Liquid Hydrogen Infrastructure Analysis

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Overview

Timeline and Budget

- Start date: January 2017
- End date: December 2017
- % Complete: 5%
- FY16 DOE funding: $50k
- FY17 DOE funding: $190k
- Total DOE Funds Received to date: $240k

Barriers

- A. Lack of Hydrogen and Infrastructure Options Analysis
- C. Reliability and Costs of Hydrogen Pumping

Partners/Collaborators

- LLNL (lead)
- Linde: LH₂ pump operation & maintenance, LH₂ delivery
- BMW: LH₂ pump operation
- Argonne National Lab: H₂ infrastructure, interface with HDSAM
Relevance: Liquid hydrogen (LH₂) has many benefits for the hydrogen infrastructure, especially at large scale(s)

- High density LH₂ allows minimum volume & mass per kg H₂, thus minimum cost
- High capacity per truck & short transfer times minimize delivery logistics/scheduling
- Low potential burst energy: 20 K and <6 bar vs. 300 K and >200 bar
- LH₂ pumps provide high throughputs (120+ kg/hr) at low dispensing costs
- High density of LH₂ can be transferred to compact onboard solutions (cryo/cold)

Challenges for LH₂:
- High cost of liquefaction (~3 X compression)
- Refueling station integration (setback distances limitations)
- Transfer and boil-off losses

Goal of effort: better understand/quantify losses along LH₂ pathway
Relevance: Cryo-compressed H$_2$ (CcH$_2$) storage exhibits high system densities and affordable cost, that scale well with capacity.

<table>
<thead>
<tr>
<th></th>
<th>Gravimetric</th>
<th>Volumetric</th>
<th>System cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 bar</td>
<td>4.4%</td>
<td>24 gH$_2$/L</td>
<td>$15 / kWh</td>
</tr>
<tr>
<td>CcH$_2$</td>
<td>7.5%*</td>
<td>45 gH$_2$/L*</td>
<td>$12 / kWh</td>
</tr>
<tr>
<td>MOF 5</td>
<td>4%</td>
<td>20 gH$_2$/L</td>
<td>$16 / kWh</td>
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</tbody>
</table>

*demonstrated at LLNL on 10 kg H$_2$ system

Challenges for CcH$_2$:
- Composite vessel outgassing in vacuum chamber necessitates mitigation
- Material performances at low temperatures not well characterized
- No recognized standards (SAE, ISO..), although CcH$_2$ mentioned in GTR
**Approach** : Simulate LH$_2$ pathway using a thermodynamic model to estimate, then mitigate, transfer & boil-off losses

Transfer and boil-off losses occur all along the LH$_2$ pathway.
**Previous work (PD134, Simon): WTW and emission for CcH₂ pathway**

**Approach to estimating potential station boil-off and net losses**

Previous work identified H₂ losses based on LLNL setup and evaluated them in the HDSAM framework.

[A] Dewar: 5.5 kg/day for a 725 kg tank.

[B] Lines: 0.3 kg/day per line.

[C] Pump: 1.1 kg/day per pump.

[D] Pumping: 0.06 kg/kg-dispensed at 700 bar.

[E] Avoided losses: 0.073 kg H₂ must be evaporated per kg H₂ dispensed.

[F] Delivery losses (cold vapor displacement, bottom-fill): up to 0.07 kg vented per kg-LH₂ delivered.

[G] Station-related losses from the high pressure section are assumed to be zero.

**Accomplishment: Illustrate all potential boil-off losses**

**Accomplishment: Cost and Emissions Analysis**

- For the analysis depicted below (320 kg/day station), the cost of hydrogen is $7.85/kg and the cost of ownership is $0.44/mi.

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Previous work identified H₂ losses based on LLNL setup and evaluated them in the HDSAM framework.
**Approach**: Simulate LH₂ pathway using a thermodynamic model to estimate, then mitigate, transfer and boil-off losses

**Task 1: Simulate boil-off losses from the liquefaction plant to car dispensing**
- Build/adapt thermodynamic model with real gas EOS and 2 phases for LH₂ pathway
- Evaluate optimal conditions that would minimize boil-off
- Propose improvements to existing procedures/setups

**Task 2: Simulate on-board losses for cryo-compressed vehicles**
- Gather real-life driving scenarios over a large population
- Build refueling/parking/driving model for cryo-compressed vehicle, including real gas EOS, tank thermal mass, para/ortho kinetics
- Quantify boil-off losses on cryo-compressed vehicles

**Task 3: Boil-off recovery technologies**
- Identify the source(s) of most significant boil-off along the LH₂ pathway
- Review main boil-off recovery options
- Evaluate costs and performances

Modeling entire LH₂ pathway enables quantitative understanding
Approach (task 1): Simulate H₂ losses from liquefaction plant to car using existing NASA code, written for rocket loading with LH₂.

From Osipov and Daigle, 2011

Interaction between two LH₂ volumes and dynamic effects

Condensation/evaporation, energy balance

Heat transfer modes with saturated film

Existing code from NASA provides framework for LH₂ transfer analysis
**Accomplishments (task 1):** NASA code is being modified in order to account for specifics of LH₂ infrastructure

Features to modify/add in original code:

- Real gas EOS, especially single to 2 phase transition for the vapor
- Geometry (tanks size and shapes, valve diameters...)
- Need non-constant liquid temperature, to simulate subcooled conditions
- Update default parameters (heat transfer coefficients, time constants....)
- Top fill into stationary Dewar
- Add return line for pump’s storage vessel

**Vapor cooling rate function of** \( \Delta(P_{\text{vap}}-P_{\text{atm}}) \)

Existing code from NASA will be adapted to our specific conditions
**Approach (task 2):** Simulate cryo-compressed vehicle’s refueling/driving/parking cycles in order to estimate boil-off losses.
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Influence of utilization patterns on boil-off (and max capacity) will be simulated using a thermodynamic model.
Approach (task 2): Simulate cryo-compressed vehicle’s refueling/driving/parking cycles in order to estimate boil-off losses

Driving data will be collected in order to simulate boil-off losses of a variety of driving cycle patterns (wide population).

**Key information needed:** parking duration and distance driven, per day.

Both passenger and fleet vehicles are being considered for now.

Sources for driving data:

- California Road Charge Pilot – 9 months, ~5000 users
- UC Davis
- NREL (Secure Transportation Data Center)
- INL (Advanced Vehicles)
- ...

Boil-off losses will be estimated using a statistical approach.
Approach (task 3) : Identify boil-off recovery technologies/processes that could reduce/eliminate $H_2$ losses along LH$_2$ pathway

Wealth of technologies have been studied by NASA (ZBO concepts).

Possible main sources of losses:

- Trailer depressurization after delivery (50-70 psi to atm)
  *Mitigation*: trailer “shake-down”, low entropy LH$_2$ pump...

- Station Dewar
  *Mitigation*: low footprint compressor (electro-chemical, metal hydride cryo-cooler), fuel cell...

- Pump Dewar:
  *Mitigation*: bottom return recirculation into main Dewar...

- Vehicle:
  *Mitigation*: charge batterie(s), run A/C...

Different approaches will be analyzed based on flow rates, T and P...
AMR 2016 feedbacks from reviewers (PD134, CcH₂ pathway analysis)

Project is estimating 'potential' boil-off, not necessarily estimating 'actual' boil-off?
Last year’s effort was focused on identifying boil-off losses at the CcH₂ station and integrate those results onto HDSAM. FY17 effort is aimed at quantifying those losses.

Not clear if initial description of cryo-compressed is 350 bar or 700 bar. Pressure is not believed to have strong impact at the station level. Both 350 bar (BMW) and 700 bar (LLNL) options are actually investigated through dedicated programs. FY17 effort will address 350 bar only.

Why are "losses from vehicles" after dispensing included in overall boil-off loses? Those losses are being paid by the customer, so they should be included in total boil-off budget.

Consider assessment of mitigation strategies for boil-off (in addition of what was presented in reviewer only slides). FY17 effort will address this.

Use of the HDSAM to perform analysis was selected because it was "directed by the program" according to the presenter. It seems, however, that this approach is backwards, and instead a complete analysis of the pathway should inform building the HDSAM model. We have an on-going relationship with ANL and changes to HDSAM can be made if needed.

Cryocompressed does not seem to be a realistic future pathway. Only a single OEM is on-board, collaborating. It is unclear why DOE funds are being allocated to this pathway. Cryo-compressed has many benefits, especially at large scale (large demand and large vehicle capacity). Although not considered for short term H₂ deployment (like some other DOE funded technologies...), cryo-compressed technology should be fully understood so that it is mature if/when limitations on current technologies are reached.
Collaborations with Industry Leaders

- **Linde**: Very cooperative, sharing detailed information throughout pump development, construction, and installation. Interpreting and sharing data from multiple pumps, and on LH$_2$ deliveries.
Risks/Challenges for FY17 milestones, Future work

- **Verify that LH$_2$ pathway code behaves as expected**
  - **Challenge**: Although the code looks appropriate to estimate losses during LH$_2$ transfer, a few modifications need to be made (2 phase EOS, top fill, subcooled...)
  - **Solution**: The code is being studied intensively and upgraded. We should know soon enough whether the code is appropriate.

- **Obtain park/drive/fill cycle patterns**
  - **Challenge**: We need to obtain parking duration and distance driven, per day, of a wide statically representative population, over a long period (week to month to year). As of now, we have not been able to secure the adequate source of data.
  - **Solutions**: On-going discussions with Cal Road Charge Pilot, reached out to UC Davis (STEPS, Dr. Nicholas). Hopeful sets of data from EV effort may be available.

Critical challenges are being addressed early in the project
Relevance
LH₂ has great benefits for large scale(s) hydrogen deployment (cost, logistics, safety..), better understanding of losses is necessary

Approach
Simulate losses mechanisms along the LH₂ pathway (transfer and boil-off : liquefaction plant -> trailer -> station Dewar -> pump -> cryo-compressed car), using real gas EOS and 2 phases, including statistical approach for variety of park/drive/fill scenarios

FY17 Progress
Project just started (3 months)
Simulation framework is being modified
Driving scenarios are being collected

Future work
Verify thermodynamics codes (pathway + park/drive/fill)
Run typical cases
Propose mitigating procedures/technologies

Summary: LLNL will develop and exercise models to simulate boil-off losses from plant to car for LH₂ pathway, propose mitigation solutions
Technical back-up slides
Cryogenic H\textsubscript{2} offers rapidly refueled storage with volume, capacity, & safety advantages that outweigh technical challenges

- High density (cryo) H\textsubscript{2} allows minimum vessel volume & mass per kg H\textsubscript{2}, thus \textit{minimum} cost
- Min burst energy @ refueling, high on-road safety factor (5-10), inert secondary containment
- Integrated with large scale LH\textsubscript{2} pathway, low station footprint (100+ kg/hour, < 1.5 kWh\textsubscript{e}/kg)

\textbf{Challenges for the technology:}

- \textit{Compact} vacuum jacket necessary for system density
- Need both minimum heat transfer (parking) \textit{AND} strong suspension (driving)
- Temperature \textit{variations} alter material properties, density, dormancy, H\textsubscript{2} burst energy

\textbf{Projections:} 5 kg H\textsubscript{2} system at 700 bar with 9+ wt\% & 50 g/L
Technical challenges for cryo-compressed H₂ storage

Cryogenic durability of Type III composite pressure vessels, especially for the liner, is unknown

- Other project addressing this by building & cycle testing specifically designed Type III vessels.
- Cryogenic durability is aided by improved material properties at low temperatures:
  Metal: Increased yield and ultimate stress. Fiber: increased stiffness.

Driving range inconsistency due to cryogenic refueling might not be acceptable for the driver

- Driving range remains constant once driving habits are established and maintained.
- Driving range is self-regulated:
  • Frequent use maintains the vessel cold and enables high density refueling
  • Infrequent use warms up vessel and reduces fill density, avoiding fuel venting
- Higher pressure helps reduce driving range variations

The composite of the vessel outgasses over time, reducing the performance of the insulation

- Preliminary results show that cryogenic temperatures reduce outgassing (“cryo-pumping”)
- It is still critical to demonstrate a long-term solution to vacuum stability
- We have proposed a promising approach and look forward to demonstrating its feasibility
**Approach (task 2):** Cryo-compressed vehicles have a very dynamic behavior in terms of Temperature, Pressure and Capacity.

*Real life data obtained w/ 10 kg proof-of-concept vehicle*