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DOE Hydrogen Program

# Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery


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# Overview

## Timeline

- Phase I July 08 – June 09
  - 100% Complete
- Phase II June 09 – June 11
  - 5% Complete
  - Looking to extend completion date to June 12

## Budget

- Total project funding (Phase I & II)
  - DOE share $3M
  - Contractor share $2.73M
- Funding received in FY10 - $610K
- Planned Funding for FY11 - $900K

## Barriers

- Barriers addressed
  - Gaseous Hydrogen Storage and Tube Trailer Delivery Costs
  - System Weight and Volume
  - Efficiency
- Targets
  - $500/kg of H2 stored by FY2010, $300/kg by FY2015
  - Volumetric capacity 0.03 kg/liter by FY2010, >0.035 kg/liter by FY 2015
  - Tube trailer delivery capacity 700 kg by FY2010 and 1,100 kg by FY2017

## Partners

- Discussions with ABS on vessel qualification
- Discussions with US DOT

# Project Objectives

- Relevance: to reduce the cost of a near-term means of transporting gaseous $H_2$ from the production or city gate site to the station.
- Design and develop the most effective bulk hauling and storage solution for hydrogen in terms of cost, safety, weight, and volumetric efficiency. This will be done by developing and manufacturing a tank and corresponding ISO frame that can be used for the storage of hydrogen in a stationary or hauling application was developed and manufactured in 2009. **Complete 4Q 2009**.
- Based on current knowledge of tube trailer design, carry out preliminary design and qualify a 3600 psi tank and ISO frame that will hold 510000 $in^3$ (~8500L) water volume. **Complete 4Q 2009**.
- Complete trade studies needed to increase vessel capacity by increasing pressure to 5000 psi (ultimately exceeds the DOE's FY01 capacity target by >15%). **Complete 1Q 2011.**
- **Based on the results of the trade studies, move forward on the design, manufacture and qualify a 5000 psi vessel/system.**

# Objectives-Technical Targets

| Hydrogen delivery targets | ISO container with four 3600 psi tanks (FY 2009 Work Scope) |
|---|---|
| $500/kg of hydrogen stored by FY2010, $300/kg by FY2015 | The current ISO assembly, with four tanks installed, can store about 600 kg of compressed hydrogen gas at 3600 psi with a safety factor of 2.35. It is estimated that the cost will be $675-$750 per kg of hydrogen depending on market demand. |
| Volumetric capacity 0.03 kg/liter by FY2010, >0.035 kg/liter by FY 2015 | The baseline tank has a capacity of 150 kg hydrogen in a volume of ~8500 liters, achieving a performance of ~0.018 kg/liter.<br><br>This performance measure can be increased 33% to 0.024 kg/liter by increasing the service pressure to 5000 psi and 95% to 0.035 kg/liter by increasing the service pressure **to 8300** psi. |
| Tube trailer delivery capacity 700 kg by FY2010 and 1,100 kg by FY2017 | The current ISO assembly, with four tanks installed, will contain about 600 kg of hydrogen.<br><br>This can be increased 33% to about 800 kg by increasing the service pressure to 5000 psi and 44% to about 1150 kg by increasing the service pressure **to 8300** psi. |

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# Approach/Milestones

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**Task 1.0 Develop and Qualify a 3600 psi Tank**

- design and qualify a tank that will hold approximately 8500 liters of water at 3600 psi
- Primary focus will be on manufacturing methods of a tank this size
- **Completed 4Q 2009**

**Task 2.0 Develop and Qualify an ISO Frame**

- ISO container assembly will be able to hold four tanks with a combined capacity of 600 kg of hydrogen
- **Completed 3Q 2009**

**Task 3.0 5000 psi Trade Study**

- A higher pressure tank will be required to meet DOE goals
- Initial review suggest a 5000 psi tank will be the most cost effective
- **Completed 1Q 2011**

**Task 4.0 Develop and Qualify a 5000 psi Tank**

- Same test will be used to qualify a higher pressure tank that was used on the 3600 psi tank

**Task 5.0 Cost Reduction Studies**

- Methods to reduce cost of the tank will be investigated meet DOE goal

**Task 6.0 Investigate Increased Capacity**

- Increased pressure will increase capacity of the tanks, but the price will also increase. Other methods to increase capacity will be researched.

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# Technical Accomplishments/ Progress/Results

- **Successful completion of all qualification tests for a 3600 pressure vessel**

  ✓Hydrostatic Burst Test
  ✓Ambient Pressure Cycle Test
  ✓LBB (Leak Before Burst) Test
  ✓Penetration (Gunfire)
  ✓Environmental Test
  ✓Flaw Tolerance Test
  ✓High Temperature Creep Test
  ✓Accelerated Stress Rupture Test
  ✓Extreme Temperature Cycle Test
  ✓Natural Gas Cycle Test with Blowdown

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# Technical Accomplishments/ Progress/Results

Completed the design, manufacture and assembly of ISO container (standard dimensions) capable of storing ~600 kg $H_2$ @ 3600 psi.

- ✓ Pressure vessel targeted at 3600 as infrastructure already in place to utilize
- ✓ Designed to meet industry standard transporting dimensions
- ✓ Completed stress analysis on frame
- ✓ Performed DFMEA
- ✓ Performed HazID analysis
- ✓ Developed pressure relief system for fire protection

Completed Testing of ISO Container

- ✓ Dimensional
- ✓ Stacking
- ✓ Lifting – Top and bottom
- ✓ Inertia Test
- ✓ Impact Test
- ✓ Bonfire

# Trade Studies

- Trade studies were undertaken to evaluate potential targets that would increase utilization storage design that best meet or exceed DOE targets
- Key Factors
  - Module Volume (increased utilization)
    - Cylinder Size
    - Packing Efficiency
  - Cylinder Design (increased H2 density)
    - Cost Reduction
    - Stress Ratio
    - Working Pressure
    - Storage Temperature

# Design Baseline/Gap Audit

- Lincoln Composites Titan Module
  - Current Lincoln Composites product (chosen as the baseline for the trade studies)
  - Intermodal ISO 668 1A Frame
  - 4x Type 4 Cylinders
    - 250 bar Working Pressure
    - Carbon Fiber, 2.35 SR
  - Increase Capacity (kg H2 per Liter)
    - Increase Pressure and/or Utilization
    - From 0.018 kg to 0.03 kg of H2 per Liter
    - From 616 kg to 700 kg H2 Capacity at 15C
  - Decrease Cost ($ per kg H2)
    - From $500 per kg to $452 per kg H2

# Trade Factor #1: Cylinder Size

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- Titan Module
  - 4 Cylinders in Horizontal 2x2 Arrangement
  - 60 % Utilization
- A Single Large Cylinder
  - 63 % Utilization
  - T/D Ratio: Liner Fabrication Limitations
    - Pipe Extrusion, Injection Molding of Heads
    - Welding of 254 mm Wall

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# Trade Factor #2: Cylinder Packing

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- Add More Cylinders to Titan
  - 4 Along Sides and 1 Center
  - 68 % Utilization
  - Difficult to Incorporate
    - L/D Ratio: Straightness and Winding Stability
      - Two Cylinders in Each Position
      - Center Support or Strap Mount
    - Plumbing Manifold
- 8 Cylinders in 3x2x3 Arrangement
  - 56 % Utilization
- Many Smaller Nested Cylinders
  - 91 Cylinders in Vertical Arrangement
    - L/D Ratio: Straightness and Winding Stability
  - 68 % Utilization
  - Complexity and Cost of Plumbing
  - Considerably More Difficult to Service

# Trade Factor #3: Working Pressure

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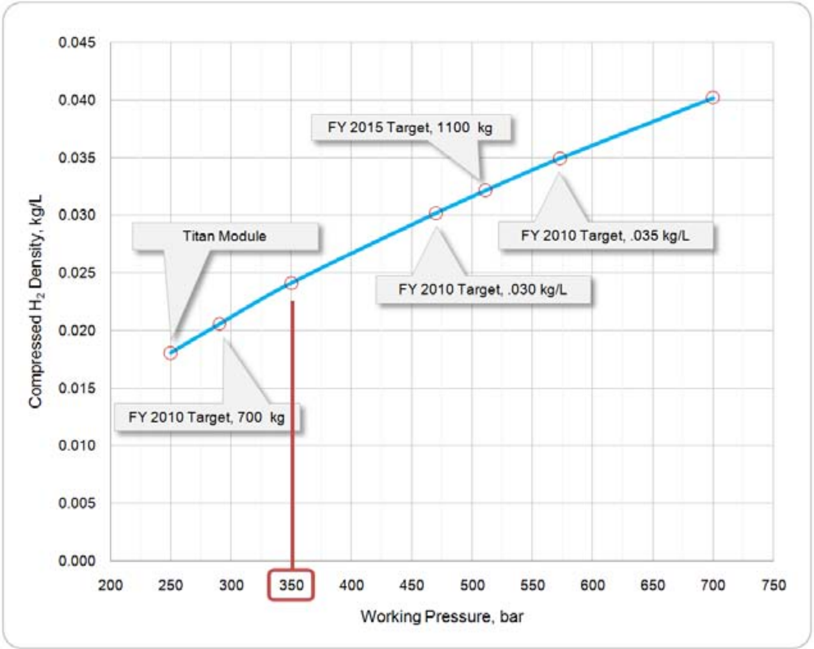


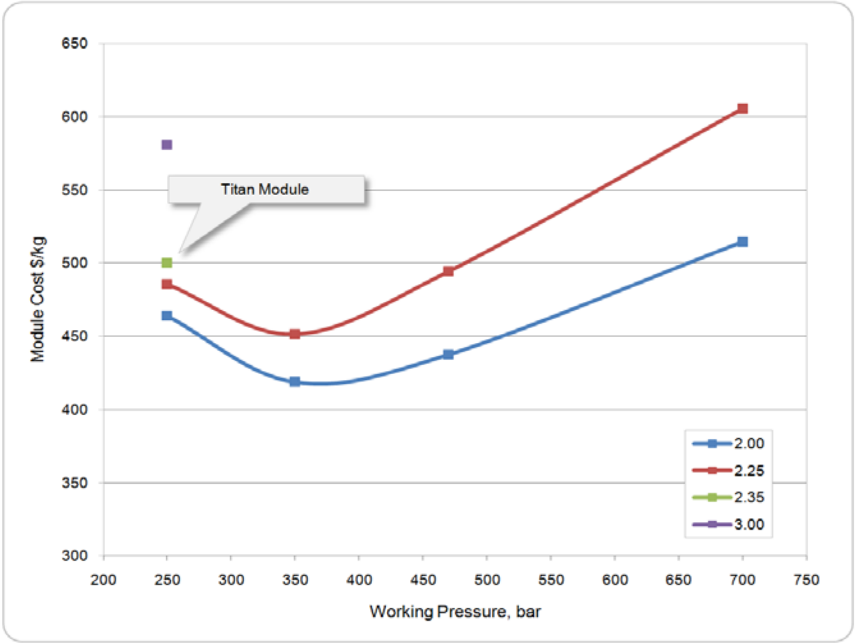


- Increasing H2 Density by Raising Working Pressure
- 33 % Increase in Capacity at 15 C
  - .024 kg/L at 350 bar
  - .018 kg/L at 250 bar

- Practical Limit is 350 bar
  - Higher pressures exacerbates thick-wall effects and reduced strength translation
  - Availability of Plumbing Hardware
  - Availability of H2 Compressors

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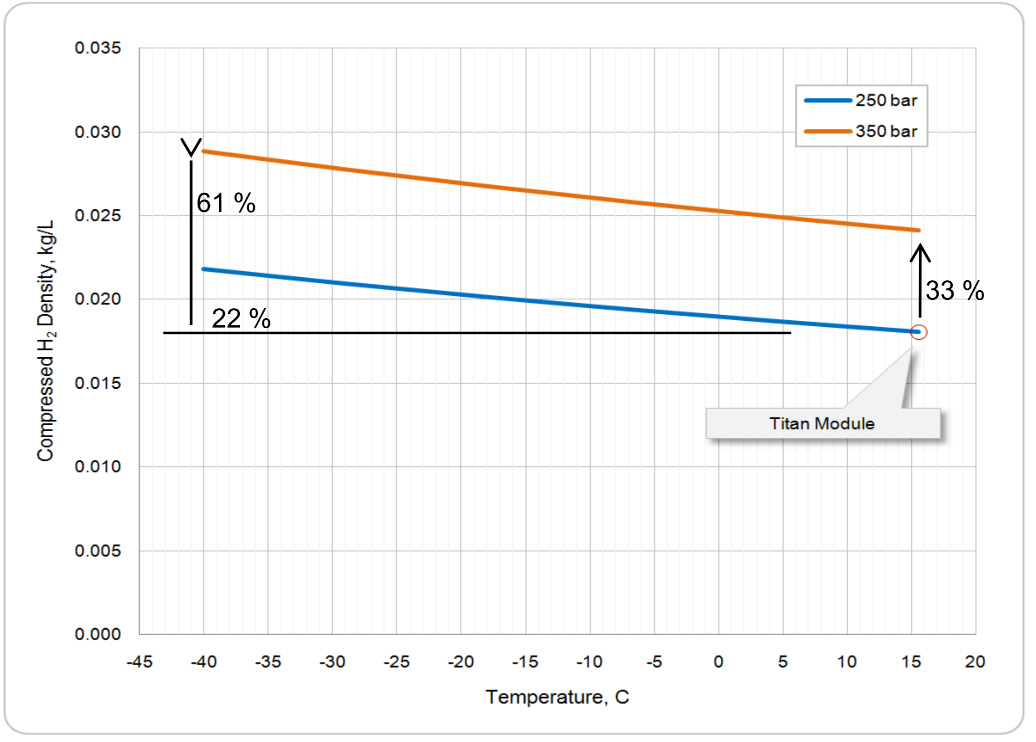
# Trade Factor #4: Storage Temperature

- Increase H2 Density by Lowering Storage Temperature
- 22 % Increase at 250 bar
  - .018 kg/L at 15 C
  - .022 kg/L at -40 C
- 61 % Increase at 350 bar
  - .029 kg/L at -40 C

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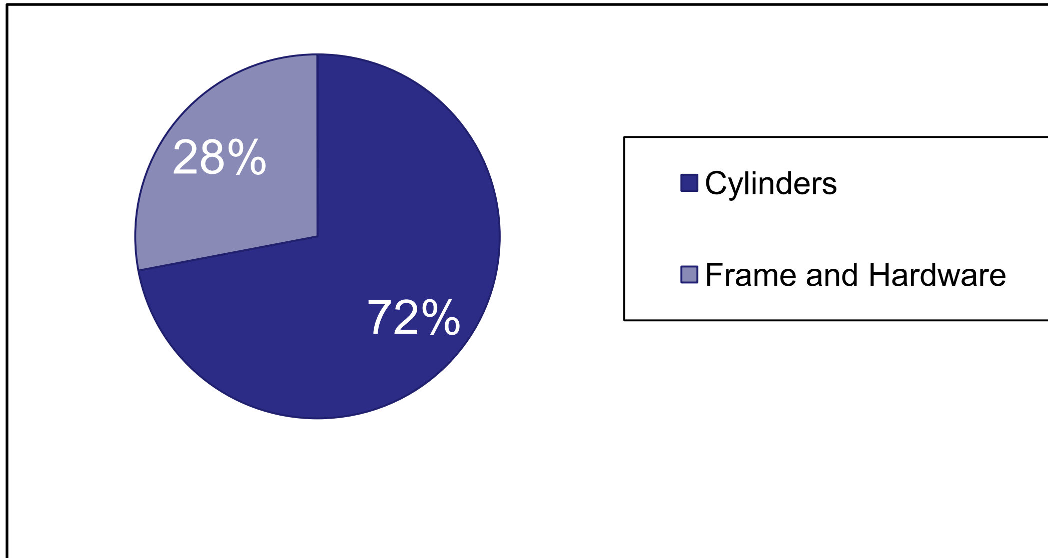
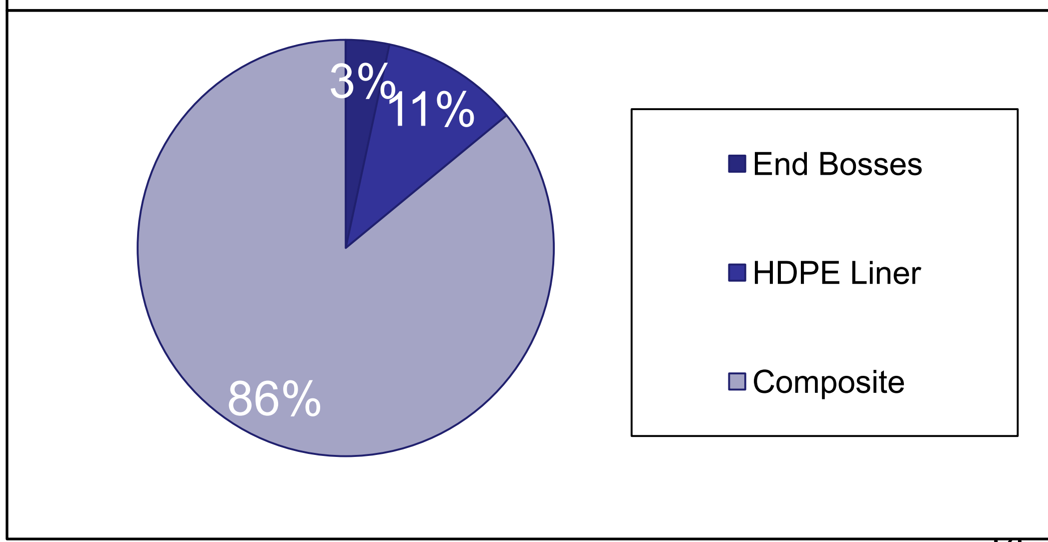
# Trade Factor #5A: Module/Cylinder Cost

- Currently Meet $500 per kg H2
  - 72 % of Cost is Cylinders
  - 86 % of Cylinder Costs is Composite



# Trade Factor #5B: Pressure Vessel Costs

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## Liner Cost

- Use Less Material or Lower Cost
  - Presently at minimum T/D ratio suitable to both liner fabrication and filament winding
  - No Known Lower Cost Alternate
    - Weldable, Cold Ductility, Permeation
- Steel End Bosses
  - Size Constrained by Mounting Interface
  - Cost Savings Have Marginal Affect

## Composite Cost

- Carbon Fiber
  - Lowest SR of Allowable Fibers
  - T700 Greatest Strength per Unit Cost
    - Direct Material (incl. Epoxy)
    - Wind Time Costs
  - Higher strength carbon fibers have a 2-4x increase in cost for 15-40% in strength

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# Trade Factor #6: Stress Ratio

- Reduce weight and cost by lowering carbon fiber usage (stress ratio)
  - Titan: 2.35 SR based on CNG Requirements
  - 2.25 SR Allowed per ASME for H2
  - 2.00 SR is Considered Safe

# Trade Studies Conclusions

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- 350 bar Titan Logical Next Step
  - 2.25 SR Design will Fit Titan Frame
  - .018 to .024 kg H2 per Liter
  - 616 to 822 kg H2 Capacity
  - $500 to $452 per kg H2
- Cold Storage Adds Cost
- Adding Cylinders Adds Cost

# Collaborations

- Current and future customers regarding hydrogen storage at 350 bar
- American Bureau of Shipping on qualification of existing and potential changes to composition of current pressure vessels
- Discussions with DOT on approval of bulk hauling container in the US

# Future Work

- **FY 11**
  - Complete design and qualification of higher pressure tank based on results from trade study. Results from the trade studies indicate this will be a 5000 psi tank.

# Summary

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- Hydrogen delivery and storage are key to the roll out of PEMFC technology
- Low cost, near-term delivery pathways such as tube trailer transport will enable early adoption of these technologies
- Developing a bulk storage unit that can be transported on an ISO frame is a critical part of this strategy.

| Technical Targets | |
|---|---|
| **DOE Goals** | **Estimated Results** |
| \$500/kg of hydrogen stored by FY2010, \$300/kg by FY2015 | 3600 psi - \$500 per kg of H2<br>5000 psi - \$452 per kg of H2 |
| Volumetric capacity 0.03 kg/liter by FY2010, >0.035 kg/liter by FY 2015 | Current 3600 psi tank – 0.018 kg/liter<br>Raising pressure to 5000 psi – 0.024 kg/liter<br>Lowering storage Temperature:<br>•0.022 kg/liter at 3600 psi<br>•0.029 kg/liter at 5000 psi |
| Tube trailer delivery capacity 700 kg by FY2010 and 1,100 kg by FY2017 | 3600 psi - contains 616 kg of hydrogen.<br>5000 psi – would contain approximately 822 kg of hydrogen. |
| Tube trailer operating pressure goal is <10,000 psi by FY2012 | Current tank is 3600 psi. |