The HyRIGHT Project: 700 bar Hydrogen Refueling Interface for Gaseous Heavy-Duty Trucks

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WBS: 8.6.3.304
Project Goals

Heavy-duty truck fueling places additional constraints on the station. The HyRIGHT project was developed to evaluate a subset of key areas around precooling, communications, and safety risks to establish that aims to:

- Utilize a dynamic model that includes the relevant station components and vehicle to develop an optimized precooling strategy based on initial precooling status, real-time communications that can support fueling protocol development.
- Perform a techno-economic cost assessment related to effects of precooling including station storage and efficiency effects.
- Develop a Cyber Vulnerability assessment and framework for refueling of HD vehicles with station communications.
- Disseminate the results in support of the HD fueling protocol development to the relevant standards development organizations.
Overview

Timeline

• Project Start Date: 10/01/2021
• Project End Date: 09/30/2023

Barriers

• Lack of Understanding between precooling performance and cost for high-flow fueling (both station and vehicle impacts)
• Potential Communications Cyber Vulnerabilities
• Risks associated with high-flow fueling

Budget

Total Project Budget: $2.5M
  Total DOE Share: $2.0M
  Total Cost Share: $0.5M
  Total Funds Spent: $846,942*
  Total Cost Share Percentage: 20%

* As of 04/07/2023

Partners

• Savannah River National Laboratory (PI)
• Argonne National Laboratory (co-PI)
• Sandia National Laboratories (co-PI)
• Nikola Motors (Industry Partner)
**Project Impact**  
**High Flow Fueling Target and Progression**

<table>
<thead>
<tr>
<th>Fueling Technology Progression</th>
<th>Current-Gen</th>
<th>Next-Gen</th>
<th>Optimized Commercial Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>Baseline</td>
<td>High-Flow Fueling Hardware</td>
<td>Next-Gen Fueling Protocol and Communications</td>
</tr>
<tr>
<td><strong>Interface Hardware</strong></td>
<td>H70F90 ISO 17268-1</td>
<td>H70F300 ISO 17268-2</td>
<td>H70F300 ISO 17268-2</td>
</tr>
<tr>
<td><strong>Fueling Protocol</strong></td>
<td>SAE TIR J2601-5</td>
<td>SAE TIR J2601-5</td>
<td>ISO 19885-3</td>
</tr>
<tr>
<td><strong>Communications</strong></td>
<td>IRDA / SAE J2799</td>
<td>IRDA / SAE J2799</td>
<td>ISO 19885-2</td>
</tr>
<tr>
<td><strong>Estimated Total Fueling Durations (minutes)</strong></td>
<td>&lt; 20</td>
<td>&lt; 15</td>
<td>&lt;&lt; 15</td>
</tr>
</tbody>
</table>

- Advancements in interface hardware and fueling protocols are expected to enable under 15 minute fueling duration capability.
- Subsequent advancements in communications technology to enable safer communications transfer and less conservative fueling protocols will enable well under 15 minute fueling duration capability.
Relevance/Impact (Precooling)
Examine the precooling temperature required for various tank systems of FC HDVs

• Understand impacts of the various Onboard Hydrogen Storage System (HSS) designs on the required precooling temperature for a range of fueling speeds and boundary conditions. The different HSS designs are provided by the industry stakeholder.

• The HSS designs are characterized by the hydrogen tank type, geometric configuration, rated pressure, and dispensed amount.

• The boundary conditions include initial pressure, ambient temperature, pressure ramp-rate and precooling temperature.

• ANL’s H2SCOPE model has been configured to conduct a large number of simulations to determine the maximum hydrogen precooling temperature required to maintain the vehicle tank temperature below 85°C, while also observing safe maximum state of charge (SOC) at various combinations of ambient temperatures, and pressure ramp rates.
Approach (Precooling)
Transient Heat Transfer Across Fueling Components have been Modeled

H2SCOPE Model

- Continuity equations
- Energy balance equations
- Heat transfer equations
- Equation of state
- Flow equations
- Finite volume method
- Expanded excel VBA based H2SCOPE model (Reddi et al., 2014) to the python version
  - Transient heat transfer for pipes, hose, nozzle, valves etc.
  - Updated ΔP\text{drop} and mass flow rate calculations
  - Used object-oriented programming

Lumped analysis for pipe and hose

Finite volume method for storage tank

Validated with experimental data

Accomplishment (Precooling)

HSS Pipe Diameter Strongly Influences the Pressure Drop, Mass Flow Rate, and Fill Duration

BASE CASE:

APRR = 8.55 MPa/min; P₀ = 10 MPa, T_{amb} = 15 °C (soaked); Pipe Length: 4m; Precooling Temp = -40 °C

Pipe diameter has strong influence on pressure drop
✓ Impacts mass flow rate and instantaneous precooling load
✓ Fill duration
Accomplishment (Precooling)
Boundary Conditions like Pressure Ramp Rate, Initial Tank Pressure and Ambient Temperature Influences Precooling Load

APRR = 8.55-20.0 MPa/min
P₀ = 10 MPa,
Tₐmb = 15 °C (soaked),
Pipe: 3/4” pipe (δ=0.165”),
Length: 4m

Higher initial tank pressure enables faster fueling and reduces the precooling load

APRR = 8.55 MPa/min
P₀ = 2-10 MPa
Tₐmb = 15 °C (soaked)
Pipe: 3/4” pipe (δ=0.165”),
Length: 4m

Lower ambient temperature requires lower cooling loads to achieve maximum SOC%

APRR = 8.55 MPa/min
P₀ = 10 MPa
Tₐmb = 15-50 °C (soaked)
Pipe: 3/4” pipe (δ=0.165”),
Length: 4m

Higher APRR requires lower precooling temperature to obtain higher SOC%
Relevance/Impact/Approach (Precooling)
Hydrogen Precooling strategies include Thermal Buffering and On-demand Cooling

<table>
<thead>
<tr>
<th>Thermal Buffering</th>
<th>On-demand Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large mass of HX (1-3 tons)</td>
<td>Compact HX, large area/volume ratio</td>
</tr>
<tr>
<td>HX mass absorbs heat from H₂</td>
<td>Direct heat exchange b/w refrigerant and H₂</td>
</tr>
<tr>
<td>Refrigerant used to cool and maintain the HX block at target temperature</td>
<td>On-demand cooling during fill</td>
</tr>
<tr>
<td>Small capacity refrigerator (~10 kW)</td>
<td>Large capacity refrigerator (~500 kW)</td>
</tr>
</tbody>
</table>

Elgowainy et al. (2017). Int. J. of hydrogen energy, 42(49), 29067-29079

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Approach (Precooling)

Cost Difference of the Refrigeration Unit for Average and Maximum Flow Rates with On-Demand Cooling HX

<table>
<thead>
<tr>
<th>T_amb (°C)</th>
<th>Max. Flow Rates</th>
<th>Avg. Flow Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$258,000</td>
<td>$541,000</td>
<td>$437,000</td>
</tr>
<tr>
<td>$201,000</td>
<td>$437,000</td>
<td></td>
</tr>
</tbody>
</table>

Uninstalled Cost Difference ~ $104,000

Max. Flow Rates

Avg. Flow Rates

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Approach (Precooling)
Determination of Baseline Refrigeration Method Candidates for Refueling Conditions

- Explored several refrigeration systems based on ANL’s early stage design data.
- Conventional single stage compression system, cascade system, mixed gas refrigeration system, reverse Brayton cycle, and vortex tubes are considered.
- Various parameters such as refrigerant mass flow rate, evaporation temperature, condensing temperature, superheat, subcooling, evaporation temperature of the interstage evaporation temperature, initial temperature difference between hot and cold flow streams, refrigerant mixture ratio, refrigeration combination, etc. are investigated.
- It is found that the reverse Brayton cycle and vortex tubes are not cost-effective solutions.
- The single stage compression system, the cascade system, and the mixed gas refrigeration system show similar performance while the cascade system and the mixed gas refrigeration system have lower equipment cost.
- The cascade system and the mixed gas refrigeration system are more complicated systems than the single stage system. It leads to more maintenance and control. The mixed gas refrigeration system has an issue with maintaining the proper ratio of refrigerants in the mixture over time due to fractionation and leaks.

### Refrigeration Method Examples:
- Single-stage vapor compression
- Cascaded
- Mixed Gas Refrigeration
- Brayton Cycle
- Vortex tube
Accomplishment (Precooling)
Printed Circuit Heat Exchangers (PCHE) Model to Estimate the Required HX Dimensions to Achieve Required Outlet Temperature

I. On-demand Cooling Capacity

Cooling Load during fill \( (P_{H X, 1}) \) = Cooling Load without Buffer \(- \frac{m_{H X} \Delta T C_{p,HX}}{t_{fill}}\)

Cooling Load during lingering time for thermal buffering \( (P_{H X, 2}) \) = \( \frac{m_{H X} \Delta T C_{p,HX}}{t_{linger}}\)

Required Refrigeration Capacity = \( \max(P_{H X, 1}, P_{H X, 2}) \)

II. Core of Heat Exchanger

III. Heat Exchanger Modeling

Computes avg. outlet temperature of \( H_2 \)

Final Design & Cost of PCHE

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Accomplishment (Precooling)
Longer Lingering Time and Larger Temperature Gain Window \((dT)\) Reduces the Precooling Load of the Station

- Achieving a balance between on-demand cooling and thermal buffering works best for heavy-duty fueling involving large flow rates.
- Developed HX model to obtain optimum design of HX providing a balance between on-demand cooling and thermal buffering.
- Cost reduction would depend upon the cost of adding mass of the HX.

The flow coefficient of the vehicle on-tank valve affects the mass flow rate of the HD-FCEV refueling thus impacting the fill time and precooling load. An additional analysis is needed to understand the influence of on-tank valve flow coefficient on the HD-FCEV fueling.
Approach (Cyber Vulnerability Analysis)

• Scope:
  ▪ Communications protocol and security for current and next generation hydrogen refueling (vehicle <-> dispenser)*

• Key Assumption:
  ▪ Incorrect or falsified information related to the fueling process or components can result in unsafe fueling procedures

• Methodology:
  ▪ Define requirements for security
  ▪ Establish what gaps in security exist between the current protocol and the state of the art in communications technologies
  ▪ Analyze solutions to bring current security procedures into the refueling process
Accomplishment (Cyber Vulnerability Analysis)

• Vulnerability assessment and analysis of current standards reveals severe lack of modern security methods

• Alter scope to solution oriented approach
  ▪ Identify pros / cons of alternative communications methodologies
  ▪ Working with industry through ISO 19885-2

• Investigating application of IEEE standards for Automotive and Industrial Ethernet as physical communication medium

• Researching potential Public Key Infrastructure (PKI) options such as CRP from SAE targeted at BEV charging infrastructure

<table>
<thead>
<tr>
<th>Media</th>
<th>Communication Protocol</th>
<th>Network Stack</th>
<th>Standard/Spec</th>
<th>Range</th>
<th>Encryption</th>
<th>Authentication</th>
<th>Bitrate</th>
<th>in-nozzle</th>
<th>native TCP</th>
<th>other applications</th>
<th>on vehicle now*</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>Wi-Fi</td>
<td>TCP/IP</td>
<td>IEEE 802.11</td>
<td>local area network, &lt;100m</td>
<td>available</td>
<td>yes</td>
<td>11 Mbps, 54 Mbps</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>RF</td>
<td>IrDA</td>
<td>IrLAP</td>
<td>IrDA Serial Infrared Physical Layer Specification, Version 1.4</td>
<td>&lt;2m</td>
<td>no</td>
<td>no</td>
<td>38400 baud</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>CAT5</td>
<td>Electrical Ethernet Contacts</td>
<td>TCP/IP</td>
<td>ISO/IEC 11801</td>
<td>physical</td>
<td>available</td>
<td>available</td>
<td>10-100 Mbps</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>RS232/RS485 Contacts</td>
<td>Electrical Ethernet Contacts</td>
<td>modbus / profinet / RS-232-C / RS-485</td>
<td>physical</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>112.5 kbps</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

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Overview

- Identify operation states of the system and potential system failure scenarios
- Analyze all components involved in transferring the hydrogen during refueling
- Develop a qualitatively ranked list of critical scenarios
- Perform numerical simulations on metrics of interest
- Quantify uncertainty in the failure modes and consequences with bounding simulations
Accomplishment (Risk Assessment)

- System was evaluated to identify the potential failure scenarios for different operating states
- A HAZOP was performed in which all critical components in the hydrogen refueling process were evaluated
- A ranked list of critical scenarios was developed from the HAZOP. The consequences from these scenarios are being evaluated for the risk assessment

A detailed CFD simulation utilizing the SIERRA suite is being conducted to evaluate a TPRD release in the onboard hydrogen storage compartment

<table>
<thead>
<tr>
<th>HAZOP Number</th>
<th>Component</th>
<th>Operation State</th>
<th>Hazard Scenario</th>
<th>Causes</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>HDX-13</td>
<td>2</td>
<td>Leakage from tubing</td>
<td>Mechanical damage, material failure, installation error</td>
<td>Potential release of H2</td>
</tr>
<tr>
<td>35</td>
<td>HDX-14</td>
<td>2</td>
<td>Leakage from filter housing or fitting</td>
<td>Installation error, material damage</td>
<td>Potential release of H2</td>
</tr>
<tr>
<td>37</td>
<td>HDX-15</td>
<td>2</td>
<td>Valve leak</td>
<td>Failure of valve, operator error</td>
<td>Potential catastrophic release of H2</td>
</tr>
<tr>
<td>38</td>
<td>HDX-16</td>
<td>2</td>
<td>Release of H2 through valve</td>
<td>Failure of valve to open/close during refueling</td>
<td>Minor release of H2</td>
</tr>
<tr>
<td>39</td>
<td>HDX-17</td>
<td>1,2,3</td>
<td>Overpressurization of cylinder</td>
<td>External fire and failure of FND to operate</td>
<td>Potential catastrophic release of H2</td>
</tr>
<tr>
<td>40</td>
<td>HDX-17</td>
<td>1,2,3</td>
<td>Overpressurization of cylinder</td>
<td>External fire and failure of FND to operate</td>
<td>Potential catastrophic release of H2</td>
</tr>
<tr>
<td>41</td>
<td>HDX-17</td>
<td>1,2,3</td>
<td>Outlet or fitting on tank fails</td>
<td>Manufacturing defect or installation or maintenance error</td>
<td>Potential catastrophic release of H2</td>
</tr>
<tr>
<td>42</td>
<td>HDX-17</td>
<td>1,2,3</td>
<td>H2 Tank rupture</td>
<td>Mechanical failure, tool or equipment injury</td>
<td>Potential catastrophic release of H2</td>
</tr>
<tr>
<td>43</td>
<td>HDX-17</td>
<td>1,2,3</td>
<td>Leakage from the cylinder</td>
<td>Accident, vandalism, crack propagation, fatigue failure, fit-up errors, mechanical tolerance</td>
<td>Potential catastrophic release of H2</td>
</tr>
<tr>
<td>44</td>
<td>HDX-18</td>
<td>1,2,3</td>
<td>TPRD leak of H2</td>
<td>Mechanical defect, material defect, installation error</td>
<td>Release of H2</td>
</tr>
</tbody>
</table>
Accomplishments and Progress: Responses to Previous Year Reviewers’ Comments

- Project has not been previously reviewed at the AMR.
Proposed Future Work

Precooling Analysis
• Evaluate the impact of different precooling systems on the levelized cost of hydrogen dispensing
• Utilizing final design condition to optimize refrigeration system.
• Contacting suppliers to obtain further detailed technical specifications and cost information.

Cyber Vulnerability Assessment
• Work to integrate modern and high performance (Proof of Concept) communication link based on IEEE 802 standards family between FCEV and dispenser
• Implement PRHYDE (or similar) advanced fueling protocol over secure link and test refueling procedures
  ▪ Capture data transfer during refueling for both advanced and current communications to illustrate security measures
• Identify path forward and communicate to nozzle manufacturers about possibility of including two-pin ethernet physical connection

Risk Assessment
• Additional scenarios, and sensitivity cases, are being evaluated in the HyRAM+ toolkit
• These results will be utilized in the final quantitative risk assessment, which will be done in Q4 of FY23
Summary

Precooling Analysis
• Evaluated precooling temperature requirement for fueling HD FCEVs at different boundary conditions
• The precooling concept has been proposed for HD FCEVs
• Explored several refrigeration systems based on ANL’s early stage design data.
• Conventional single stage compression system, cascade system, mixed gas refrigeration system, reverse Brayton cycle, and vortex tubes are considered.

Cyber Vulnerability Assessment
• Results to date indicate that current communication protocols lack modern security features
• Identified possible path forward to utilize previous work in other IT and automotive sectors to accelerate development
• Working with Nikola to understand industry needs and increase awareness in industry of modern cybersecurity methodologies

Risk Assessment
• A HAZOP was performed in which all critical components in the hydrogen refueling process were evaluated
• Developed a ranked list of critical scenarios and evaluated the consequences from these scenarios.