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

Project ID: IN040

Will James (SRNL)-PI, Krishna Reddi (ANL), Sajag Poudel (ANL), Hla Tun (ANL), Amgad Elgowainy (ANL), Benjamin Karch (SNL), Craig Rodine (SNL), Austin Glover (SNL), Elizabeth Saade (Nikola Corporation), Renju Zacharia (Nikola Corporation), and Livio Gambone (Nikola Corporation)

WBS: 8.6.3.304

May 7, 2024

DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

Overview

Timeline

- Project Start Date: 10/01/2021
- Project End Date: 09/30/2024

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: $2.0 M *

Total Cost Share Percentage: 20%

* As of 03/01/2024, includes cost share

Partners

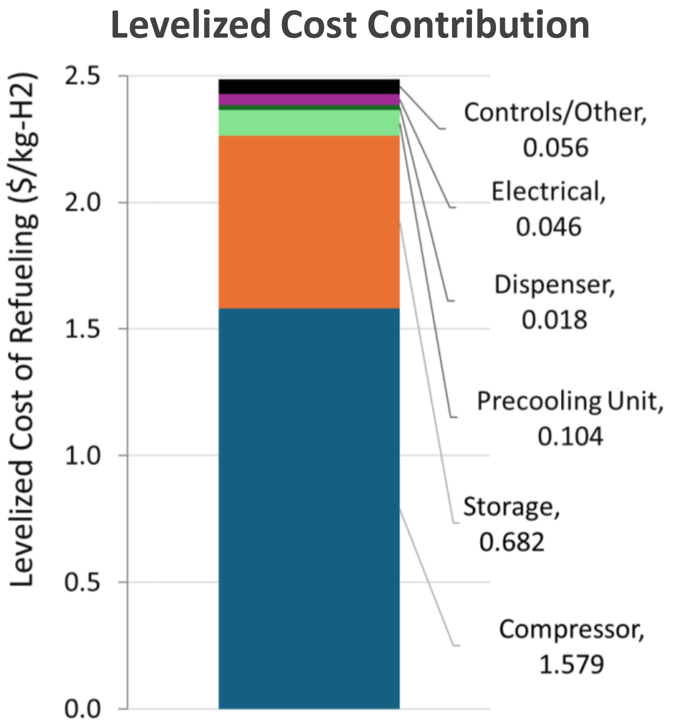
- Savannah River National Laboratory (PI)
- Argonne National Laboratory (co-PI)
- Sandia National Laboratories (co-PI)
- Nikola Motors (Industry Partner)

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 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 (TEA) 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.

Station Configuration: Back-to-back fill with 2 dispensers
Daily Fleet: 100
H_2 dispense: 59 kg/vehicle
Dispensing option: 700 bar
Station's Total Capital Cost of Investment: $15.8 M



*Other includes: Site preparation, Engineering design, project contingency, etc.

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 F90	SAE TIR J2601-5 F300	**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.

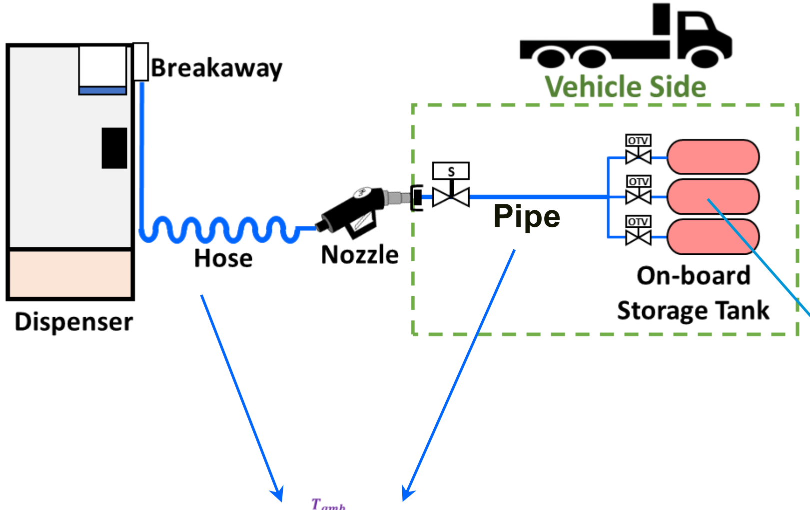
Relevance/Impact (Precooling)

Examine the precooling temperature required for various tank systems of FC HDVs

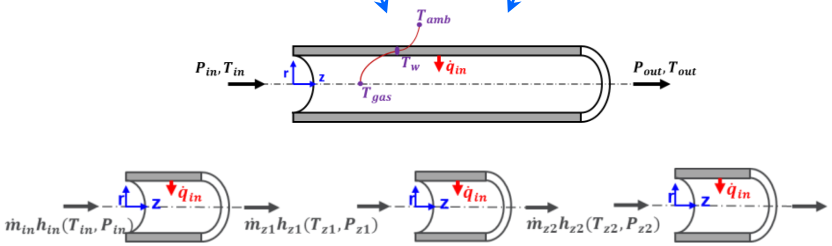
- Understand impacts of the various Onboard Hydrogen Storage System (HSS) designs on the required precooling temperature for a range of fueling speeds and boundary conditions. The different HSS designs are provided by the industry stakeholder.
- The HSS designs are characterized by the hydrogen tank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

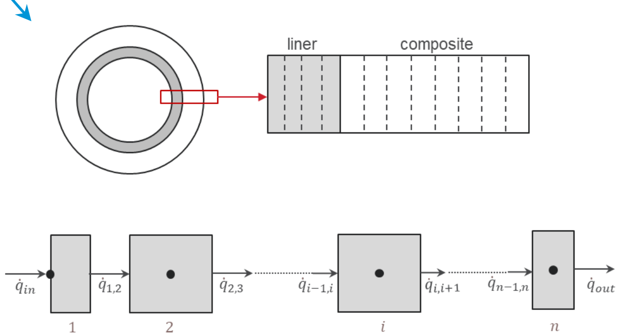
ANL's H2SCOPE Model



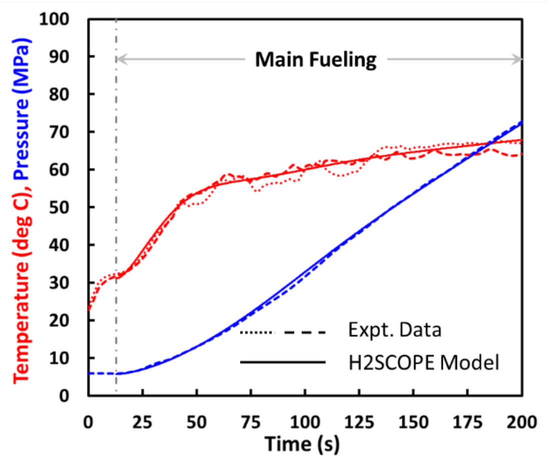
- Python based model
- Continuity equations
- Energy balance equations
- Heat transfer equations
- Equation of state
- Flow equations
- Finite volume method

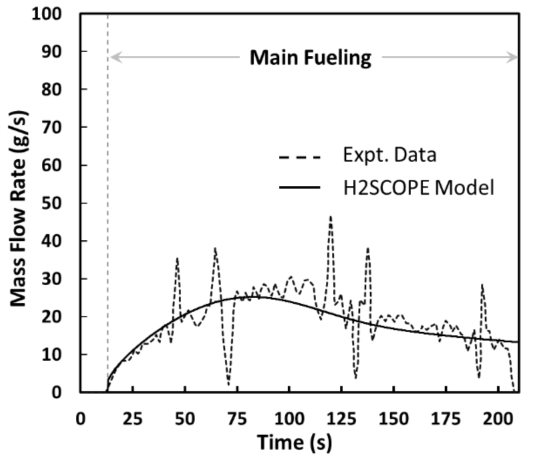


Lumped analysis for pipe and hose



Finite volume method for storage tank





Validated with experimental data

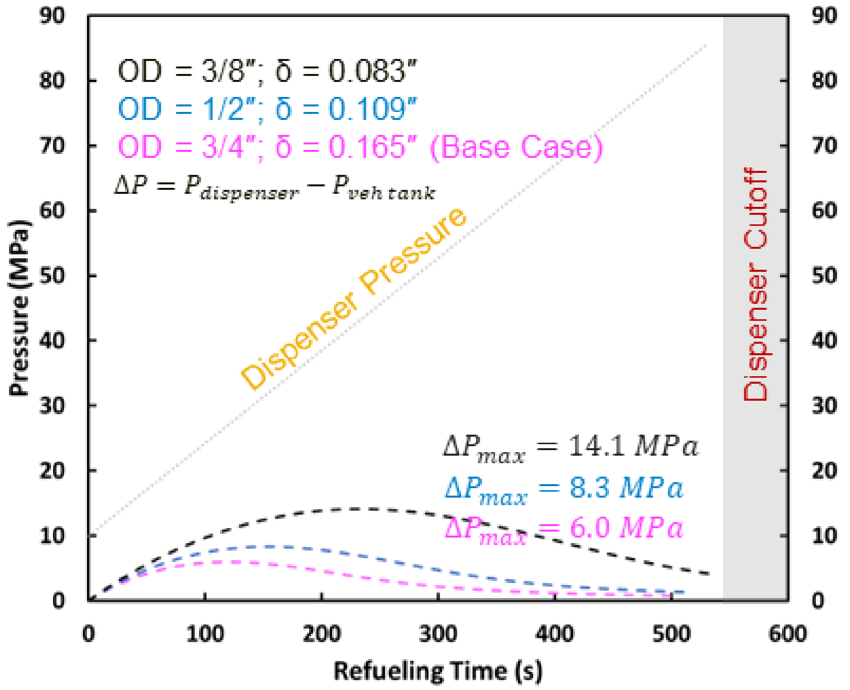
Reddi, et al., (2014). International Journal of Hydrogen Energy 39(33): 19169-19181.
Tun, H., et al., (2023). International Journal of Hydrogen Energy 48(74): 28869-28881

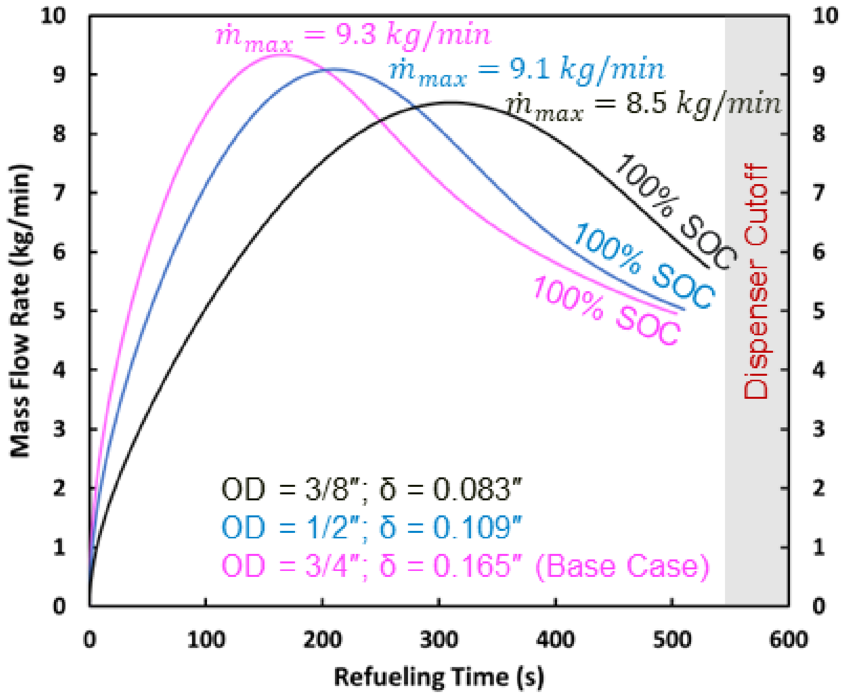
Accomplishments (Precooling)

Influence of pipe diameter

Updated based on latest data for flow coefficients of receptacle-nozzle pair and on-tank valve

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**
- ✓ **Fill time**
- ✓ **Affects instantaneous precooling load**

Argonne NATIONAL LABORATORY

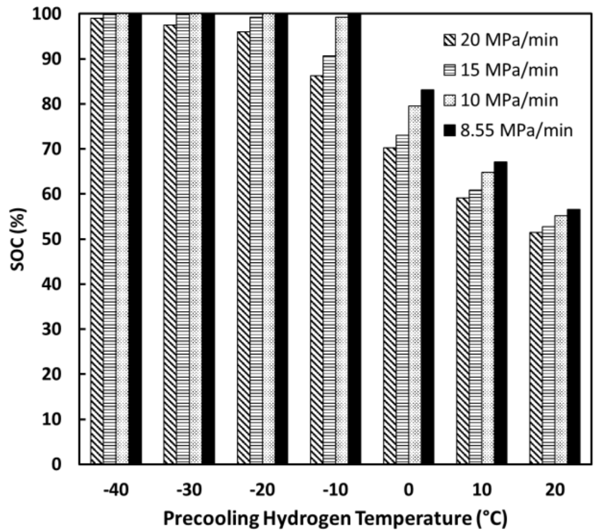
Savannah River National Laboratory

Accomplishments (Precooling)

Influence of APRR, Initial tank pressure, and T_{amb}

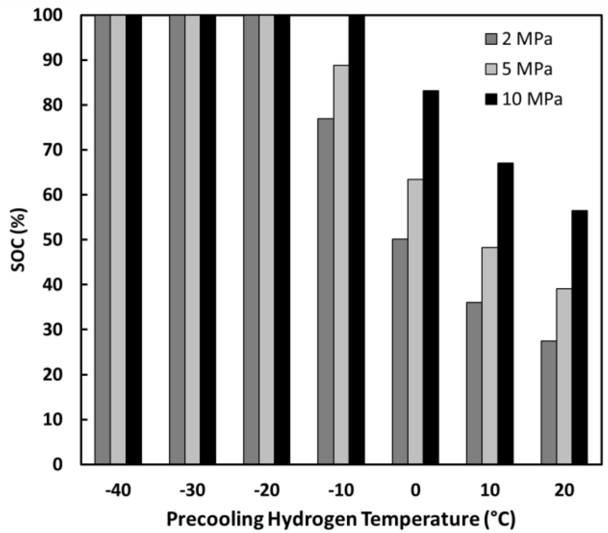
Updated based on latest data for flow coefficients of receptacle-nozzle pair and on-tank valve

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



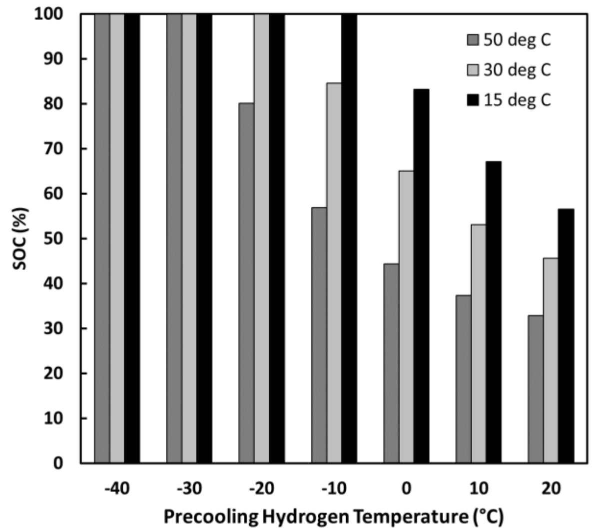
Higher APRR requires lower precooling temperature to obtain higher SOC%

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



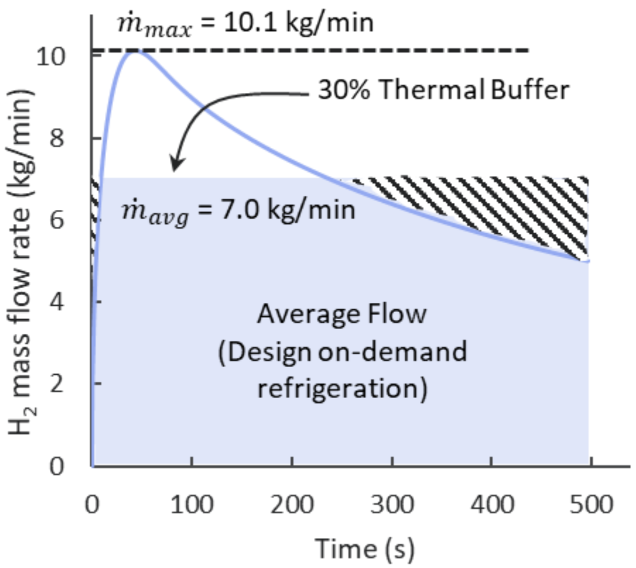
Lower ambient temperature requires less cooling loads to achieve maximum SOC%

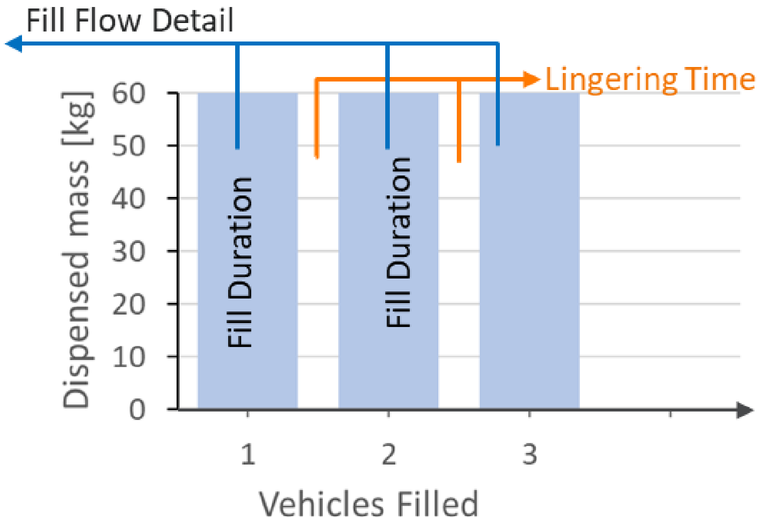
Accomplishments (Precooling)

Hybrid HX Strategy for Precooling H_2 for heavy-duty fueling applications

- Size the on-demand HX to address the average H_2 flow rate instead of maximum flow rate during fill.
- Add thermal mass to the HX to supplement the H_2 precooling when the flow rate is higher than the average flow rate.
- Thermal mass of HX would be brought back to original temperature during the lingering period and when the flow rate is below average during the fill
- Potential reduction of refrigeration unit capacity and cost of precooling system

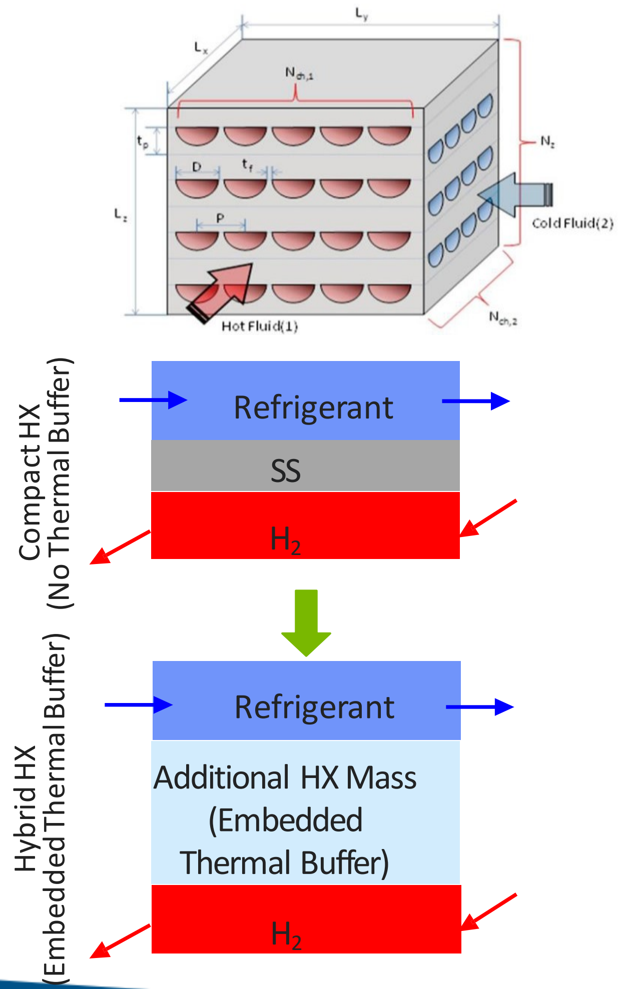
Ambient Temperature = 15°C,
APRR = 8.55MPa/min,
Initial tank pressure = 5 MPa,
Precooling temperature = -40°C





Accomplishments (Precooling)

Developed and used a PCHE Model to study the performance of the hybrid HX



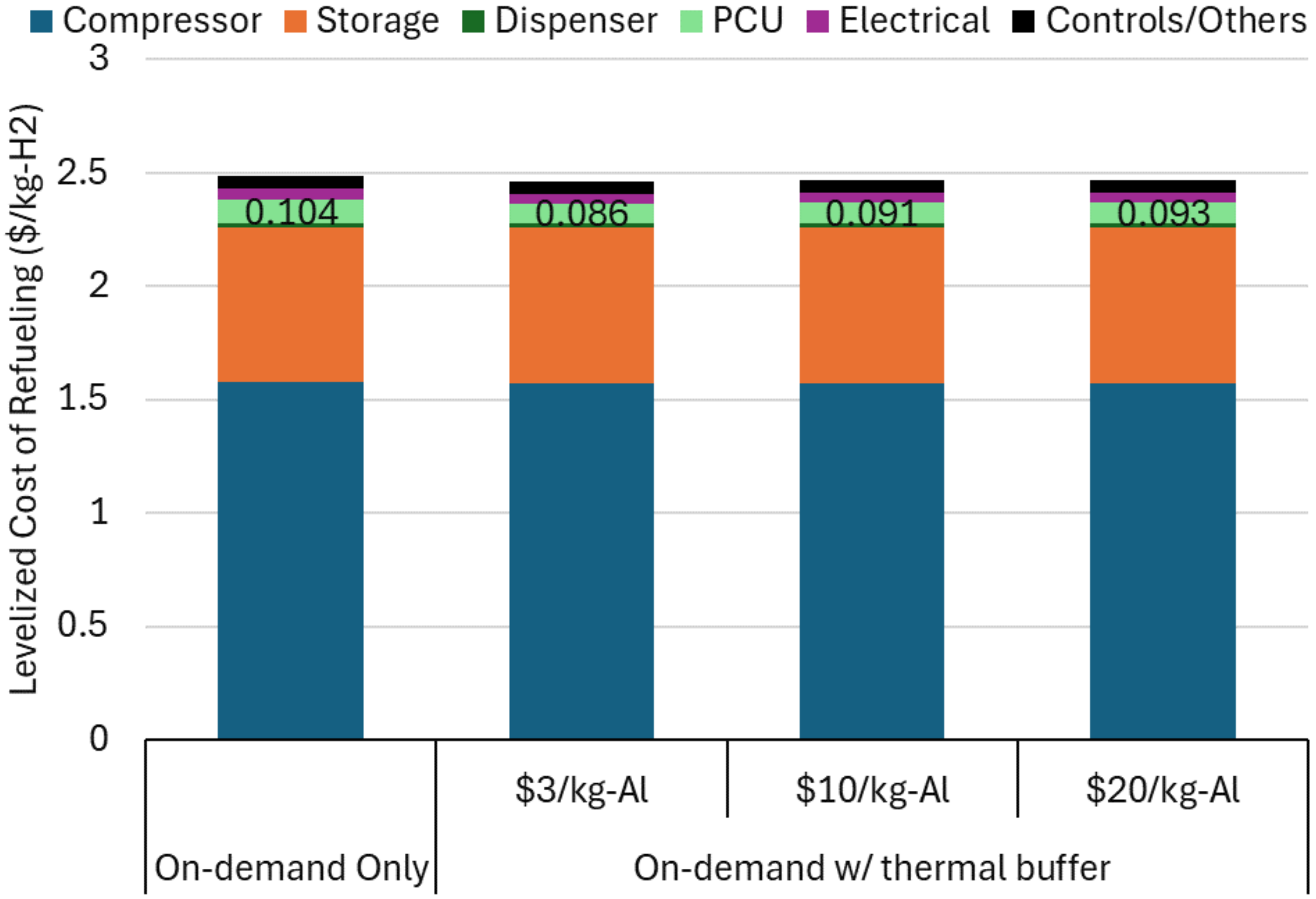
- Adding mass to HX increases thermal resistance and reduces its performance
- Strength of material (plate-thickness) to withstand pressure difference between the hot and cold fluid needs to be considered.
- Design of new compact HX capable to provide required cooling duty needs is investigated
- Printed Circuit Heat Exchanger (PCHE) model[1-2] is utilized to study the design and performance of HX to be used in H_2 precooling unit
- PCHE model is developed using Python Code which is validated with parameters from OEM's quote & further utilized to obtain the optimized design and cost of compact HX with the added thermal buffer.

[1]Chen et al. (2018). Dynamic behavior of a high-temperature printed circuit heat exchanger: Numerical modeling and experimental investigation. *Applied Thermal Engineering*, *135*, 246-256.
[2]*Ravindran, et al., (2014).* Modeling a Printed Circuit Heat Exchanger with RELAP5-3D for the Next Generation Nuclear Plant. Idaho National Laboratory.

Accomplishments

Impact of the hybrid precooling unit design on refueling cost

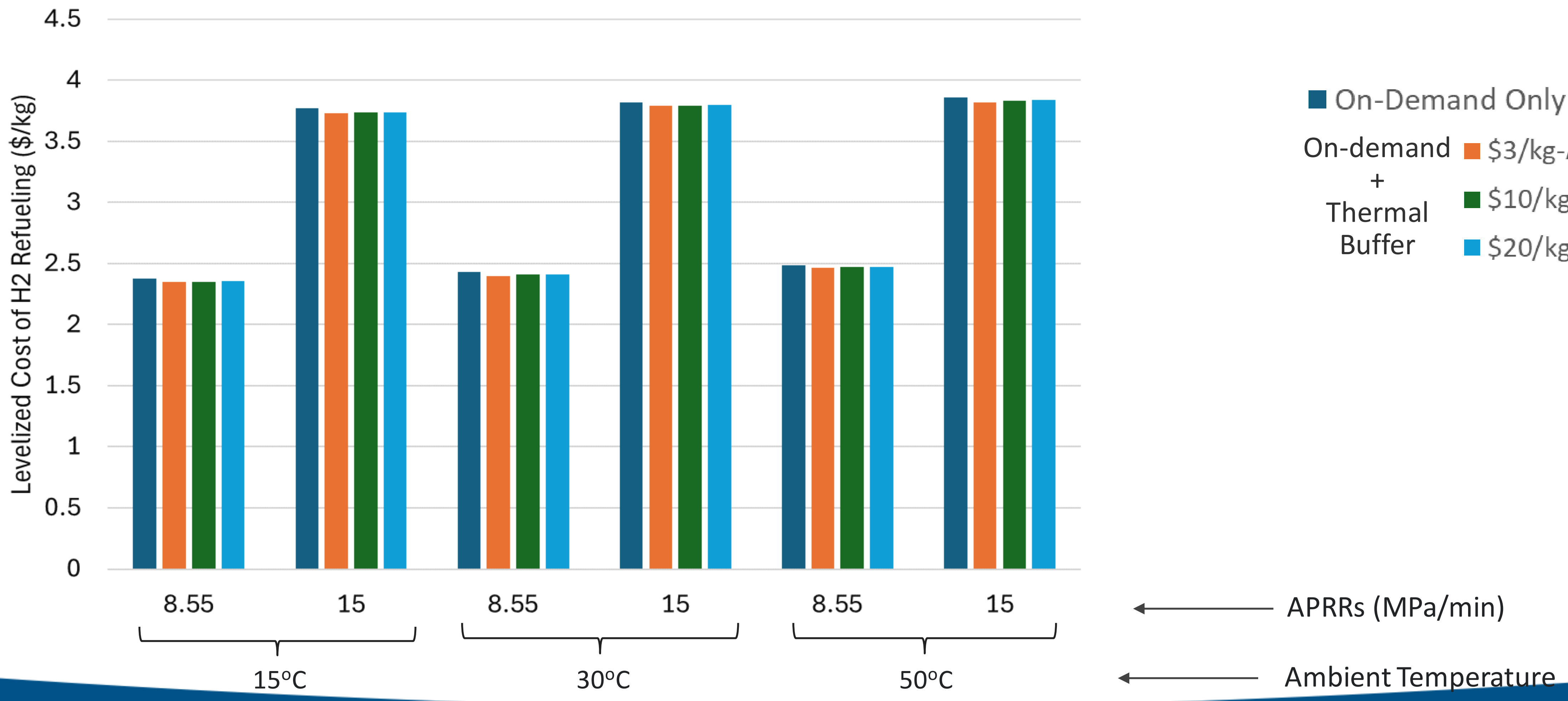
Parameters	Values
Ambient Temperature (°C)	50
APRR (MPa/min)	8.5
HX Inlet Temperature (°C)	50
HX Outlet Temperature (°C)	-40
Maximum Flow Rate (kg/min)	9.22
Minimum Flow Rate (kg/min)	6.63
Mass Dispensed (kg)	60
Fill Duration (min)	8.9
Ambient Temperature (°C)	50



Cost of compression includes the initial compression from delivered H_2 at 20 bar

Accomplishments

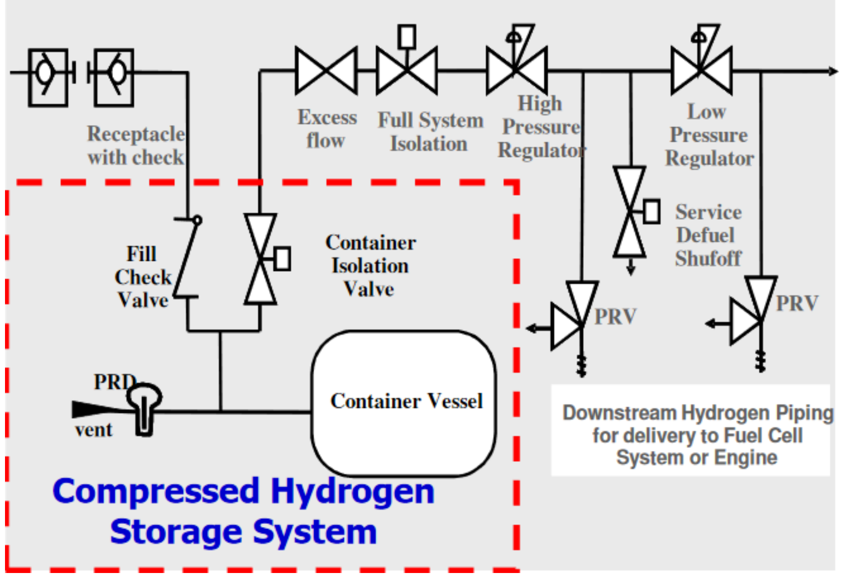
Scenarios of H_2 dispense and corresponding levelized cost of refueling



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

Overview

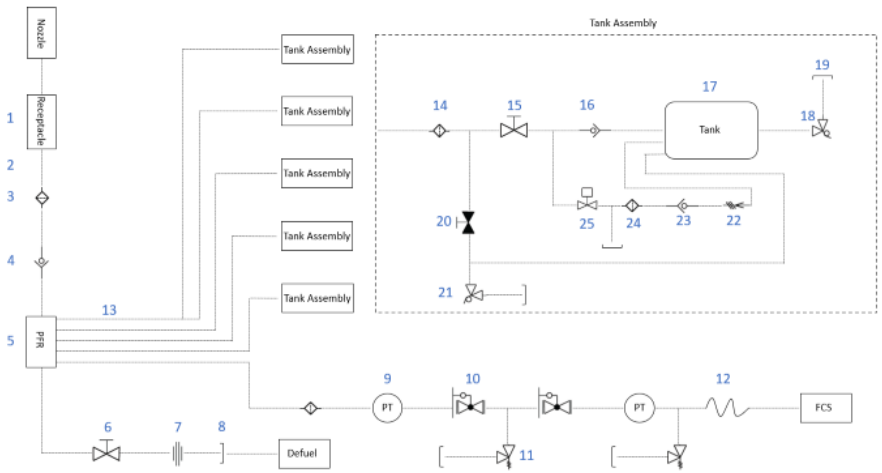
- Identify operation states of the system and potential system failure scenarios
- Analyze all components involved in transferring the hydrogen during refueling
- Develop a qualitatively ranked list of critical scenarios
- Perform numerical simulations on metrics of interest
- Quantify uncertainty in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



Sandia National Laboratories
Savannah River National Laboratory

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

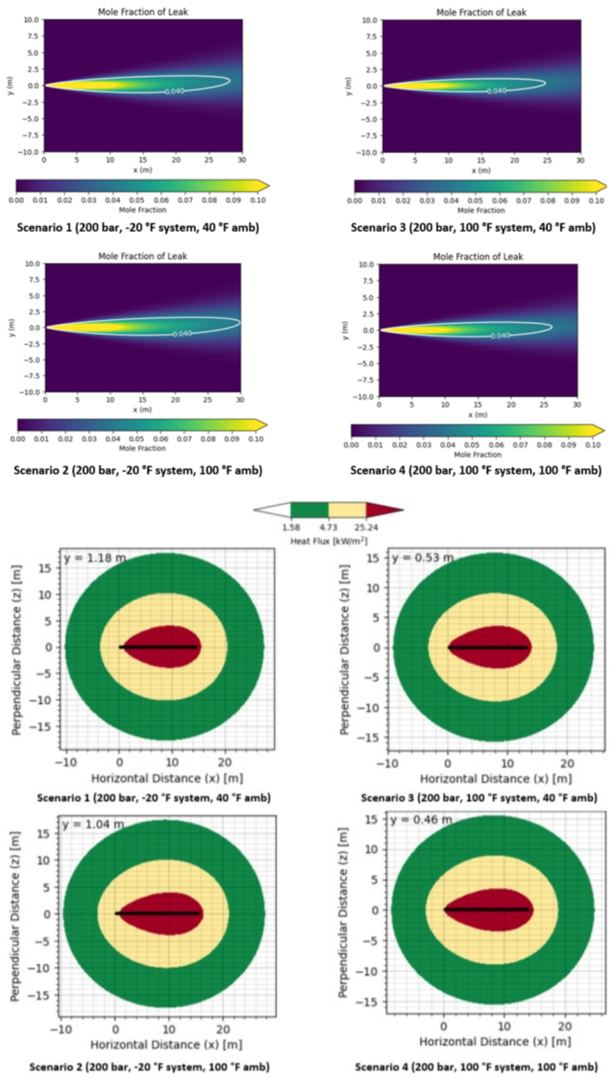


HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences
⋮	⋮	⋮	⋮	⋮	⋮
35	HDV-13 (Hydrogen Tubing (1/2"))	2	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of H2
36	HDV-14 (Filter)	2	Leakage from filter housing or fitting	Installation error, 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

Accomplishment (Risk Assessment)

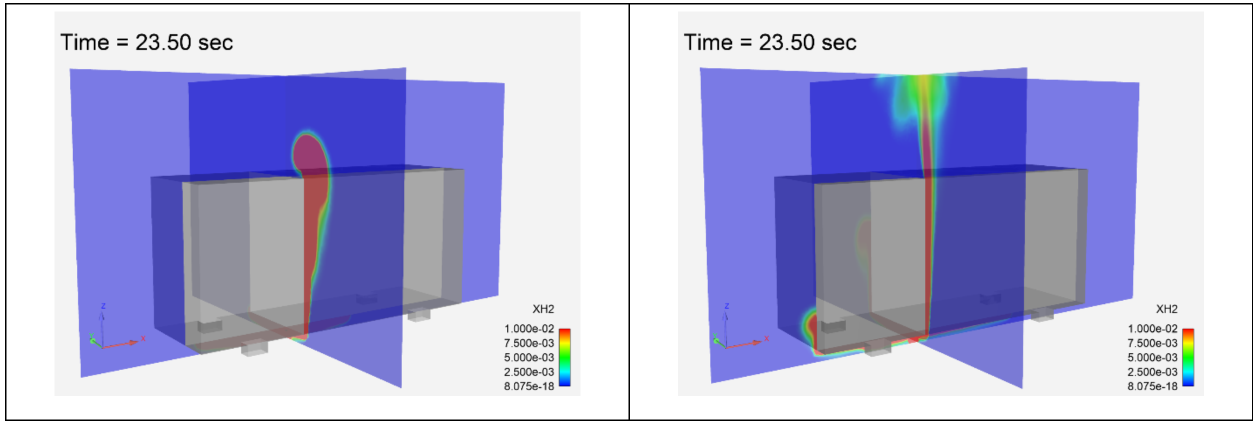
- Utilized the results of the HAZOP to evaluate the consequence of critical scenarios
- HyRAM+ Version 5.0 was used to evaluate the leak scenarios in the hydrogen distributions system at the refueling station
- Two potential consequences were evaluated in HyRAM+ for the select scenarios
  - The dispersion of hydrogen is characterized by the unignited jet or plume of hydrogen
  - The radiative heat flux from an ignited hydrogen plume



The consequences from the critical scenarios in the hydrogen distribution system at the refueling station were evaluated in HyRAM+ Version 5.0

Accomplishment (Risk Assessment)

- A Computational Fluid Dynamics (CFD) model was used to visualize the spread of the flammable mass released under the vehicle from TPRD release of a single tank
- Two scenarios were evaluated in CFD, a slower velocity and higher mass flow rate and a faster velocity and lower mass flow rate
- The CFD simulations show that the hydrogen is released downward and quickly becomes buoyant and spreads outward along the bottom of the vehicle



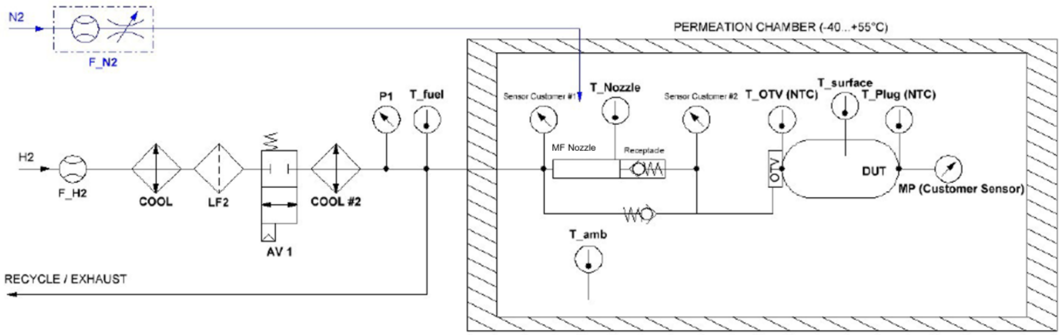
A detailed CFD model utilizing the SIERRA suite was used to evaluate a TPRD release in the onboard hydrogen storage compartment

Accomplishment (Fueling Protocol)

Single-tank testing campaign for fueling interface has been completed

Scope:

- ❑ Evaluation of F90 (9 runs) and F300 (3 runs) fueling protocols, as per SAE J2601-5.
- ❑ Evaluation of the effect of precooling on the final tank temperatures.
- ❑ Evaluation of the performance of MF hardware with flows up to 90 g/s.



Key output variables:

- ❑ Final pressure and gas temperatures → should not exceed tank limits
- ❑ Final SOC → greater than 95%
- ❑ Peak mass flow rate
- ❑ Total fueling time → goal is to fuel in less than 20 minutes
- ❑ Pressure drop (using P_{tank}=10 MPa as a reference condition)
  - ✓ Between nozzle and receptacle
  - ✓ Vehicle: from downstream of receptacle to tank
  - ✓ Total: Station + vehicle

Test matrix:

Test No.	Test Description	Initial VFS Pressure (MPa)	Chamber Temp. (°C)	Initial VFS Gas Temp. (°C)	Dispenser Pre-cooling (°C)
1	Baseline F90 fueling	5	15	15	-20 +0/-5
2	F90 Pre-cooling eval.	5	15	15	-30 +0/-5
3	F90 Pre-cooling eval.	5	15	15	-15 +2/-3
4	F90 rates, hot, mass flow constrained	5	45	45	-30 +0/-5
5	F90 rates, temperature constrained case 1	2	50	50	-30 +0/-5
6	F90 rates, temperature constrained, hot soak	2	30	36.7	-20 +0/-5
7	F90 rates, Post-drive fueling	10	15	-15	-20 +0/-5
8	F90 rates, Winter Fueling Eval.	5	-15	-15	-15 +0/-5
9	F90 rates, Change in precooling	5	40	40	Start at -30 +0/-5 , then -20 +0/-5 after 10 minutes
10	F300 rates, mass flow constrained	5	40	40	-40 +0/-5
11	F300 temperature constrained case 1, low Pini, Option A	2	40	40	-30 +0/-5
12	F300 with PRR taper	3	-15	-15	-40 +0/-5

NIKOLA

Savannah River National Laboratory

Accomplishment (Fueling Protocol)

Single-tank tests showed that SAE J2601-5 performs as intended: no overtemperature, fueling times under 20 minutes

Test No.	Test Description	Dispenser Pre-cooling (°C)	Chamber Temp. (°C)	Initial tank Pressure (MPa)	Final tank pressure (MPa)	Initial VFS Gas Temp. (°C)	Final VFS Gas Temp. (°C)	Total fueling time (min)	Final SOC (%)	Peak mass flow rate (g/s)	Pressure drop nozzle + receptacle (MPa) *	Vehicle pressure drop (MPa)*	Total pressure drop (MPa)*
1	Baseline F90 fueling	-20 +0/-5	15	5	80.6	15	**69.5**	**16.2**	**97.5**	19.9	1.0	1.7	**3.6**
2	F90 Pre-cooling eval.	-30 +0/-5	15	5	78.5	15	**56.7**	**16.0**	**98.3**	19.9	1.1	1.6	**3.5**
3	F90 Pre-cooling eval.	-15 +2/-3	15	5	82.2	15	**75.8**	**16.5**	**97.6**	19.9	1.0	1.7	**3.6**
4	F90 rates, hot, mass flow constrained	-30 +0/-5	45	5	81.2	45	**74.9**	**16.4**	**97.0**	20.3	2.1	0.6	**3.3**
5	F90 rates, temperature constrained case 1	-30 +0/-5	50	2	82.2	50	**78.3**	**17.2**	**97.1**	24.3	2.4	1.1	**4.1**
6	F90 rates, temperature constrained, hot soak	-20 +0/-5	30	2	83.3	36.7	**81.1**	**17.4**	**97.5**	23.4	1.8	1.6	**4.2**
7	F90 rates, Post-drive fueling	-20 +0/-5	15	10	77.3	-15	**56.3**	**14.5**	**97.4**	18.9	0.5	0.2	**1.4**
8	F90 rates, Winter Fueling Eval.	-15 +0/-5	-15	5	78.7	-15	**60.0**	**15.7**	**97.8**	19.8	-0.5	2.6	**3.4**
9	F90 rates, Change in precooling	Start at -30 +0/-5 , then -20 +0/-5 after 10 minutes	40	5	84.3	40	**84.8**	**18.0**	**97.6**	19.5	2.0	0.8	**3.5**
10	F300 rates, mass flow constrained	-40 +0/-5	40	5	77.7	40	**73.0**	**5.1**	**94.4**	68.7	3.0	5.5	**9.7**
11	F300 temperature constrained case 1, low Pini, Option A	-30 +0/-5	40	2	82.6	40	**81.8**	**8.0**	**96.8**	47.3	2.9	5.8	**9.9**
12	F300 with PRR taper	-40 +0/-5	-15	3	69.4	-15	**55.2**	**5.6**	**90.5**	48.3	0.86	9.6	**12.4**

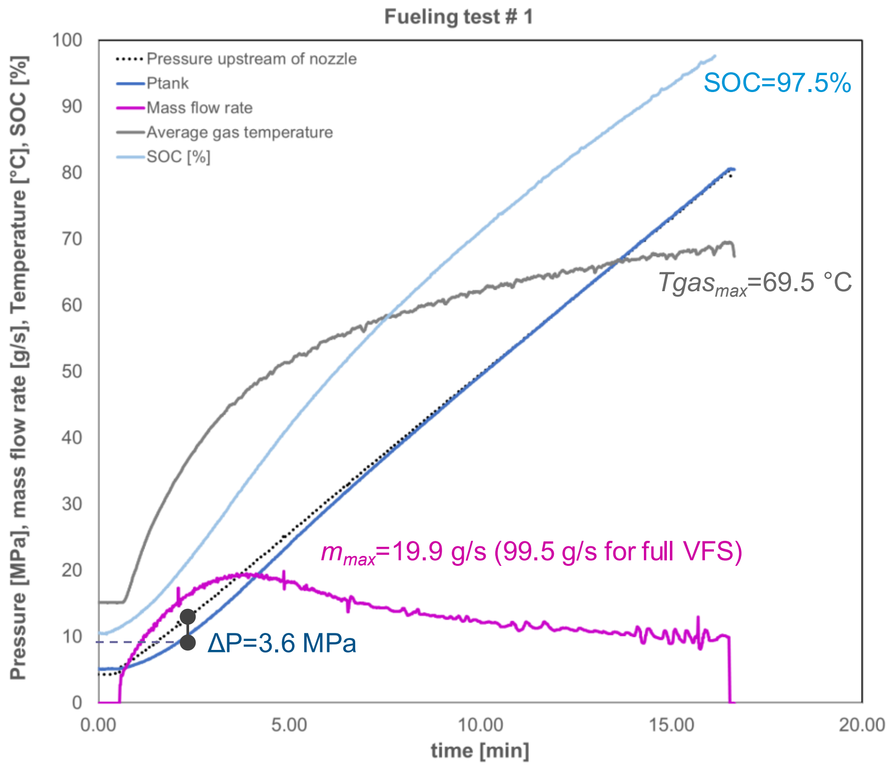
NIKOLA

Savannah River National Laboratory

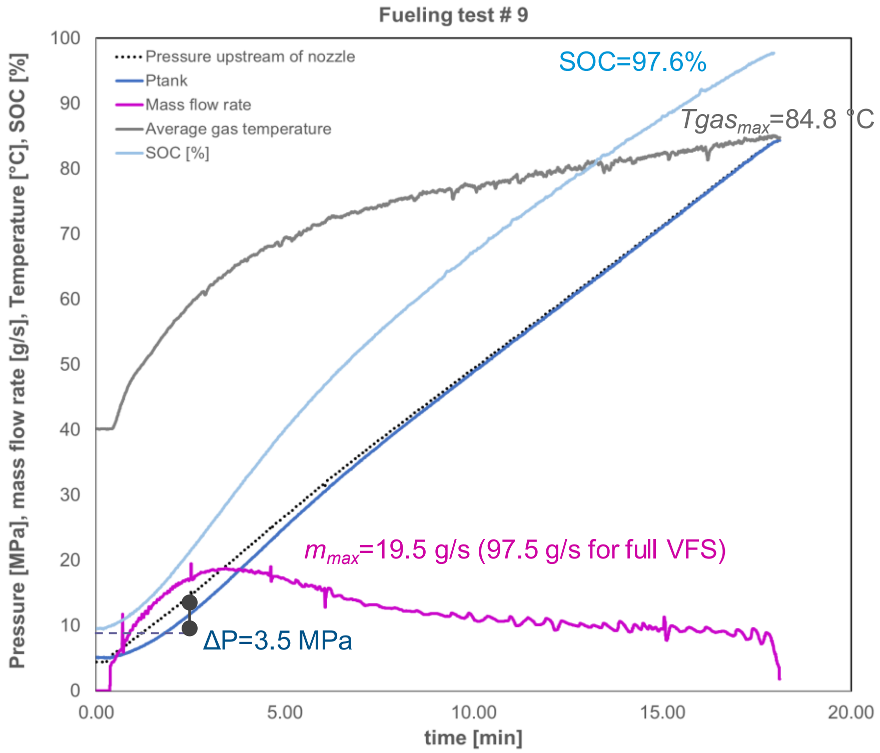
Accomplishment (Fueling protocol)

F90 fueling tests: fueled to at least 97% SOC in under 18 minutes, without exceeding tank temperature limits

BASELINE CASE (No.1): P_0 = 5 MPa, T_{amb} = 15 °C (soaked), T_{fuel}= -20 °C ;



CHANGE IN PRECOOLING (No.9): P_0 = 5 MPa, T_{amb} = 40 °C (soaked), T_{fuel} start at -30 °C, after 10 min. switch to -20 °C ;

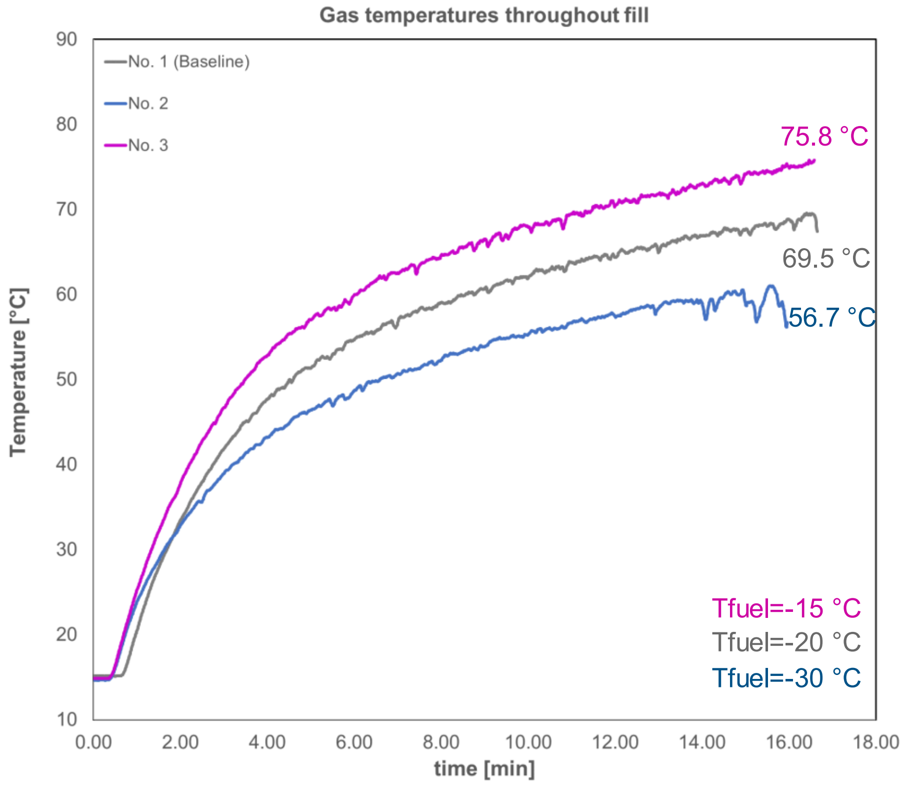


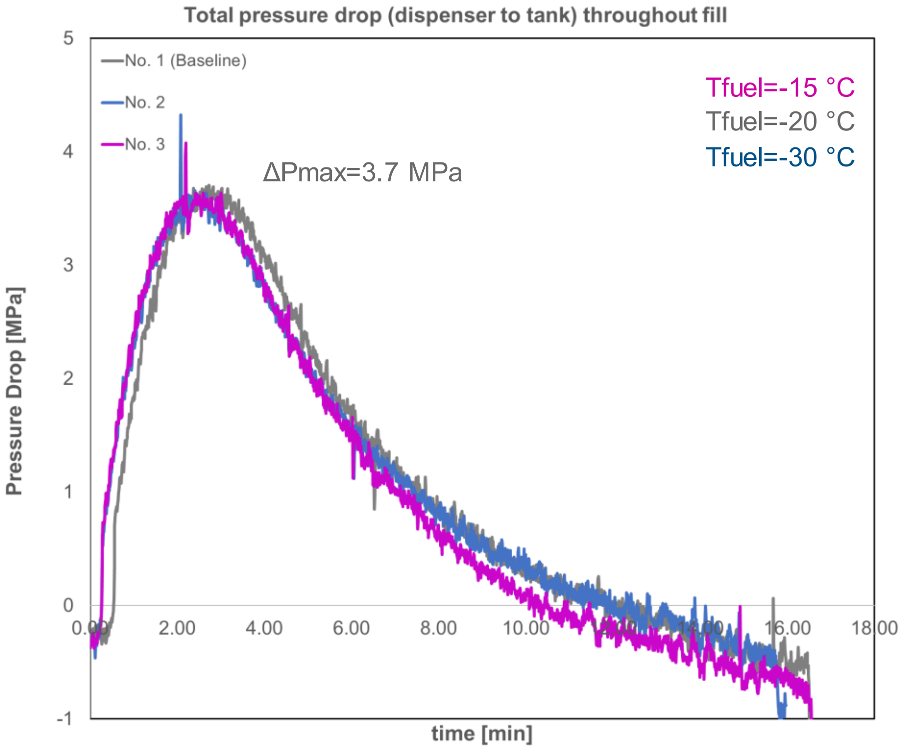
- **Maximum flow rate for a 5-tank system would have exceeded the limit of 90 g/s. Even so, maximum observed temperature in single tank was 84.8 °C. This was for the case of Tam=40 °C with precooling change mid-fill.**
- **Total pressure drop (at reference conditions) below 4.2 MPa.**

Accomplishment (Fueling protocol)

Effect of precooling temperature: changes in final gas temperature, no effect on pressure drop

Precooling temperature effect using maximum F90 pressure ramp rates, T_{amb}=15°C



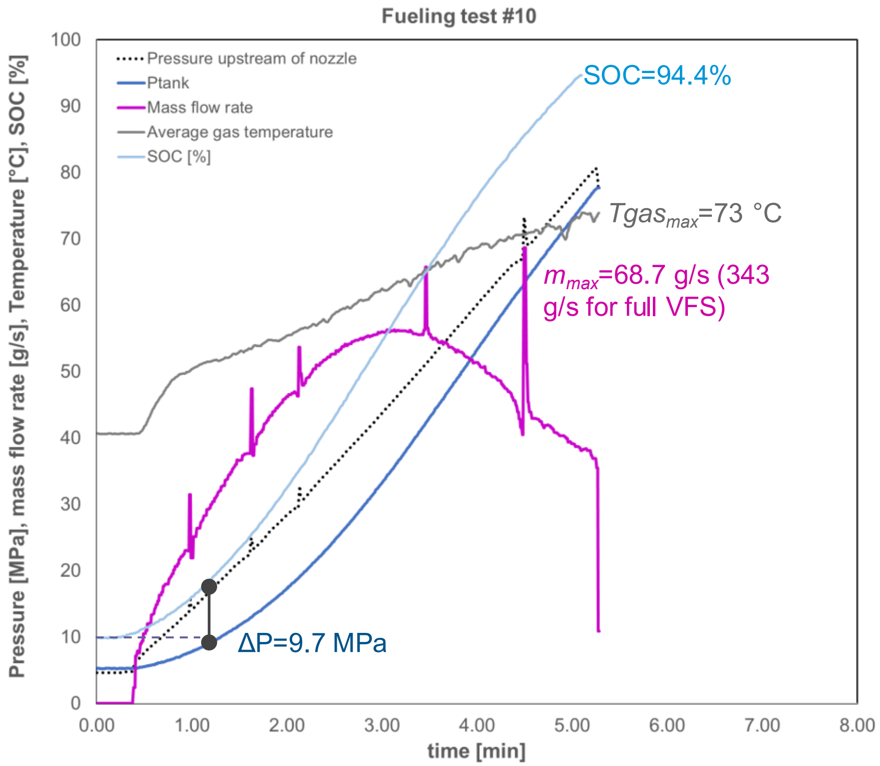


- ❑ Decreasing the temperature of dispensed H_2 from -20°C to -30°C, decreased the final gas temperature by 12.8 °C.
- ❑ Increasing the temperature of dispensed H_2 from -20°C to -15°C, increased the final gas temperature by 6.3 °C.
- ❑ The change in precooling temperature in the range -30°C to -15°C had no effect in the total pressure drop.

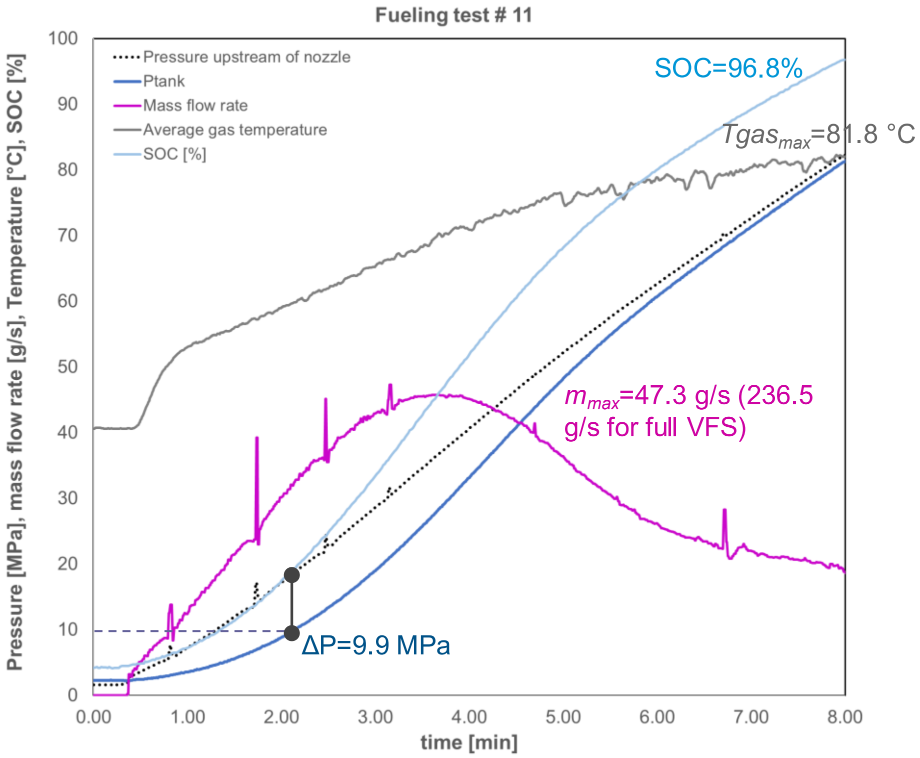
Accomplishment (Fueling protocol)

F300 tests: fueling time under 10 minutes, without exceeding tank temperature limits, but high pressure drop

Mass flow constrained (No.10): P_0 = 5 MPa, T_{amb} = 40 °C (soaked), T_{fuel}= -40 °C ;



Temperature constrained (No.11): P_0 = 2 MPa, T_{amb} = 40 °C (soaked), T_{fuel} =-30 °C;



- ❑ **Fueling times were under 10 minutes, but final SOC was only 90-97% due to high pressure drop.**
- ❑ **Test set up did not include actual HF hardware and line sizes, so the pressure drop experienced is larger than what a HF set up for the full VFS would have experienced.**

NIKOLA

Savannah River National Laboratory

Accomplishment (Fueling protocol)

MF Hardware test: pressure drop through nozzle and receptacle increased with decreasing inlet pressure

Test No.	Test Description	Dispenser Pressure [MPa]	Nozzle inlet pressure [MPa]	Outlet Pressure [MPa]	Inlet gas temperature (recorded) [°C]	Mass flow rate (recorded) [g/s]	Pressure drop through nozzle + receptacle pair [MPa]
1	Receptacle test, pressure 1	87.5	79.3	75.6	-32.2	84.4	3.7
2	Receptacle test, pressure 2	70	62.3	57.8	-29.5	86.8	4.5
3	Receptacle test, pressure 3	60	54.3	49.2	-31.1	89.0	5.0
4	Receptacle test, pressure 4	50	35.1	26.4	-29.0	97.5	8.8
5	Receptacle test, pressure 5	40	33.1	25.9	-30.6	86.7	7.3

- **Maximum pressure drop seen through this test was 8.8 MPa, but the mass flow rate for this case exceeded 90 g/s (97.5 g/s).**
- **The maximum pressure drop for flow rates under 90 g/s was 7.3 MPa, for the case with inlet pressure of 40 MPa.**
- **The kv corresponding to that case would be 0.232 m^3/h.**
- **There were no leaks through the nozzle-receptacle interface during the leak tests.**

NIKOLA

Savannah River National Laboratory

Proposed Future Work

Fueling protocol testing

- Full VFS test sequence with F90 and F300 fueling rates, per SAE J2601-5.

Summary

Precooling Analysis

- Analyzed precooling temperature requirement for updated flow coefficients of receptacle-nozzle pair and on-tank valve
- Obtained the optimum design of HX to employ for precooling H2 by using a printed circuit heat exchanger model
- Employed Argonne's Heavy Duty Refueling Station Analysis Model (HDRSAM) to perform technoeconomic analysis and study the impact of the hybrid HX on refueling cost.
- Evaluated the impact of precooling systems: (i) on-demand cooling only, (ii) hybrid precooling with on-demand HX and embedded thermal buffer.

Risk Assessment

- A Computational Fluid Dynamics (CFD) model was used to visualize the spread of the flammable mass released under the vehicle from TPRD release of a single tank
- Two scenarios were evaluated in CFD, a slower velocity and higher mass flow rate and a faster velocity and lower mass flow rate
- The CFD simulations show that the hydrogen is released downward and quickly becomes buoyant and spreads outward along the bottom of the vehicle

Full Scale Single-Tank Testing

- Single-tank testing campaign for fueling interface has been completed with a planned full VFS tests planned for April.
- Demonstrated successfully both F90 and F300 fueling at different conditions using MF hardware.

Technical Backup and Additional Information

Task progress after 2023 AMR (TPs for other slides)

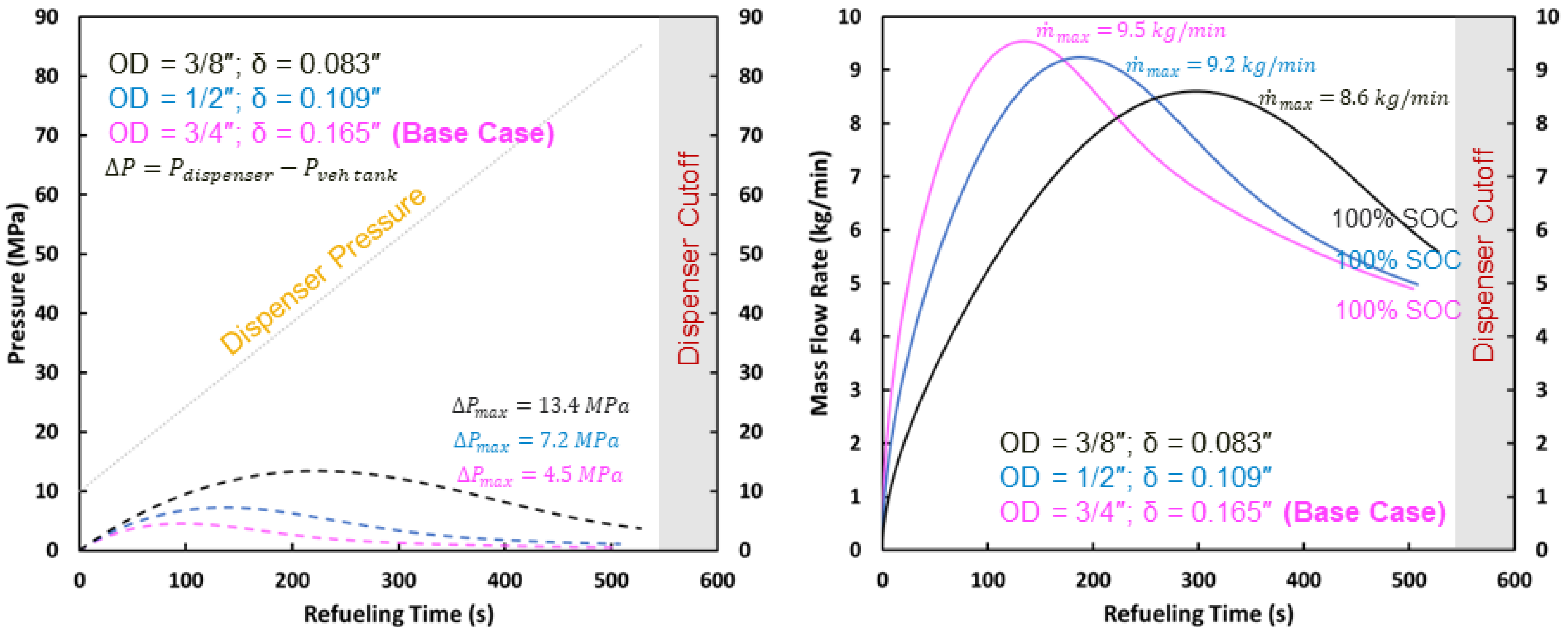
- Updated the analysis of required precooling temperature based on latest data for flow coefficients of receptacle-nozzle pair and on-tank valve
- Investigated and proposed a hybrid on-demand cooling HX design for HD fueling applications.
- Employed printed circuit heat exchanger modeling to study the performance of the Hybrid HX design
- Evaluated the impact of the hybrid precooling HX with embedded thermal buffer, on the levelized cost of hydrogen refueling

AMR23 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



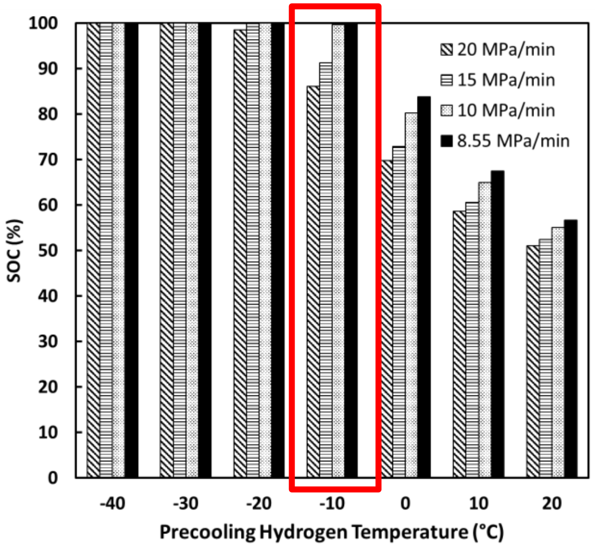
Pipe diameter has strong influence on pressure drop

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

AMR23 Accomplishment (Precooling)

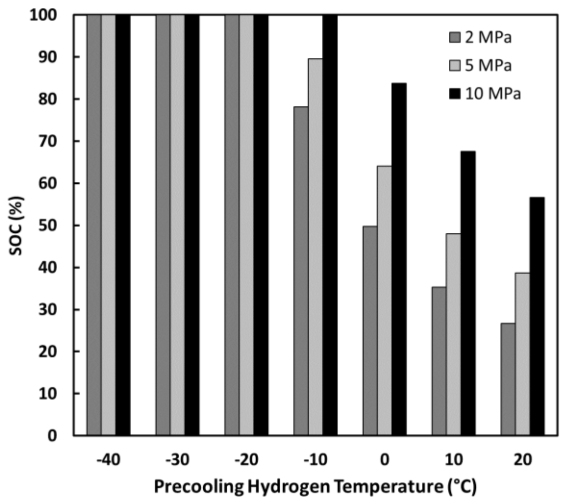
Boundary Conditions like Pressure Ramp Rate, Initial Tank Pressure and Ambient Temperature Influences Precooling Load

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



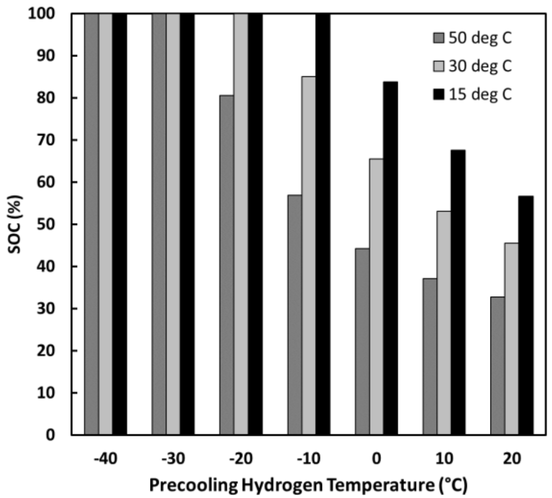
Higher APRR requires lower precooling temperature to obtain higher SOC%

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

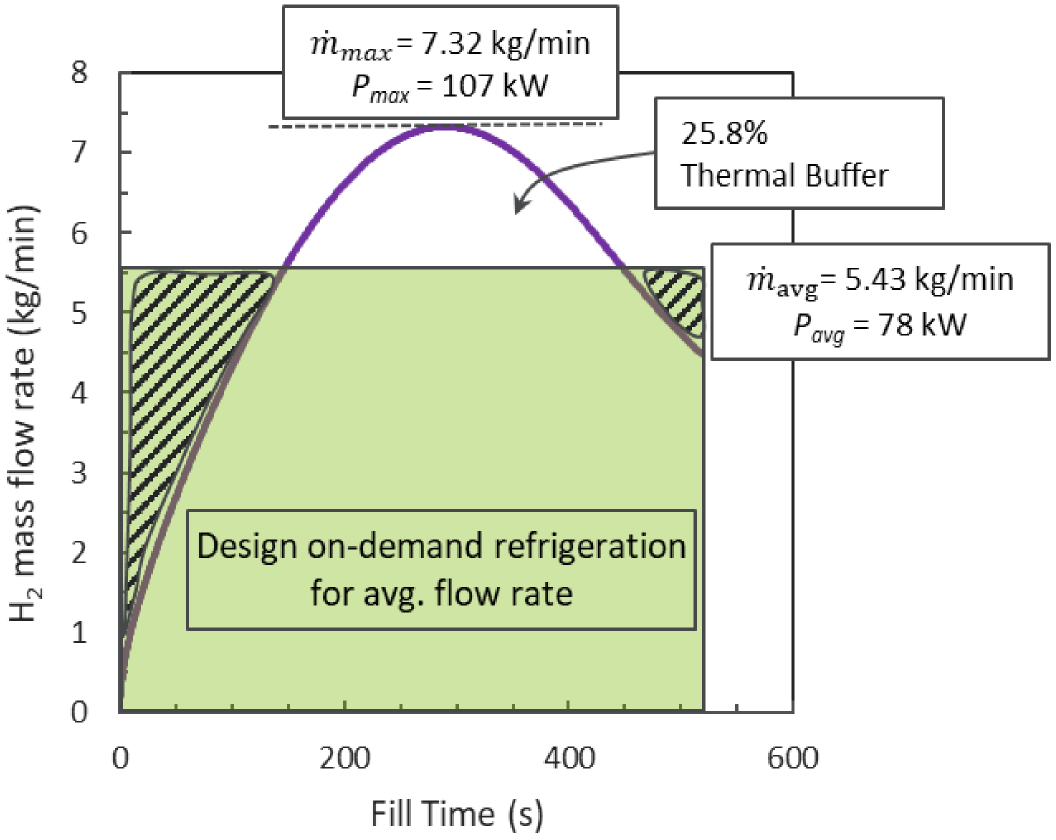


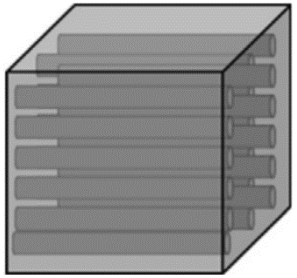
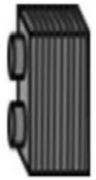
Lower ambient temperature requires lower cooling loads to achieve maximum SOC%

Relevance/Impact/Approach (Precooling)

Hydrogen Precooling strategies include Thermal Buffering and On-demand Cooling

Flow properties & Cooling Duty



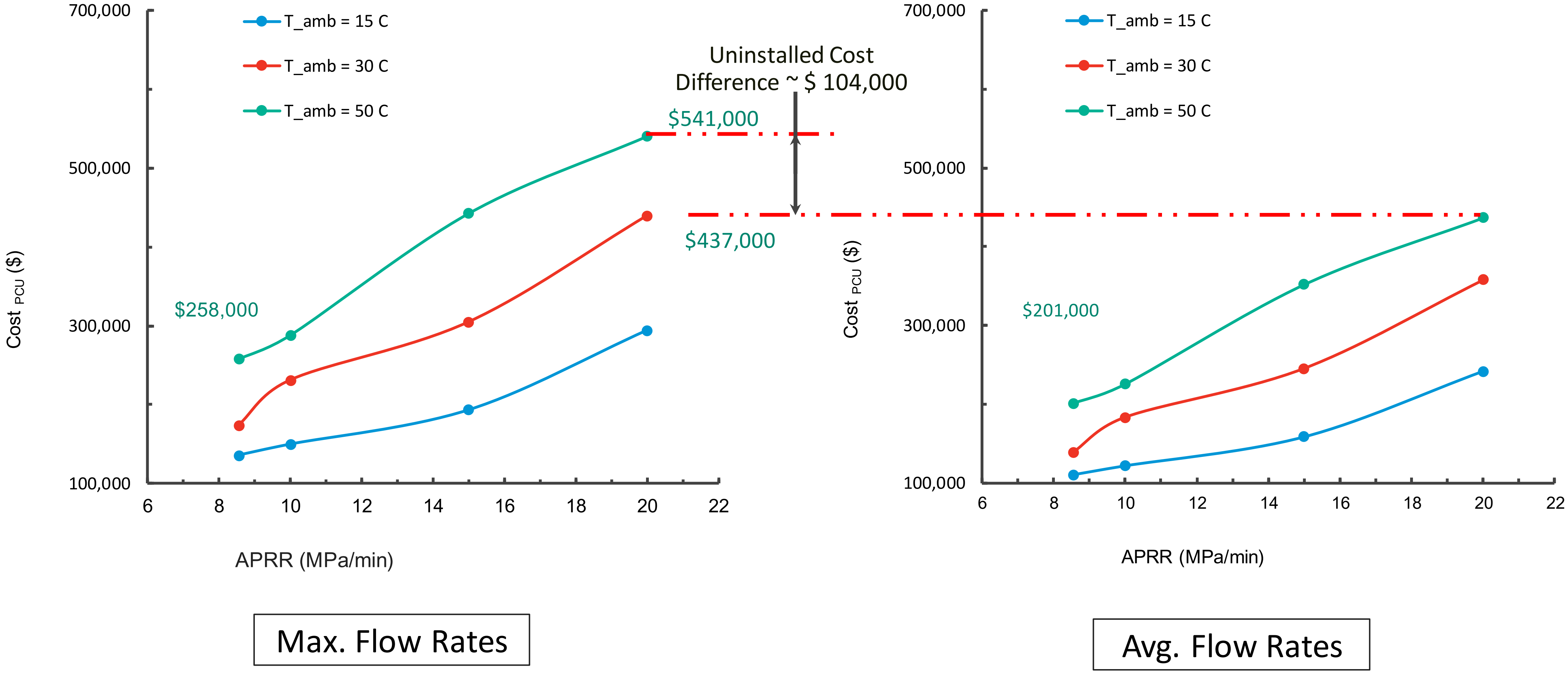
Thermal Buffering	On-demand Cooling
	
Large mass of HX (1-3 tons)	Compact HX, large area/volume ratio
HX mass absorbs heat from H_2	Direct heat exchange b/w refrigerant and H_2
Refrigerant used to cool and maintain the HX block at target temperature	On-demand cooling during fill
Small capacity refrigerator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

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

Argonne NATIONAL LABORATORY Savannah River National Laboratory

AMR23 Approach (Precooling)

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



Argonne NATIONAL LABORATORY
Savannah River National Laboratory

FY23 Approach (Precooling)

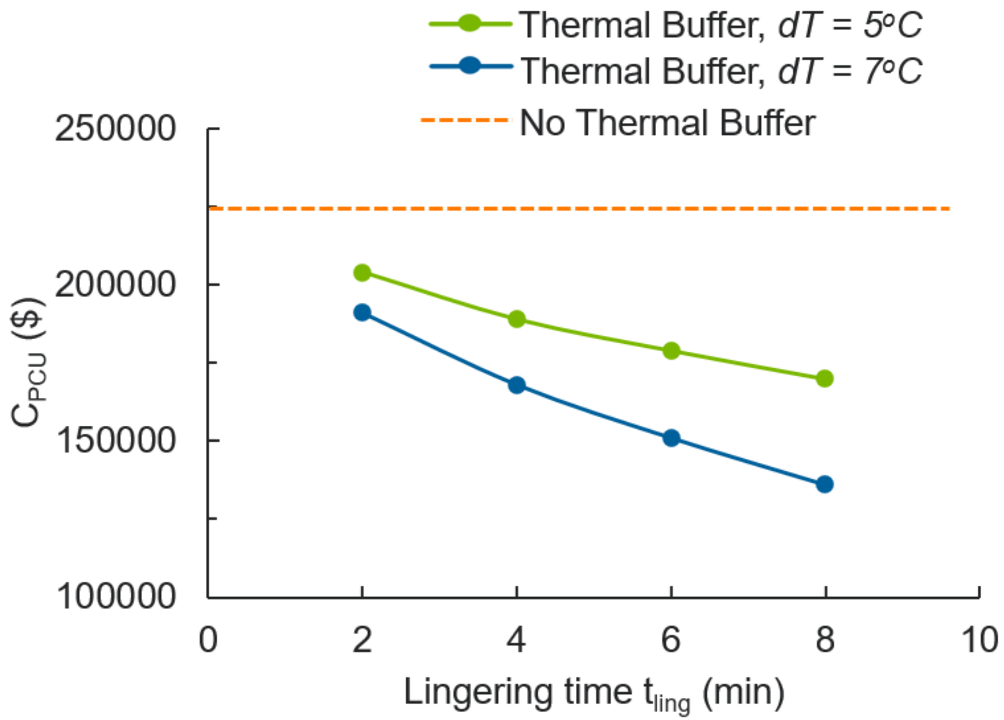
Determination of Baseline Refrigeration Method Candidates for Refueling Conditions

- 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

AMR23 Accomplishment (Precooling)

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

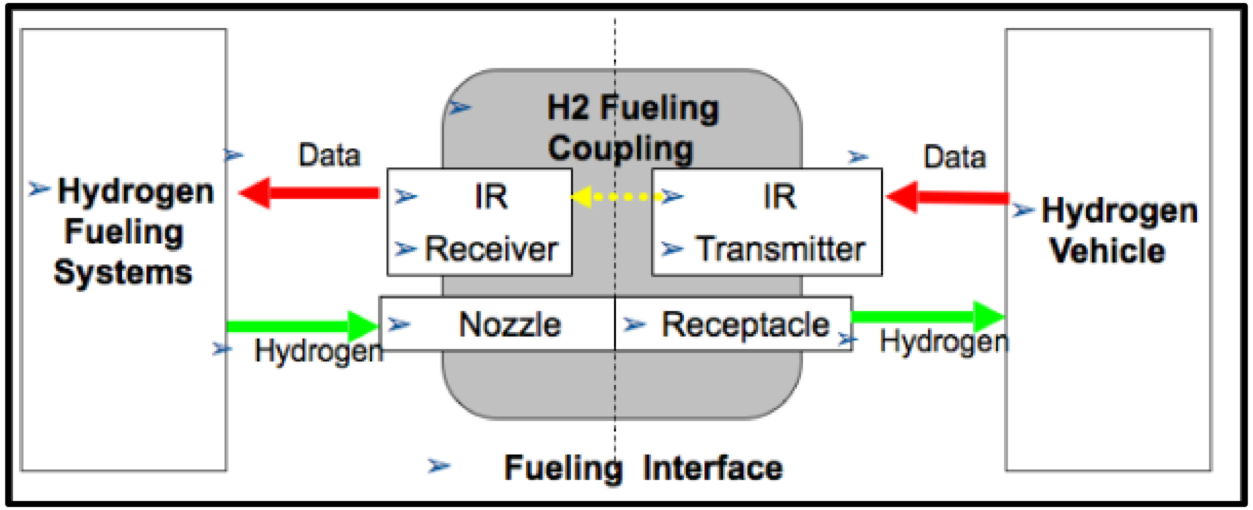


- Achieving a balance between on-demand cooling and thermal buffering works best for heavy-duty fueling involving large flow rates.
- Developed HX model to obtain optimum design of HX providing a balance between on-demand cooling and thermal buffering.
- Cost reduction would depend upon the cost of adding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

Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- Project has not been previously reviewed at the AMR.

Technology Transfer Activities

- There are currently no technology transfer activities.
- The team is currently exploring opportunities to expand activities around the communications work that would involve expanding industry partnerships.

Publications and Presentations (Update Slide)

- Team is active participant in the WG24 and SAE discussions.
- Publication(s):
  - 2023 ASHRAE Conference Proceeding: "Refrigeration System Design Exploration for a Heavy-Duty Hydrogen Refueling Station"

Reviewer-Only Slides