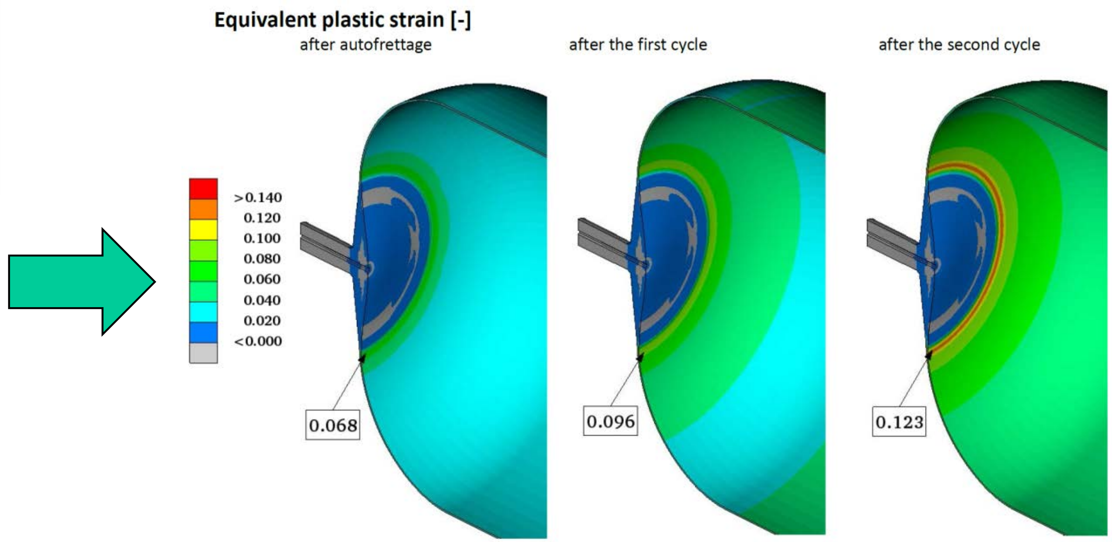
Finite element modeling of thin-lined vessel

Fatigue life calculations for warm and cold cycles

Cryogenic vessel designed for 6400 cycles (1600 cycles, safety factor=4)

Accomplishment: In collaboration with BMW, we have analyzed thermomechanical stresses caused by rapid fill of initially warm cryogenic pressure vessels

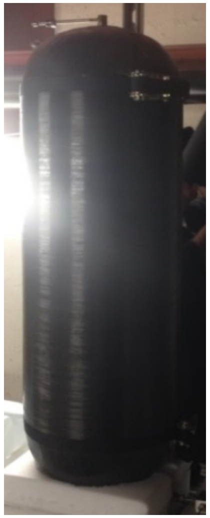




Linked thermo-fluid analysis of warm vessel fill

Hand-off information to stress analysis code for calculation of fatigue life

Accomplishment: We have built and cycle tested five cryogenic vessels with continuously improving cycle life



(#1) initial prototype (32 kg)
1.7 mm SS 316 liner/epoxy
Modified neck, 1560 bar LN_2 burst

(#2) Aggressive design (28 kg)
1.3 mm SS liner/cryogenic resin
buckled during autofrettage
(H_2O burst at 8,000 psi)

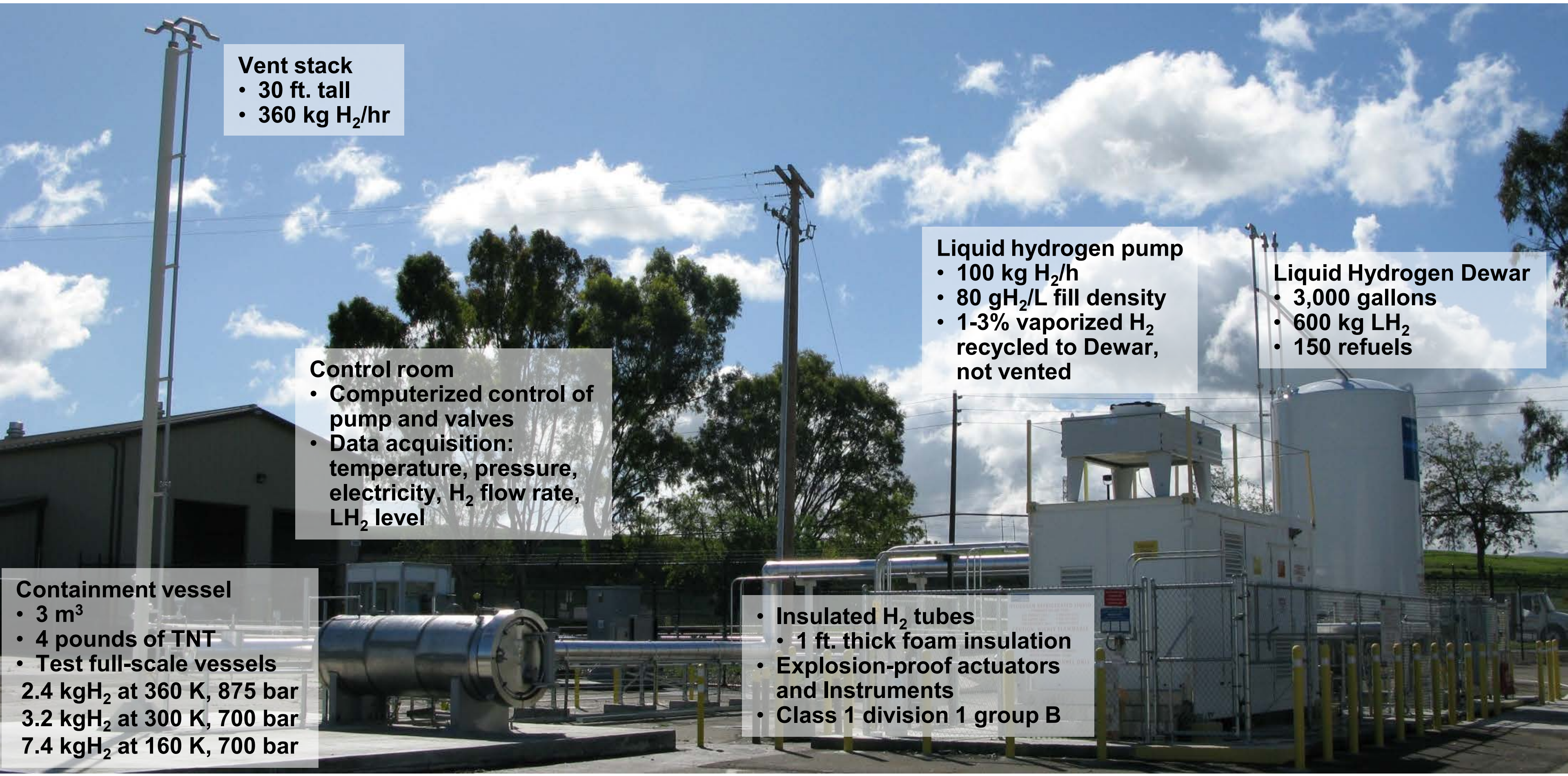
(#3) Conservative design
1.5 mm liner/epoxy
buckled during autofrettage
(H_2O burst at 11,000 psi)

(#4) Conservative design
1.7 mm liner/epoxy
pinhole leak after 133 cycles @ 700 bar
(6,000 psi H_2O leak at T-weld by X-Ray)

(#5 Vessel Dome)
1.5 mm liner/epoxy
Analyzed by Optical, X-ray, Dye Penetration
(T-weld ruled out, but root cause not found)

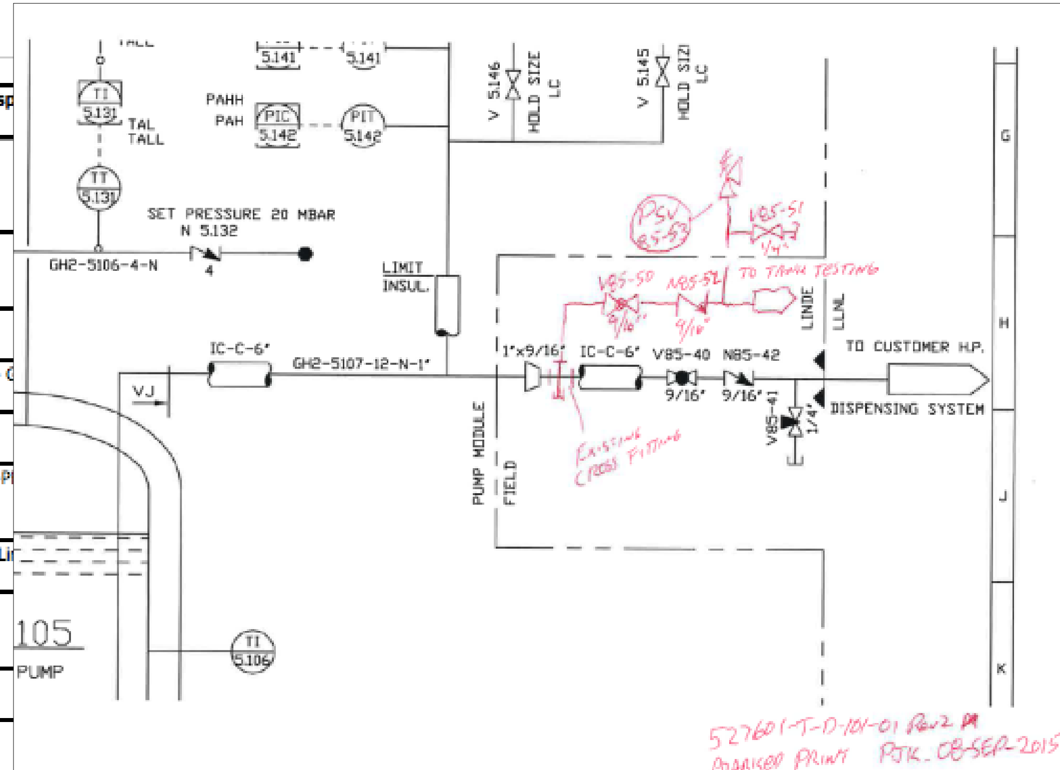
(#5) Conservative design
1.5 mm liner/epoxy
pinhole leak after 247 cycles @ 700 bar
(8,000 psi H_2O leak NOT at T-weld)

Accomplishment: We have built a Hydrogen Test Facility for cost effective durability, cyclic, thermomechanical, permeation, leak, and burst testing



Accomplishment: In collaboration with Linde, we conducted extensive HAZOP review of Hydrogen Test Facility

Action	Notes	Status	Resp	
LLNL to ensure Linde staff are not allowed onsite during strength testing.	Deliviers to be schedule outside of test dates. Gates will be closed with signage.		LLNL	
Change setpoint for PRD4 to 13,920 PSIG or lower if MAWP of E-001 is less that 13,920 PSIG.	LLNL Agrees. Setting is 13,400 P&ID to be changed.		LLNL	
Change PRD0 to 13,920 PSIG.	LLNL Agrees. Setting is 13,400 P&ID to be changed.		LLNL	
Linde Gas to acquire data sheet for E-001 to confirm MAWP of heat exchanger.	Linde to contact LHS		Linde- G	
Confirm PRD4 is sized for full flow through E-001.	LLNL to provide calculation sheet.		LLNL	
Update P&ID to show tie in point for Cyclic vessel testing connection.	Need to verify location with pictures of current installed branch fitting.		Linde-P	
Install manual isolation valve at tie point.	Eric to witness installation of manual valve.		LLNL/Li	
Ensure LLNL provides allowance for pipe stresses at tie-in due to thermal expansion and contraction.	LLNL to provide pipe layout drawings showing VJ Expansion joints		LLNL	
Ensure valves in field are tagged to match the P&ID.			LLNL	
Ensure LLNL has a procedure which specifies correct valve lineup for each use point from the LH2 supply scheme.			LLNL	
Add a thermal relief valve between new manual isolation valve at tie in point and 1-CV-0.			LLNL	1.1 High pressure — LLNL Tie In Point
Linde site staff to create energy isolation procedure for tie in work to LLNL cyclic pressure testing.			Linde-ET	1.13 Deviation During Startup — LLNL Tie In Point
Ensure insulation is replaced after tie in connection is made.			LLNL	1.13 Deviation During Startup — LLNL Tie In Point
LLNL consider adding a purge supply and outlet connection on distribution manifold for high pressure storage cycling system.(Downstream of isolation valve at tie in point)			LLNL	1.13 Deviation During Startup — LLNL Tie In Point 1.15 Deviation During Maintenance — LLNL Tie In Point
If LLNL requires remote access to control/monitor LH2 pump, then a review meeting must risk assess this activity. (Linde	Linde to review hookup and software for remote access with LHS		LLNL/Linde-PK	1.13 Deviation During Startup — LLNL Tie In Point



Responses to reviewers' comments

The project is a logical extension of a storage concept that has been under development for many years. The goals of the project are relevant but may be obsolete if industry (beyond BMW) does not pick up the technology. While it is obviously important to obtain buy-in from stakeholders, cryogenic H_2 storage has fundamental advantages (safety, driving range, ownership cost, and weight) over all existing alternatives that makes this project valuable beyond individual company strategies. In this project we are exploring the limits of the technology with a new generation of cryogenic vessels that may demonstrate 3X higher volumetric capacity and 2X higher H_2 weight fraction over 700 bar CGH_2, in addition to being safe and cost effective. It is our opinion that these results will be valuable to the future of hydrogen transportation regardless of near-term corporate decisions.

The convincing demonstration for the need for cryogenic storage is not evident. It is not clear whether 10%–20% is adequate to justify the additional cost and complexity of cryogenic containment. According to analysis by Argonne, compressed gas vessels can achieve 17-18 gH_2/L and 4-5.5% H_2 weight fraction. This project is aiming at 50 gH_2/L and 9% H_2 weight fraction. This would be 3X and 2X higher performance than compressed gas – not 10-20%. These advantages are obtained simultaneously with an overall reduction in cost of ownership and safety advantages.

Responses to reviewers' comments

A project weakness is the lack of a broader liquid hydrogen research community and stakeholders to share and build knowledge to advance the technology. The dispensing of liquid hydrogen would need additional investments that would be difficult to expect in the short term. Niche markets within the hydrogen FCEV (already) niche market would need to be found. While it is true that today's vehicles use compressed gas vessels, most of today's fueling stations store liquid H_2. When LH_2 is available at the station, a LH_2 pump followed by a heat exchanger is the most economic option to refuel compressed gas vehicles (Argonne). *The same pump* would then be available for cryogenic refueling, only the heat exchanger is bypassed.

The specific performance benchmarks can be more fully specified. For instance, acceptable/anticipated heat leaking into the thinly insulated vessel is not specified. We did set an insulation performance target as a part of this project (4 Watts). This will result in good dormancy considering the maximum operating pressure of the vessel (700 bar), enough to contain the hydrogen for a long time even if the vehicle is seldom driven.

The cost of the system is not addressed. We are currently collaborating with Argonne for a cost analysis of the technology. See AJ Simon's PD134 at Delivery session on Thursday PM.

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). Conducted extensive HAZOP review of LLNL's Hydrogen Test Facility**

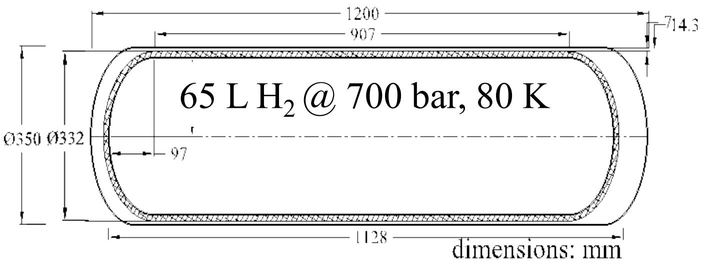
- *BMW:* **Long standing collaboration with LLNL through two cryogenic pressure vessel CRADAs. Contributing detailed thermofluid/stress analysis, automotive perspective, and expertise. Advancing cryogenic pressure vessel technology & demonstration vehicles**

Remaining Challenges and barriers:

- ***Demonstrate cryogenic cyclability of thin-lined, high fiber fraction pressure vessels:*** **Next two prototypes will be cycled 1000 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 by pumping 24 tonnes of LH_2**
- ***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 (1000 cycles) and pump (24 tonnes LH_2)
Light, compact insulated vessel with acceptable dormancy

Future work: demonstrate rapid refueling of 700 bar cryogenic H_2 vessels with high system density, small diameter (~35 cm), & cryogenic durability (1000 refuels)



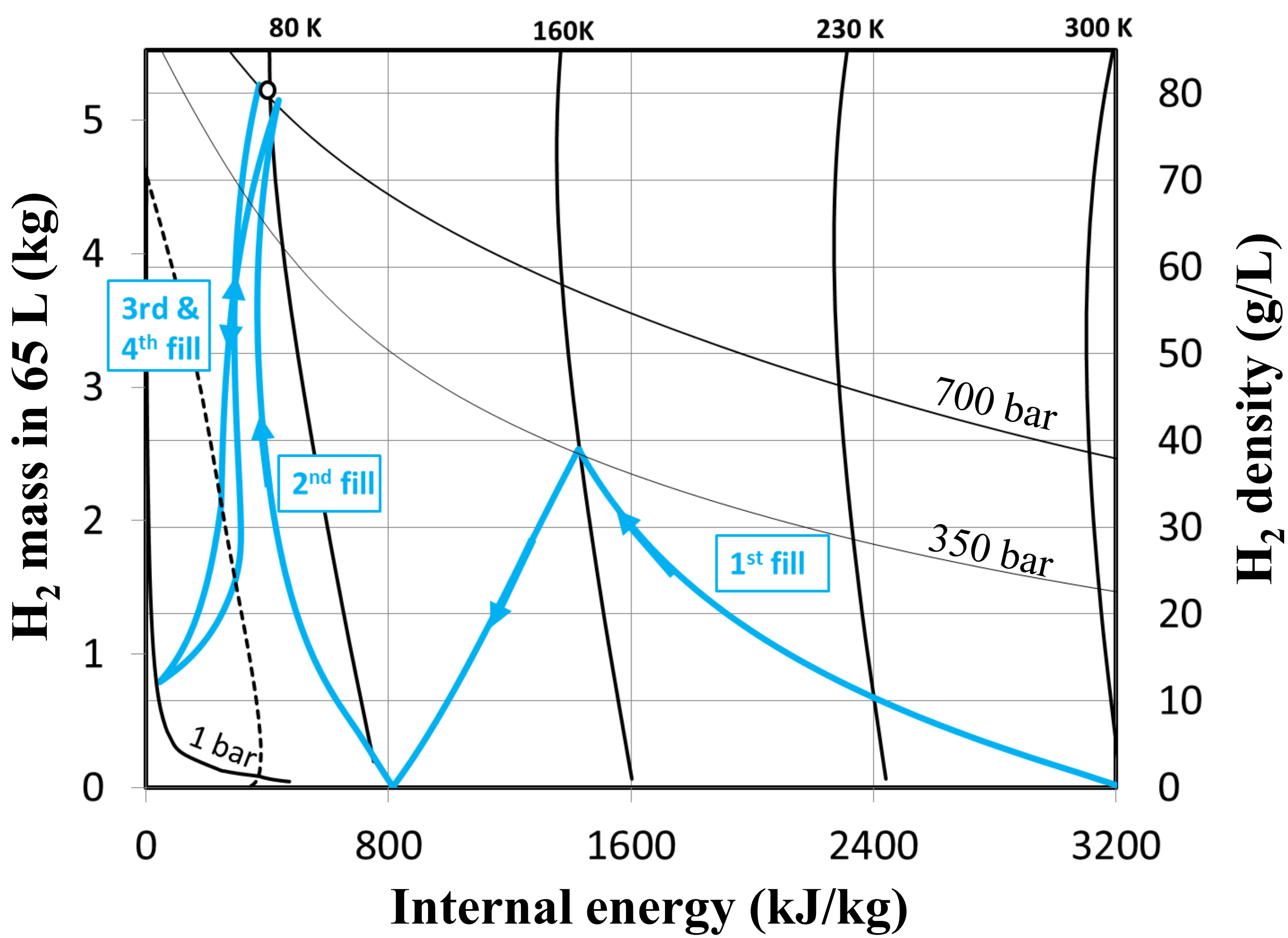
Volumetric efficiency at 65 L capacity

- 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 by pumping 24 tonnes LH_2

Future work: Monitor pump degradation by performing test fill sequence every 500 cycles while recording key pump performance parameters




power analyzer


boil-off meter


temperature sensor

Pump performance metrics: duty cycle, peak density, boil-off, outlet H_2 temperature, electricity consumption, and fill time

Proposed Future Work

Future work includes:

- Manufacture and cycle testing of four thin-lined high fiber fraction vessels
- Test pump durability by dispensing 24 tonnes of LH_2
- Thin (1 cm) vacuum insulation of top cryogenic vessel design

Second Go/No Go successful cryogenic 1300 bar strength test of prototype vessel after 1,000 pressure and temperature cycles

Milestones	Description
Q2/FY16	Complete 1,000 accelerated thermomechanical cycles on two 65 L 700 bar, 80+% volume ratio vessels
Q3/FY16 *2nd Go/No-Go*	Demonstrate 1,300 bar minimum strength for at least one of the two cycled prototype vessels
Q4/FY16	Deliver compact vacuum jacket to exceed 50 gH_2/L and 9 wt% H_2 when integrated with thin metallic liner
Q1/FY17	Complete 1000 cycles on two vessels with 1.5 mm metallic liners. Deliver 24 tonnes H_2 through LH_2 pump while measuring electricity use, venting, and fill speed
Q2/FY17	Vacuum jacket prototype thin-lined high fiber fraction vessel and demonstrate 50 g/L, 9% H_2 weight fraction

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:**
  - Espinosa-Loza, F, Ross, TO, Switzer, V., Aceves, SM, Killingsworth, NJ, Ledesma-Orozco, E, **Threaded Insert for Compact Cryogenic Capable Pressure Vessels**, United States Patent US 9057483 B2, June 2015.
  - Weisberg AH. **Methods for tape fabrication of continuous filament composite parts and articles of manufacture thereof**. United States Patent US 8545657 B2, November 2013.

- **A provisional patent:**
  - Petitpas G, Aceves SM, Ortho-H2 Refueling for Extended Cryogenic Pressure Vessel Dormancy, United States Patent Application 2015-0330573, June 2015.

- **and two records of invention**

Project Summary

Relevance
- Demonstrate performance limits for cryo-compressed storage and delivery technology in the most adverse conditions by manufacturing small, durable vessels with thin insulation refuelable to high density with LH_2 pump.

Approach
- Combine fundamental experiments and detailed finite element models to produce thin-walled, durable (1,000 cycles) cryogenic vessels.
- Test pump performance, durability with 24 tonnes LH_2.
- Demonstrate compact (<1 cm thick) vacuum insulation with acceptable dormancy (4 W)

Accomplishments
- Design and build vessels to meet desired cycle life
- Model stresses during operation and warm fill (BMW)
- Build most capable Hydrogen Test Facility
- Conduct HAZOP analysis of H_2 Test Facility (Linde)

Future work
- Cycle test new 65 L thin lined vessel prototypes
- Demonstrate strength of cycled vessel (1300 bar)
- Vacuum jacket future 65 L vessel prototype
- Demonstrate pump durability with 24 tonnes LH_2