Cost Assessment and Evaluation of Liquid Hydrogen Storage for Medium- and Heavy-Duty Applications

R. K. Ahluwalia, H. S. Roh, J-K Peng, X. Wang, and D. Papadias (ANL)

S. Aceves and N. Killingsworth (LLNL)

B. Ehrhart, E. Hecht, and J. Ronevich (SNL)

C. Houchins (SA)

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Project ID: ST223

Argonne NATIONAL LABORATORY

Project Overview and Relevance

Timeline

- Project start date: October 2020
- Project end date: September 2021

H_2 Storage Barriers Addressed

- A: System Weight and Volume
- B: System Cost
- C: Efficiency
- E: Charging/Discharging Rates
- J: Thermal Management
- K: Life-Cycle Assessments

Budget

- FY21 DOE Funding: $500K
- ANL: $240K
- LLNL: $140K
- SNL: $95K
- SA: $25K

Partners/Interactions

- Argonne National Laboratory (ANL)
- Lawrence Livermore National Laboratory (LLNL)
- Sandia National Laboratories (SNL)
- Strategic Analysis (SA)

Project Goals and Milestones

Conceptualize and analyze liquid H_2 (LH_2) storage system for medium- and heavy-duty trucks

- Usable H_2 storage capacity >60 kg for 750-mile range
- Refueling rate of 8-10 kg/min with a low-pressure LH_2 pump
- No-loss dormancy requirements for truck duty cycles to be met with Type-1 insulated tanks
- Storage life >5,000 refueling cycles, 11,000 cycles
- Target cost: 8-9 $/kWh
- Performance exceeding 15 wt.% gravimetric capacity and 35 g/L volumetric capacity (internal project goal)
- Identify LH_2 refueling interface issues and opportunities
- Address safety issues, codes and standards

	Type	Progress Measures, Milestones, Deliverables	Due Date	% Complete
1	Progress Measure	Establish the operating windows for different storage options considering at least three vocations of Class-8 trucks (long haul, sleeper cabin, urban, multi-purpose, and regionals) and their duty cycles	12/31/2020	100%
2	Progress Measure	Finalize baseline packaging options (tank sizes) and system layouts inclusive of all balance-of-plant components. Determine the baseline system attributes (weight, volume, storage capacity, insulation and dormancy, boil-off loss, refueling time, cost) for different storage options. Compare with HDV targets: 50-60 kg usable H_2 for 750-mile range, 8-10 kg/min refueling rate, 8-9 $/kWh cost, 5,000 storage cycles, 11,000 cycles	3/31/2021	100%
3	Go/No-Go	Match the storage options with vocations and duty cycles, and for further analysis, narrow the choice of tank sizes (outer length and diameter), packaging options, vocations, duty cycles and storage options to 1 or 2.	6/30/2021	25%
4	Progress Measure	Analyze advanced concepts for boil-off and thermal management, integrate system analysis with LH_2 refueling protocols, and construct and analyze next-generation LH_2 storage system for medium and heavy-duty trucks.	7/30/2021	0%
5	Milestone / Deliverable	Prepare the final report to document the performance and cost of baseline and advanced LH_2 refueled storage systems for heavy-duty trucks, compare them with 350-bar and 750-bar cH_2 systems, identify technology gaps, and recommend future directions of research.	9/30/2021	0%

Technical Approach

Task	Metric	Lab Call Goal	Analysis Approach
1	**Storage System Range**	750 miles	Assemble and analyze duty cycles Harmonize with 21st Century Truck Partnership
2	**Storage System Capacity**	>60 kg	Consider packaging and sizes of CNG tanks for MD and HD trucks Frame Mounted, Roof Mounted and Behind the Cab Configurations
3	**Refueling Rate**	8-10 kg/min	Develop specifications for off-board refueling pump Develop model for refueling dynamics
4	**Discharge Rate**	4.6 g-H_2/s 16.6 kg/h	Consider 275-kW fuel cell system with 80-kWh battery storage system Develop thermal management requirement Simulate tank discharge dynamics with and without on-board pump Develop pump requirements: 1-stage or 2-stage
5	**Hydrogen Loss**		Analyze duty cycles and determine duration of idle periods with engine on or off
6	**Insulation and Dormancy**		Consider multi-layer vacuum insulation Conduct heat transfer analysis to determine number of layers and vacuum pressure
7	**Structural Analysis**	5,000 refueling cycles 11,000 cycles	Finite element analysis of liner failure modes Finite element analysis of shell buckling Fatigue analysis
8	**Strucural Materials**		Aluminum 2219 -T87 for cryogenic applications Aluminum 5083 for cryogenic applications
9	**Gravimetric Capacity**	15 wt.% (project goal)	Conceptualize system with all BOP components Estimate component weights
10	**Volumetric Capacity**	>35 g/L (project goal)	Conduct system analysis and estimate componet volumes
11	**System Cost**	8-9 $/kWh	Bottom-up cost analysis
12	**Safety Codes and Standards**	Applicable SAE and and GTR standards	Conduct FMEA analysis Review codes
13	**LH_2 Refueling Interface**		Conceptual design of LH_2 refueling station

Class 8 HD Truck Duty Cycles

Semi Trailer Long Haul Truck

365 questionnaires collected at 6 private stop chains for trucks: Journal of the Transportation Research Board, No. 1880, pp. 29-38

- An average long-haul truck driver travels ~112,000 mi annually during a 292-day period
- Average fuel consumption: 6.3 mpg (0.85 gallons/h at idling)
- An average long-haul day includes ~10.5 h driving, ~6 h extended idling and ~3.4 h with the engine off.
- This is consistent with the typical 6 hours per day of extended idling estimated by the American Trucking Associations and by Caterpillar: ANL/ESD-43, 2000

Class 8 – Refuse Trucks

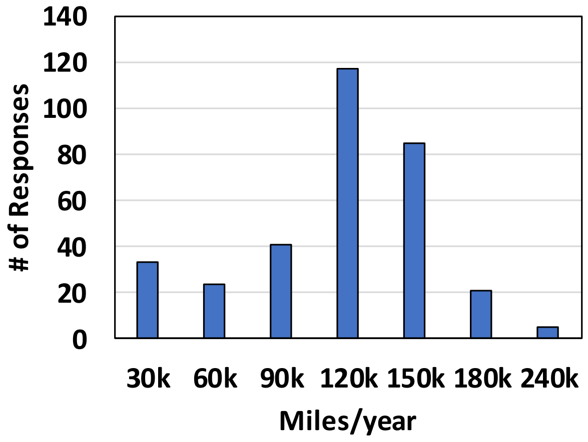
- Fleets used for residential refuse pickup 5 to 6 days per week: 72-gallon diesel tank, 2.93 mpg fuel economy, 11.5 mph average speed
- Between Nov. 1998 and May 2000, data were collected on selected LNG and diesel trucks from Waste Management as part of the U.S. DOE Fuel Truck Evaluation Project: www.doe.gov/bridge
- Diesel trucks averaged 2,295 miles/month.
- On a given day of operation, the trucks' engines run the entire time the driver is working, 7 to 12 hours per day
- Assuming 6 days of operation, the average daily operation from the data is ~8.5 h/day

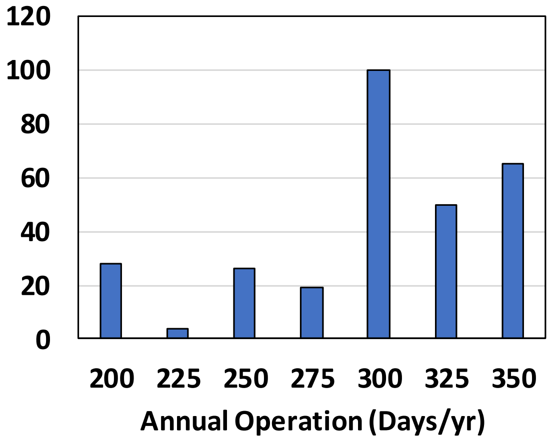
Class 8 – Drayage Truck

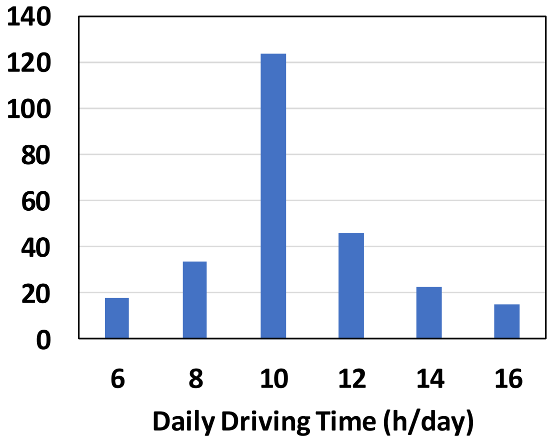
2018 Feasibility Assessment for Drayage Trucks. San Pedro Bay Ports Clean Air Action Plan. March 2019

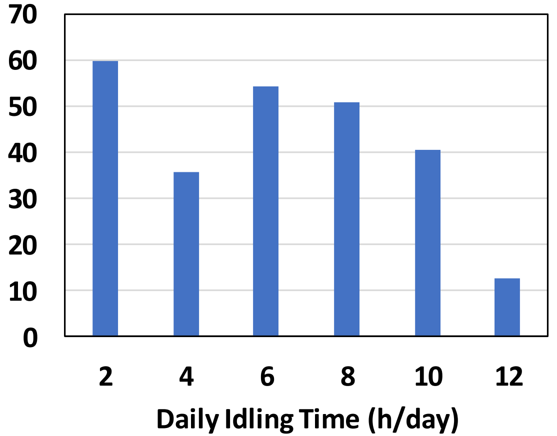
- ~17,500 registered Class 8 trucks in the San Pedro Bay Ports' drayage fleet
- Refueling interval: 2-4 days for diesel, daily for LNG
- Shifts per day: 1 typical, 10-15% of operators do two shifts
- Durability: 500,000 miles or at least 8 years for diesel
- Availability: 90%, down 2-3 days per month for maintenance
- Operating time per day ~10-14 hrs.

Semi trailer long haul truck duty cycle: 10.5 h driving, 6 h engine idle, and 7.5 h engine off, 1-3 d dormancy





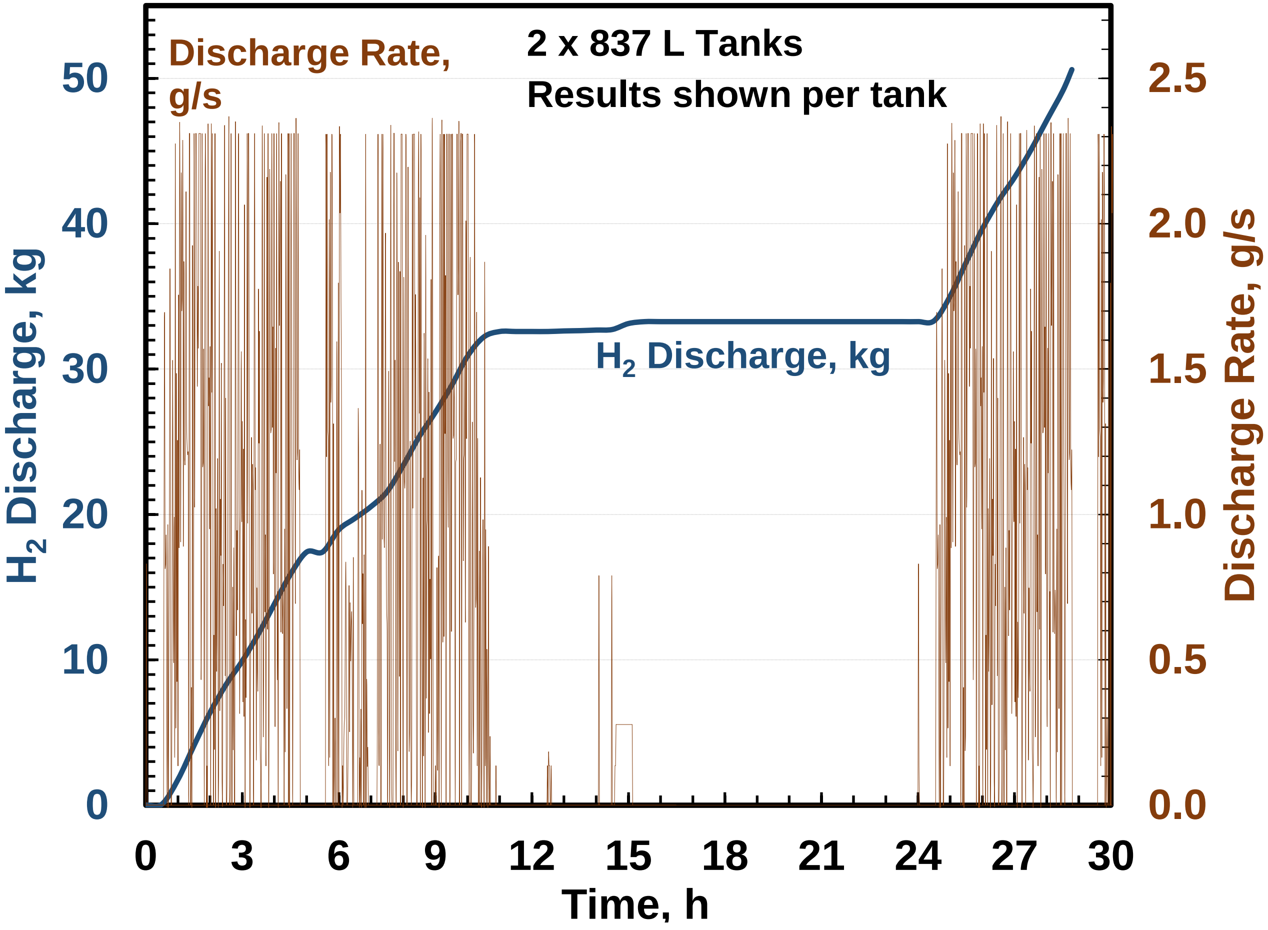




LH_2 Storage for Heavy Duty Trucks: Packaging Options and Capacity

- **Autonomie Simulation of Power Demand** by Vincent Freyermuth (ANL): 21st Century Partnership platform for long-haul class 8 HD truck
- **Fuel Cell Simulation of Hydrogen Consumption**: 275 kW FCS hybridized with 70 kWh battery

LH_2 Storage System Requirements and Performance
- Peak H_2 flow rate: 4.6 g/s (16.6 kg/h)
- H_2 storage system (S1-1d) range with two FM 66 cm (OD) x 305 cm (OL) tanks with 101 kg usable H_2 capacity: 769 miles

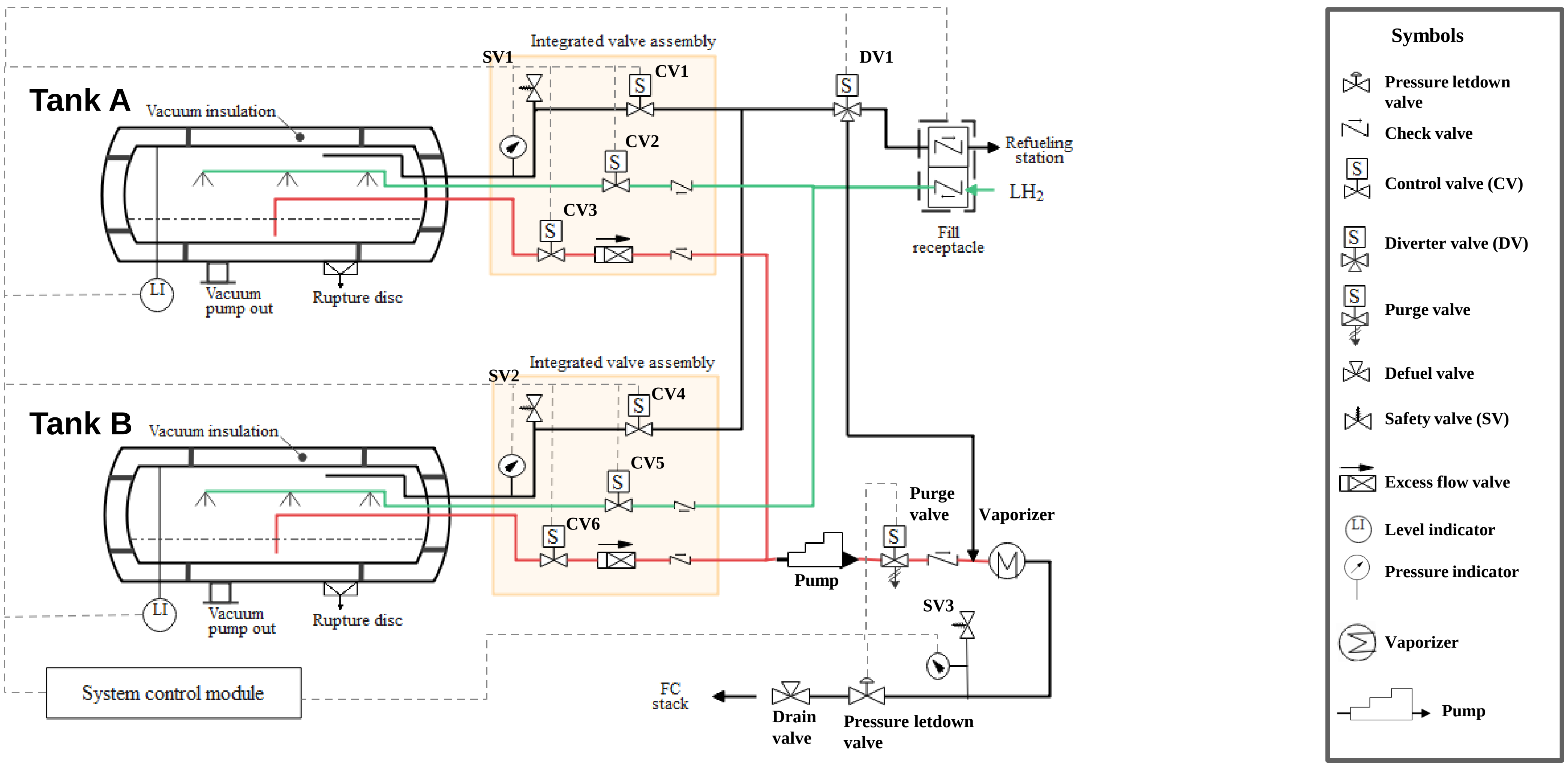


Baseline Packaging Options		
Outer Diameter (cm) X Outer Length (cm)		
Frame Mounted, FM	**Roof Mounted, RM**	**Behind the Cab, BTC**
2 Tanks	4 Tanks	2, 3 or 4 Tanks
53 X 152	41 X 203	41 X 203
53 X 203	41 X 246	53 X 203
53 X 120	30 X 246	
66 X 152		
66 X 203		
66 X 229		
66 X 305		

LH_2 Storage for Heavy Duty Trucks: System with Pump

System options and operating pressures

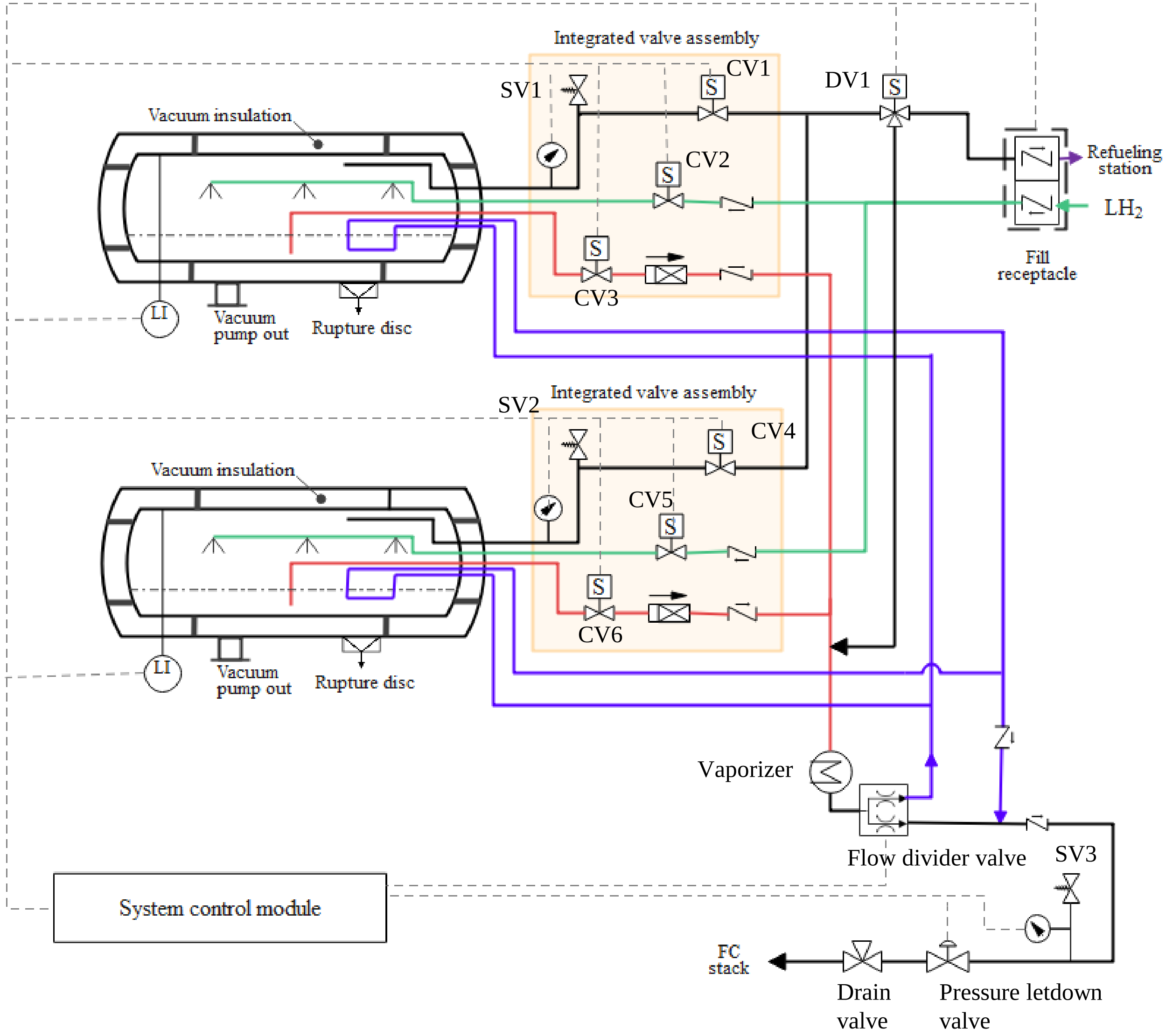
- External or internal on-board pump
- Off-board refueling pump: Low (near ambient) and medium-pressure (5-8 bar)
- Tank operating pressure range: low pressure determined by the refueling pump
- May need to return some gaseous H_2 to station storage tank during refueling

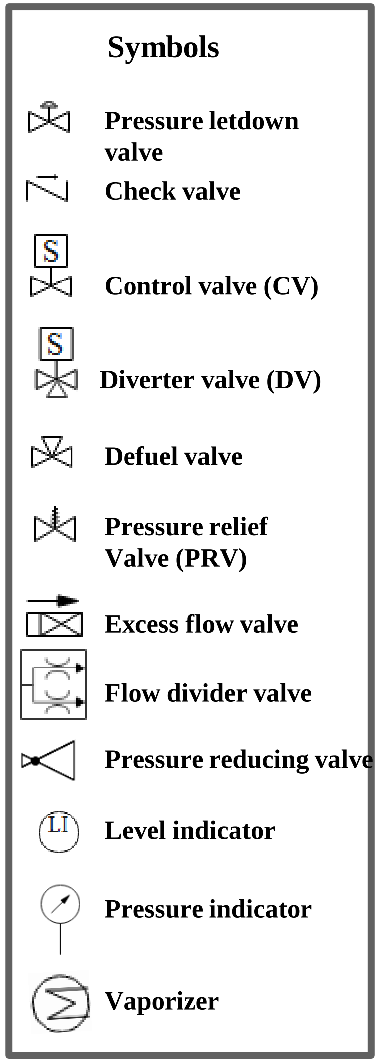


LH_2 Storage for Heavy Duty Trucks: System without Pump

System options and operating pressures

- No on-board pump
- Tank operating pressure range: 5-8 bar
- May require an in-tank heat exchanger
- Withdraw liquid or vapor from tank
- Off-board refueling pump: medium-pressure (5-8 bar)
- May need to return some gaseous H_2 to station storage tank during refueling

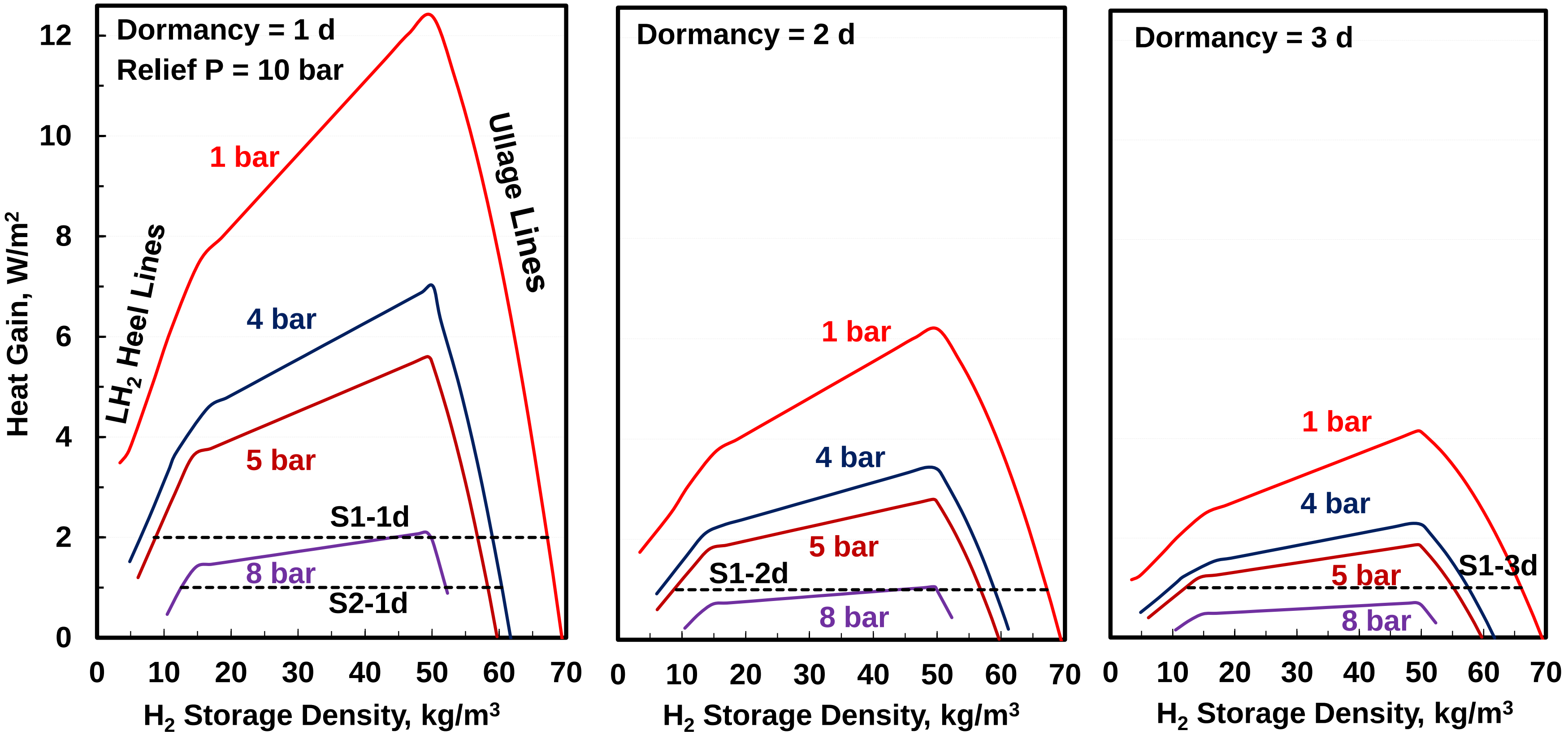




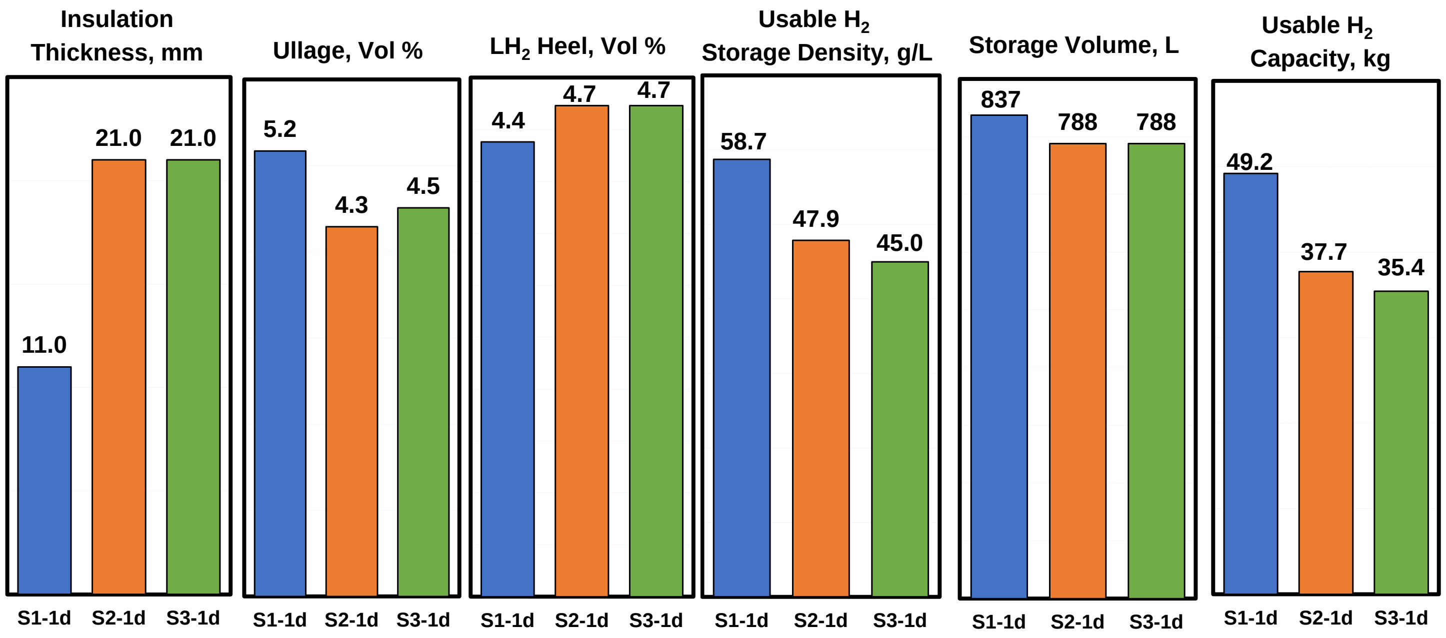
Ullage and Heel

- Ullage: Minimum vapor space required to meet dormancy with full fuel tank. Determines tank H_2 storage capacity. Ullage may also be limited by dynamic loads.
- Heel: LH_2 reserve (vol%) for zero boil-off loss within specified dormancy. Heel and ullage determine the tank usable H_2 storage capacity.

System	On-Board Pump (ΔP)	Fuel Cell Inlet Pressure	Tank Operating Pressure	Feasibility / Dormancy (Q)		
				1 day (1d)	2 days (2d)	3 days (3d)
S1	Yes (4 bar)	5 bar	1 - 5 bar	Yes (2 W/m^2)	Yes (1 W/m^2)	Yes (1 W/m^2)
S2	Yes (4 bar)	8 bar	4 - 8 bar	Yes (1 W/m^2)	TBD (0.8 W/m^2)	No
S3	No	5 bar	5 - 8 bar	Yes (1 W/m^2)	TBD (0.8 W/m^2)	No

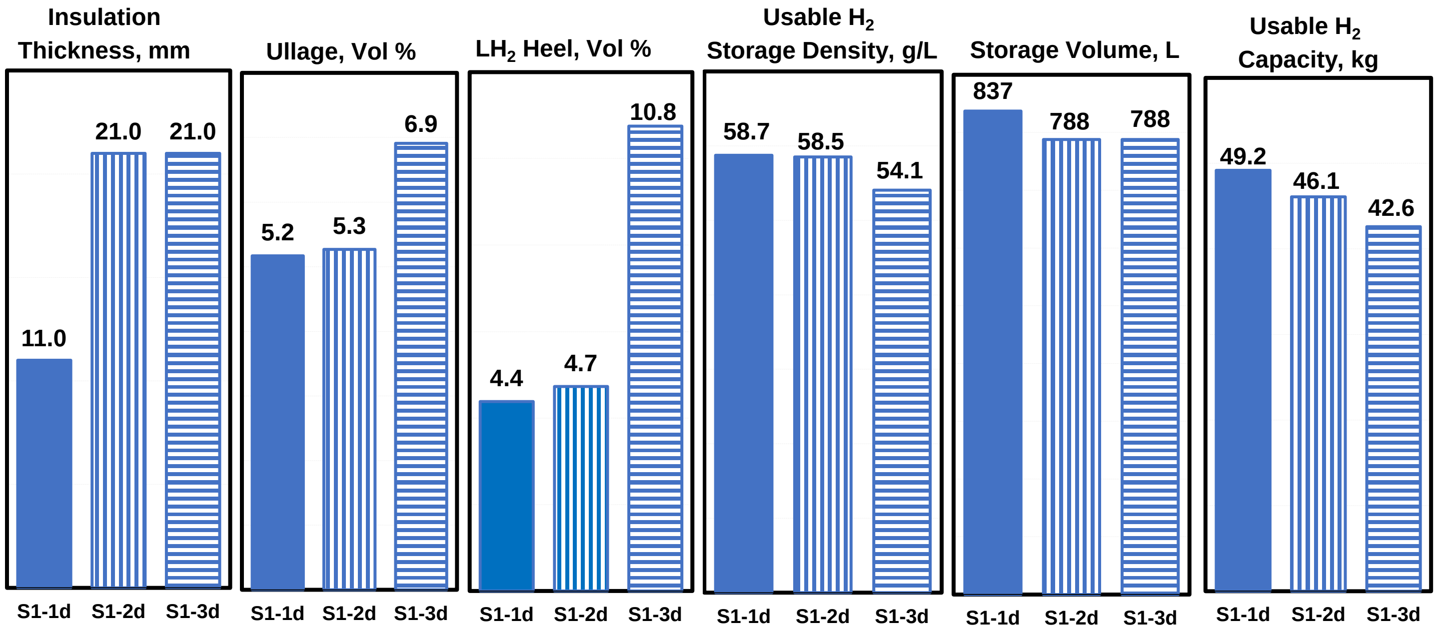


LH_2 Storage System Performance



Performance of Systems S1, S2 and S3 with 1-d Dormancy

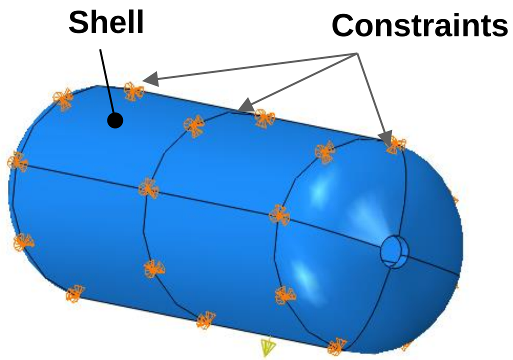
- Effect of FC inlet pressure (5 vs. 8 bar) on system performance: 23% loss in usable H_2 capacity from 49.2 to 37.7 kg
- Advantage of on-board pump (5 bar): 28% in usable H_2 capacity from 49.2 to 35.4 kg



Effect of Dormancy on Performance of System S1

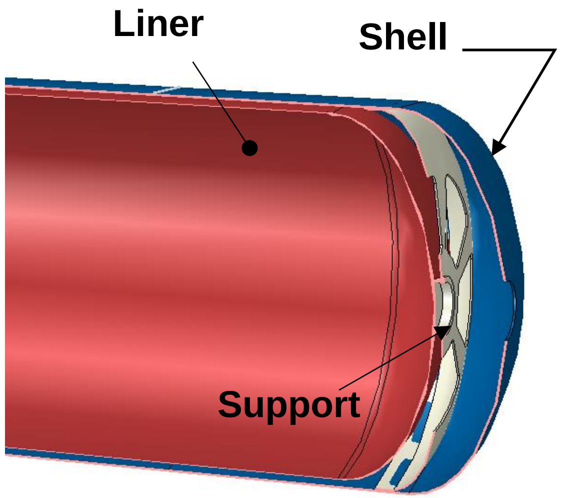
- 1-d vs. 2-d dormancy: 9% loss in usable H_2 capacity from 49.2 to 46.1 kg, mainly due to lower storage volume
- 2-d vs. 3-d dormancy: 9% loss in usable H_2 capacity from 46.1 to 42.6 kg due to lower usable H_2 storage density

LH_2 Tank Analysis: Liner and Liner Support

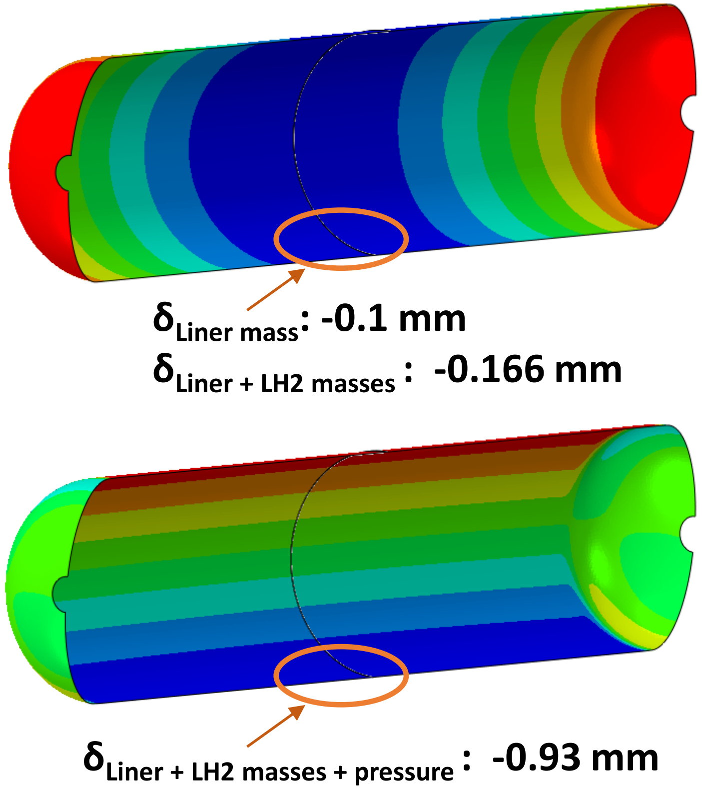


Static FE Model

- Aluminum 2219-T87 LH_2 tank mounted to the frame by straps, 8 bar operating pressure. Maximum allowable working pressure (MAWP) of 10 bar
- Liner suspended inside the shell using brackets at the two ends that are welded to shell and liner.
- Static analysis result shows that the liner is mostly deflected by internal pressure rather than the combined weight of the liner and stored LH_2
- Liner support experiences 8 MPa maximum stress at the connecting region
- 1.57-mm liner thickness needed to withstand 10 bar MAWP.

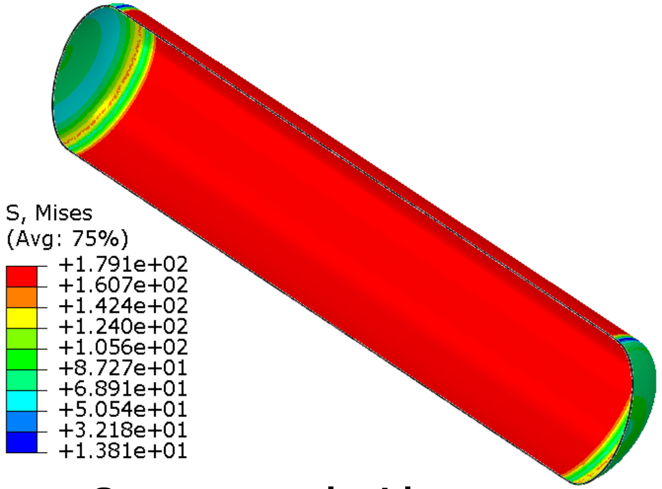


Section View of LH_2 Tank showing Liner Support



Deflections

	Al 5083 O[1]	Al 2219 T87[2]
σ_{ult} @RT	269 MPa	454 MPa
$\sigma_{allowable}$ @78K	95.7 MPa	
Density	2,660 kg/m^3	2,840 kg/m^3



Stresses on the Liner

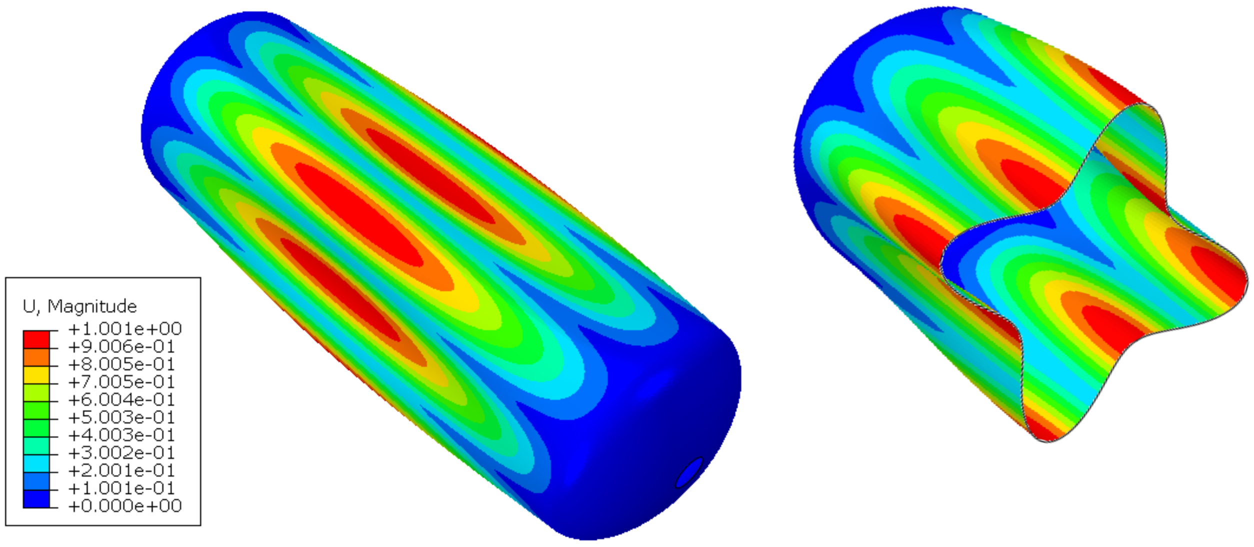
[1] BPVC-VIII, ASME Boiler and Pressure Vessel Code. *Section VIII, Division* 1, 2019
[2] *Cryogenic materials data handbook,* Volume 1, 1970.

LH_2 Tank Shell Analysis

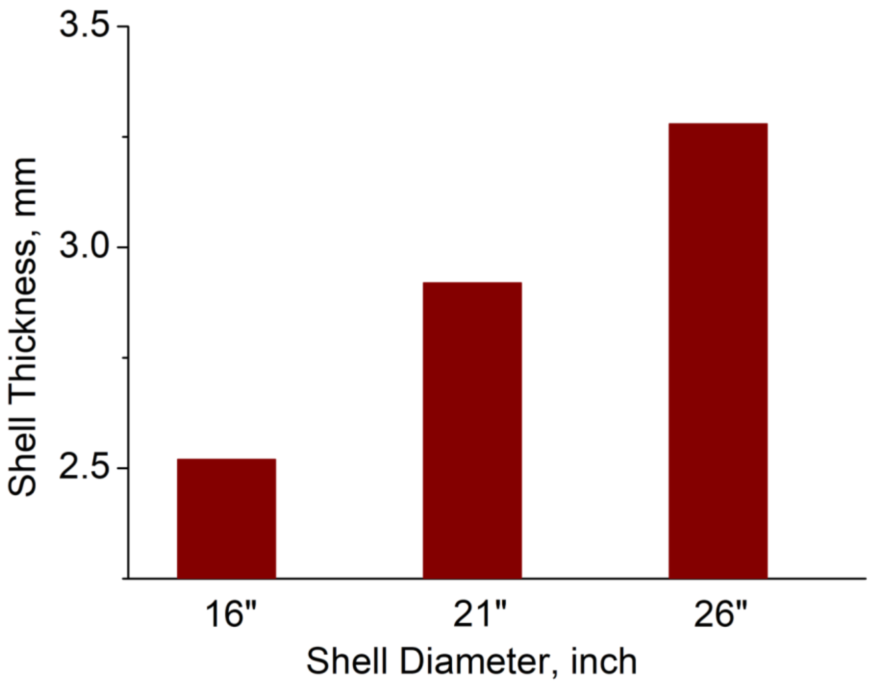
- The inside of the 2219-T87 LH_2 shell is a MLI layer (in a vacuum state) and the outside of the shell is exposed to 1 bar
- Buckling analysis with 1.2 bar (adding 20% for safety) performed on the shell to determine the shell thickness.
- Analysis results show that 3.98 mm shell thickness is needed to overcome the buckling load (26″ OD, 120” OL).
- Since the 1st buckling mode is found in the circumferential direction, adding stiffeners along the circumferential direction will reduce the shell thickness.

Shell thickness vs Tank Diameter

Tank	D, in	L/D	t_{shell}, mm
1	16	5	2.52
2	21	3.8	2.92
3	26	3.1	3.28



Shell Buckling Mode



Tank Length: 80 inch

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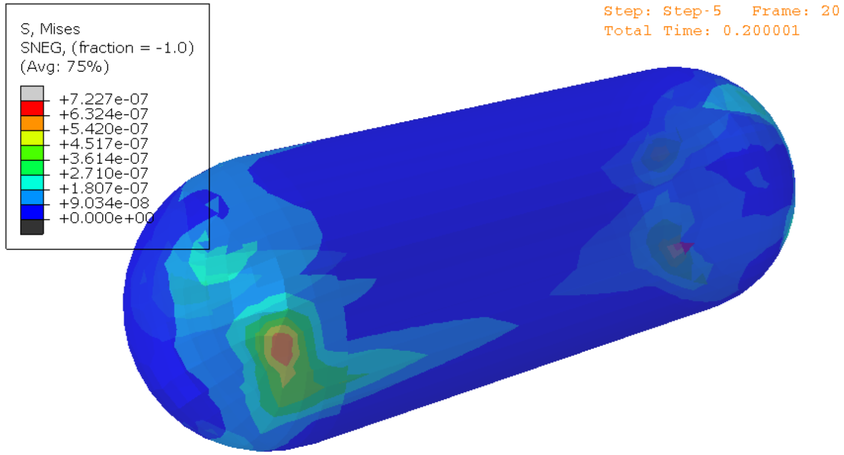
Sloshing Analysis

Finite element (FE) model of fluid-structure interaction based on coupled Eulerian-Lagrangian (CEL) method

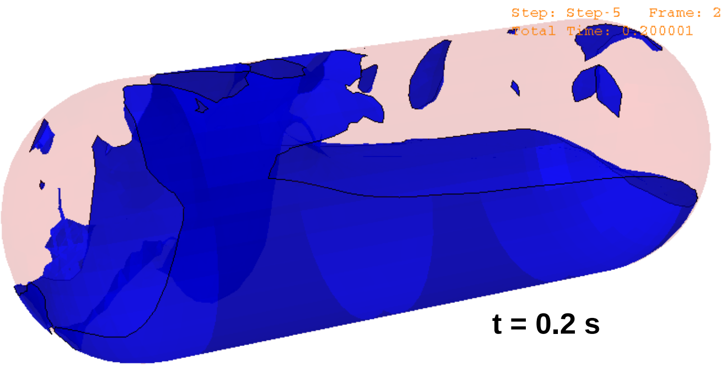
- Estimate the hydrodynamic pressure due to fluid sloshing
- Perform static and fatigue analyses of the fuel tank and mounting components including the hydrodynamic pressure
- Determine baffle location to effectively suppress fluid sloshing in a tank and optimize baffle shape to minimize the weight

Developing a slosh model of 21″(D) x 60″(L) LH_2 Tank

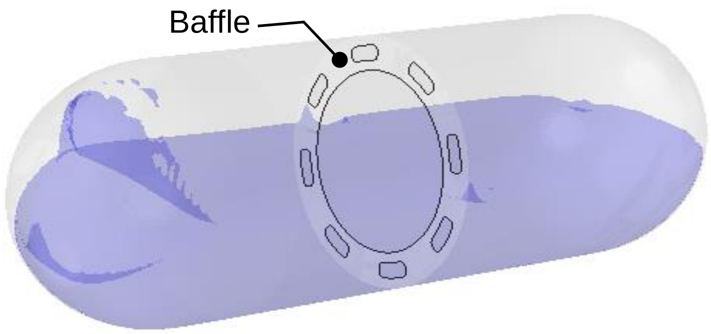
- From preliminary analysis result, a half-filled tank with 10-G deceleration experiences a maximum stress of 0.7 Pa in the liner. Also, confirmed that the baffle has an influence on reducing the liquid slosh.
- Optimization of the baffle sizing is required to reduce the weight of baffles.
- Further investigate temperature change inside the tank due to sloshing



Stress Distribution on the Liner (without a baffle)

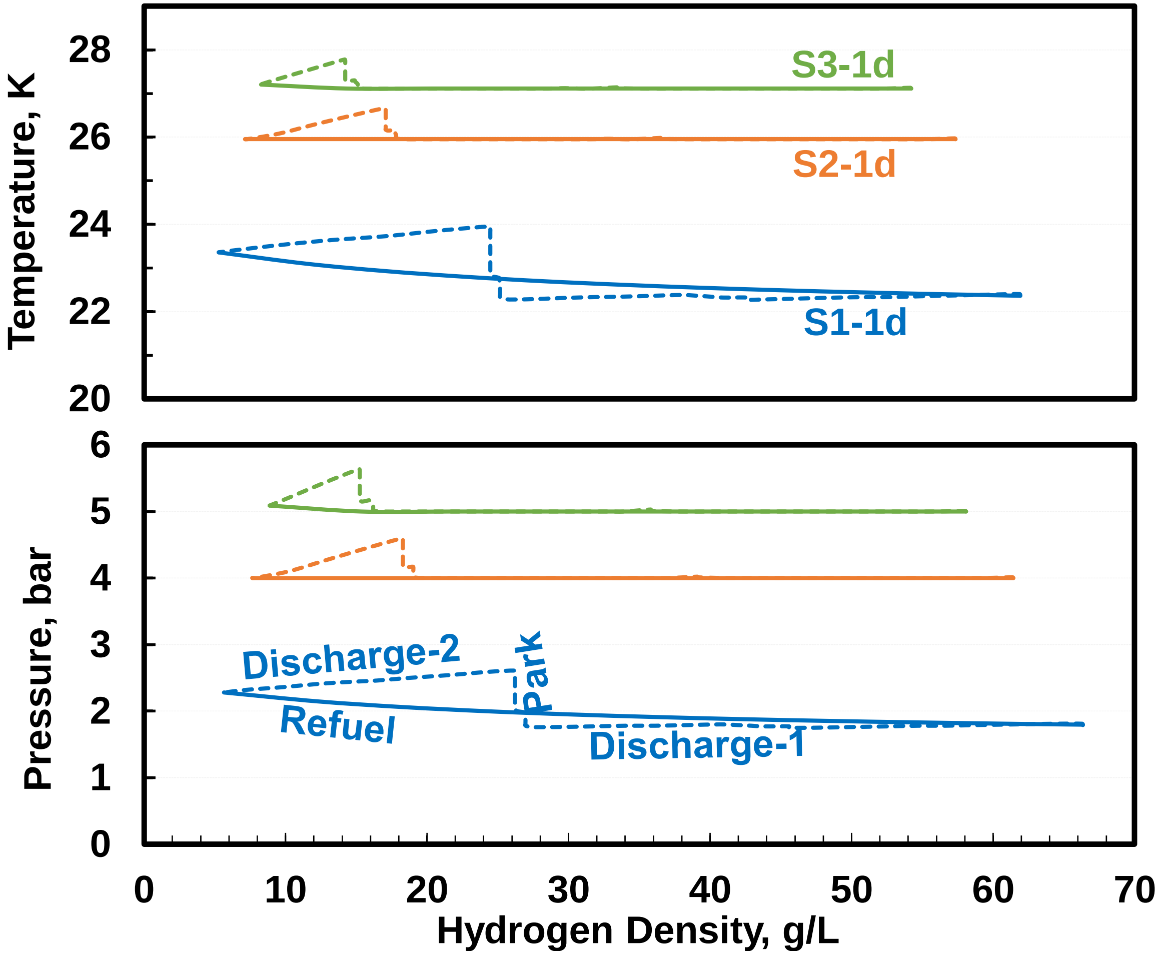


Sloshing at t=0.2s (without a baffle)



Sloshing at t=0.2s (with a baffle)

Refueling and Discharge Dynamics



Important Conclusions from Drive Cycle Simulations

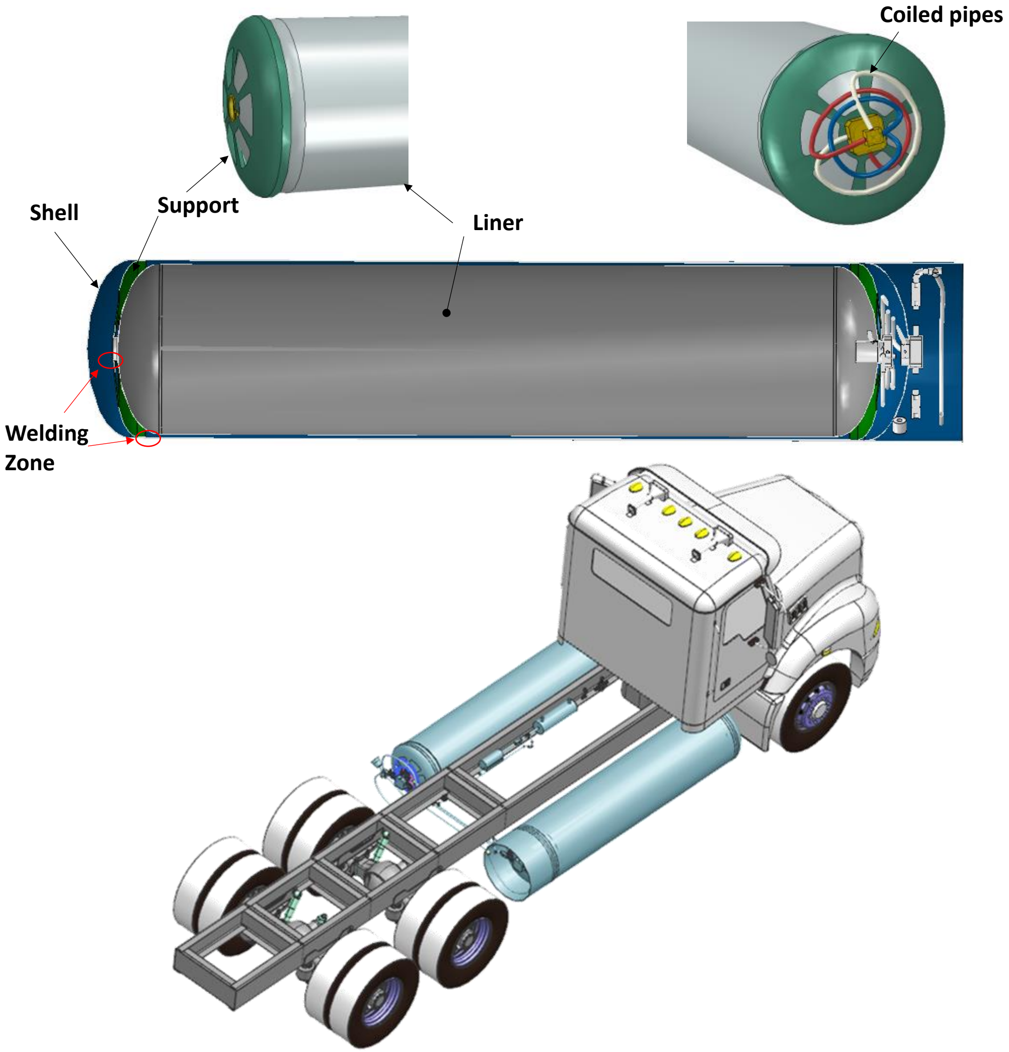
- Systems S2-1d and S3-1d require heat to be supplied during refueling and discharge
- System S3-1d may be impractical if the requirement for 8 bar FC inlet pressure cannot be relaxed
- Systems S1-1d and S2-1d have identical performance if the on-board LH_2 pump provides 8-bar pressure lift

Parameters	Units	S1-1d	S2-1d	S3-1d
Stationary Pump Pressure	bar	5	5	8
Vacuum Pressure	mtor	1.4	1.1	1.1
Peak Tank Pressure	bar	2.5	4.6	5.6
Ullage	%	5.2	4.3	4.5
LH_2 Heel	%	4.4	4.7	4.7
Usable H_2	%	91.5	87.5	85.3
H_2 Storage Density	kg/m^3	66.1	61.1	59.6
Usable H_2 Density	kg/m^3	60.4	53.5	50.8
H_2 Returned to Station during Refueling	%	0	0	0
Heat Supplied during Refueling	kJ	0	1333	1455
Heat Supplied during Discharge	kJ	0	908	1181
H_2 Stored after Refueling	kg	55.3	48.1	46.9
Usable H_2	kg	50.6	42.1	40.0

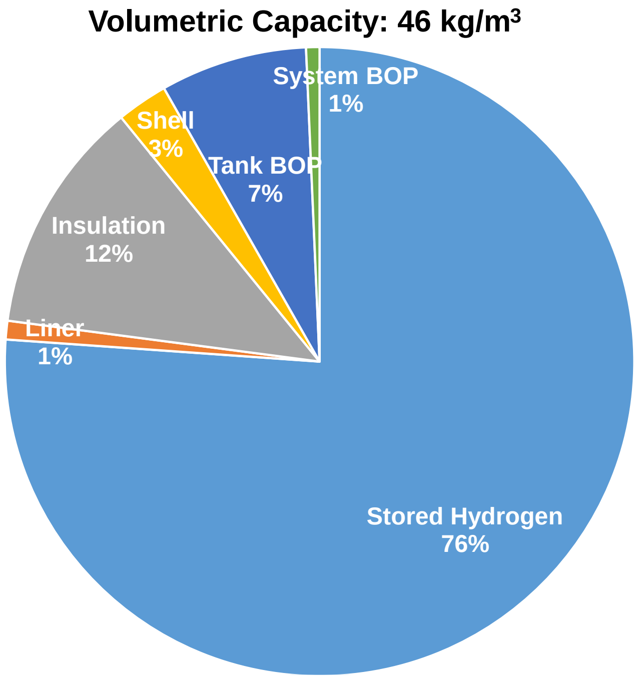
System Conceptualization and Performance

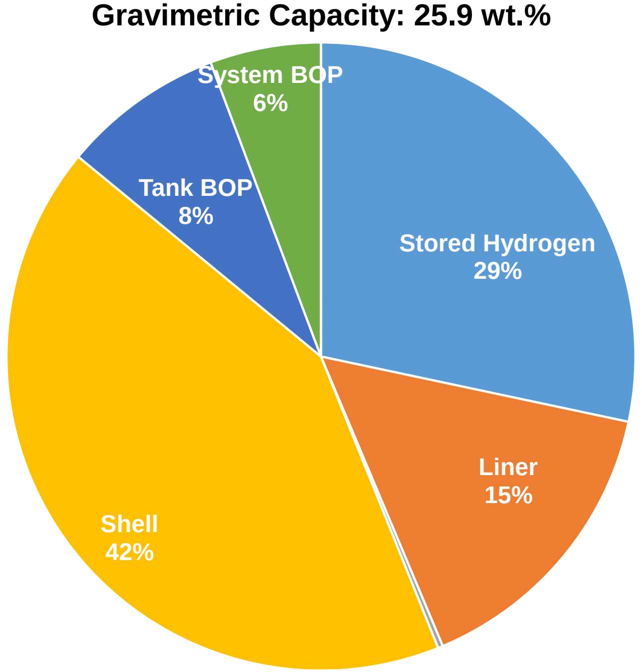
- Supports welded to the liner and shell
- Coiled pipes to reduce heat transfer
- Con: Welding to shell may enhance heat transfer. Thermal conductivity: 236 (Al) vs. 54 (SS) W/m.K

Parameters	Units	S1-1d	S2-1d	S3-1d
H_2 Stored	kg	110.5	96.2	93.7
System Gravimetric Capacity	wt.%	25.9	22.6	21.6
System Volumetric Capacity	kg/m^3	46	38.3	36.4
Range Between Refueling	miles	769	641	608



Storage System S1-1d Weight and Volume Distributions





Progress: Safety Codes and Standards – FMEA and Code Review

- FMEA has been initiated to determine the highest risk components within the LH_2 fuel system
  - Failure modes for each component considered, as well as outcomes/effects for each
  - Assigning a **probability** and **severity** to estimate the overall risk of each component

- Review of relevant codes and standards begun to identify gaps in current design
  - NFPA 52 - Section 16.4 LNG Engine Fuel Systems
  - SAE J2343 - Recommended Practices for LNG Powered Heavy-Duty Trucks
  - SAE J2578 - Recommended Practice for General Fuel Cell Vehicle Safety- Liquid or Heavy Duty Specific
  - SAE J2579 - Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles- Liquid or Heavy Duty Specific

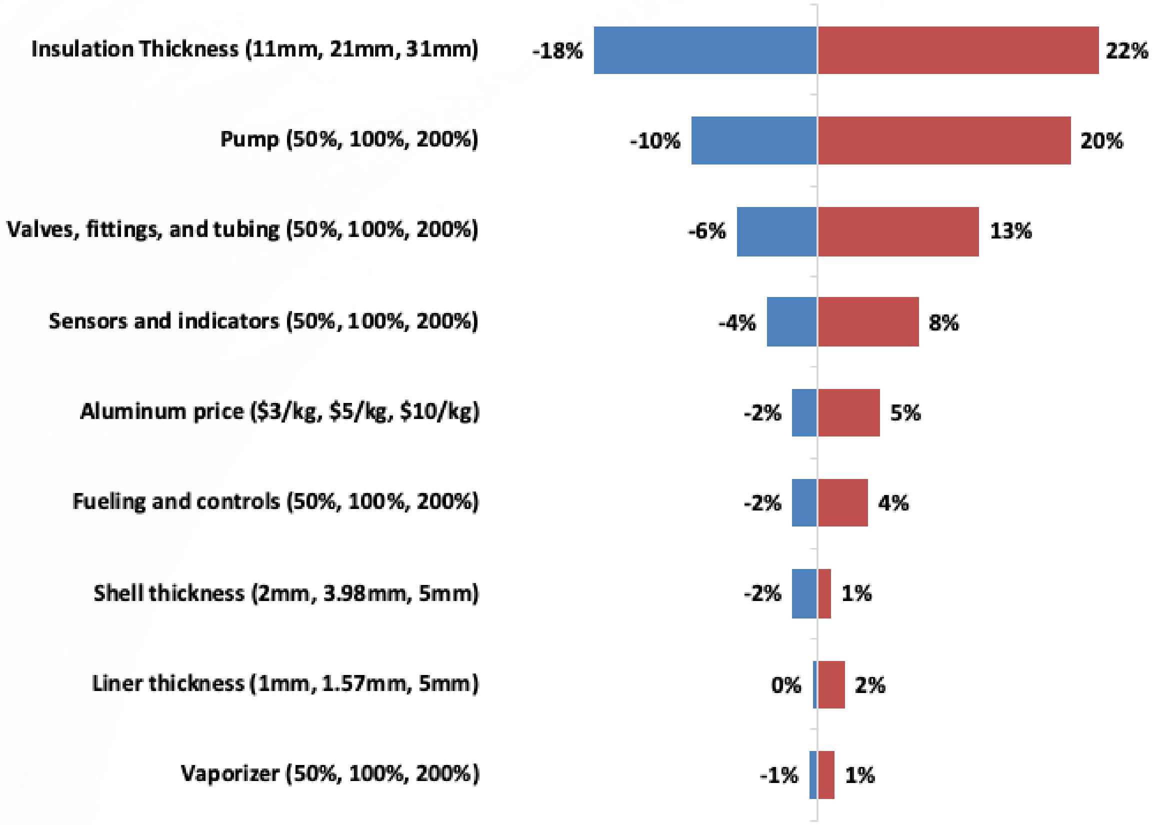
Probability Class	**Definition**
Frequent	Occurs often, continuously experienced
Likely	Occurs several times
Occasional	Unlikely, but could occur at some time
Unlikely	Can assume it will not occur

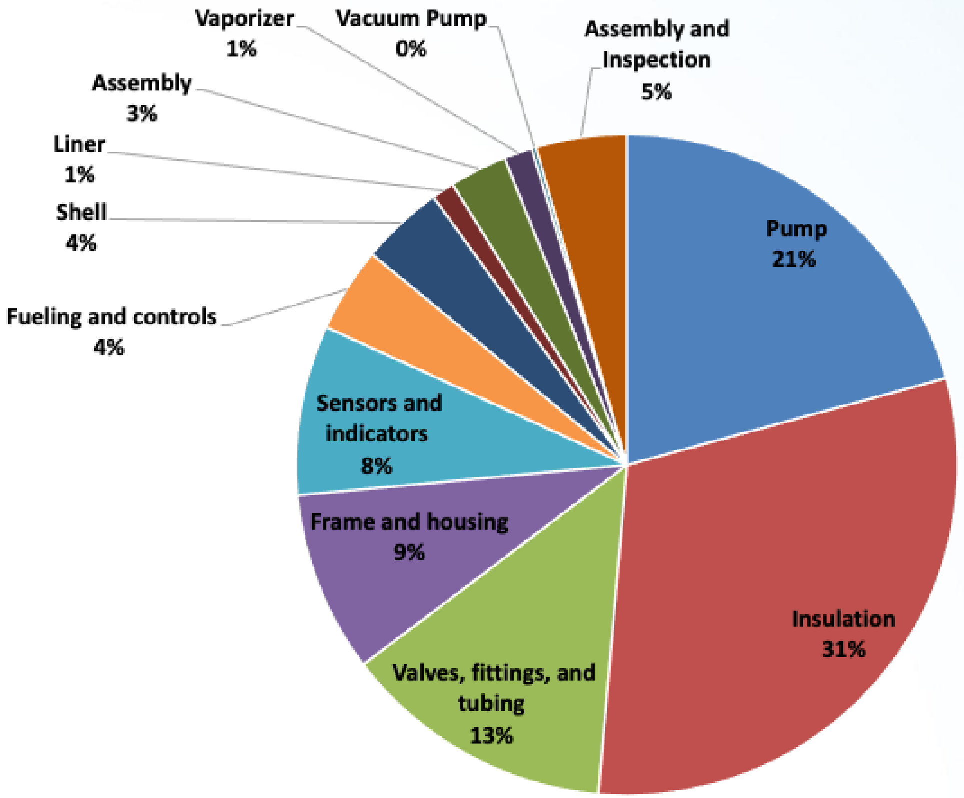
Severity Class	**Definition**
1	No potential release of LH_2 or GH_2
2	Potential leak or small-scale release of GH_2
3	Potential leak or small-scale release of LH_2
4	Potential for catastrophic release of LH_2 and GH_2

Probability Class					
	Frequent	M	H	H	H
	Likely	L	M	H	H
	Occasional	L	L	M	H
	Unlikely	L	L	L	M
		1	2	3	4
		Severity Class			

Bottom-up Cost Analysis

- Completed a preliminary bottom-up capital cost analysis for the baseline 110.5 kg H_2 frame mounted two-tank LH_2 storage system
- Breakdown and sensitivity analysis are shown for annual production of 100k systems
- Balance of plant components and insulation dominate the system cost and have the greatest impact on cost sensitivity
- Additional work is planned to refine and understand pump costs





FY2021 Collaborations

		Organization			
Task	**Task Description**	**ANL**	**LLNL**	**SNL**	**SA**
1.0	**Baseline On-board LH_2 System**				
1.1	Operating Windows of Storage Options 1, 2, 3 and 4	Lead	Support		
1.2	Packaging Options and Tank Sizes	Lead	Support		Support
1.3	System Layout and Components	Lead	Support		
1.4	Insulation and Dormancy	Support	Lead		
1.5	Structural Materials	Support	Support	Lead	Lead
1.6	Duty Cycles - Refueling, Discharge	Lead			
1.7	On-board System Performance and Cost	Lead	Support	Support	Support
2.0	**Advanced Concepts**				
2.1	Boil-off Loss Management	Support	Lead		
2.2	Alternate Thermal Management Concepts	Support	Lead		
3.0	**Off-Board Refueling and Codes**				
3.1	Off-board Refueling Integration	Support	Support	Lead	Lead
3.2	Safety, Codes and Standards			Lead	Lead
4.0	**Advanced On-Board LH_2 System**	Lead	Support	Support	Support
5.0	**Final Report**				
5.1	System Performance Relative to cH2 Systems and DOE Targets	Lead	Support	Support	Support
5.2	Gap Analysis	Support	Support	Lead	Lead
5.3	Future Directions	Support	Lead	Support	Support

External Reviewers

1. Cummins: Existing Letter of Support, experience with LNG storage for trucks
2. Navistar: Existing Letter of Support, truck duty cycles
3. Air Liquide: Primary reviewer of results, experience with LH_2 pumps and LH_2 storage for LDVs
4. General Electric: Cryogenic insulation, materials, and aviation systems

Future Work

1. LH_2 Storage System for Trucks
   - Complete the ongoing performance and structural analyses
   - Investigate on-board LH_2 pumps in more detail and evaluate in-tank vs. ex-tank options
   - Complete cost analysis
   - Consider alternate or advanced options of boil-off and thermal management, structural materials, and packaging options (Progress Measure 4)
   - Arrange external reviews of results and analysis methodology
   - Prepare final report (Progress Measure 5)
2. Safety Codes and Standards Assessment
   - Finalize FMEA based on updated information and final design
   - Finalize code/standard review based on final design
3. Conceptual Design of LH_2 Refueling Facility
   - Refueling of LH_2 trucks based on concepts from LNG refueling
   - Sizing components (e.g., pump flowrates) to match desired fill-times
   - Facility would refuel many (>10) trucks per day (>1000 kg_{H2}/day)
   - Layout based on current codes and standards
   - Rough cost estimate

Summary

Relevance:	Independent analysis to conceptualize and analyze LH_2 storage system for MD and HD trucks
Approach:	System analysis of Type-1, vacuum-insulated cryogenic vessels for heat transfer, dormancy, LH_2 refueling, H_2 discharge, FEMA based codes and standards, manufacturability and cost ABAQUS finite-element analysis of liner and shell failure modes, liner/tank materials of construction, sloshing behavior, tank weight
Progress:	Conceptualized LH_2 storage systems with and without on-board LH_2 pumps Identified operating modes for delivering H_2 to fuel cells at 5 bar or 8 bar Constructed duty cycles for three vocations of Class 8 HD trucks and determined 1-3 days as desired dormancy time Determined ullage, heel, and 45-60 g/L as usable hydrogen density for 1 to 3 day dormancy Established the principal failure modes as internal pressure for liner and buckling for shell; estimated the minimum Al 2219-T87 liner/shell thicknesses as 1.6/4 mm for 66 cm (OD) X 305 cm (OL) tank Initial results for frame mounted system with two 66 cm (OD) X 305 cm (OL) tanks: 25.1 wt.% gravimetric capacity, 46 g/L volumetric capacity, 101 kg usable H_2 capacity, 769 miles range
Collaborations:	Project Partners: ANL, LLNL, SNL, SA Reviewers: Air Liquide, Cummins, General Electric, Navistar
Future Work:	Analyze advanced concepts for boil-off and thermal managements Analyze material and operating strategies for 30 wt.% gravimetric capacity and 50 g/L volumetric capacity Complete analyses of cost, safety codes and standards assessment, and refueling interface Seek external review and vetting of results

Technical Backup Slides and Additional Information

Technical Transfer Activities

- Engaging with various stakeholders and OEMs including Air Liquide, Cummins, General Electric, and Navistar
- 21st Century Trucks: Duty cycles
- M2FCT Consortium: Hydrogen demand on duty cycles
- SA: Cost analysis
- Publications, presentations, and discussions

Progress Toward DOE Goals

Task	Metric	Lab Call Goal	Progress of Analysis Toward Lab Call Goals
1	**Storage System Range**	750 miles	Met, 608 - 769 miles
2	**Storage System Capacity**	>60 kg	Met, 90 - 110 kg
3	**Refueling Rate**	8-10 kg/min	Met. Pump development not withing scope of analysis.
4	**Discharge Rate**	4.6 g-H_2/s 16.6 kg-H_2/h	Met. In-tank pump development not within scope of analysis.
5	**Hydrogen Loss**		No loss within dormancy period.
6	**Insulation and Dormancy**		1-3 d dormancy feasible with existing 11-22 mm MLI, 1-2 mtorr vacuum pressure
7	**Structural Analysis**	5,000 refueling cycles 11,000 cycles	Method developed to design against liner and shell failure modes Fatigure analysis to be carried out.
8	**Strucural Materials**		Aluminum 2219 -T87 preferred for LH_2 trucks
9	**Gravimetric Capacity**	15 wt.% (project goal)	Met. 21.6 - 25.9 wt.%.
10	**Volumetric Capacity**	>35 g/L (project goal)	Met. 36.4 - 46 g/L.
11	**System Cost**	8-9 $/kWh	Cost analysis in progress.
12	**Safety Codes and Standards**	Applicable SAE and and GTR standards	FMEA analysis in progress Code review in progress.
13	**LH_2 Refueling Interface**		Not started yet.

Remaining Barriers and Challenges

- Building hardware to validate results, tank qualification
- On-board and off-board LH_2 pumps
- Evaluation of in-tank vs. ex-tank LH_2 pumps
- Vacuum stability
- Liner support, manufacturability, leakage path
- MLI stability, ruggedness, application in high volume manufacturing environment

Response to Reviewers' Comments

- Not applicable. This is a new 1-year lab call project.