Inexpensive delivery of compressed hydrogen with advanced vessel technology

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May 25, 2005

Project ID #
PDP54

Overview

Timeline

- Project start date: **October 2004**
- Project end date: **September 2005**
- Percent complete: **20%**

Budget

- Total project funding
  - DOE share: **$100 k**
- Funding received in FY04: **new project**
- Funding for FY05: **$100 k**

Barriers

A. Lack of options analysis

F. Transport storage costs

Partners

- Participating in the **H2A** and in the **delivery tech team** meetings

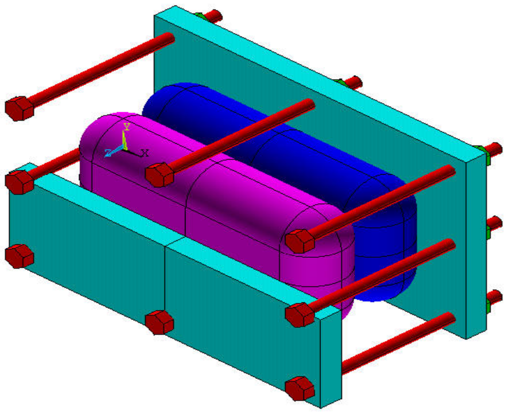
Objectives

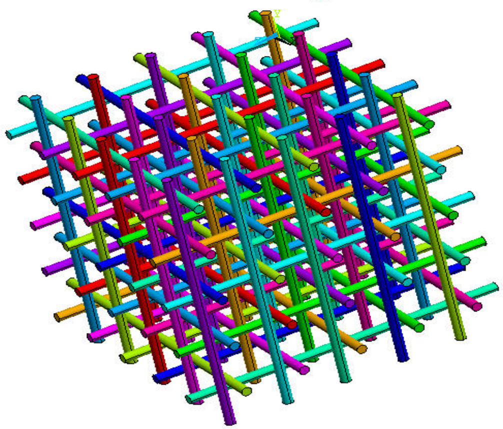
- Examine two approaches to reducing the cost of hydrogen delivery by truck and storage at refueling stations:
  - Low cost vessels
  - High capacity vessels (cryogenic or high pressure)
- This is necessary to achieve DOE targets for total hydrogen cost (<$1.50/kg) delivered to the user

Approach

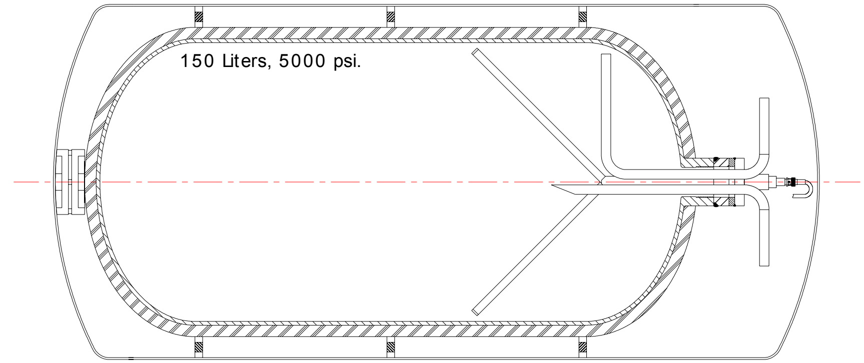
- Reduce the cost of hydrogen containment by mass production of modular components that can be assembled into hydrogen storage systems
- Increase the capacity of hydrogen storage systems through cooling and/or cryogenics
- We will focus on the thermodynamics and logistics of hydrogen storage and delivery to efficiently use capital and energy costs

Accomplishments: we have developed and tested innovative hydrogen storage technologies that can be efficiently applied to hydrogen delivery

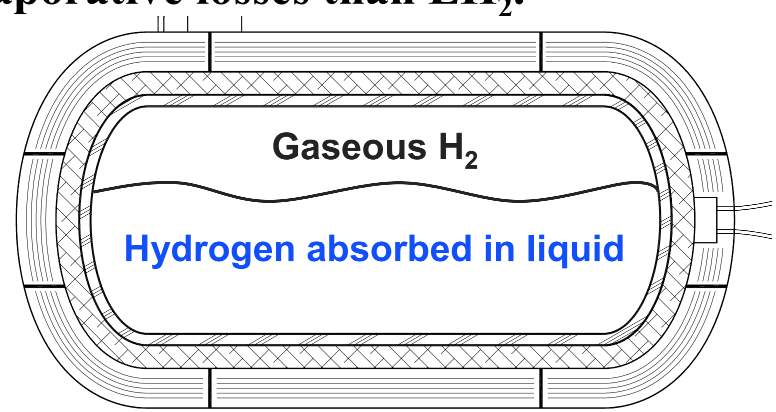




Conformable pressure vessels efficiently use available space in the vehicle, increasing truck hydrogen delivery capacity

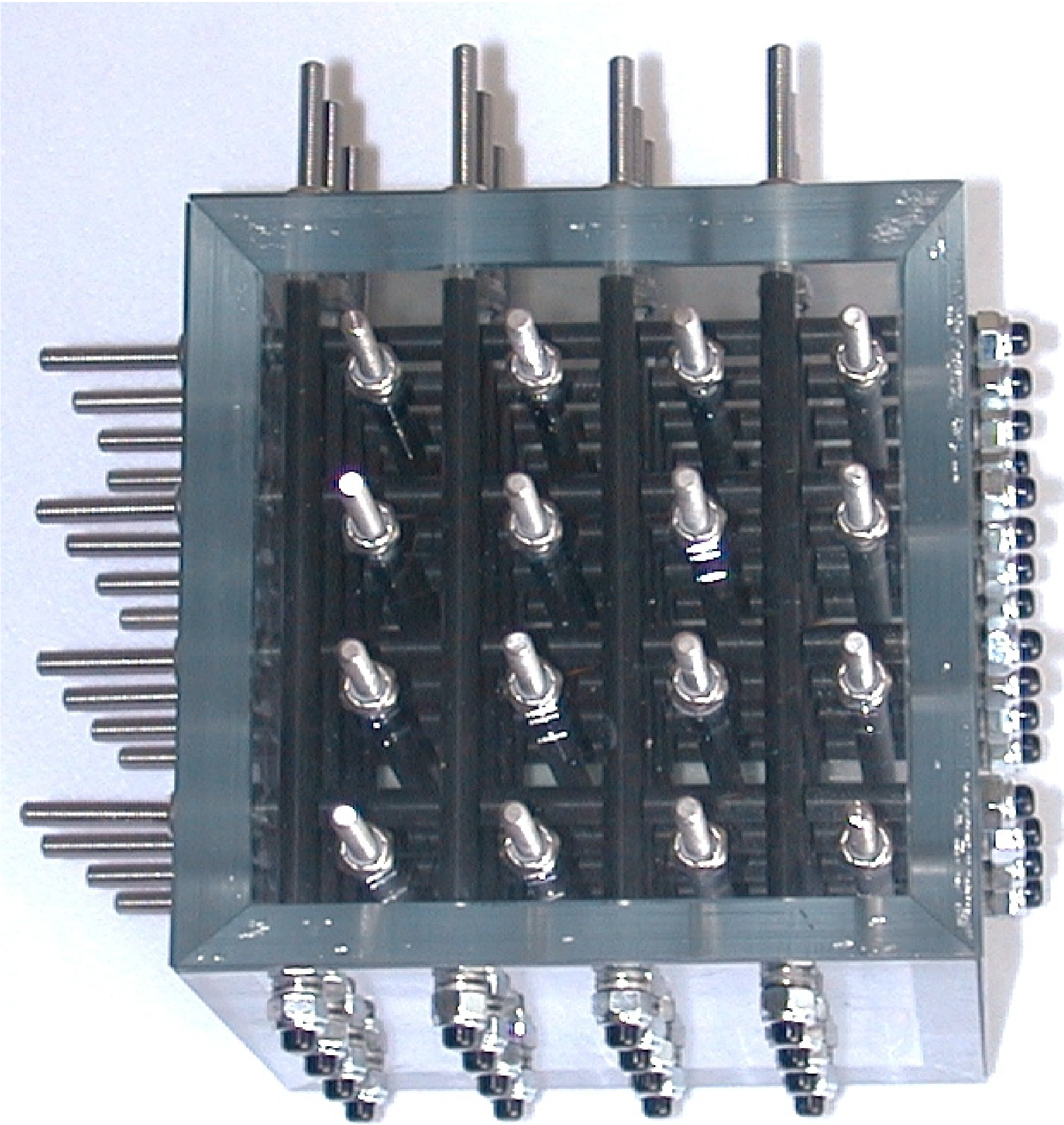


Cryo-compressed hydrogen (~80 K, ~5000 psi) requires considerably less storage energy (~18% of LHV) than LH_2 (~35% of LHV), has high density (~63 kg/m^3), and considerably lower evaporative losses than LH_2.



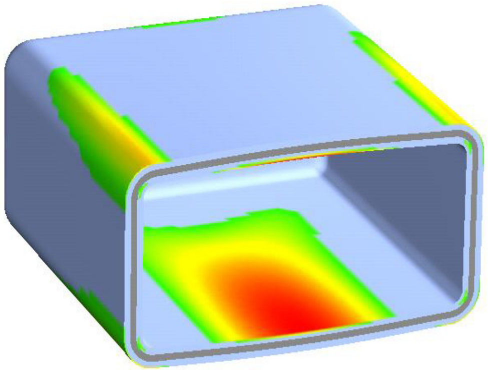
Hydrogen absorbed in liquid nitrogen is safe, easy to dispense, light and compact

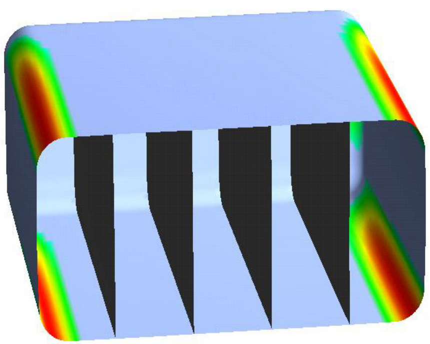
We have developed a new replicant-based conformable container that will be pressure tested this year to demonstrate the validity of the concept

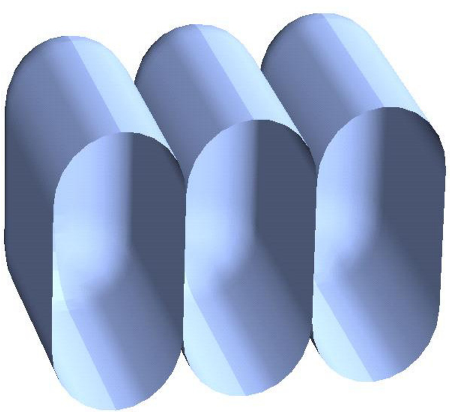


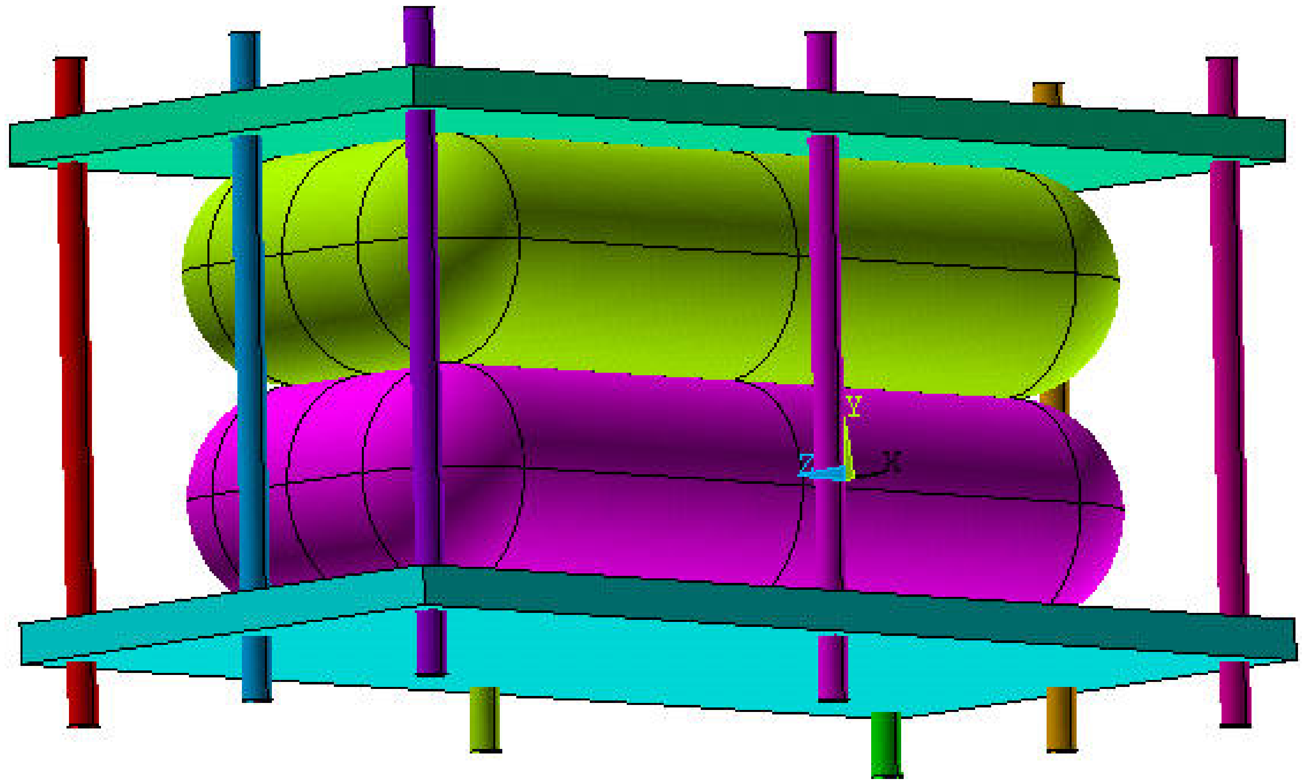
- **Design and construction completed**
- **Vessel has high volumetric efficiency (projected 84%)**
- **Extensively analyzed by finite element**
- **Improves volume utilization, increasing capacity of delivery trucks**

We have determined an optimum design for continuous fiber conformable containers and we are moving toward experimental testing of small scale components



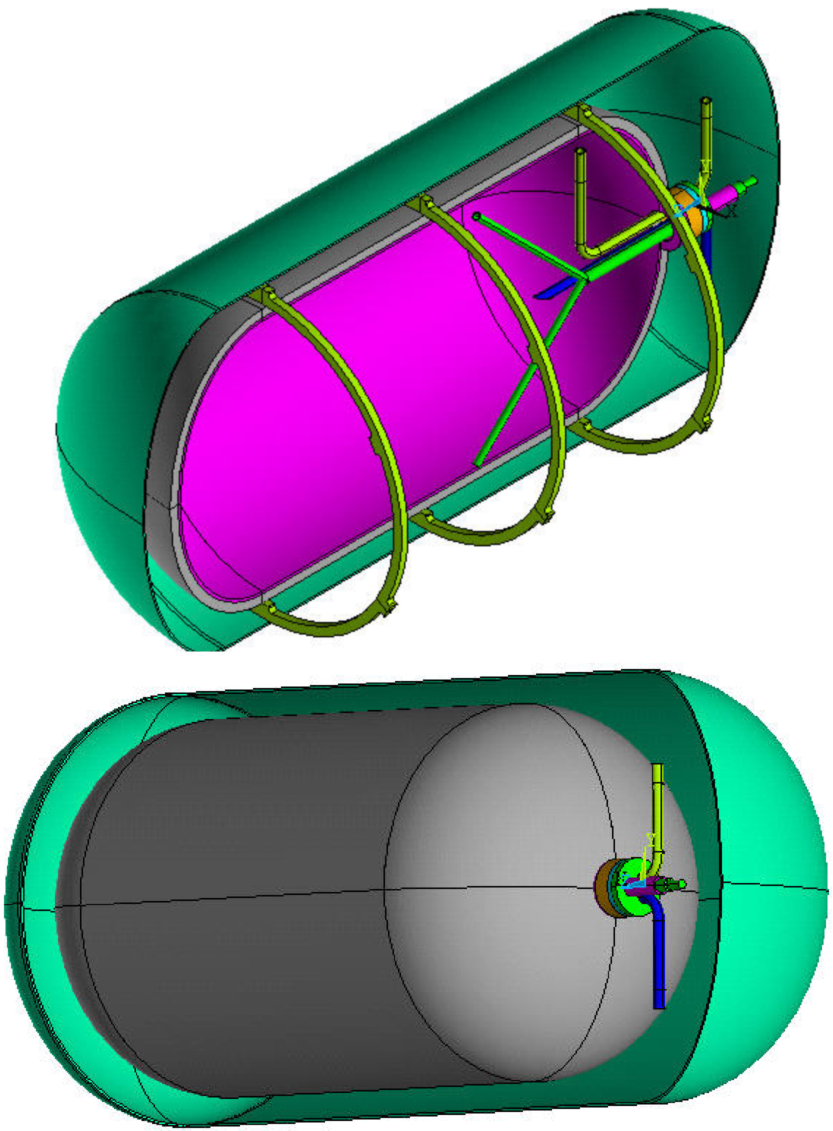






- **Conducted extensive finite element analysis and selected optimum geometry**
- **In the process of building small scale vessels (10 cm long) for component testing**
- **Steel plates simulate series of segments**
- **To be tested in high pressure lab**

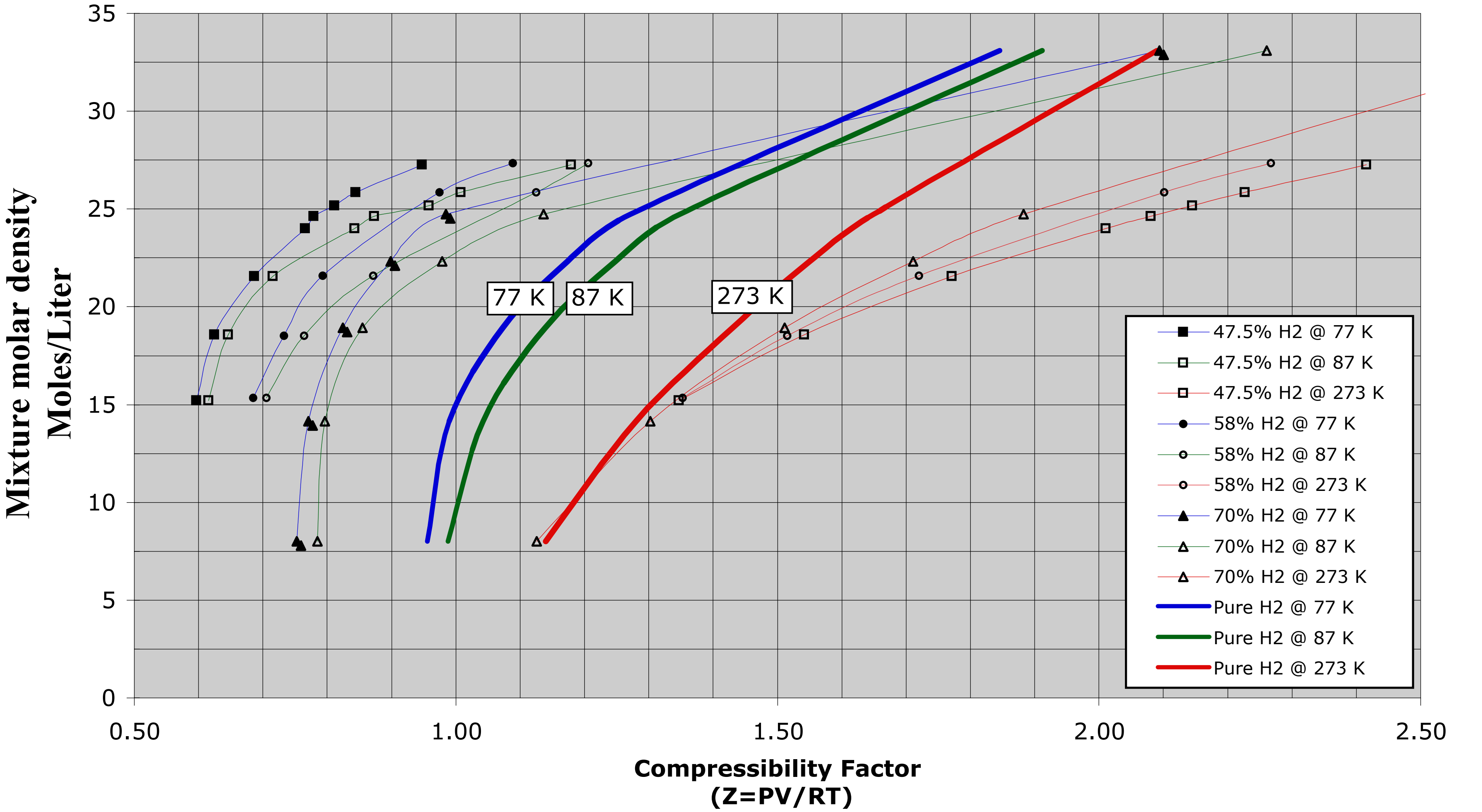
Our insulated pressure vessels have demonstrated compatibility for operation with cryo-compressed hydrogen



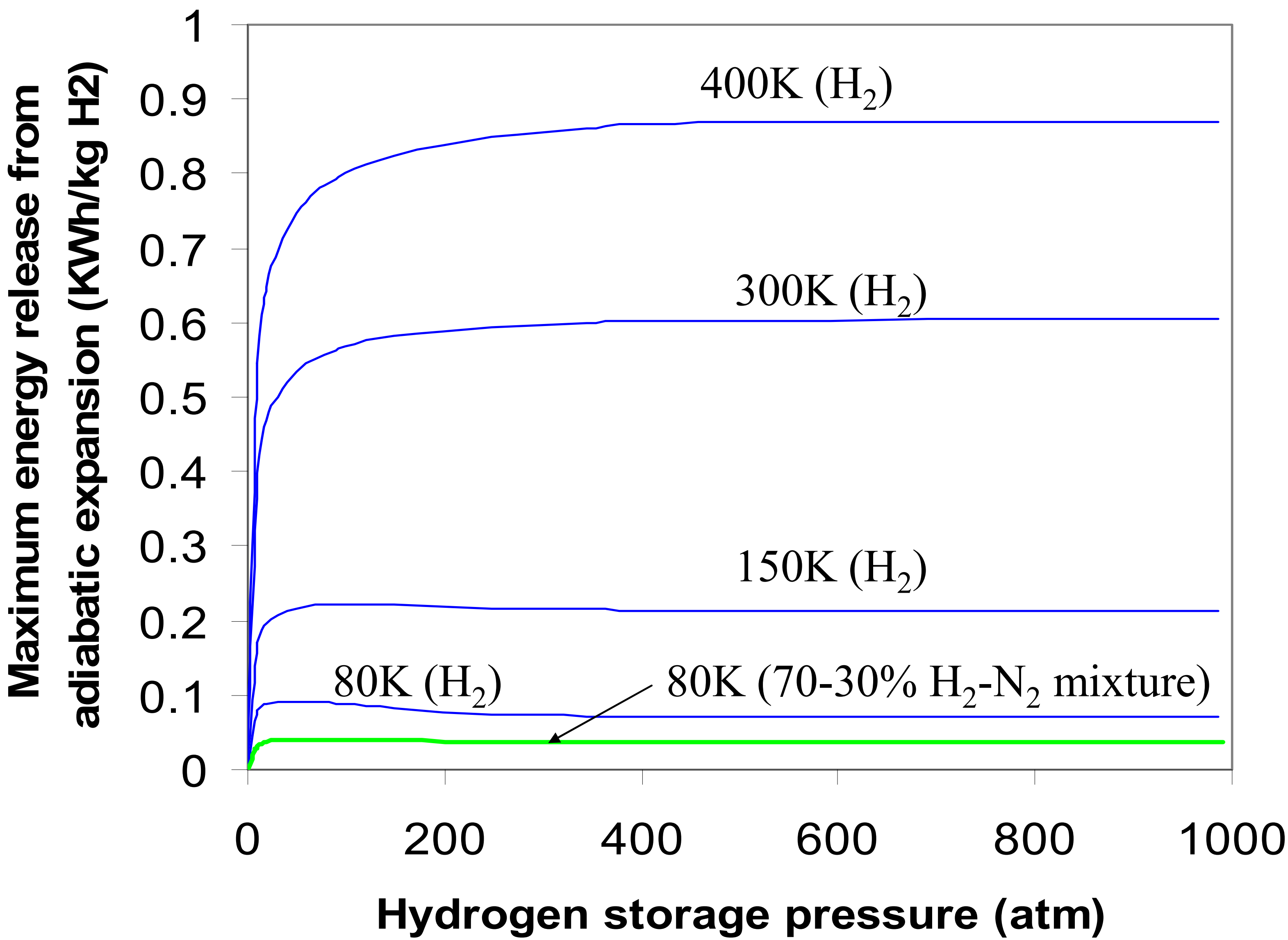
- **Inexpensive: regular ambient temperature pressure vessels can operate at cryogenic temperature**
- **Considerably less energy for hydrogen storage than LH_2 (16% vs. 34% of LHV)**
- **Considerably lower evaporative losses than a LH_2 tank**
- **Successfully conducted proof of concept experiment in SunLine pickup truck (funded by SCAQMD)**
- **Wrote set of certification standards for cryo-compressed vessels**

We have characterized hydrogen absorption in liquid nitrogen with anticipated refuelability and safety advantages

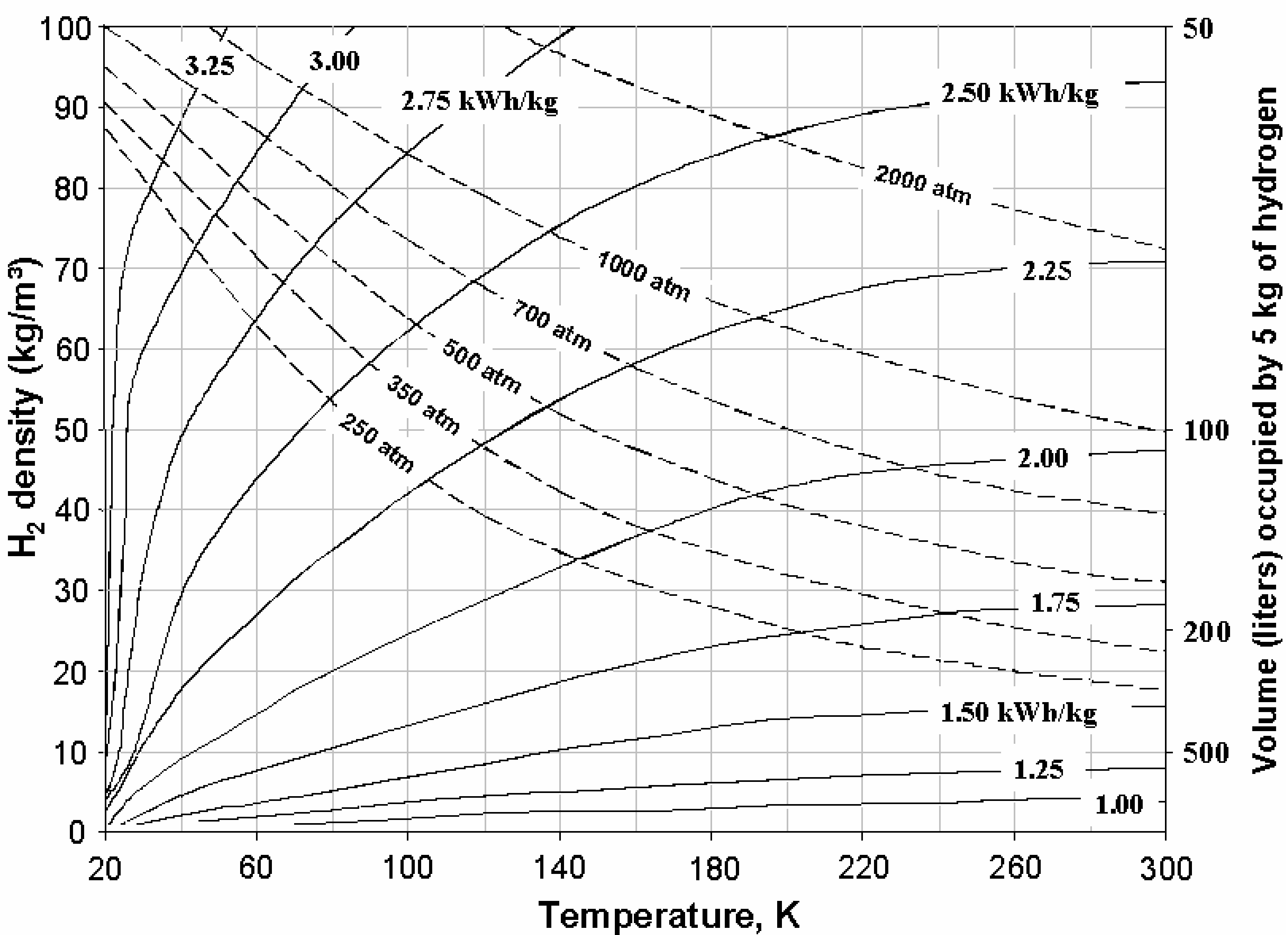
Our results indicate favorable absorption of H_2 into LN_2



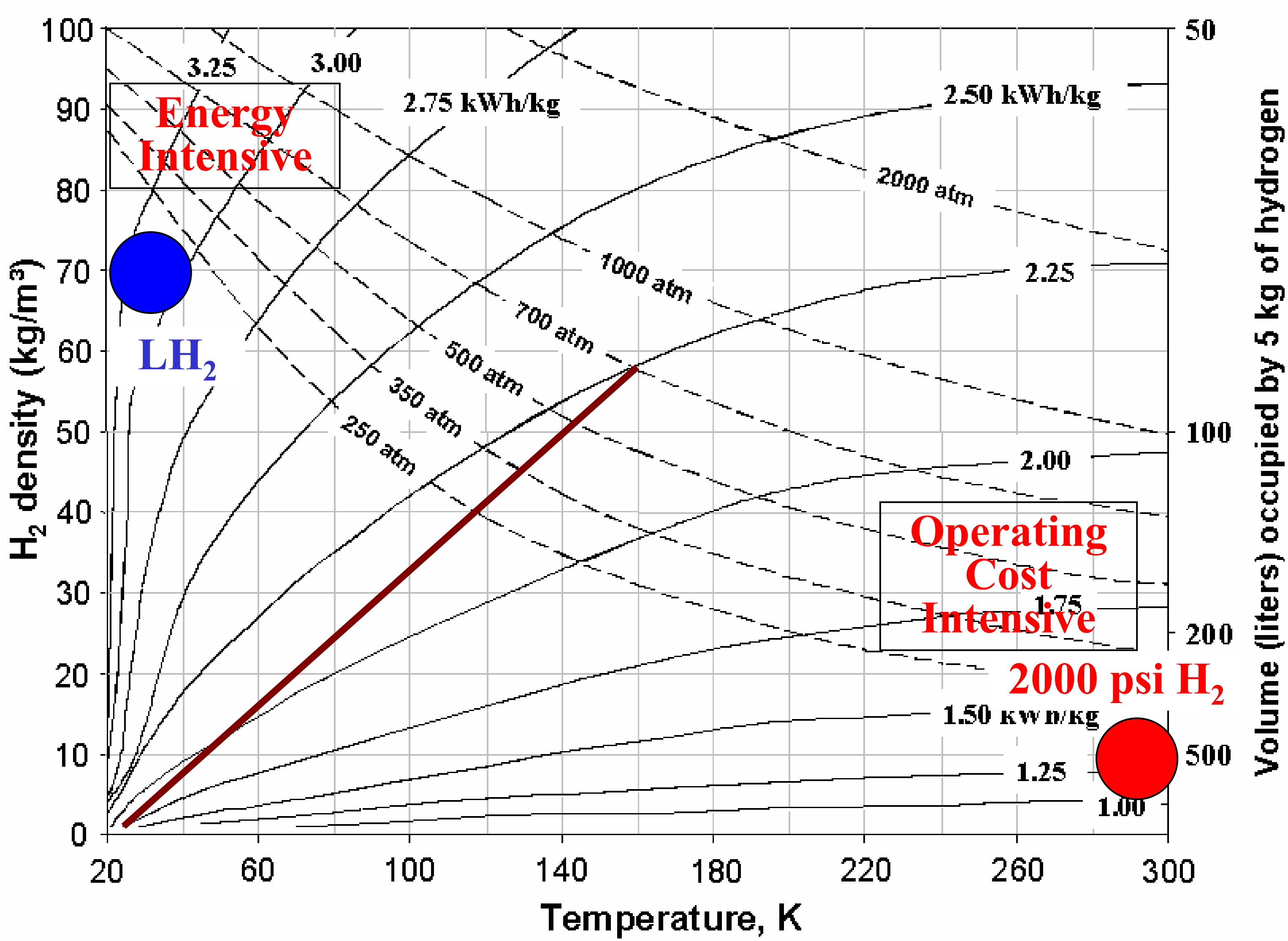
Cooling hydrogen makes it safer: energy release during a sudden failure is a weak function of pressure but a strong function of temperature



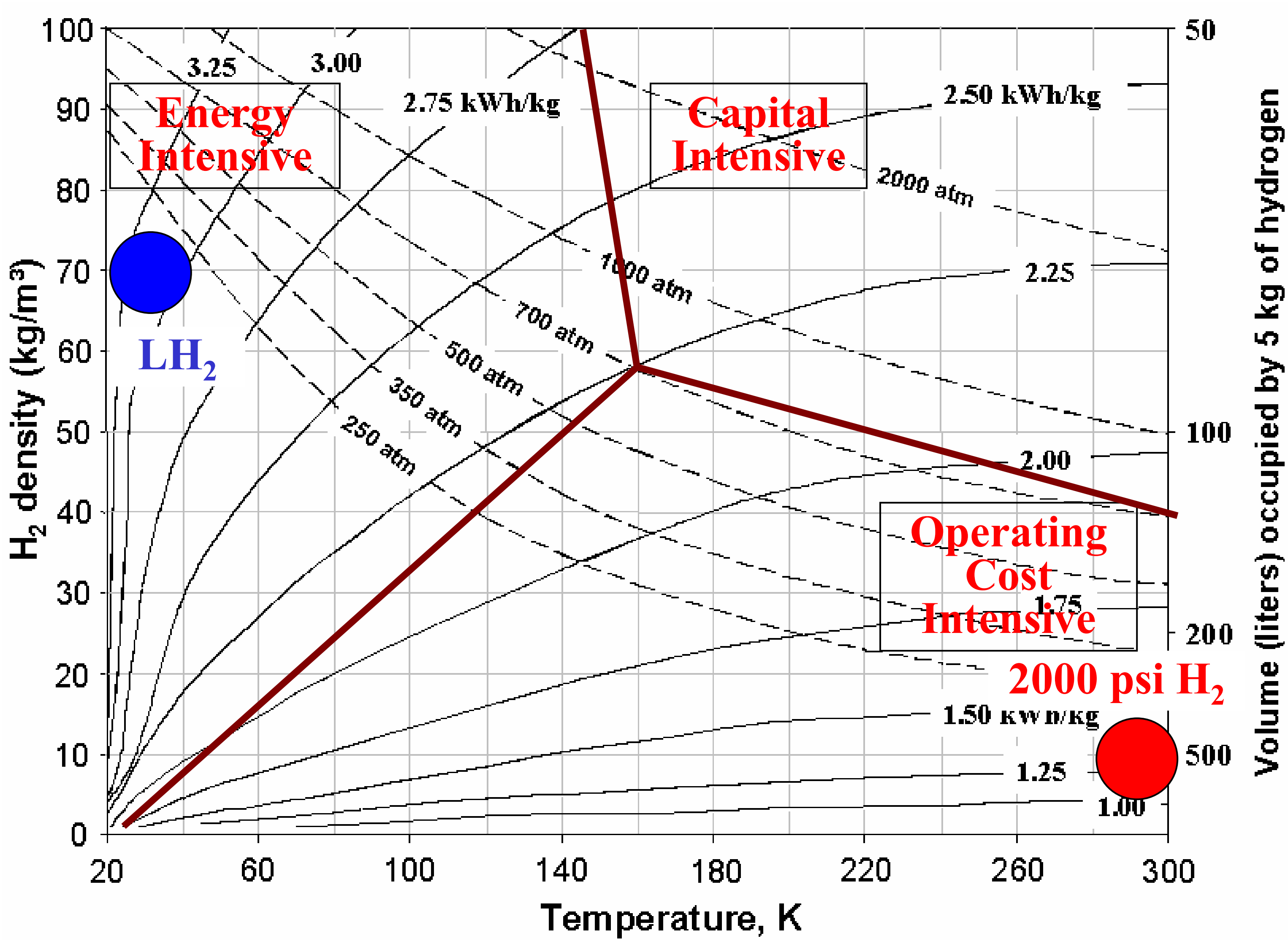
The PVT properties of H_2 drive the costs of storage and delivery (capital, energy, and transport)



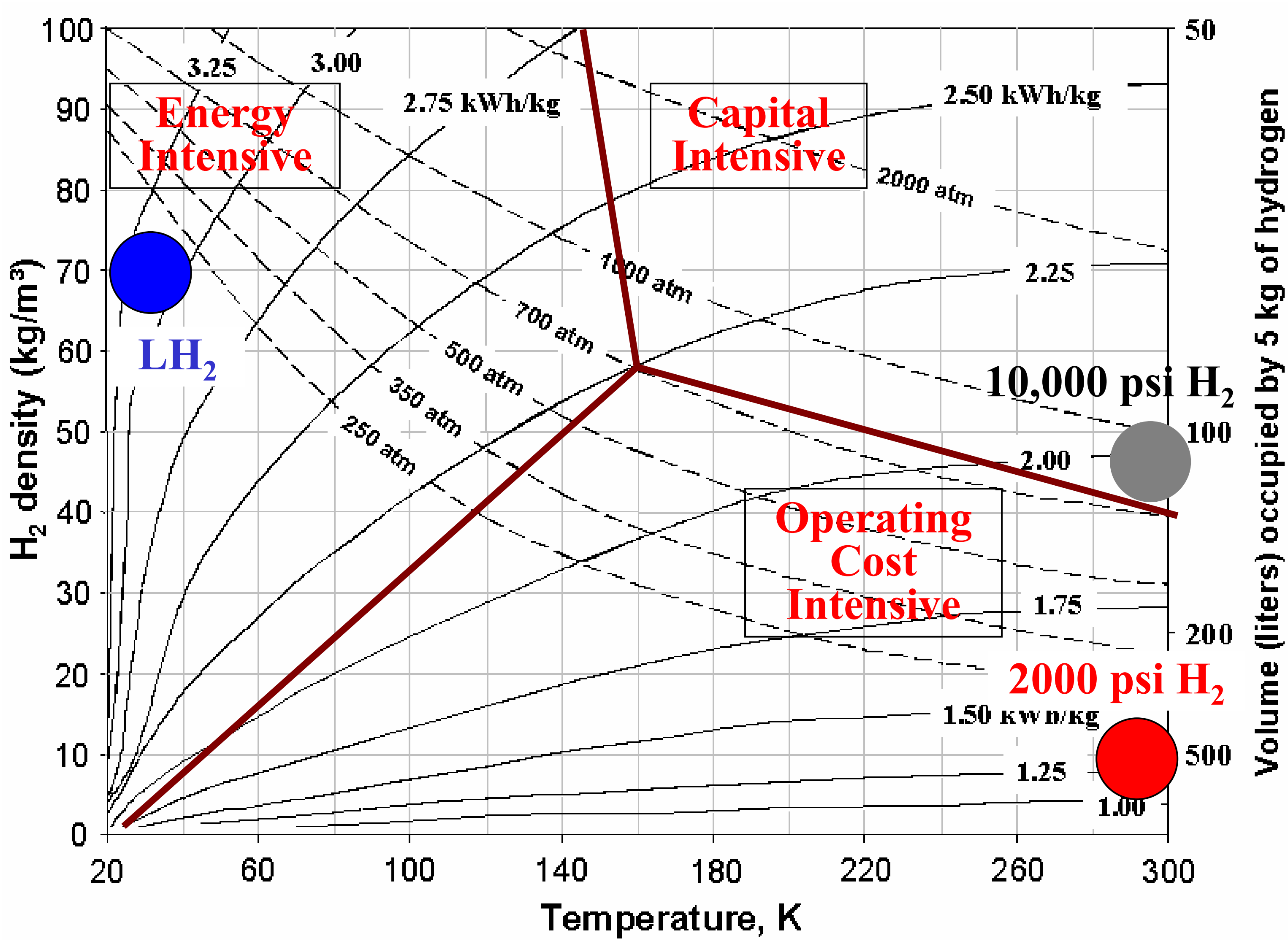
Current commercial hydrogen delivery approaches occupy extreme delivery strategy spaces



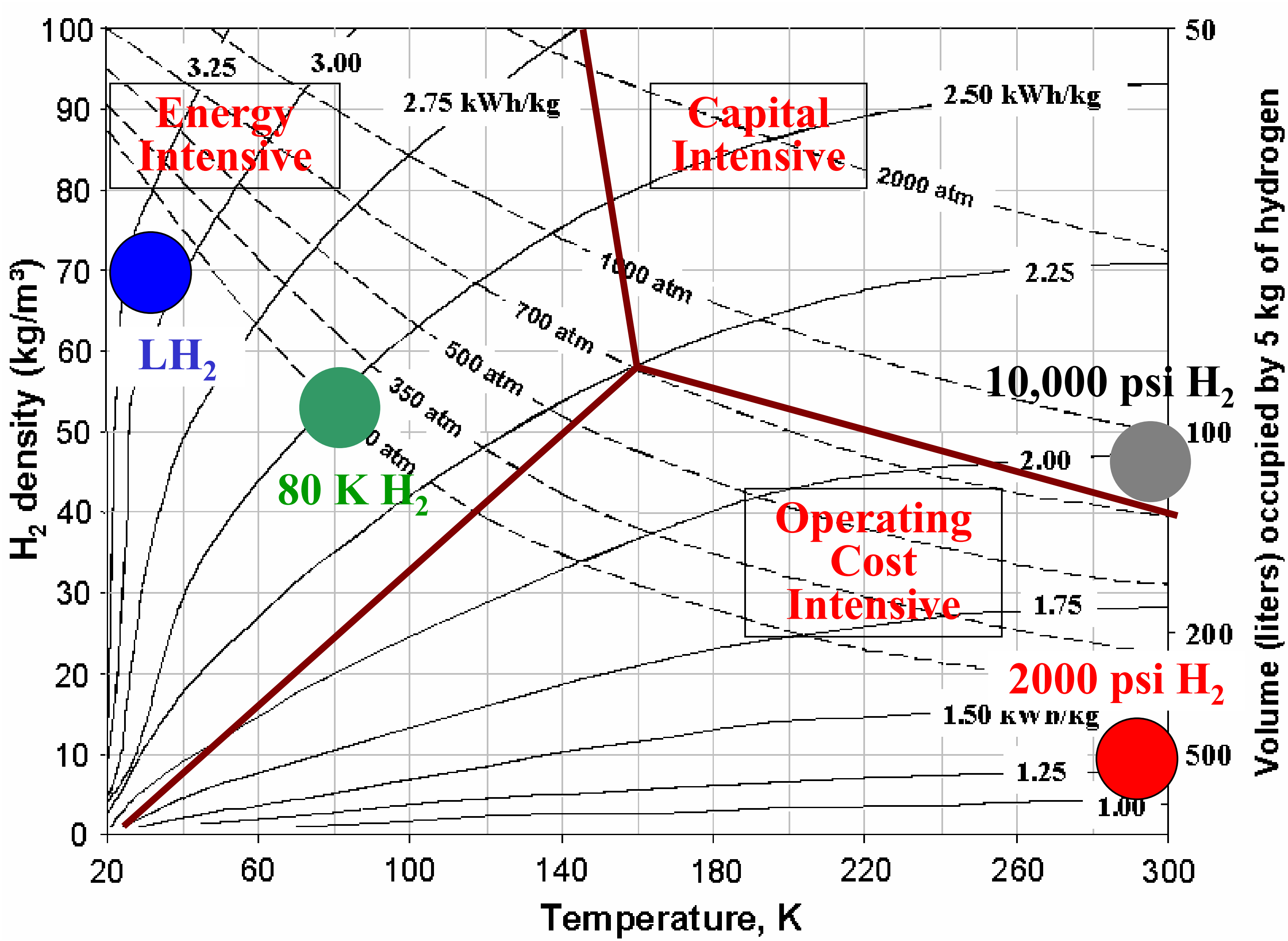
In principle, capital investment could reduce energy and operating costs



High pressure tube trailers maximize storage density for minimum energy, but for higher capital investment



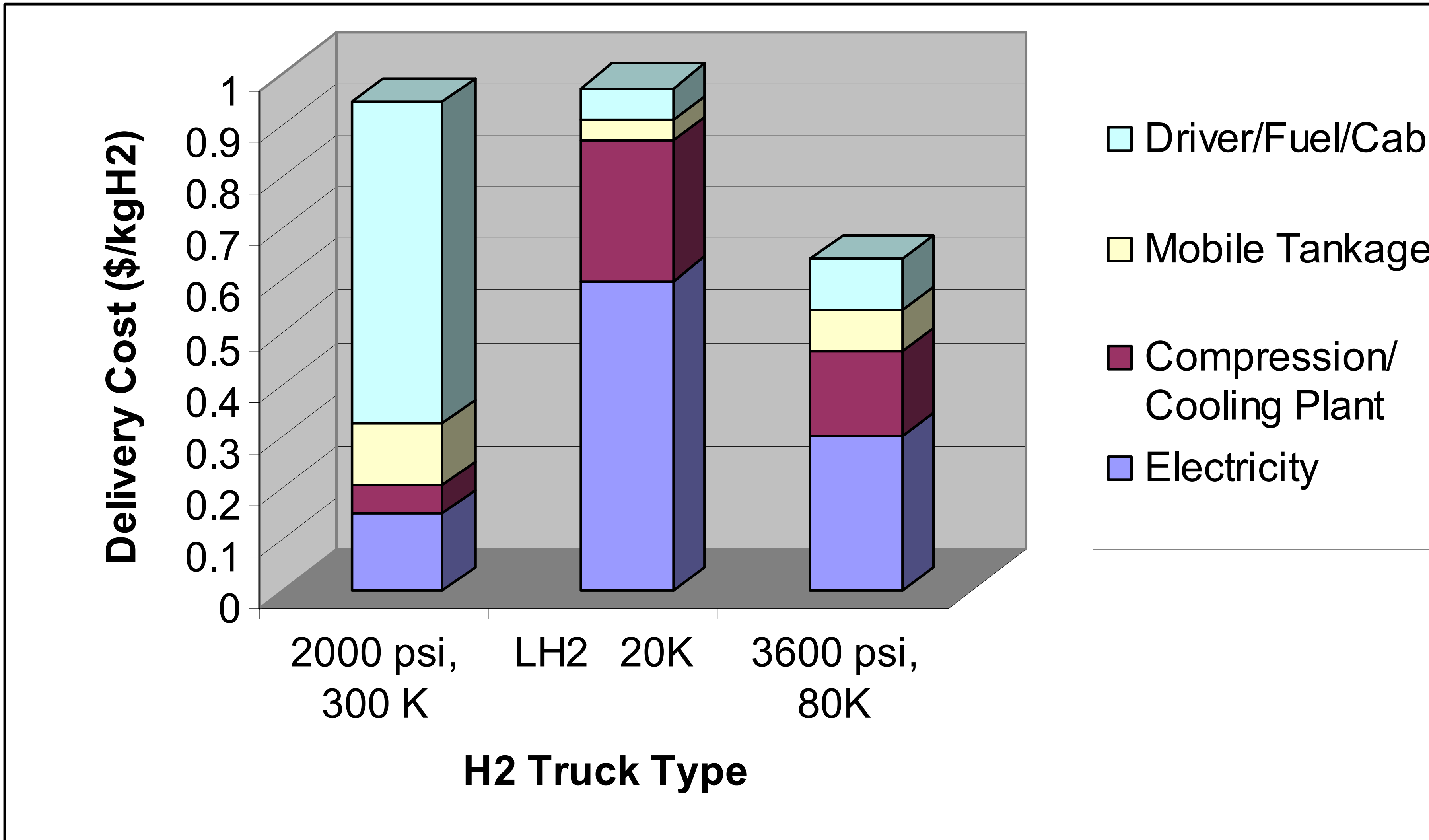
Would cryogenic compressed hydrogen better balance capital and energy costs?



"Back of the envelope" thought experiment delivery cost assumptions Calculations to be repeated with H2A data

- Delivery distance 100 miles (200 mile round trip)
  - Average speed 50 mph
  - \$1.50/kg H_2 @ 6 mpg equivalent
  - \$50/hour for driver and cab
- Hydrogen delivery technologies
  - 2000 psi tube trailer at \$120k (400 kg H_2 @ \$300/kg H_2)
  - Liquid hydrogen at \$400k (4000 kg LH_2 @ \$100/kg H_2)
  - 3600 psi cryo vessel at \$500k (2500 kg H_2 @ \$200/kg H_2)
- Hydrogen compression/liquefaction costs (\$0.05/kWh_e)
  - 2000 psi H_2 at 3 kWh_e/kg and \$100/kW H_2
  - LH_2 at 12 kWh_e/kg and \$500/kW H_2
  - Cryo compressed at 6 kWh_e/kg and \$300/kW H_2

Cryogenic H_2 trucks could reduce 100 mi delivery costs by saving per mile transport costs and energy



Responses to reviewers' comments: This is a new project, but has been presented to the delivery tech team and the H2A analysis group

- *Use H2A code to determine cost and performance parameters for system evaluation:* **we have obtained the H2A code and will use their values in our pressure vessel evaluation**

Future work (FY05-06)
Proposed analysis scope would include
H_2 thermodynamics, logistics, and engineering

- **Consider the full phase diagram**
  - **Pressure ranges (2000-10,000 psi)**
  - **Temperature ranges (77-300 K)**
  - **Exergetics of compression and/or cooling**
  - **Cost of the trucks that can deliver H_2 at desired conditions**
- **Analyze on-site implications**
  - **Drop-off trailers vs H_2 delivery *per se*.**
  - **Necessity of on-site compression**
  - **Cryogenic dormancy requirements**

Supplemental slides

Publications and presentations

Patents

- **Lightweight Cryogenic-Compatible Pressure Vessels for Vehicular Fuel Storage,** Salvador M. Aceves, Gene Berry, Andrew H. Weisberg, US Patent 6,708,502 B1, March 23, 2004. World Patent WO 2004/029503 A2, April 8 2004.
- **Storage of H2 by Absorption and/or Mixture within a Fluid,** Gene Berry and Salvador Aceves, World Patent WO 2005/015076 A1, February 24, 2005.

Publications in Books and Technical Journals

- **Hydrogen Storage and Transportation,** Gene Berry, Joel Martinez-Frias, Francisco Espinoza-Loza, Salvador Aceves, Invited chapter, Encyclopedia of Energy, Volume 3, pp. 267-281, Elsevier Academic Press, New York, 2004.
- **Hydrogen Production,** Gene Berry, Invited chapter, Encyclopedia of Energy, Volume 3, pp. 282-294, Elsevier Academic Press, New York, 2004.
- **The Case for Hydrogen in a Carbon Constrained World,** Gene D. Berry and Salvador M. Aceves, Invited discussion paper, ASME Journal of Energy Resources Technology, 2005.
- **Vehicular Storage of Hydrogen in Insulated Pressure Vessels,** Salvador M. Aceves, Gene D. Berry, Joel Martinez-Frias, Francisco Espinosa-Loza, Submitted to the International Journal of Hydrogen Energy, 2005.
- **Cryogenic Hydrogen Storage**, Gene Berry and Salvador Aceves, Invited paper for "Materials for the Hydrogen Economy," CRC Press, 2005.
- **Liner Materials for Composite Tanks**, Andrew Weisberg, Invited paper for "Materials for the Hydrogen Economy," CRC Press, 2005.

Publication in Refereed Proceedings

- **Development and Demonstration of Insulated Pressure Vessels for Vehicular Hydrogen Storage,** Salvador M. Aceves, Gene D. Berry, Proceedings of the 15th World Hydrogen Energy Conference, Yokohama, Japan, June 27-July 2, 2004.

Technical Report

- **Hydrogen Absorption in Fluids: An Unexplored Solution for Onboard Hydrogen Storage,** Gene D. Berry, Lawrence Livermore National Laboratory Report UCRL-TR-209650, Livermore, CA, February 2005.

Presentations

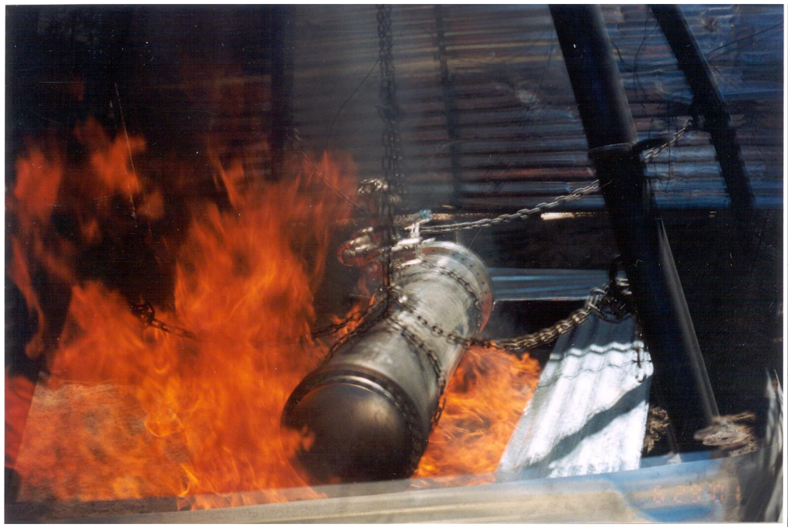
- **Advanced Hydrogen Containers,** Andrew Weisberg, Invited presentation, American Physical Society, March 2005.
- **Cryogenic Hydrogen Storage**, Salvador Aceves, Invited Presentation, Materials for the Hydrogen Economy, September 2005

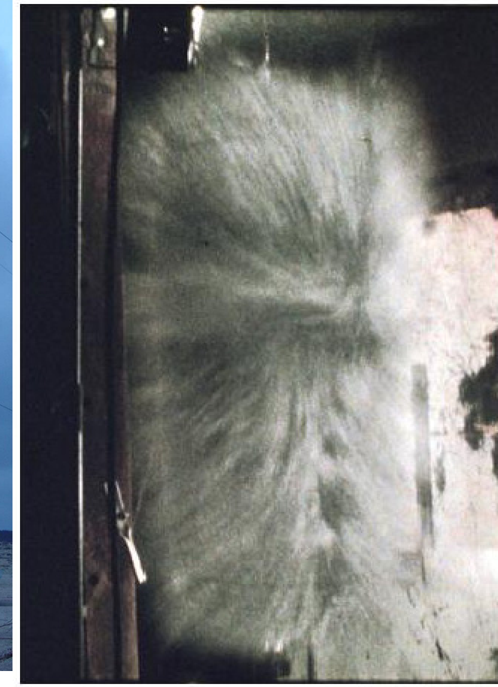
Hydrogen safety

The most significant hydrogen hazard associated with this project is:

- **Hydrogen containers may fail, liberating considerable energy in a short time and possibly causing personnel and property damage**
- **Energy liberated in a sudden expansion is a strong function of temperature and a weak function of pressure beyond the first ~50 bar**
- **Cryogenic hydrogen is safest**
- **Hydrogen absorbed in nitrogen is dilute and therefore reduces flammability and detonation ranges**

Hydrogen safety:
our approach to deal with this hazard is:





- **container testing and certification**
  - ♦ **ISO certification for pressurized containers**
  - ♦ **SAE LNG tests for cryogenic containers**
  - ♦ **Developed a set of standards for cryo-compressed H_2**
- **Innovative approaches to container safety (e.g. turn to dust failure)**