Cryogenic Pressure Vessels: Progress and Plans

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This presentation does not contain any proprietary or confidential information
The cryogenic pressure vessel concept has evolved from thermodynamic analysis into manufacture and demonstration.

1998: thermodynamics

2000: DOT/ISO testing

2004: demonstration

2007-2009: compact vessels

2010: para-ortho H₂ conversion

2011: LH₂ pump
LLNL has refined three generations of cryogenic vessels exceeding 2015 storage targets fueled with 70g/L liquid H₂.
In a month long dormancy experiment, *para-ortho* conversion reduced heat transfer by half between days 12 and 24.
Experimental tests have been run over a wide range of conditions (temperature, density, vacuum quality).

- July 13th
- October 20th
- December 20th

Refueling
Para-ortho conversion became significant at ~75 K and extended dormancy by ~5 days for 70-90% full 151 L vessel.
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In both industrial and laboratory environments, low heat transfer requires < 1 mTorr vacuum quality.

**Industrial**
- Horizontal pipeline sagging

**Laboratory**
- Vertical MLI sheets
- No penetrations
- No supports
- No trapped residual gases
- No layer pinching

Source: NASA.

Performance characterization of perforated multilayer insulation blankets, Fesmire, Augustynowicz, Darve

Thermal performance of cryogenic piping multilayer insulation in actual field installations. Fesmire, Augustynowicz.
LLNL insulation performance follows the same trend.
Experiments show viable indicated vacuum levels up to \(~150\) K for 4 months
Most cryogenic vessels may remain colder than 150 K due to expansion work during hydrogen extraction.

Source: BMW
Experiments show viable indicated vacuum levels up to ~150 K for 4 months.
LH$_2$ pump will enable rapid high density refueling even for initially warm and/or pressurized vessels

- A high pressure (up to 880 bar) LH$_2$ pump offers rapid single phase refueling without boil-off
- Single flow refueling can be reliable and cost effective
- Pump expected ~12 months after contract, possibly 2/12
- Contract is now in procurement. To be finalized within 1-2 months
- LLNL is also responsible for basic services: electricity, phone line, concrete pad, foundation
An 80 L 700 bar cryogenic vessel will be located forward of existing 151 L 350 bar vessel. Fueling both explores scale and transient vs. steady state refueling differences.
We project 55% volumetric efficiency for 80 L & 700 bar cryogenic vessel design with aspect ratio ~2.5

- **Capacity:** 5.6-7.4 kg (L)H₂ @ 1-700 bar
- **Volume:** 153 liters (10 L accessories)
- **Weight:** 90 kg total (15 kg accessories)
- **3 mm aluminum vacuum jacket** 13 kg
- **80 L capacity 700 bar vessel** 62 kg
Fully capturing *para-ortho* conversion demands $P > 5000$ psi and/or vessel volume $> 80$ L.

80 L vessel
Initially stores 5.6 kg H$_2$ @ 20.3 K, 1 atm, 95% *para-H$_2$*
Summary: we will combine a high pressure LH₂ pump & lighter, smaller vessel with a comprehensive experimental strategy

- **Rapid low loss refueling at higher density** up to 880 bar, 90 gH₂/L
- **Simpler high pressure operation** with single inlet/outlet line
- **Realistic (warm) refueling conditions**: partially full, <99% para H₂
- **Measure H₂ temperature in addition to vessel, piping and jacket temperatures** by inserting silicon diodes in vessel
- **Second independent capacity measurement** by weighing vessel ideally *during* refueling
- **Aluminum jacket material** to improve weight, capacity measurement, and thermal uniformity
- **Determine vacuum quality intrinsic to composite wall vessels**