System Level Analysis of Hydrogen Storage Options


U.S. DOE Hydrogen and Fuel Cells Program
2020 Annual Merit Review and Peer Evaluation Meeting
Washington, D.C.
May 19 - 21, 2020

Project ID: ST001

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline
- Project start date: Oct 2009
- Project end date: N/A
- Project continuation and direction determined annually by DOE

Barriers
- H₂ Storage Barriers Addressed:
  - A: System Weight and Volume
  - B: System Cost
  - C: Efficiency
  - E: Charging/Discharging Rates
  - J: Thermal Management
  - K: Life-Cycle Assessments

Budget
- FY19 DOE Funding: $500K
- FY20 DOE Funding: $500K

Partners/Interactions
- HyMARC: PNNL, NREL, LBNL
- Delivery Team, Hydrogen Interface Taskforce (H2IT), ANL-H2A, ANL-HDSAM
- HMAT, TARDEC, BMW, LLNL
- Ford, ORNL, UM
- Strategic Analysis, PNNL, Ford
Develop and use models to analyze the on-board and off-board performance of physical and material-based automotive hydrogen storage systems

- Conduct independent systems analysis for DOE to gauge the performance of H₂ storage systems
- Provide results to material developers for assessment against system performance targets and goals and help them focus on areas requiring improvements
- Provide inputs for independent analysis of costs of on-board systems.
- Identify interface issues and opportunities, and data needs for technology development
- Perform reverse engineering to define material properties needed to meet the system level targets

Impact of FY2020 work

- Established benchmark costs for H₂ production by SMR, liquefaction, storage, transmission, distribution, and dispensing.
- Developed a model for fracture durability of Type-2 tanks and determined pressure limits for 25-year lifetime.
- Calibrated ABAQUS models for H₂ storage in Type-3 and Type-4 tanks and showed the possibility of lowering the status number for carbon fiber composite requirement.
- Showed that 33–54 kg of usable H₂ can be stored in roof mounted, behind-the-cab and frame-mounted tanks being offered for compressed natural gas trucks.
Approach

- Develop thermodynamic and kinetic models of processes in physical, complex metal hydride, sorbent, and chemical H\(_2\) storage systems
  - Address all aspects of on-board and off-board storage targets, including capacity, charge/discharge rates, emissions, and efficiencies
  - Perform finite-element analysis of compressed hydrogen storage tanks
  - Assess improvements needed in materials properties and system configurations to achieve storage targets

- Select model fidelity to resolve system-level issues
  - On-board system, off-board spent fuel regeneration, reverse engineering
  - Conduct trade-off analyses, and provide fundamental understanding of system/material behavior
  - Calibrate, validate, and evaluate models

- Work closely with DOE technology developers, national labs and others in obtaining data, and provide feedback

- Participate in meetings and communicate approach and results to foster consistency among DOE-sponsored analysis activities
1. Liquid Hydrogen Carrier (FY2020 Q1)
   – Completed initial analysis of liquid hydrogen (LH$_2$) carrier.
   – Determined costs of liquefaction, and LH$_2$ storage, ship transmission & distribution.

2. Bulk Storage at Forecourt (FY2020 Q2)
   – Developed models for dynamics of pressure fluctuations and durability of Type-2 tanks.
   – Determined optimum conditions and arrangements for a 250 kg-H$_2$/day dispenser subject to 25-year lifetime and complete refueling of vehicles.

3. Hydrogen Storage for Medium and Heavy Duty Trucks (FY2020 Q3)
   – Validated ABAQUS models for H$_2$ storage in Type-3 and Type-4 tanks.
   – Refined analysis of 33-53 kg hydrogen storage for medium and heavy-duty trucks.

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Due Date</th>
<th>Date Completed</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyze liquid hydrogen carrier relative to the 2020 targets of $2/kg hydrogen</td>
<td>12/31/2019</td>
<td>12/31/2019</td>
<td>100%</td>
</tr>
<tr>
<td>production and $2/kg delivery cost.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete analysis of hydrogen storage in Type-2 tanks at forecourt. Determine</td>
<td>3/31/2020</td>
<td>3/31/2020</td>
<td>100%</td>
</tr>
<tr>
<td>tank sizes, pressure cycles, and lifetime.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validate capacities and carbon fiber requirements for hydrogen storage on-board</td>
<td>6/30/2020</td>
<td>6/30/2020</td>
<td>75%</td>
</tr>
<tr>
<td>medium and heavy-duty trucks.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prepare a report on liquid hydrogen storage for trains and ships documenting</td>
<td>9/30/2020</td>
<td>9/30/2020</td>
<td>25%</td>
</tr>
<tr>
<td>system attributes and costs.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Task 1. Comparing GH₂ and LH₂ Pathways

**Scenario:** GH₂ or LH₂ pathways for LDV refueling

- **Hydrogen Production:** Central SMR 50-350 TPD in CA, 350 TPD in TX
- LH₂ transmission from Gulf coast to northern CA by cryogenic tankers (up to 180,000 m³ capacity)
- LH₂ storage at plant site and satellite terminal. Storage requirements depend on number of ships utilized on route
- GH₂ pathway includes 10 days of geological storage (lined rock cavern) for plant outages

**Shipping Distance Examples:**
- Port of LA to Tokyo = 4,853 nm
- Geelong (Australia) to Tokyo = 4,910 nm

*ECA=Environmentally Controlled Area (SOₓ+NOₓ)*
Liquefaction of Hydrogen – Cost factors

**LH₂ Storage Costs**

**Current Technology**
- Storage: Spherical layout, vacuum insulation with glass-bubbles
- Boil-off losses modeled using NASA data for spherical vessels
- H₂ losses during unloading: 0.15%
- Cost of storage dominated by material and welding costs. Cost similar between LNG and LH₂

**LH₂ Liquefaction Costs**

**Current Technology**
- LN₂ pre-cooled Claude cycle
- Max liquefier unit: 100,000 kg/day
- Electricity consumption: 10 kWh/kg-H₂
- H₂ losses due to compressor seal: 0.5%
- LH₂ storage: A minimum of 10 days for plant outages at plant gate

---

1 Connelly, E., Penev, M., Elgowainy, A. and Hunter, C. DOE Hydrogen and Fuel Cells Program Record, Record #: 19001, September 9, 2019
Carrier limited in capacity to ~178,000 m³ based on Panama Canal size restrictions

- LH₂ carrier specifications and cost structure assumed similar as LNG Moss type carriers (cost of storage between LH₂ or LNG essentially same)
- Round-trip time: 23-31 days depending on carrier size (15-20 kts at sail; 8 h to pass Panama Canal, 24 h to unload and load shipment)
- Ships that operate in Emissions Control Areas (ECA) must limit sulfur content in fuel to <0.1% and use more costly low-sulfur marine gas oil (LSMGO).
- Carrier will spend 27% of its time in ECA zones (sail & at berth). LSMGO as fuel will be used during entire trip
- Panama canal fees vary with ship length, width and laden conditions
- Insulation thickness limited to 1.8 m based on usable¹ storage and width of ship

¹Usable storage: 90% (5% ullage, 5% heel to keep tanks cooled during return trip)
We are using LSMGO as the reference fuel for maritime applications considered in this study.

- Small difference in price of MGO and LSMGO. As of end of 2019 cost of LSMGO is $650/Tonne (LHV = 42.8 MJ/kg, 900 m$^3$/kg)
- Main fuel consumption occurs at sail. Engine operates at 90% of rated power for maximum fuel efficiency. Auxiliary power needed typically 10% of propulsion power
- Specific fuel consumption decreases with engine size (bigger engines operate at low RPM ~100 with efficiencies approaching 50%)

\[\text{Specific Fuel Consumption, g/kWh}\]

\[\text{Carrier Capacity, m}^3\]

---

Carrier Cost Factors (Capex + Opex)

Panama canal fees per roundtrip are based on laden conditions (MCH/Toluene)

- Canal fees decrease (on DWT basis) as ship increases in cargo capacity.
- Additional port fees included at $2/DWT-day.
- Capex of ship as function of size (DWT) based on statistical data around global shipyards. Additional cost of 25% will be included due to maritime commerce between U.S. ports

- Crew size complement: 4 Deck officers, 4 engineers, rest as deckhand

---

1 The Jones Act requires goods shipped between U.S. ports to be transported on ships that are built, owned, and operated by United States citizens or permanent residents

Symbols: $2016 adjusted costs from multiple literature sources

Majority of current LNG fleet
Crew: 25-30

CAPEX ($/m$^3$)=$243,772x(vol)^{-0.435}$
LH₂ Transmission Costs Consider an Optimum of Ship vs. Storage Costs

- **Economy of scale favors large tankers (single ship per route)**
- **Lowest cost is an optimum of more ships per route vs. lower storage costs**
- **Lowest cost for carriers larger than 50 TPD daily demand is ~3 ships per route**

### Carrier Specific Costs
- Capacity: 30 TPD
- 2 Carriers @ 12,000 m³ (18 days of storage)

- Capacity: 350 TPD
  - 3 Carriers @ 51,000 m³ (12 days of storage)
  - 1 Carrier @ 51,000 m³ (27 days of storage)

### Cost Breakdown

- **CAPEX [-25% 0 +30%]**
- **Fuel Cost [450 650 1000]**
- **Service Life [30 25 18]**
- **IRR [8% 10% 15%]**

### Symbols:
- Model data

### Transmission Cost, $/kg-H₂

- **Cost Factor**: $0.99/kg-H₂
- **Symbols**: LH₂ Transmission Cost, $/kg-H₂

### Daily Demand vs. Number of Carriers on Route

- **350 TPD Case**
- **Ship**, **Storage**, **Total**

### Cost Breakdown Summary

- **O&M = Fuel, Fees, Maintenance, Insurance, Crew+Administrative fees (Admin.)**
### Pathway Cost of Hydrogen

<table>
<thead>
<tr>
<th>Pathway Cost of Hydrogen, $/kg-H₂</th>
<th>50 TPD (50 TPD liquefier unit train)</th>
<th>350 TPD (100 TPD liquefier unit train)</th>
<th>Liquefaction Cost Break-Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA (GH₂)</td>
<td>$8.58</td>
<td>$6.17</td>
<td>$2.15/kg-H₂</td>
</tr>
<tr>
<td>CA (LH₂)</td>
<td>$3.27</td>
<td>$2.27</td>
<td>$2.86/kg-H₂</td>
</tr>
<tr>
<td>TX-&gt;CA (LH₂)</td>
<td>$10.41</td>
<td>$7.05</td>
<td></td>
</tr>
</tbody>
</table>

#### Liquefier TX¹ (100 TPD Train)
- CAPEX: 12%
- Energy: 60%
- O&M: 28%

#### Liquefier CA¹ (100 TPD Train)
- CAPEX: 46%
- Energy: 45%
- O&M: 9%

---

- **GH₂ pathway** incurs lowest costs for application end-use (LDV fleet) at demands from 50-350 TPD (700 bar on-board storage).
- **Dispensing assumptions.** 50 TPD (400 kg/day refueling station), 350 TPD (1,000 kg/day refueling station).
- **Utilizing a lower H₂ production costs in TX** is counteracted by high storage and transmission costs.
- **Advantage of lower costs of LH₂ distribution and dispensing vs GH₂** at large capacities (350 TPD) restrained by high liquefaction costs (capital + energy) given incumbent technology.

¹*Price of Electricity (EIA.gov 2019 industrial yearly average): TX = c5.79/kWh, CA = c12.5/kWh*
1000 kg-H₂/Day Modular Refueling Station

- 4 x 250 kg-H₂/day dispensers
- 250- or 540-bar tube trailer
- Storage tubes valved separately or as high-, medium- and low-pressure cascade

Translated Hourly Demand to Charging Schedule

- 72 vehicles charged daily per dispenser
- 3.5-kg H₂ charged per vehicle, 1 kg/min H₂ refueling rate
- 2-min lingering time prior to post charging
Fracture Durability of Type-II Tanks


- Code Case 2938: Design equations for high pressure cH₂ storage vessels
- Fracture mechanics test methods and testing validity
- Formulation of master curve for fatigue crack growth in gaseous hydrogen*

**Model Parameters**

- **Design Pressure:** 932 atm
- **Safety Factor:** 2.5
- **Tank ID:** 33.1 cm
- **Liner Material:** SA-372 Grade J
- **Liner Thickness:** 38.1 mm
- **CF Thickness:** 14 mm
- **Initial Crack Thickness:** 0.84 mm

*Fatigue Design Curves. ASME BPVC VIII.3KD-10.*
Buffer Storage Requirement

Constrained optimization model

- Variable 1: Tank volume
- Variables 2-N: Upper pressure limits for N tanks
- Constraint 1: Refuel all vehicles on busiest day
- Constraints 2-N: 25-year durability of N tanks

Summary of important results

- Larger compressors → Smaller buffer storage requirement
- Larger compressors → Higher cost, more idle time and on-off cycles
- More number of tanks → Smaller buffer storage requirement
- More number of tanks → More control valves
- Smaller buffer storage requirement with separate charge and discharge tubes
Buffer storage requirement minimized by utilizing lower pressure tanks more than higher pressure tanks

- Refueling priority: HP1 > HP2 > MP > LP2 > LP1
- Discharge priority: LP1 > LP2 > MP > HP2 > HP1
- H₂ discharge (250 kg/day total): Daily H₂ demand met by a tank

Sample results for compressor flow rate 150% of average daily demand

- 5-tank cascade: 76 kg-H₂ stored 360 L tanks storing 17.2, 16.8, 14.4, 14.6, and 13.6 kg-H₂ per tank
- 24-tank cascade: 68 kg-H₂ stored 70 L storing 2.5 - 3.3 kg-H₂ per tank
Pressure and Temperature Cycles

5-tank buffer storage system, 150% compressor discharge flow rate, 360 L/tank

- High pressure limit: 932/896/711/724/652 atm for HP1/HP2/MP/LP2/LP1
- Maximum pressure swing: 94/214/328/168/346 atm for HP1/HP2/MP/LP2/LP1
Fracture life depends on pressure swing ($\Delta P$), mean pressure, and actual pressure cycles

- Possible to track residual tank life by recording its pressure history
- Modeled life: 25 years (657,000 vehicles)
Optimizing as Tube Banks

Optimum 3-bank arrangement: sample results for 150% compressor flow rate

- 5-tube cascade: 2 in high-pressure bank, 2 in medium-pressure bank, and 1 in low-pressure bank
  High pressure limit: 932/807/674 atm for HP/MP/LP banks
  Maximum ΔP: 104//260/340 atm for HP/MP/LP banks

- 24-tube cascade: 8 in high-pressure bank, 12 in medium-pressure bank, and 4 in low-pressure bank

2-2-1 Cascade Storage System
Task 3: Hydrogen Storage for Medium and Heavy-Duty Trucks

Packaging Options

- Behind the Cab
- Frame Mounted
- Roof Mounted

Results for fixed OD and OL tanks: 15/26.5/32-DGE CNG tanks
- Storage volume loss compared to CNG tanks: up to 20%, ΔV CcH₂ > 700 bar > 350 bar
- LHV loss compared to CNG tanks: up to 72%, ΔLHV 350 bar > 700 bar > CcH₂

http://www.a1autoelectric.com

OD: outer diameter; OL: outer length
Carbon fiber composite requirements for same usable H₂
- ABAQUS/WCM FEA and FE-SAFE simulations
- 2.25 burst safety factor
- 15,000 pressure cycles
- CcH₂ << 350 bar Type-3 cH₂ ~ 350 bar Type-4 cH₂ << 700 bar Type-4 cH₂
Model Calibration and Validation

- ANL-Ford working group set up to calibrate and validate ANL ABAQUS model with data available at Ford and simulations using their FE model

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>T700 Fiber</th>
<th>T700 Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>4900 MPa</td>
<td>2550 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>230 GPa</td>
<td>135 GPa</td>
</tr>
<tr>
<td>Strain at Failure</td>
<td>2.10%</td>
<td>1.70%</td>
</tr>
<tr>
<td>Tensile Strength (Failure Strain Basis)</td>
<td>2295 MPa</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>1.8 g/cc</td>
<td></td>
</tr>
<tr>
<td>Translation Efficiency</td>
<td></td>
<td>78%</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>0% for hoop</td>
<td>15% for helical</td>
</tr>
</tbody>
</table>

![Graph showing Tank Volume vs. Outer Diameter](image)

![Graph showing Composite Thickness vs. Outer Diameter](image)
New T700 composite data shows 12% higher tensile strength and 19% higher failure strain

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank type</td>
<td>IV</td>
<td></td>
</tr>
<tr>
<td>Tank interior diameter</td>
<td>cm</td>
<td>39.6</td>
</tr>
<tr>
<td>Tank interior length</td>
<td>cm</td>
<td>118.9</td>
</tr>
<tr>
<td>Usable H₂</td>
<td>kg</td>
<td>5.6</td>
</tr>
<tr>
<td>Total H₂ stored</td>
<td>kg</td>
<td>5.8</td>
</tr>
<tr>
<td>Nominal working pressure</td>
<td>bar</td>
<td>700</td>
</tr>
<tr>
<td>Minimum empty pressure</td>
<td>bar</td>
<td>15</td>
</tr>
<tr>
<td>Hydrogen temperature</td>
<td>°C</td>
<td>15</td>
</tr>
<tr>
<td>Liner material</td>
<td></td>
<td>HDPE</td>
</tr>
<tr>
<td>Liner thickness</td>
<td>cm</td>
<td>0.5</td>
</tr>
<tr>
<td>Carbon fiber</td>
<td></td>
<td>T700S</td>
</tr>
<tr>
<td>CF tensile strength</td>
<td>MPa</td>
<td>4900</td>
</tr>
<tr>
<td>Fiber density</td>
<td>g/cc</td>
<td>1.8</td>
</tr>
<tr>
<td>Resin</td>
<td></td>
<td>Vinyl Ester</td>
</tr>
<tr>
<td>Resin density</td>
<td>g/cc</td>
<td>1.138</td>
</tr>
<tr>
<td>Fiber volume fraction</td>
<td></td>
<td>60%</td>
</tr>
<tr>
<td>Translation efficiency</td>
<td></td>
<td>Hoop: 92% Helical: 78%</td>
</tr>
<tr>
<td>Composite strength</td>
<td>MPa</td>
<td>2860</td>
</tr>
<tr>
<td>Design safety factor</td>
<td></td>
<td>2.25</td>
</tr>
<tr>
<td>Manufacturing COV</td>
<td></td>
<td>3.30%</td>
</tr>
<tr>
<td>Fiber COV</td>
<td></td>
<td>3.30%</td>
</tr>
<tr>
<td>Manufacturing overdesign</td>
<td></td>
<td>14%</td>
</tr>
<tr>
<td>Effective safety factor</td>
<td></td>
<td>2.57</td>
</tr>
</tbody>
</table>

Material Properties

<table>
<thead>
<tr>
<th>T700 Fiber</th>
<th>T700 Composite Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2018 Data</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>4900 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>230 GPa</td>
</tr>
<tr>
<td>Strain at Failure</td>
<td>2.10%</td>
</tr>
<tr>
<td>Tensile Strength based on Failure Strain</td>
<td>2295 MPa</td>
</tr>
<tr>
<td>Density</td>
<td>1.8 g/cc</td>
</tr>
<tr>
<td>Translation Efficiency (Failure Strain Based)</td>
<td>78%</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>15% for Hoop</td>
</tr>
<tr>
<td></td>
<td>28% for Helical</td>
</tr>
</tbody>
</table>

We are projecting that, with the new T700 composite data, the composite mass for a 5.8 kg, 700-bar tank can be reduced to 78 kg

- 2.57 effective safety factor as in 2018 record
- 92% hoop translation efficiency
- 78% helical translation efficiency

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hoop</td>
</tr>
<tr>
<td>Hoop</td>
<td>36.8</td>
</tr>
<tr>
<td>Helical</td>
<td>26.1</td>
</tr>
</tbody>
</table>

2015 Baseline, Prior T700S Data

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hoop</td>
</tr>
<tr>
<td>Hoop</td>
<td>16.5</td>
</tr>
<tr>
<td>Helical</td>
<td>11.9</td>
</tr>
</tbody>
</table>

2020 Baseline, 2020 T700S Data
Reinforced Dome and Doilies (90 L Tank)

- **Metal-Reinforced Dome Concept**
  - Covering the dome section with varying thickness
  - 17% reduction in composite weight: 51 kg to 42.5 kg

- **Doily-Reinforced Dome Concept**
  - Ford simulations confirm that doilies can reduce the composite weight by 6%.

---

Presented by Bert (Ford Motor)
Alternate Fiber (90 L)

- Composite properties (failure strain, $\varepsilon_f$)
  - T700/epoxy: 1.7%
  - Alternative fiber: 1.35%

- Alternative fiber in outer hoop layers only
  - Replacing 4.95-mm of outer hoop with alternative fibers reduces T700 composite mass by 10.7%, but the overall composite mass increases 2.5%

- Alternative fiber in outer hoop and helical layers (100%)
  - Low-cost alternative fiber represents ~50% of total composite weight
  - 46% decrease in high-cost T700 composite
  - 6.4% increase in total composite weight

<table>
<thead>
<tr>
<th></th>
<th>Fiber</th>
<th>Baseline</th>
<th>Hoop</th>
<th>Hoop &amp; Helical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoop T700</td>
<td>13.2</td>
<td>8.25</td>
<td>8.25</td>
<td></td>
</tr>
<tr>
<td>alt</td>
<td>0</td>
<td>5.78</td>
<td>5.78</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>13.2</td>
<td>14.03</td>
<td>14.03</td>
<td></td>
</tr>
<tr>
<td>Helical T700</td>
<td>16.5</td>
<td>16.5</td>
<td>9.9</td>
<td></td>
</tr>
<tr>
<td>alt</td>
<td>0</td>
<td>0</td>
<td>7.43</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>16.5</td>
<td>16.5</td>
<td>17.33</td>
<td></td>
</tr>
<tr>
<td>Total T700</td>
<td>29.7</td>
<td>24.75</td>
<td>18.15</td>
<td></td>
</tr>
<tr>
<td>alt</td>
<td>0</td>
<td>5.78</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>29.7</td>
<td>30.53</td>
<td>31.35</td>
<td></td>
</tr>
</tbody>
</table>
Argonne develops the storage system configuration, determines performance, identifies and sizes components, and provides this information to SA for manufacturing cost studies.

<table>
<thead>
<tr>
<th>Hydrogen Carriers</th>
<th>HyMARC: PNNL, NREL, LBNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Storage</td>
<td>ANL (H2A Group), ANL (HDSAM), H2IT Taskforce</td>
</tr>
<tr>
<td>Compressed Hydrogen (cH₂) Storage for Trucks</td>
<td>SA Team: SA, ANL, PNNL Ford</td>
</tr>
<tr>
<td>Cryo-Compressed Hydrogen (CcH₂) Storage for Trucks</td>
<td>HMAT: PNNL, SNL LLNL</td>
</tr>
<tr>
<td>Liquid Hydrogen Storage (LH₂) for Locomotives and Marine Applications</td>
<td>Chart Industries</td>
</tr>
<tr>
<td>Off-Board Cost</td>
<td>ANL (H2A Group), ANL (HDSAM), H2IT Taskforce</td>
</tr>
<tr>
<td>On-Board Cost</td>
<td>Strategic Analysis Inc (SA)</td>
</tr>
</tbody>
</table>
Future Work

1. Hydrogen Carriers
   - Scenarios that favor hydrogen carriers such as by-product H₂
   - Case studies with different demand and supply scenarios
   - Carriers that are particularly suitable for renewable hydrogen production and energy storage
   - Reverse engineering to determine desirable properties of liquid carriers including ease of dehydrogenation and H₂ purification
   - Coordination with HyMARC consortium to analyze emerging materials
   - Investigate H₂ liquefaction cycles to understand limitations in unit train capacity, and possible cost and energy reduction

2. Bulk Storage of Hydrogen
   - Continue to explore different storage methods (geological and non-geological), storage capacities (1-10 days), and storage locations (city gate vs. forecourt)
   - Investigate advanced H₂ liquefaction cycles to understand limitations in unit train capacity, and possible cost and energy reduction
   - Alternate bulk LH₂ storage methods, boil-off recovery and reliquefaction

3. Hydrogen Storage for Heavy-Duty Applications
   - Continue to conduct finite element simulations to verify cycle life and carbon fiber requirements
   - Liquid hydrogen storage for locomotives and maritime applications

Any proposed future work is subject to change based on funding levels
## Project Summary

<table>
<thead>
<tr>
<th>Relevance:</th>
<th>Independent analysis to evaluate on-board and off-board performance of materials and systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach:</td>
<td>Develop and validate physical, thermodynamic and kinetic models of processes in physical and material-based systems. Address all aspects of on-board and off-board targets including capacities, rates and efficiencies</td>
</tr>
<tr>
<td>Progress:</td>
<td>Established benchmark costs for H₂ production by SMR, liquefaction, storage, transmission, distribution, and dispensing. Developed a model for fracture durability of Type-2 tanks and determined pressure limits for 25-year lifetime. Calibrated ABAQUS models for H₂ storage in Type-3 and Type-4 tanks and showed the possibility of lowering the status number for carbon fiber composite requirement. Showed that 33–54 kg of usable H₂ can be stored in roof mounted, behind-the-cab and frame-mounted tanks being offered for compressed natural gas trucks.</td>
</tr>
<tr>
<td>Collaborations:</td>
<td>Ford, HyMARC, LLNL, PNNL, SA, Delivery Team</td>
</tr>
<tr>
<td>Proposed Future Work:</td>
<td>Determine desirable material properties and analyze scenarios that favor hydrogen carriers. Complete analysis of stationary hydrogen storage for different scales, duration and applications. Validate results for hydrogen storage on-board HDVs and MDVs</td>
</tr>
</tbody>
</table>
Generally favorable reviews with the following comments/recommendations

- The approach is straightforward and rational. This project continues to serve a valuable role.
- The inclusion of large production plants for the carriers demonstrates notable progress. The bulk storage analysis is a helpful reference for infrastructure and H2@Scale analysis.
- This project is very relevant to DOE’s current focus. The inclusion of MD and HD vehicles to the scope of interest and the prevalence of H2@Scale and its associated projects further enhance the project’s relevance.
- FY20 work scope consistent with recommendations
  - Fostered closer interactions with Ford to calibrate and validate ANL ABAQUS model with data available at Ford and simulations using their FE model.
  - The hydrogen carriers were compared to liquid hydrogen as to complete the baseline scenarios.
  - Calibrated ABAQUS models for H₂ storage in Type-3 and Type-4 tanks and showed the possibility of lowering the status number for carbon fiber composite requirement.
  - Developed models for fracture durability of Type-2 tanks and determined pressure limits for 25-year lifetime.