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

Project ID: IN040

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WBS: 8.6.3.304

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DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

SRNL SAVANNAH RIVER NATIONAL LABORATORY · Argonne NATIONAL LABORATORY · Sandia National Laboratories · NIKOLA

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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

Fueling Technology Progression	Current-Gen	Next-Gen	Optimized Commercial Solution
Description	Baseline	High-Flow Fueling Hardware	Next-Gen Fueling Protocol and Communications
Interface Hardware	H70F90 ISO 17268-1	**H70F300** **ISO 17268-2**	H70F300 ISO 17268-2
Fueling Protocol	SAE TIR J2601-5	SAE TIR J2601-5	**ISO 19885-3**
Communications	IRDA / SAE J2799	IRDA / SAE J2799	**ISO 19885-2**
Estimated Total Fueling Durations (minutes) 60-80 kg Fill	**< 20**	**< 15**	**<< 15**

- 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.

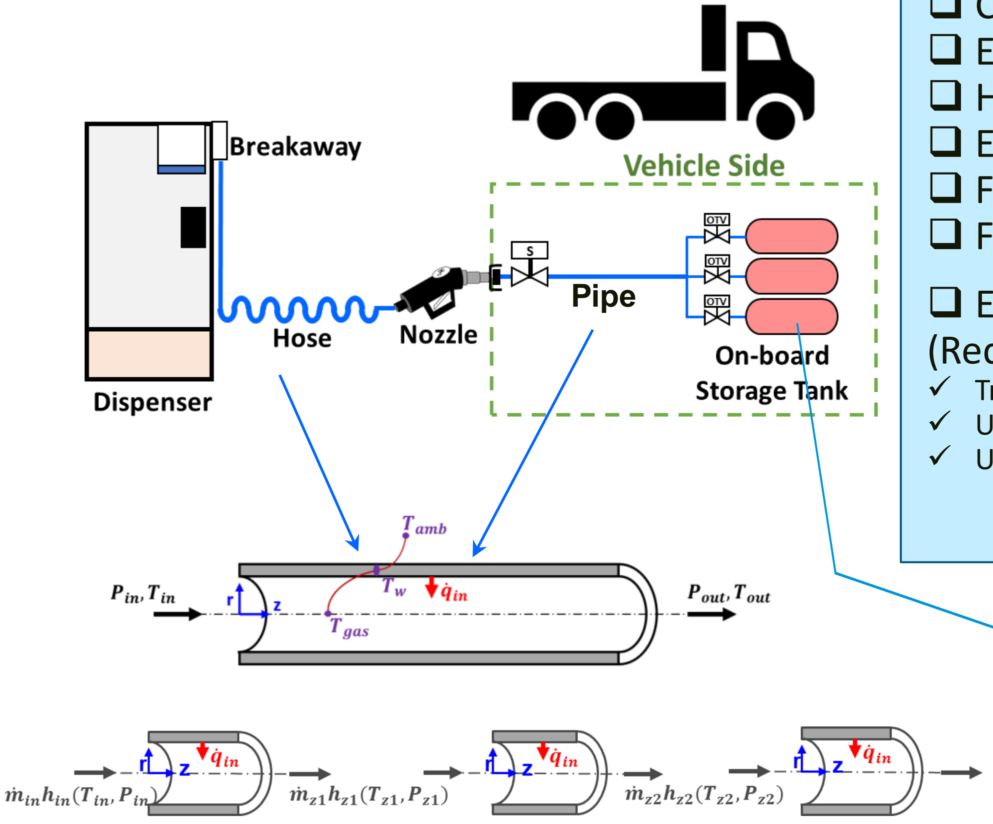
Relevance/Impact (Precooling)

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

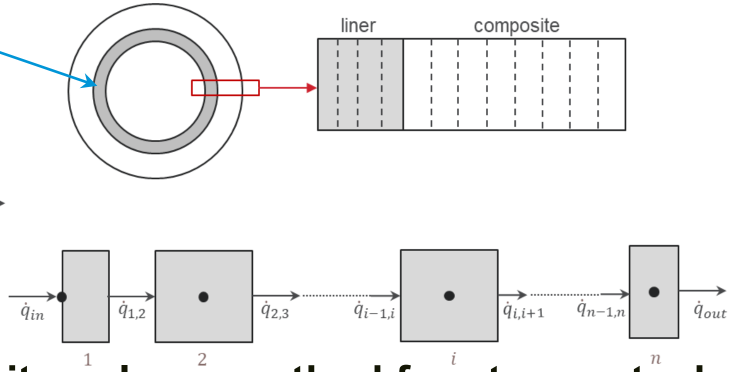
H2SCOPE Model



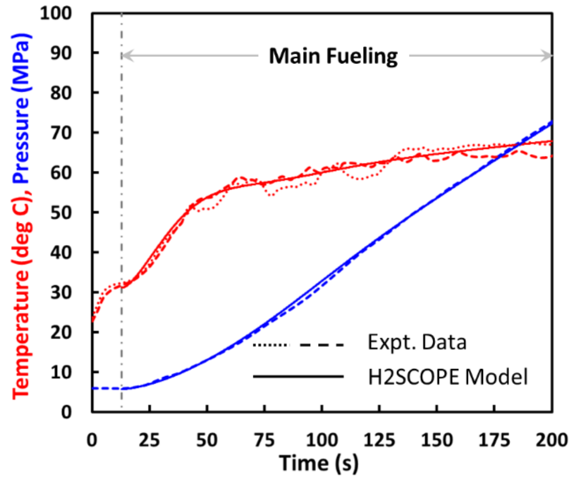
Lumped analysis for pipe and hose

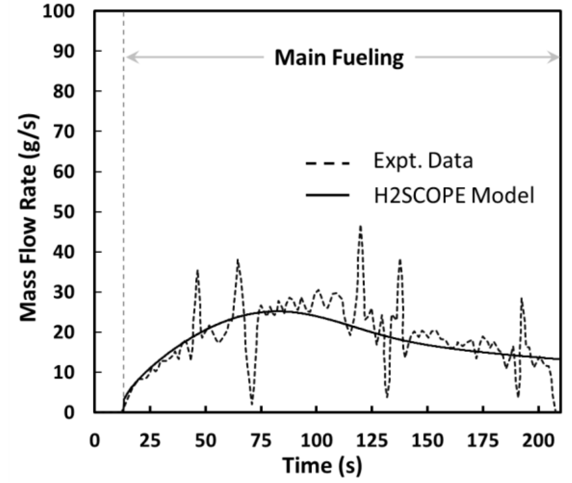
- ❑ Continuity equations
- ❑ Energy balance equations
- ❑ Heat transfer equations
- ❑ Equation of state
- ❑ Flow equations
- ❑ Finite volume method

- ❑ Expanded excel VBA based H_2SCOPE model (Reddi et al., 2014) to the python version
  - ✓ Transient heat transfer for pipes, hose, nozzle, valves etc.
  - ✓ Updated ΔP_{drop} and mass flow rate calculations
  - ✓ Used object-oriented programming



Finite volume method for storage tank





Validated with experimental data

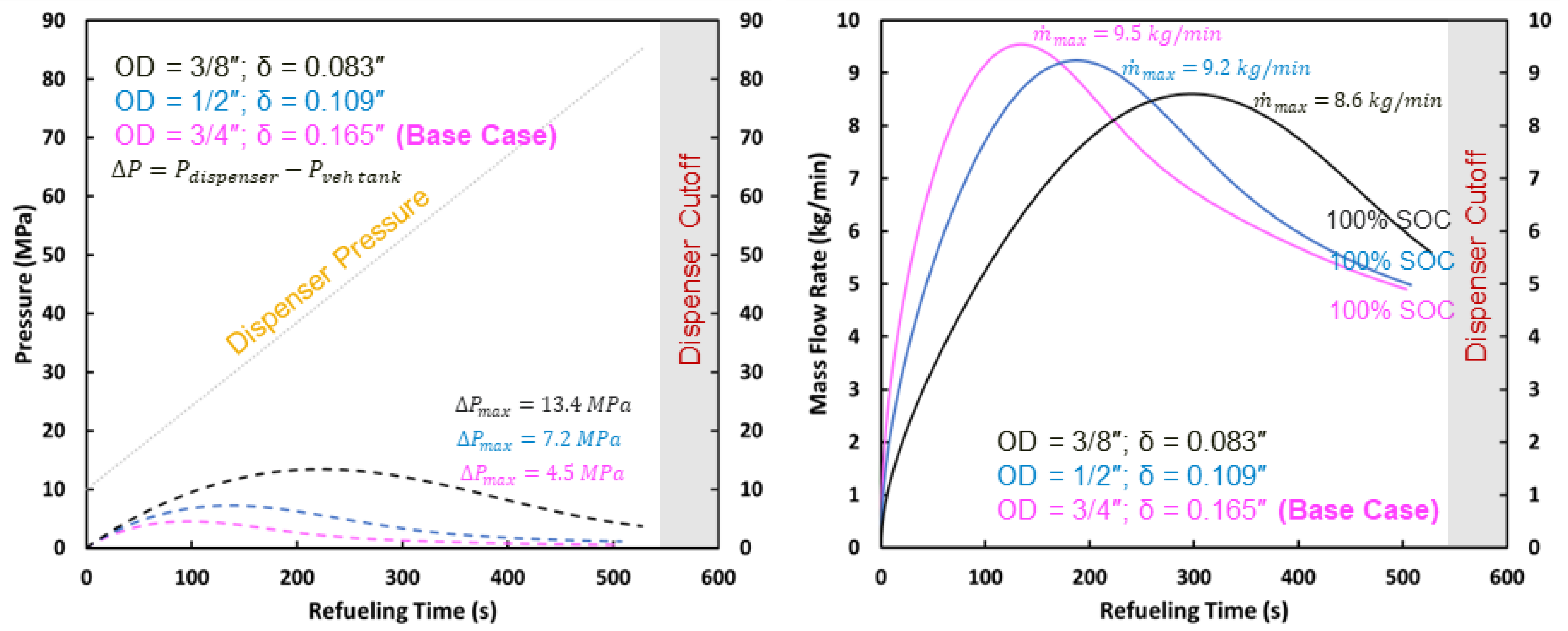
Reddi, et al., (2014). International Journal of Hydrogen Energy 39(33): 19169-19181.
Kuroki, T., et al., (2021). International Journal of Hydrogen Energy 46(42): 22004-22017.

Accomplishment (Precooling)

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

BASE CASE:

APRR = 8.55 MPa/min; P_0 = 10 MPa, T_{amb} = 15 °C (soaked); Pipe Length: 4m; Precooling Temp = -40 °C



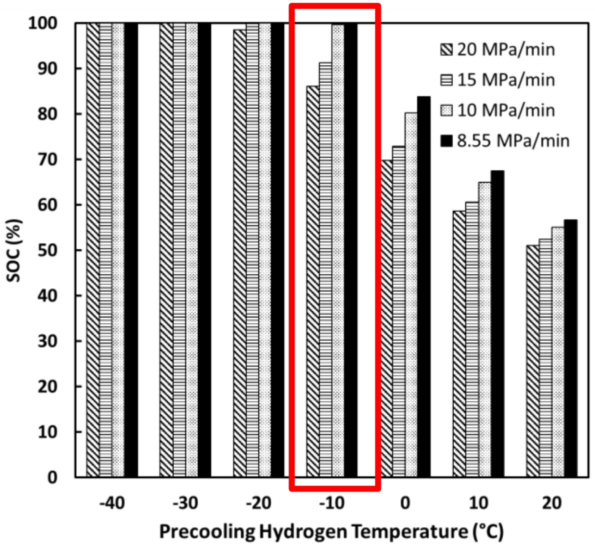
Pipe diameter has strong influence on pressure drop

- ✓ **Impacts mass flow rate and instantaneous precooling load**
- ✓ **Fill duration**

Accomplishment (Precooling)

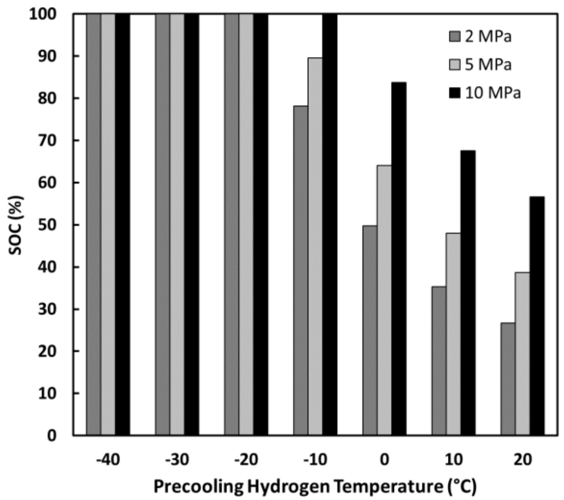
Boundary Conditions like Pressure Ramp Rate, Initial Tank Pressure and Ambient Temperature Influences Precooling Load

APRR = 8.55-20.0 MPa/min
P_0 = 10 MPa,
T_{amb} = 15 °C (soaked),
Pipe: 3/4" pipe (δ=0.165"),
Length: 4m



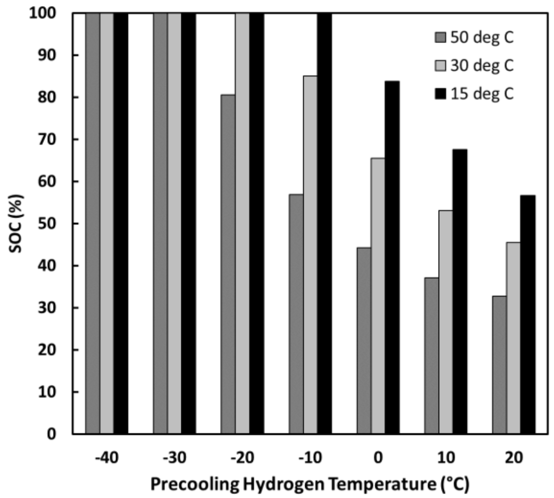
Higher APRR requires lower precooling temperature to obtain higher SOC%

APRR = 8.55 MPa/min
P_0 = 2-10 MPa
T_{amb} = 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
P_0 = 10 MPa
T_{amb} = 15-50 °C (soaked)
Pipe: 3/4" pipe (δ=0.165"),
Length: 4m



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

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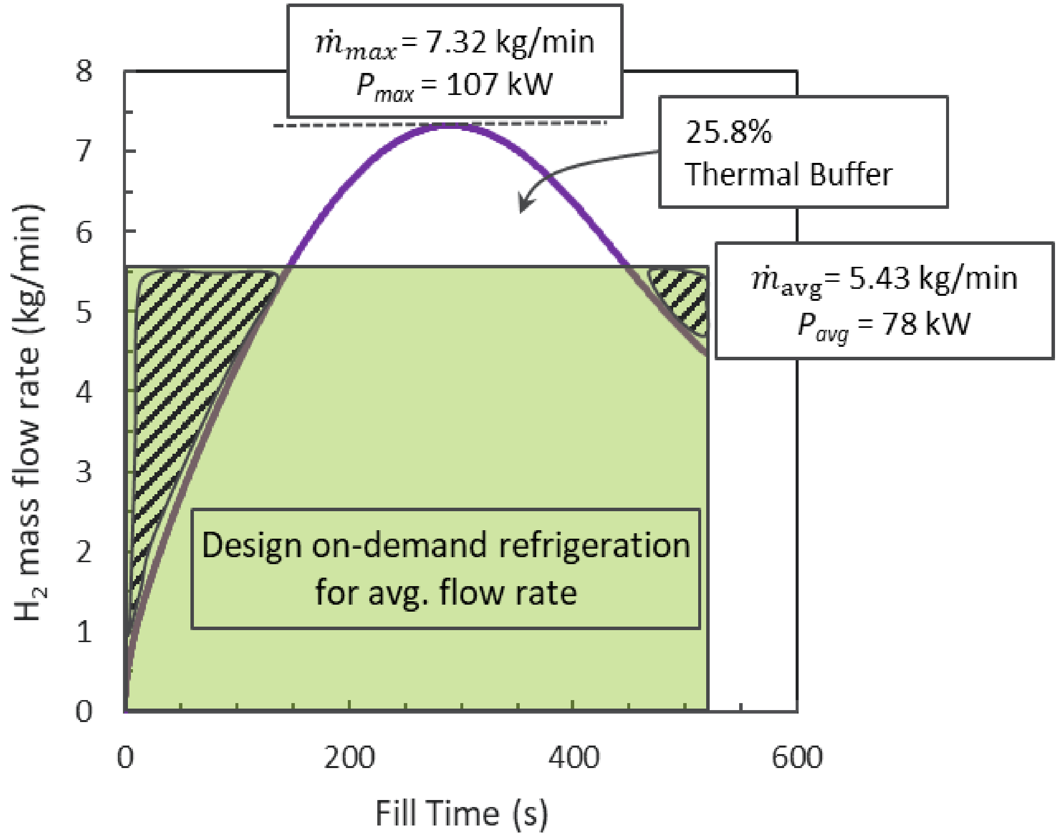
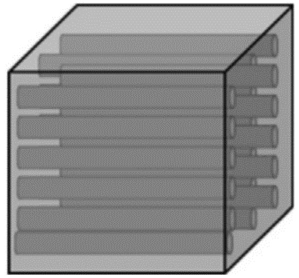
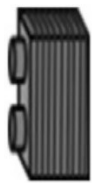
Relevance/Impact/Approach (Precooling)

Hydrogen Precooling strategies include Thermal Buffering and On-demand Cooling

Flow properties & Cooling Duty



Thermal Buffering	On-demand Cooling
	
Large mass of HX (1-3 tons)	Compact HX, large area/volume ratio
HX mass absorbs heat from H_2	Direct heat exchange b/w refrigerant and H_2
Refrigerant used to cool and maintain the HX block at target temperature	On-demand cooling during fill
Small capacity refrigerator (~10 kW)	Large capacity refrigerator (~500 kW)

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

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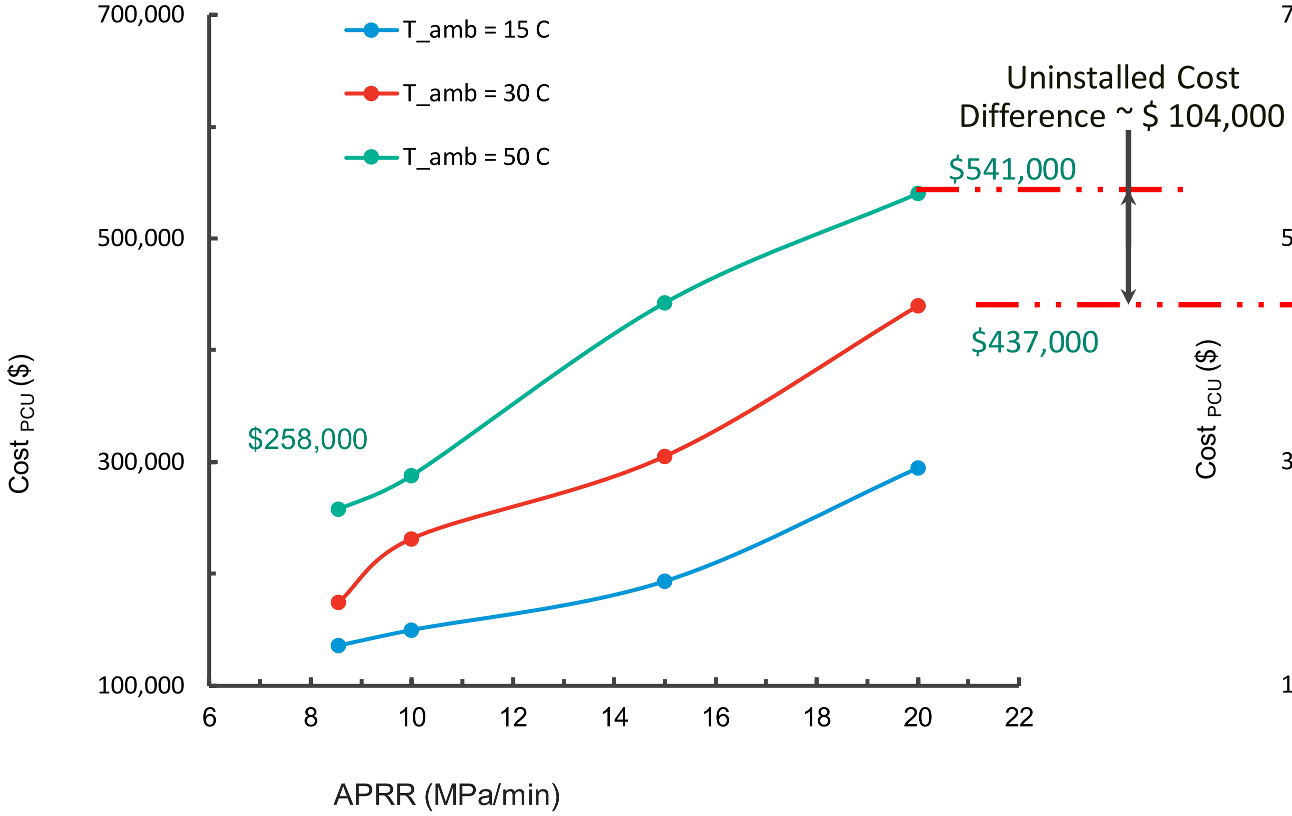
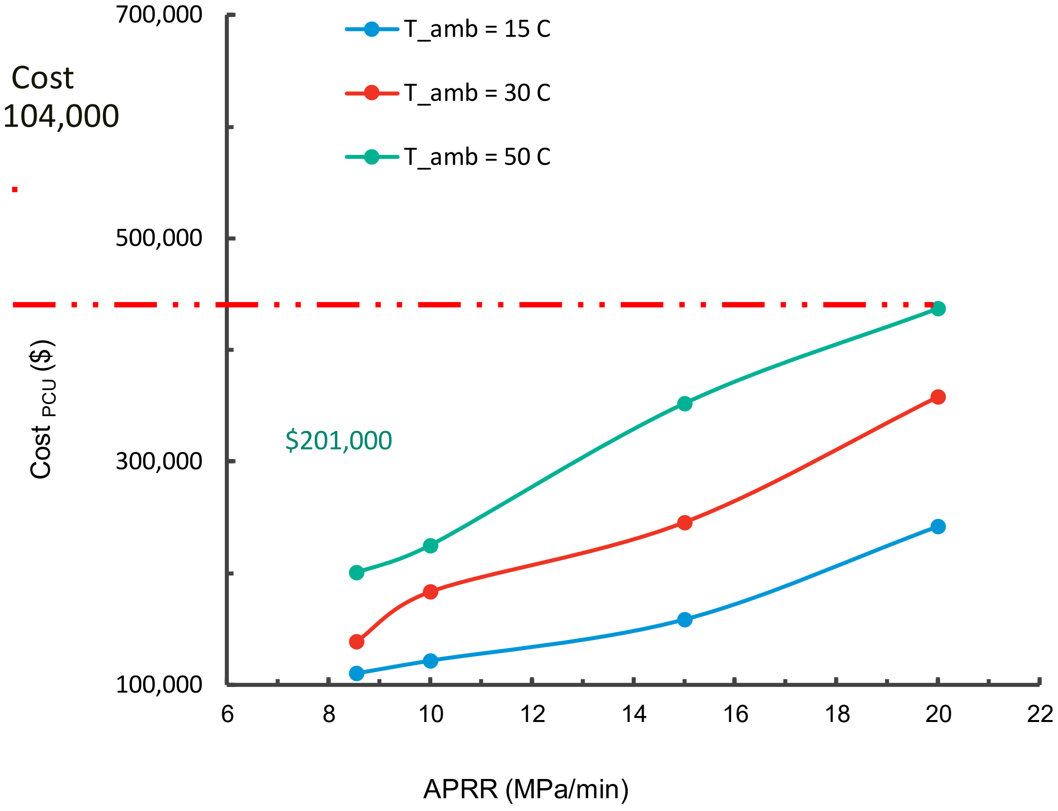
Approach (Precooling)

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



Max. Flow Rates



Avg. Flow Rates

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

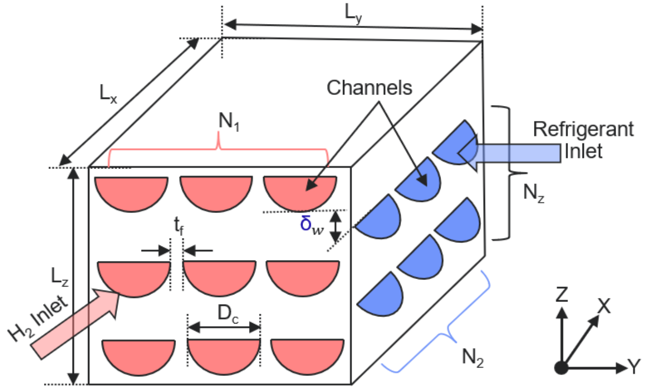
I. On-demand Cooling Capacity

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

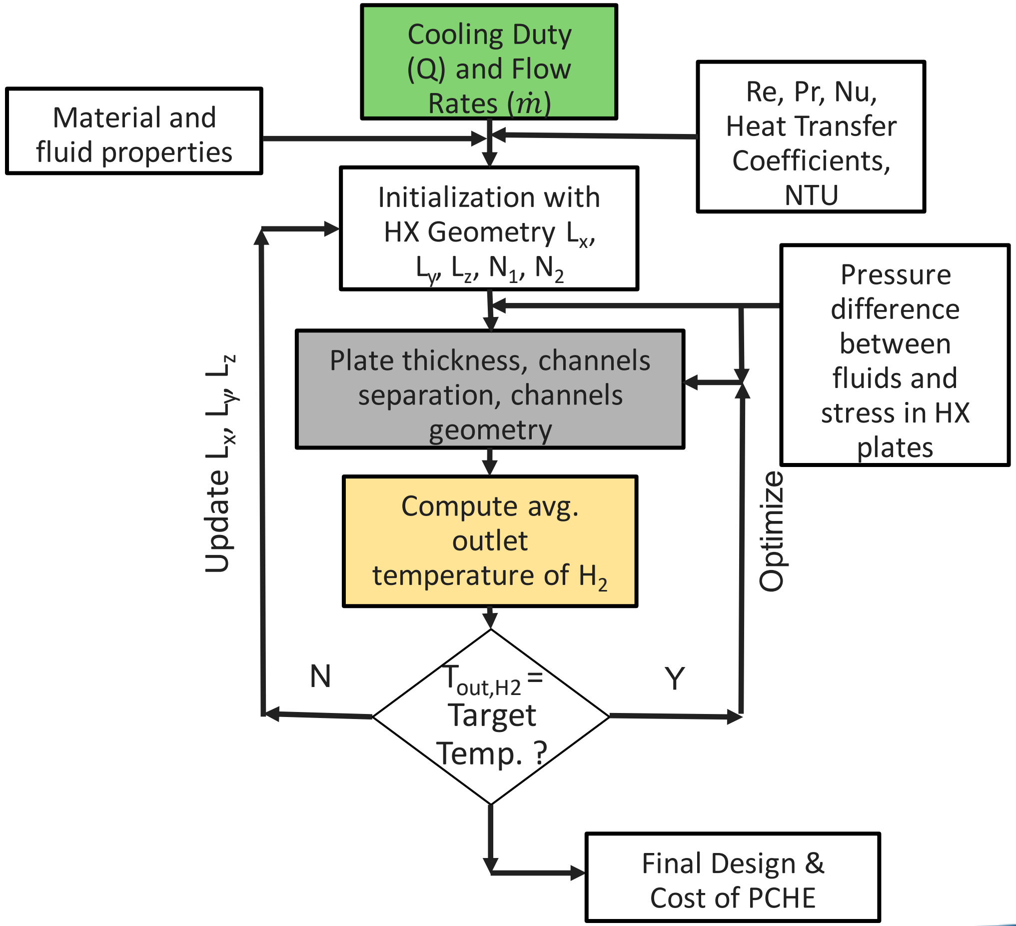
$$\text{Cooling Load during lingering time for thermal buffering } (P_{HX,2}) = \frac{m_{HX}\Delta T C_{p,HX}}{t_{linger}}$$

Required Refrigeration Capacity = max($P_{HX,1}$, $P_{HX,2}$)

II. Core of Heat Exchanger



III. Heat Exchanger Modeling



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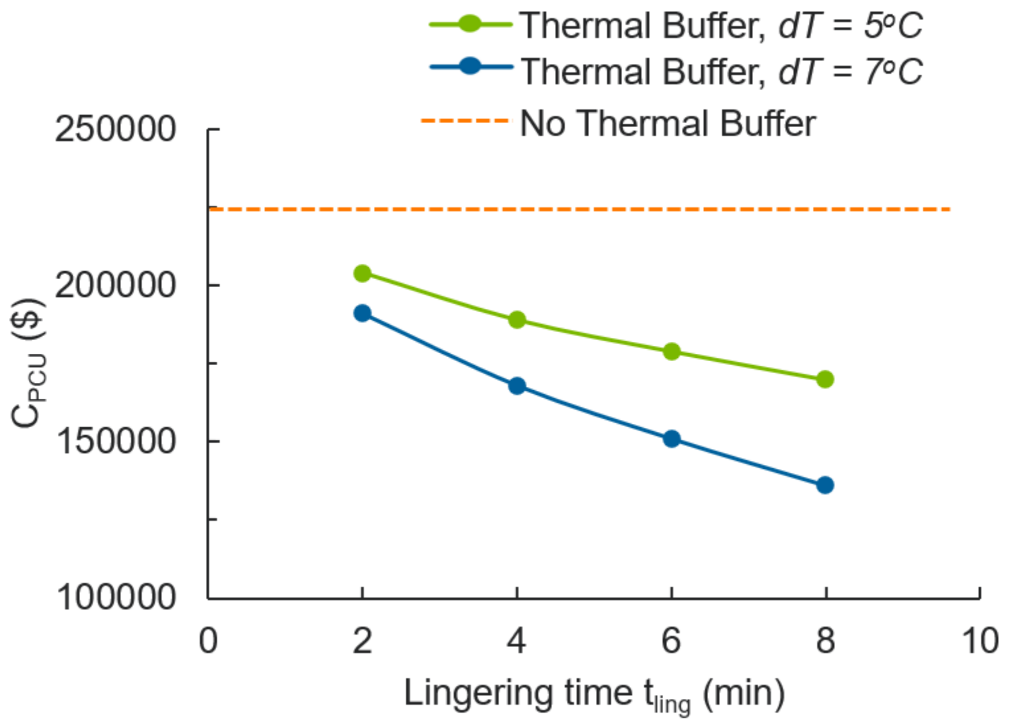
Accomplishment (Precooling)

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

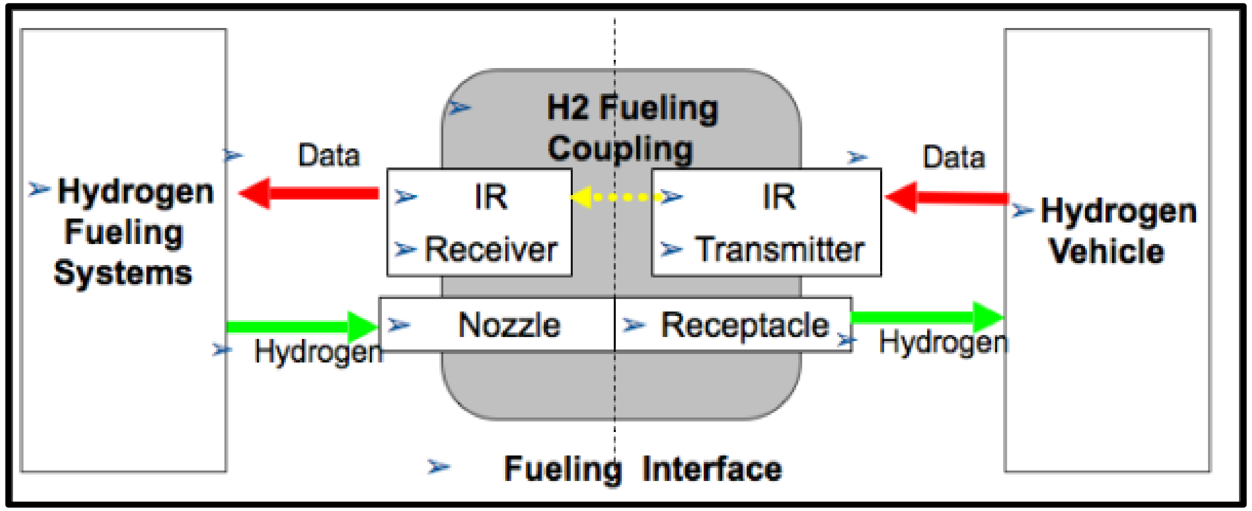


- Achieving a balance between on-demand cooling and thermal buffering works best for heavy-duty fueling involving large flow rates.
- Developed HX model to obtain optimum design of HX providing a balance between on-demand cooling and thermal buffering.
- Cost reduction would depend upon the cost of adding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

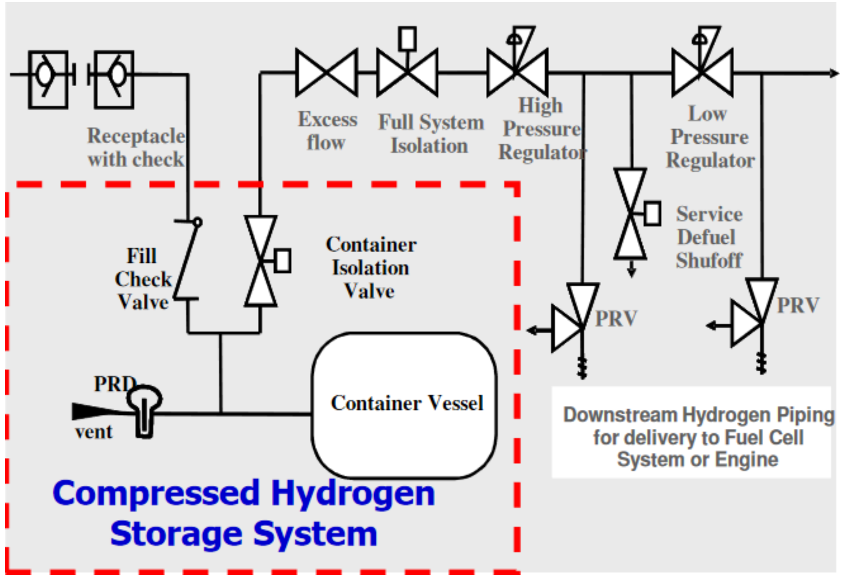
- Vulnerability assessment and analysis of current standards reveals severe lack of modern security methods
- Alter scope to solution oriented approach
  - Identify pros / cons of alternative communications methodologies
  - Working with industry through ISO 19885-2
- Investigating application of IEEE 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

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

Approach (Risk Assessment)
Quantitative Risk Assessment to Identify and Address the Risk of Refueling Heavy Duty Fuel Cell Vehicles

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



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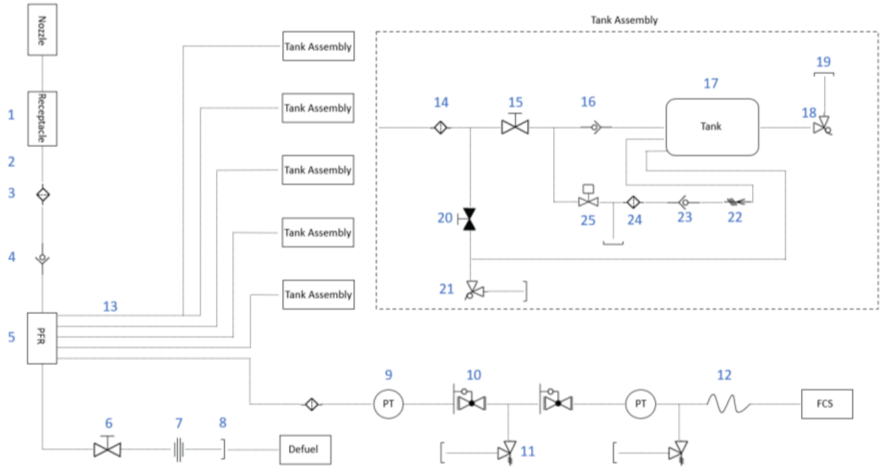
Accomplishment (Risk Assessment)

- 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



HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences
⋮	⋮	⋮	⋮	⋮	⋮
35	HDV-13 (Hydrogen Tubing (1/2"))	2	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of H2
36	HDV-14 (Filter)	2	Leakage from filter housing or fitting	Installation error, material damage	Potential release of H2
37	HDV-15 (Manual Valve (N.O.)	2	Valve leaks	Failure of seals, operator error	Potential Catastrophic release of H2
38	HDV-16 (Check Valve)	2	Release of H2 through valve	Failure of valve to open/close during refueling	Minor release of H2
39	HDV-17 (Hydrogen Tank)	1,2,3	Overpressurization of Cylinder	External fire AND failure of PRD to operate	Potential catastrophic release of H2
40	HDV-17 (Hydrogen Tank)	1,2,3	Overpressurization of Cylinder	External fire and successful operation of PRD	Potential Catastrophic release of H2
41	HDV-17 (Hydrogen Tank)	1,2,3	Outlet or fitting on tank fails	Manufacturing defect or installation or maintenance error	Potential Catastrophic release of H2
42	HDV-17 (Hydrogen Tank)	1,2,3	H2 Tank Rupture	Mechanical Damage, tool or equipment impingement	Potential Catastrophic release of H2
43	HDV-17 (Hydrogen Tank)	1,2,3	Leakage from the cylinder	Accident, vandalism, crack propagation, fatigue failure, Fill rate exceeds mechanical tolerance	Potential Catastrophic release of H2
44	HDV-18 (TPRD)	1,2,3	TPRD leak of H2	Mechanical defect, material defect, installation error	Release of H2
⋮	⋮	⋮	⋮	⋮	⋮

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

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.