Rapid High Pressure LH_2 Refueling for Maximum Range and Dormancy

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June 19, 2014

PD092

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Overview

Timeline

- **Start date: October 2010**
- **End date: September 2013**

Barriers

- **C. Reliability and cost of LH_2 pumping**

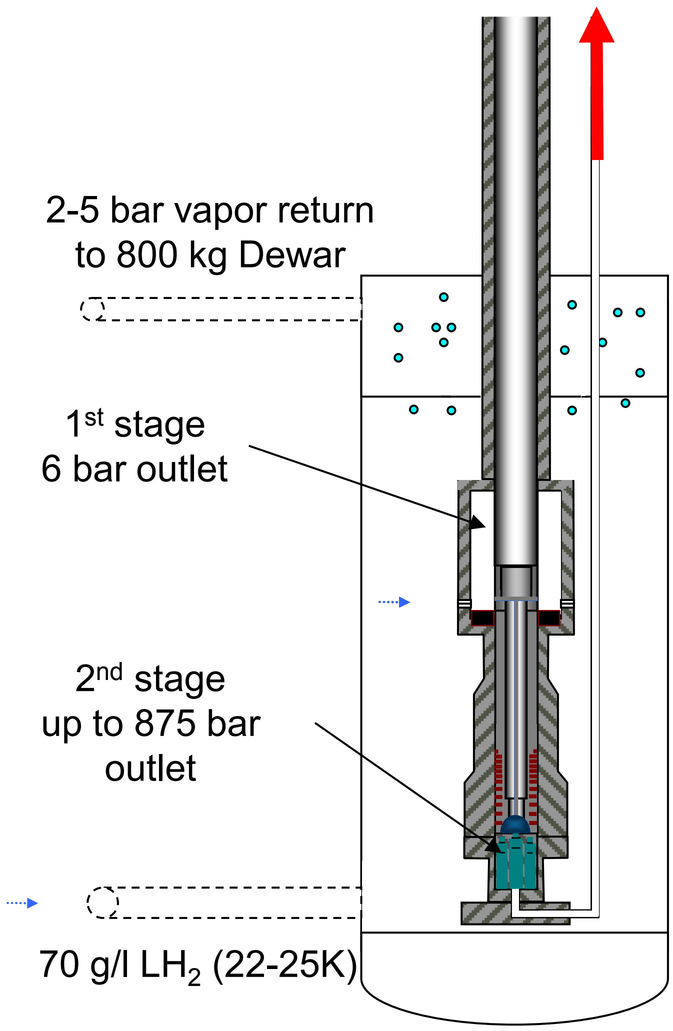
Budget

- **Total project Value: $2.4M**
  100% Complete
- **Cost share percentage: 0%**

Partners

- **Linde 875 bar LH_2 pump supply, operation & maintenance**
- **BMW thermal insulation, performance requirements, automotive perspective**

Relevance: H_2 refueling is limited by onboard heating and power & capital at the station



High pressure LH_2 pump resolves refueling challenges due to upstream liquefaction and no onboard cooling

LH_2 pump provides rapid fueling

- Pump provides flow rate of 100 kgH_2/hour
- Refuel time decoupled from compression heating

Pressurized LH_2 refueling has high density and low power use

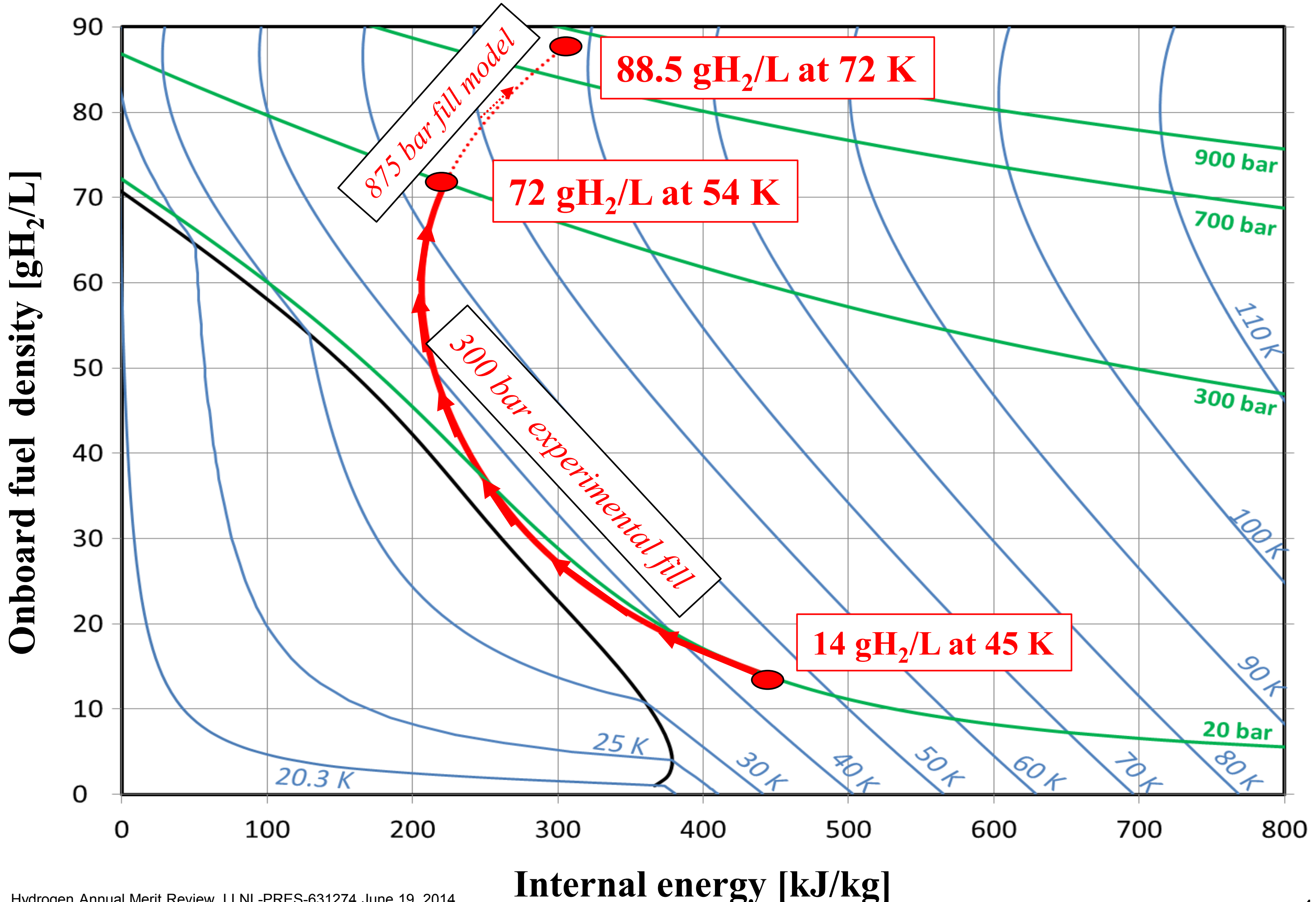
- The pump starts with high density LH_2
- Moderate compression (70 to 90 gH_2/L)

High pressure LH_2 pump makes cryogenic refueling practical

- H_2 (at up to 70 K) sent rapidly to cryogenic vessel
- Negligible impact on station boil-off (1-3% of fill)
- Refuel onboard system of any temperature
- Can refuel adsorbents or ambient storage

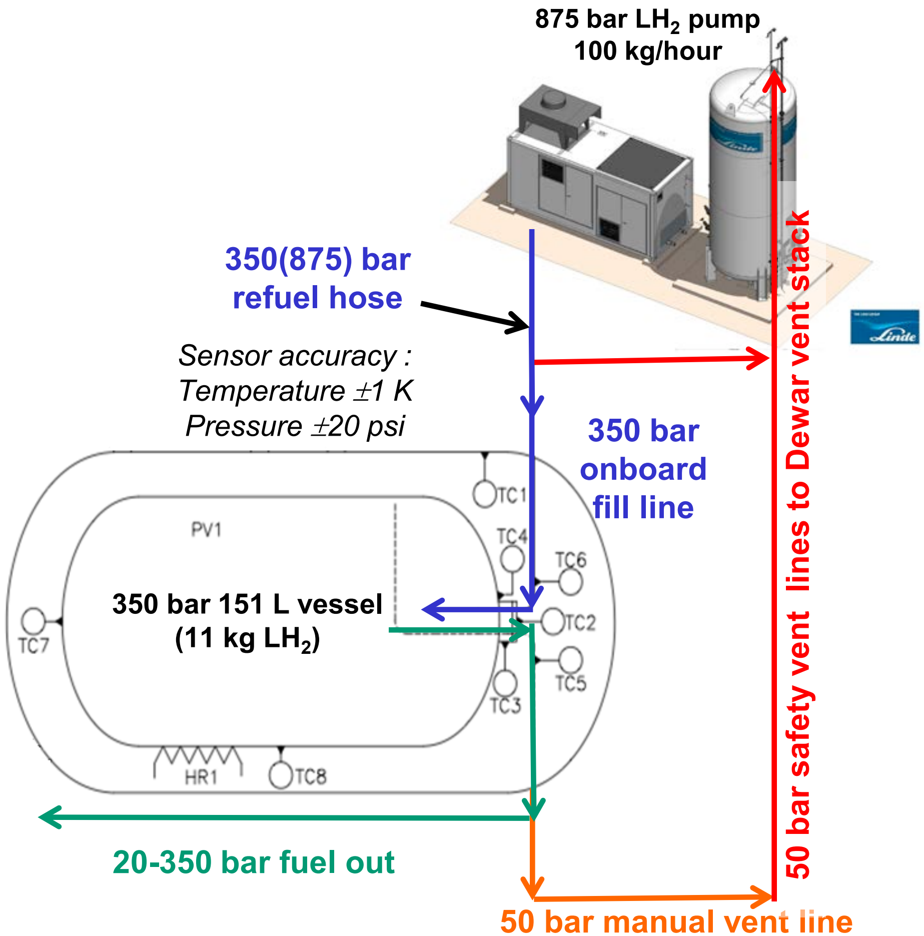
Relevance: LH_2 is compressible with very moderate heating

LLNL fill model predicts 88.5 gH_2/L onboard at 875 bar using 300 bar experimental data from BMW



Approach: Verify LH_2 pump performance up to 350 bar

Determine 1) LH_2 fill time, 2) onboard density 3) refueling efficiency, and 4) LH_2 pump boil-off



LLNL experimental system upgraded for 350 bar refueling and venting through Dewar stack

Accomplishments: Site preparation and pump installation

Electrical, civil, and mechanical work necessary for LH_2 pump & Dewar operation completed in 4 months

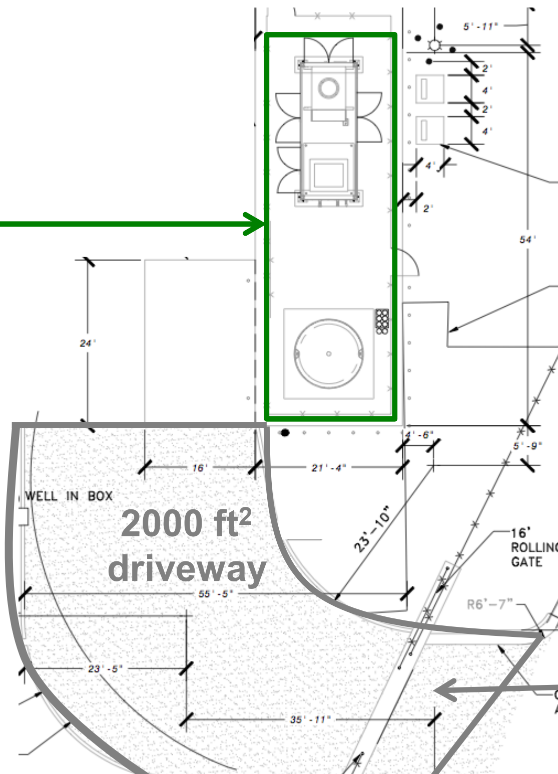

Dewar and pump installation


LH_2 pump commissioning


200 m overhead power line


Foundation construction

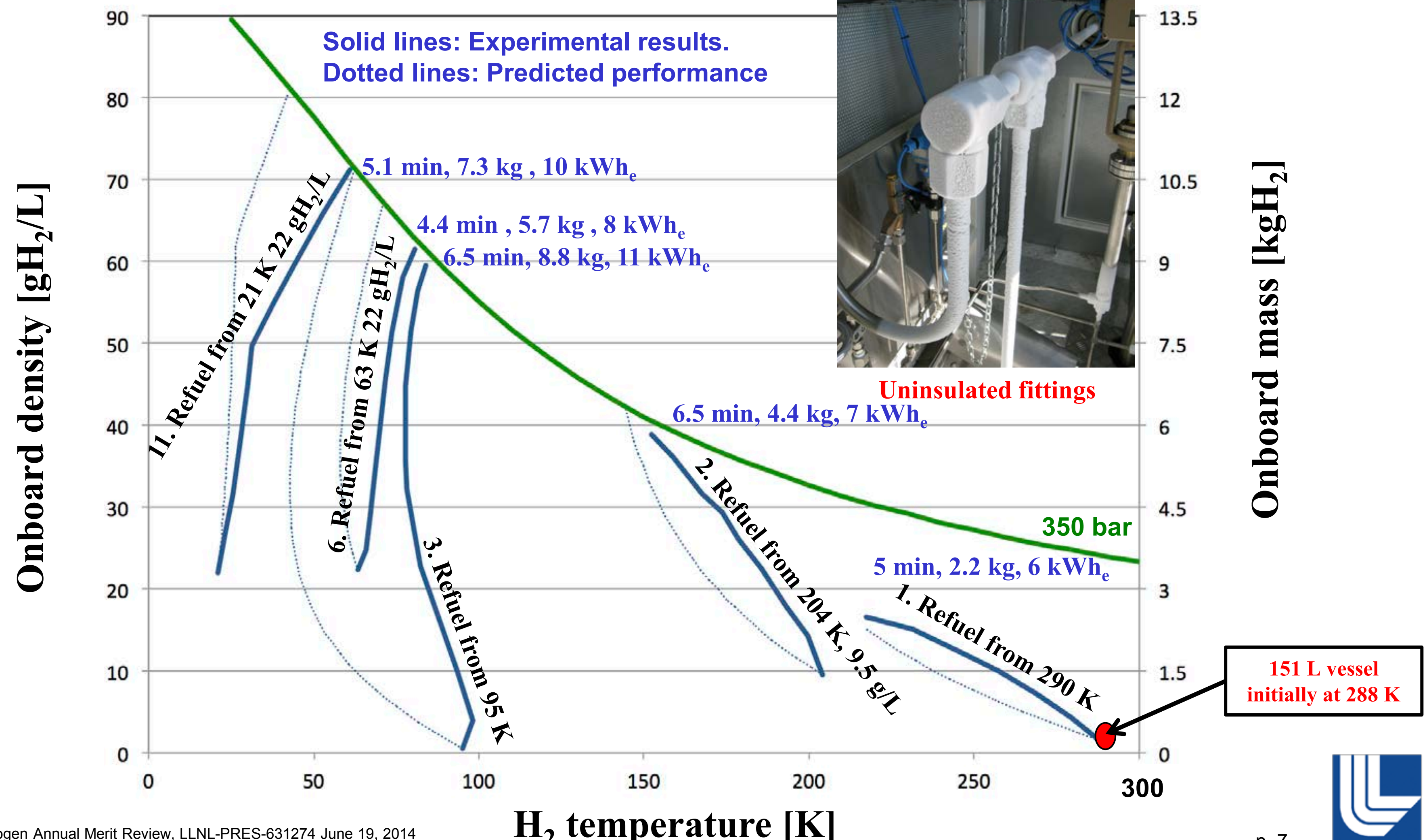

500 kVA, 480 V transformer




2000 ft² driveway

Accomplishment: Measure pump performance at 350 bar delivery (onboard refueling)

We have conducted eleven 350 bar vessel fill experiments for initial conditions from 288 to 21 K



Uninsulated fittings

Accomplishments: Measure pump performance at 350 bar delivery (onboard refueling)

We have conducted eleven 350 bar vessel fill experiments for initial conditions from 288 to 21 K

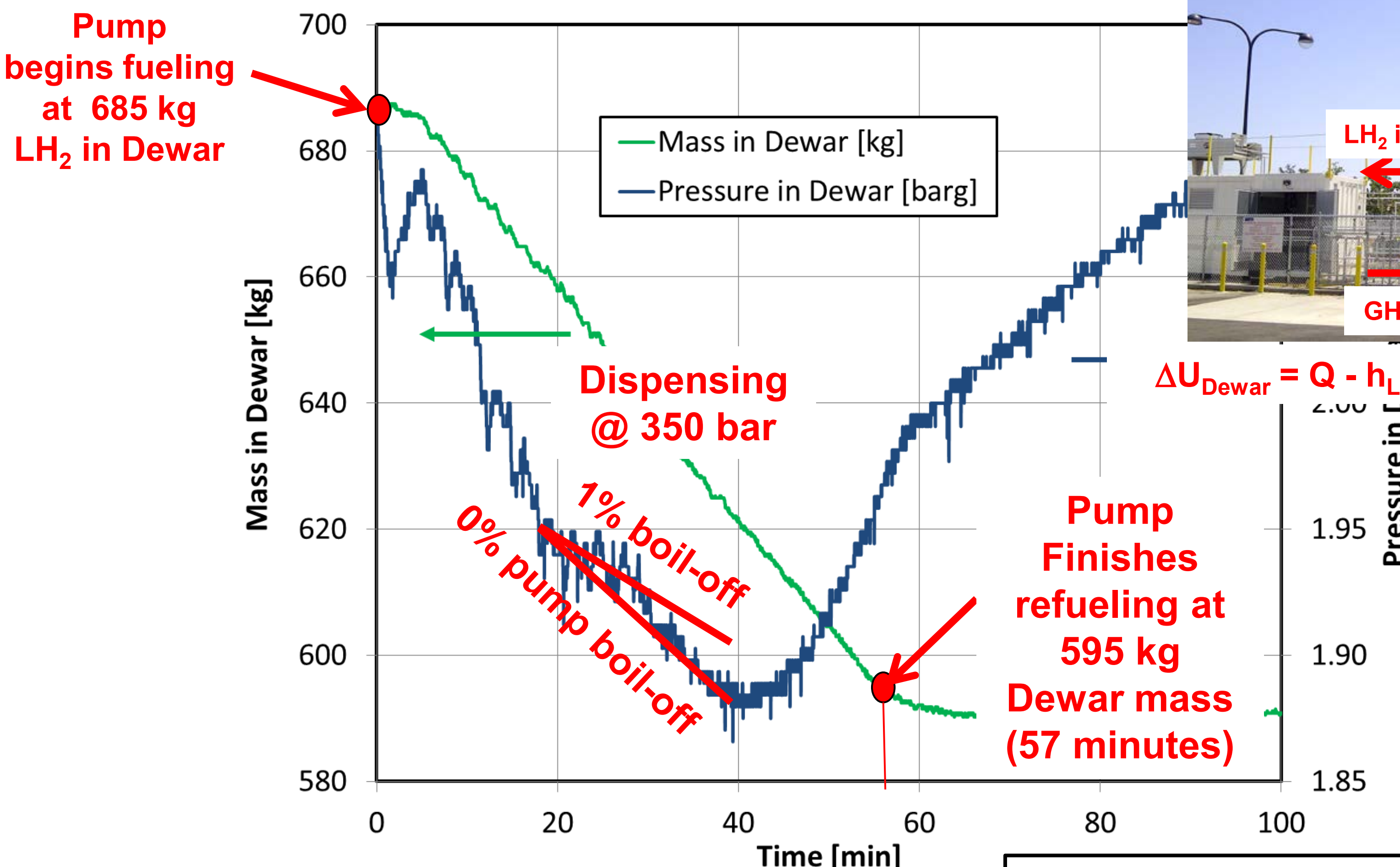
Experi-ment	Initial T K	Initial Pressure bar	Initial density g/L	Final T K	Final pressure bar	Final density g/L	H_2 mass pumped kg	Refuel time minutes	Average flow rate kg/hr	Steady flow rate Kg/hr	Refuel energy kWh	Refuel energy kWh/kg
1	288	18.93	1.58	219	166.5	16.4	2.24	5	26.8		6	2.62
2	204	85.1	9.52	153	330	38.6	4.39	6.5	40.5	103	7	1.58
3	95	1.25	0.32	87	333	58.5	8.78	6.5	81.1	108	11	1.22
4	21	1.25	5	74	340	64.7	9.0	7	77.3	94.2	13	1.45
5	21	1.25	12.5	67	338	67.9	8.4	6.25	80.3	94.8	12	1.48
6	63.2	51.3	22.4	84.6	338	59.9	5.67	4.38	77.6	97.2	8	1.43
7	21	1.25	4.13	71.4	338	65.8	9.31	6.46	86.5	110	13	1.39
8	21	1.25	11.4	67.1	338	67.8	8.52	5.8	88.1	111	11	1.29
9	21	1.25	18	64	338	69.3	7.75	5.6	83	106	10	1.28
10	21	1.25	22	61.9	339	70.4	7.31	5.26	83.4	106	10	1.37
11	21	1.25	22	61.9	339	70.4	7.31	5.13	85.5	108	10	1.37

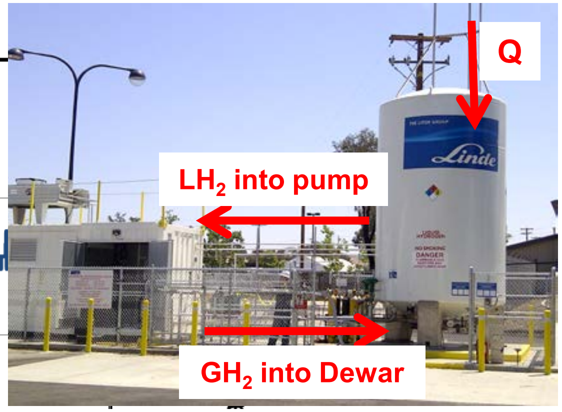
Points in blue are within 2-phase region

Average measured efficiency: 96% (electricity/LH_2 out)
Maximum refuel pressure: 350 bar (vessel-limited)
Maximum flow rate: 111 kg/hr

Accomplishment: Inferred pump boil-off during operation

Thermodynamic analysis of Dewar mass vs. pressure data reveals near zero pump boil-off rate when dispensing H_2 at 350 bar





$$\Delta U_{Dewar} = Q - h_{LH2}\, m_{LH2} + h_{gH2}\, m_{gH2}$$

Data from pump acceptance test (10/15/2012, Linde, Germany)

Responses to reviewers' comments

The project too closely replicates the work of BMW: **BMW is *producing a commercial product* that may succeed in the market due to longer driving range, improved safety, and rapid refueling. LLNL is *researching* (1) The thermodynamics and behavior of H_2 at superliquid (70+ g/L) densities, (2) The viability of improvements to high pressure (>350 bar) cryogenic H_2 storage, (3) Thermomechanical lifecycle & strength testing with cryogenic H_2, and (4) High pressure (875 bar) cryogenic refueling station performance and durability**

This project should add specific technology gaps and a cost model. **Analysis of technology gaps and potential led to the proposed project. Argonne has conducted extensive cost modeling revealing that cryogenic pressurized storage has lowest cost of ownership. We are planning to work with Argonne to develop accurate cost models**

The project should add a variety of other FCEV manufacturers. **Other OEMs have expressed interest in conducting experiments at LLNL and/or joining the project**

Responses to reviewers' comments

The Linde LH_2 pump has the potential of 1–3% hydrogen boil-off loss and additional boil-off from the LH_2 storage tank. A 3% loss has a significant detrimental impact on WTW energy efficiency and cost**:** **Pump evaporation does not result in Dewar boil-off. Pump extracts LH_2 from Dewar, and returns a fraction of evaporated LH_2 back into Dewar. Dewar typically *depressurizes* when running at these conditions. Boil-off from Dewar is due to environmental heat transfer or LH_2 transfer during Dewar fill**

This approach to hydrogen refueling results in a variable amount of hydrogen in the fuel tank at the end of refueling, depending on the temperature, pressure, and amount of hydrogen in the tank at the start of refueling. Vehicle owners may not accept this. **H_2 density in cryogenic pressurized storage is *self-regulated:* Frequent drivers keep vessel cold and refuel to high density while infrequent drivers' warm vessel reduces storage density. Self-regulated density minimizes H_2 venting for all users. Two cold refuels are sufficient to transition from minimum to maximum range during continuous driving**

Collaboration with global leaders

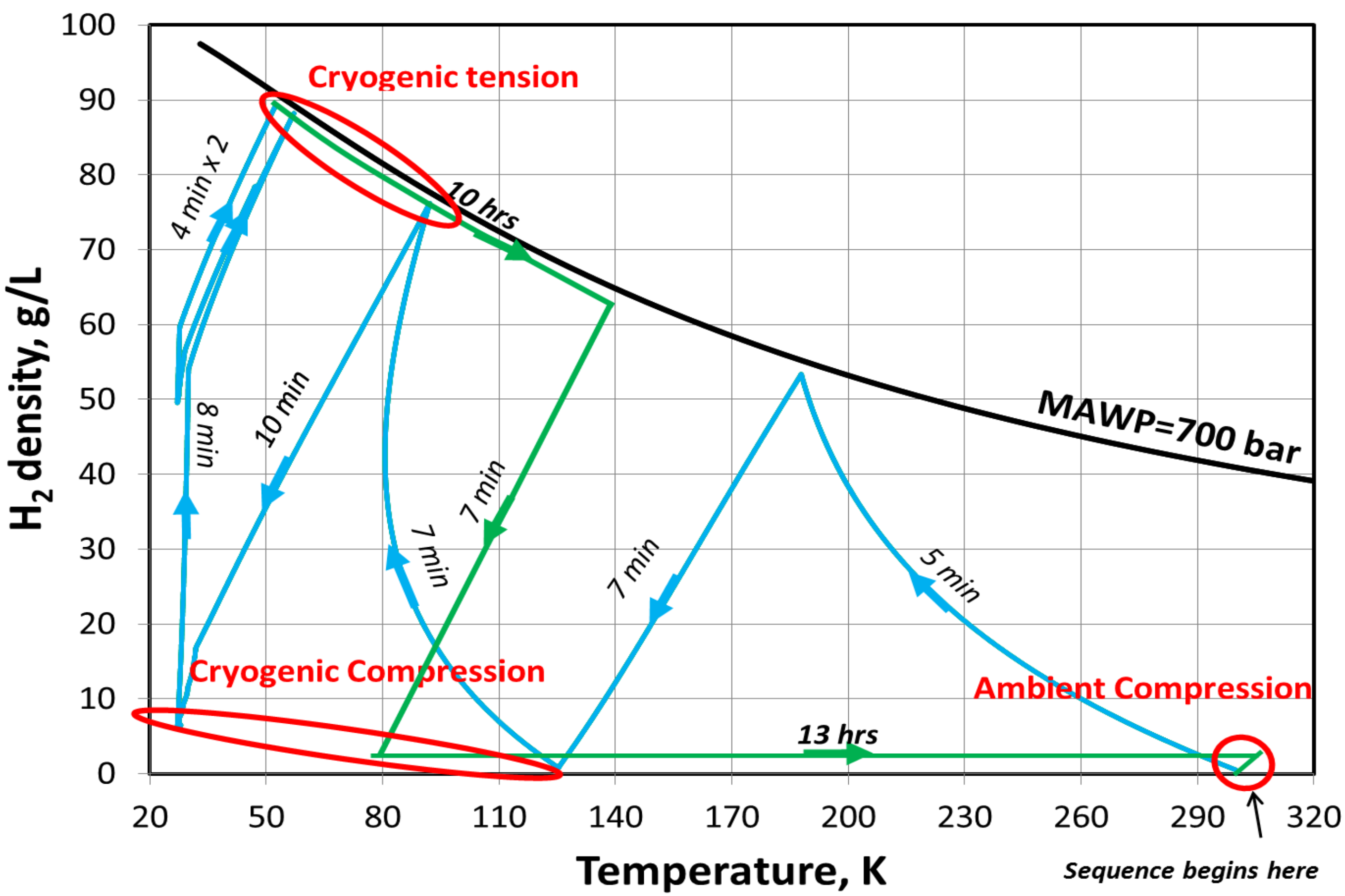
- ***Linde:*** **World class cryogenics experience. Manufactures maximum efficiency LH_2 pump. Delivered first commercial system to BMW in 2009 (300 bar). Very cooperative, sharing detailed information throughout LH_2 pump development, construction and installation.**
- ***BMW:*** **Long standing collaboration with LLNL through cryogenic pressure vessel CRADA. Contributing technical information and expertise. Advancing cryogenic pressure vessel technology and preparing demonstration vehicles**

Challenges and barriers: Demonstrating LH_2 pump technical performance leading to improved onboard H_2 storage targets

- ***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**

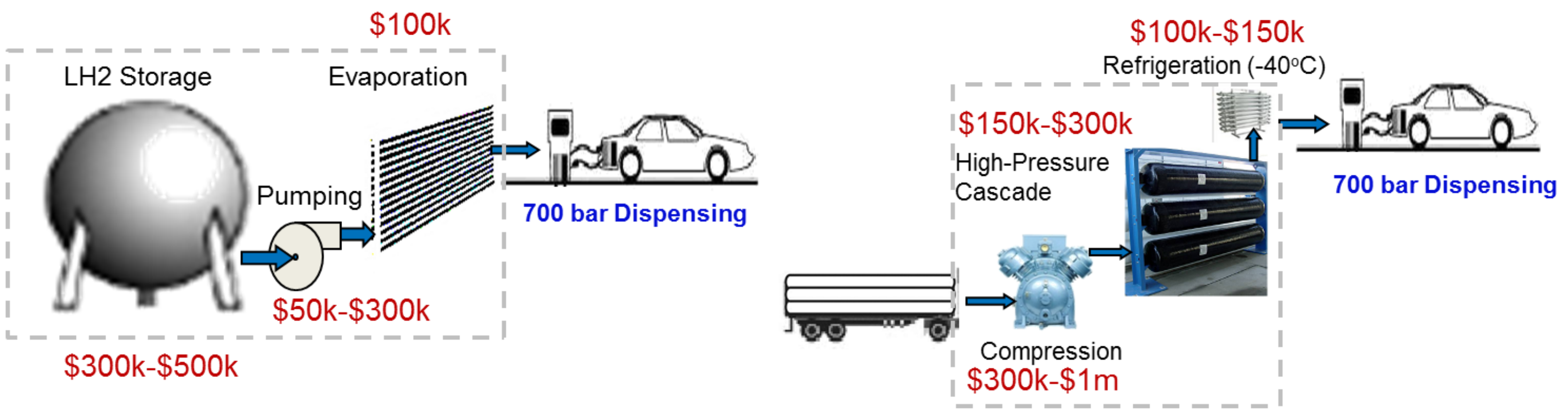
Proposed future work: As a part of new Storage/Delivery/Techval project, characterize LH_2 pump performance to 700 bar

Generate LH_2 pump performance map by conducting multiple partial and total fills



Future work: LLNL will assist ANL develop cost models for cryogenic pressurized hydrogen storage and delivery

Liquid delivery has advantages over gaseous delivery



	LH2	GH2
Station capital investment	More favorable (with sizable demand)	Less favorable (high compressor/cascade capital)
GHG emissions	Less favorable (**high liquefaction GHG**)	More favorable
Delivery logistics	More favorable	Less favorable
Other issues	Boiloff rate	Cooling to -40°C
	Can benefit from surplus liquefaction capacity	Tube trailers eliminate need for onsite storage

Summary: 875 bar LH_2 pump can refuel onboard H_2 storage rapidly, efficiently, and to very high densities

- *H_2 fueling limited by onboard heating, forecourt power & capital*
- *LH_2 pumping offers fundamental thermodynamic advantages*: **maximum refueling density, lowest theoretical refueling work, refueling speed not limited by heating**
- *Pump installation complete, experimental vessel and refueling hose ready:* **Commissioning in early July 2013, first refuel experiments in early August 2013**
- *Planned experiments characterize key aspects of LH_2 pump:* **H_2 flow rate, efficiency and boil-off**
- *Need higher pressure vessel (875 bar) to test full pump capability:* **flow rate, evaporation rate, maximum refuel density**