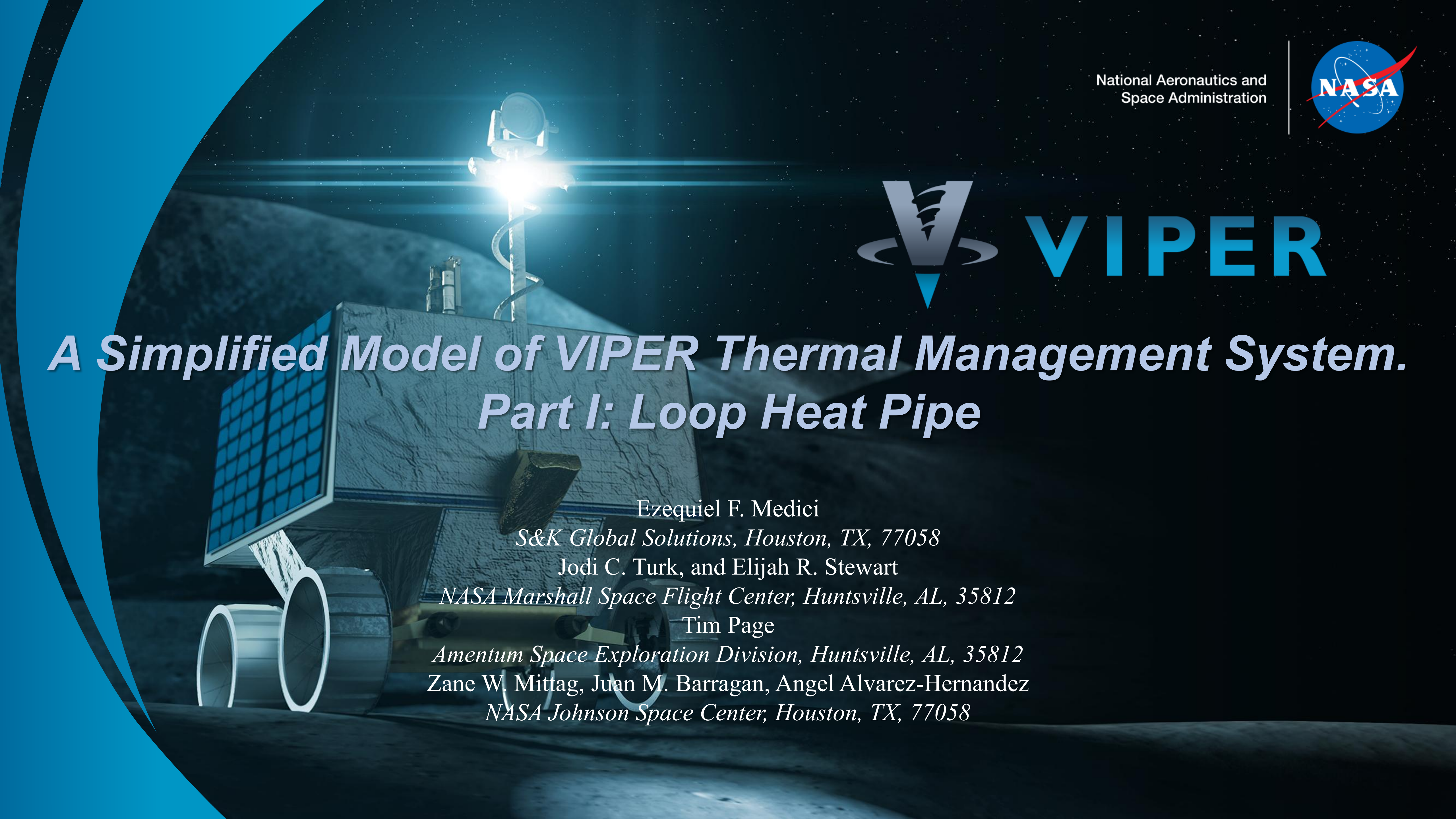

A Simplified Model of VIPER Thermal Management System. Part I: Loop Heat Pipe

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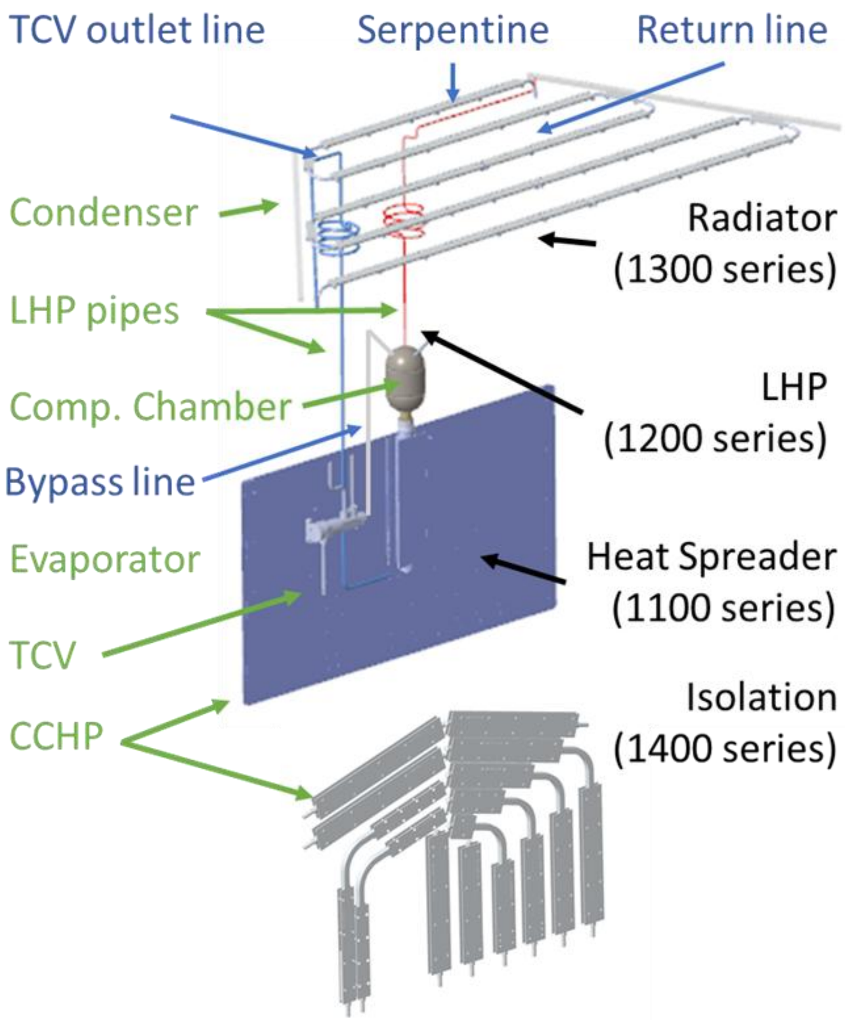
Background

- VIPER Mission: Prospecting the south pole of the Moon, especially for water ice.
- Payloads: TRIDENT, NSS, NIRVSS, and MSOLO.
- General Mission Requirements and Goals:
  - 100 days mission.
  - 50 hours of hibernation.
  - 7.2 hour of lunar permanent shadow region.
  - 70 hours of payload instruments bakeout.
- Thermal Management System:
  - 4 Heat spreaders (with embedded ammonia CCHPs), warmbox, to collect the electronic waste heat.
  - 4 Loop heat pipes, filled with propylene, to dissipate electronics waste heat into the sky.
  - 7 Ammonia heat pipes around the warmbox, balancing the thermal load and providing LHP redundancy.
  - 3 Ammonia heat pipes supporting the cooling of the MSOLO and NIRVSS payloads.
  - 4 Radiators.
  - MLI and isolators.

LHP Configuration

- Components:
    - 1 Heat spreader with embedded ammonia CCHPs. 42.9g of ammonia.
    - No mass simulators.
    - 1 Evaporator and compensation chamber. assembly. 209.4g of propylene.
    - 1 Aluminum phase sheet radiator.
    - 1 TCV, temperature set points [0°C to 20°C].
    - Liquid and vapor lines.

- Baseline configuration :
    - Vertical heat spreader and LHP.



Model Objectives

Model Characteristics:

- Computational light.
- Capable of doing transient simulations.
- Easy to add ad-hoc logic to simulate LHP shutdown, LHP startup, and fault injections.

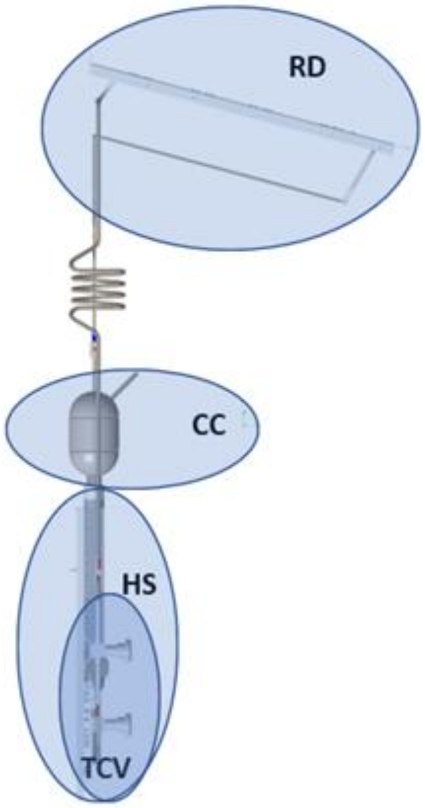
Model will be used to:

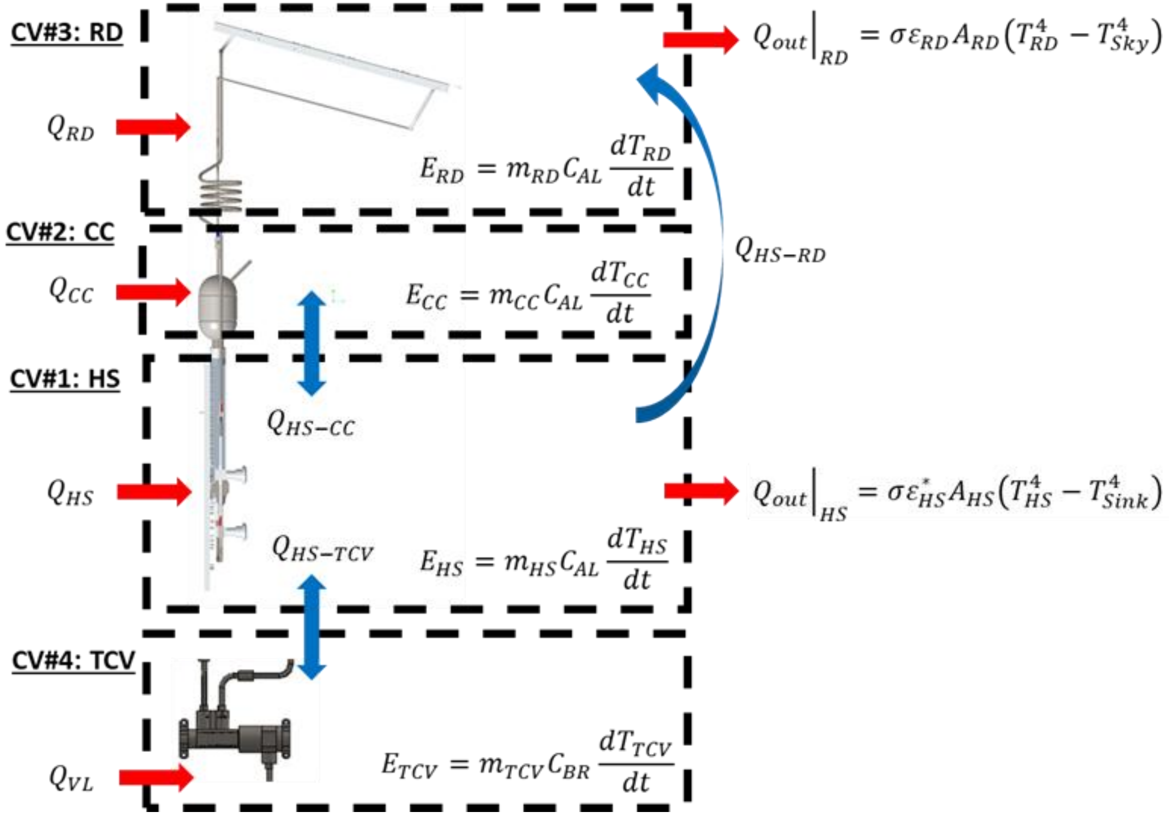
- Provide quick performance assessments.
- Perform real time simulations, especially those dedicated to console operator training.
- Serve as the building block for a larger model. “A Simplified Model of VIPER Thermal Management System. Part II: Integrated Vehicle”

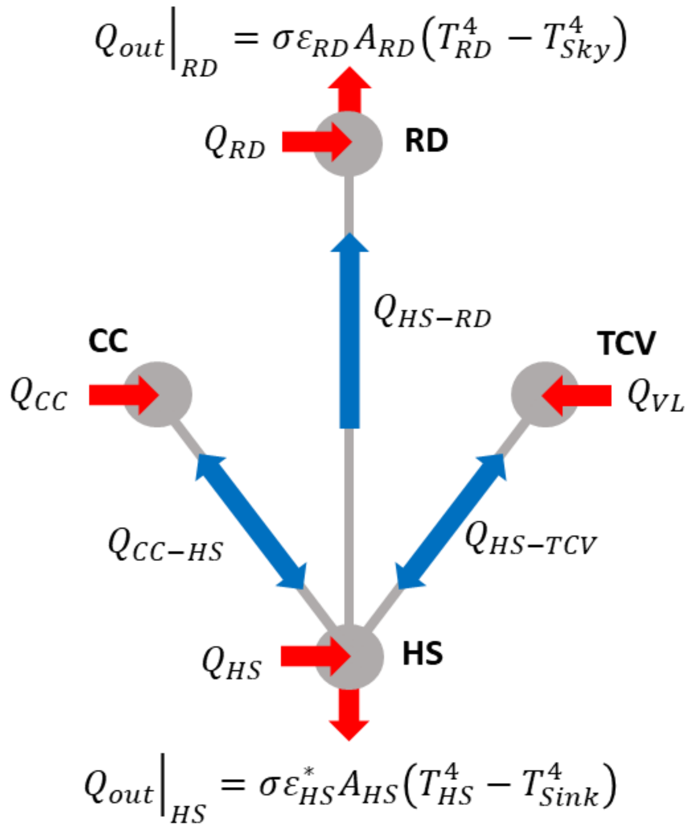
Modeling Approach:

- Develop an in-house model of a single LHP using control volume approach.
- Complex geometry of the LHP, and the components attached to it, are reduced to thermal lump capacitances.
- Model correlated using thermal vacuum (TVAC) test data.

Modeling Approach







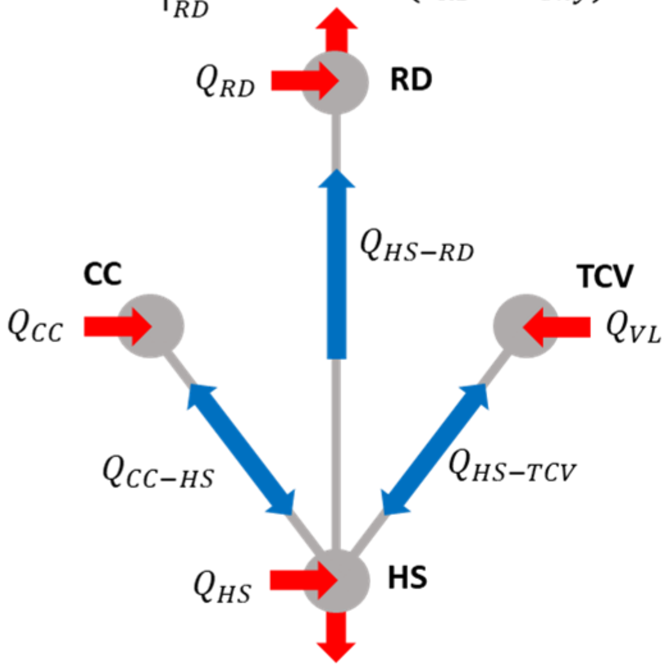
- Control Volume Approach
- Energy balance around the control volumes

- Energy Balance: $\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out}$

Energy Balance

- Energy Balance: $\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out}$

$$Q_{out}\Big|_{RD} = \sigma \varepsilon_{RD} A_{RD} \left(T_{RD}^4 - T_{Sky}^4\right)$$



$$Q_{out}\Big|_{HS} = \sigma \varepsilon_{HS}^{*} A_{HS} \left(T_{HS}^4 - T_{Sink}^4\right)$$

- Energy exchange
- Stored energy
- Qout
- Qin

$$m_{HS} C_{AL} \frac{dT_{HS}}{dt} = Q_{HS} - G_{CC}(T_{HS} - T_{CC}) - G_{TCV}(T_{HS} - T_{TCV}) - Q_{HS-RD} - \sigma \varepsilon_{HS}^{*} A_{HS} \left(T_{HS}^4 - T_{Sink}^4\right)$$

$$\frac{dT_{HS}}{dt} = \frac{Q_{HS}}{m_{HS} C_{AL}} - \frac{G_{CC}}{m_{HS} C_{AL}}(T_{HS} - T_{CC}) - \frac{G_{TCV}}{m_{HS} C_{AL}}(T_{HS} - T_{TCV}) - \frac{Q_{HS-RD}}{m_{HS} C_{AL}} - \frac{\sigma \varepsilon_{HS}^{*} A_{HS}}{m_{HS} C_{AL}}\left(T_{HS}^4 - T_{Sink}^4\right)$$

$$m_{CC} C_{AL} \frac{dT_{CC}}{dt} = Q_{CC} + G_{CC}(T_{HS} - T_{CC})$$

$$\frac{dT_{CC}}{dt} = \frac{Q_{CC}}{m_{CC} C_{AL}} + \frac{G_{CC}}{m_{CC} C_{AL}}(T_{HS} - T_{CC})$$

$$m_{RD} C_{AL} \frac{dT_{RD}}{dt} = Q_{RD} + Q_{HS-RD} - \sigma \varepsilon_{RD} A_{RD} \left(T_{RD}^4 - T_{Sky}^4\right)$$

$$\frac{dT_{RD}}{dt} = \frac{Q_{RD}}{m_{RD} C_{AL}} + \frac{Q_{HS-RD}}{m_{RD} C_{AL}} - \frac{\sigma \varepsilon_{RD} A_{RD}}{m_{RD} C_{AL}}\left(T_{RD}^4 - T_{Sky}^4\right)$$

$$m_{TCV} C_{BR} \frac{dT_{TCV}}{dt} = Q_{VL} + G_{TCV}(T_{HS} - T_{TCV})$$

$$\frac{dT_{TCV}}{dt} = \frac{Q_{VL}}{m_{TCV} C_{BR}} + \frac{G_{TCV}}{m_{TCV} C_{BR}}(T_{HS} - T_{TCV})$$

- 4 Equations with 4 unknown: T_{HS}, T_{CC}, T_{TCV}, and T_{RD}

LHP Model

LHP forward flow:

- Evaporator – Vapor Line – Radiator – Liquid Line – Evaporator

LHP reverse flow:

- Evaporator – Liquid Line – Radiator – Vapor Line – Evaporator

Forward Flow

$$Q_{HS-RD}\Big|_{forward} = \varphi_{TCV}\beta_T\left[\sigma\varepsilon_{RD}A_{RD}\left(T_{HS}^4 - T_{Sky}^4\right) - Q_{RD}\right]$$

Maximum dissipated heat

$$\dot{m}_{LHP}\Big|_F = \frac{Q_{HS-RD}|_F}{h_{fg}}$$

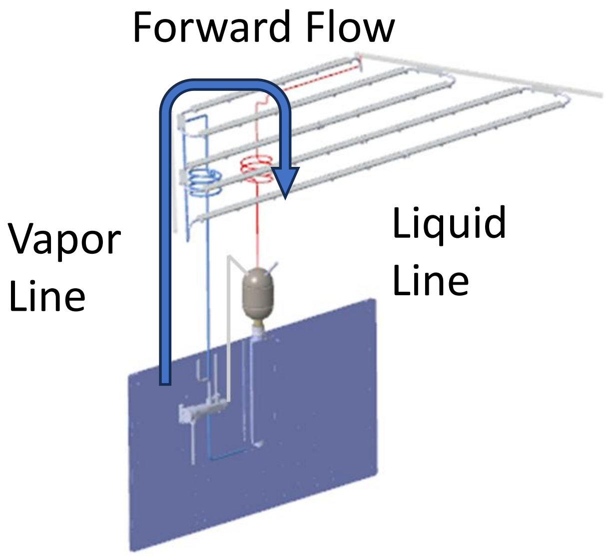
Reverse Flow

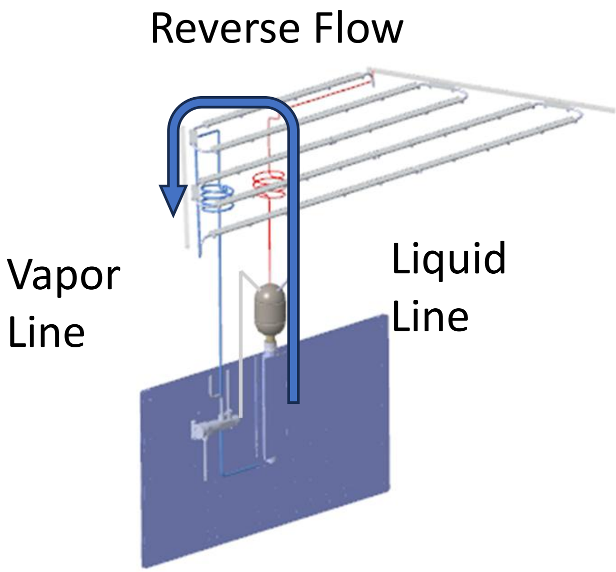
$$\Delta P = g(\rho_{HS} - \rho_{RD})H$$

Buoyancy

$$\dot{m}_{LHP}\Big|_R = \rho_{HS}A_p\frac{k_w\Delta P}{\mu L_w}$$

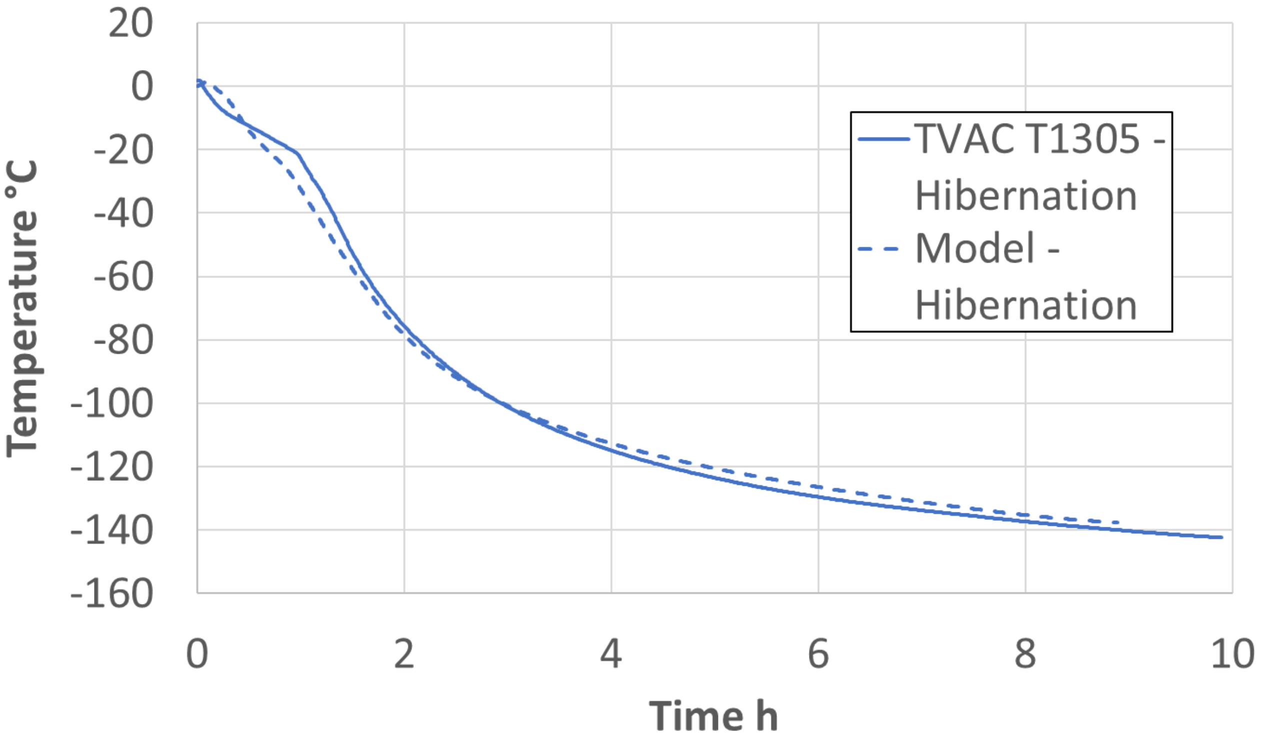
$$Q_{HS-RD}\Big|_R = \dot{m}_{LHP}\Big|_R c_P(T_{HS} - T_{RD})$$

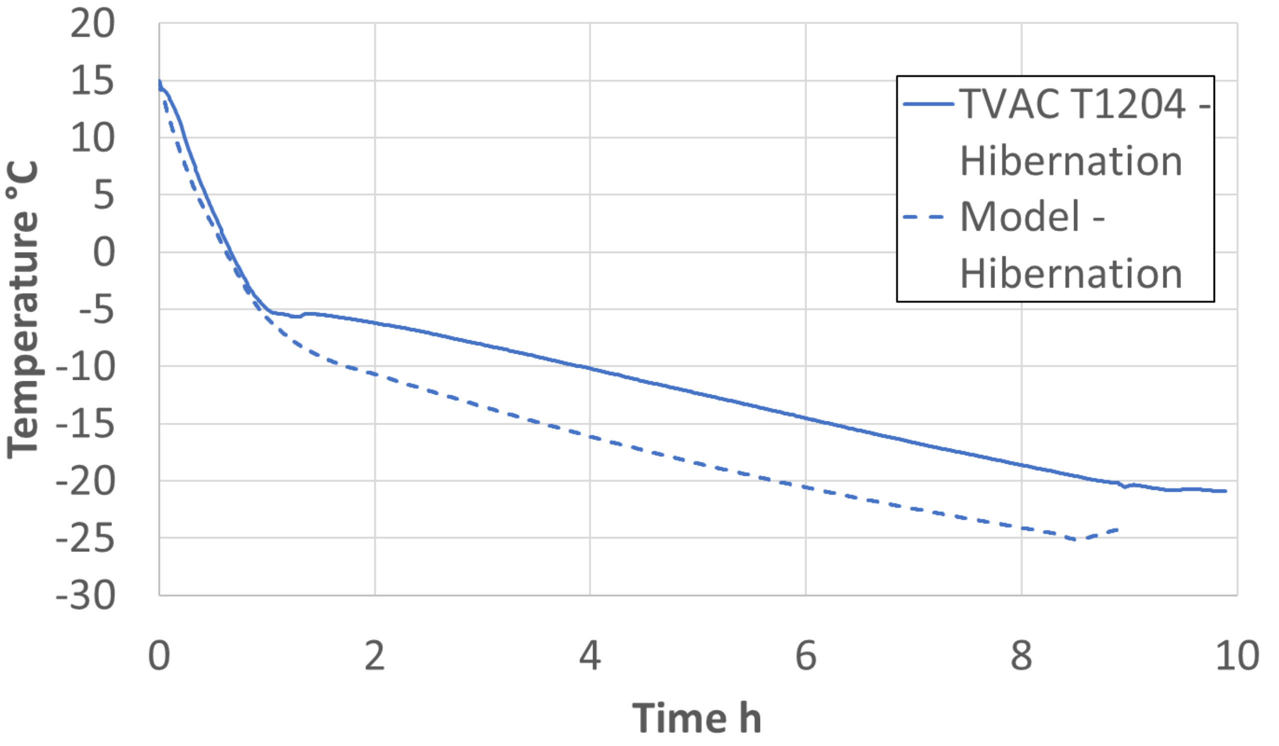




Model Correlation: Step #1, Hibernation

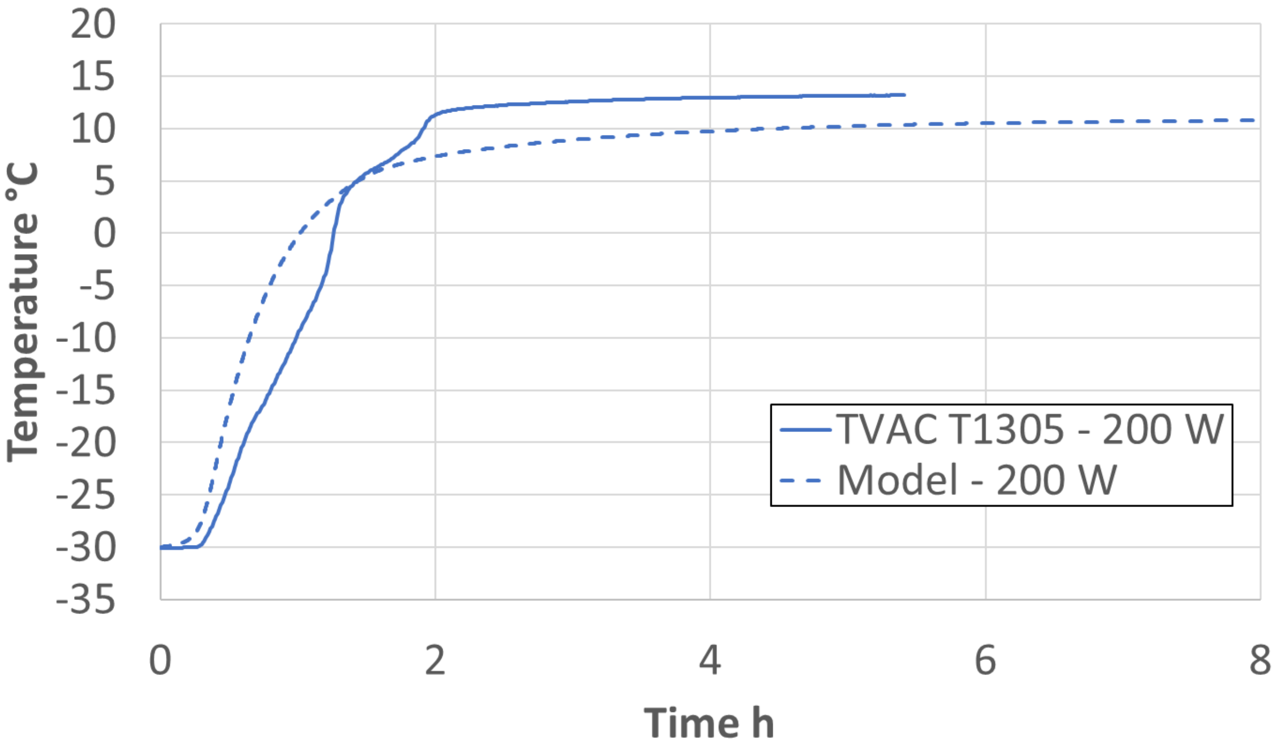
- Model correlation using the data from TVAC test campaign.
  - Description of the test: “Simulated Lunar Gravity Testing of VIPER Loop Heat Pipe”
- Characterization of the heat leaks during hibernation.
  - TCV fully closed.
  - Adjusting effective emissivities for 10.5 W heat dissipation. The resulting ε_{HS}^{*}, ε_{RD} were 0.04 and 0.9.

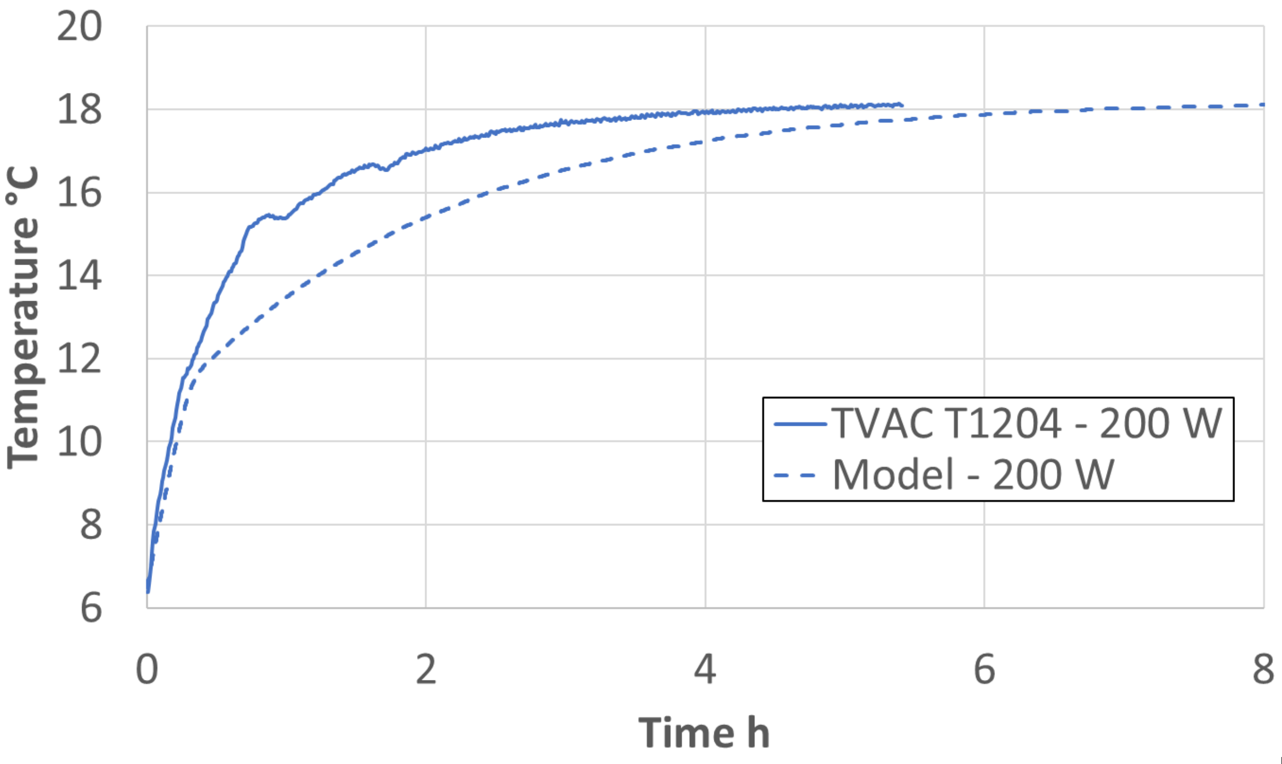




Model Correlation: Step #2, Hot Thermal Balance

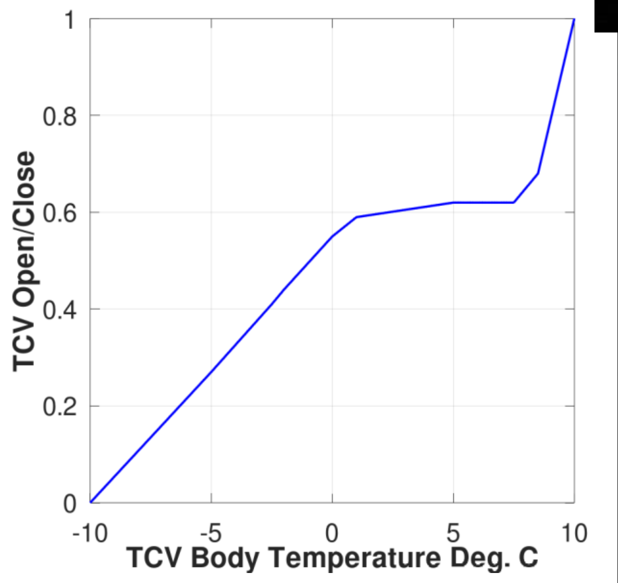
- Characterization of the transport limitation coefficient β_T.
  - TCV fully open.
  - Adjusting effective the transport limitation coefficient for 200 W heat dissipation. The resulting β_T was 0.9.

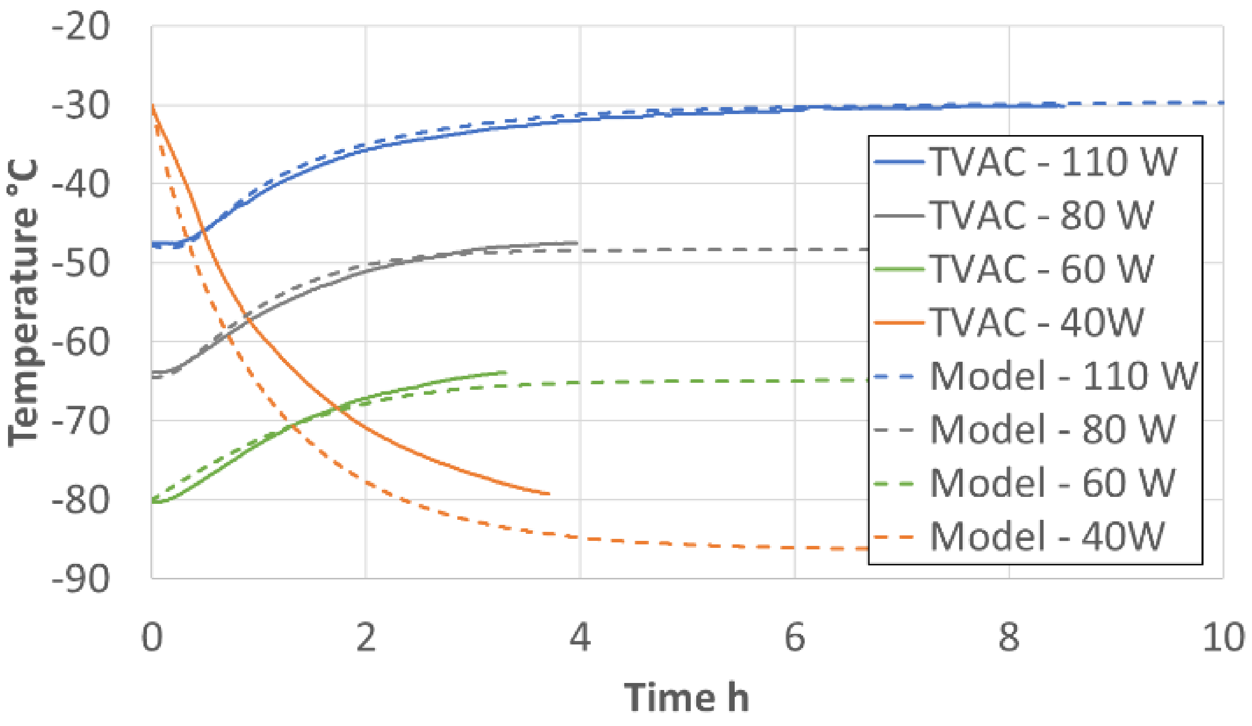


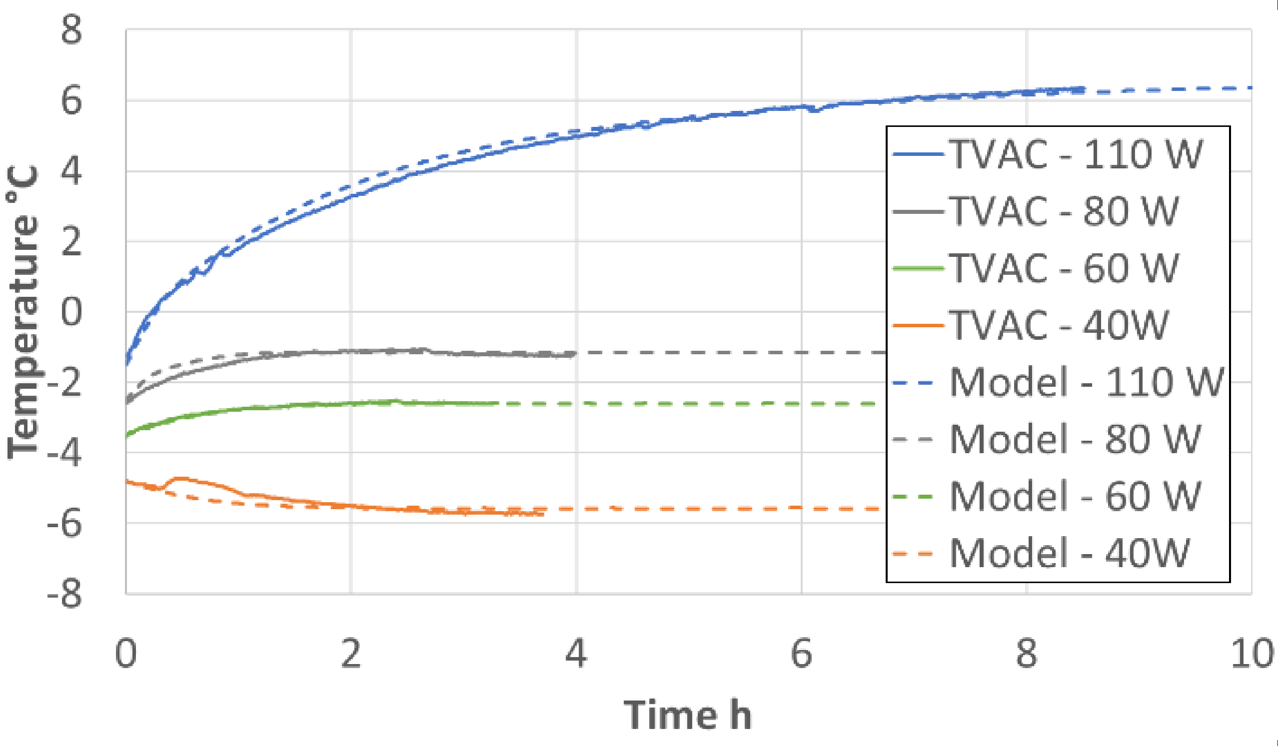


Model Correlation: Step #3, Ops.

- Characterization of the TCV opening/closing function φ_{TCV}.
  - TCV partially open.







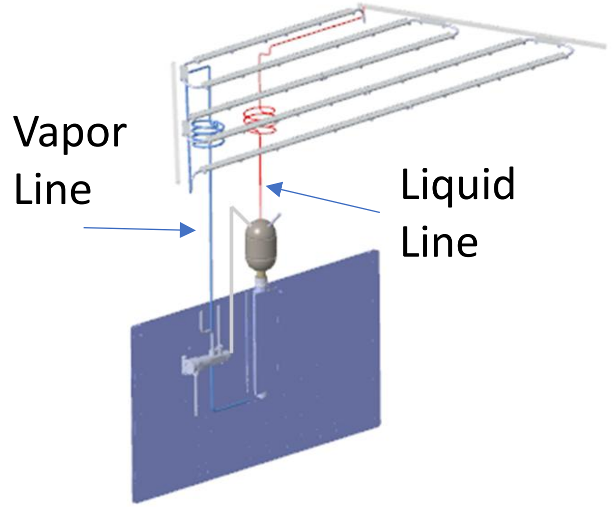
Model Correlation: Steady State Error Summary.

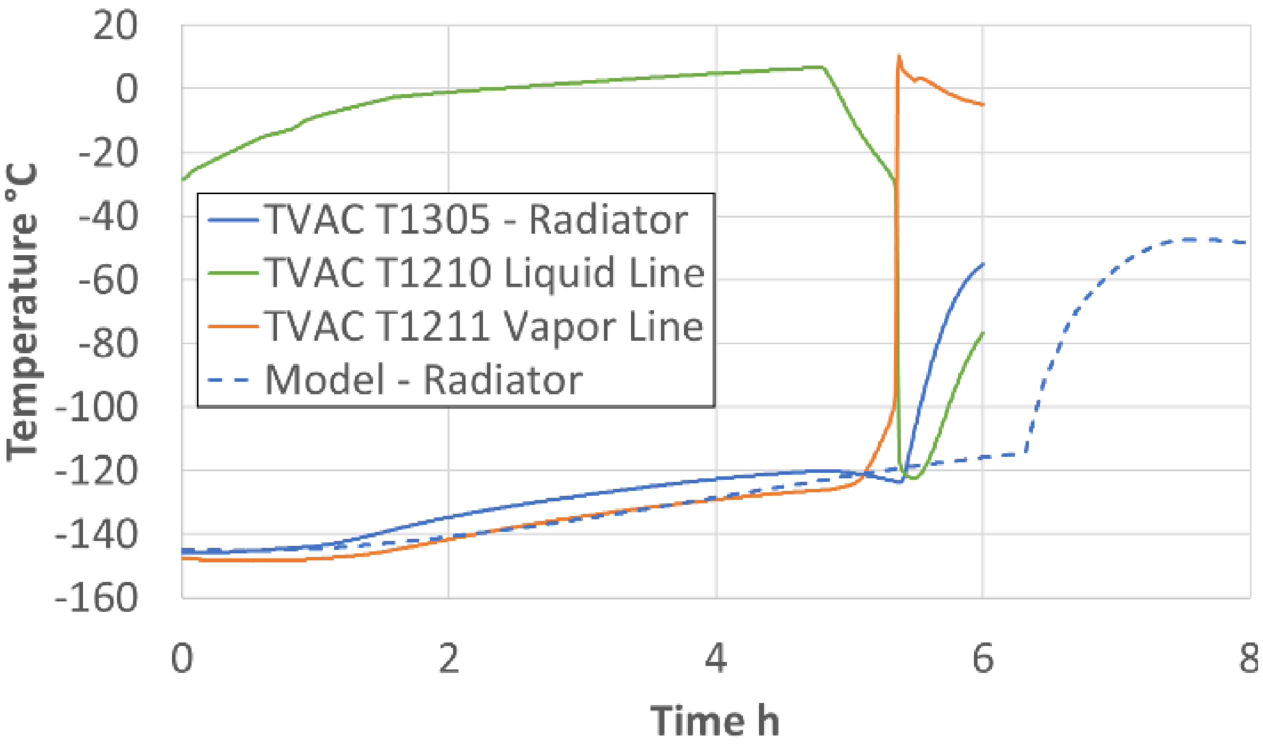
- Model Correlation completed in three steps.
- Error calculations at the four control volumes for each test configuration.

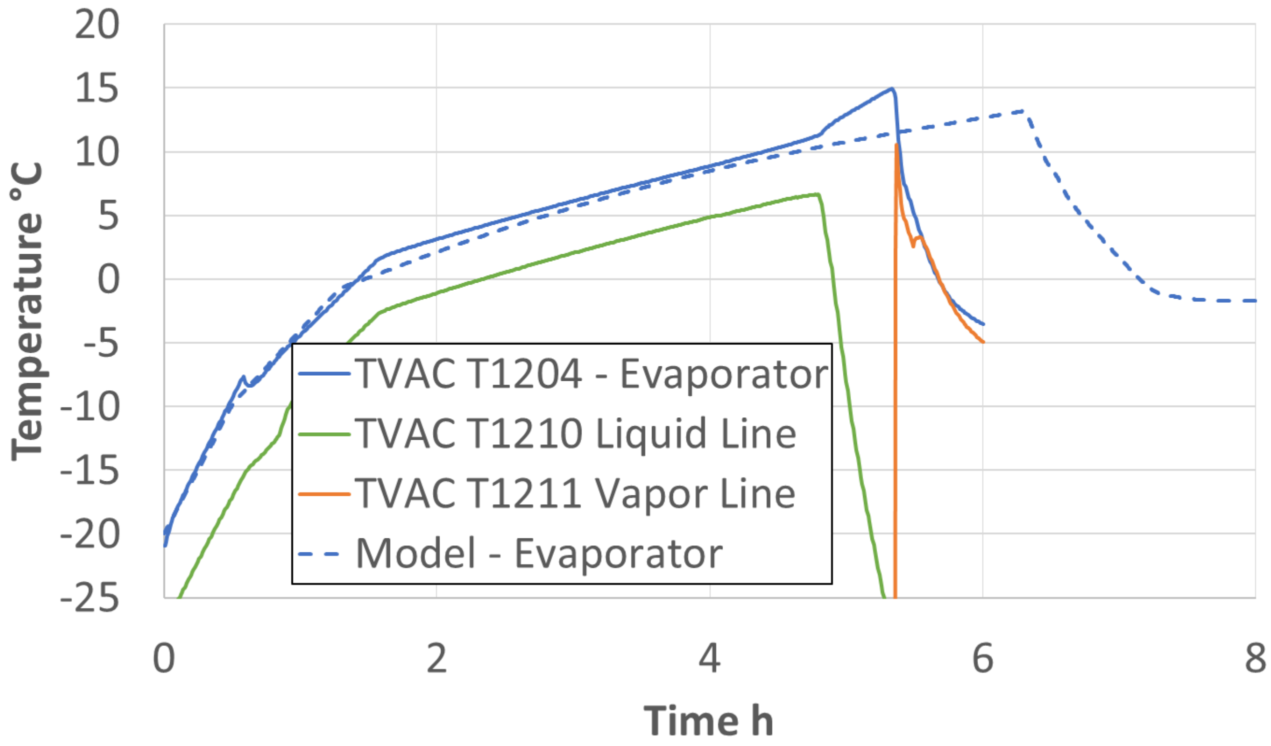
Power		TVAC-4				Simplified Model				Error				Cumulative Error
Heat Spreader	RAD.	EVAP. TC 1204	CC TC1206	RAD. TC 1305	TCV TC 1222	EVAP.	CC	RAD.	TCV	EVAP.	CC	RAD.	TCV	
145 W	110 W	30.74	28.72	27.94	30.20	31.45	31.35	27.15	31.44	-0.71	-2.63	0.79	-1.24	-3.79
110 W	106 W	17.98	17.40	16.93	17.77	19.35	19.16	15.44	19.34	-1.38	-1.77	1.49	-1.56	-3.22
110 W	64 W	14.23	13.56	1.81	14.10	9.62	9.85	1.43	9.63	4.61	3.70	0.37	4.47	13.15
80 W	64 W	4.22	3.82	-7.76	4.07	8.29	8.10	-11.70	8.28	-4.07	-4.28	3.94	-4.20	-8.62
200 W		18.09	14.84	13.18	17.14	18.18	18.32	10.87	18.18	-0.09	-3.48	2.30	-1.04	-2.31
110 W		6.35	5.41	-30.12	6.01	6.37	6.12	-29.70	6.34	-0.02	-0.71	-0.42	-0.32	-1.48
80 W		-1.23	-1.68	-47.48	-1.43	-1.16	-1.06	-48.32	-1.15	-0.07	-0.62	0.84	-0.28	-0.12
60 W		-2.59	-2.85	-63.88	-2.62	-2.60	-2.56	-64.88	-2.60	0.01	-0.29	1.00	-0.02	0.70
40 W		-5.74	-5.85	-79.28	-5.62	-5.58	-5.47	-86.36	-5.57	-0.16	-0.38	7.08	-0.04	6.49
10.6 W		-20.89	-20.75	-142.37	-20.60	-21.56	-22.18	-139.79	-22.03	0.67	1.43	-2.58	1.43	0.94

LHP Startup

- LHP remained closed until TVC reached its fully open temperature setpoint.
- LHP startup is almost instant.

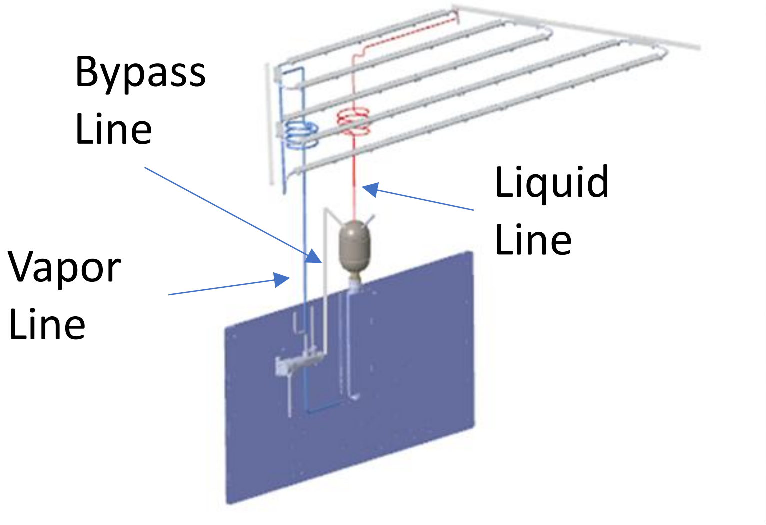


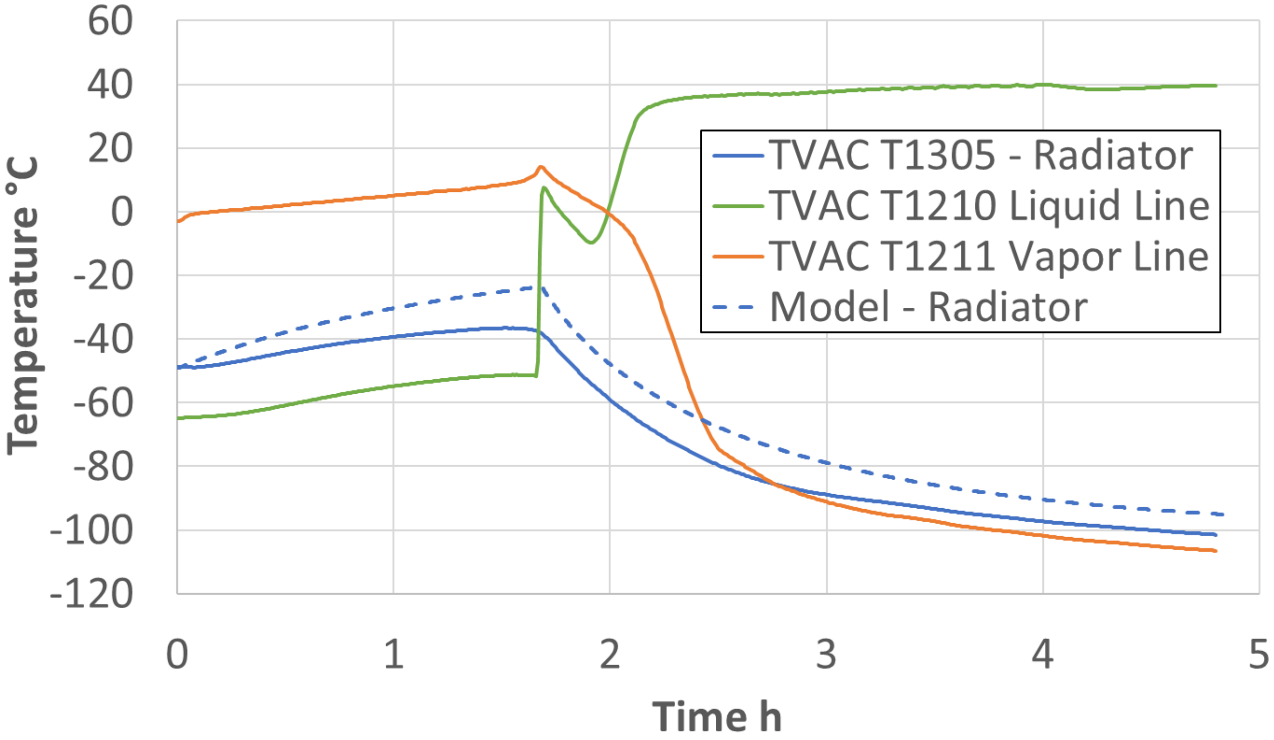


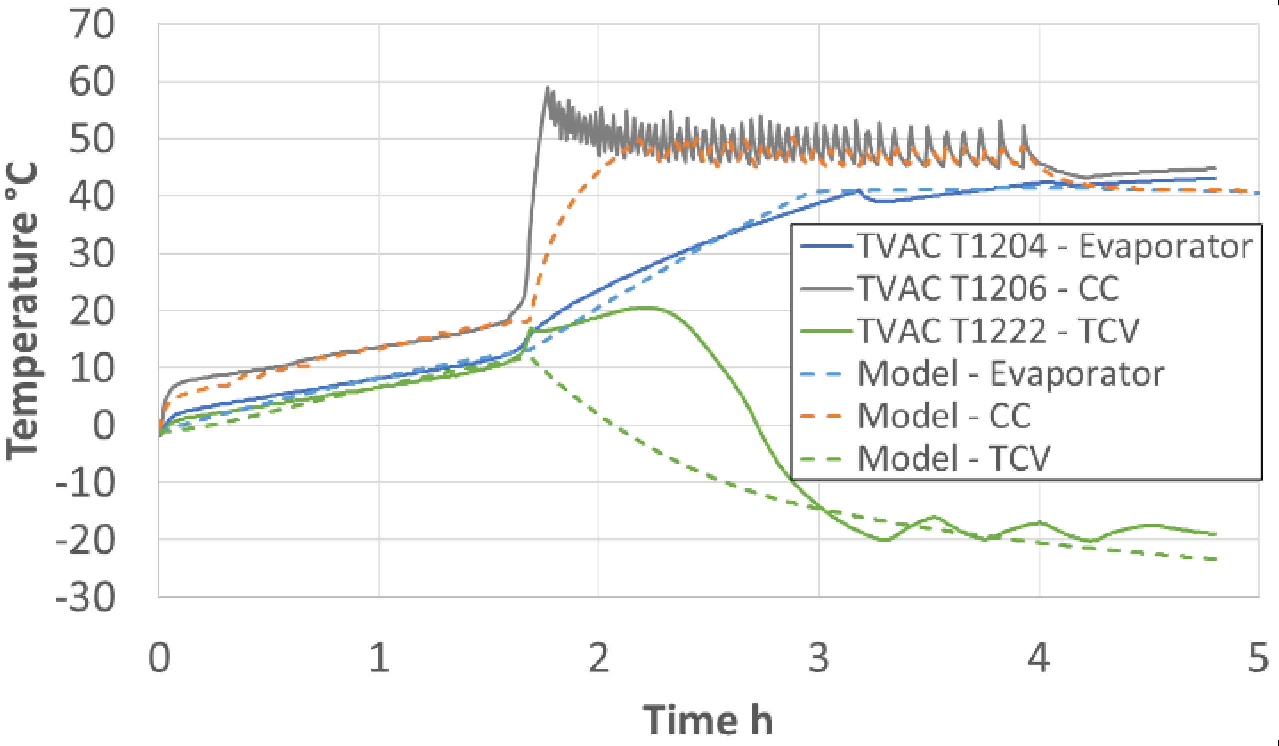


LHP Hot Shutdown

- LHP can be configured to operate in reverse flow by adding heat to the compensation chamber, 47 W.
- LHP hot shutdown happened when the TCV is fully open the bypass line is closed.







Summary

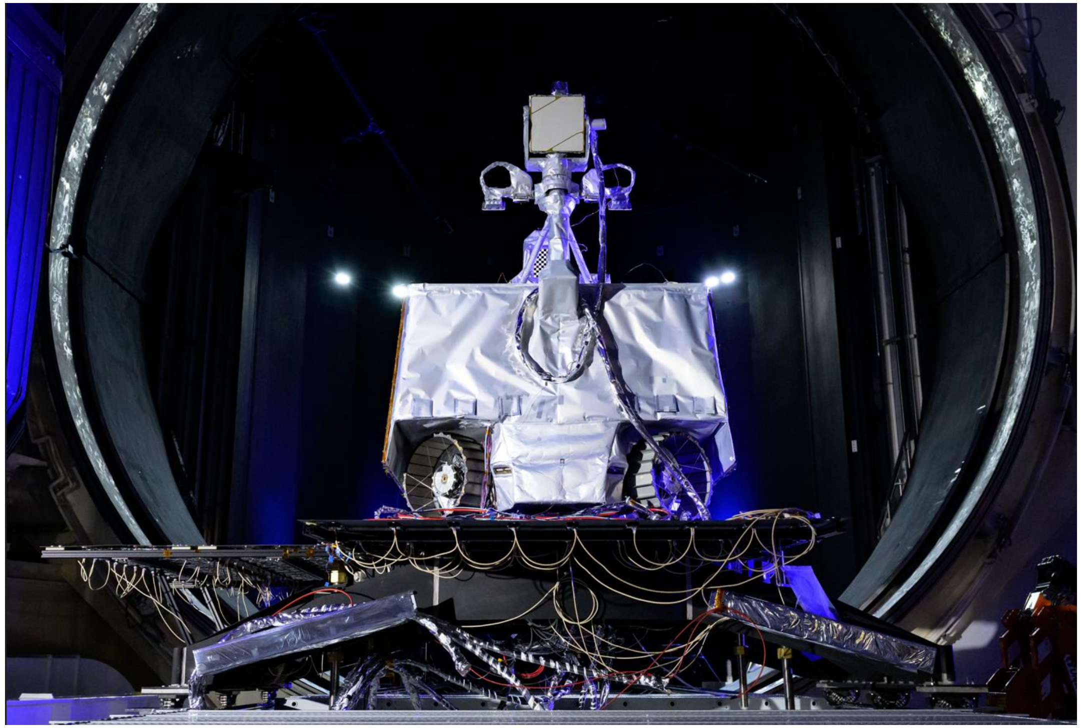
- Control volume approach allowed simplification of the geometry of the LHP. This resulted in a four-node network model which significantly reduced the computational effort.

- This simplification allows quick performance assessments, and real time simulations, especially those dedicated to console operator training.

- Simple correlation effort with only a few number of parameters.

- The model captured the bulk transient and steady temperatures LHP response under a broad range of thermal load. The model also captured the LHP shutdown and LHP startup.

- Disadvantage is the spatial (and not necessarily temporal) resolution of the model which is limited to only four lump capacitance nodes.



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Questions?