Rail Refueling Analysis

TA047 – AOP 9.2.0.2

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2021 DOE Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR)

June 10, 2021
Assess **gaseous and liquid** hydrogen refueling for **freight and passenger** rail to identify examples of **scale, size, and cost** of refueling infrastructure.

This assessment will better inform future efforts for rail stakeholders on the configuration of rail refueling infrastructure and identify areas for future improvements.

- Scale and capacity of refueling facility designs will *identify needs* for future component development
- Comparison of different facility designs will show examples to *quantify trade-offs* of technologies and scale
- Approximate cost estimates can *inform future analyses* and identify areas for future research and development
Overview

Timeline
Project start date: May 2020
Project end date: June 2021

Budget
FY20 DOE Funding: $200k

Barriers
A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis
   I. Other Fueling Site/Terminal Operations
   K. Safety, Codes and Standards, Permitting

Partners
Research collaborators:
• Argonne National Laboratory
Rail Stakeholders:
• Caltrans, SBCTA, DB Engineering & Consulting
Relevance: Refueling Infrastructure for New Rail Applications

Goal: Assess gaseous and liquid hydrogen refueling for freight and passenger rail to identify examples of scale, size, and cost of refueling infrastructure.

<table>
<thead>
<tr>
<th>Barrier from 2015 Delivery MYRDD</th>
<th>Impact</th>
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</thead>
<tbody>
<tr>
<td>A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis</td>
<td>Provide example designs, including equipment sizes, facility cost, and facility footprint</td>
</tr>
<tr>
<td>I. Other Fueling Site/Terminal Operations</td>
<td>Evaluate how refueling facilities can scale to larger systems and what trade-offs may arise</td>
</tr>
<tr>
<td>K. Safety, Codes and Standards, Permitting</td>
<td>Identify main drivers of station footprint, including physical equipment and separation distances</td>
</tr>
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</table>
Approach: Bottom-Up Example Designs for Rail Refueling

Example designs, not complete enumeration/optimization
- Individual real-world needs will differ

Illustrate trade-offs **between designs**
- Gaseous vs. liquid hydrogen
- Large vs. small (economies of scale)
- Passenger vs. freight rail (operational needs)

Identify **key metrics** for each design
- Scale – conditions, flowrates, number of components
- Footprint – physical layout of refueling facility
- Cost – approximate current capital cost estimates

**Milestone**: Draft report of at least 5 designs
- On track – June 2021

<table>
<thead>
<tr>
<th>Design</th>
<th>Trains/Day</th>
<th>State</th>
<th>Config.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Units</td>
<td>10</td>
<td>GH2</td>
<td>MU Train</td>
</tr>
<tr>
<td>Passenger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Locomotive</td>
<td>50</td>
<td>GH2</td>
<td>Locomotive</td>
</tr>
<tr>
<td>Passenger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Freight</td>
<td>5</td>
<td>LH2</td>
<td>Tender</td>
</tr>
<tr>
<td>Freight</td>
<td>50</td>
<td>LH2</td>
<td>Tender</td>
</tr>
<tr>
<td>Medium Freight</td>
<td>50</td>
<td>LH2</td>
<td>Tender</td>
</tr>
<tr>
<td>Large Freight</td>
<td>200</td>
<td>LH2</td>
<td>Tender</td>
</tr>
</tbody>
</table>
Hypothetical Multiple Units Fleet

- **10 MU trains**
  - Actual single-train demonstrations likely to use direct-truck fueling
- **Refueling once per day**
- **260 kg H₂ per MU at 350 bar** (per ANL)

**Time per Refueling**
- 15 minutes → 17.3 kg/min
- 30 minutes → 8.7 kg/min
  - Context: 10 kg/min DOE target for heavy-duty road vehicles
- Not counting connection/idle time

**Total Facility Capacity:**
- **2,600 kg/day**
  - Context: FirstElement Sunnyvale light-duty vehicle station total capacity: 1,600 kg/day

Example H₂ Multiple Units Trains

Small MU fleet refueling facility capacity ~2X capacity of current light-duty vehicle refueling stations

https://cafcp.org/blog/sunnyvale-hydrogen-station-opens
Images:
Progress: Pump vs. Compressor and Pressure Cascade Sizing Options

LH2 on-site storage, dispensing GH2
Assuming LH2 delivery; GH2 delivery trailers have much less capacity
- H2 could also be produced on-site or delivered via pipeline
- LH2 cryopump would need on-site liquefaction

Liquid $\text{H}_2$ storage with gaseous $\text{H}_2$ dispensing gives many options for sizing/optimization

Four Configurations for LH2 Storage

1. Compressor Refuels Directly
   - Larger compressor mass flow rate able to refuel directly
   - Very small cascade system only to stabilize the flow

2. Compressor Supplies Cascade System
   - Smaller compressor replenishes cascade system
   - Larger cascade system capacity supplies refueling

3. CryoPump/Evaporator Refuels Directly
   - Larger cryopump/evaporator flow rate able to refuel directly
   - Very small cascade system only to stabilize the flow

4. CryoPump/Evaporator Supplies Cascade System
   - Smaller cryopump/evaporator replenishes cascade system
   - Larger cascade system capacity supplies refueling
## Progress: Multiple Units Passenger Rail Preliminary Results

<table>
<thead>
<tr>
<th></th>
<th>Compressor Direct</th>
<th>Compressor Cascade</th>
<th>CryoPump Direct</th>
<th>CryoPump Cascade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Compressor/CryoPump Flow Rate [kg/hr]</td>
<td>520-1040*</td>
<td>108</td>
<td>520-1040*</td>
<td>108</td>
</tr>
<tr>
<td>Number of Compressors/CryoPumps</td>
<td>1-2</td>
<td>1</td>
<td>3-6</td>
<td>1</td>
</tr>
<tr>
<td>Number of Evaporators</td>
<td>3-6</td>
<td>1</td>
<td>3-6</td>
<td>1</td>
</tr>
<tr>
<td>Cascade Useable Capacity [kg]</td>
<td>22**</td>
<td>2058</td>
<td>22**</td>
<td>2058</td>
</tr>
<tr>
<td>Number of Cascade Storage Tanks</td>
<td>1</td>
<td>341</td>
<td>1</td>
<td>341</td>
</tr>
</tbody>
</table>

All systems dispense same flowrate of GH2: 520-1040* kg/hr

Example commercially-available components used for number needed to meet flow rate requirements

Evaporator pressures low for pre-compressor, high for post cryopump

* Flow rate ranges for 30 minute and 15 minute fill

** Cascade capacity for direct fill not strictly required, just to even out flow

** Total cost depends on trade-off in component costs; optimum may be somewhere in between extremes
Hypothetical Passenger Locomotive Fleet

- **50 locomotives**
  - Actual single-train demonstrations likely to use direct-truck fueling

- Refueling **once per day**
  - **400 kg** H2 per locomotive at **350 bar**

Time per Refueling

- 40 minutes → 10 kg/min
  - Context: 10 kg/min DOE target for heavy-duty road vehicles

- Not counting connection/idle time

Total Facility Capacity:

- **20,000 kg/day**
  - 7.7X more capacity than MU facility
Progress: Locomotive Passenger Rail Preliminary Sizing Results

50 locomotives, minimum of 40 minutes to refuel each: >33.3 hours of refueling per day

• Simultaneous refueling needed

Assuming 10 hours to refuel entire fleet

• Overnight, passenger operation during the day
• 50 locomotives over 10 hours: 5 locomotives per hour
• Gives 60 minutes total refueling time

Compressor/cryopump flowrate

• LH2 storage, dispensing GH2
• Direct refueling:
  • 5 x 10 kg/min = 5 x 600 kg/hr (individual compressor/pump per dispenser)
  • 50 kg/min = 3,000 kg/hr for consolidated compressor/cryopump(s)
• Cascade refueling
  • 13.9 kg/min = 833.3 kg/hr total to supply cascade over 24 hours (minimum flowrate)
  • Resulting cascade: >11,667 kg dispensed capacity

Larger fleet and more H2 per train means higher capacity components needed for scale
Progress: Liquid Hydrogen Refueling for Freight Rail

LH2 on-site storage, dispensing LH2
- Assuming LH2 delivery
  - H2 could also be produced on-site or delivered via pipeline with on-site liquefaction
- Pressure-build loop could potentially replace cryopump
- Adds heat to storage tank

Direct refueling from pump; no cascade storage
- Vapor return line can be returned to tank or vented
- Could potentially be used for other refueling

Example LNG Fuel Tender Supplying 2 Locomotives [from Chart Industries]

Storage and dispensing of LH2 more conceptually simple, but still multiple possible design options
Progress: Liquid Hydrogen Freight Rail Preliminary Design Inputs

Assuming **7,500 kg** H$_2$ per fuel tender car (from ANL)

Filling Times
- **10 kg/min** (12.5 hours), **300 kg/min** (25 minutes), or **1,200 kg/min** (6.25 minutes)
- Higher flow rates depend on cost and pump availability

Multiple hypothetical designs
- **Small**: 5 trains per day → 37,500 kg/day dispensed capacity
- **Medium**: 50 trains per day → 375,000 kg/day dispensed capacity
- **Large**: 200 trains per day → 1,500,000 kg/day dispensed capacity

Context: current LH2 liquefaction facilities ~10,000-30,000 kg/day; total ~370,000 kg/day in U.S.
  - Largest facilities likely far in future, would represent significant future capacity increase

Simultaneous fueling likely needed for larger stations
- Depends on refueling window (e.g., 24 hours/day or less)
- Individual pumps per dispenser or single variable-flow pump?

Submerged pumps can operate on-demand, no need for pre-cooling

**Freight rail refueling is orders of magnitude greater capacity than vehicle refueling stations**
Progress: Setback Distance Gaps for Siting

Facility footprint depends on **physical equipment footprint** and the **fire code setbacks**

- **Different setback distances to different exposures** (i.e., lot lines, other flammable liquids)
- **Gaseous** hydrogen setback distances depends on **pressure** and **inner diameter**
  - Footprint depends on the pressure and flowrate (which gives diameter) for each design
- **Liquid** hydrogen setback distances depends on amount of **volume** stored
  - May be revised in the near future

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**Separate GH2 and LH2 Setbacks**

**LH2 Setbacks Only**

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Same physical equipment can have different required setback distances depending on facility design and nearby exposures

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Ehrhart et al. SAND2020-2796 [https://doi.org/10.2172/1604872](https://doi.org/10.2172/1604872)
Response to Reviewer Comments

This project was not reviewed previously
Collaboration and Coordination

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Category</th>
<th>Collaborator</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collaborator</td>
<td>National Lab</td>
<td>Argonne National Laboratory</td>
<td>Design inputs based on locomotive design and costing analysis</td>
</tr>
<tr>
<td>Stakeholder</td>
<td>Government Agency</td>
<td>Caltrans</td>
<td>Feedback on design inputs, operating assumptions, and component choices for refueling facility</td>
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<td>San Bernardino County Transit Authority</td>
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Remaining Challenges and Barriers

**Larger-capacity** components *not currently in widespread use*
- Physical dimensions and cost estimates for uncommon equipment difficult to obtain

**Individual project/location** needs will *differ from hypothetical* reference designs
- Many possible optimization options for all designs

**Source of hydrogen** dependent on local availability
- Delivery by truck for very large capacity facilities may be impractical
- On-site production or liquefaction will require additional footprint

Opportunities for **refueling** facilities for **other transportation modes**
- E.g., ports, vehicles
Proposed Future Work

Rest of FY21:
• Obtain basic cost estimates for all designs
• Estimate basic footprint for facility designs
• Estimate basic delivery or production needs for each design

Proposed Work in FY22:
• Assess designs for combined refueling facilities for other transportation modes

Any proposed future work is subject to change based on funding levels
Goal: Assess gaseous and liquid hydrogen refueling for freight and passenger rail to identify examples of scale, size, and cost of refueling infrastructure.

Approach: Bottom-up scale, size, and cost estimates for facility components
- Illustrate trade-offs between designs

Technical Progress:
- Cascade sizing and compressor/cryopump selection examined for multiple units
- Larger gaseous H₂ dispensing system considered for passenger locomotives
- Three sizes of freight rail refueling dispensing liquid H₂ onto tenders
- Facility size depends on equipment layout and fire code requirements

Cost and sizing estimates can help inform future analyses and develop technical targets
Technical Backup and Additional Information
Technology Transfer Activities

Soliciting feedback from and will distribute final technical report to various stakeholders including:

- Caltrans
- San Bernardino County Transit Authority
- Association of American Railroads
- Federal Railroad Administration
- Deutsche Bahn Engineering & Consulting
- Various component manufacturers
Progress Toward DOE Targets or Milestones

2015 Delivery MYRDD, Barrier A: Lack of Hydrogen/Carrier and Infrastructure Options Analysis

- This work analyses a new transportation mode for which hydrogen could make a significant impact
- Initial work considering currently available technology and components will help to inform future analyses, including feasibility studies and technical targets for future research
Special Recognitions and Awards

None for this year.
Publications and Presentations

Presentations:
