SHIIVER assembly thermal model for transient test conditions

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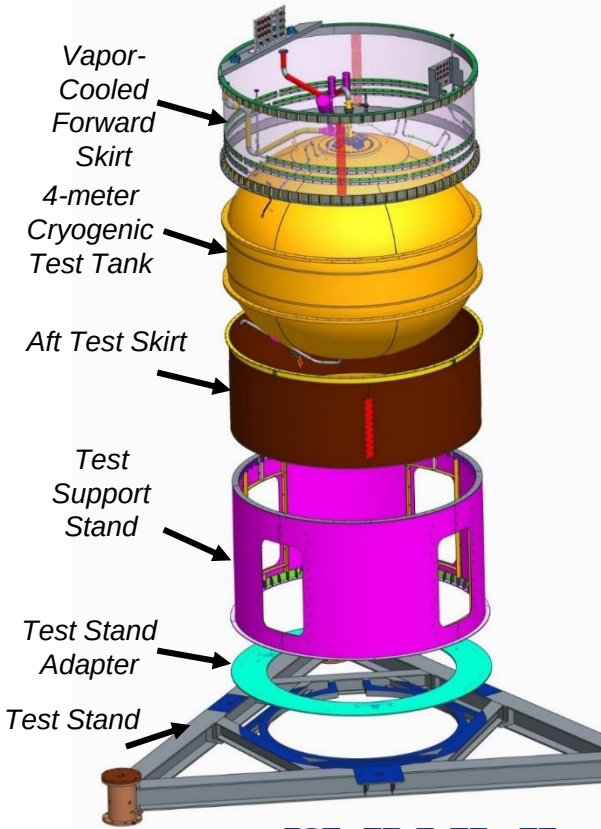


Outline

- Overview of the test and development of the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER)
- Thermal model of the SHIIVER assembly
- Test operation timeline and transient test conditions
- Thermal Model results
  - For the 75% fill level
  - For the 50% fill level
  - Summary of the heat reduction and boiling off reduction for different fill levels
- Summary
- Acknowledgements

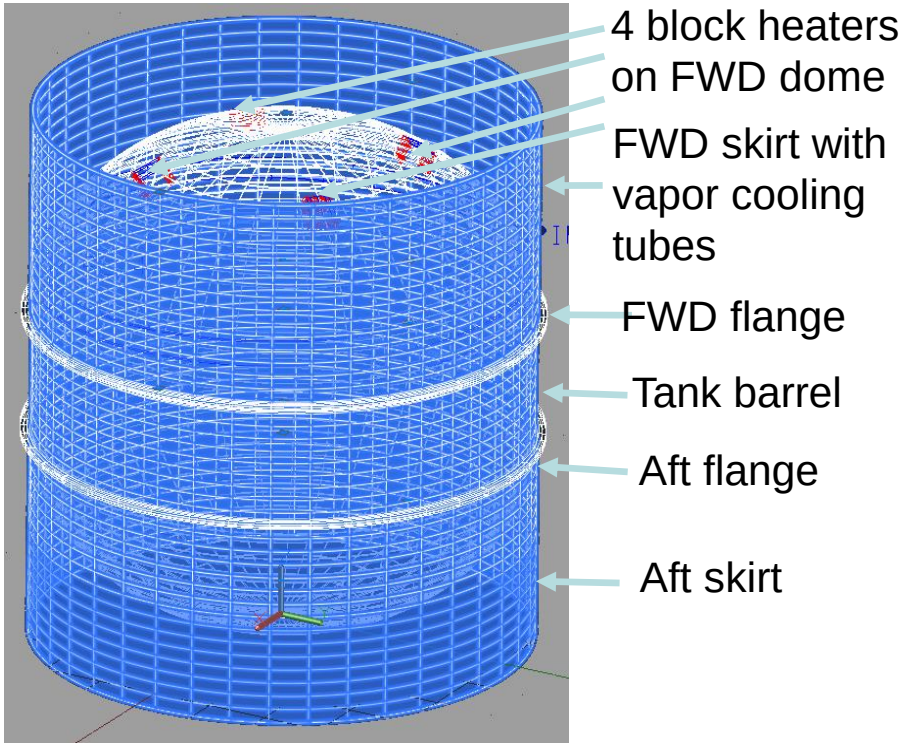
SHIIVER Overview

- SHIIVER consists of a large cryogenic tank assembly with geometry, support structure, skirt and fluid penetrations comparable to an actual space flight vehicle configuration, such as EUS LH2 tank.
- SHIIVER will be used to investigate three main concepts:
  - Structural cooling using tank boil off vapor to intercept conductive heat leak
  - Design, construction, and performance of MLI on a large flight tank configuration
  - MLI blanket durability under launch acoustic vibration conditions
- A thermal modeling effort has been undertaken to predict system level performances of the technologies being tested.
  - Understand system transient behaviors
  - Perform trade studies of different vapor cooling designs
  - Define the test operations matrix
  - Address thermal related questions at different phases of SHIIVER project



SHIIVER Assembly Thermal Model Summary (I)

- Thermal Desktop/Sinda-Fluint is used
- Geometry includes tank (FWD dome, barrel, AFT dome), FWD skirt and AFT skirt, vapor cooling tubes on FWD skirt, FWD flange, AFT flange
- Inside the tank: use twin lump to model the convection and phase change and pressure of the fluids
- Pressure control of the tank: use PID controller
- Heater control: use logic to turn on or off the heaters, heater are on FWD dome
- Heater power: define as a register to vary the power



SHIIVER Assembly Thermal Model Summary (II)

Baseline configuration:

- SOFI on all tank surfaces: ON
- MLI on FWD and AFT domes: OFF
- MLI on inside of FWD skirt: ON
- Vapor cooling: OFF

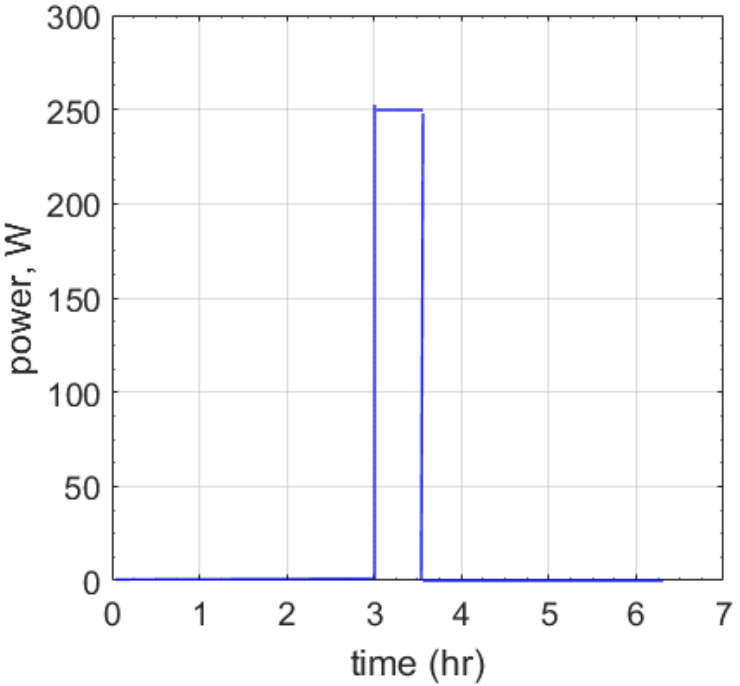
Other configurations:

- Vapor cooling ON (only)
- Dome MLI ON (only)
- Both Vapor cooling and Dome MLI ON



SHIIVER Assembly Test Operation Timeline

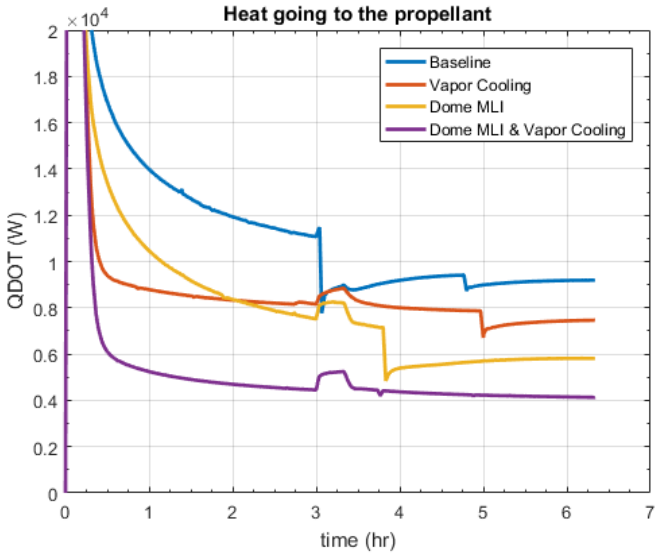
- Fill the tank to defined fill level for each case
- Hold for 3 hours to establish initial conditions for tank and skirts
- Activate four forward dome heaters at t = 3 hr, 250 W each, for 20.15 minutes to simulate autogenous pressurization during engine burn
- Deactivate heaters at t = 3.336 hr and hold for 3 hrs to simulate vehicle coast after engine burn
- Maintain 293 K wall temperature, 10^{-5} torr pressure environment in chamber
- Maintain 20 psia tank pressure, venting to atmosphere at sea level pressure

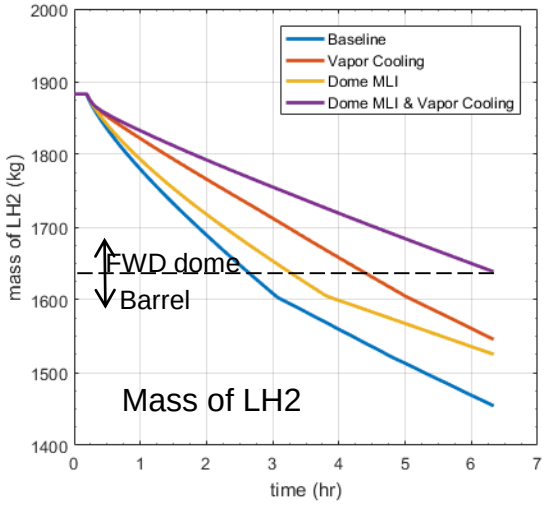


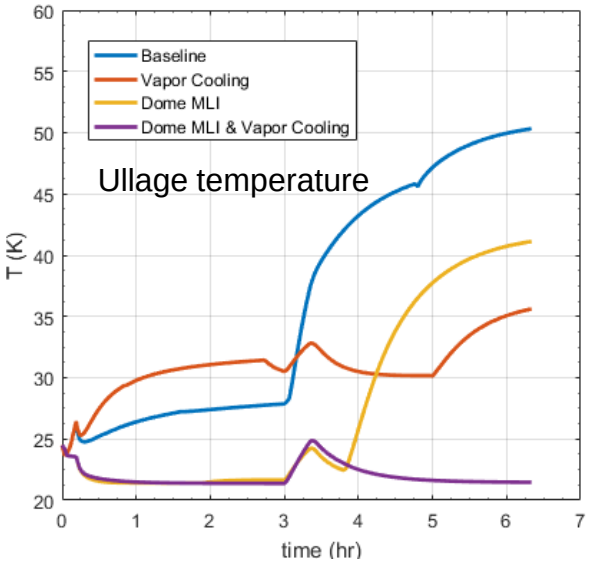
Modeling Cases for SHIIVER Transient Test Matrix

- 7 propellant fill levels: 90%, **75%**, 67%, 58%, **50%**, 41%, and 33% that corresponds to engine burns (autogenous pressurization heating)
- 2 forward dome heater powers: 0 and 250 W each
- 4 configurations:
  - Baseline – No vapor cooling, SOFI only on domes and barrel
  - Vapor cooled forward skirt
  - MLI on domes
  - Vapor cooled forward skirt and MLI on domes

SHIIVER Thermal Model Results (75% fill level)



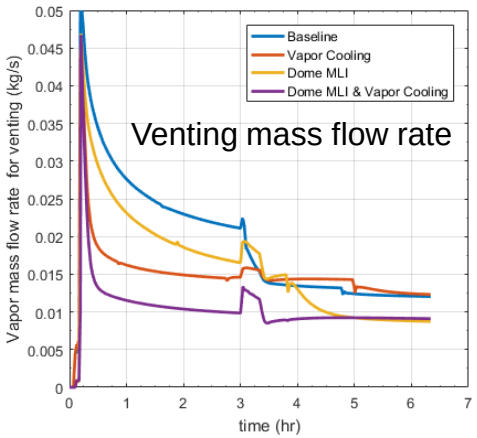


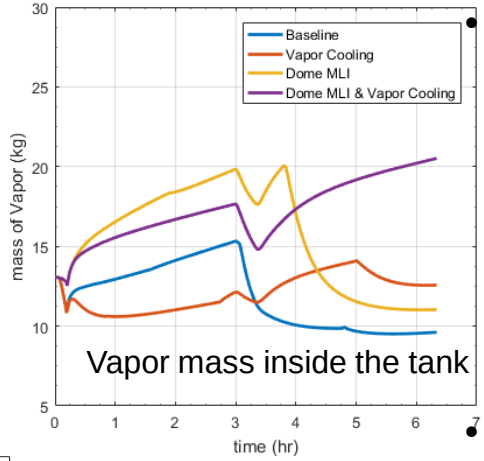


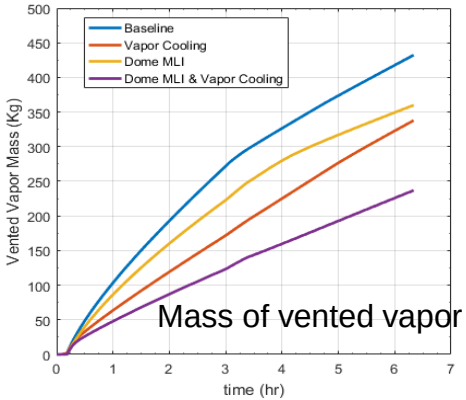
Vapor cooling on FWD skirt and/or MLI on the domes:

- Reduce the heat going to propellant, thus reduce the boiling-off rate of LH2.
- Vapor region is cooler than the baseline except the vapor cooling results in warmer ullage temperature than the baseline from t = 0 to 3.22 hr.
- The heaters are turned on at t = 3 hr then turned off at t = 3.336 hr as shown in QDOT and T vapor versus time plots.

SHIIVER Thermal Model Results (75% fill level)





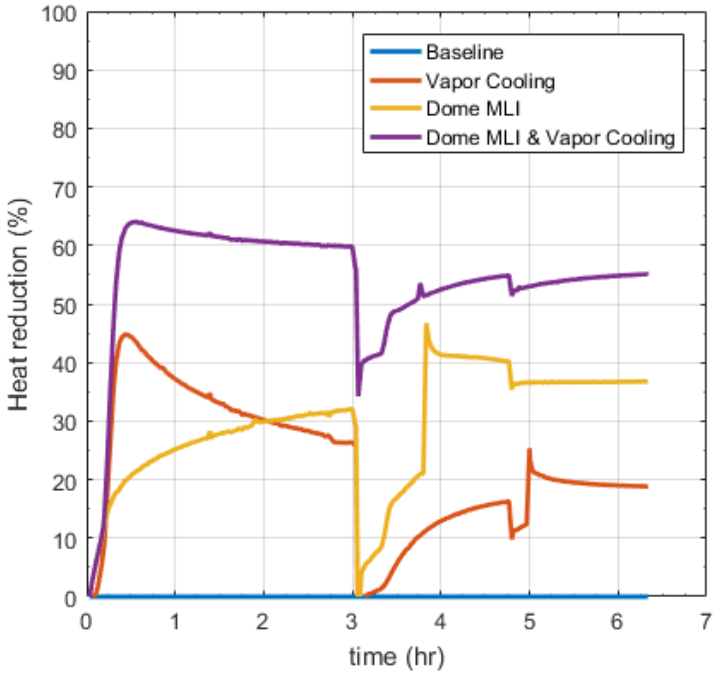


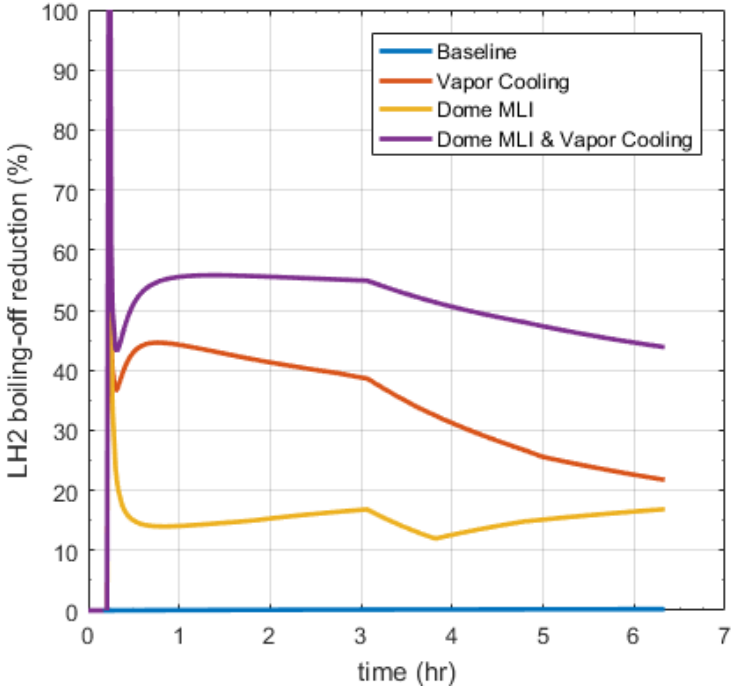
- Vapor cooling on FWD skirt
  - Decreases vapor mass in ullage prior to and during heater activation, increases mass after deactivation
  - Decreases venting rate prior to and during heater activation, increases venting rate after deactivation
  - Decreases boil off and vented mass
- MLI on the domes
  - Increases vapor mass in ullage
  - Decreases venting rate except during and immediately after heater activation
  - Decreases boil off and vented mass
- Vapor cooling on FWD skirt with dome MLI
  - Increases vapor mass in ullage
  - Decreases venting rate
  - Decreases boil off and vented mass

Summary of the Heat Reduction and Boiling-off Reduction at t = 6.33 hr (75% Fill level)

		baseline	Vapor cooling On FWD skirt	MLI on Domes	Vapor cooling & Dome MLI
	Q to LH2 (w)	5318.5	5431.0	3852.7	4123.7
Heaters ON	Q to vapor (w)	3874.1	2031.0	1959.2	11.04
	Q to propellant (w)	9192.6	7462.0	5812.0	4134.8
	Vapor temperature (K)	50.3	35.6	41.1	21.47
	Heat reduction (w)		1730.6	3380.6	5057.8
	Heat reduction (%)		**18.8%**	**36.8%**	**55%**
	Venting mass flow rate (kg/s)	0.012	0.012	0.008	0.012
1875.0 kg	Vapor mass (kg)	2.155	2.261	2.237	2.361
75% fill level	LH2 mass (kg)	1454.2	1545.7	1525.1	1638.6
	Boiling off (kg)	420.8	329.3	349.9	236.4
	Boiling off reduction (%)		**21.7%**	**16.8%**	**43.8%**

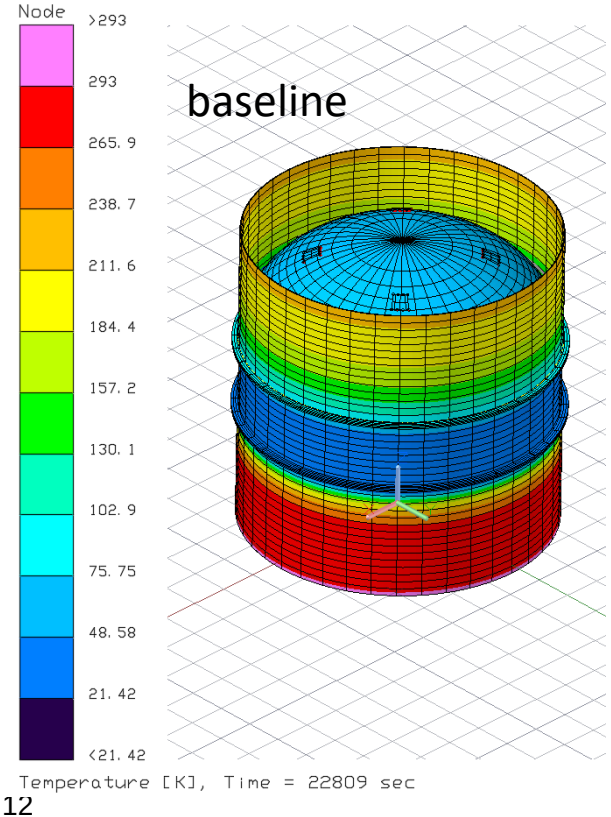
SHIIVER Thermal Model Results (75% fill level)

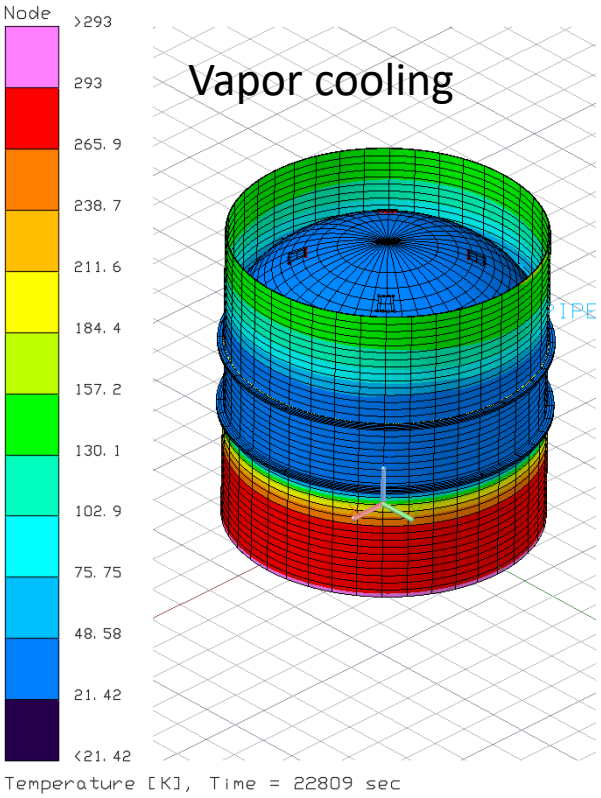




Heat reduction and boiling-off reduction change in time

Temperature Contour of the SHIIVER at t = 6.33 hr (75% Fill Level)

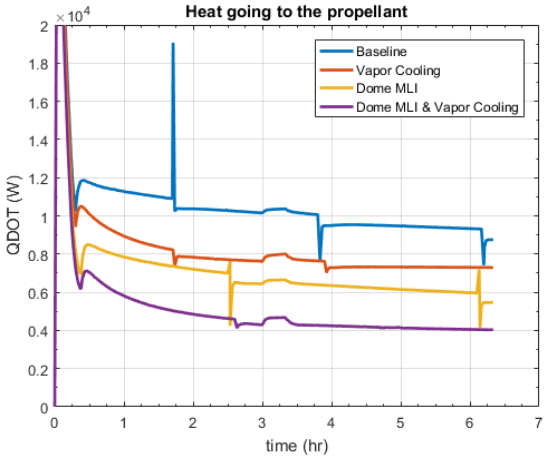


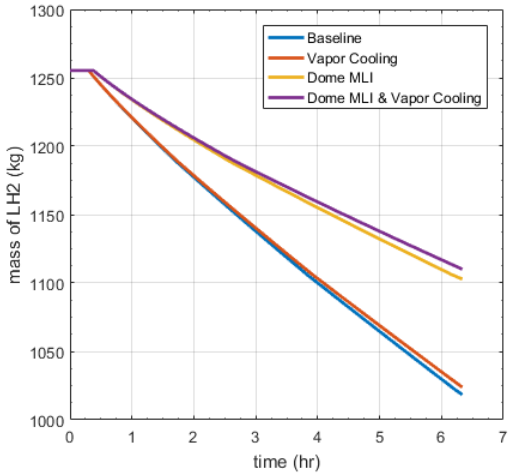


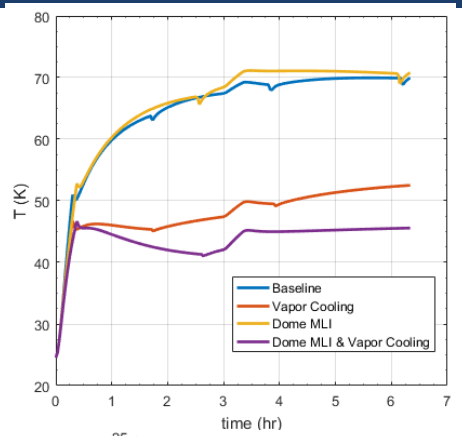
With vapor cooling on, the FWD skirt is cooler. (SOFI temperature is not plotted in each figure)

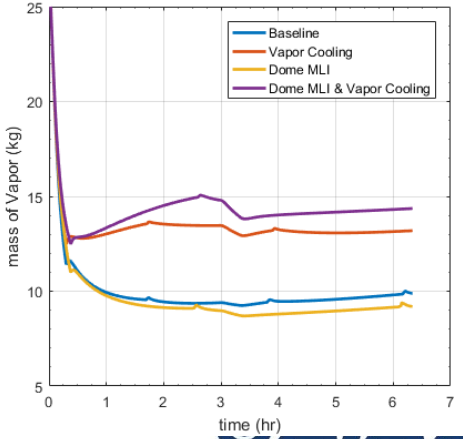
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SHIIVER Thermal Model Results (50% fill level)



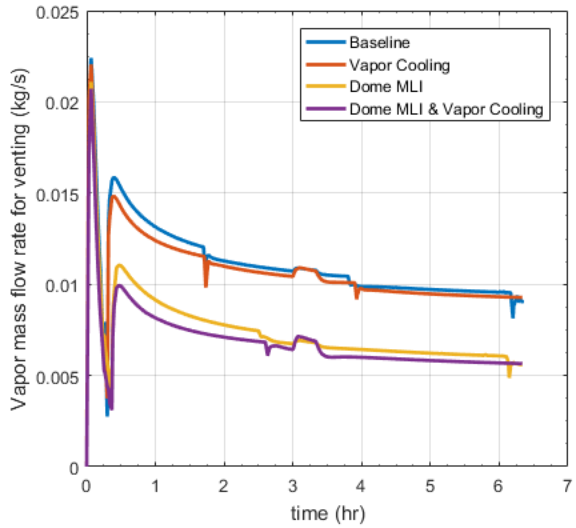


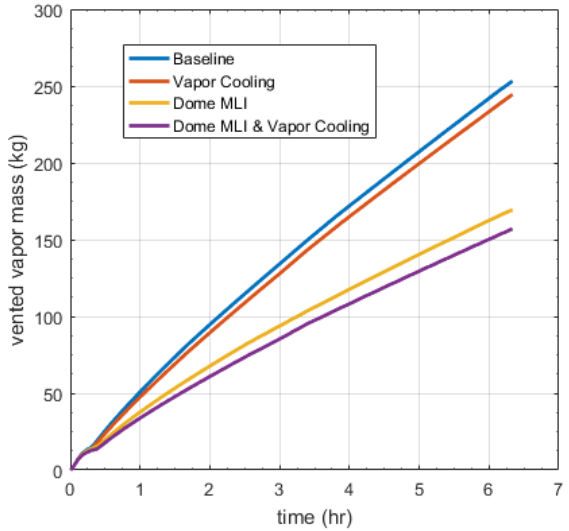




- Vapor cooling results in lower ullage temperature but much more vapor mass, while heat going into LH2 is similar to the baseline, showing that vapor cooling effect is on vapor region.
- MLI on domes results in slightly warmer ullage and slightly less vapor mass as the baseline, while heat into LH2 is significantly reduced.

SHIIVER Thermal Model Results (50% fill level)



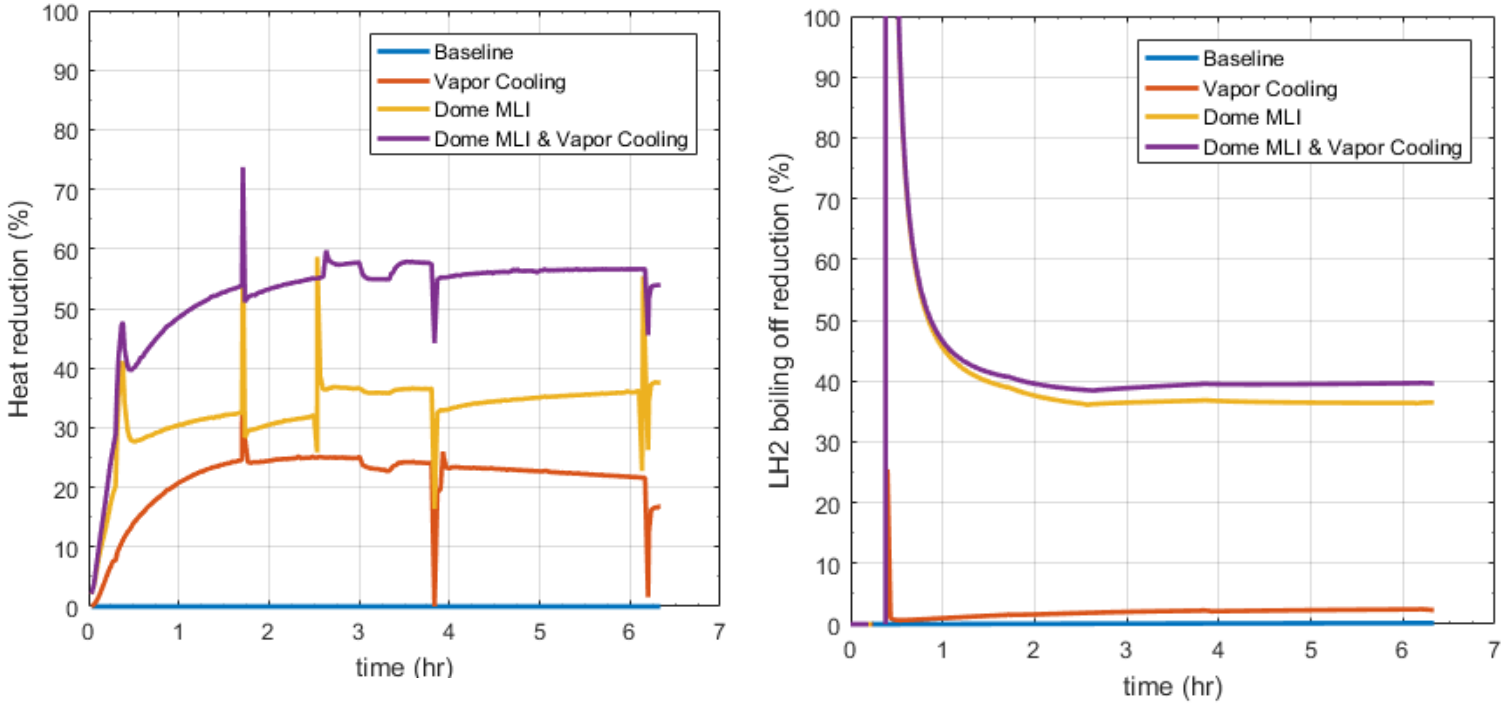


- Vapor cooling results in similar vapor venting flow rate and the total vapor vented.
- MLI on domes results in much less vapor venting flow rate and total vapor vented.

Summary of the Heat Reduction and Boiling-off Reduction at t = 6.33 hr (50% Fill level)

		baseline	Vapor cooling On FWD skirt	MLI on Domes	Vapor cooling & Dome MLI
	Q to LH2 (w)	3903.6	4092.3	2376.9	2498.8
Heaters ON	Q to vapor (w)	4857.3	3202.5	3091.1	1533.1
	Q to propellant (w)	8760.9	7294.9	5468.0	4031.9
	T vapor (K)	69.9	52.5	70.8	45.6
	Heat reduction (w)		1466	3232.9	4729
	Heat reduction (%)		**16.7%**	**36.9%**	**54%**
	Venting mass flow ate (kg/s)	0.01	0.01	0.006	0.006
1250 (kg)	Vapor mass (kg)	1.650	1.656	1.747	1.7557
50% fill level	LH2 mass (kg)	1018.4	1023.7	1102.8	1110.1
	Boiling off (kg)	231.5	226.3	147.2	139.9
	Boiling off reduction (%)		**2.2%**	**36.4%**	**39.6%**

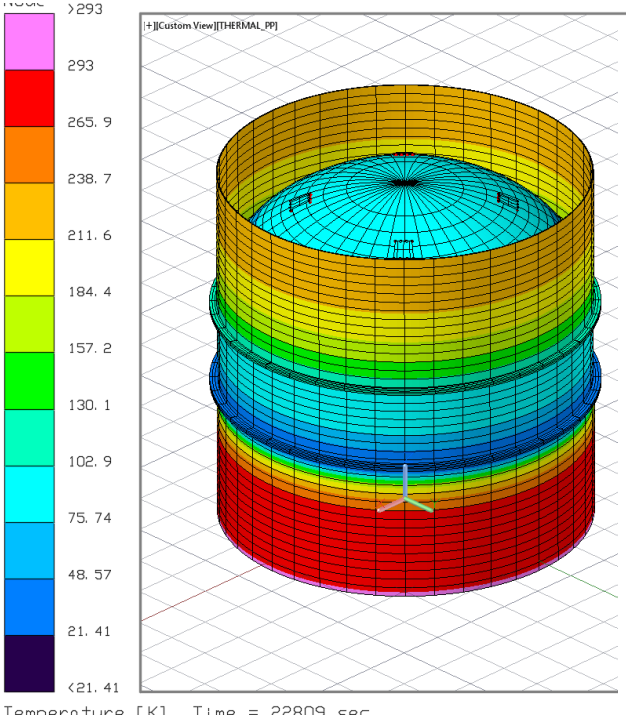
SHIIVER Thermal Model Results (50% fill level)



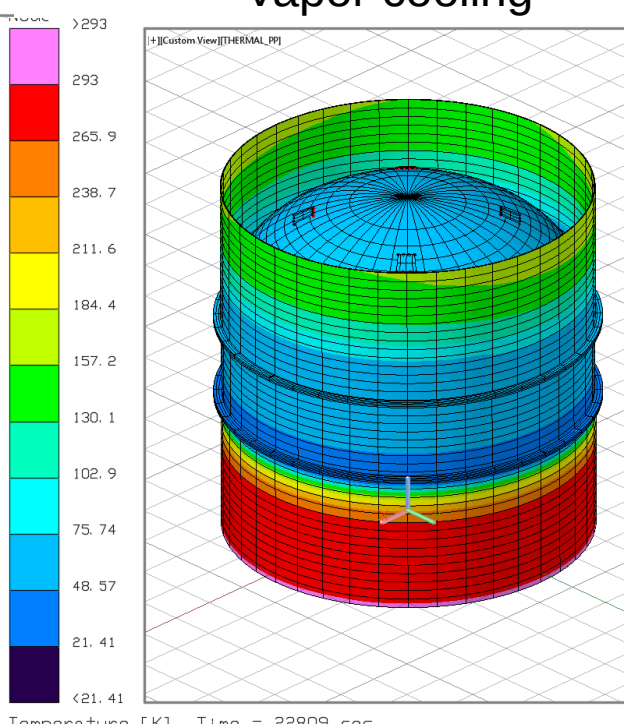
Heat reduction and boiling-off reduction change in time (50% Fill Level).

Temperature Contour of the SHIIVER at t = 6.33 hr (50% Fill Level)

baseline



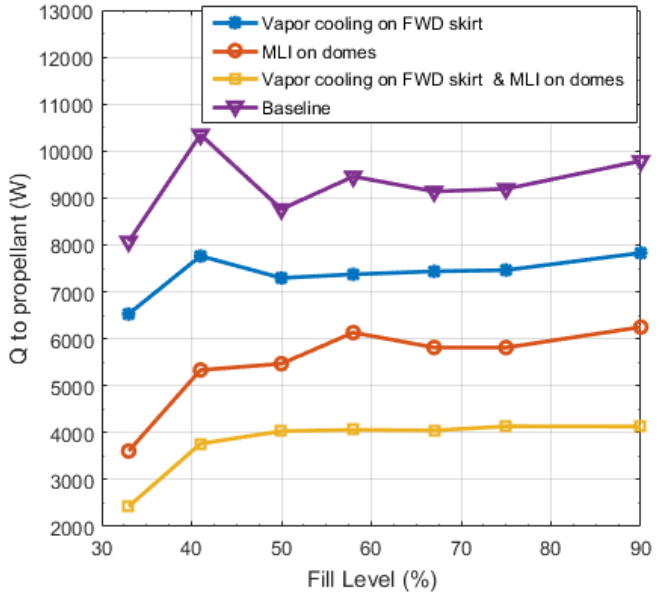
Vapor cooling

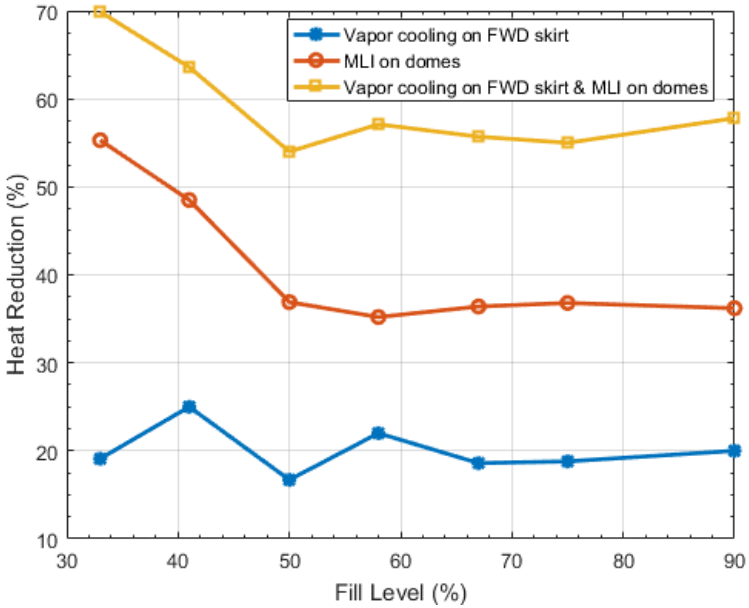


Summary of the heat reduction to the propellant and boiling off reduction at different fill levels at t = 6.33 hr

	Fill level	90%	75%	67%	58%	50%	41%	33%
Heat reduction	Vapor cooling On FWD skirt	20%	18.8%	18.6%	22%	16.7%	25%	19.1%
	MLI on Domes	36.2%	36.8%	36.4%	35.2%	36.9%	48.5%	55.3%
	Vapor cooling & Dome MLI	57.8%	55%	55.7%	57.1%	54%	63.6%	69.9%
Boiling-off reduction	Vapor cooling On FWD skirt	33.6%	21.7%	9.7%	2.3%	2.2%	5.6%	6.3%
	MLI on Domes	19.1%	16.8%	24.1%	32.8%	36.4%	45.3%	44.3%
	Vapor cooling & Dome MLI	53.3%	43.8%	35.0%	35.9%	39.6%	48.3	49.9%

Summary of the heat reduction to the propellant at different fill levels at t = 6.33 hr

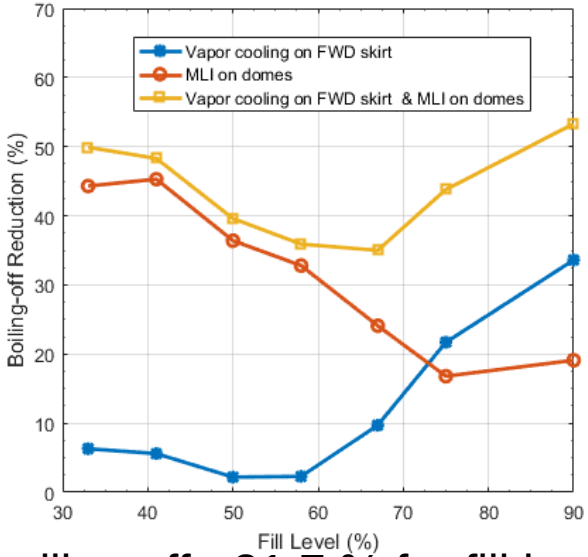




- For the fill level from 90% to 33%:
  - Vapor cooling can reduce heat into propellant by 16.7% - 25%
  - MLI on dome can reduce heat into propellant by 35% - 55%
  - Both of them can reduce heat into propellant by **54% - 70%**

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Summary of the boiling off reduction to the propellant at different fill levels at t = 6.33 hr



- For the fill level from 90% to 33%:
  - Vapor cooling can reduce LH2 boiling off >21.7 % for fill level 75% above, for fill levels below 67%, the vapor cooling goes to vapor region instead of liquid region.
  - MLI on dome can reduce LH2 boiling off by 17% - 45%.
  - Both of them can reduce LH2 boiling off by 35% - 52%.

Summary (I)

- Thermal model results show that vapor cooling on FWD skirt reduces the heats going from FWD skirt to the barrel section, thus reduces the heat to the fluids that is in contact with barrel section. The fluids can be vapor or liquid depending on the fill level. The heat reduction can be 20% for the fill level 30% - 90%.
  - For fill level of 90%, the boiling off reduction is 32% at t = 6.33 hr.
  - For fill level < 67%, the boiling off reduction is < 10% at t = 6.33 hr since most heat reduction going into the vapor region.
- The MLI on the domes reduces the heat significantly into the tank as expected. The heat reduction can be 37% at t = 6.33 hr.
  - For fill level > 75%, the boiling off reduction is 20 % at t = 6.33 hr.
  - For fill level < 75%, the boiling off reduction is 18% - 45% at t = 6.33 hr.
- With both MLI dome and vapor cooling on the FWD skirt, the heat reduction is 54% - 70% and boiling off reduction is 35% - 52% at t = 6.33 hr.

Summary (II)

- Uncertainties on the initial conditions: the model adjusts to reach a reasonable solution within the first 10-15 mins.
- Uncertainties on the contact resistance:
  - Between FWD skirt to FWD flange
  - Between AFT skirt and AFT flange
  - AFT and FWD flanges to the barrel
  - Vapor cooling tube to the FWD skirt
- Stratification effect for the low fill level case might be significant.
  - Use GRC in-house stratification model in Sinda (in working progress)
  - Use the tank with pipe core in TD done by KSC and CRtech tech support (in working progress)
  - GT-Suite: tech support from Gamma-technologies
- Validation with the test data is being performed with the SHIIVER test data.

Acknowledgements

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