On-board Liquid Hydrogen Storage for Long Haul Trucks

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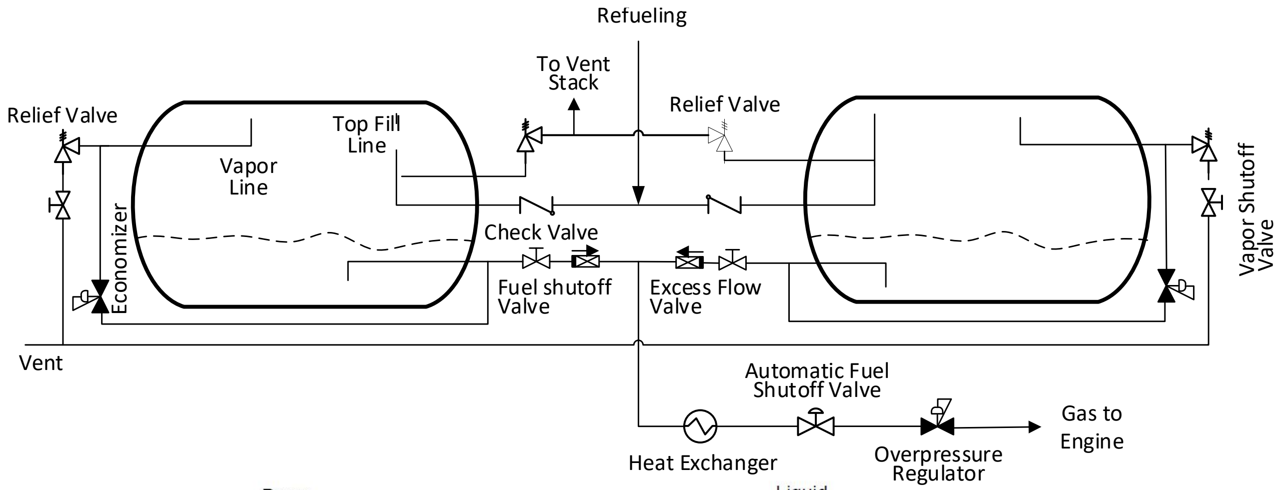
Argonne NATIONAL LABORATORY

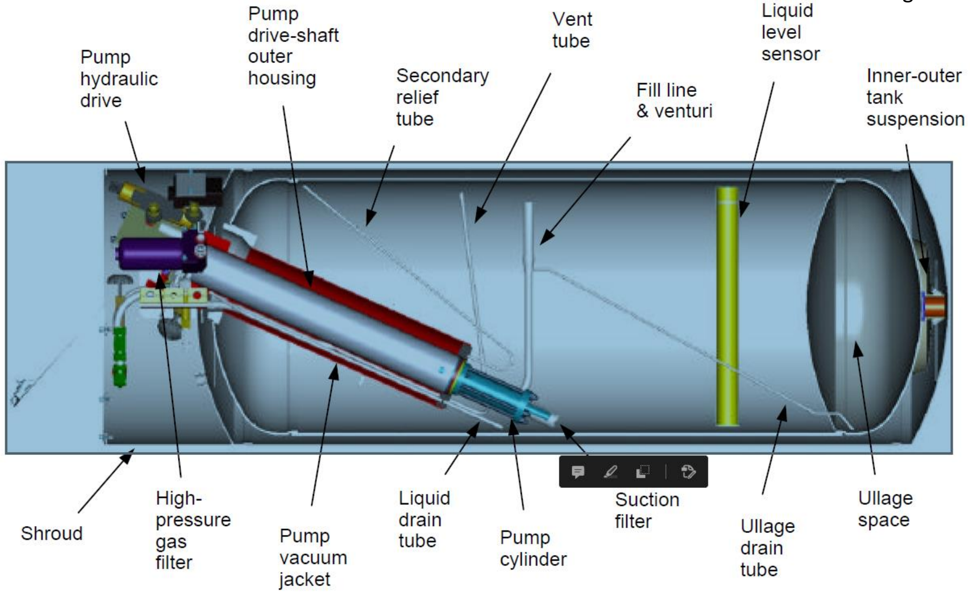
On-Board Storage System Metrics

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

LNG vs. LH_2 Storage for Heavy-Duty Trucks

System with No Pump, Adapted from LNG Vehicle Fuel Tank System Operation Manual, www.ChartLNG.com





Cummins Westport Incorporated (CWI) System with an In-Tank Reciprocating Pump (https://digital.library.unt.edu/ark:/67531/metadc777077/#description-content-main)

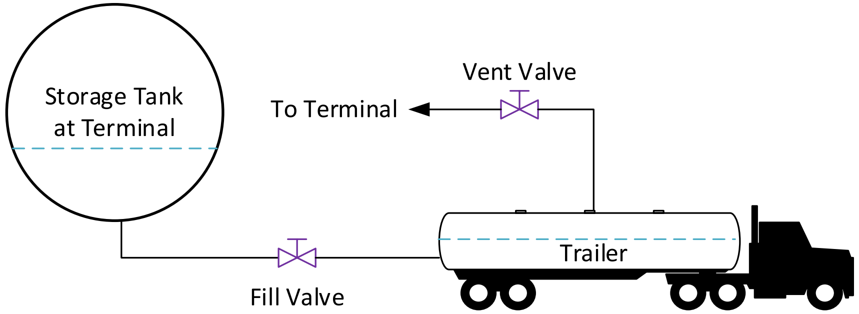
LH_2 vs. LNG

- Requires larger storage volume: LH_2 has 62% smaller LHV on MJ/L basis
- Narrower range of operating temperatures: 20 K NBP and 33 K T_c for LH_2, 111 K NBP and 190 K T_c for LNG
- Similar range of maximum allowable working pressures (MAWP): 10-15 bar

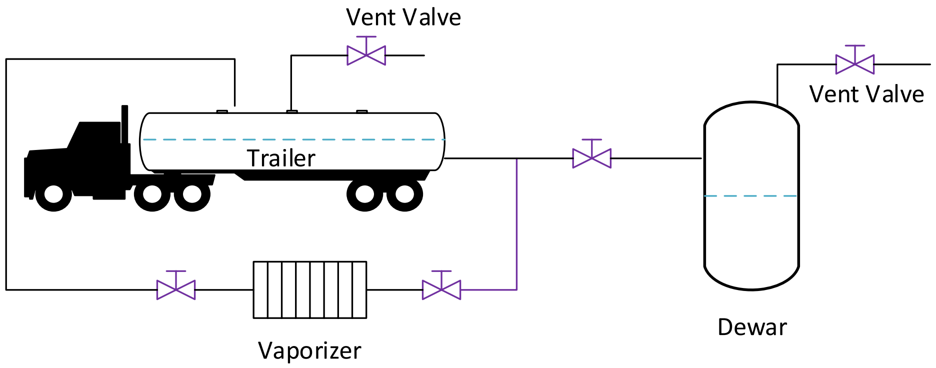
Metric	Units	LNG	LH_2
Normal Boiling Point (NBP)	K	111.7	20
Critical Temperature (T_c)	K	190.6	33
Critical Pressure (P_c)	bar	46.0	13
Density at NBP	kg/m3	422	71
Lower Heating Value (LHV)	MJ/kg	49	120
	MJ/L	20.5	8.5
Heat Capacity at Constant Pressure (C_p)	kJ/kg.K	3.48	14.3
Latent Heat of Vaporization at NBP	kJ/kg	511	449
Tank Storage Pressure	bar	5.4 - 11.5	5.0 - 8.0
Tank Storage Temperaure	K	122 - 147	22 - 33
Maximum Allowable Working Pressure	bar	15	10
Engine/FC Pressure			
SING: Spark Ignition Natural Gas Engine	bar	5 - 8 (SING)	2.5 (H_2 FC)
PIDF: Port Injected Diesel Fuel Engine	bar	8 (PIDF)	
HPDI: High Pressure Direct Injection Engine	bar	>205 (HPDI)	

LH_2 Scenario

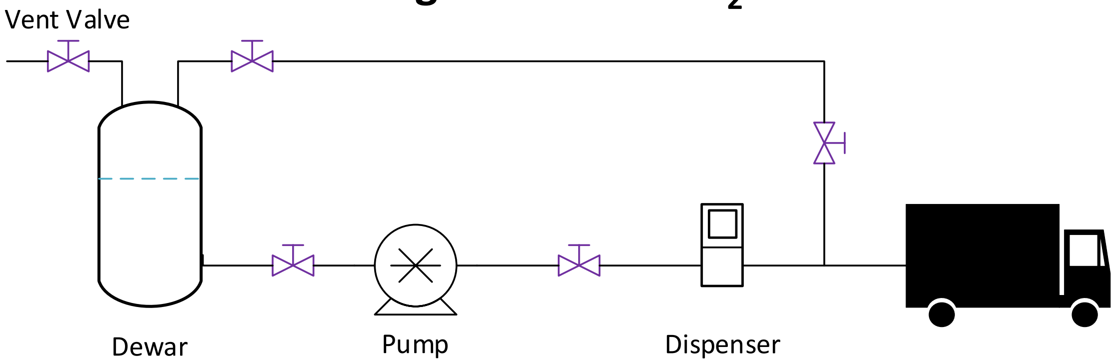
Trailer Loading at Terminal



Dewar Loading at Refueling Station

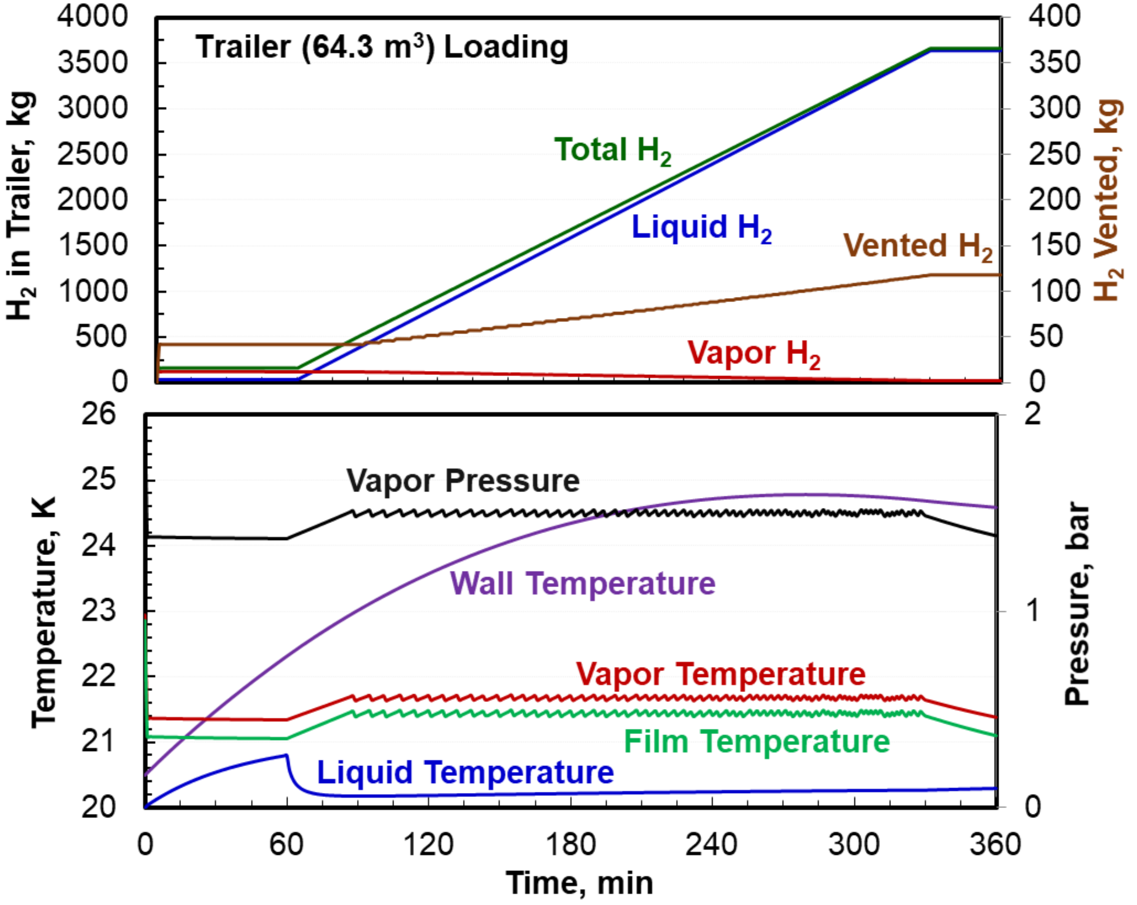


Refueling of FC Truck LH_2 Tank



Trailer Loading at Terminal (Liquefaction Plant)

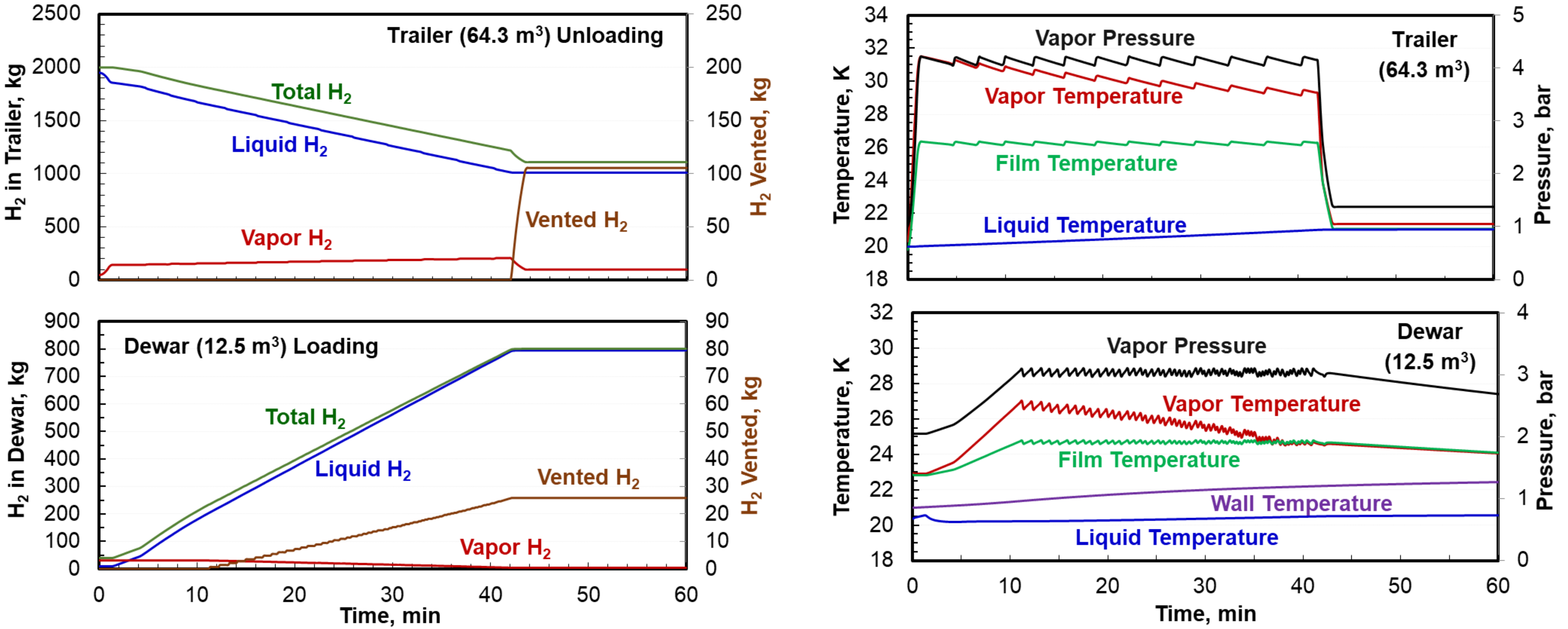
- Reference: Guillaume Petitpas, "Simulation of boil-off losses during transfer at a LH_2 based hydrogen refueling station," IJHE, 43 (2018) 21451-21463
- Pressure transfer from terminal at 24 psia to trailer at 20-22 psia, ~800 kg/h LH_2 transfer rate
- 3.3% total boil-off during loading and initial trailer depressurization



Dewar Loading by Pressure Transfer

Dewar Loading at Refueling Station

- Reference: Guillaume Petitpas, "Simulation of boil-off losses during transfer at a LH_2 based hydrogen refueling station," IJHE, 43 (2018) 21451-21463
- Pressure transfer from trailer pressurized to 60 psia to dewar maintained at 45 psia, ~1100 kg/h average LH_2 transfer rate
- 16% total boil-off loss including 3% from dewar during loading and 12% from final depressurization of trailer to 20 psia



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

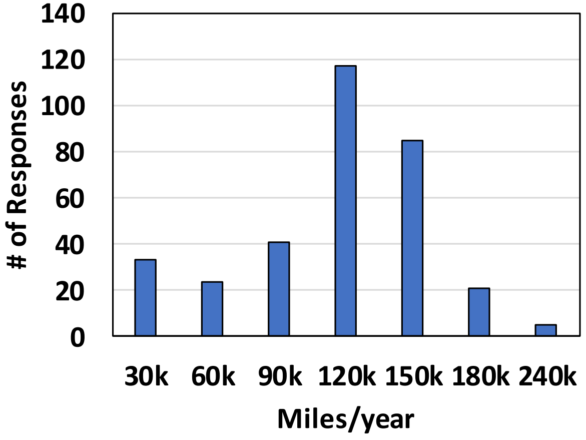
- Fleets used for residential refuse pickup 5 to 6 days per week: 72-gallon diesel tank, 2.93 mpg fuel economy, 11.5 mph average speed
- Between Nov. 1998 and May 2000, data were collected on selected LNG and diesel trucks from Waste Management as part of the U.S. DOE Fuel Truck Evaluation Project: www.doe.gov/bridge
- 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

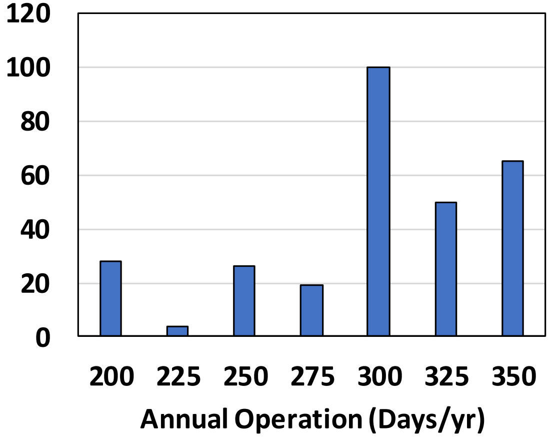
Class 8 – Drayage Truck

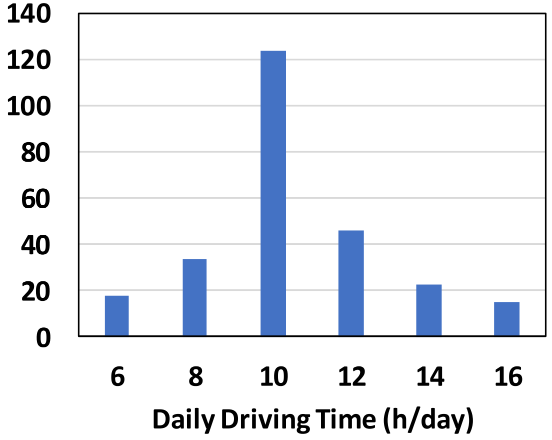
2018 Feasibility Assessment for Drayage Trucks. San Pedro Bay Ports Clean Air Action Plan. March 2019

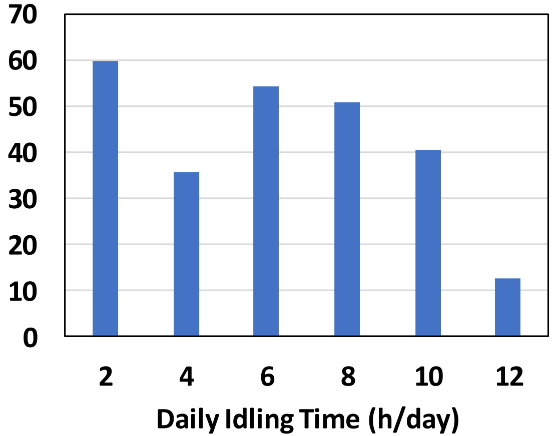
- ~17,500 registered Class 8 trucks in the San Pedro Bay Ports' drayage fleet
- Refueling interval: 2-4 days for diesel, daily for LNG
- Shifts per day: 1 typical, 10-15% of operators do two shifts
- Durability: 500,000 miles or at least 8 years for diesel
- Availability: 90%, down 2-3 days per month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







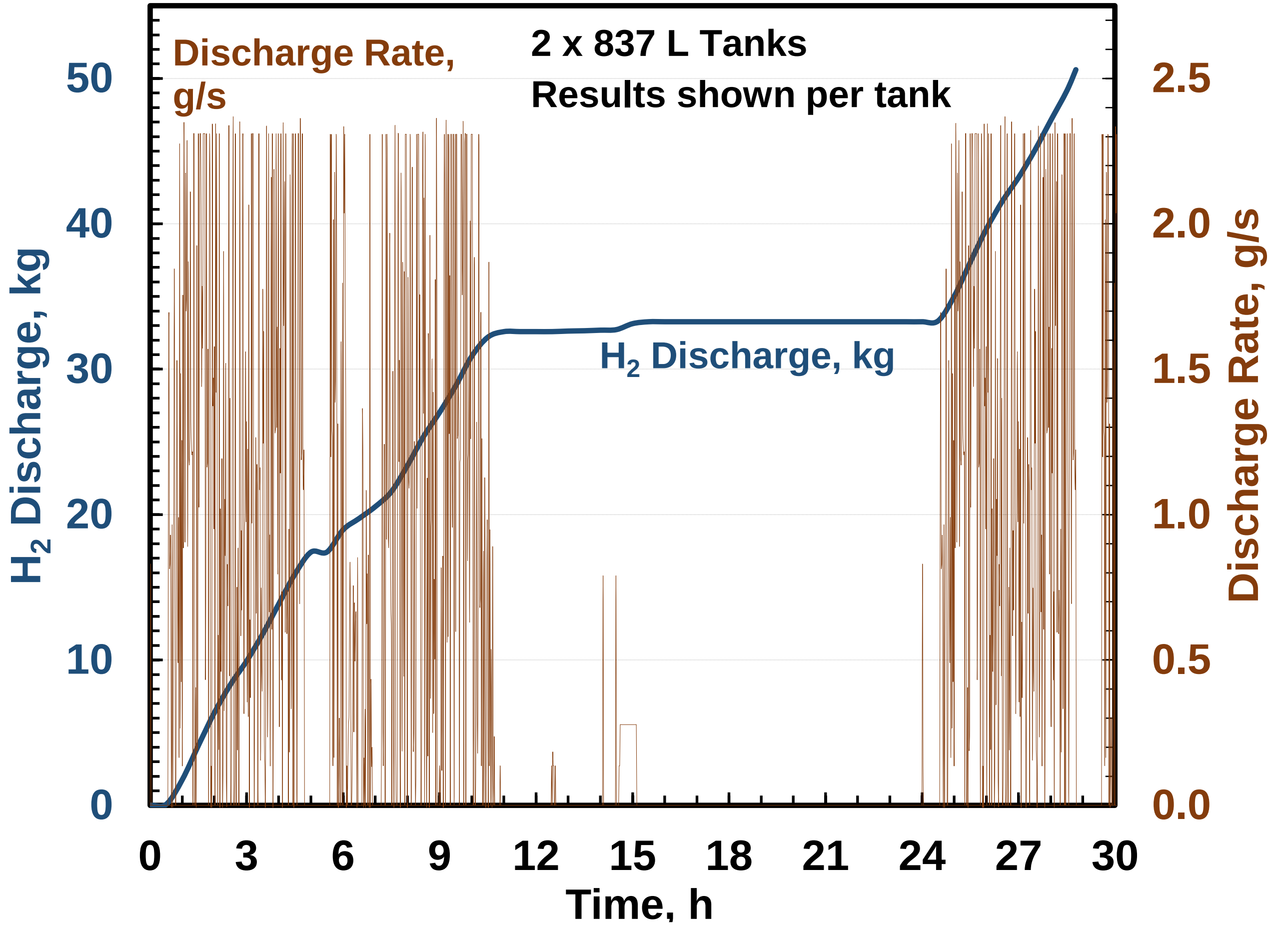


LH_2 Storage for Heavy Duty Trucks: Packaging Options and Capacity

- **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 82 kg usable H_2 capacity: 621 miles

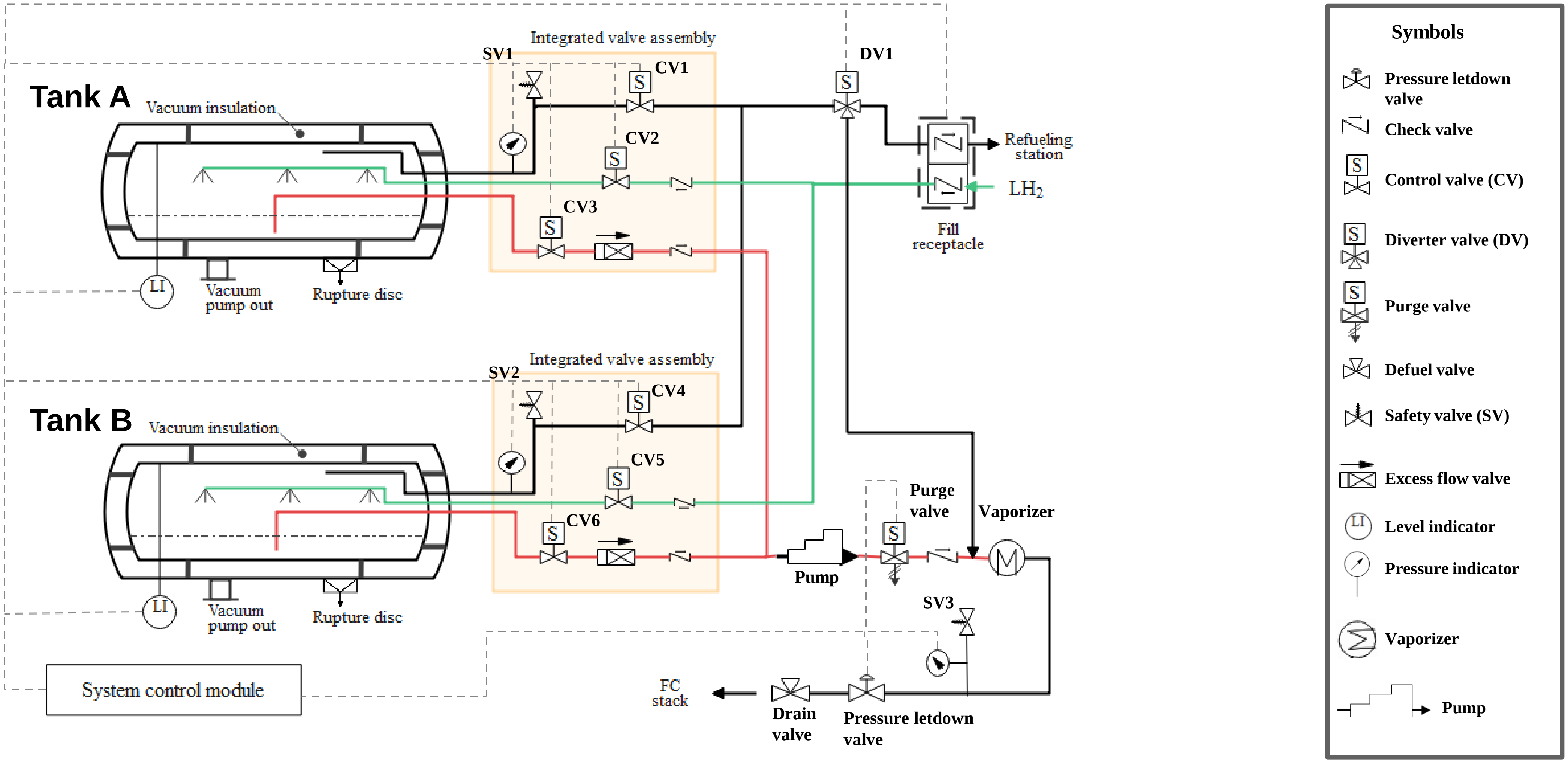


Baseline Packaging Options		
Outer Diameter (cm) X Outer Length (cm)		
Frame Mounted, FM	**Roof Mounted, RM**	**Behind the Cab, BTC**
2 Tanks	4 Tanks	2, 3 or 4 Tanks
53 X 152	41 X 203	41 X 203
53 X 203	41 X 246	53 X 203
53 X 120	30 X 246	
66 X 152		
66 X 203		
66 X 229		
66 X 305		

LH_2 Storage for Heavy Duty Trucks: System with Pump

System options and operating pressures

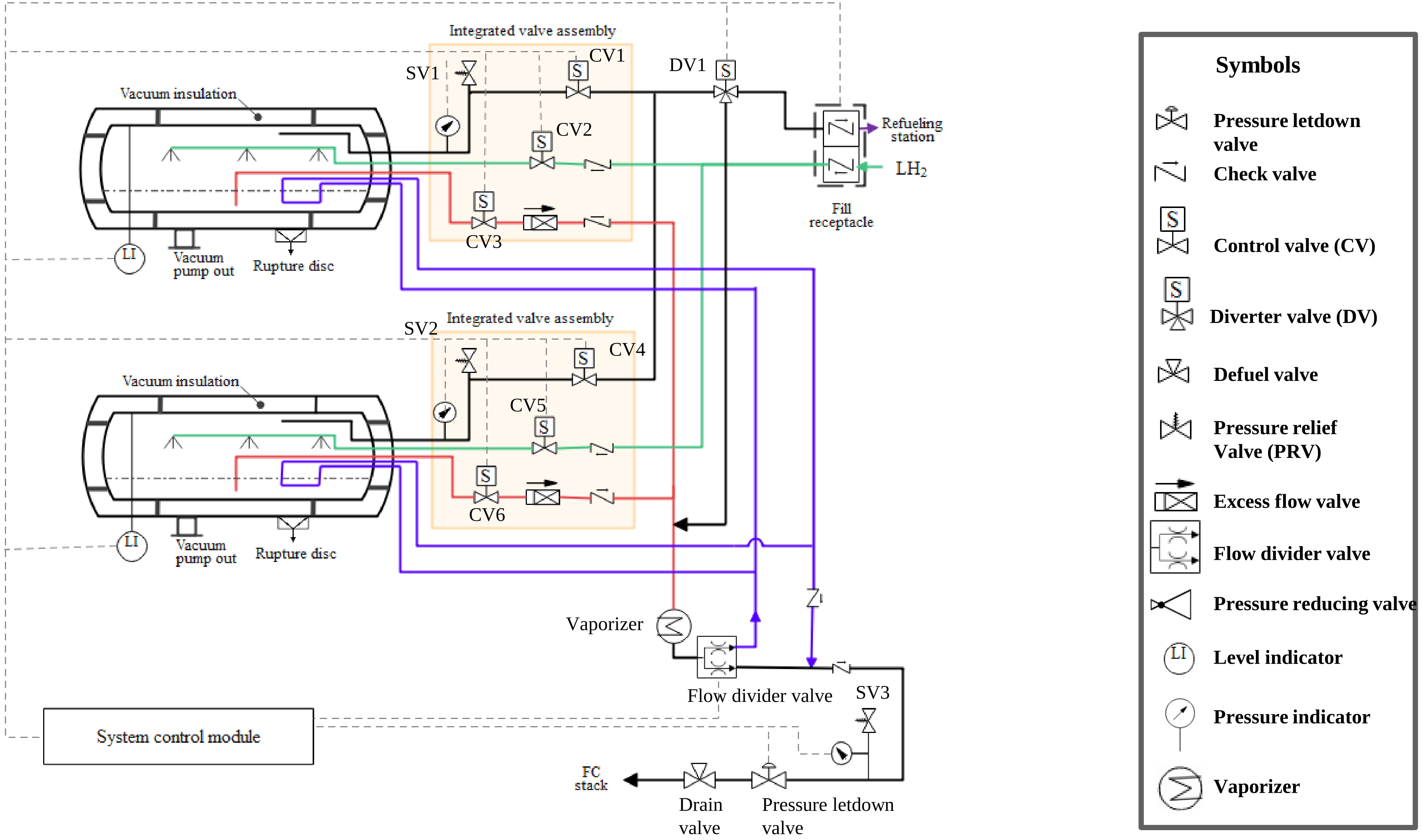
- External or internal on-board pump
- Off-board refueling pump: Low (3-5 bar) and medium-pressure (5-8 bar)
- Tank operating pressure range: low pressure determined by the refueling pump
- May need to return some gaseous H_2 to station storage tank during refueling



LH_2 Storage for Heavy Duty Trucks: System without Pump

System options and operating pressures

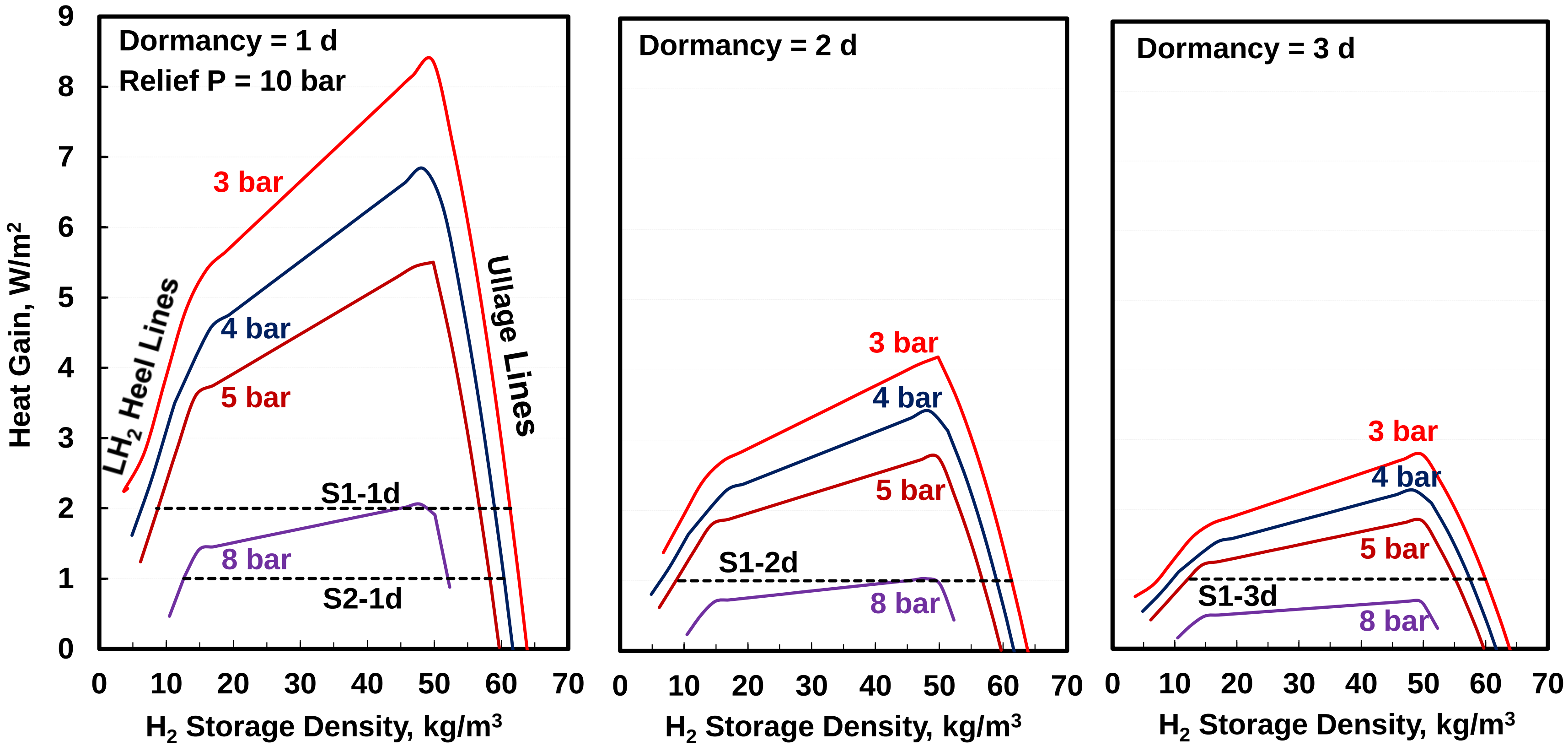
- No on-board pump
- Tank operating pressure range: 5-8 bar
- May require an in-tank heat exchanger
- Withdraw liquid or vapor from tank
- Off-board refueling pump: medium-pressure (5-8 bar)
- May need to return some gaseous H_2 to station storage tank during refueling



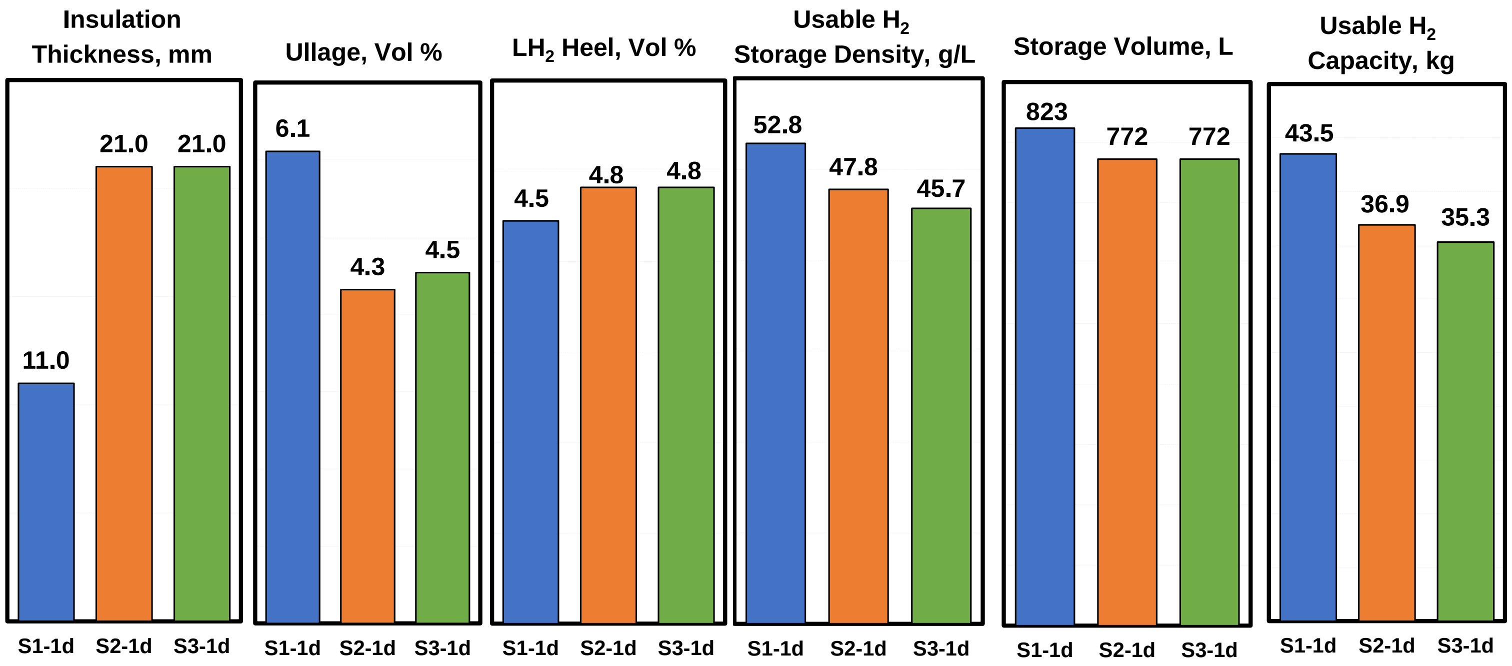
Ullage and Heel

- 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	Fuel Cell	Tank Operating	Feasibility / Dormancy (Q)		
	(ΔP)	Inlet Pressure	Pressure	1 day (1d)	2 days (2d)	3 days (3d)
S1	Yes (4 bar)	5 bar	3 - 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

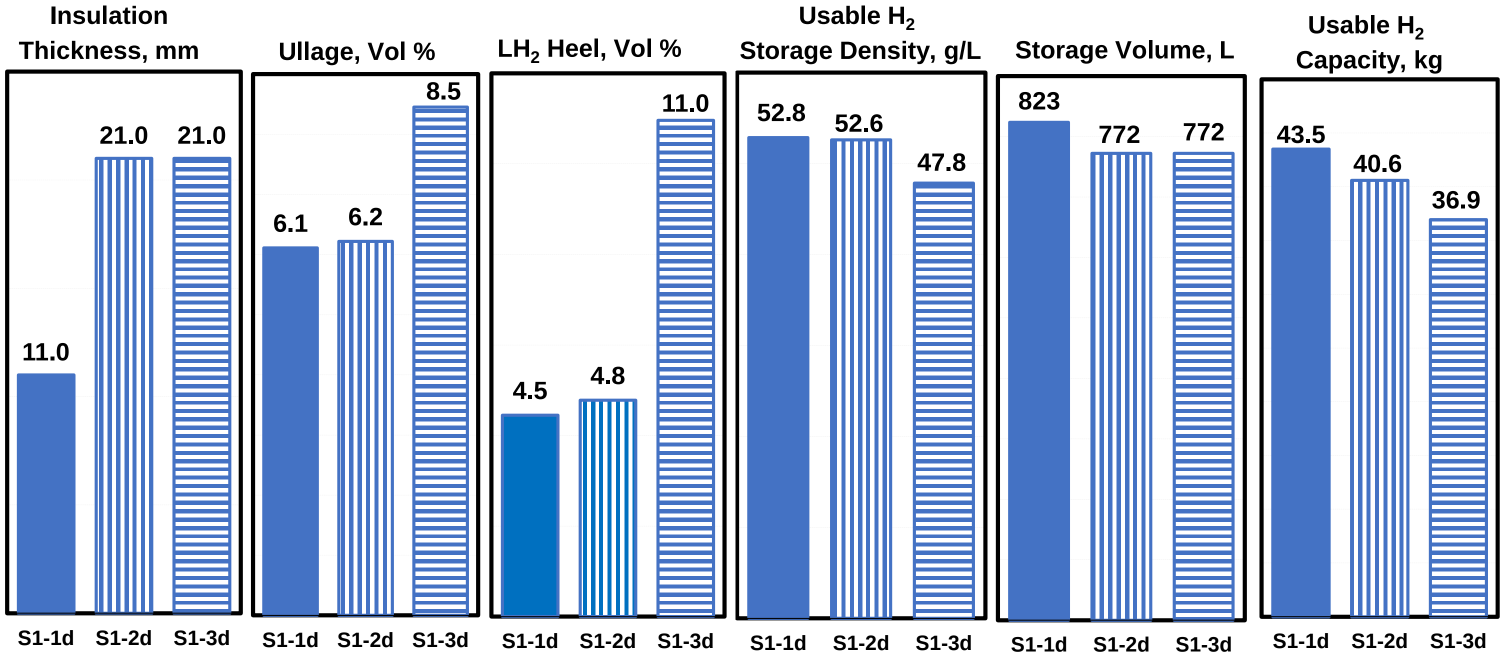


LH_2 Storage System Performance



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

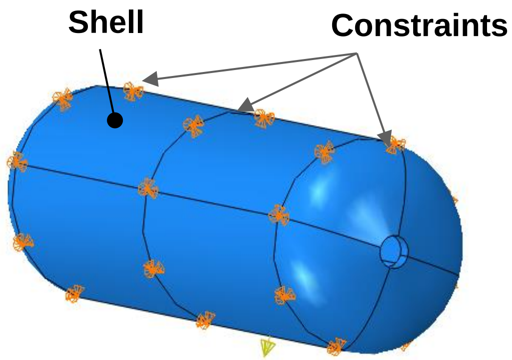
- Effect of FC inlet pressure (5 vs. 8 bar) on system performance: 15% loss in usable H_2 capacity from 43.5 to 36.9 kg
- Advantage of on-board pump (5 bar): 19% in usable H_2 capacity from 43.5 to 35.3 kg



Effect of Dormancy on Performance of System S1

- 1-d vs. 2-d dormancy: 7% loss in usable H_2 capacity from 43.5 to 40.6 kg, mainly due to lower storage volume
- 2-d vs. 3-d dormancy: 9% loss in usable H_2 capacity from 40.6 to 36.9 kg due to lower usable H_2 storage density

LH_2 Tank Analysis: Liner and Liner Support



Static FE Model

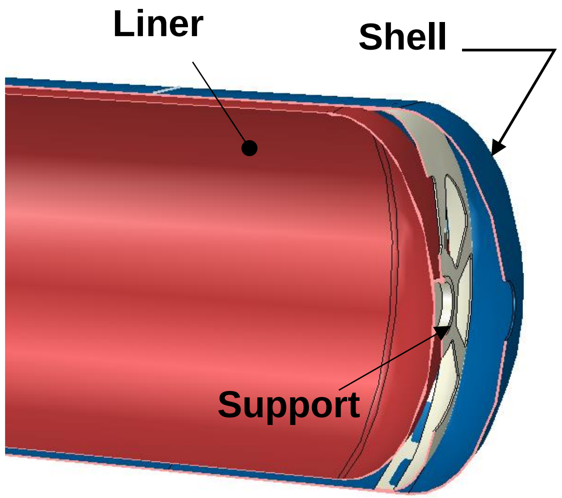
- LH_2 tank mounted to the frame by straps, 8 bar operating pressure. Maximum allowable working pressure (MAWP) of 10 bar
- Liner suspended inside the shell using brackets at the two ends that are welded to shell and liner.
- Analysis Method: ASME BPVC VIII Div-1 code and room temperature material properties for liner thickness, ABAQUS FE analysis for maximum stress and safety factor

Material Properties

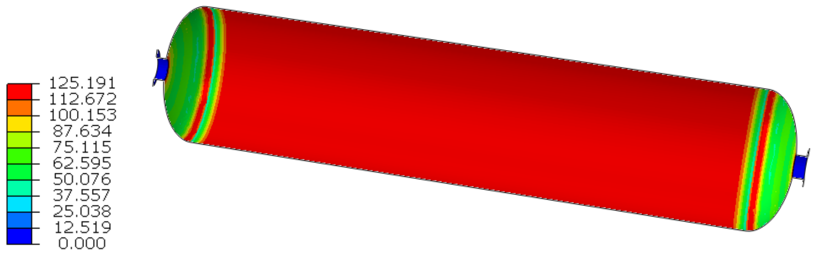
Prop. / Mat.	σ_{ult} MPa	σ_y MPa	E GPa	$\sigma_{allowable,\ MPa}$ RT	$\sigma_{allowable,\ MPa}$ -195 °C	Density g/cc	S.F.
Al 2219-T87[1]	454	344	70	129.7	196.9	2.84	3.5
Al 5083-O[2]	276	124	70	78.8	107	2.66	3.5
SS 304, 316[2]	515	205	200	137	243	8.0	3.76

Liner Thickness

Prop. / Mat.	Liner Thickness, mm	Liner Weight, kg
Al 2219-T87[1]	2.7	44
Al 5083-O[2]	4.4	74
SS 304, 316[2]	2.6	139.4



Section View of LH_2 Tank showing Liner Support

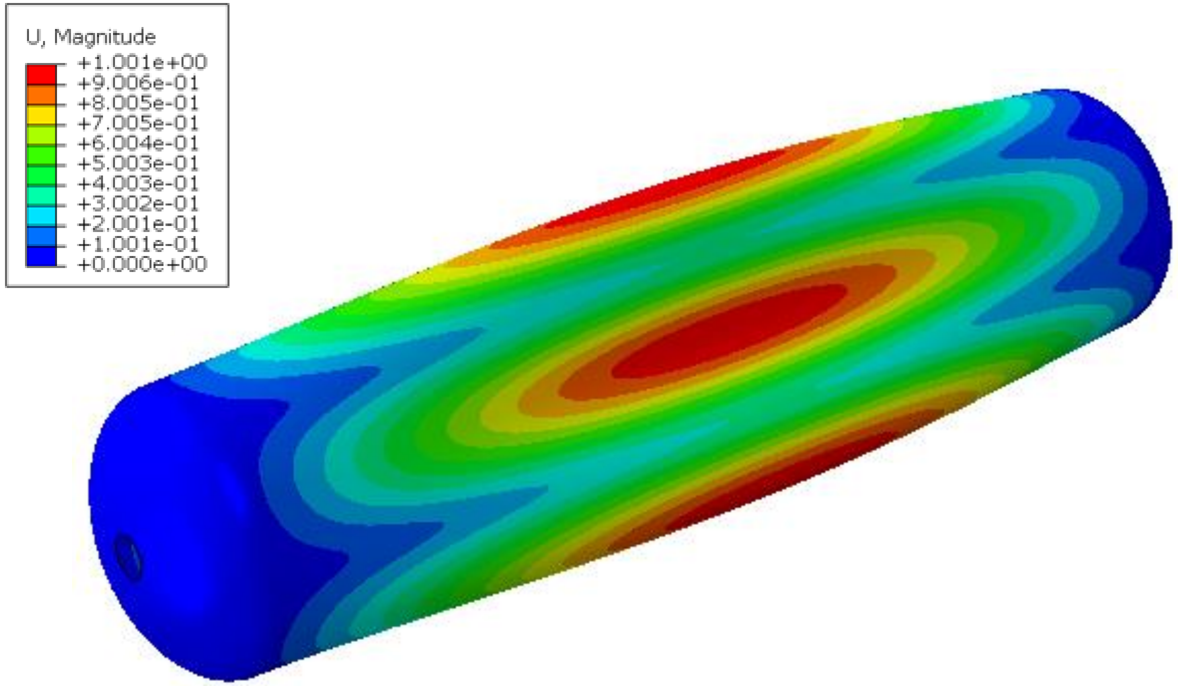


Principal Stresses on The Liner (D660_L3050)

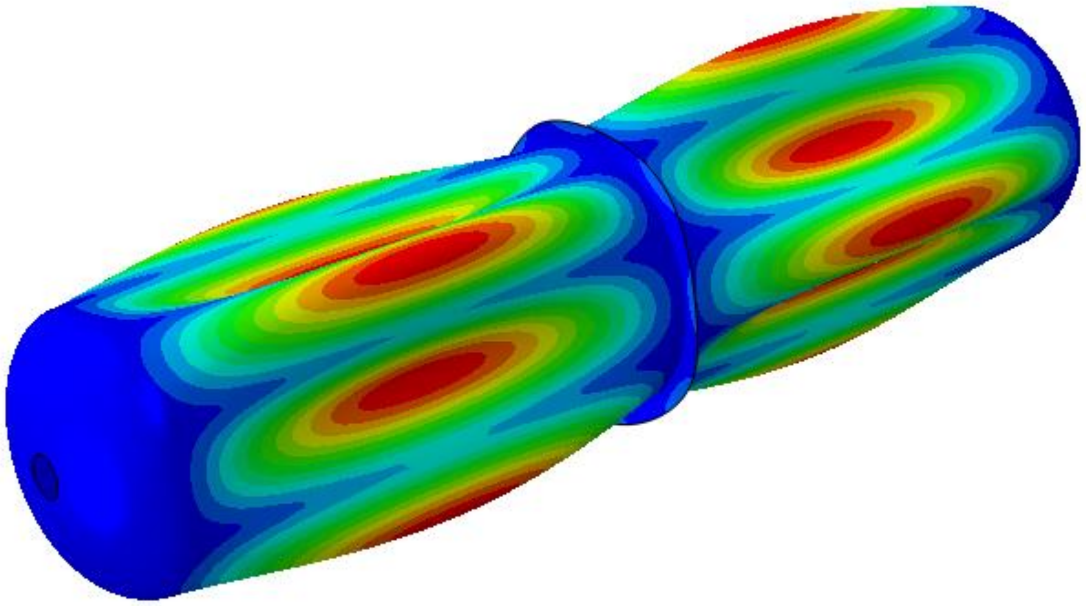
[1] BPVC-VIII, ASME Boiler and Pressure Vessel Code. *Section VIII, Division* 1, 2019
[2] *Cryogenic materials data handbook,* Volume 1, 1970.

LH_2 Tank Shell Analysis

- Shell failure mode: The shell is subject to buckling because it has MLI layer in a vacuum state inside and is exposed to 1 bar outside
- Analysis method: ASME BPC BPV VIII Div-1 code, and ABAQUS FE analysis for maximum stress and safety factor
- Calculated safety factor: 3 for 26” x 120” tank
- Since the 1st buckling mode is found in the circumferential direction, adding a 6-mm x 50-mm stiffener along the circumferential direction reduces the shell thickness from 5.8 mm to 4.5 mm and the shell weight from 107 kg to 85 kg.

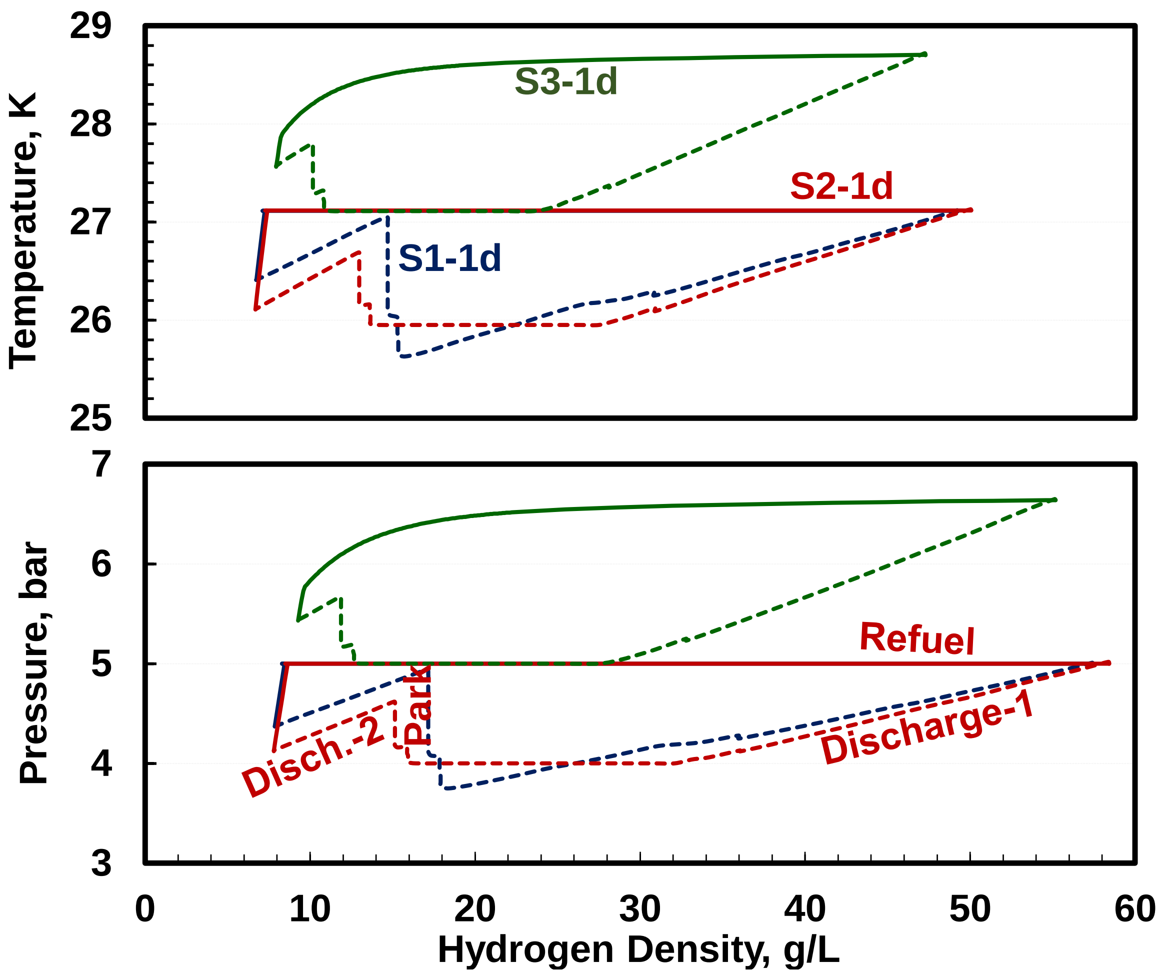


Shell without a Ring



Shell with a Stiffening Ring

Refueling and Discharge Dynamics



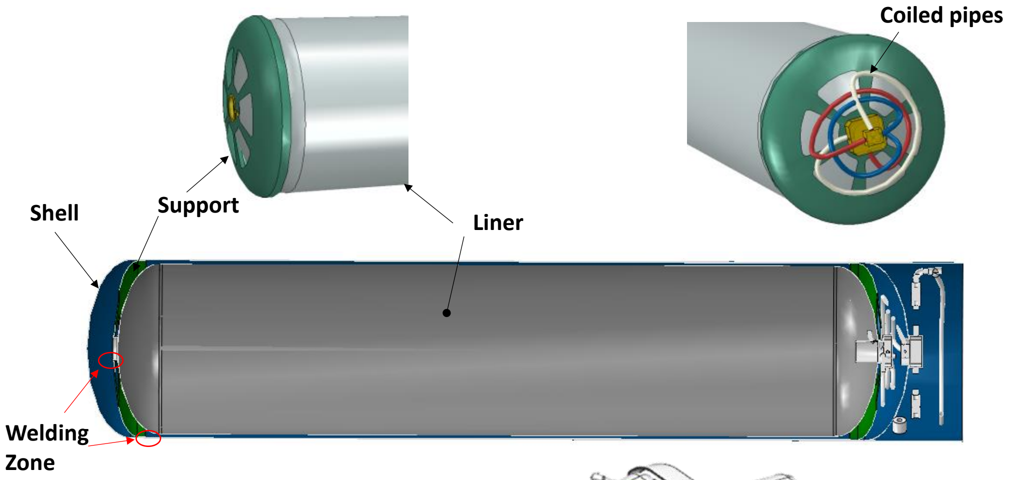
Important Conclusions from Drive Cycle Simulations

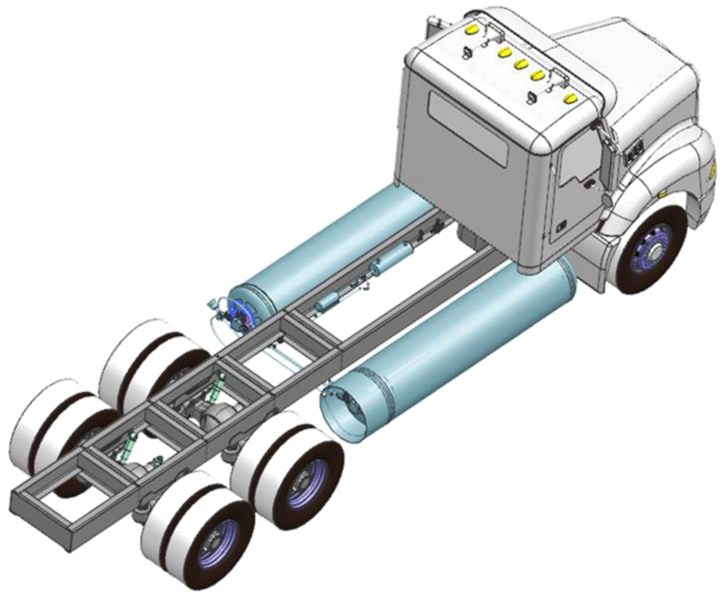
- The amount of H_2 returned to the station during refueling is 9.7% in S1-1d, 9.2% in S2-1d, and 0 in S3-1d.
- Systems S2-1d and S3-1d require heat to be supplied during discharge.
- System S3-1d may be impractical if the requirement for 8 bar FC inlet pressure cannot be relaxed.

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	5.0	5.0	6.6
Ullage	%	6.1	4.3	4.5
LH_2 Heel	%	4.5	4.8	4.8
Usable H_2	%	86.3	86.7	83.2
H_2 Storage Density	kg/m^3	57.5	58.4	55.2
Usable H_2 Density	kg/m^3	49.6	50.6	45.9
H_2 Returned to Station during Refueling	%	9.7	9.2	0.0
Heat Supplied during Discharge	kJ	0	324	412
H_2 Stored after Refueling	kg	47.3	45.1	42.6
Usable H_2	kg	40.8	39.1	35.5

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

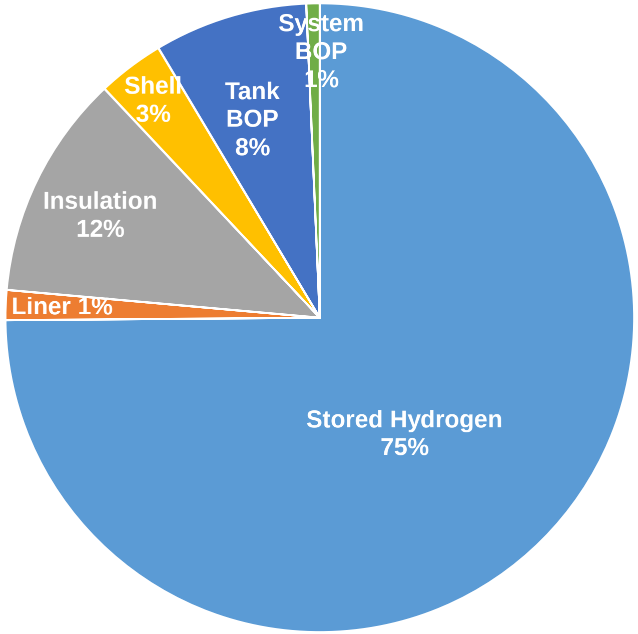




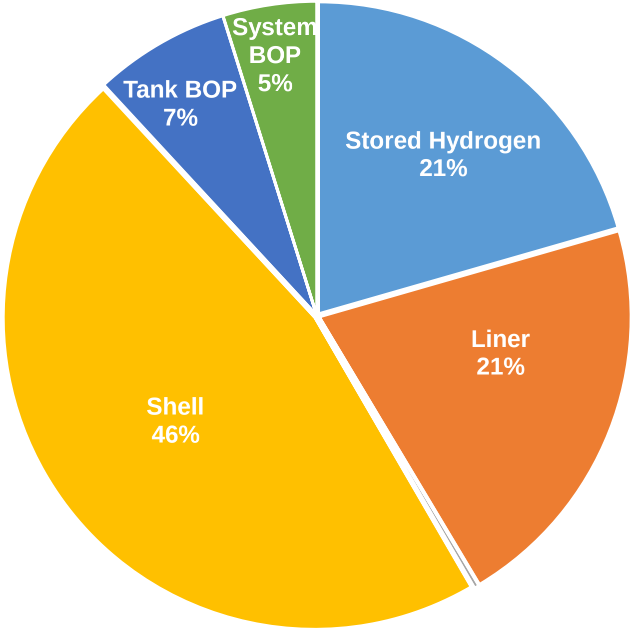
Parameters	Units	S1-1d	S2-1d	S3-1d
H_2 Stored	kg	94.6	90.2	85.2
System Gravimetric Capacity	wt.%	17.7	17.4	15.9
System Volumetric Capacity	kg/m^3	37.1	35.5	32.2
Range Between Refueling	miles	621	595	539

Storage System S1-1d Weight and Volume Distributions

Volumetric Capacity: 37.1 kg/m^3

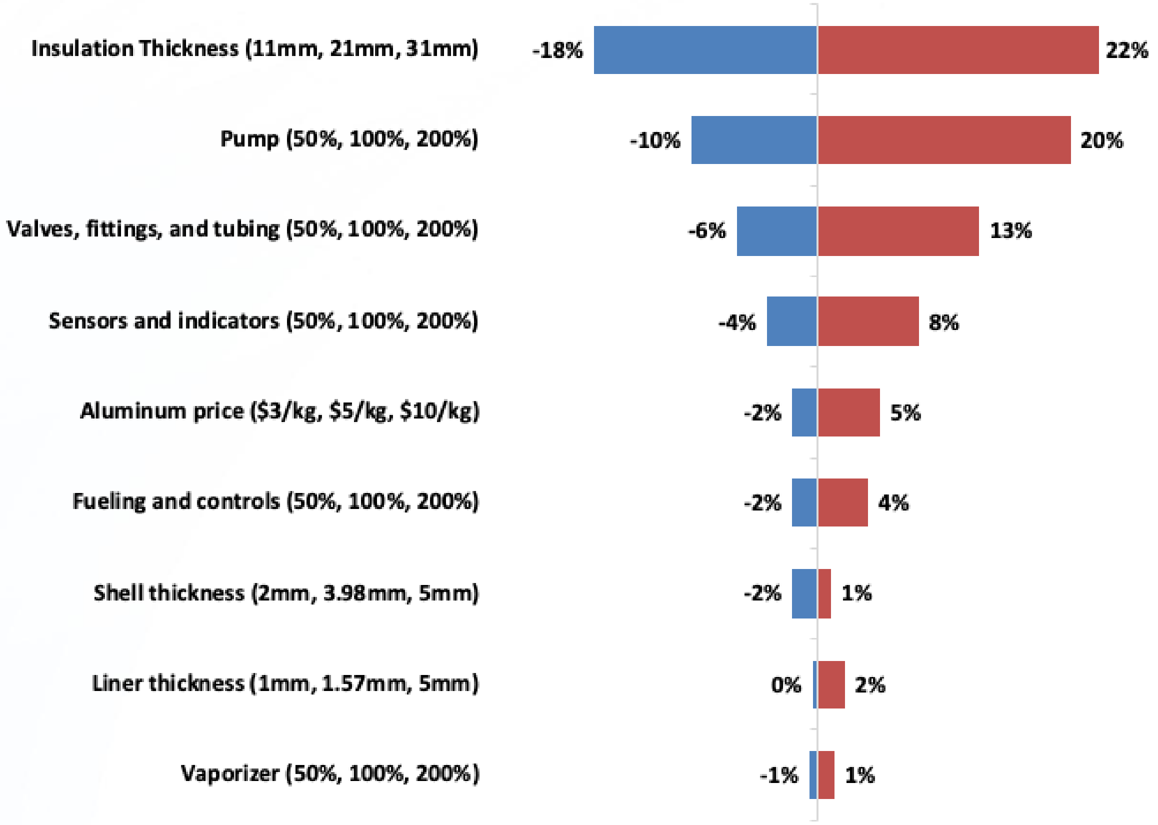


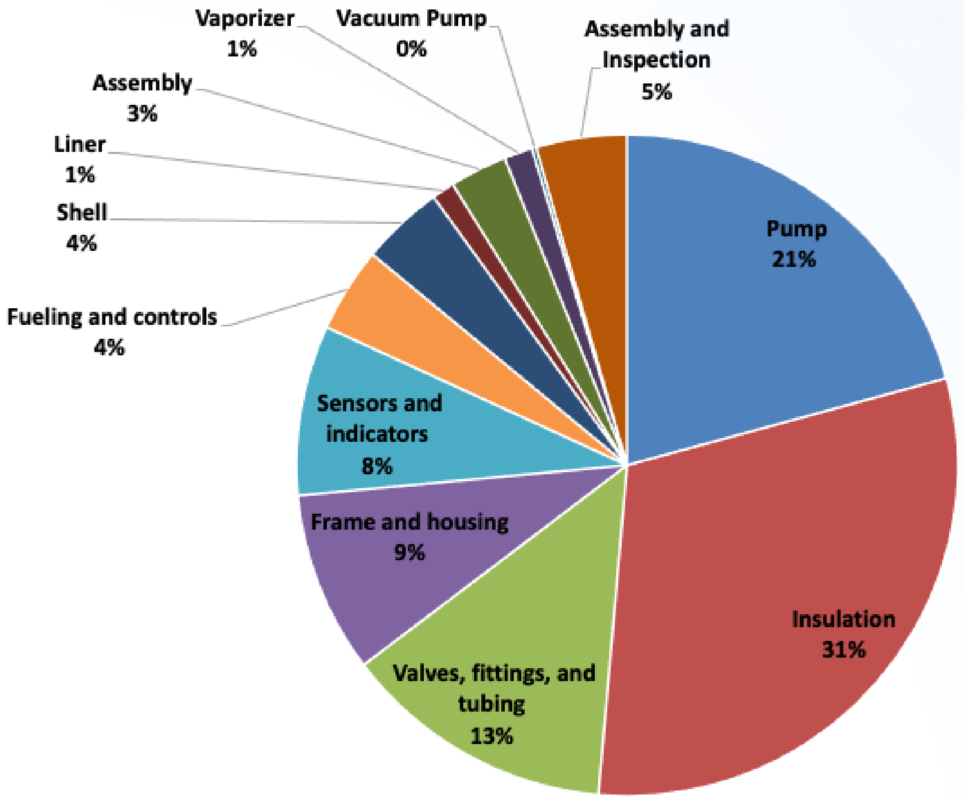
Gravimetric Capacity: 17.7 wt.%



Bottom-up Cost Analysis (ST223)

- 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



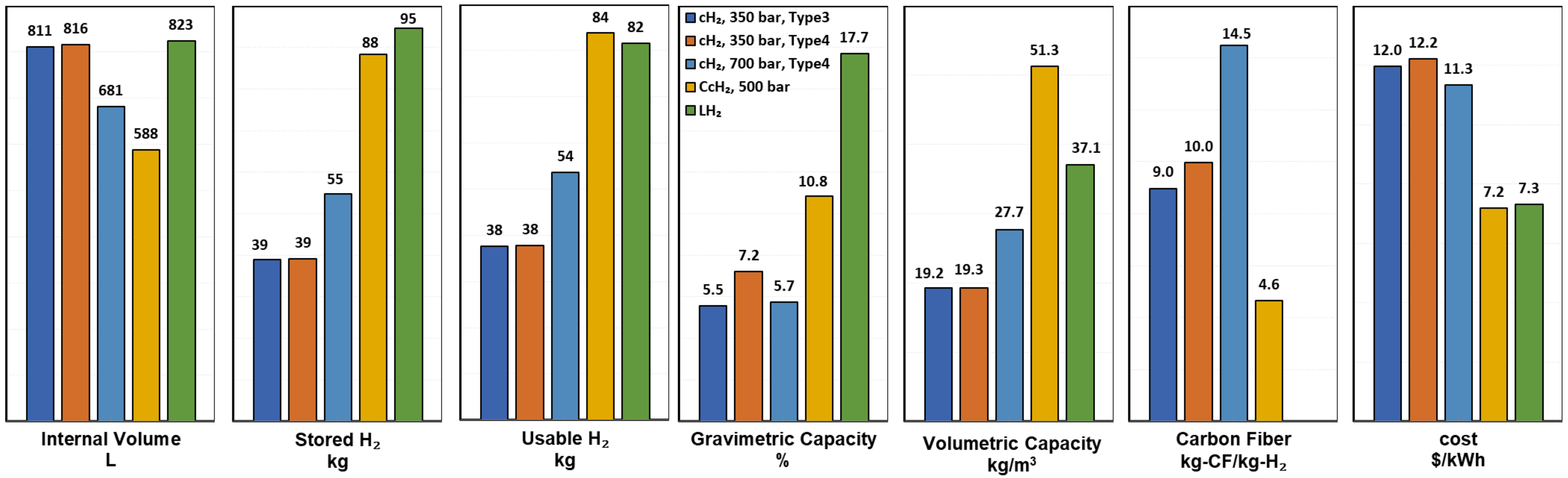


STRATEGIC ANALYSIS INC

Comparative Performance of Liquid (LH_2), Compressed (cH_2) and Cryo-Compressed (CcH_2) H_2 Storage Systems

Packaging Options[1]

[1]http://www.a1autoelectric.com



Summary: Progress Toward DOE Goals

Task	Metric	Lab Call Goal	Progress of Analysis Toward Lab Call Goals
1	**Storage System Range**	750 miles	539 - 621 miles
2	**Storage System Capacity**	>60 kg	71 - 82 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)	15.9 - 17.7 wt.%.
10	**Volumetric Capacity**	>35 g/L (project goal)	32.2 - 37.1 g/L.
11	**System Cost**	8-9 $/kWh	<8 $/kWh
12	**Safety Codes and Standards**	Applicable SAE and GTR standards	FMEA analysis in ST223 Code review in ST223.
13	**LH_2 Refueling Interface**		Finished in ST223.