Advanced Concepts for Containment of Hydrogen and Hydrogen Storage Materials
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Overview

Timeline
• Start date: **October 2003**
• End date: **September 2008**
• Percent complete: **30%**

Budget
• Funding received in FY04: **$500 k**
• Funding for FY05: **$625 k**
• SCAQMD funding: **$500 k**

Barriers
• B. Weight and volume
• D. Durability
• E. Refueling Time
• H. Sufficient fuel storage for acceptable vehicle range
• I. Materials
• K. Balance of plant (BOP) components
• M. Hydrogen capacity and reversibility

Partners
• Demonstrating cryotank technology (**SCI, SunLine**, funded by **SCAQMD**)
• Working with **BMW** on cryo storage
• **Spencer composites**, CRADA with **Automotive Composites Consortium**, aerospace work funded by **DARPA**
• Collaboration with many **Universities**
Objectives: We are developing high performance conformable containers that can operate under extreme conditions, as needed for hydrogen and hydrogen storage material containment.

Liquid: develop conformable containers that can operate at extremely low temperature (20 K) and wide range of pressures (100-5000 psi)

Compressed: develop containers for very high pressure (10,000 psi) and moderate temperature (up to 100°C)

Chemisorbed: develop conformable containers for high temperature operation and efficient thermal management

Physisorbed: develop compact containers that operate over wide range of conditions and provide efficient thermal management
Approach: we are developing innovative concepts for hydrogen and hydrogen storage material containment for efficient thermal management at cryogenic or high temperatures.

Conformable containers efficiently use available space in the vehicle. Ribs and struts provide heat transfer paths for efficient thermal management.

Insulated pressure vessels are needed for cryogenic operation with low evaporative losses. Supercritical hydrogen \((p \sim 5000 \text{ psi, } T \leq 50 \text{ K})\) has the potential to meet the 2015 DOE goals.

Hydrogen absorbed in liquid nitrogen is safe, easy to dispense, light and compact.
Accomplishments: We have analyzed multiple geometries for continuous fiber conformable containers and selected an optimum design.

- Conformable vessels can improve the volumetric efficiency of hydrogen containers.
- Determined optimum geometry and conducted extensive finite element analysis.
- Colors in figures indicate regions with stress concentration.
We have determined an optimum design for continuous fiber conformable containers and we are moving toward experimental testing of small scale components.

- Have conducted extensive finite element analysis of our vessel design
- 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
We have produced the first manufacturable macrolattice structure for conformable pressure vessels

- 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) was designed for 22,000 psi burst with uniaxial struts that are built to fail at 400,000 psi
We have built a generation zero prototype (functional model that can be pressurized) of a macrolattice pressure vessel.

- Design and construction completed
- Vessel has high volumetric efficiency (projected 84%)
- Extensively analyzed by finite element
Our second generation zero prototype is capable of resisting pressure and it has hollow struts for improved thermal management

- Seals added in second prototype
  - Details include piston-like o-ring seal between core rods and faces (rigid in bending) which can tolerate 0.035” expansion to mimic composite strain; and edge seal backing groove to tolerate very high proof pressures (to qualify prototype at 5:1 SF)

- Shear tolerant seals
  - Seals tolerate 0.8% shear strain
  - Much lower shear stiffness vs. axial stiffness (100:1) enables demo of major safety feature = content retention while warped

- Tubing replaces solid core rods to demo heat exchange
Our first generation insulated pressure vessel has demonstrated the possibility of flexible refueling and operation with liquid and compressed hydrogen

- Fueling with CH2 for lower energy consumption (75% less storage energy vs. LH2)
- 2X-3X longer range with LH2
- Successfully conducted proof of concept experiment in SunLine pickup truck (funded by SCAQMD)
- Meets 2005 DOE weight goal
- 1.67 kWh/kg, 0.77 kWh/L, 3600 psi
- Works in the vertical position
- Can be used for storage materials (cryogenic carbon)
- Wrote set of certification standards (funded by AQMD)
Our second generation insulated pressure vessel has much improved volume, weight and operational performance with respect to previous design.

- Much improved performance
- Meets 2010 DOE weight and 2005 volume goals
- 2.32 kWh/kg, 1.22 kWh/L, 5000 psi
- Works in the horizontal position
- Fits across the bed of a compact pickup truck or inside the trunk of a midsize car
- Projected to virtually eliminate evaporative losses
- Very good liquid hydrogen tank
- To be tested in collaboration with BMW
We have characterized hydrogen absorption in liquid nitrogen with anticipated refuelability and safety advantages. Our results indicate favorable absorption of H₂ into LN₂.

Thick lines are for pure hydrogen and thin lines are for mixtures of hydrogen and nitrogen. At ice temperature (273 K), the compressibility factor (and therefore the volume) is higher for the mixture than for the pure H₂ because no absorption occurs. At LN₂ temperatures, considerable absorption occurs, and the mixtures are more compact than the pure H₂.
We have examined the entire phase diagram for hydrogen and we have identified supercritical hydrogen (80 K, 1000 bar) as a promising operating point for meeting the 2015 goals.

Supercritical hydrogen has the potential of meeting the 2015 DOE weight and volume goals with future advanced pressure vessels.
Cooling hydrogen makes it safer: energy release during a sudden failure is a weak function of pressure but a strong function of temperature.

Hydrogen absorbed in nitrogen has lower energy because the nitrogen is near the point of liquefaction. Once liquefied, the density of nitrogen is fairly constant and therefore it does not contribute to the expansion energy.
Summary of accomplishments: we have achieved considerable progress towards developing high performance containers for hydrogen and hydrogen storage materials

- Designed and built prototype macrolattice conformable vessels
- Analyzed and designed continuous fiber conformable container
- Installed insulated pressure vessel in pickup truck and demonstrated flexible refueling with liquid and compressed H₂
- Designed a new insulated pressure vessel that works in the horizontal position and meets the 2010 DOE weight goal and the 2005 DOE volume goal
- Characterized absorption of hydrogen in nitrogen at low temperatures with anticipated safety and delivery advantages
- Identified supercritical hydrogen as an operating condition that has potential for meeting the 2015 DOE goals
- Wrote 2 patents, 5 invited papers, 2 contributed papers, 1 technical report, 1 set of safety standards and to deliver 2 invited presentations
Responses to reviewers’ comments:
We have refocused our project plans to directly address the reviewers’ comments

- **Would like to see more actual testing and see it earlier in the program.** We have developed prototypes for conformable vessels and insulated pressure vessels that will be tested this year.

- **Need to work with pressure vessel manufacturers.** We have worked with SCI for multiple years on cryogenic pressure vessels and with Thiokol/Quantum on lightweight vessels.

- **It is difficult to see how the 2015 or even the 2010 targets can be met.** We are planning to meet the 2010 weight goal with our new insulated pressure vessel. The 2015 targets require the development of high performance tanks for supercritical operation.

- **Compressed hydrogen is not the answer to on-board storage.** Our work is not limited to storage of compressed hydrogen. Our container designs are necessary for cryogenic H₂ and enable efficient thermal management of hydrogen storage materials.
Future work (FY05-06)

Analysis
- Continue conceptual analyses and begin detailed analyses
- Begin application analysis
- Analyze thermal management capability of macrolattice

Design
- Conclude conceptual design by creating CAD models of the elements
- Develop engineering requirements for macrolattice components
- Finalize design of second generation insulated pressure vessel

Building and Testing
- Pressure test newly built macrolattice conformable container
- Build and pressure test new insulated pressure vessel
- Build and pressure test continuous fiber conformable container
- Build and test new insulated pressure vessel (with BMW)
Supplemental slides
Publications and presentations

Patents

Publications in Books and Technical Journals

Publication in Refereed Proceedings

Technical Report
• Proposed Standards for Hydrogen and Liquefied Natural Gas Insulated Pressure Vessels, Report to the South Coast Air Quality Management District Auugust 2004

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
The most significant hydrogen hazard associated with this project is:

- Gigajoules of chemical energy released in the chaos of a vehicle crash
- Benchmark is 1 gigajoule = 278 kWh (lower heating value) of 8.33 kg of hydrogen stored on a vehicle
- Chemical energy sufficient to drive 300 miles dwarfs the mechanical energy in compressed fluids or in strained solids (several megajoules of 'spring' energy are stored in a 10,000 psi pressure vessel of automotive size)
- Roughly 5% of motor vehicle accidents result in a fire, all of these penetrate fuel storage, and these accidents are much more lethal (NTSB expert 2002)
Approach to Safety

- Develop containers able to keep their contents inside despite significant impact and deformation
- Develop failure localization features that fail first when hydrogen pressure increases due to a crash
- Work on cryogenic containment of hydrogen or hydrogen materials, which has lower mechanical energy than ambient temperature or hot storage
- Work on liquid nitrogen absorption medium for reduced mechanical energy and reduced possibility of combustion in contact with air
- Demonstrate fast disposal through nozzles that mix released hydrogen with surrounding air to concentrations below the explosive and flammable limits without the possibility of combustion
- Avoid the possibility of combustion using the temperature drop of sonic nozzles and flow velocities above the flame speed of hydrogen+air
- Develop safety standards for cryo-compressed pressure vessels
- Build these nozzles in a slit-shaped form that can be realized in the post-rupture shape of a failure localization feature
- Demonstrate slow disposal through catalytic venting
- Convince those capable of volunteering for regulatory activities to re-word ISO TC197 so that hydrogen released within a container subassembly and mixed with air below the ignition limit or converted to water vapor is considered safe