Cryogenic Pressure Vessels for H_2 Vehicles Rapidly Refueled by LH_2 pump to 700 bar

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The Road Ahead

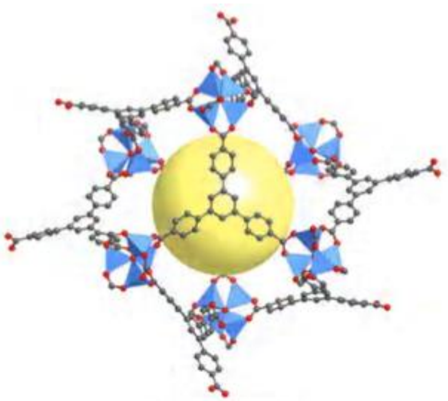
- Cryogenic H_2 Onboard Storage
  - Temperature as a Degree of Freedom in H_2 storage
  - LLNL Cryocompressed Project History
  - 350 Bar Test Vehicle Park & Drive Results
- Current Project
  - 700 bar prototype (cryogenic) vessels
  - Refueling with LH_2 Pump
  - Test Vessel Cycling Facility
- System Considerations
  - Vacuum Jacketing
  - Vacuum, Temperature, Heat Transfer
  - Material properties at low temperatures

LLNL 350 bar cryogenic pressure vessel stores 10 kg LH_2 onboard a 2005 Prius

Onboard H_2 storage approaches face thermodynamic challenges

Cryogenic Liquid H_2 (28 Kelvin, 6 bar)
evaporation when parked 3-4 days

Compressed Gas (350-700 bar)
H_2 *volume,* fast fill *heating*



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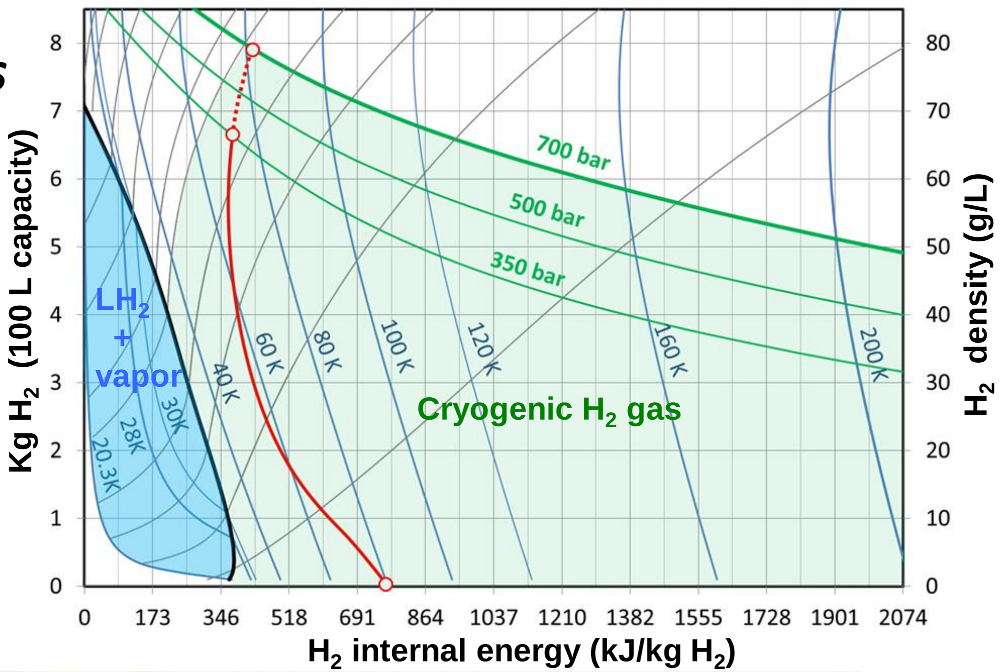
Adsorbed H_2: parasitic volume,
exothermic refueling & cryogenics

Hydrides: parasitic mass,
refuel *speed/temperature*

Thermodynamic limits of LH_2 & ambient H_2 storage can be overcome with H_2 pressure vessels operable across broad range of temperatures

- ***Maximum Density, Minimum Mass***
- ***Extended Thermal Endurance***
- ***Superior Refuel Thermodynamics***
- ***Thermal Isolation***
- ***Low Internal Energy***



Thermodynamics of high pressure cryogenic H_2 refuel/storage can provide powerful automotive/driver characteristics

- *Maximum Density, Minimum Mass*
- *Extended Thermal Endurance*
- *Superior Refuel Thermodynamics*
- *Thermal Isolation*
- *Low Internal Energy*

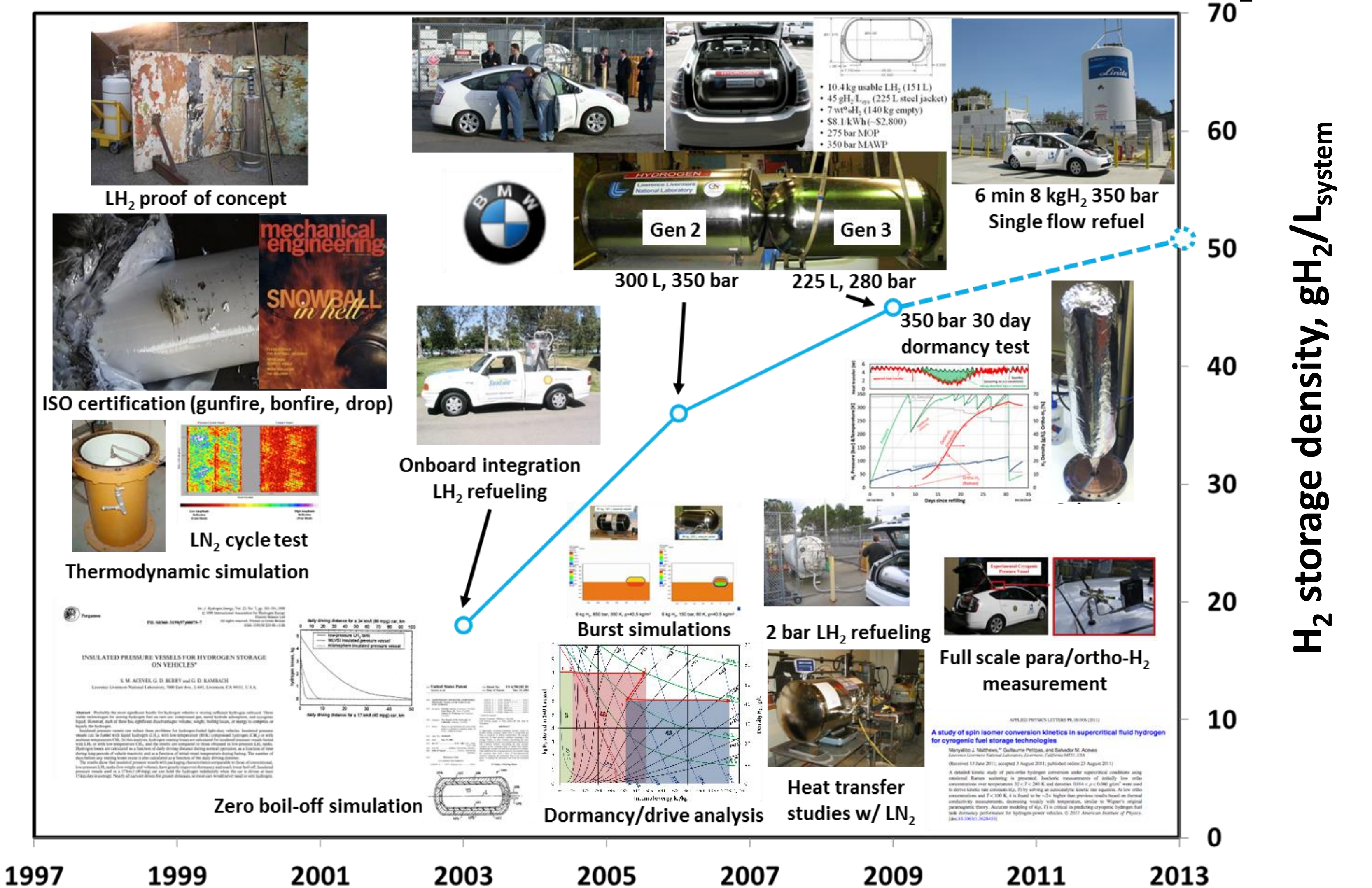
- *Minimum Size/Cost*
- *Fuel Economy, Parking Time*
- *Low Energy Rapid Refueling*
- *High on-road Safety Factor (5-10)*
- *Low Burst Energy (3-5x)*

LLNL has pioneered cryogenic H_2 gas with a comprehensive approach while improving storage density, dormancy, safety, cost, & refueling

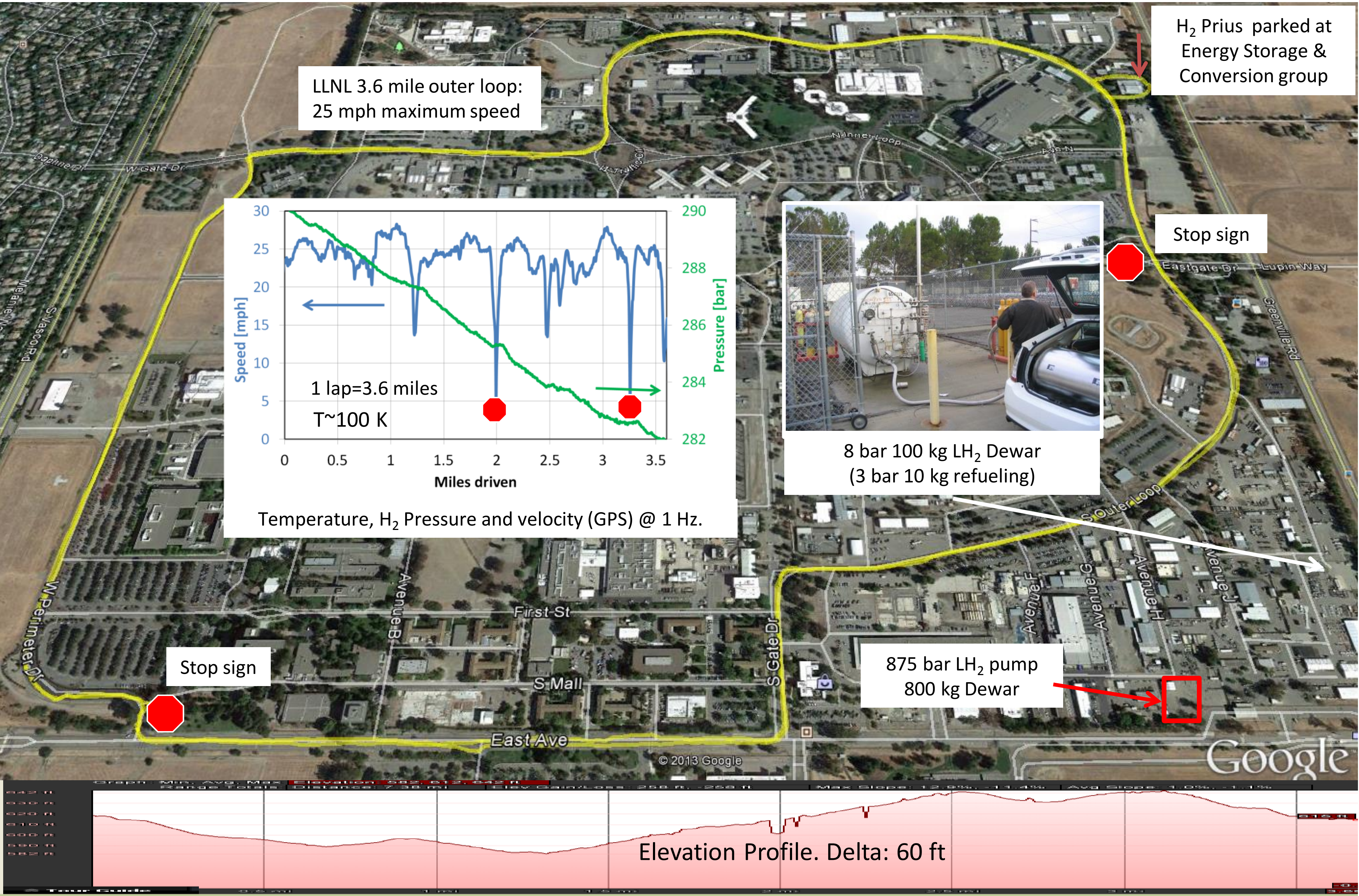
1997-2003
Dormancy simulation
Subscale vessel testing

2003-2010
Onboard Commercial vessels
350 bar, 10 kg LH_2

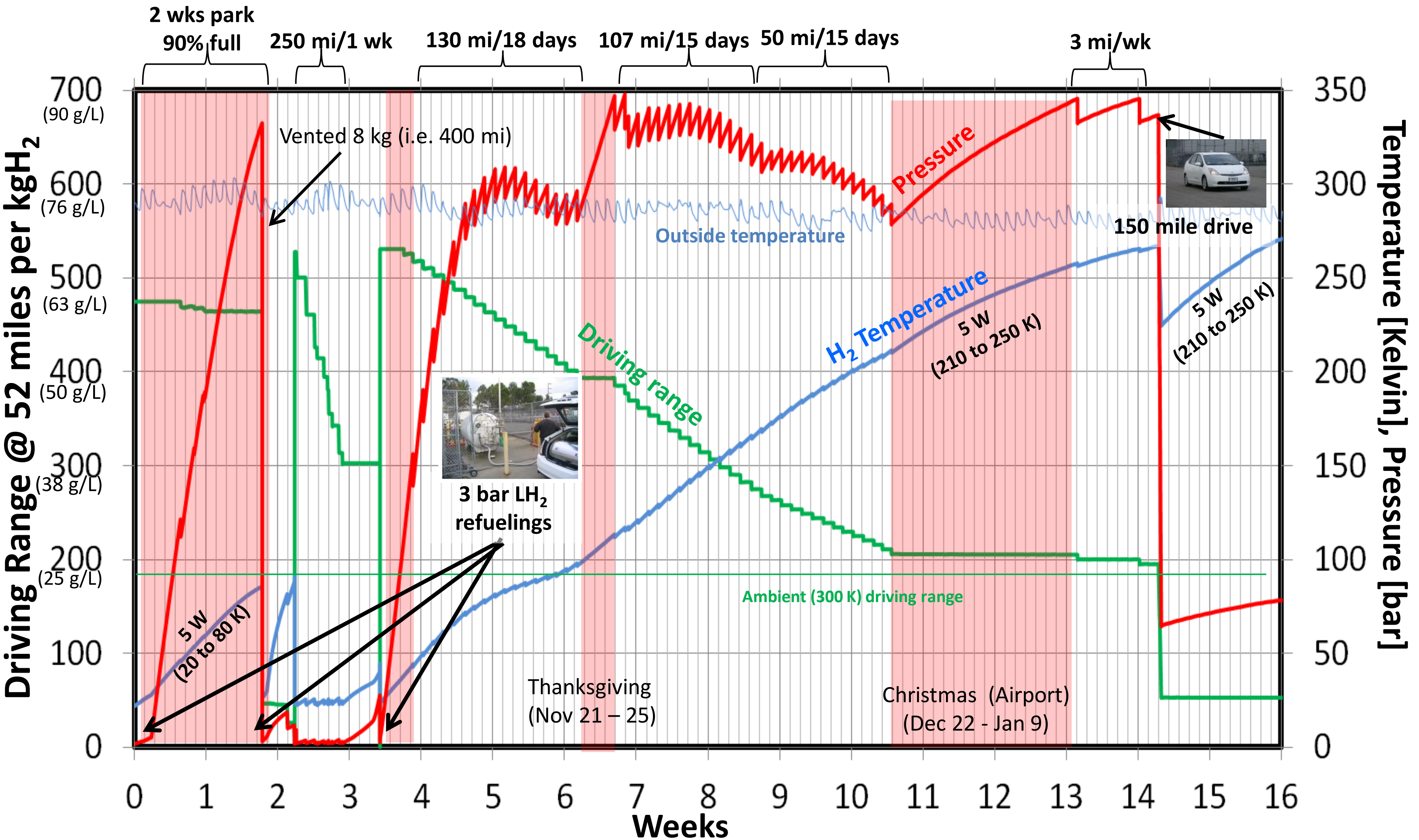
2010-2013
Heat transfer
350 bar refuel w/ LH_2 pump



Key aspects of cryogenic H_2 onboard storage were explored during 200 lap LH_2 refuel/park/drive experiment of 350 bar H_2 Prius

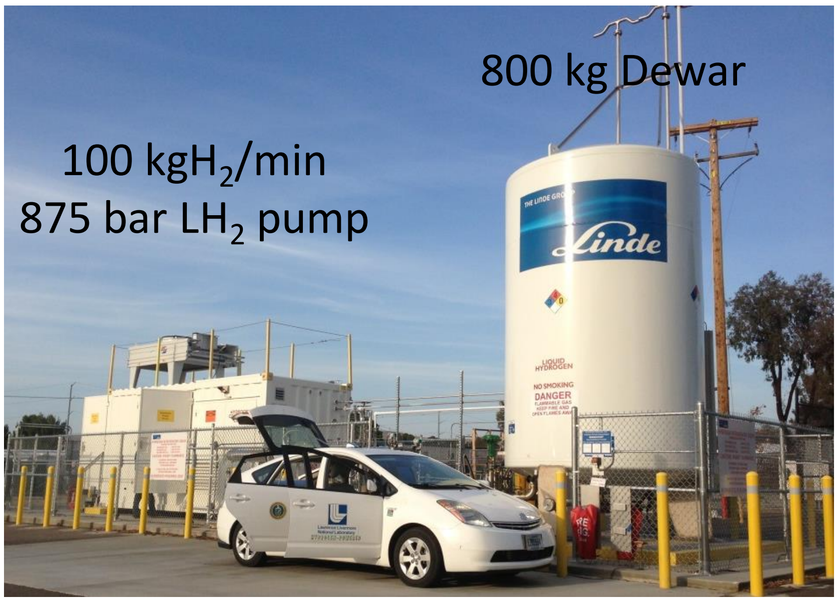


4 month refuel/park/drive demonstrated: (A) 2 week dormancy @ 90% full (B) return to 20 K (400 miles) (C) under 350 bar envelope for 7 mi/day (full)

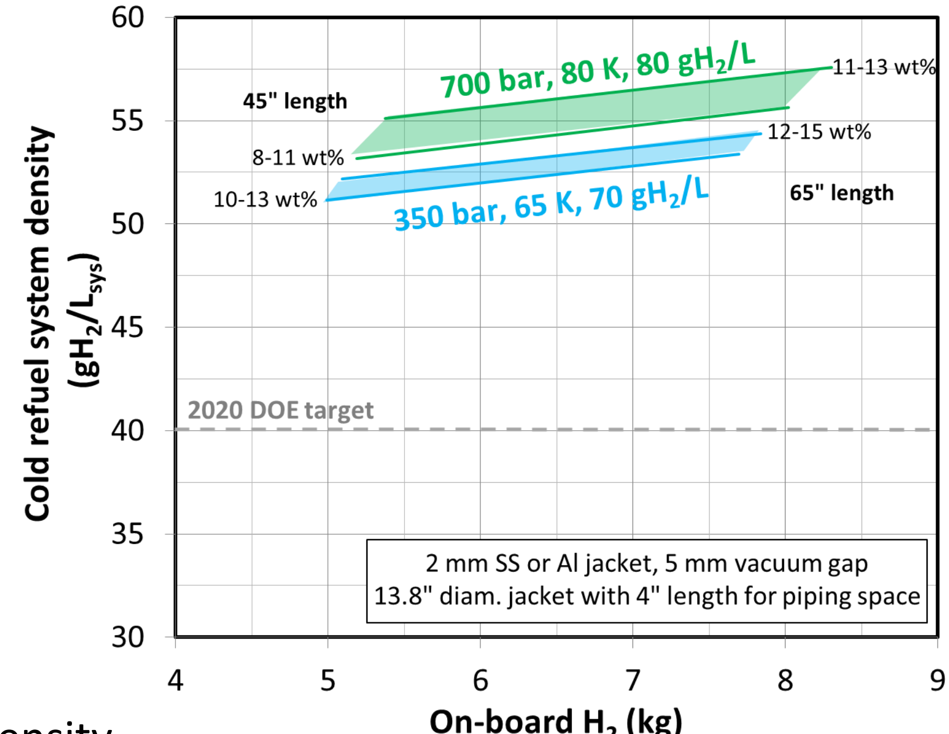


700 bar cryogenic H_2 refueling offers volume, capacity, & safety advantages balanced by increasing technical demands

- High density (cold) H_2 allows minimum vessel volume, mass, & cost with rapid refueling
- Large capacities improve cryogenic valve/vacuum jacket cost, mass, & volume per kg of H_2
- Inert secondary containment, min burst energy @ max tension, on road safety factor of 5-10



7 minute 10 kgH_2 fill to 70 g/L (350 bar, 65 K)

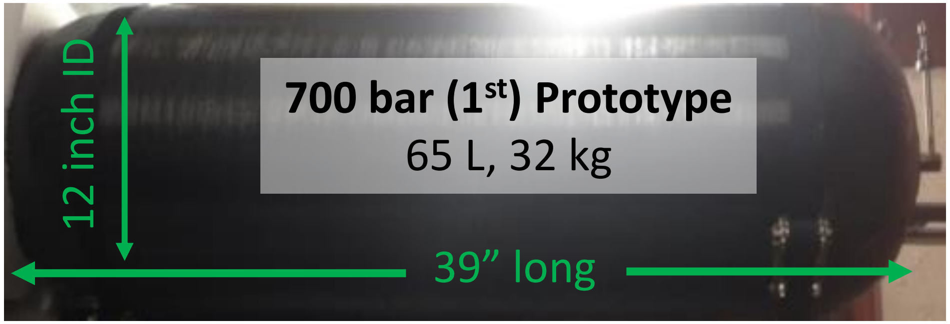


- Small vacuum space necessary for system density
- Temperature *variations* alter system/material behavior, density, dormancy, H_2 burst energy
- Competing design objectives: *acceleration* (strong suspension) vs. *parking* (thermal isolation)

We will demonstrate 5 kg H_2 storage at 700 bar (50 g/L, 9+ wt%)

Our objective is to explore thermomechanical limits of 12 inch vessels designed specifically for cryogenic H_2 storage

70% volumetric efficiency
9 mm Al liner



81% volumetric efficiency
1.8 mm non-Al liner

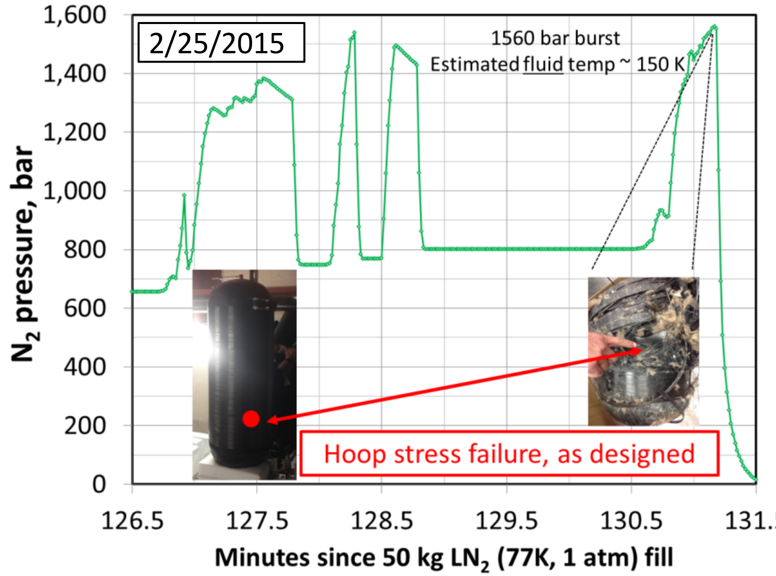
Ultra Thin liner (1.3-1.5 mm): necessary for small diameters
Non-Al liner: liner, piping, and weld durability under cryogenic H_2 cycling
Maximum fiber fraction: minimum wall volume & thermal inertia

We are demonstrating 700 bar prototype cryogenic vessels designed for 80+% volumetric efficiency

1^{st} go/no-go (LN_2) test demonstrated vessel cryogenic strength Cryogenic durability (1,500 LH_2 refuels) to be shown in 2^{nd} test

FY15 Go/No-Go milestone

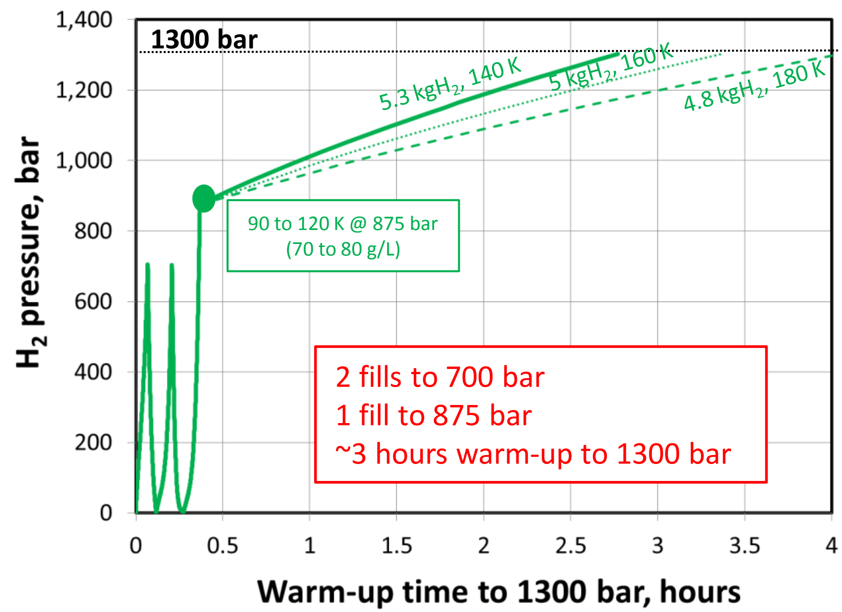
Demonstrated cryogenic 2.23 safety factor (1560 bar)
32 kg vessel,1.8 mm liner with 81% volumetric efficiency
4 rapid pressurizations of 50 kg LN_2 with warm N_2 gas



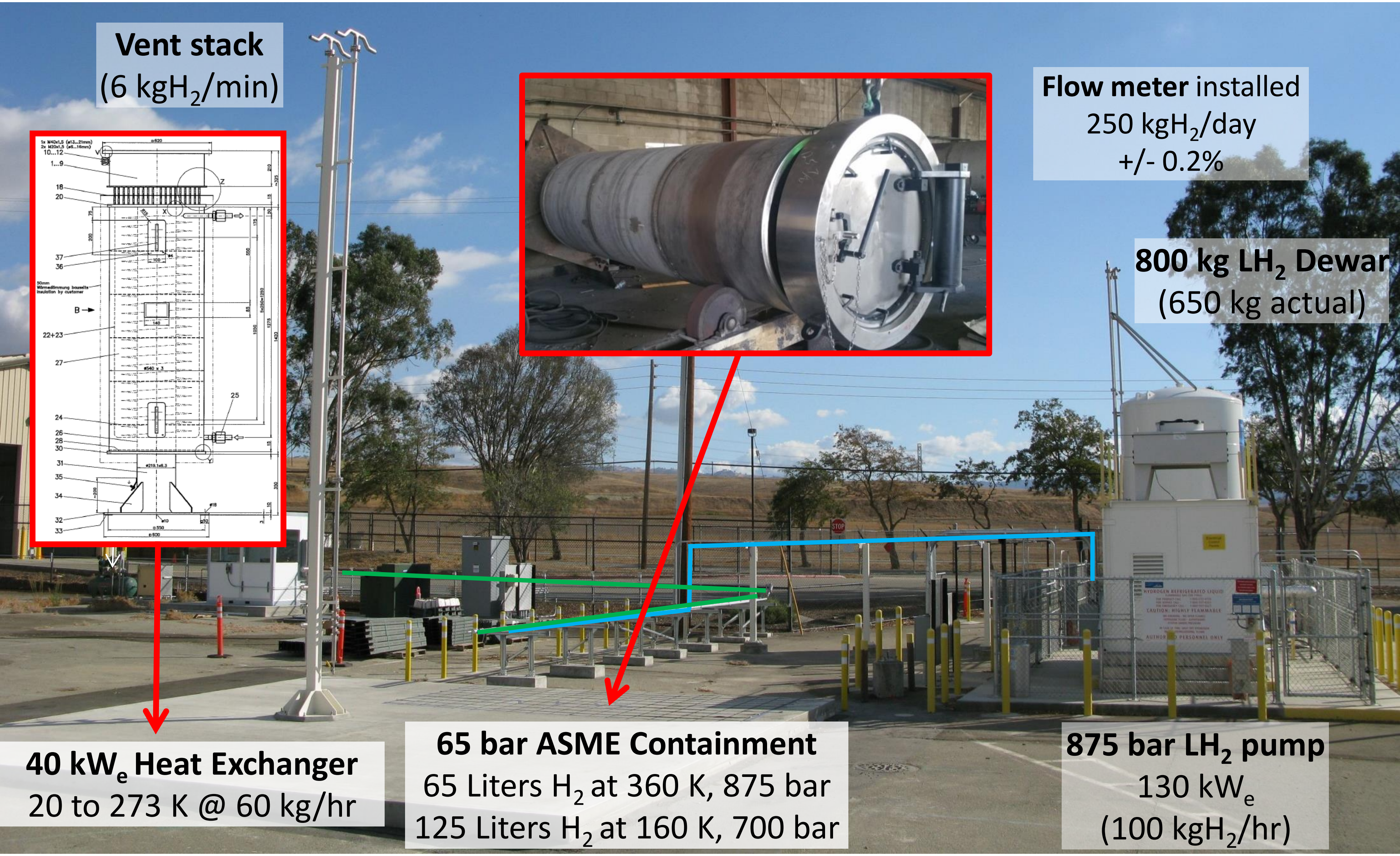
FY16 Go/No-Go milestone

Demonstrate EOL cryogenic safety factor > 1.85
after 1,500 LH_2 fuelings

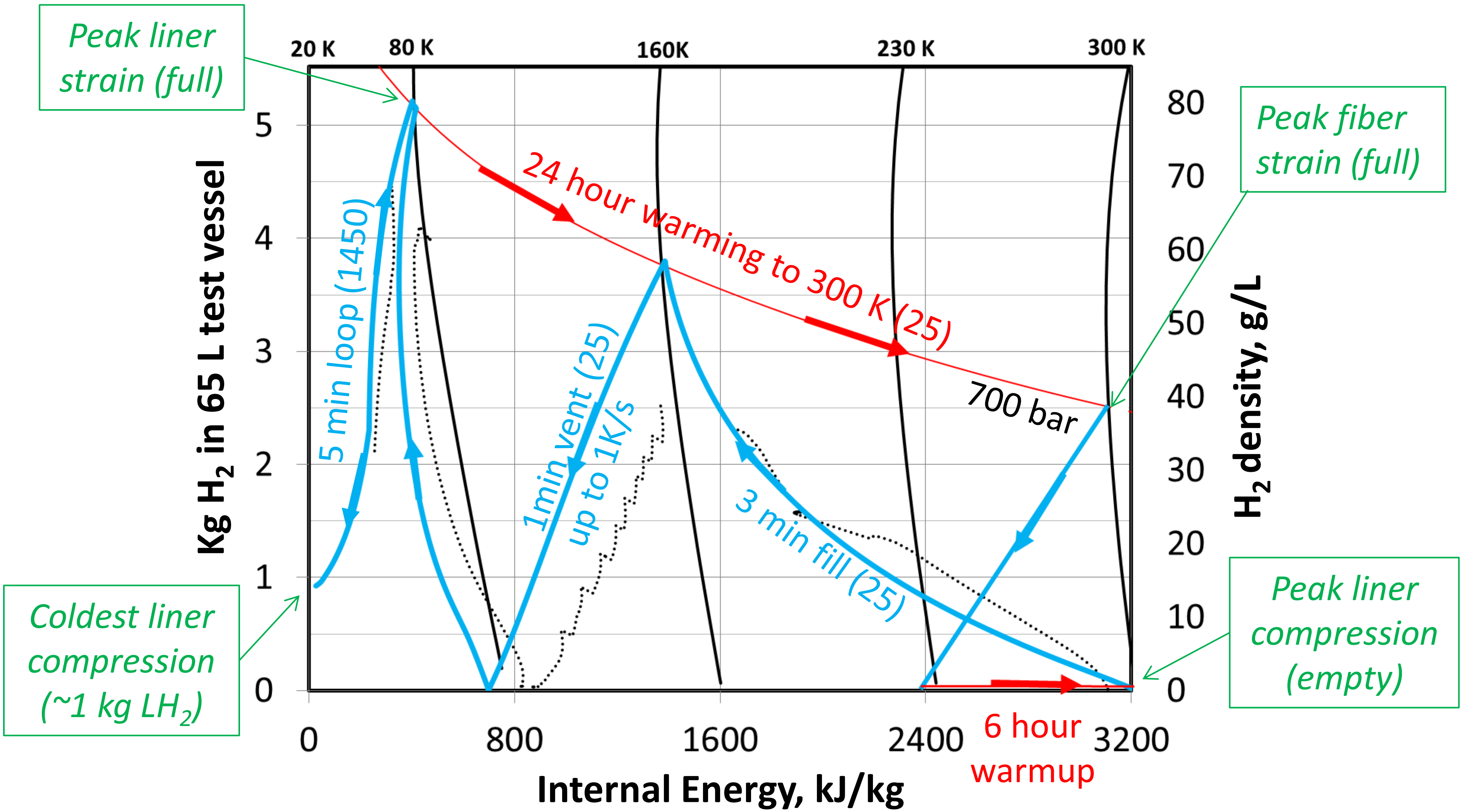
1,300 bar test from 875 bar H_2 at 90-120 K
Slow (~3 hr) temperature rise to 140-180 K



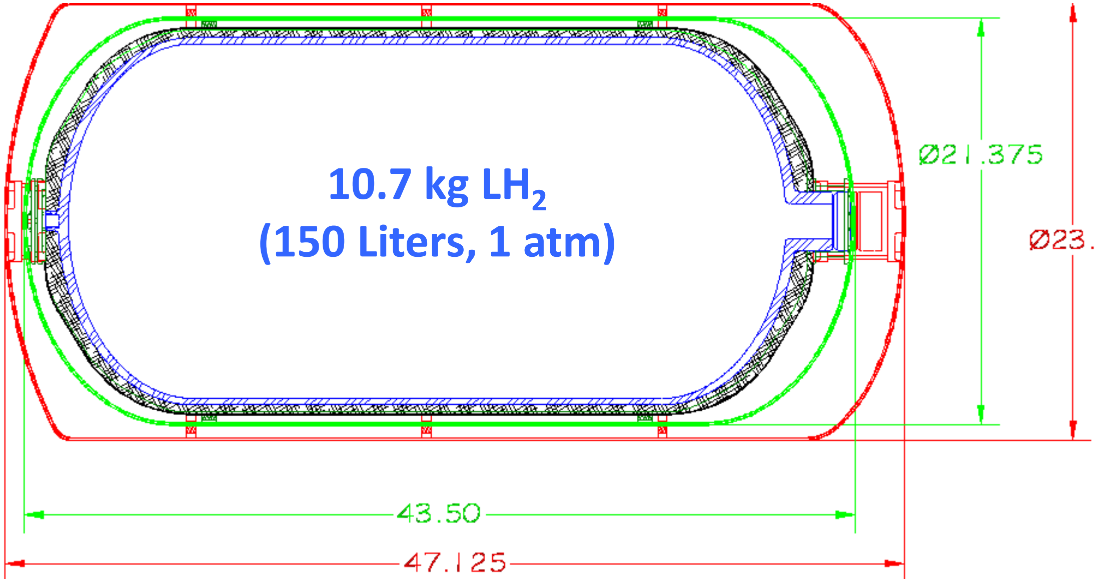
100 kg H_2/hr, 800 kg LH_2 facility for cycling (120-200 fills/day) of full-scale prototype vessels

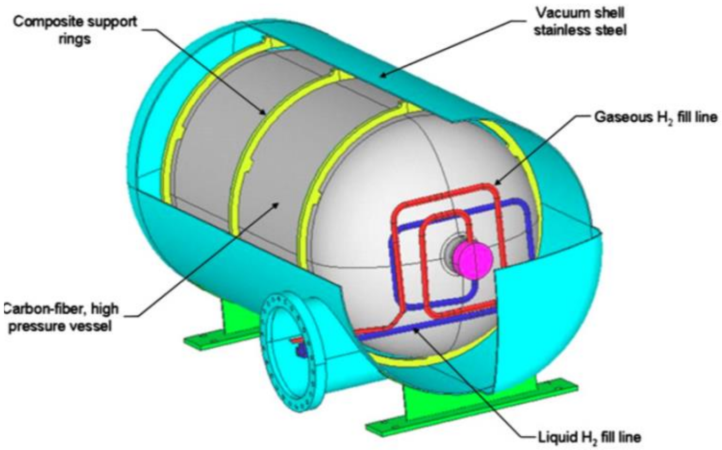


Ideal cryogenic H_2 cycling covers full pressure & temperature range, emphasizing maximum thermomechanical stress and time at pressure



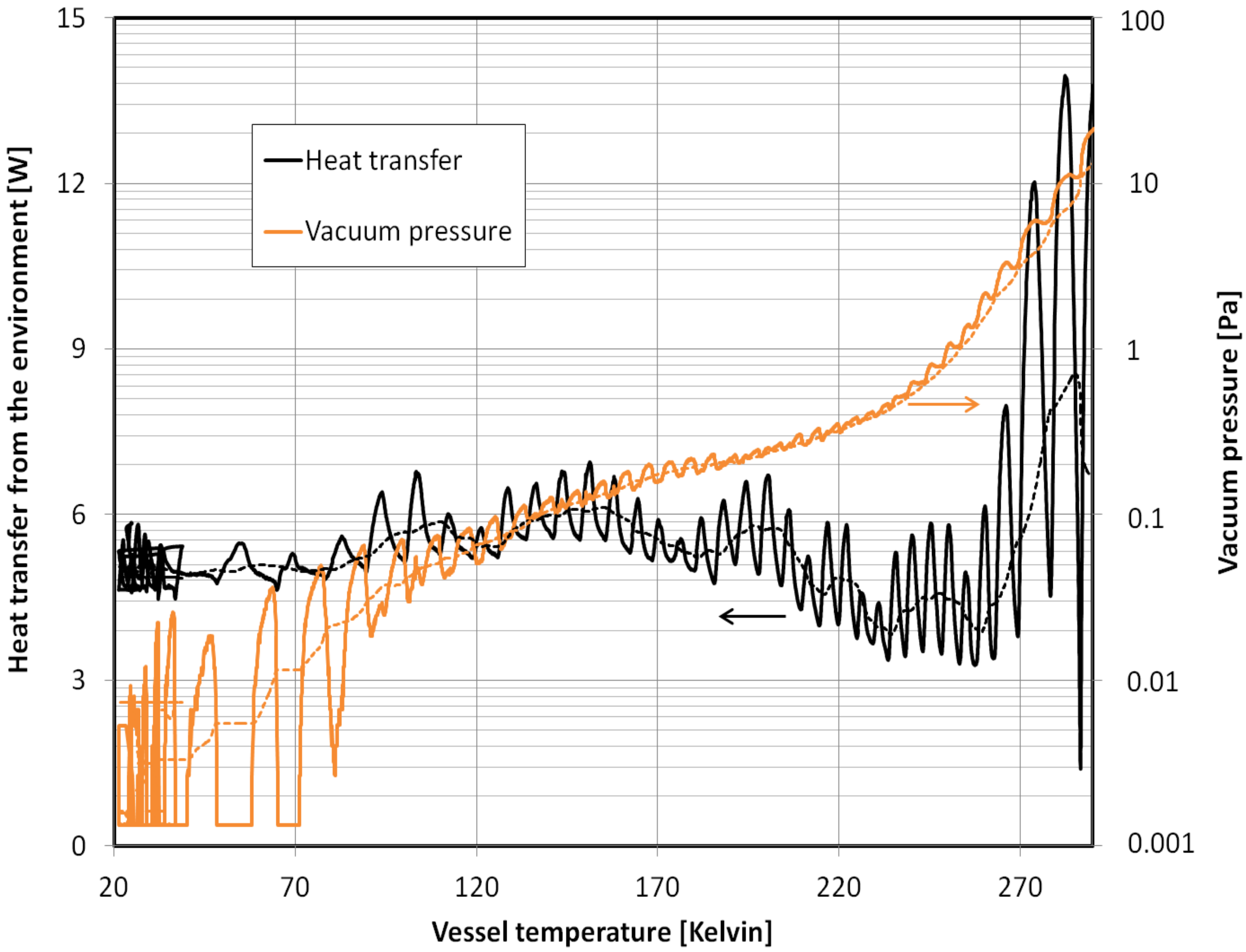
LLNL developed two vacuum jacket generations for 150 L cryogenic H_2 the smallest 3mm steel jacket was 225 L, 60 kg with <1" vacuum gap



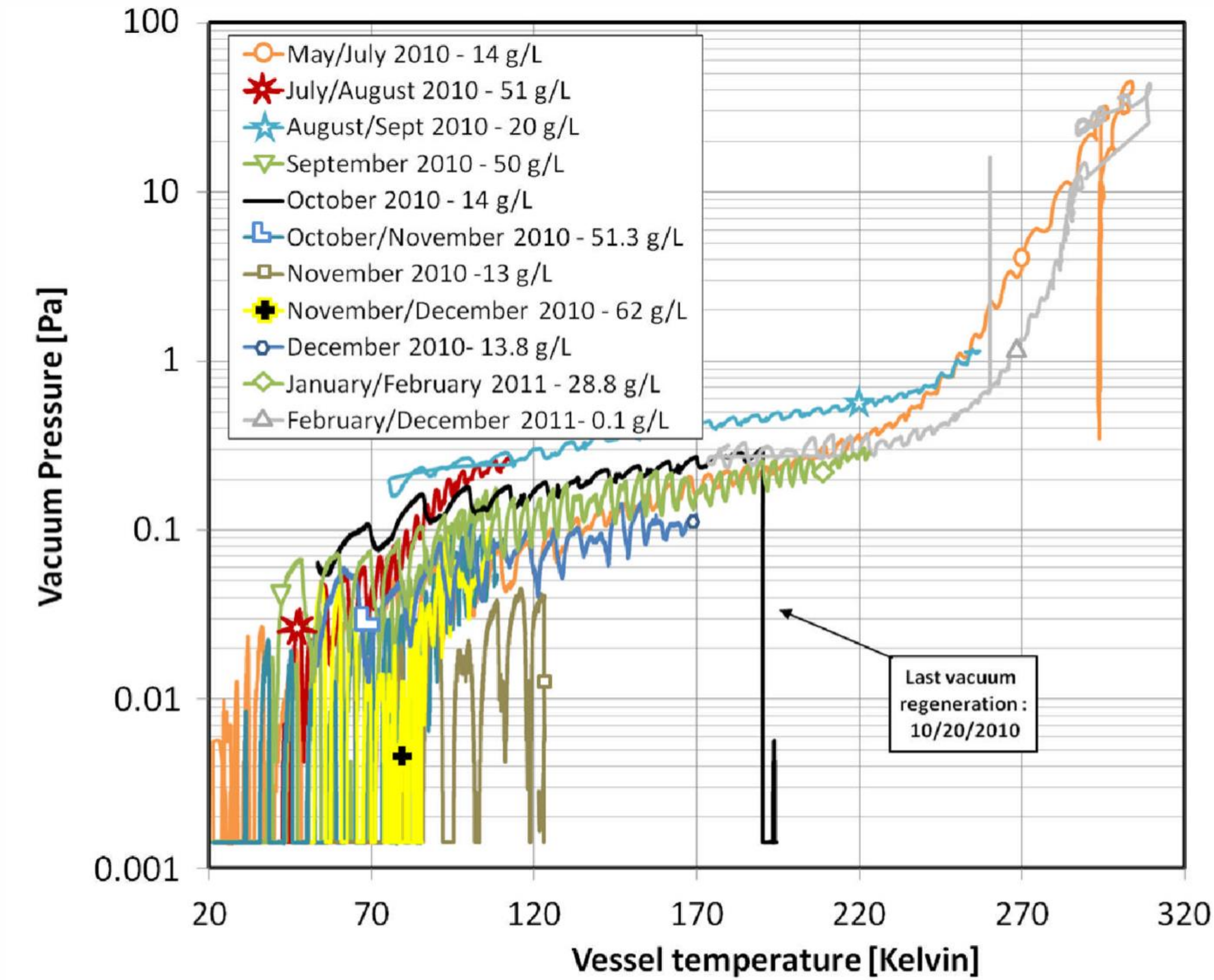


	Weight (kg)	wt%H_2	Volume (L)	kgH_2/m^3
4,000 psi vessel+boss	60.9	14.9	179	59.7
Steel vacuum jacket	57.1	8.3	225	47.4
Ancillary components	16	**7.4**	11	**45.2**

Preliminary long term vacuum pressure data did not indicate increased heat transfer below ~250 K



Multiple month experiments indicated vacuum pressure followed vessel temperature



Low temperature material properties offer opportunity and challenge for cryogenic pressure vessels

Opportunities greatest at <u>coldest</u> temperatures (typically <100 Kelvin)

- Increased composite fatigue life
- Increased composite stiffness
- Increased metal strength, cycle life
- Declining thermal conductivity
- Asymptotic heat capacity
- Asymptotic thermal contraction coefficient

Challenges due to temperature <u>change and variation</u>

- Aluminum minimizes gradients but high CTE
- Stainless steel sustains gradients but medium CTE
- Composites sustain highest gradients with small CTE

- Majority of thermal contraction typically occurs between 300 K and 200 K
- 10% of thermal contraction at T < 100 Kelvin

Focus on gradients at moderate temperatures & dissimilar materials
Extreme cold can maximize thermomechanical properties