Refueling and discharge of cryo-compressed hydrogen storage systems for heavy trucks

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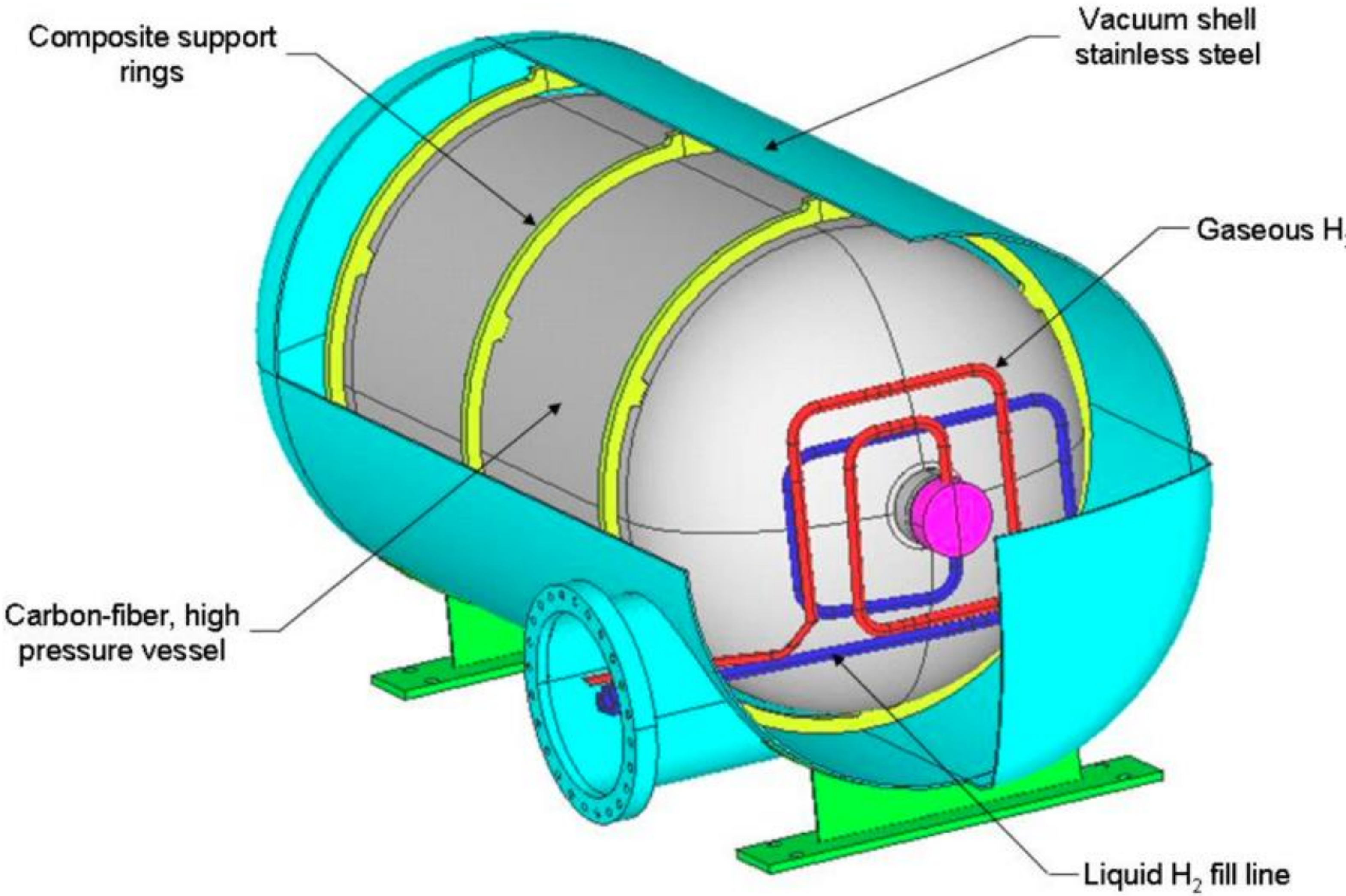
Cryo-compressed (CcH2) vessels comprise an MLI-wrapped type 3 high pressure vessel surrounded by a vacuum jacket



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CcH2 vessels provide safety, cost and weight advantages over alternative approaches to long-range zero emissions transportation

- ***The storage density of LH_2 vessels without the vent losses:*** **~10x longer thermal endurance than low pressure LH_2 tanks essentially eliminates boil-off**
- ***Less expensive than compressed hydrogen vessels:*** **LH_2 capable vessels use 2-3x less carbon fiber than conventional compressed H_2 vessels**
- ***Compelling safety advantages:*** **vacuum jacket protects composite vessel, reduced H_2 expansion energy due to cold operation**

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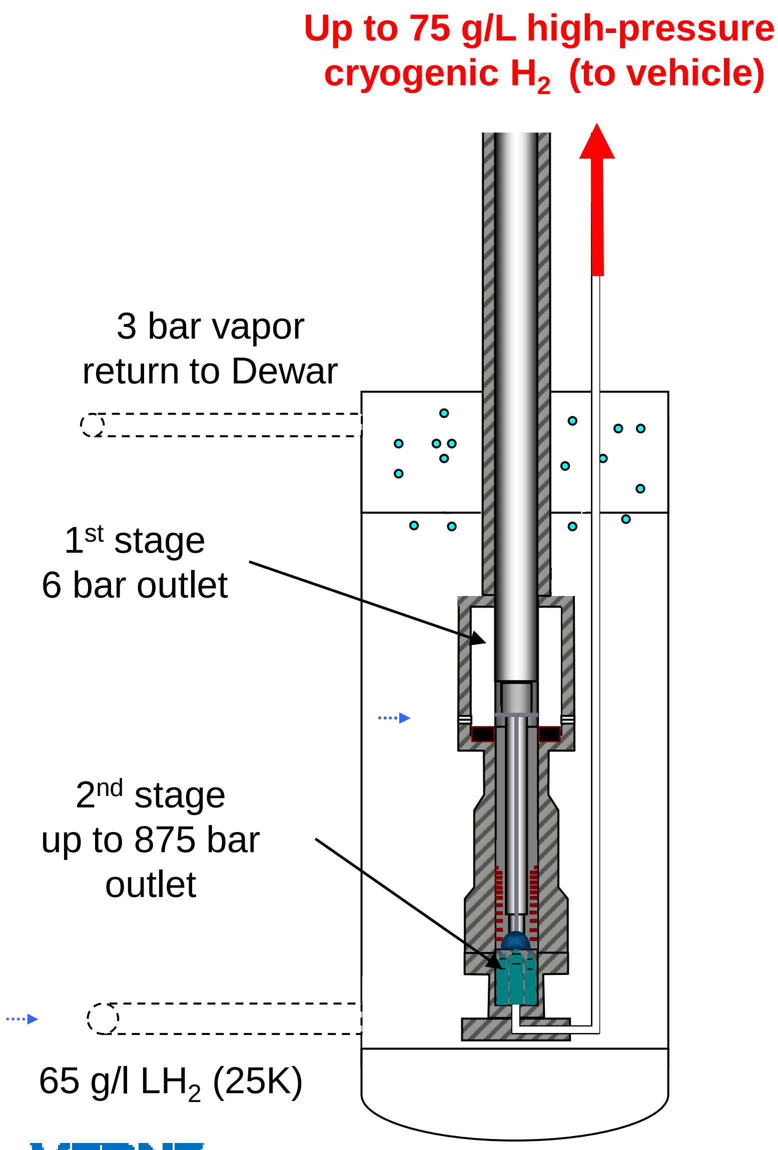
LH_2 pump (Linde) enables practical CcH_2 storage through rapid, high density refueling of initially warm and/or pressurized vessels

LH_2 pump pressurizes H2 in two stages for efficient and cavitation-free operation with saturated LH2



High pressure LH_2 pump makes cryogenic refueling practical

- Pump provides flow rate of 100 kgH_2/hour
- High density fill possible (up to 75 gH_2/L)
- Refuel warm and/or pressurized vessels
- No need for data communication with vehicle
- Unlimited back-to-back refuels
- Can refuel compressed gaseous H2 vessels

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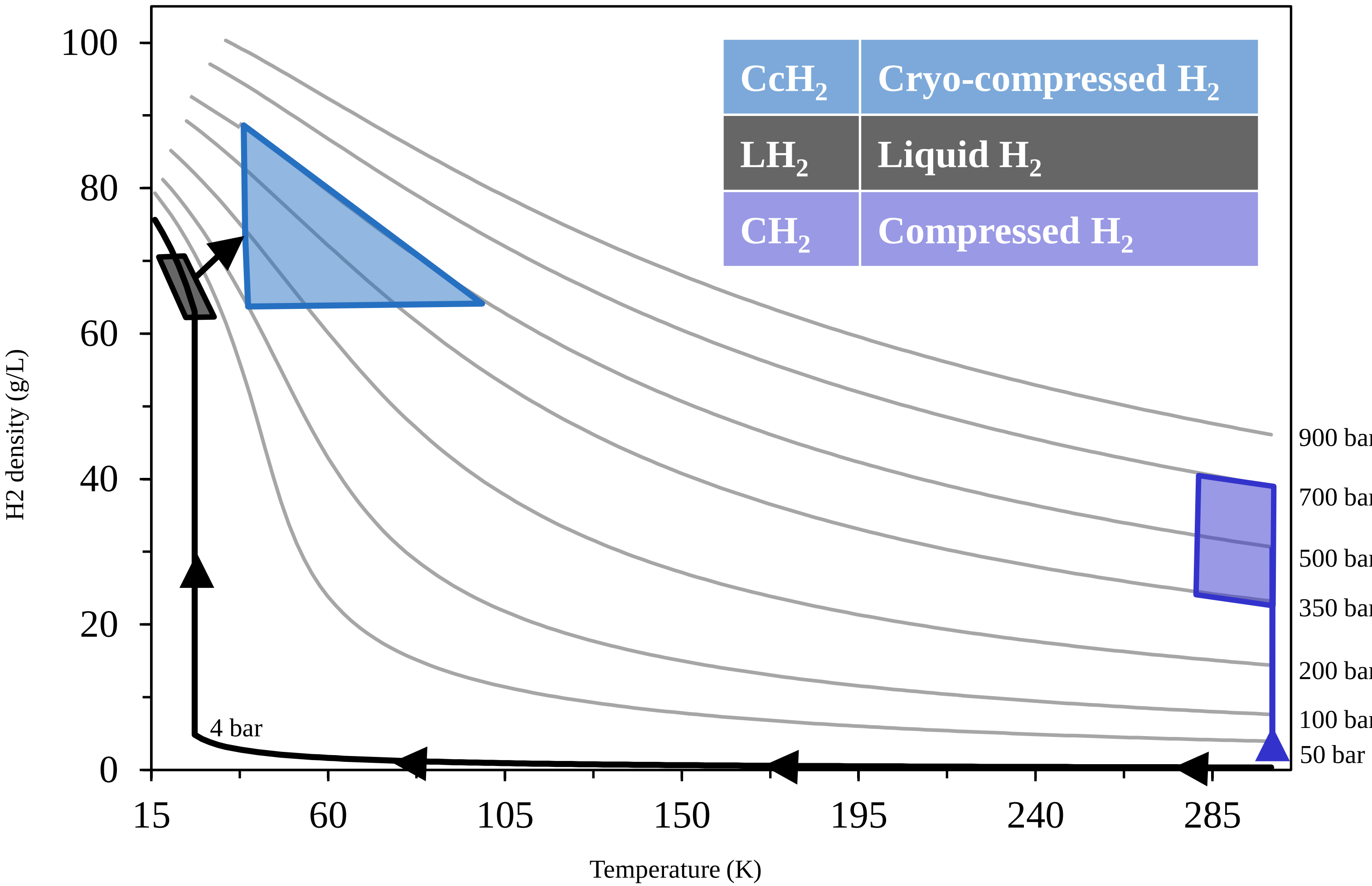
Cryo-compressed hydrogen offers high density with minimal complexity and supply flexibility



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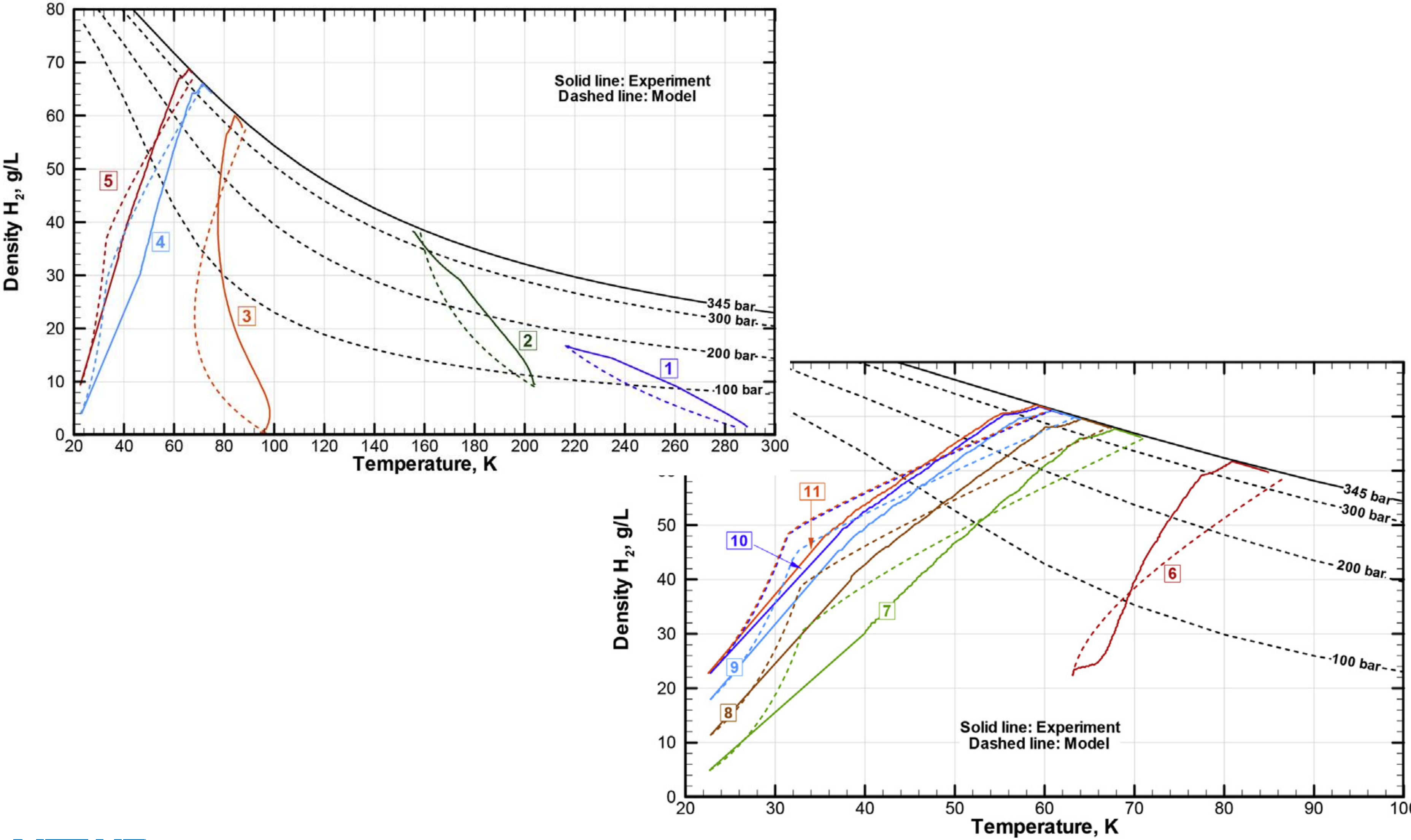
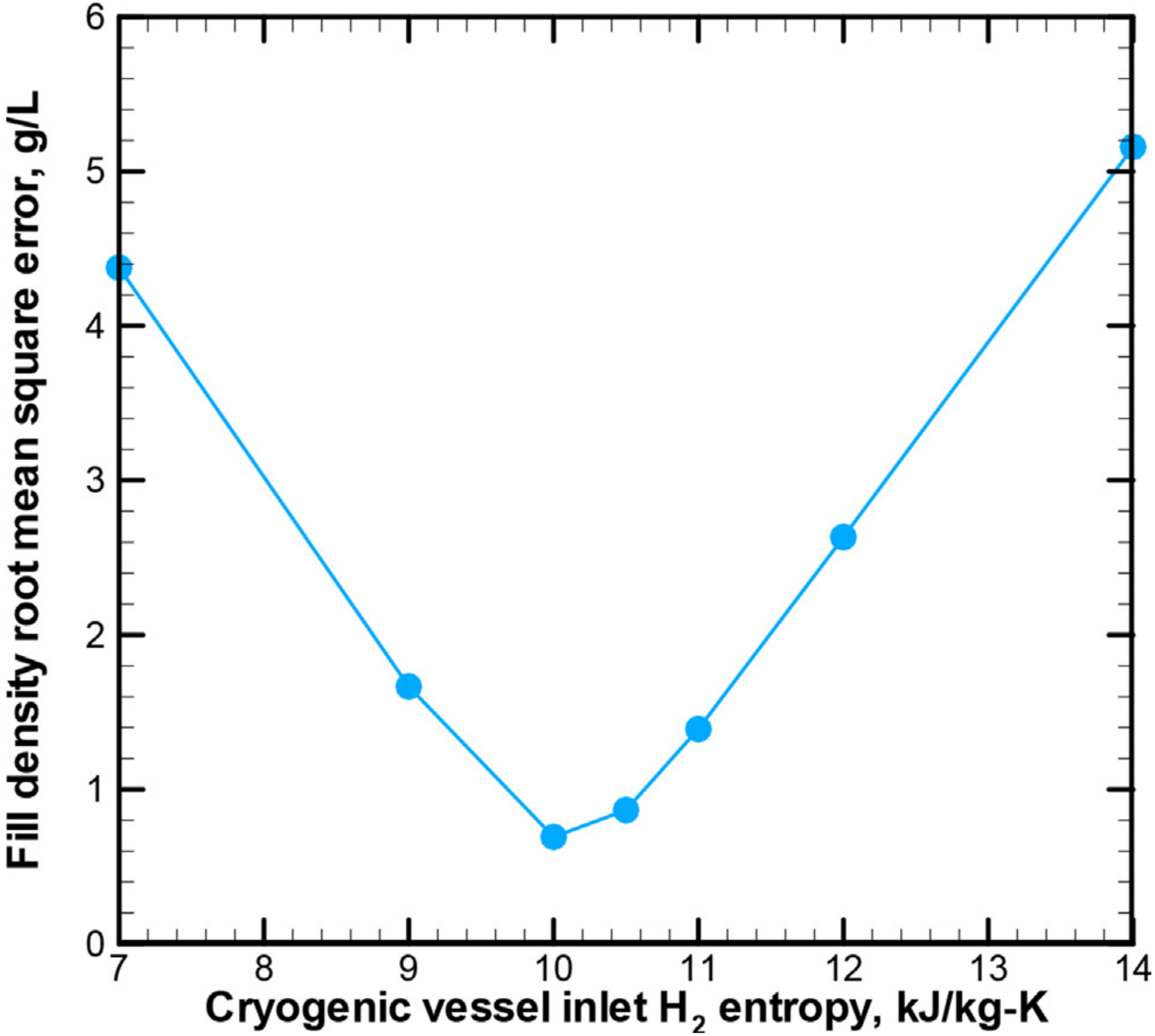
LLNL conducted 24 experiments to characterize pump performance enabling detailed modeling of CcH_2 fill process



Fill processes can be accurately modeled assuming 10 kJ/kg·K vessel inlet entropy



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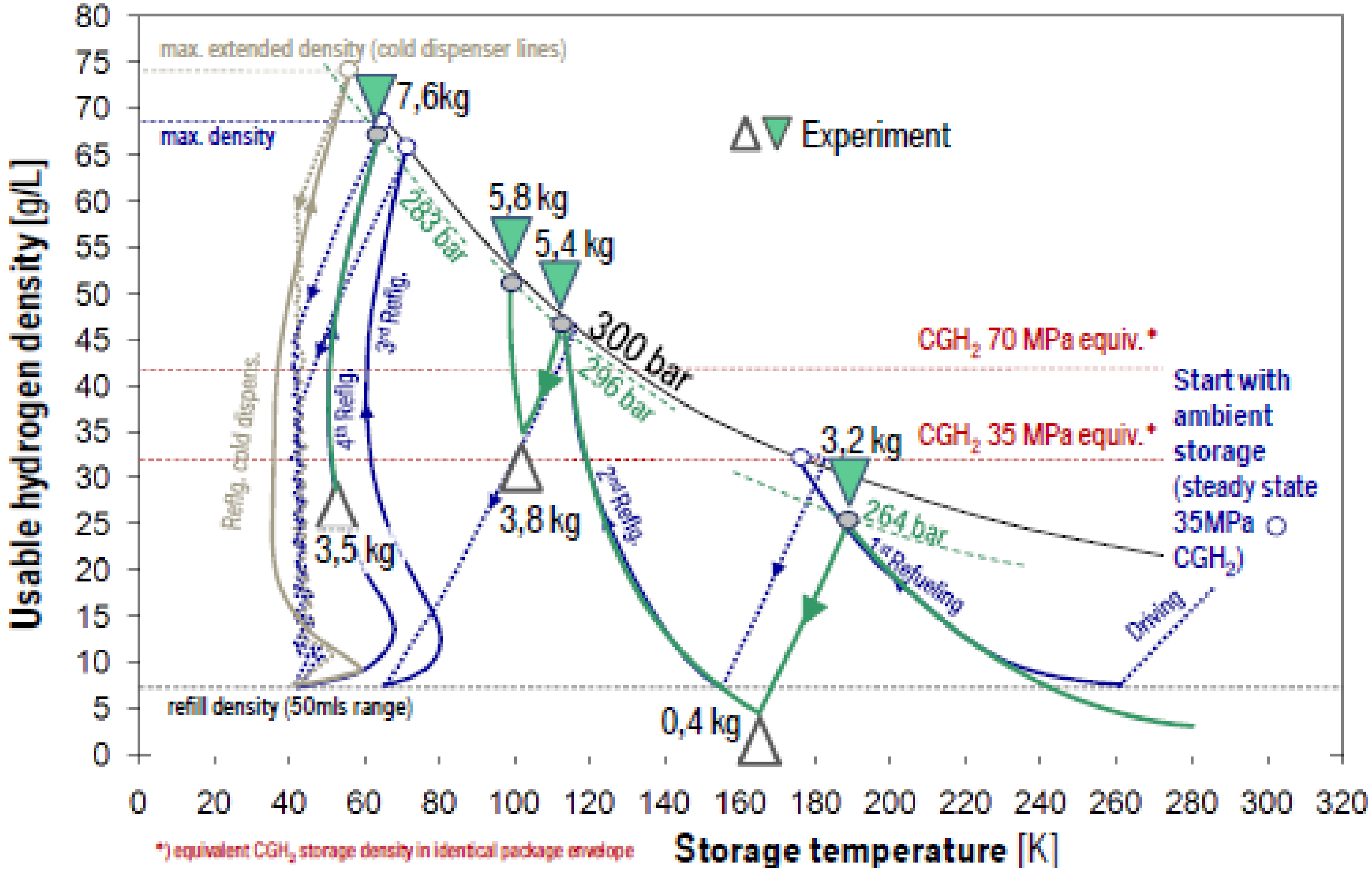
Rapid high-density cryogenic pressure vessel filling to 345 bar with a liquid hydrogen pump, Petitpas et al., international Journal of Hydrogen Energy, Volume 43, Issue 42, 18 October 2018, pp. 19547-19558, https://doi.org/10.1016/j.ijhydene.2018.08.139.

BMW experiments with an LH_2 pump in a commercial setting, vacuum insulated line, and compact station layout demonstrated improved LH_2 pump performance (6 kJ/kg·K vessel inlet entropy)

8kg reference CcH_2 system, consecutive cold 30 MPa refuelings, constant discharge



From warm to cold operation with consecutive CcH_2 refuelings.

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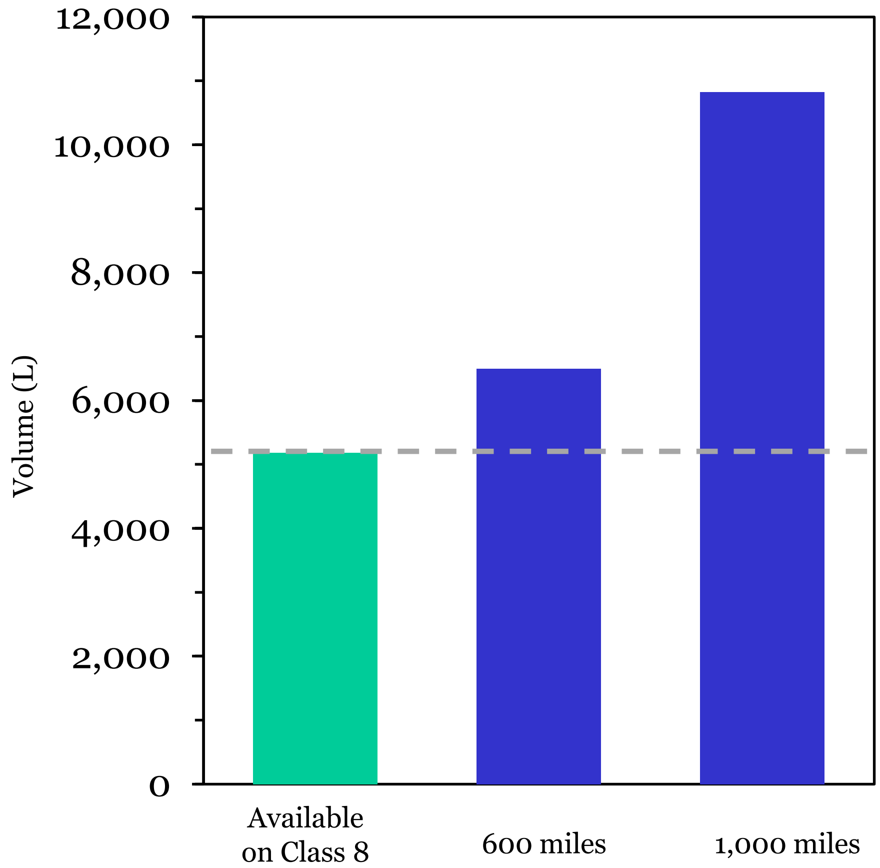
Kampitsch M. BMW - Cryocompressed hydrogen refueling, Proceedings of the World Hydrogen Energy Conference (WHEC), Toronto, Canada, 2012.

700 bar cH_2 doesn't meet volumetric energy densities for long-haul trucking

Volume available and volume needed



Back-of-cab 700 bar storage system

700 bar storage does not meet 500+ miles range for long-haul

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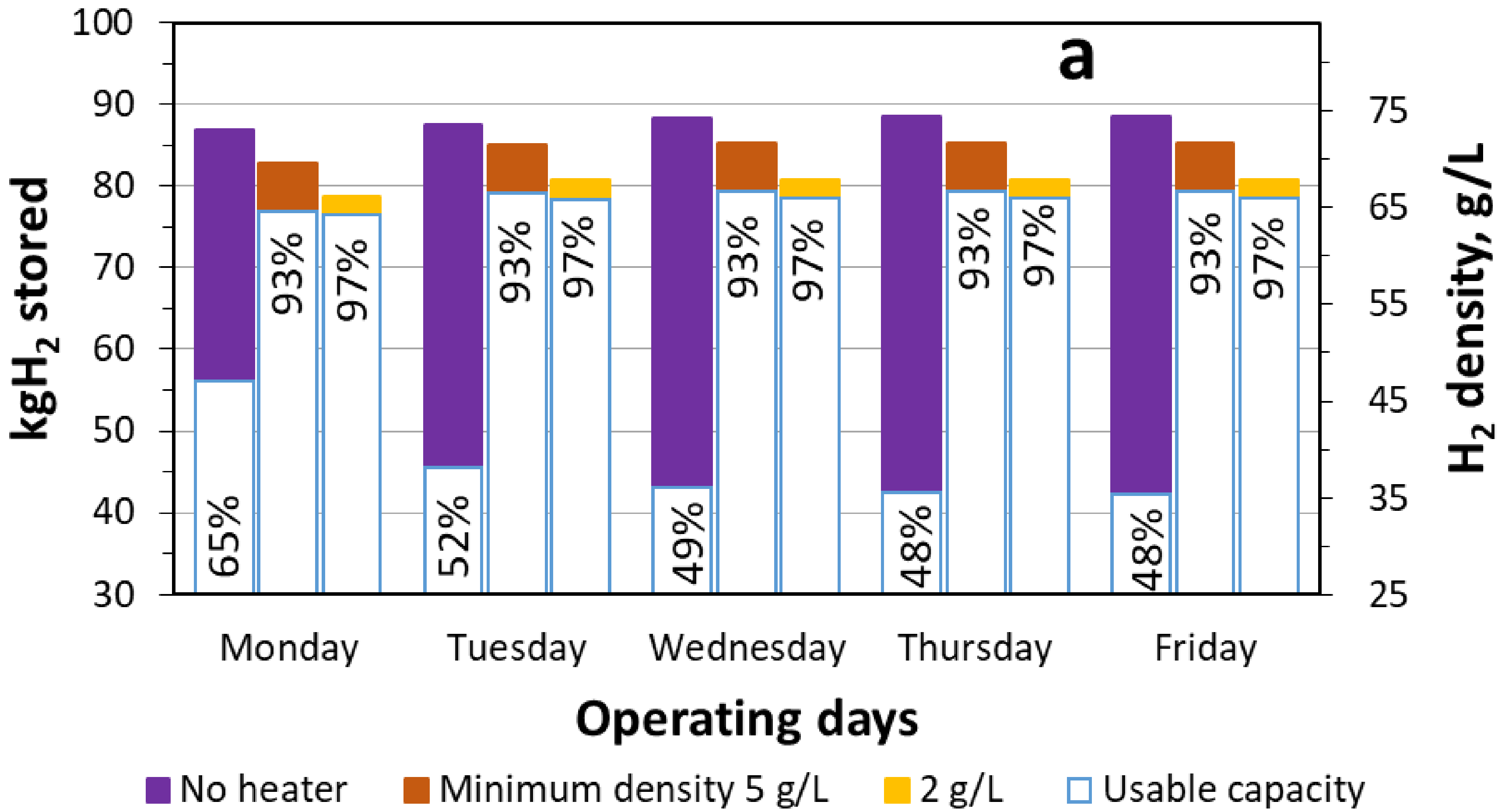
Image on the right: Kenworth.com

Thermodynamic modeling predicts 68 g/L *usable* storage density of CcH2 truck vessel



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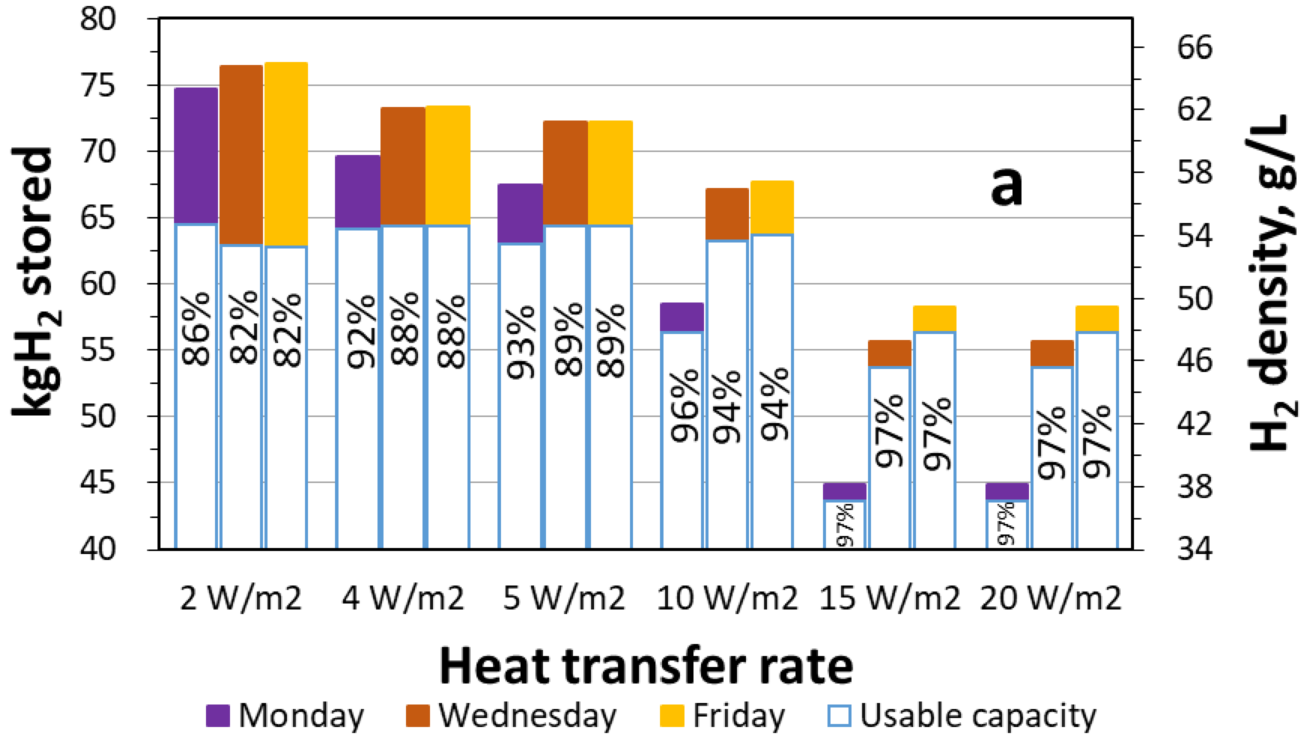
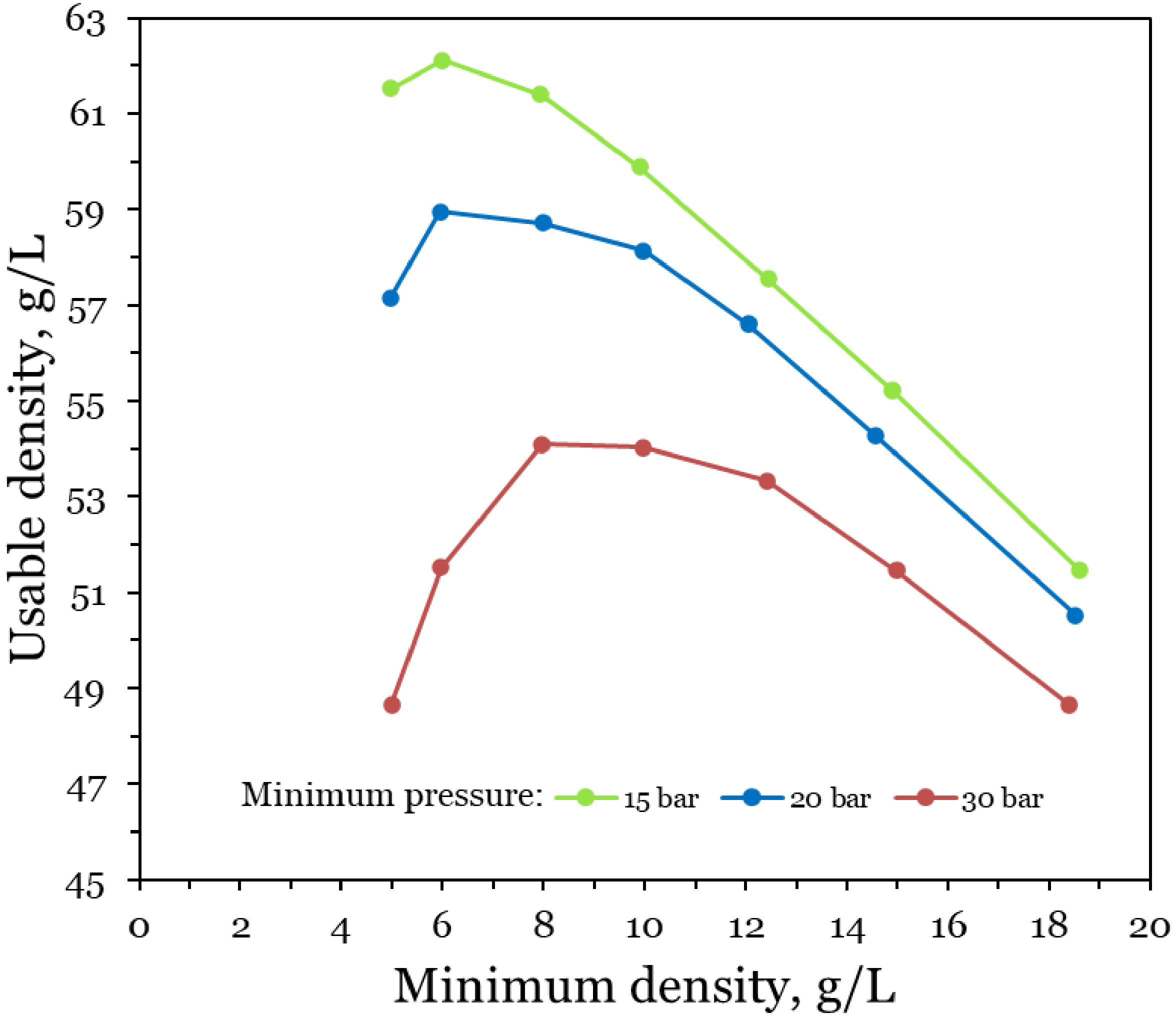
Insensitivity of CcH2 vessels to heat transfer rate broadens design space, reducing cost and/or insulation thickness



- No vent losses anticipated even at very high heat transfer rates
- The main effect of increased heat transfer rate is reduced fill density
- Increasing the heat transfer rate from 2 to 20 W/m² decreases usable storage density by only 20%

High pressure capability of CcH2 vessels enables supply of H2 at elevated pressure to meet demand of e.g., direct injected hydrogen internal combustion engines



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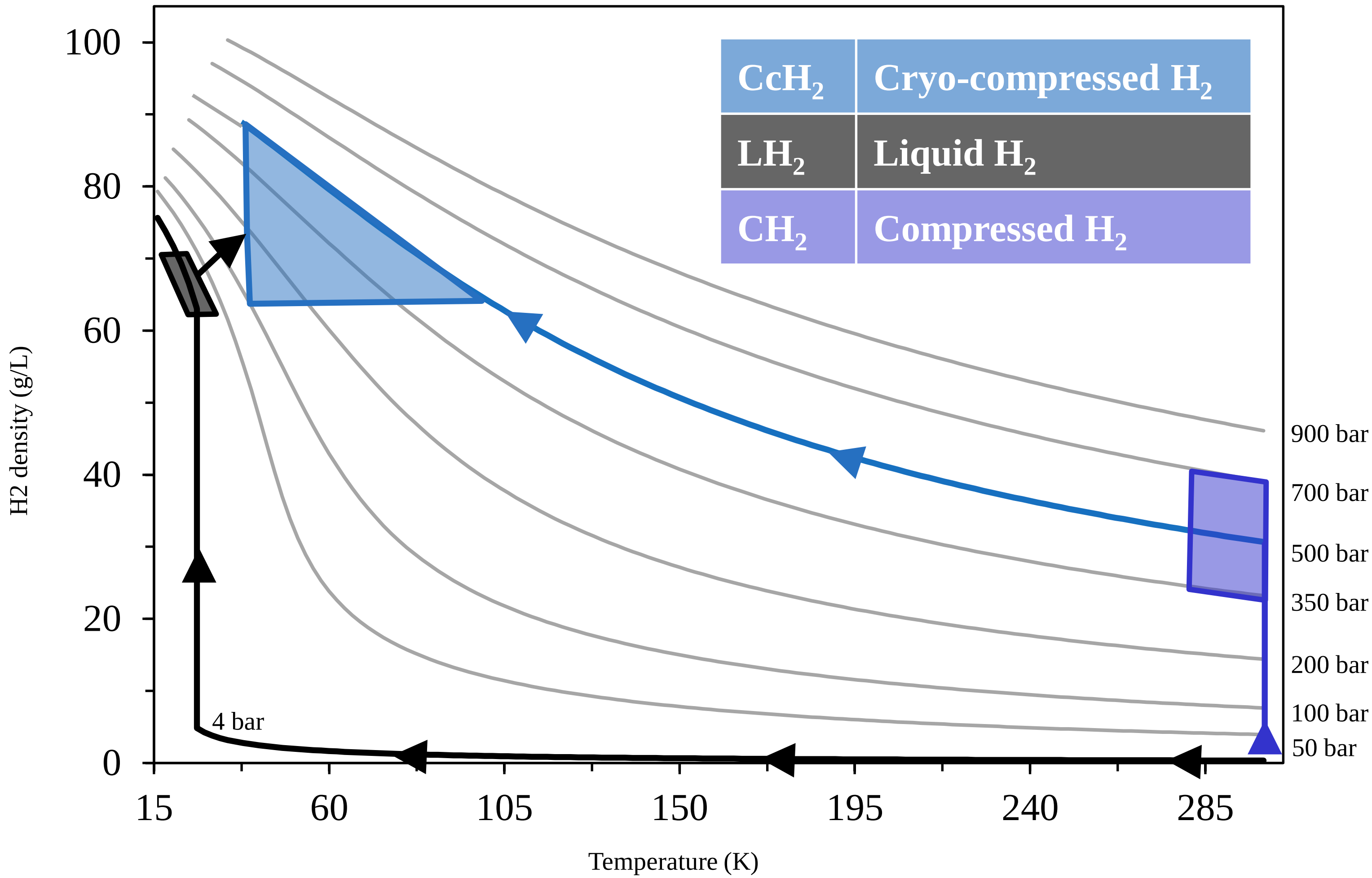
15% loss in usable density when delivering H_2 at 30 bar vs. 15 bar

cH2 chilling provides a second approach to CcH2 dispensing and storage, mitigating the scarcity of LH2 infrastructure



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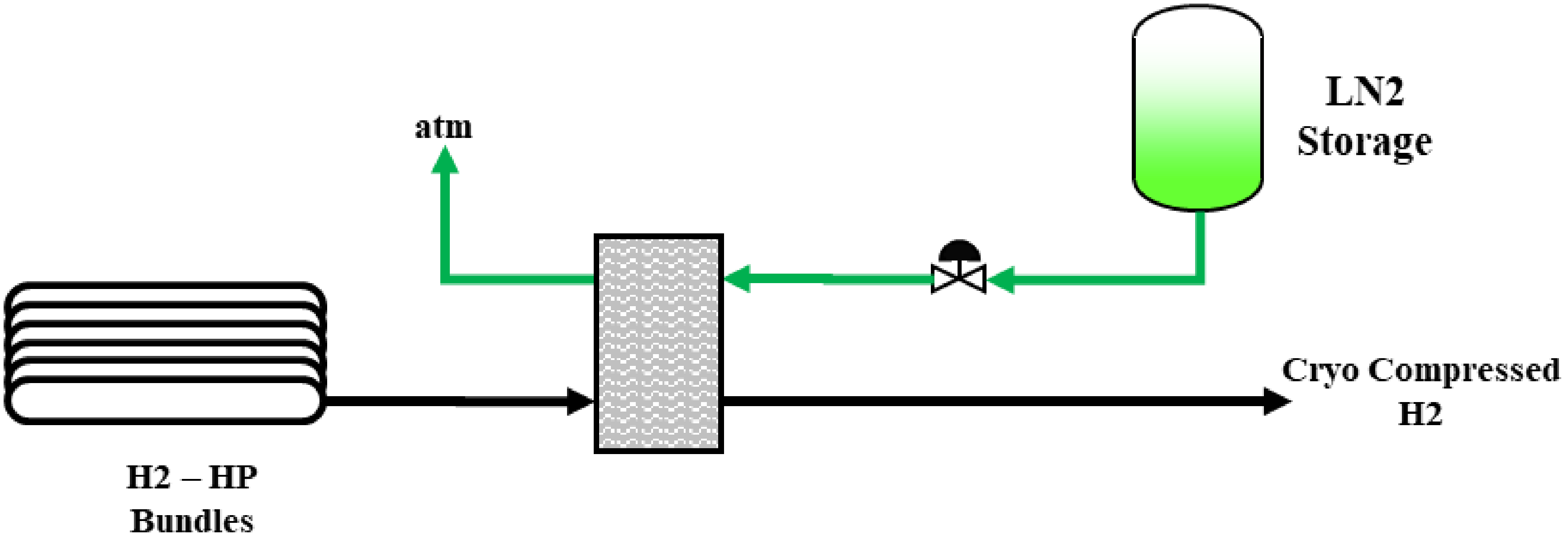
LN2 chilling, cascade, or mixed refrigerant systems may be used for densifying pressurized H2 to practical values



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Favorable thermodynamics gives CcH2 key advantages for truck propulsion

- ***Highest usable density:*** **68 g/L with fill density as high as 73 g/L and small residual fraction (5 g/L)**
- ***High delivery pressure:*** **30+ bar possible with relatively small (15%) impact on usable density**
- ***No vent losses anticipated during filling or operation:*** **insensitivity to heat transfer broadens design space, reducing cost and/or insulation thickness**
- **Delivery flexibility:** **LH2 and chilled cH2 are possible pathways; compatibility with cH2 extends usability**
- ***Compelling safety advantages:*** **vacuum jacket protects composite vessel; reduced H_2 expansion energy due to cold operation**

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