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

Project ID: IN040

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DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

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

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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

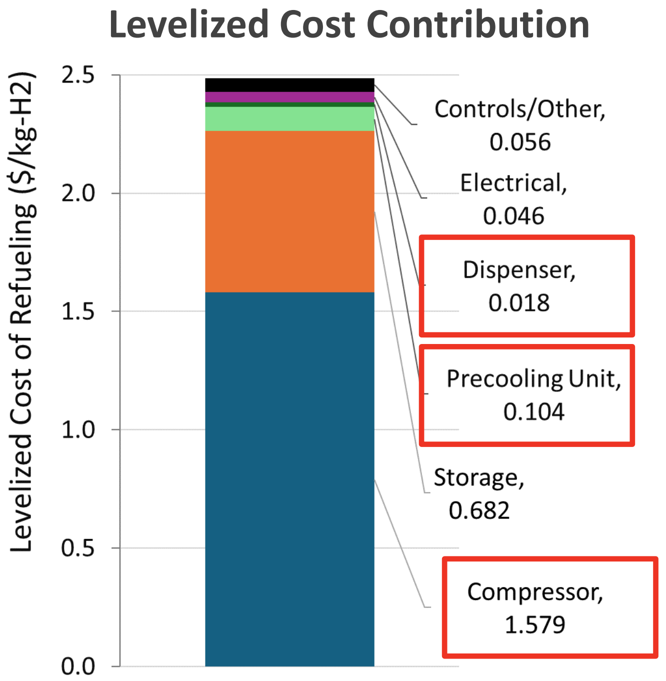
- Savannah River National Laboratory (PI)
- Argonne National Laboratory (co-PI)
- Sandia National Laboratories (co-PI)
- Nikola Motors (Industry Partner)

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. → [Cost, Reliability]
- 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 for next generation fueling.
- 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.

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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.

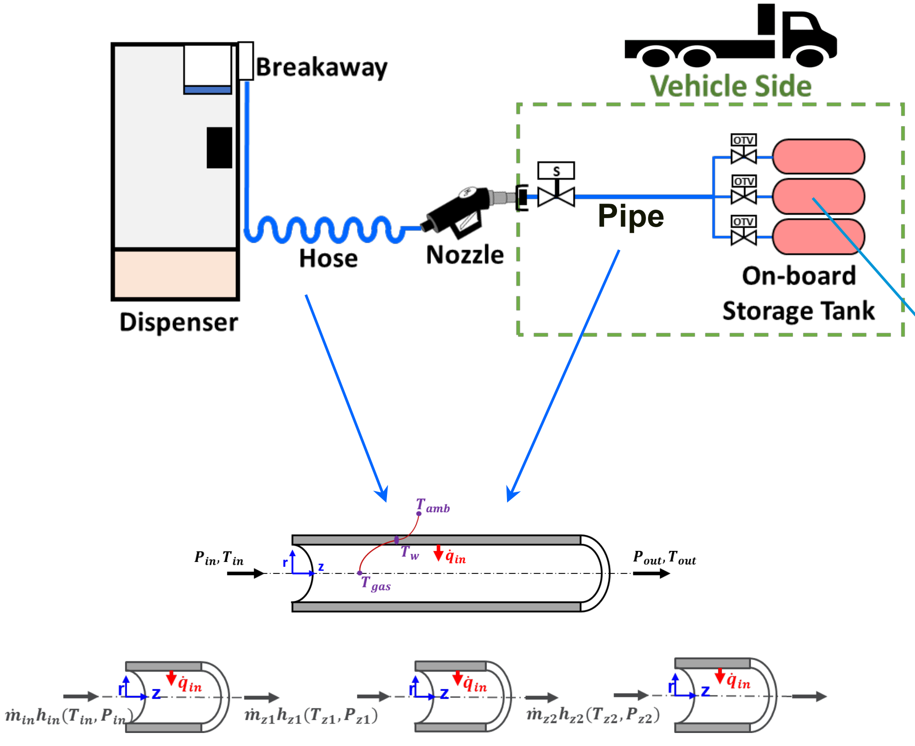
Relevance/Impact (Precooling)

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

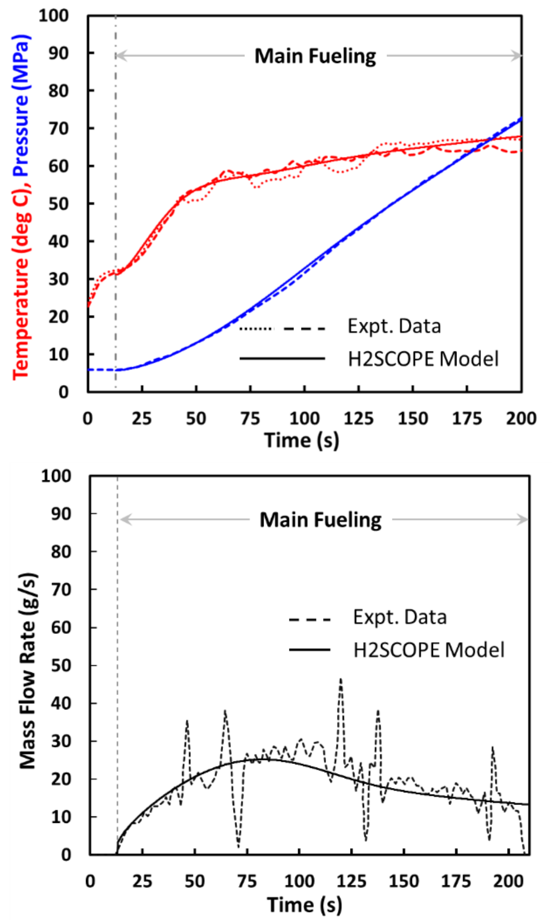
- Understand impacts of the various Onboard Hydrogen Storage System (HSS) designs on the required precooling temperature for a range of fueling speeds and boundary conditions. The different HSS designs are provided by the industry stakeholder.
- The HSS designs are characterized by the hydrogen tank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

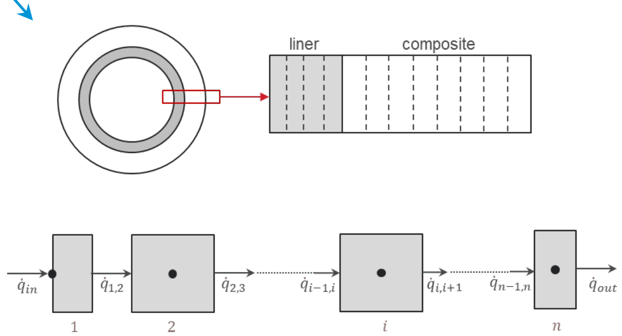
APPROACH (Precooling)
Transient Heat Transfer Across Fueling Components have been Modeled

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

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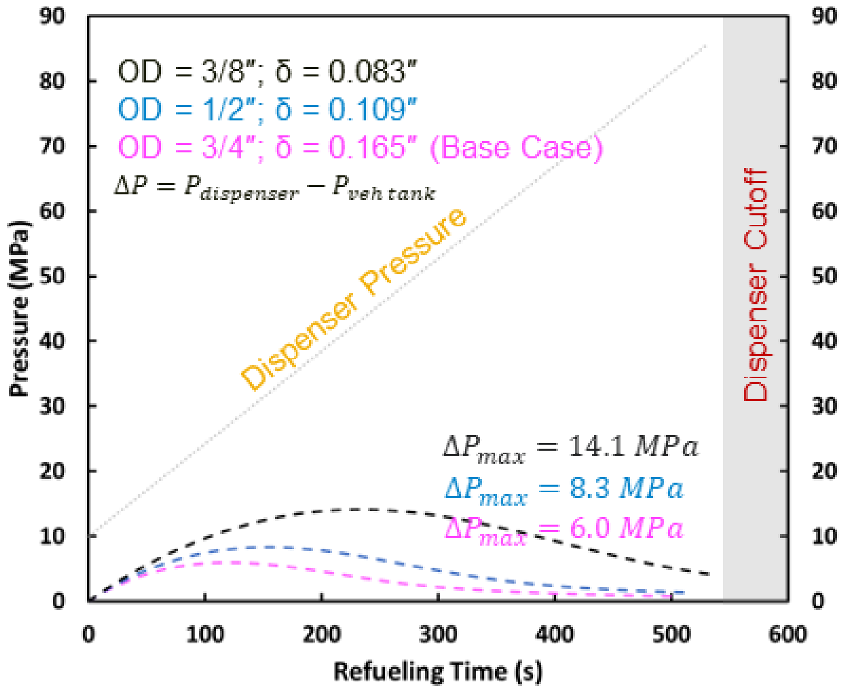
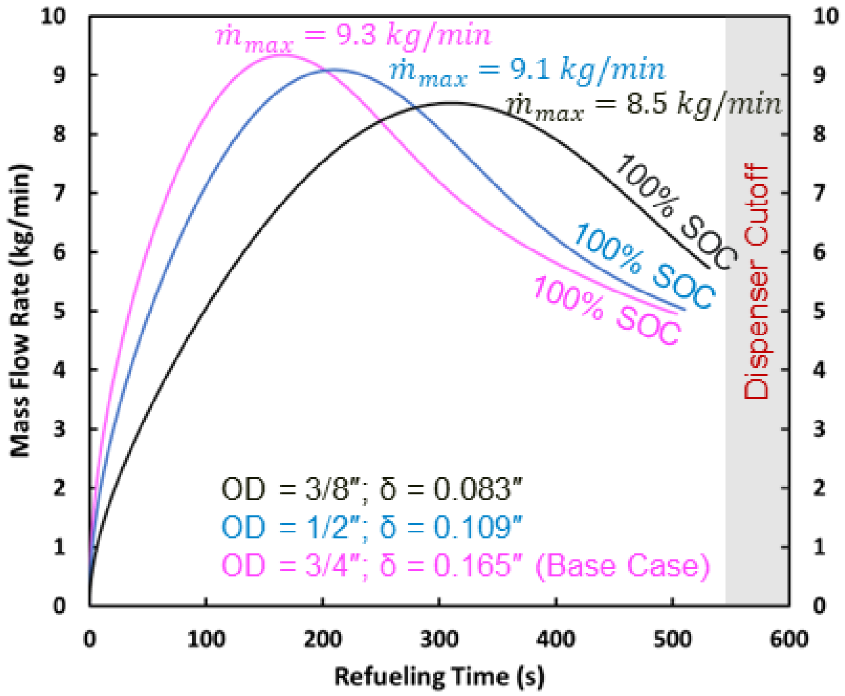
Accomplishments (Precooling)

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





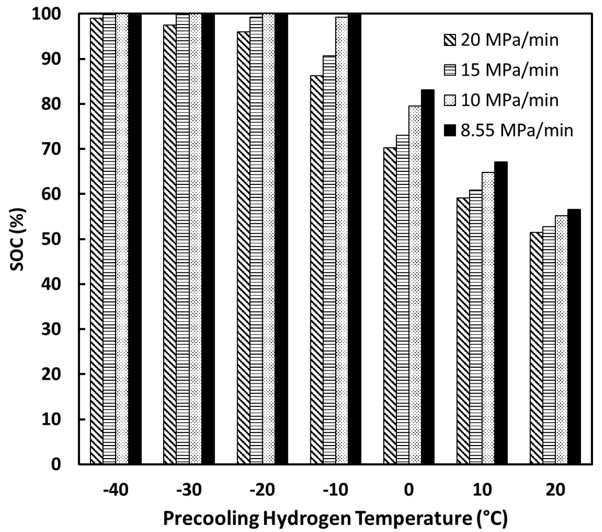
Pipe diameter has strong influence on pressure drop
- ✓ **Impacts mass flow rate**
- ✓ **Fill time**
- ✓ **Affects instantaneous precooling load**

Accomplishments (Precooling)

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

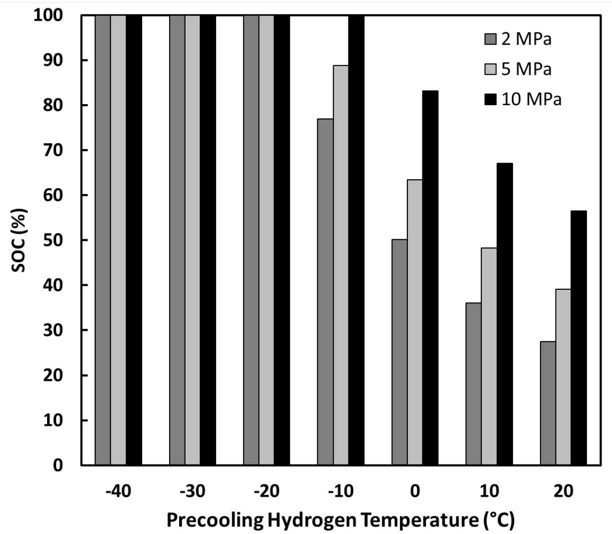
Updated based on latest data for flow coefficients of receptacle-nozzle pair and on-tank valve

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



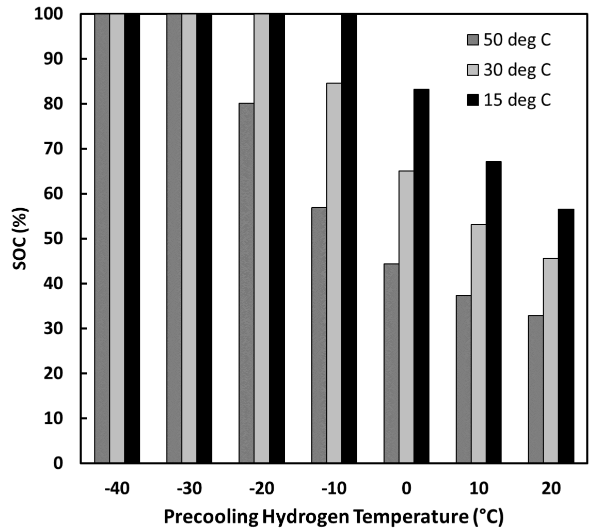
Higher APRR requires lower precooling temperature to obtain higher SOC%

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



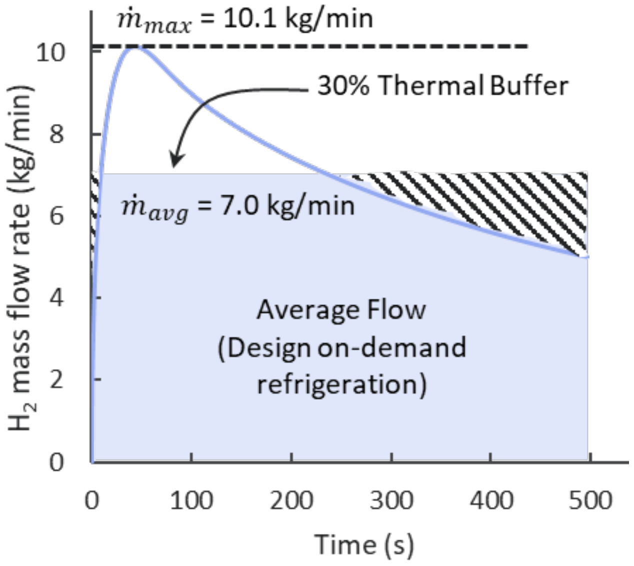
Lower ambient temperature requires less cooling loads to achieve maximum SOC%

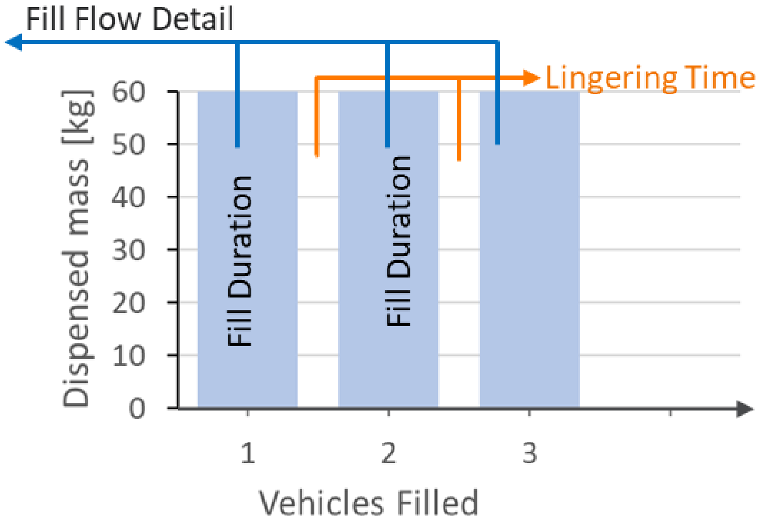
Accomplishments (Precooling)

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





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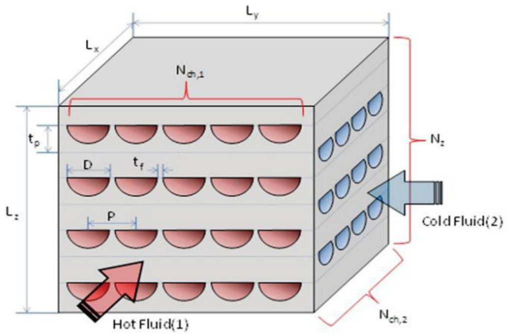
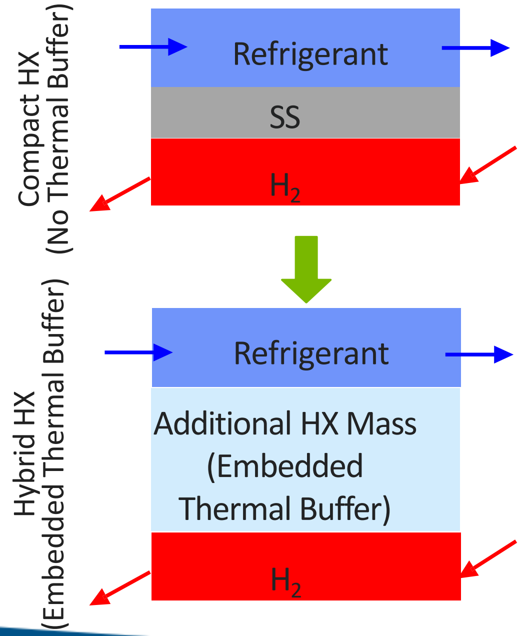
Accomplishments (Precooling)

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





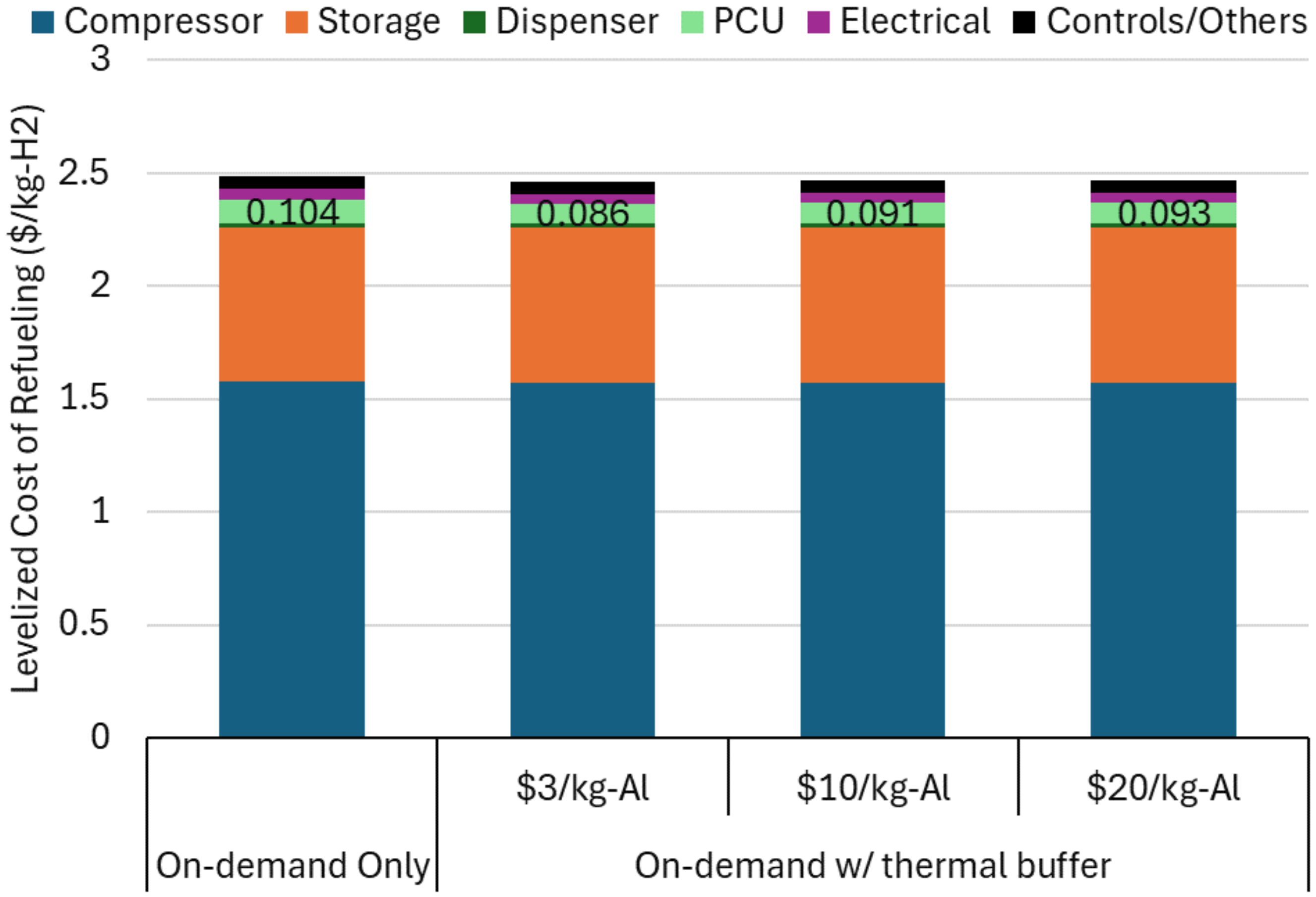
- Adding mass to HX increases thermal resistance and reduces its performance
- Strength of material (plate-thickness) to withstand pressure difference between the hot and cold fluid needs to be considered.
- Design of new compact HX capable to provide required cooling duty needs is investigated
- Printed 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

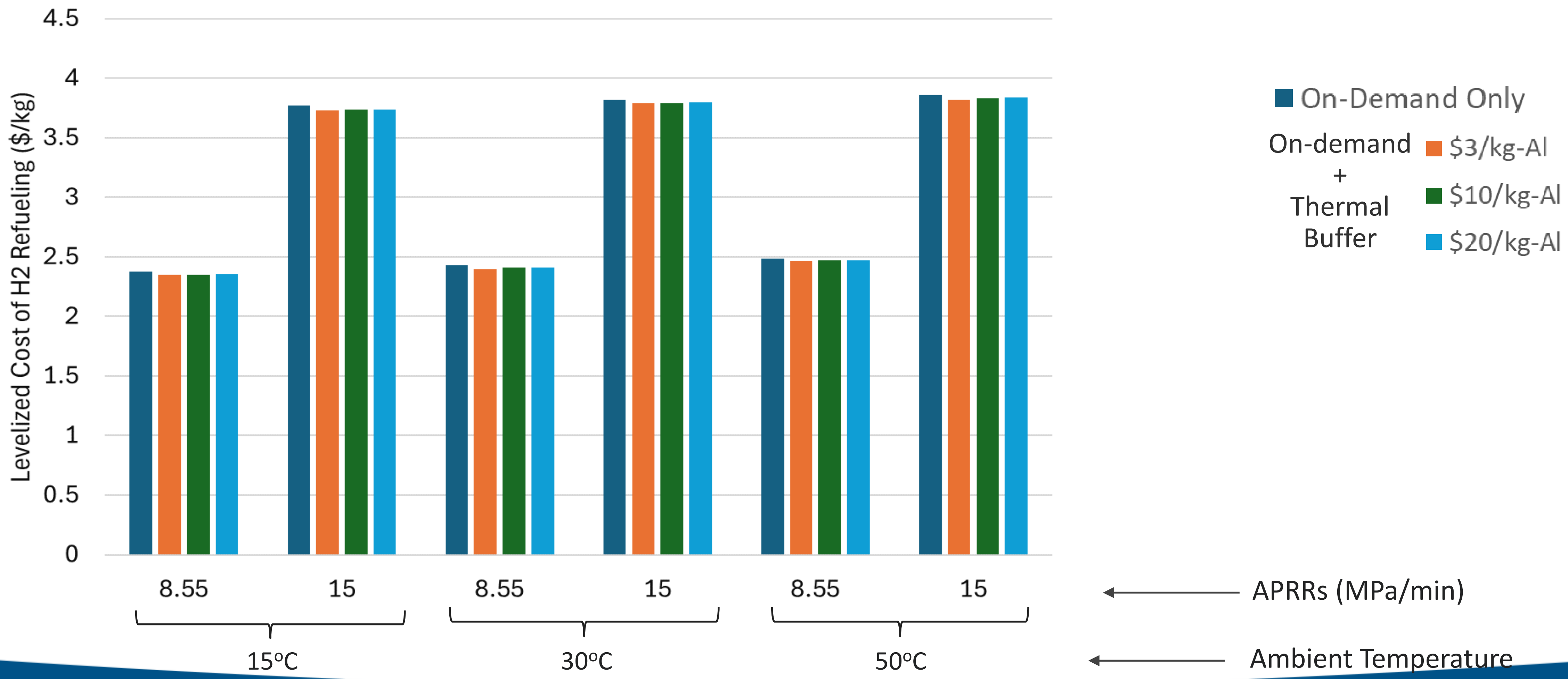
Parameters	Values
Ambient Temperature (°C)	50
APRR (MPa/min)	8.5
HX Inlet Temperature (°C)	50
HX Outlet Temperature (°C)	-40
Maximum Flow Rate (kg/min)	9.22
Minimum Flow Rate (kg/min)	6.63
Mass Dispensed (kg)	60
Fill Duration (min)	8.9
Ambient Temperature (°C)	50



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

Accomplishments

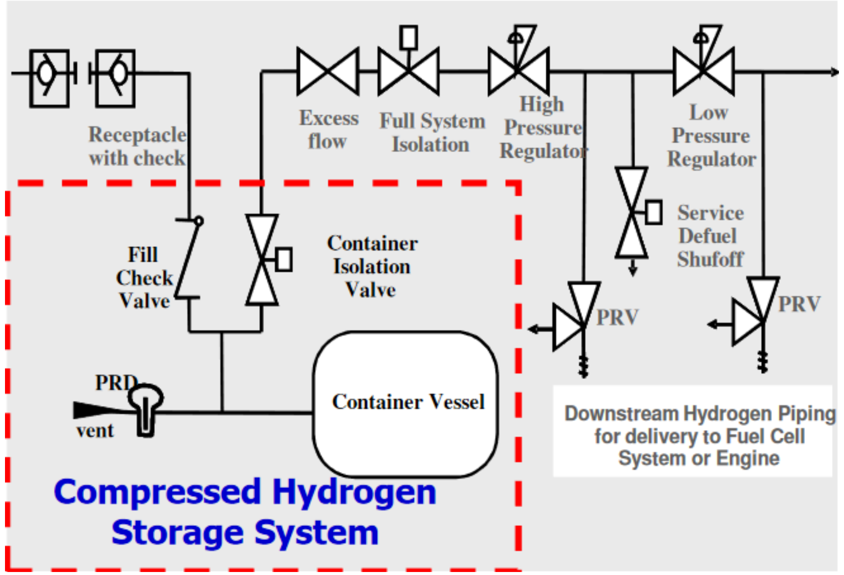
Scenarios of H_2 dispense and corresponding levelized cost of refueling



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

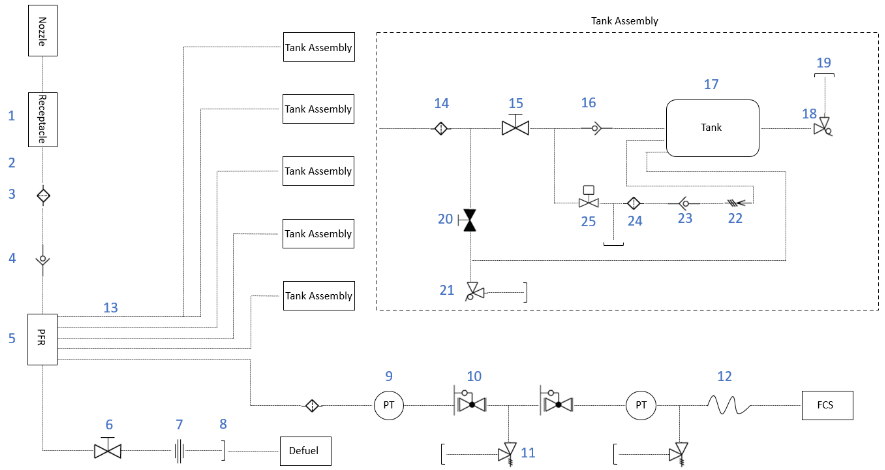
Overview

- 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



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

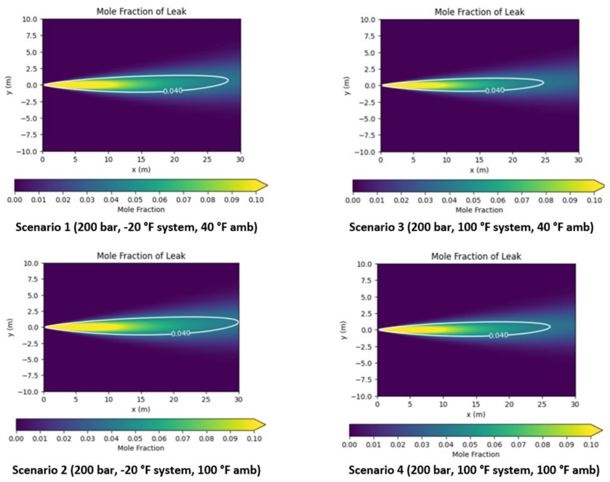


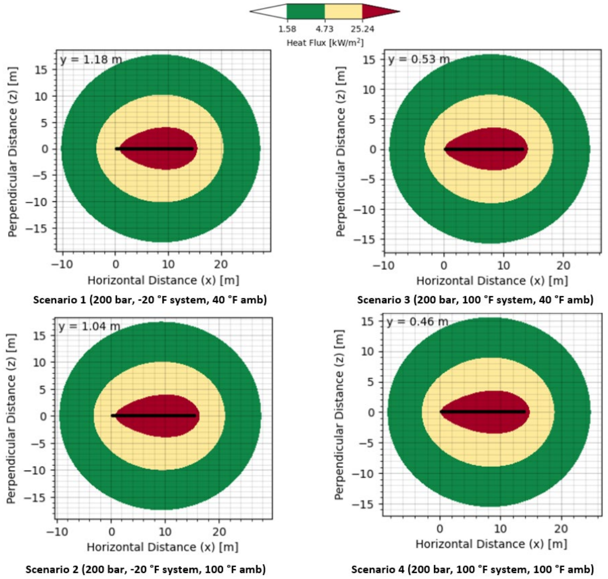
HAZOP Number	Component	Operation State	Hazard Scenario	Causes	Consequences
⋮	⋮	⋮	⋮	⋮	⋮
35	HDV-13 (Hydrogen Tubing (1/2"))	2	Leakage from tubing	Mechanical damage, material failure, installation error	Potential release of H2
36	HDV-14 (Filter)	2	Leakage from filter housing or fitting	Installation error,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

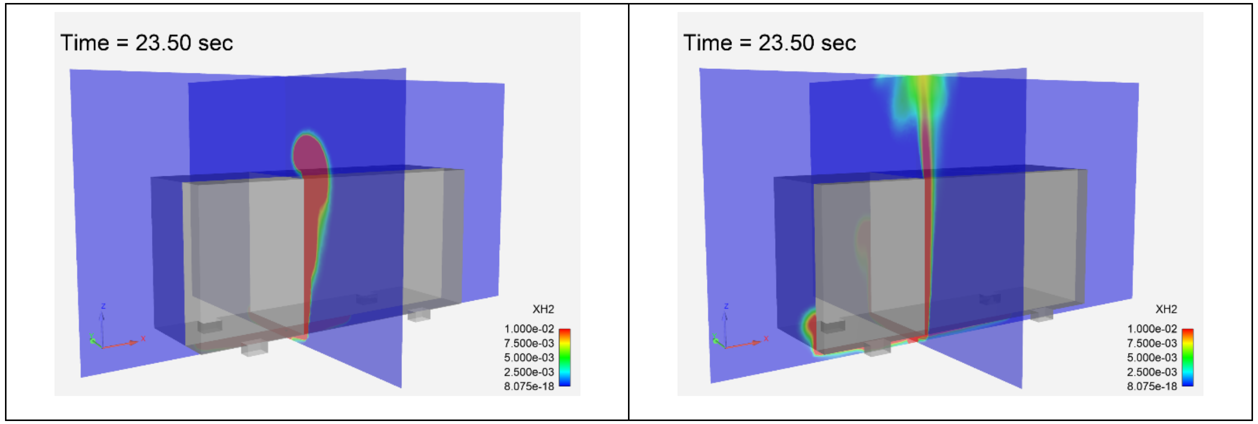




The consequences from the critical scenarios in the hydrogen distribution system at the refueling station were evaluated in HyRAM+ Version 5.0

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

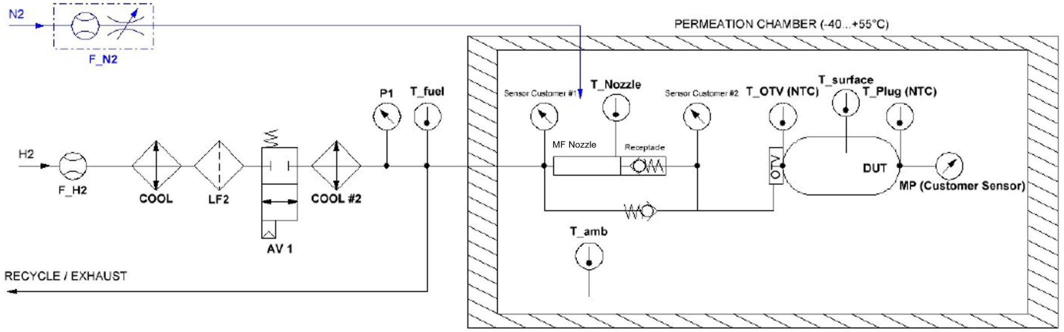
Temperature-controlled chamber

MF/F90 nozzle

Single 363 L tank

MF/F90 receptacle

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

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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**

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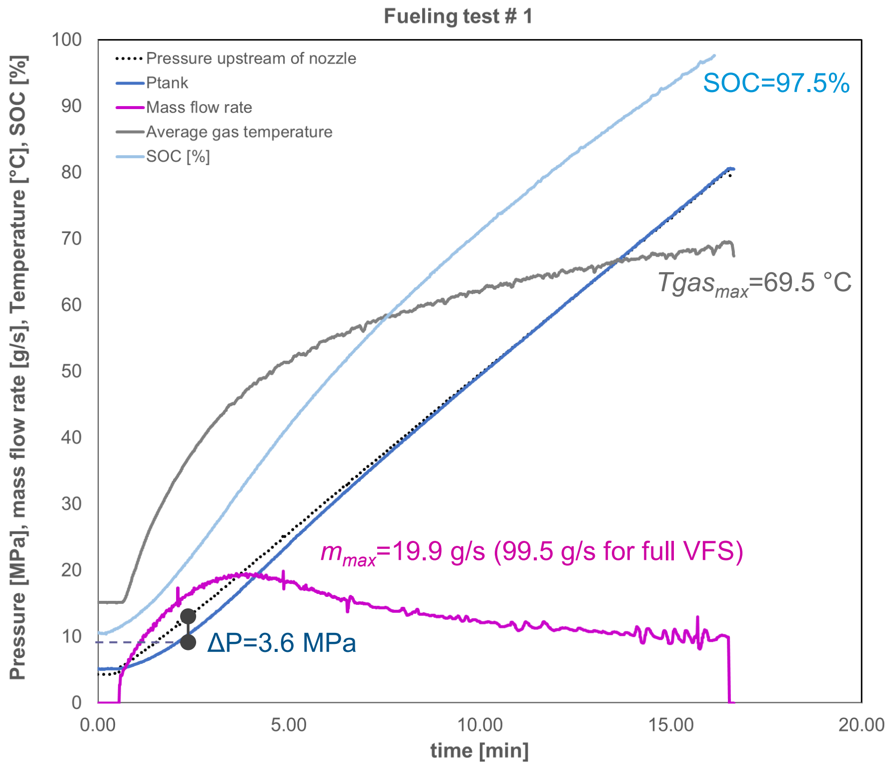
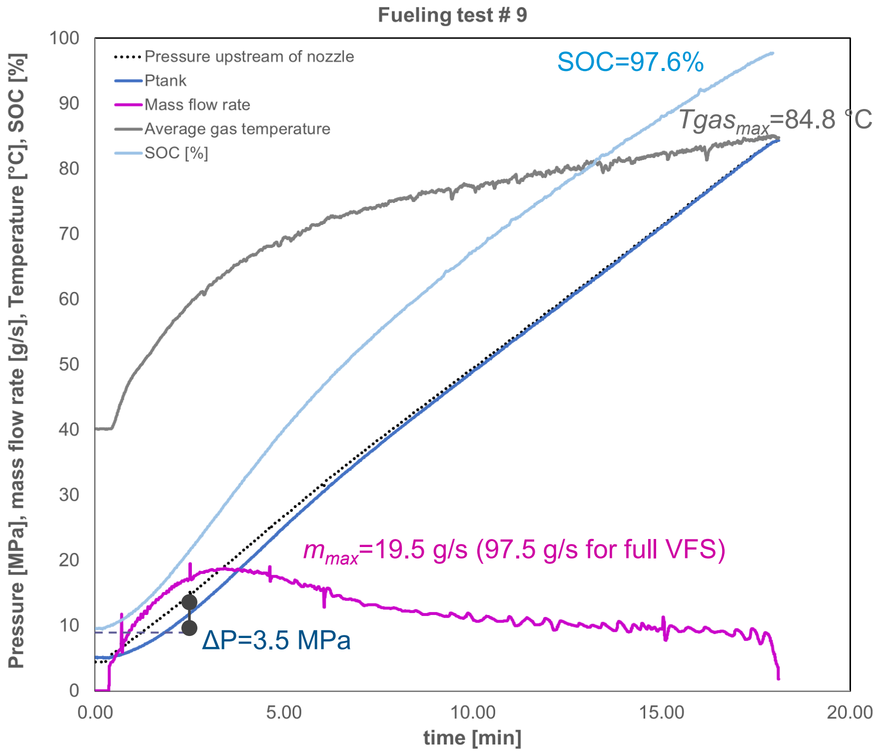
Accomplishment (Fueling protocol)

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.**

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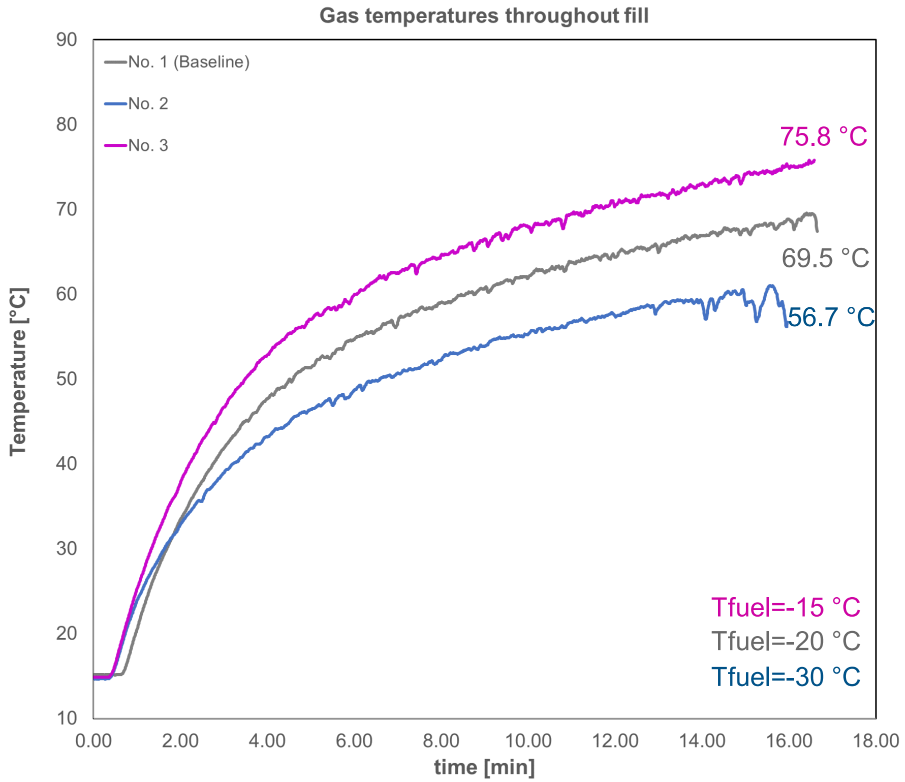
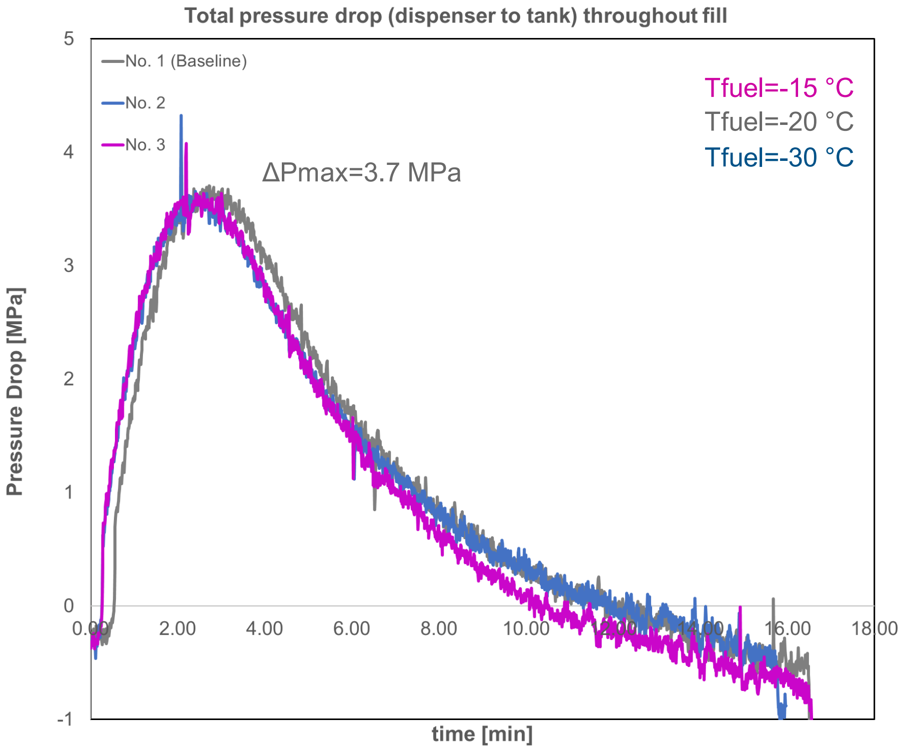
Accomplishment (Fueling protocol)

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



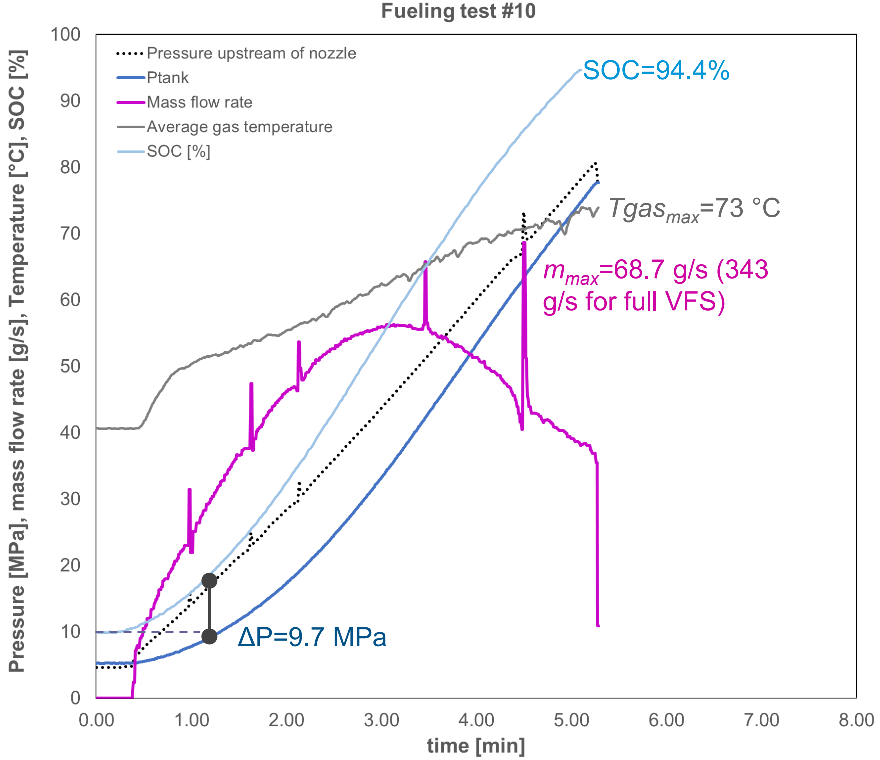


- ❑ Decreasing the temperature of dispensed H_2 from -20°C to -30°C, decreased the final gas temperature by 12.8 °C.
- ❑ Increasing the temperature of dispensed H_2 from -20°C to -15°C, increased the final gas temperature by 6.3 °C.
- ❑ The change in precooling temperature in the range -30°C to -15°C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

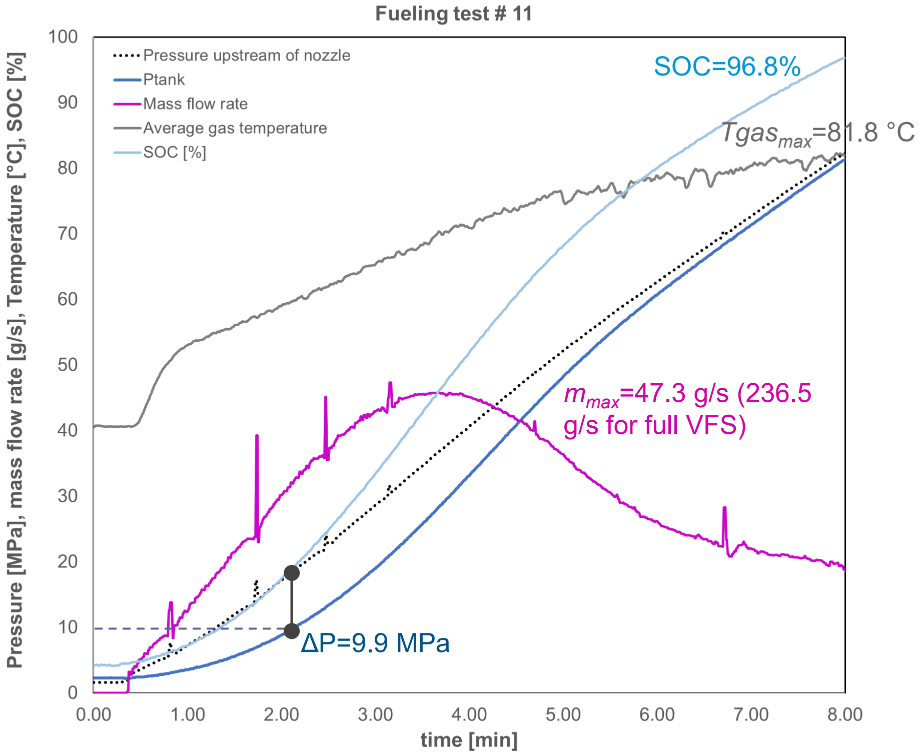
Accomplishment (Fueling protocol)

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.**

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

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **Project Structure and Connection between Tasks**

Known is the fact that heavy-duty truck fueling places additional constraints on the station compared to light-duty. Reliability, costs, and safety were big drivers in the project development. Therefore, the HyRIGHT project was developed to evaluate a subset of key areas around precooling, communications, and safety risks that would complement other HFTO activities around refueling and support fueling standardization development proactively.

- **CRADA Partner Role**

Nikola has provided significant technical assistance within the project since the start and especially in the last year. In addition, they have provided resources and data to support all the tasks including hardware/software for cyber vulnerability testing as well as single tank and full VFS validation tests in their start-of-the-art test facility. In addition, Nikola was instrumental in involving the HyRIGHT team within PREHYDE and various standardization activities under ISO and SAE.

- **Collaboration**

Agree with the reviewer comments. At the start of the CRADA, the HyRIGHT team was involved in the most relevant fueling activities at the time, which were PREHYDE and ISO 19885 development. Of course, we are open to additional collaboration as move forward with HD trucking fueling.

Proposed Future Work

Fueling protocol testing

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

Any additional proposed future work is subject to change based on funding levels.

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.