Inexpensive delivery of compressed hydrogen with ambient temperature or cryogenic compatible vessels

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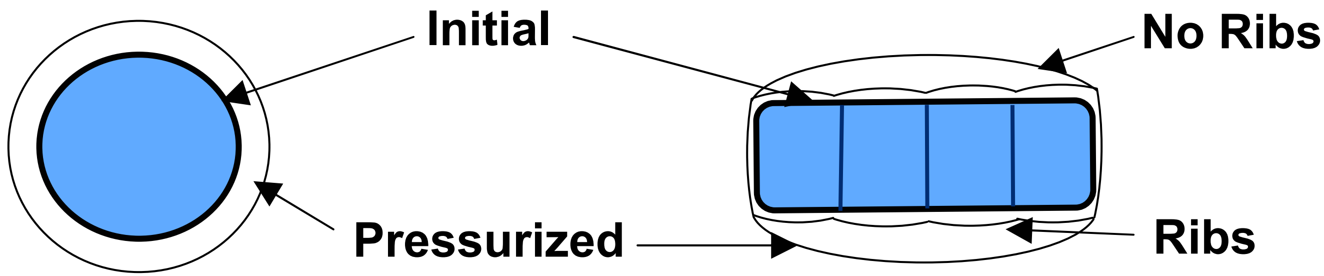
Outline

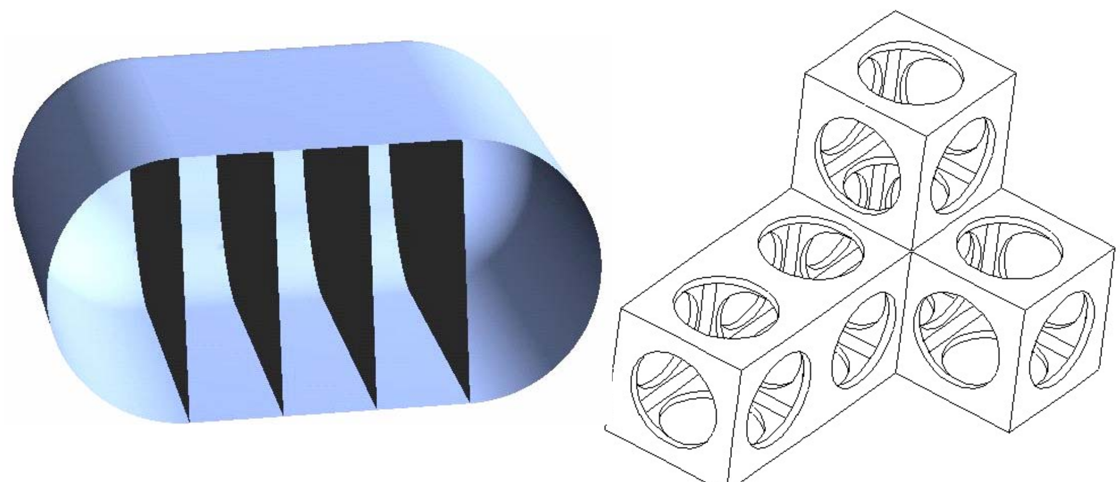
- Pressure vessel research at LLNL
  - Conformable (continuous fiber and replicants)
  - Cryo-compressed
- Overview of delivery options
- The thermodynamics of compressed and cryo-compressed hydrogen storage
- Proposed analysis activities
- Conclusions

We are investigating two techniques for reduced bending stress: continuous fiber vessels and vessels made of replicants



Spherical and cylindrical tanks naturally resist "bending" without internal stiffeners

Conformable tanks require internal stiffeners (ribs) to efficiently support the pressure and minimize bending stresses



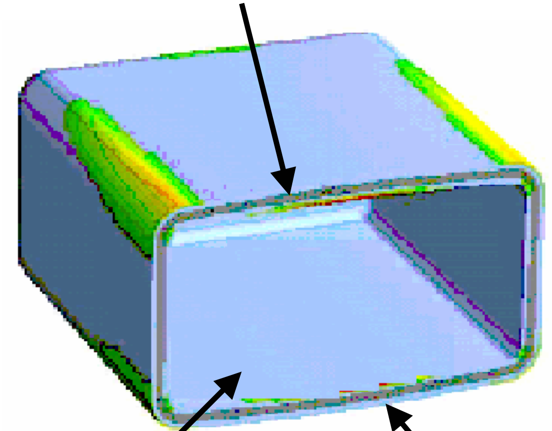
Continuous fiber vessels have to be designed to reduce the bending moments

Vessels made of replicants rely on mass-produced parts joined together

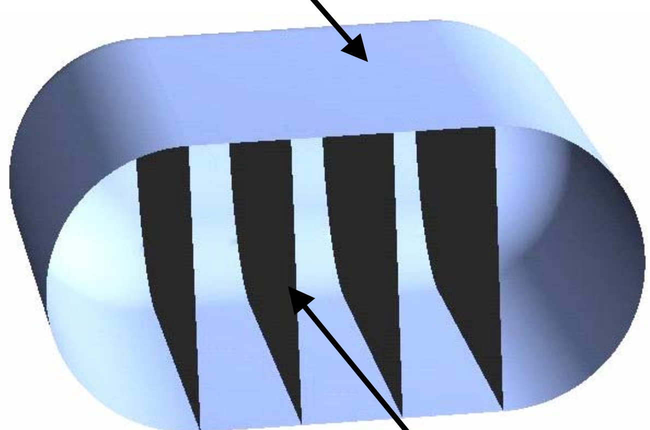
Metaphor = architecture
not many domes or arches compared to 'endoskeletal' structures built routinely by assembling multi-use parts

We have analyzed three possible designs for continuous fiber conformable pressure vessels

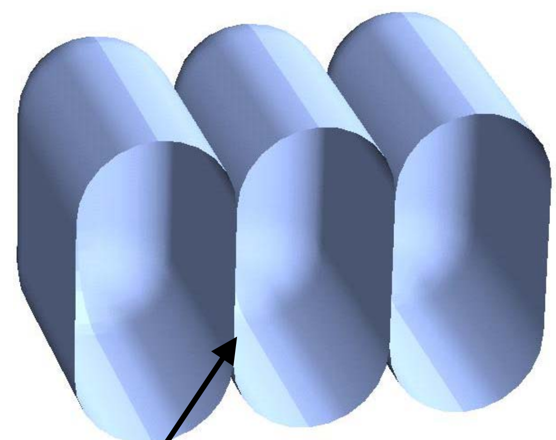
"Sandwich" construction:
Two layers of composite separated by a foam material that transmits shear stresses between the composite layers



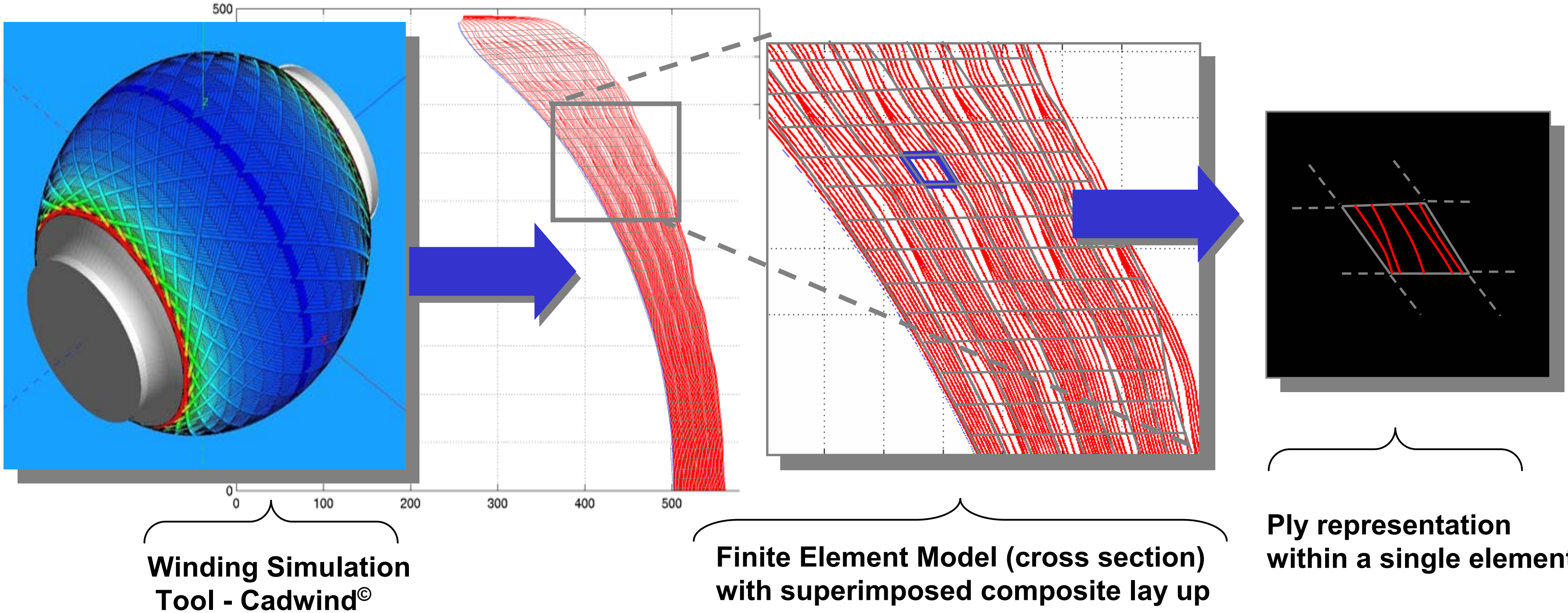
Ribbed construction:
Ribs hold the tank together and reduce bending stresses on the composite



"bucking" construction:
uses advantageous geometry in combination with "force cancellation" to control bending

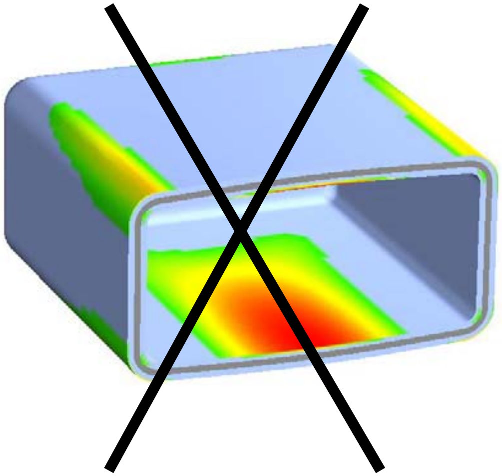


We have the computational tools necessary for conducting high fidelity analysis of composites



Current LLNL computational tools analyze the mechanical response of each composite ply

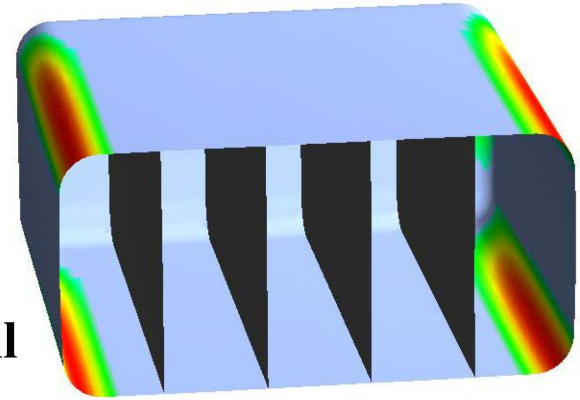
We have used FEA to evaluate and downselect conceptual designs for continuous fiber conformable vessels

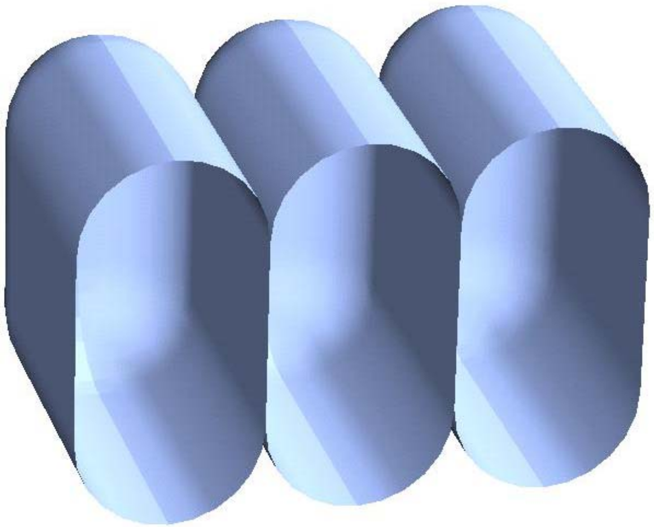


Sandwich structure does not offer clear advantages

Ribs control deflection of flat faces, considerably reducing stresses.

Outstanding issue is how to attach ribs to outer shell

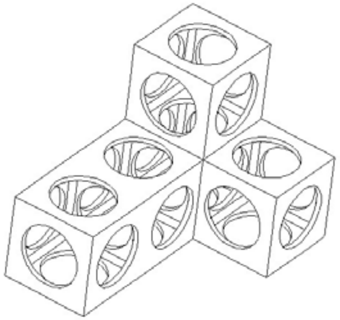


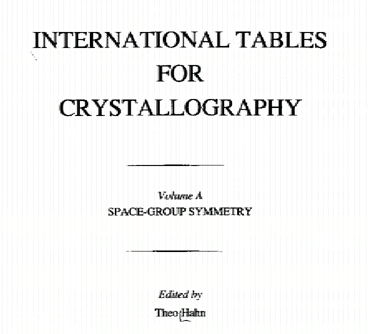


“Bucking” system is very successful in reducing bending stresses, resulting in a very homogeneous stress distribution

Pressure vessels made of replicants allow much flexibility in overall pressure vessel shape

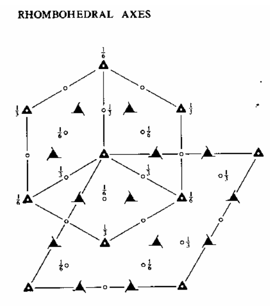
- Reject possibility of customized components (e.g. Space Shuttle tiles)
- Design for mass production and re-use of tooling across applications
  - Process engineering -> parts, common CAD/CAM tooling -> applications
  - Specializing for one application undermines statistical advantages
- Relax the assumption of replicated unit cells (made in FY02)
  - Costly to transfer tensile loads across cuts in fiber, so join ‘cells’
  - Struts can cross multiple cells, made only in a small list of exact lengths
    - Or joined in log-n vocabulary of cell length multiples to minimize vocabulary size
- Select among lattice classes for crash safety
  - Strength is not a noun, its a 3-tensor!
  - No valid reason to be too strong in shear
    - Good tanks can easily be stronger than their vehicle
    - Only need strength in 3 of 9 tensor elements to withstand internal Pressure loads



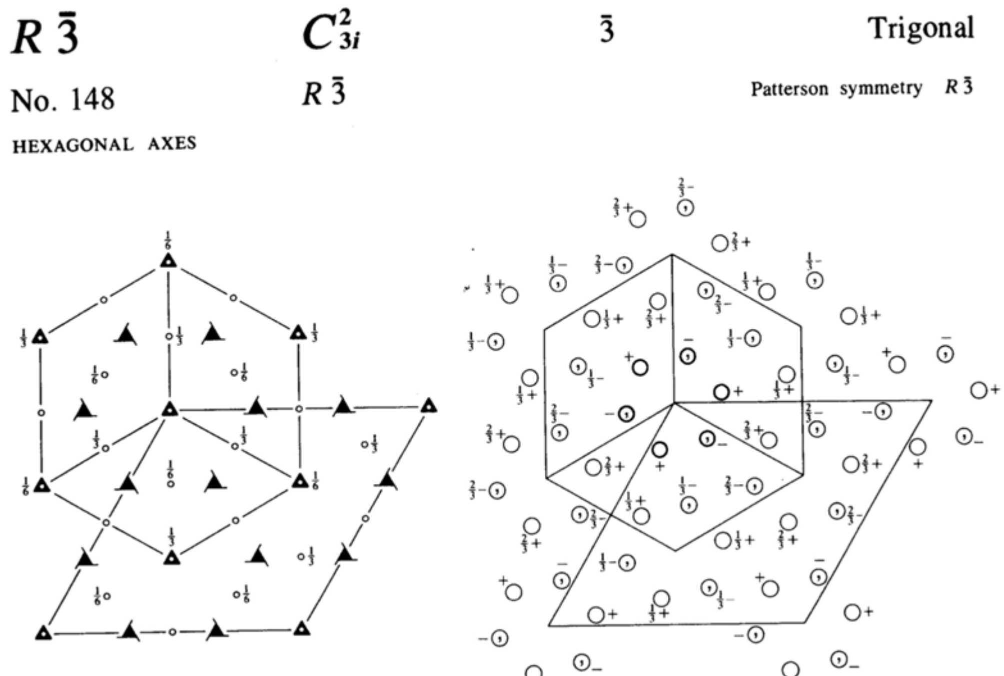

INTERNATIONAL TABLES
FOR
CRYSTALLOGRAPHY

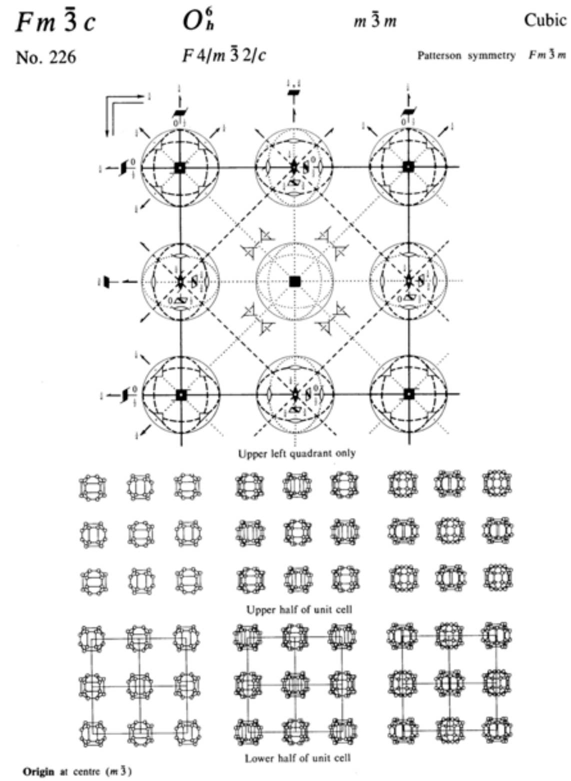
Volume A
SPACE-GROUP SYMMETRY

Edited by
Theo Hahn



Crystallography Provides Exhaustive Enumeration Describing All Possible Symmetric Macrolattice Cores

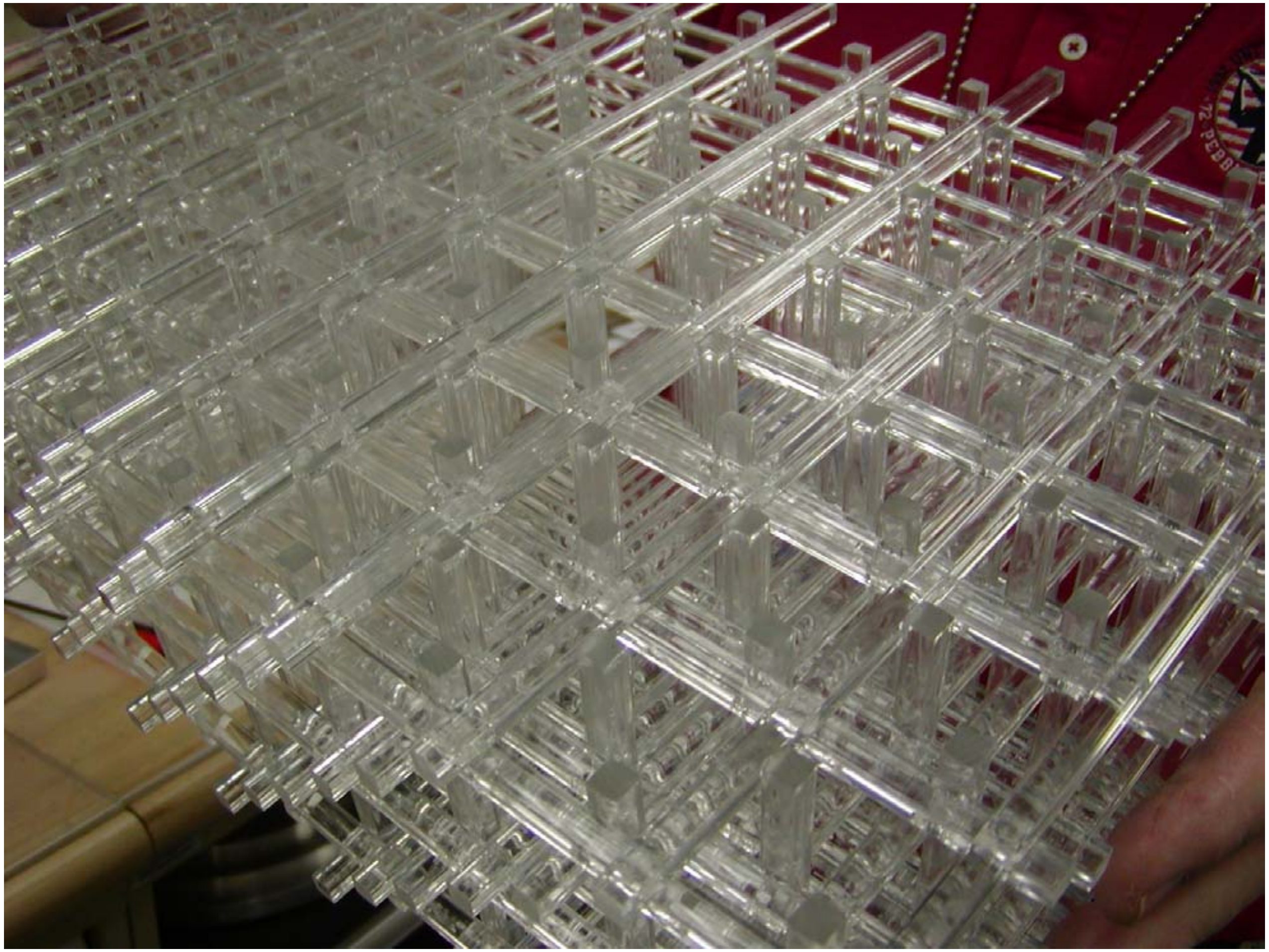




Space groups exhaust all possibilities for

- Packing 3D space with identical, symmetric unit cells
- Identifying which of the 230 Space Groups corresponds to a symmetric structure can be performed by locating axes of rotational and mirror symmetry, projected onto the mid-plane of the unit cell using these elegant diagrams (from Hahn '94 tables)

Model of ‘Most-Manufacturable’ ‘Cubic’ Macrolattice Core
Acrylic Mimics Struts Replicated to Fill 3Λ x 5Λ x 7Λ



Appears cubic

Actually C3i

- Reduced Symmetry
- Struts pass each other, avoid any nodes

Only 2 struts pass close to one another at any point (not 3)

- Weak glue bonds
- ‘Stitched’ together by robot bonder
- Bond corridors

Model has correct volume fraction for best composite structure

- Area ratio 1/18 on each axis (or 1/6th struts by volume) designed for 22,000 psi burst with uniaxial struts that fail at 400,000 psia

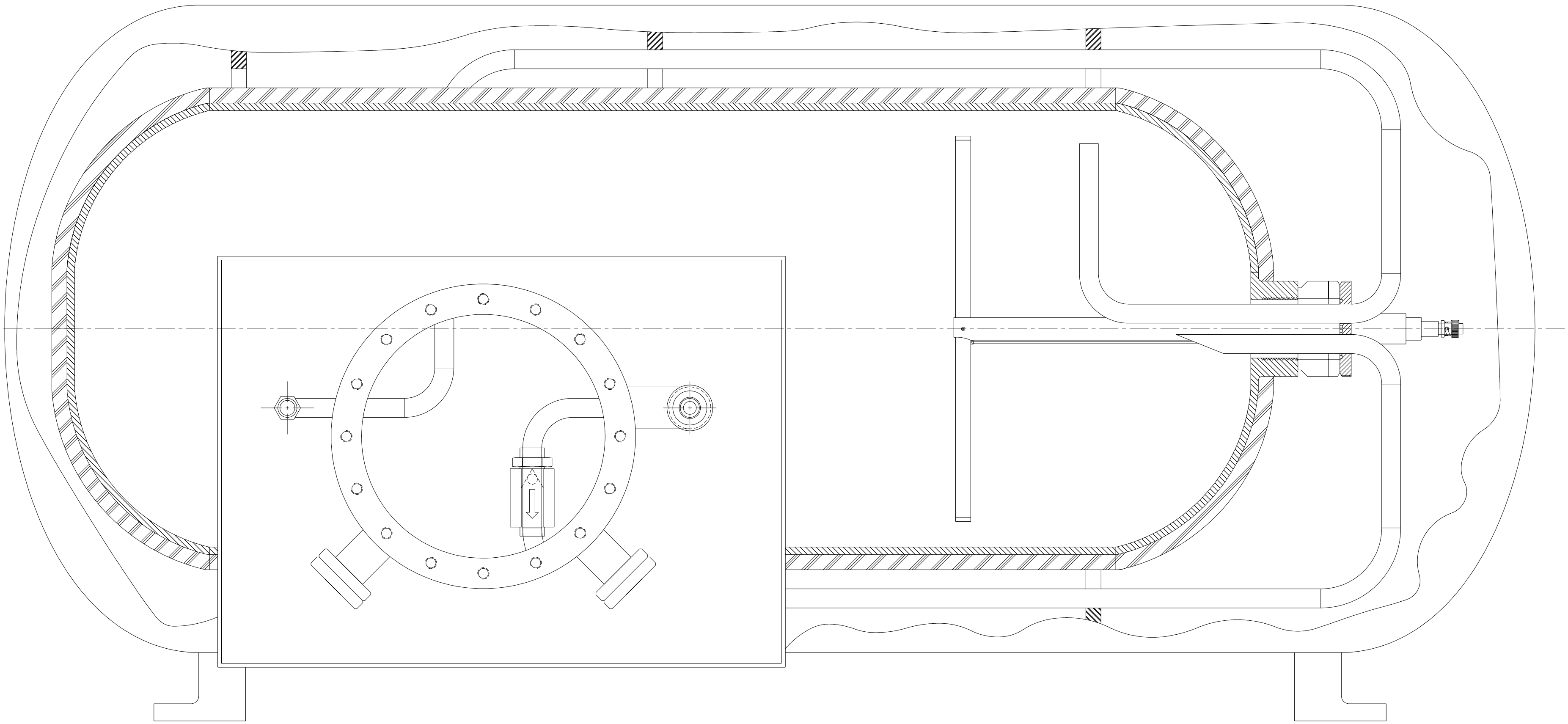
Insulated pressure vessels (cryotanks)

- **Pressure vessels that can be fueled with ambient-temperature compressed hydrogen or cryogenic hydrogen, either liquid hydrogen or cryo-compressed hydrogen**
- **Compatible with both LH_2 and CH_2**
  - **If filled with CH_2, low energy consumption for fuel processing**
  - **If filled with LH_2, high storage density, low evaporative losses, fill to 100% (no ullage space required)**
- **Cryotanks can use LH_2, but do not *need* LH_2. Can save substantial energy (25% of the total LH_2 energy) by:**
  - **Fueling with CH_2 for city driving**
  - **Fueling with LH_2 for long distance driving**

We are demonstrating insulated pressure vessel operation on both compressed and liquid hydrogen

- Conducted fueling and preliminary drive tests at LLNL
- Demonstrated compatibility with both compressed and liquid hydrogen
- In SunLine Transit (Palm Springs) for long-term testing

We are developing new designs for improved Cryogenic-compatible pressure vessels



- Horizontal pressure vessel design
- Higher volumetric efficiency
- Better insulation

Hydrogen delivery options

On-site generation

- Electrolysis
- Steam reforming

- Compressed hydrogen (truck)
  - Ambient temperature
  - Cryo-compressed
- LH_2 (truck)
- pipeline

Hydrogen delivery options

On-site generation

- **Electrolysis**
- **Steam reforming**

- **Compressed hydrogen (truck)**
  - **Ambient temperature**
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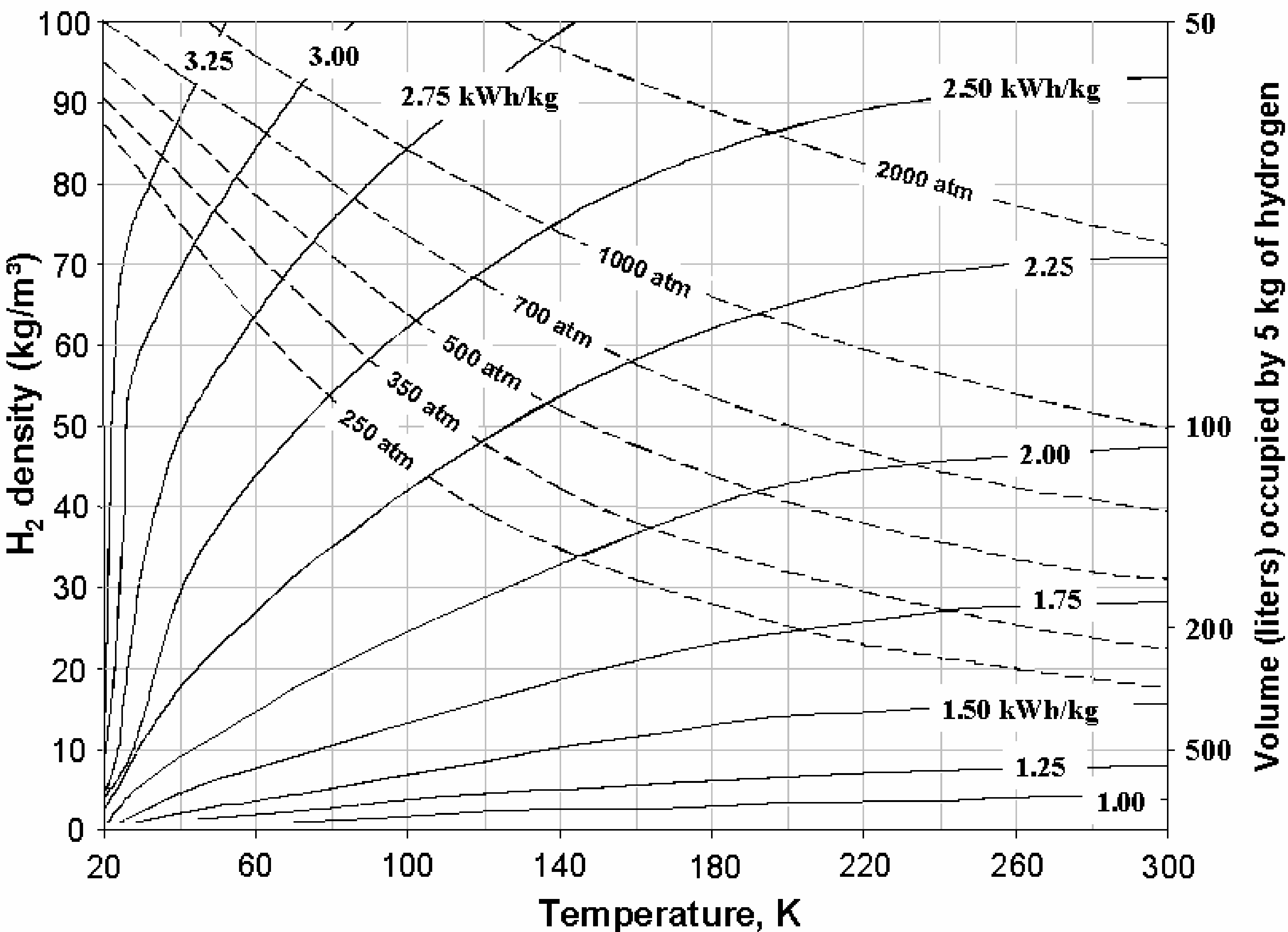
- **LH_2 (truck)**

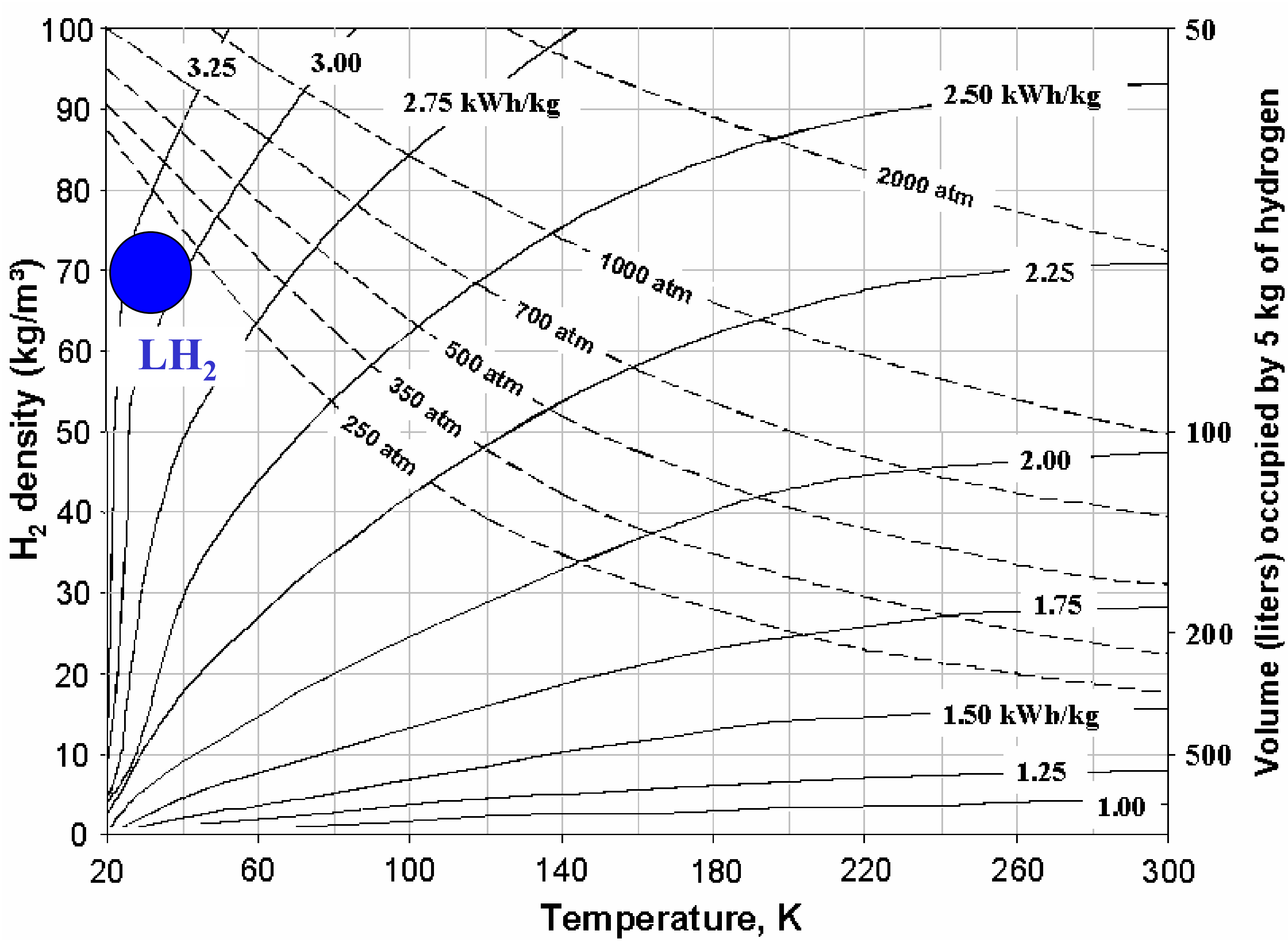
- **pipeline**

For this work, we will analyze compressed hydrogen delivery

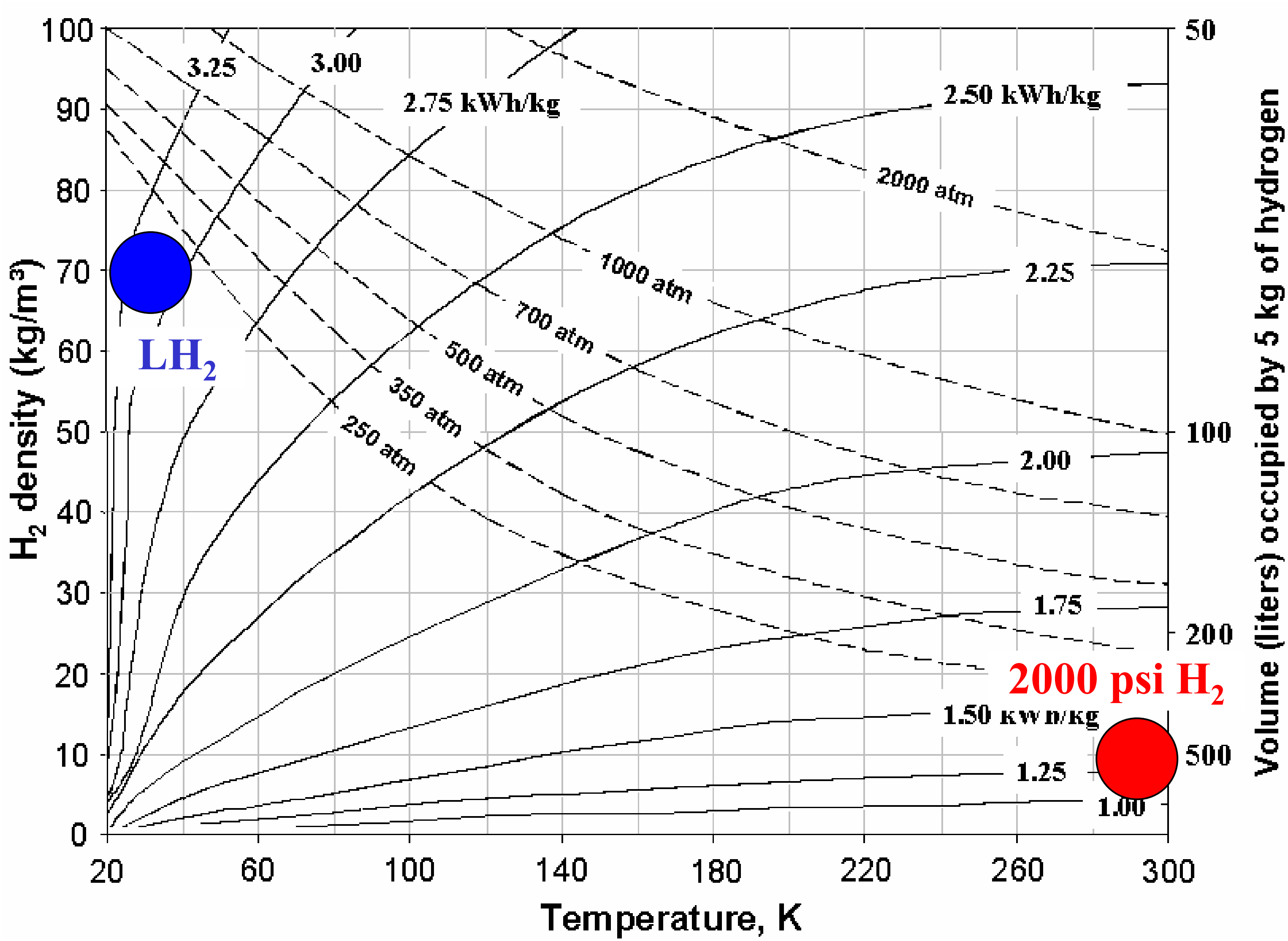
The PVT properties of H_2 drive the costs of storage and delivery (capital, energy, and transport)



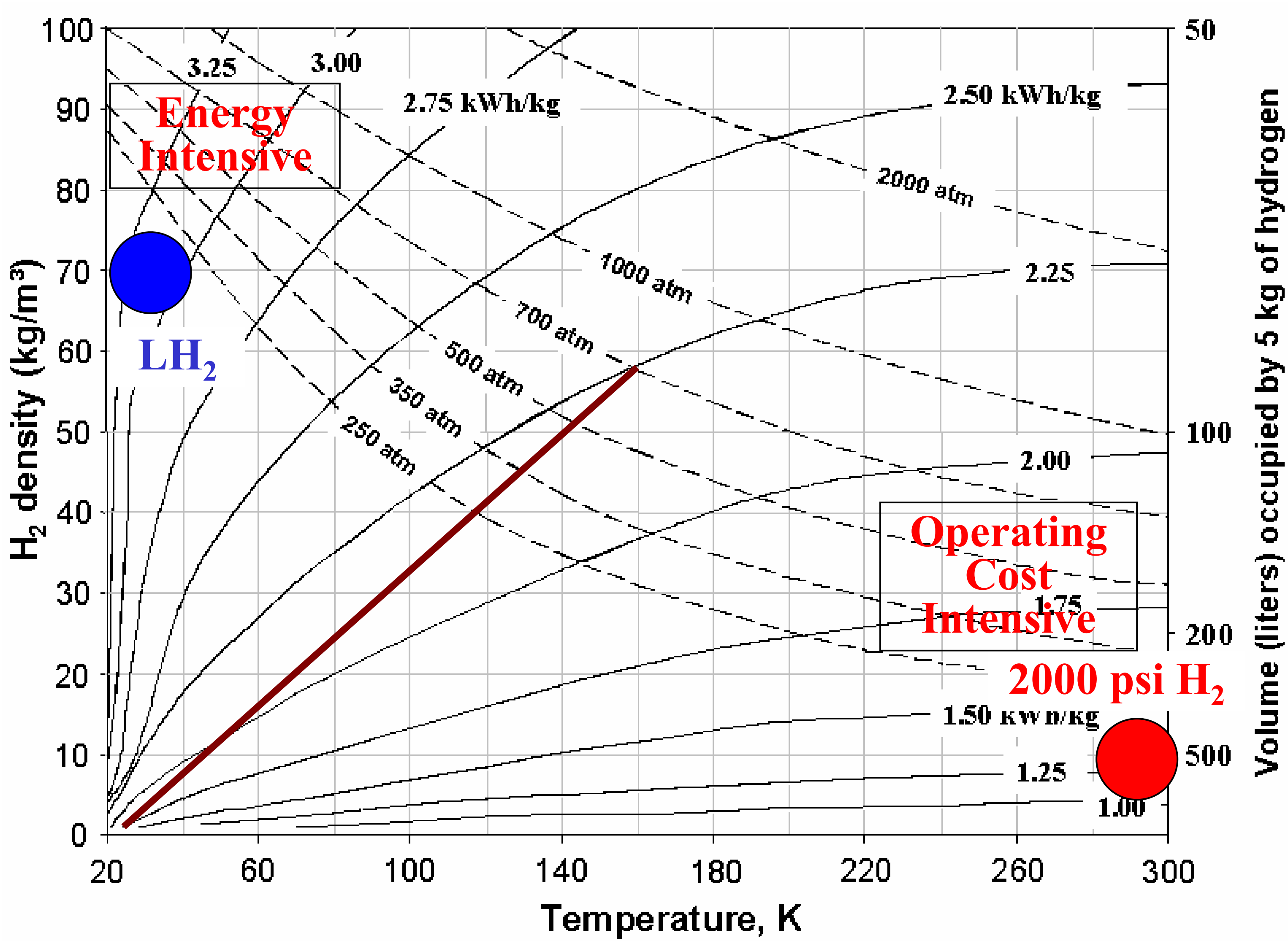
Liquid hydrogen delivery invests maximum energy for minimal capital and operating costs



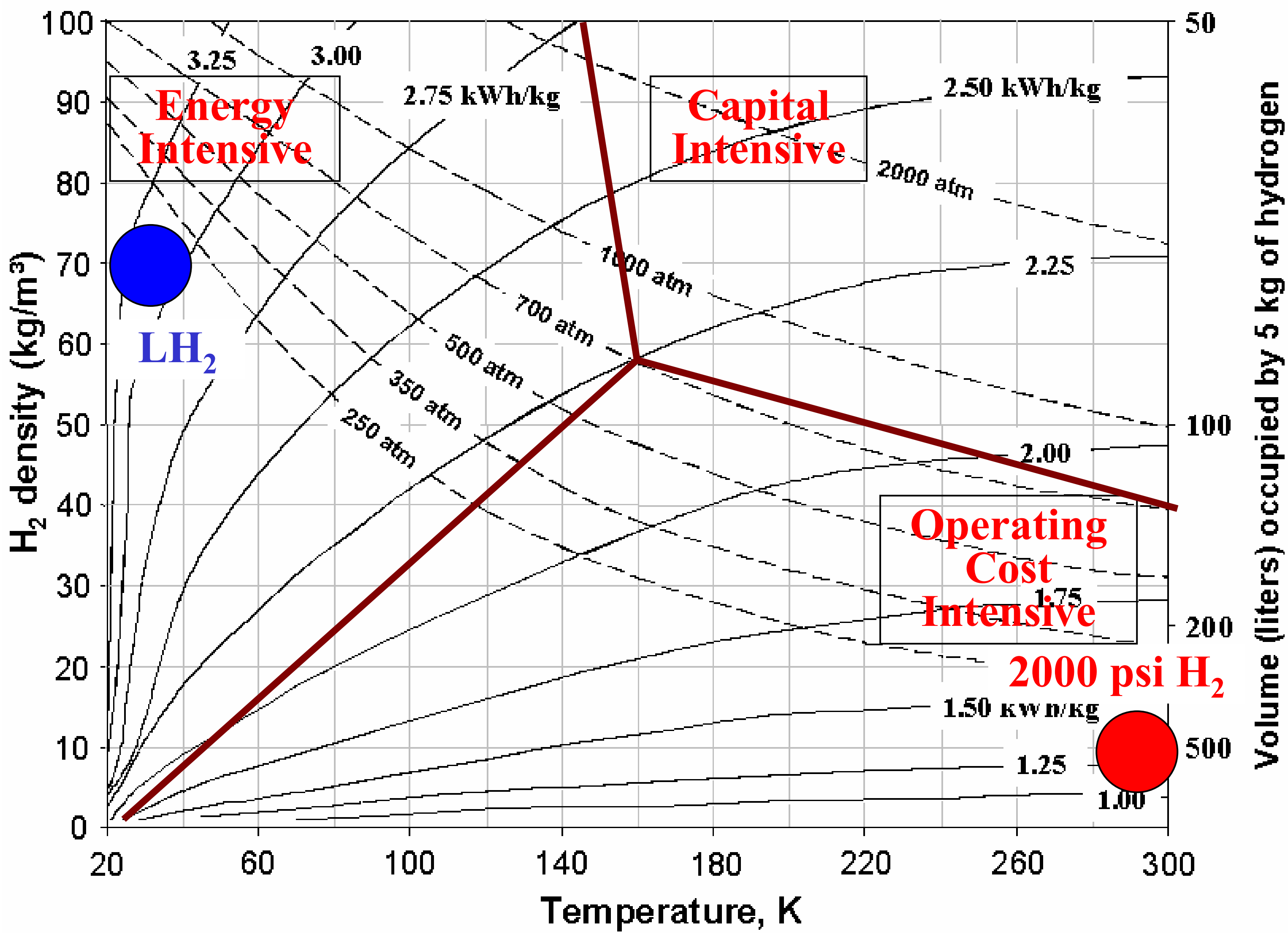
Compressed hydrogen in metallic cylinders (~2000 psi) minimizes compression energy at the expense of high delivery cost



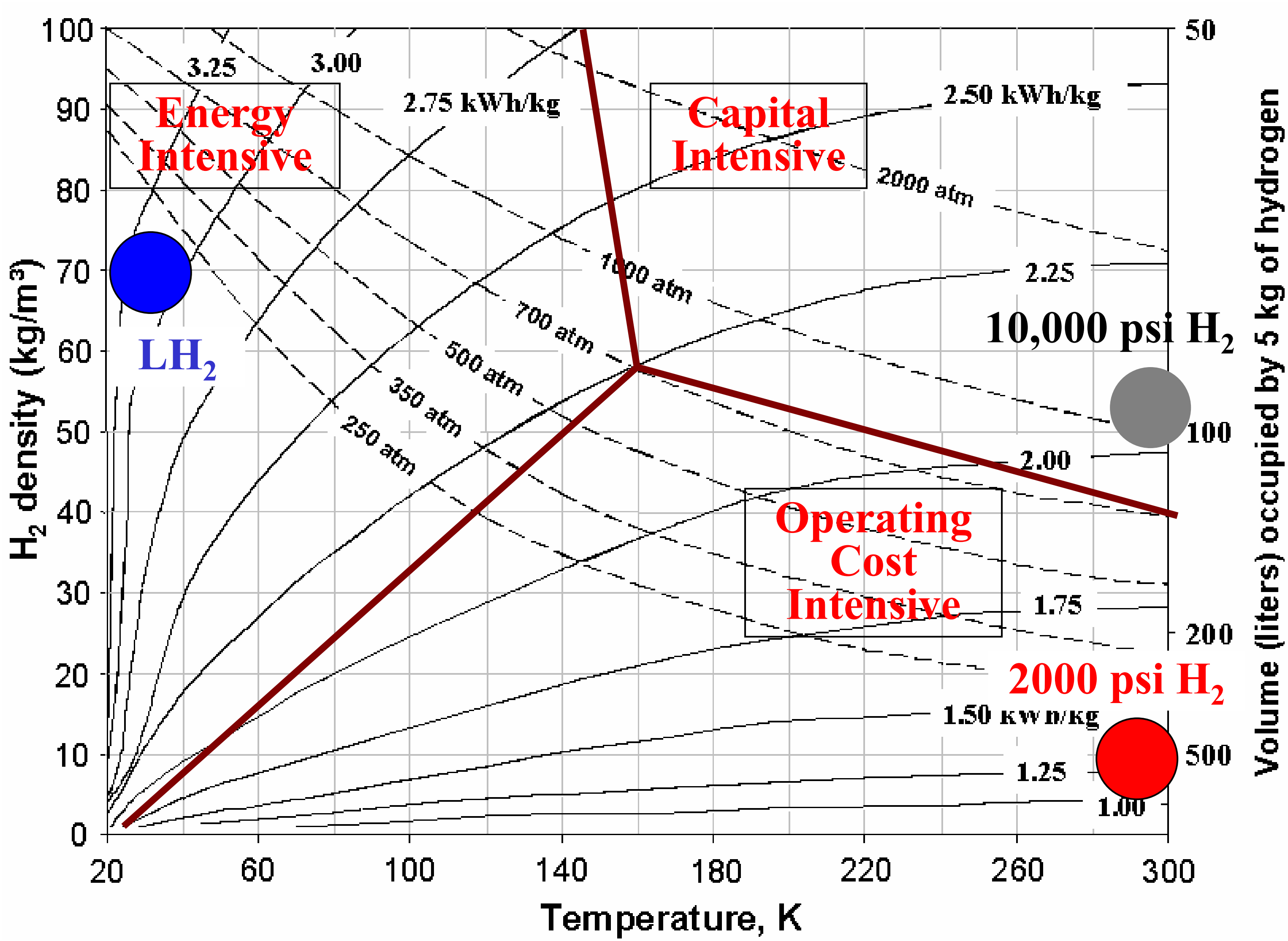
Both commercial hydrogen delivery approaches occupy extreme delivery strategy spaces



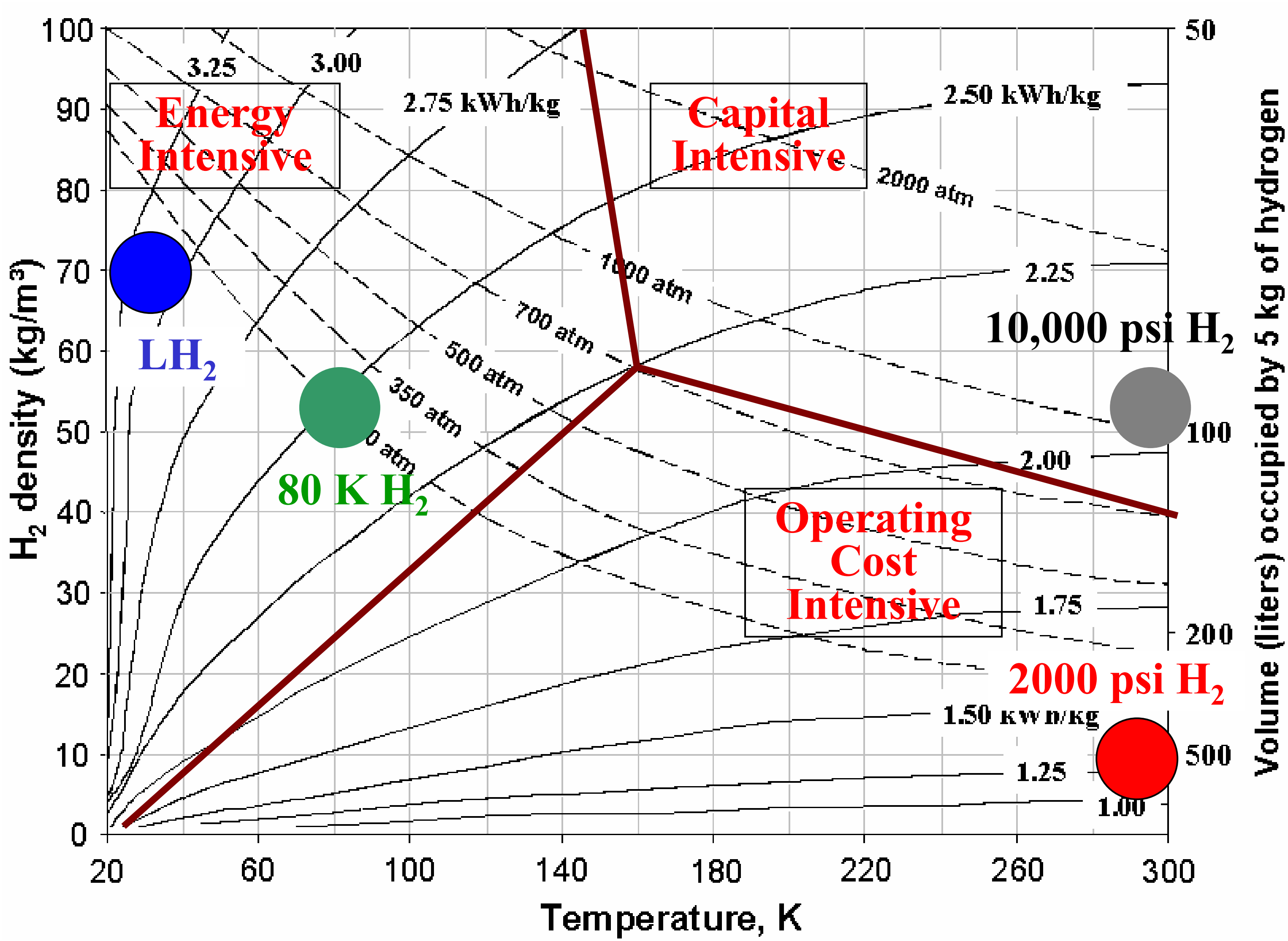
In principle, capital investment could reduce energy and labor costs



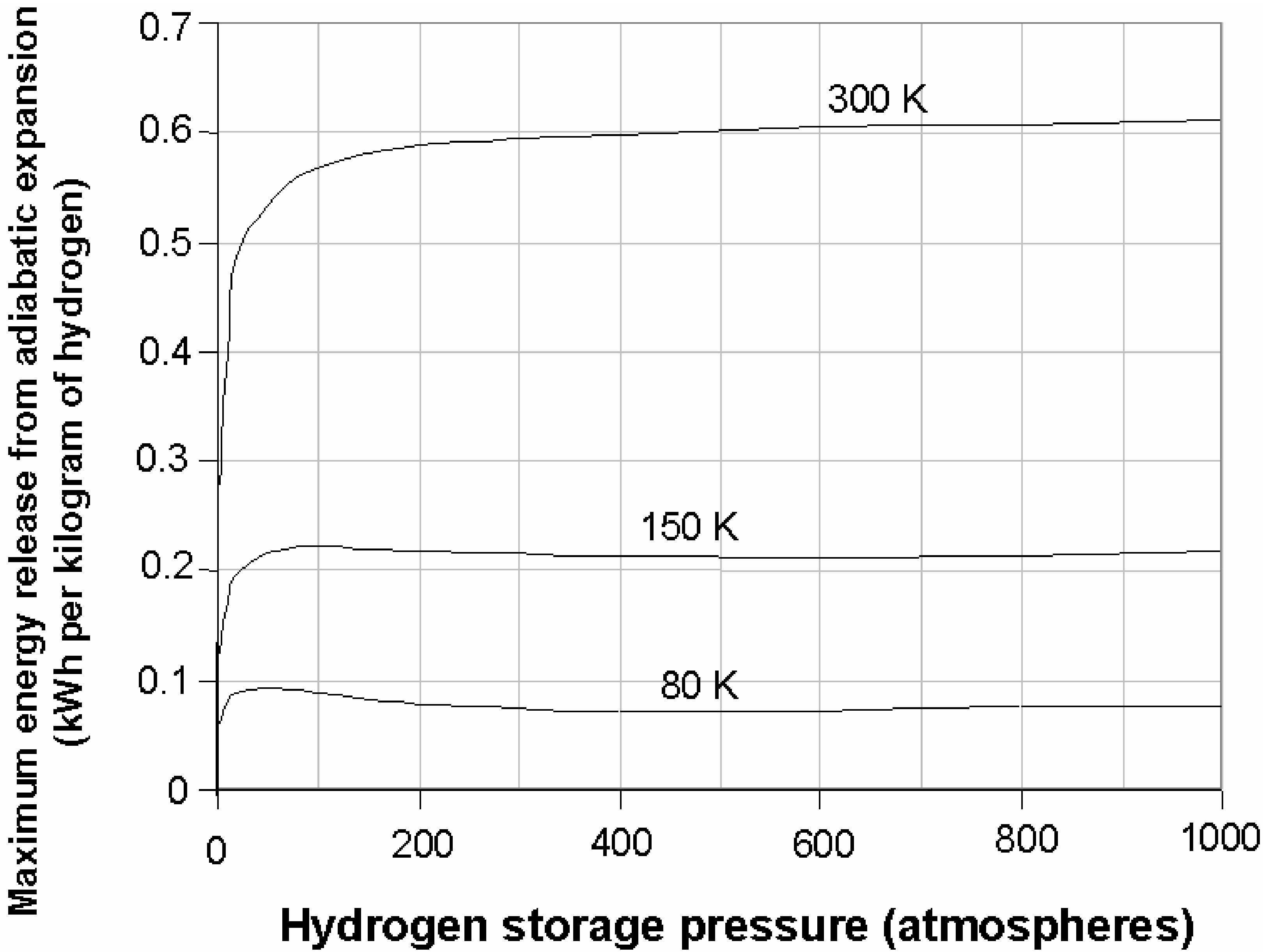
High pressure tube trailers maximize storage density for minimum energy, but for higher capital investment



Would cryogenic compressed hydrogen better balance capital and energy costs?



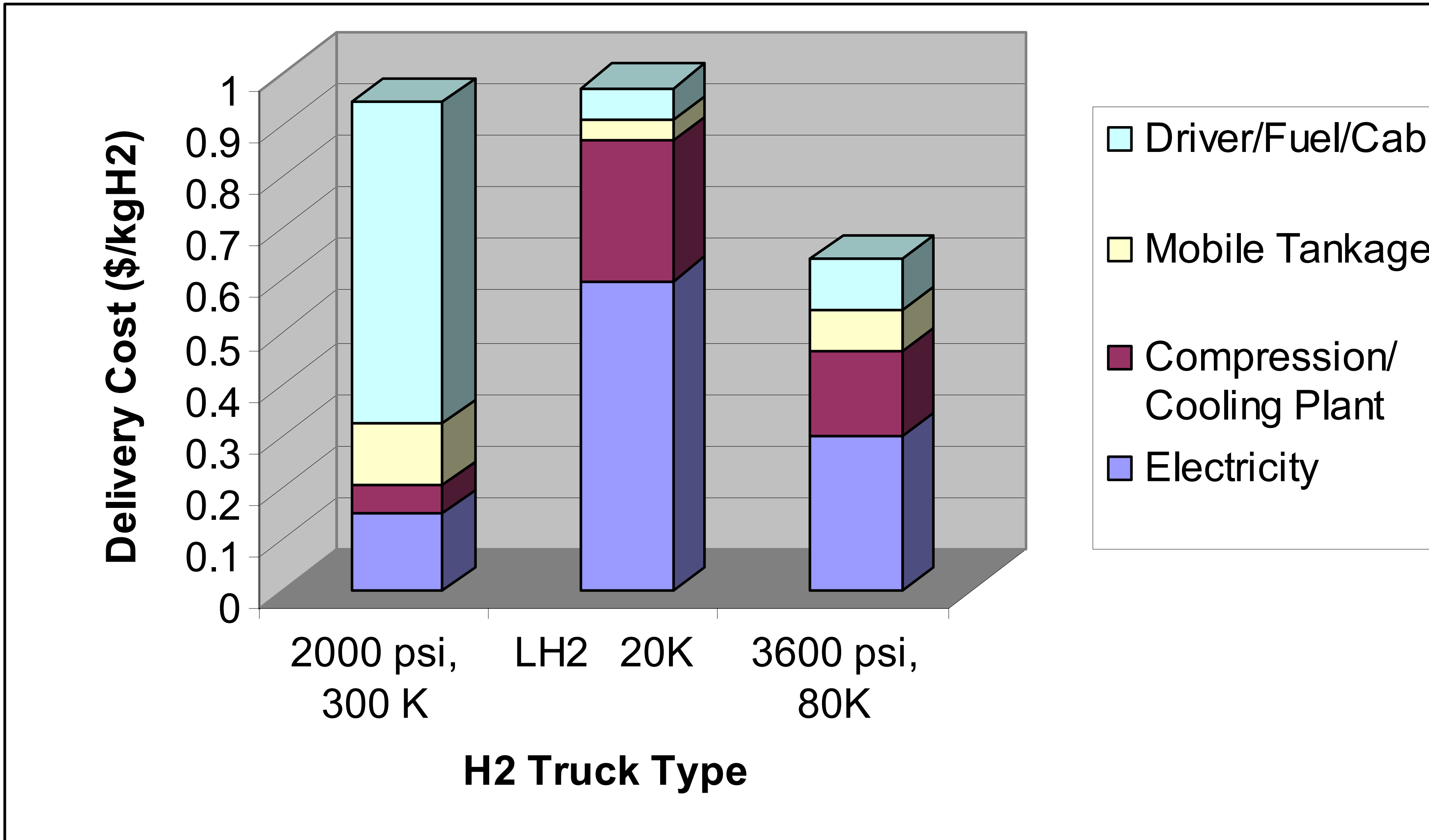
Cryogenics can offer intrinsic safety advantages



"Back of the envelope" thought experiment delivery cost assumptions

- **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 100mi delivery costs by saving per mile transport costs and energy



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**
- **Explore flexibility of delivery options**
  - **Delivery Distance**
  - **Delivery Speed**
  - **Deliveries/day**
- **Analyze on-site implications**
  - **Drop-off trailers vs H_2 delivery *per se.***
  - **Necessity of on-site compression**
  - **Cryogenic dormancy requirements**