Non-Integrated Hot-Reservoir Variable Conductance Heat Pipe Tested on Peregrine Lander

Presented by: **Calin Tarau**

THERMAL & FLUIDS ANALYSIS WORKSHOP
Ames Research Center 2025

Calin Tarau, Jeff Diebold: Advanced Cooling Technologies
William Johnson: NASA Marshall Space Flight Center
Jason Carter, Eric Conaway: Astrobotic Technology

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Outline

- Presenter's Short Bio
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- HR-VCHP Pre-Flight Testing at MSFC
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- Conclusion

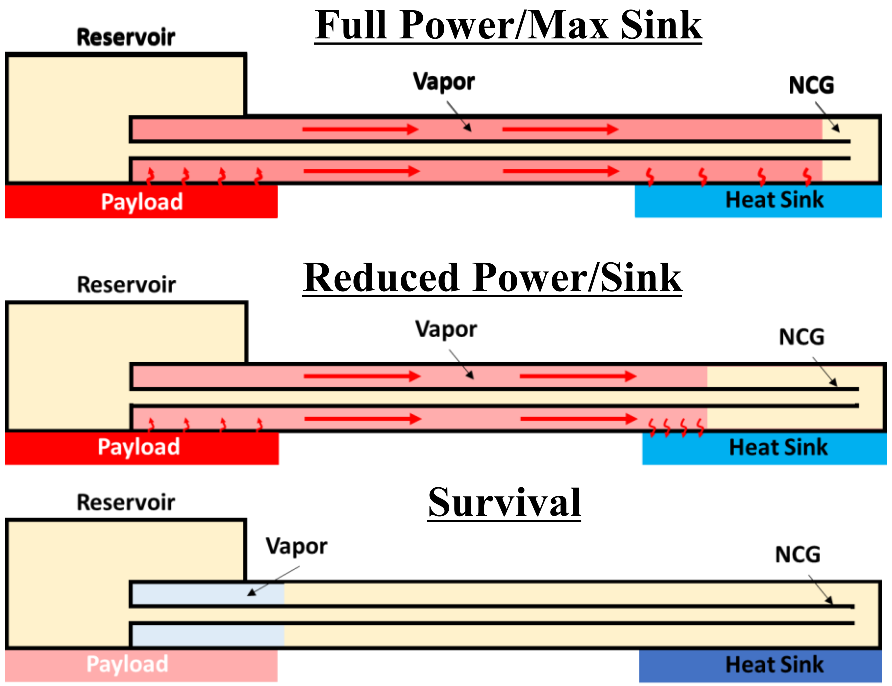
Presenter’s Short Bio

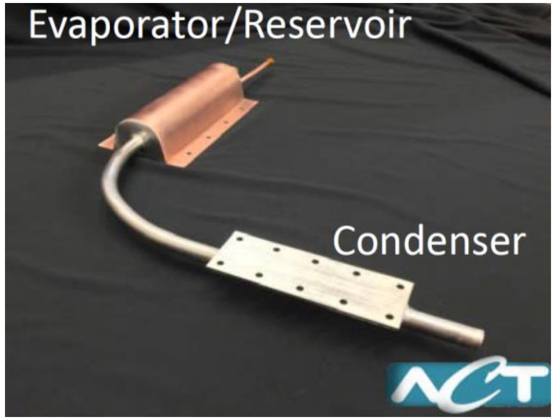
- **Presenter: Calin Tarau**
- **Education: PhD Aerospace Engineering, Polytechnic Institute of NYU**
- **Principal Engineer at Advanced Cooling Technologies**
  - **Primary Research Interests:**
    - **Passive and active two-phase thermal management and thermal control**
    - **Heat pipes, variable-conductance heat pipes, loop heat pipes, thermal switches, thermal storage**
    - **Applications: Spacecraft, landers/rovers, nuclear power, energy conversion, electric aircraft, extreme environments**

Background and Motivation

Background and Motivation

- Warm-reservoir VCHPs provide tighter thermal control and larger turndown ratio than a conventional cold-reservoir VCHP
  - Ideal for applications with highly variable thermal environments such as lunar night survival
- Two key challenges for warm-reservoir VCHPs on the lunar surface
  - Mitigating the negative effects of working fluid migrating to the NCG reservoir
  - Reliable startup and operation in both microgravity and gravity aided environments
- ACT designed a fabricated two Non-Integrated Warm-Reservoir VCHPs with Hybrid Wicks for lunar surface applications
  - EDU for NASA's VIPER Thermal Management System
  - Flight hardware for Astrobotic's Lunar Lander Peregrine I



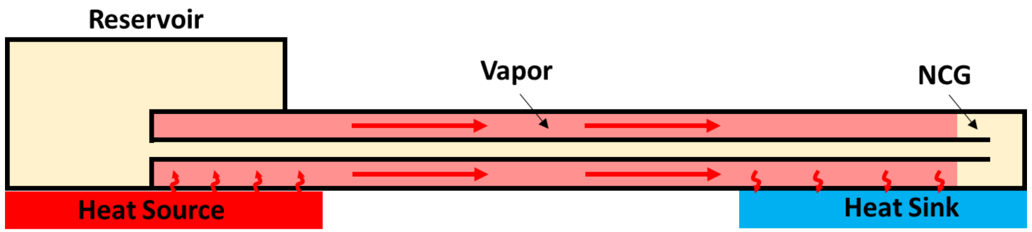


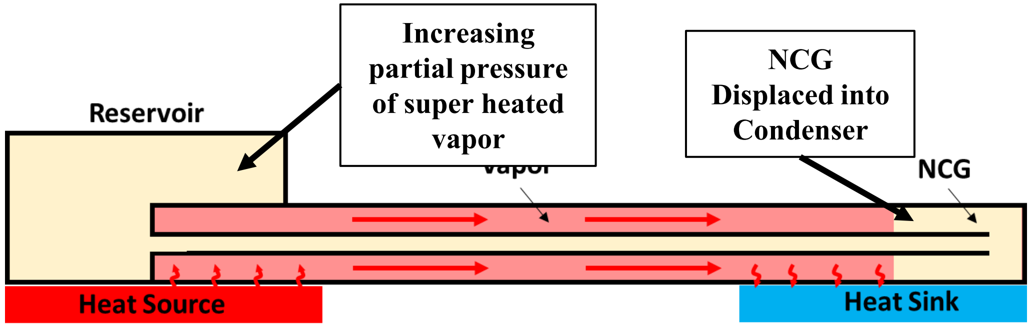
VCHP Tested onboard ISS

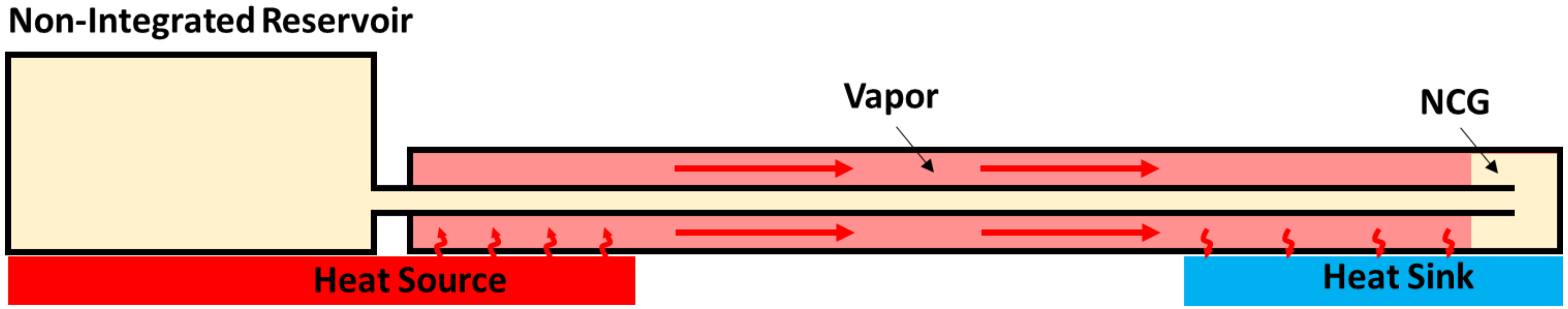
Non-Integrated Warm Reservoir

- Humidity in the reservoir displaces NCG increasing overall thermal resistance
  - Diffusion during long periods of non-operation
  - Disturbances can cause working fluid to move to the reservoir

- Independent heating of the reservoir can be used to purge the reservoir of working fluid
  - A non-integrated reservoir allows the reservoir to be heated separately from the evaporator
  - Prior to operation, independent low-power heating can be applied to the reservoir to purge working fluid and restore ideal operation



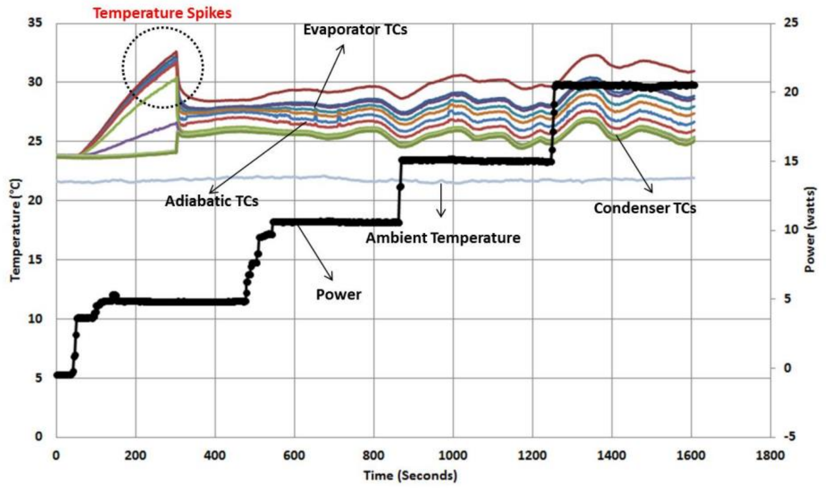


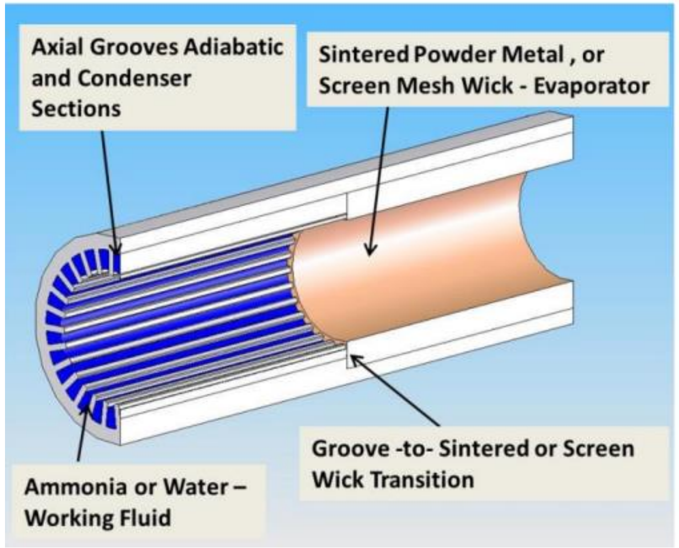


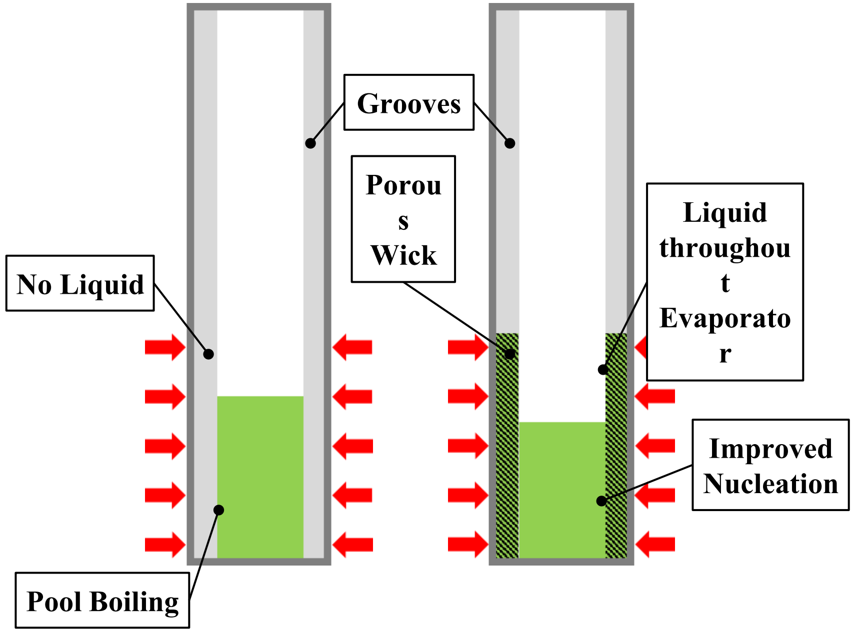
Hybrid Wick

- Grooved heat pipes are commonly used in microgravity
  - High permeability allows for large powers carried over long distances
- On the lunar (or planetary surface) gravity-aided orientation is preferred
  - Liquid pooling in the evaporator can lead to temperature spikes during startup
- A hybrid wick combines a porous wick in the evaporator with grooves in the adiabatic/condenser
  - Improved nucleation in the pool
  - Improved liquid distribution in the evaporator

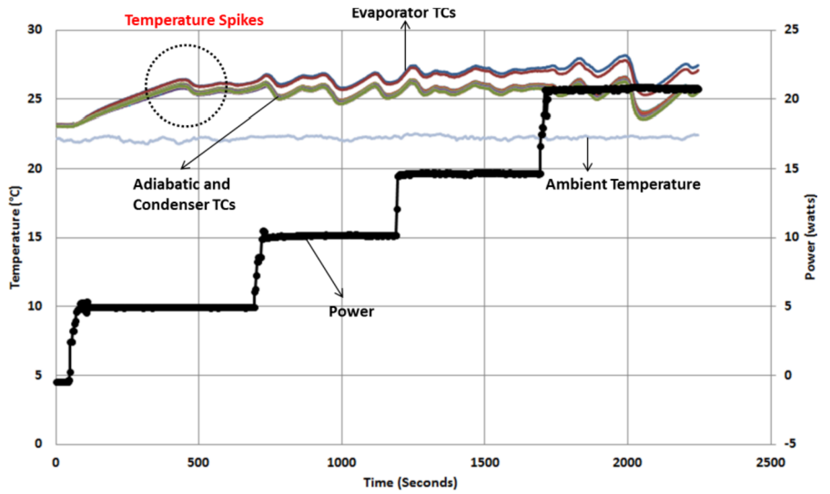
Startup of Grooved Heat Pipe







Startup of Hybrid Wick Heat Pipe



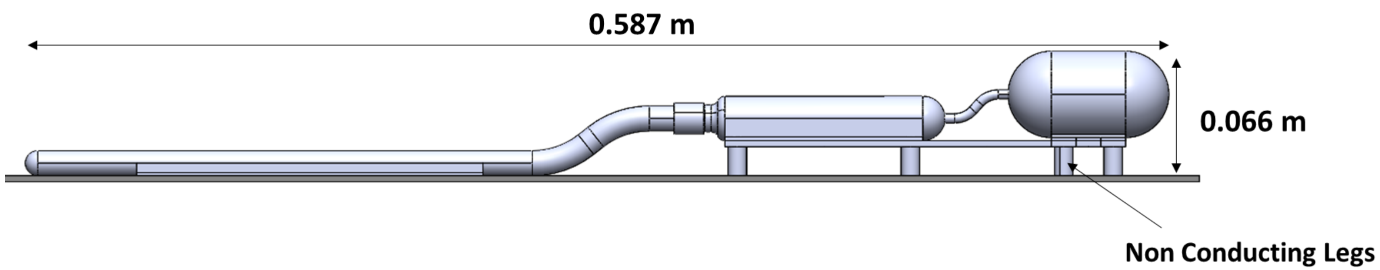
Abaneh, M. et al. "Hybrid Heat Pipes for Lunar and Martian Surface and High Heat Flux Space Applications," ICES-2016-51

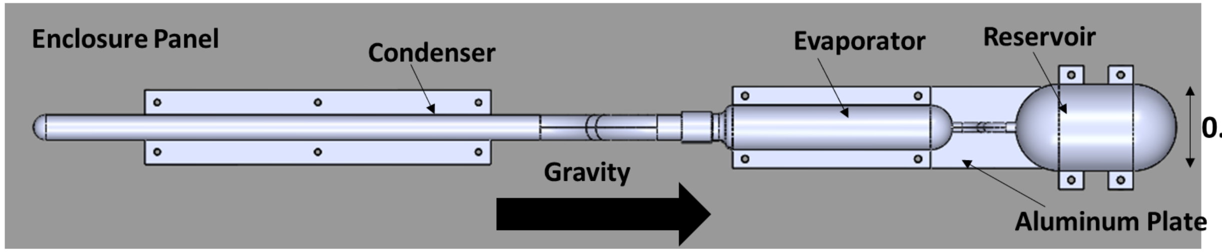
HR-VCHP Development at ACT

HR-VCHP Design

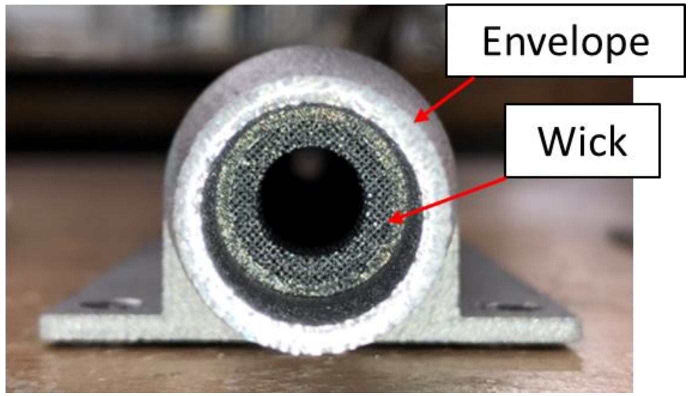
- **ACT designed/fabricated a warm-reservoir VCHP as flight-hardware Astrobotic's Lunar Lander Peregrine I**
  - **Will operate as a stand alone Technology Demonstration Unit**
  - **Will operate in microgravity and on the lunar surface**
- **Aluminum-Ammonia Non-Integrated Warm-Reservoir VCHP**
  - **3D printed evaporator**
  - **3D printed wick interfaces with grooved extrusion**

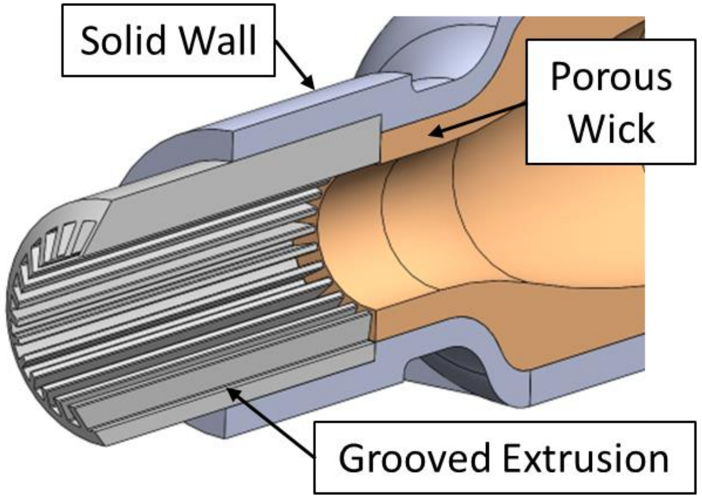
Astrobotic's Peregrine Lunar Lander in Mid-Latitude Configuration

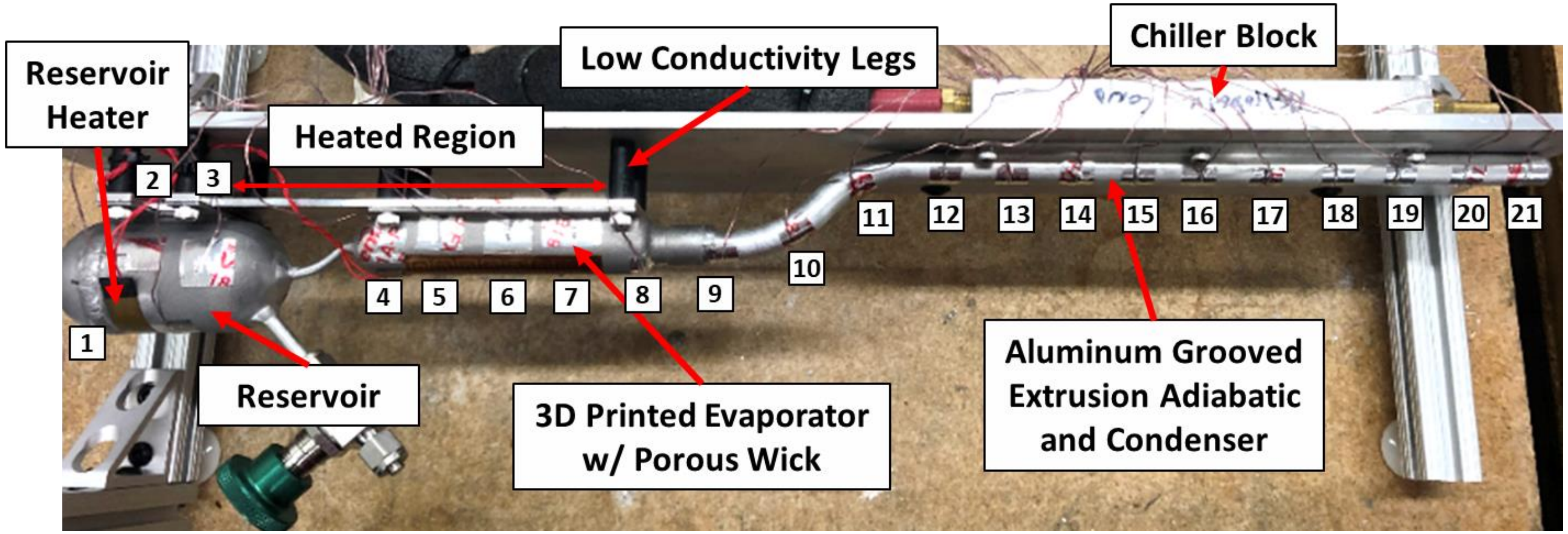




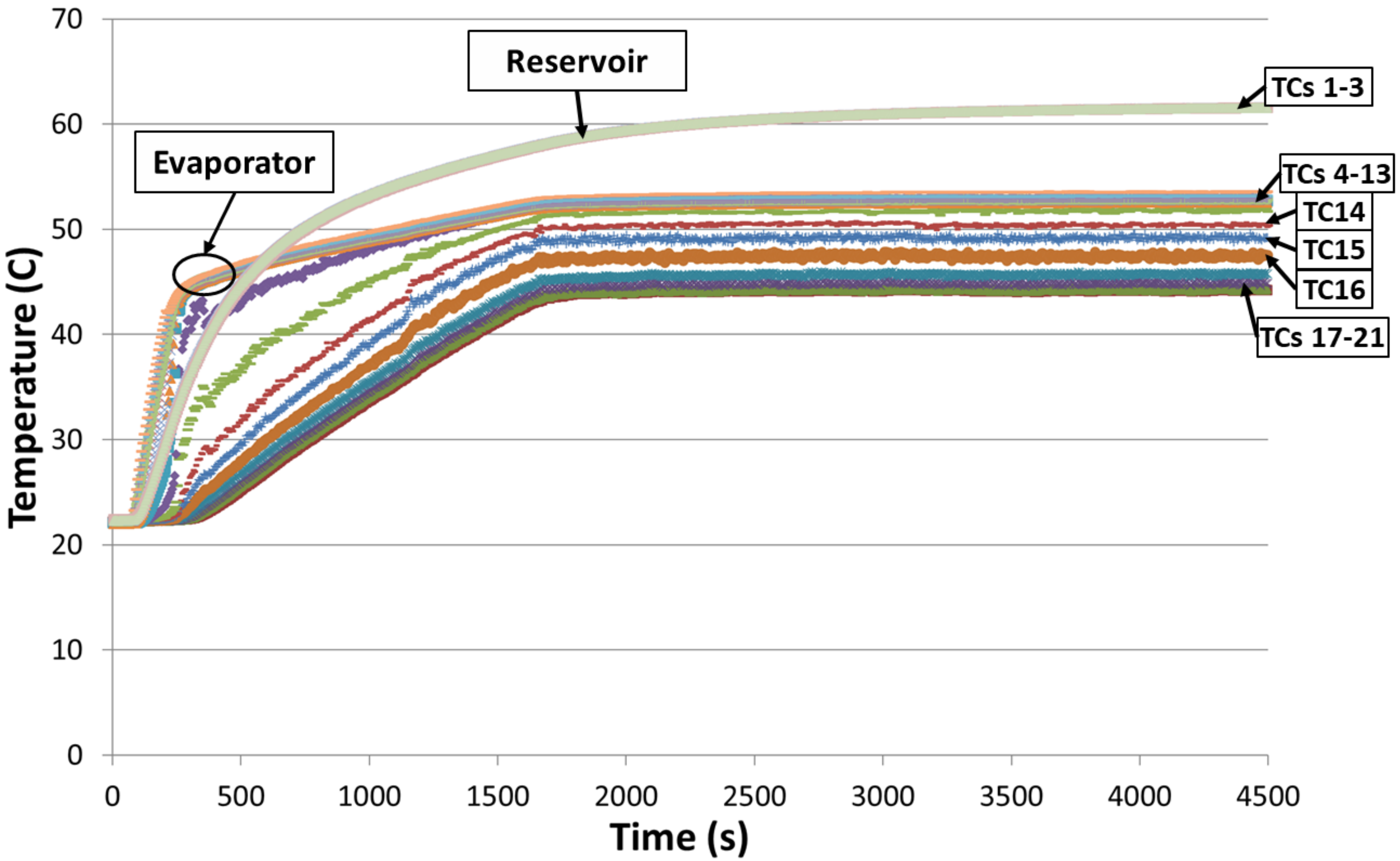
HR-VCHP Fabrication

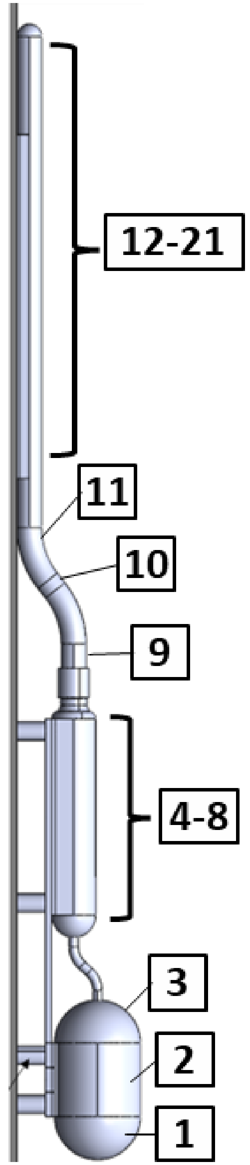






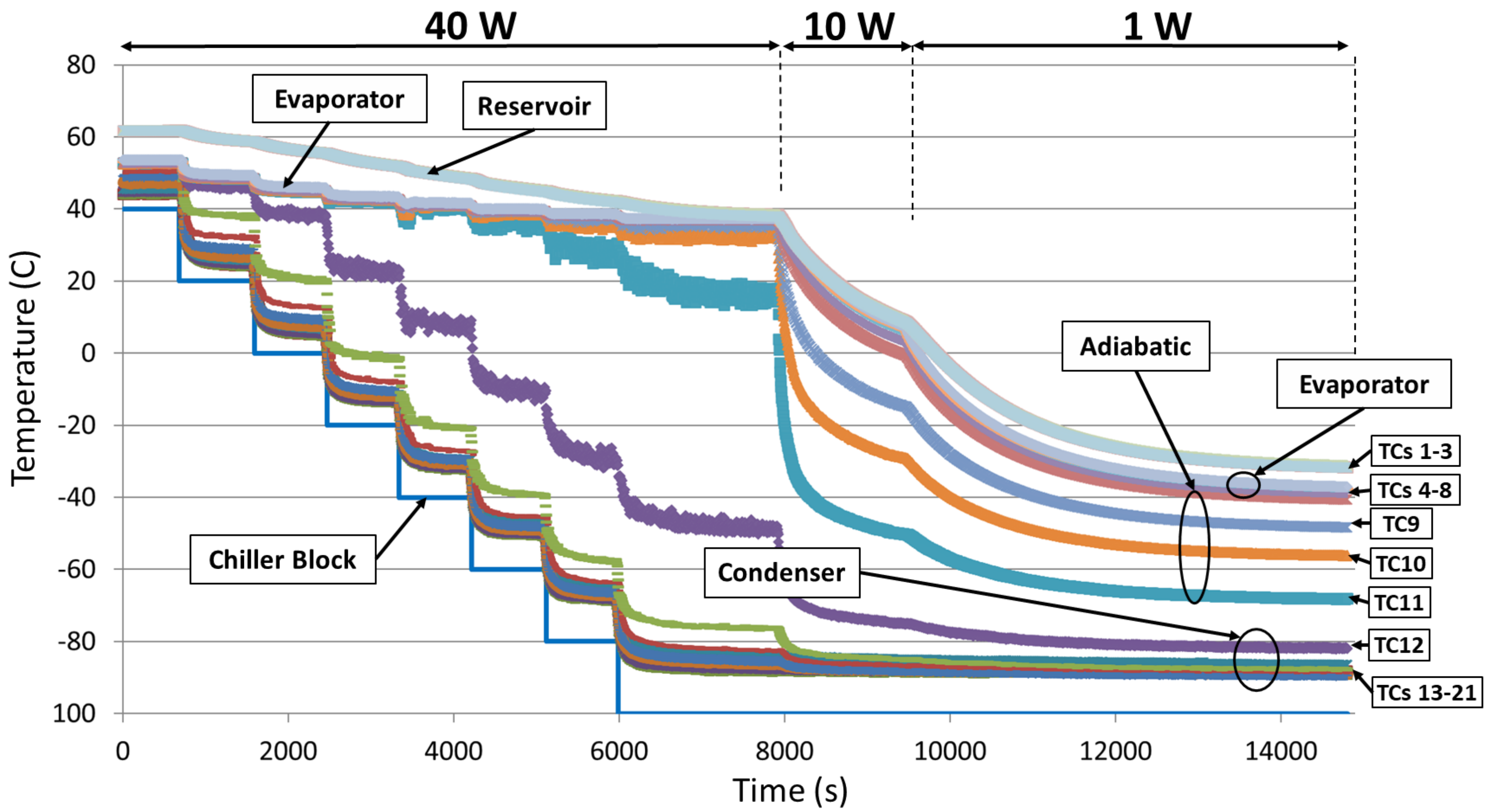
HR-VCHP Testing: Startup

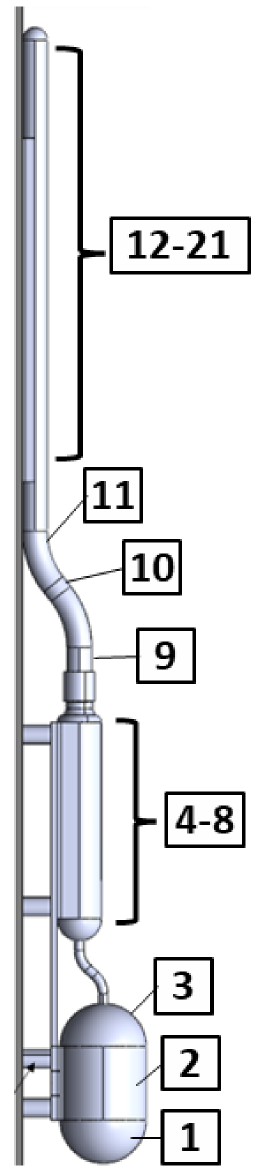




- 40 W applied to evaporator
- 3D Printed wick in the evaporator successfully prevents temperature spikes during startup

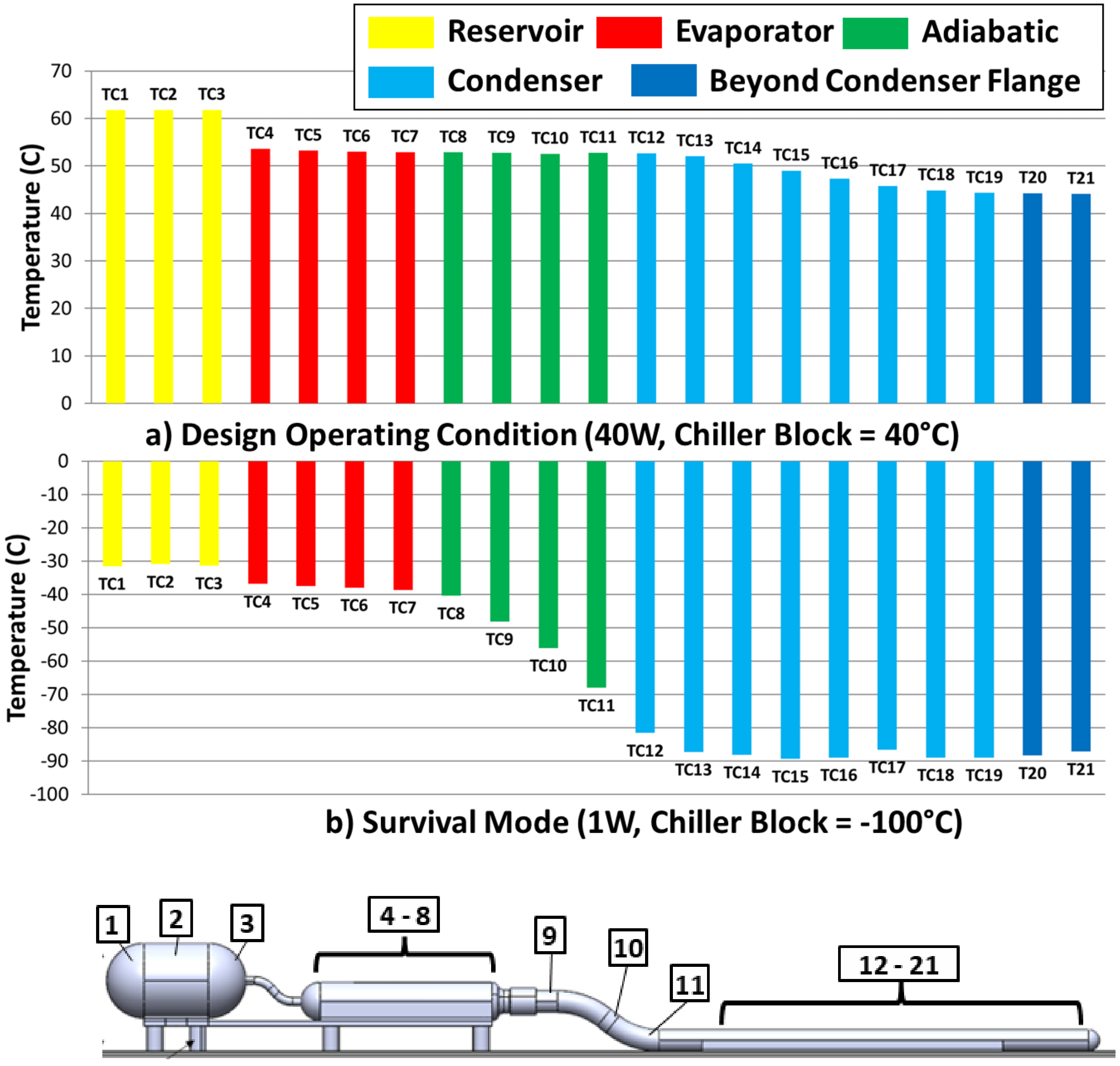
HR-VCHP Testing: Thermal Control Demonstration

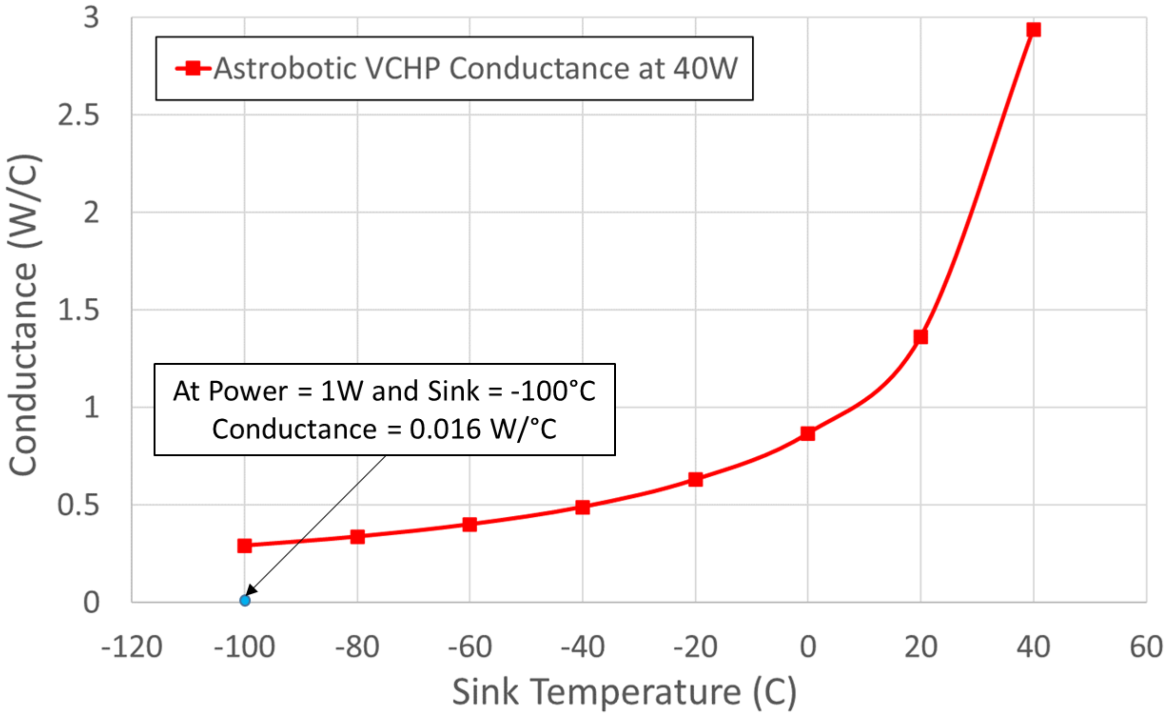




- At 40W and chiller block set point reduced from +40° C → -100° C
  - Evaporator temperature: 53.6° C → 37.3° C
- Chiller block setpoint -100° and power reduced from 40W → 1W
  - Evaporator temperature: 37.3° C → -37.0° C

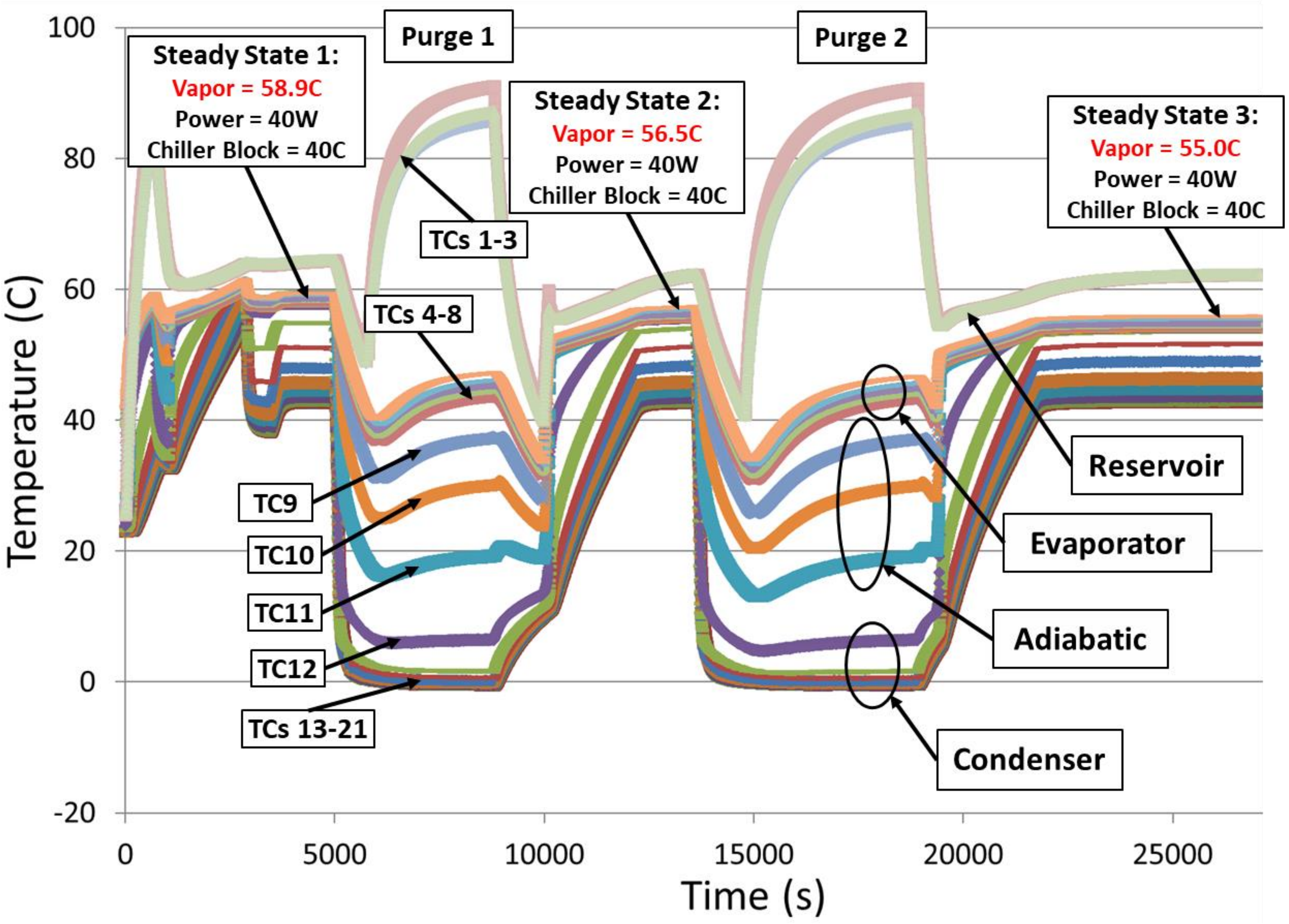
HR-VCHP: Turndown Ratio





- **Maximum Conductance: 2.93 W/K**
- **Minimum Conductance: 0.0158 W/K**
- **Turndown Ratio: 185:1**

HR-VCHP Testing: Reservoir Purge Demonstration

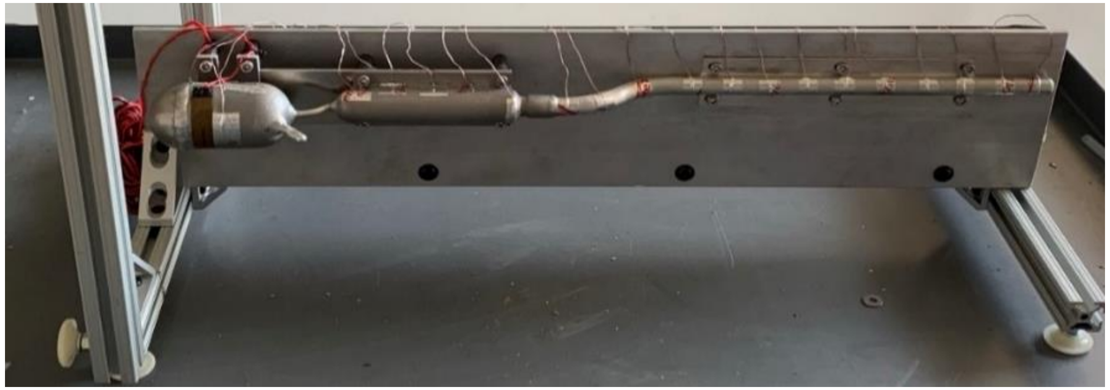


- **Initial Steady State:**
  - **Vapor = 58.9° C**
  - **40W to Evaporator**
  - **Chiller Block Setpoint = 40° C**
- **Purge Test:**
  - **Apply 12W to Reservoir**
  - **Chiller Block Setpoint = 0° C**
- **After First Purge Test:**
  - **Vapor = 56.5° C**
- **After Second Purge Test:**
  - **Vapor = 55.0° C**

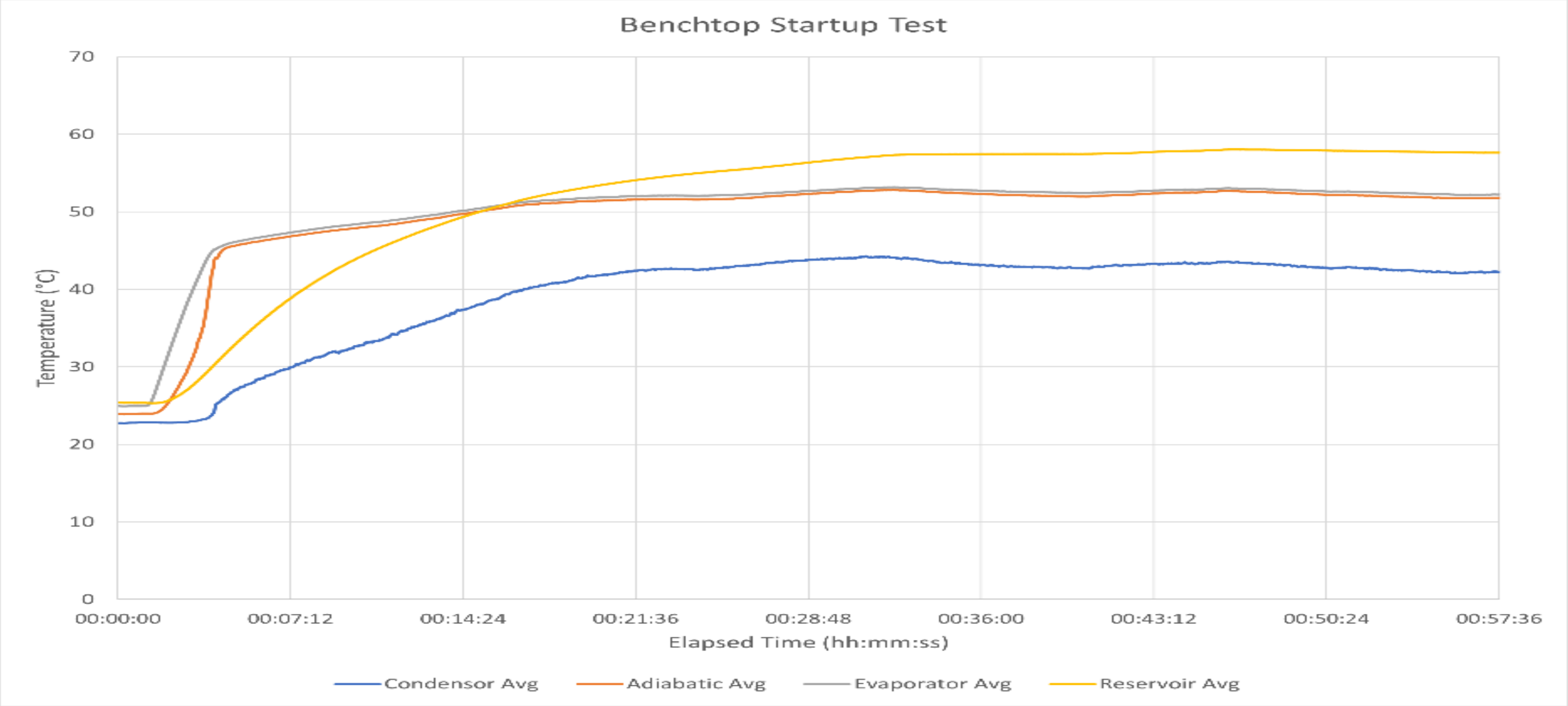
HR-VCHP Pre-Flight Testing at NASA MSFC

Benchtop Thermal Testing

HR-VCHP before benchtop testing ->



Benchtop startup testing ->

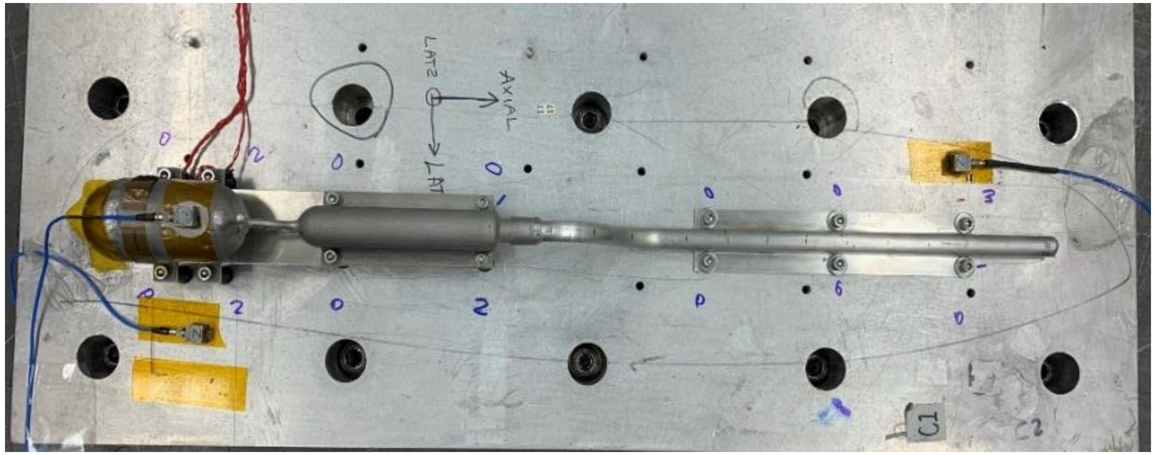


Vibration Testing

Vibration load cases

Random			Lateral Sine		Axial Sine	
Freq (Hz)	Limit (G^2/Hz)	Qual (G^2/Hz)	Freq (Hz)	Qual (g)	Freq (Hz)	Qual (g)
20	0.013	0.026	10.0	9.00	10.0	10.00
50	0.080	0.16	40.0	9.00	15.0	10.00
800	0.080	0.16	40.0	8.00	15.0	5.00
2,000	0.013	0.026	100.0	8.00	100.0	5.00
Grms	10.0	14.1				

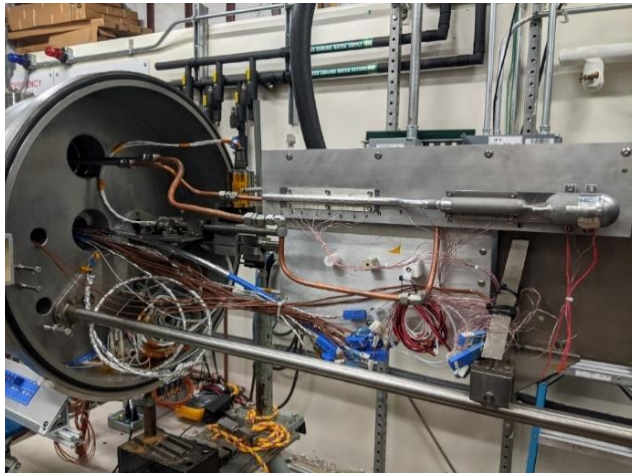
HR-VCHP on Shaker Table



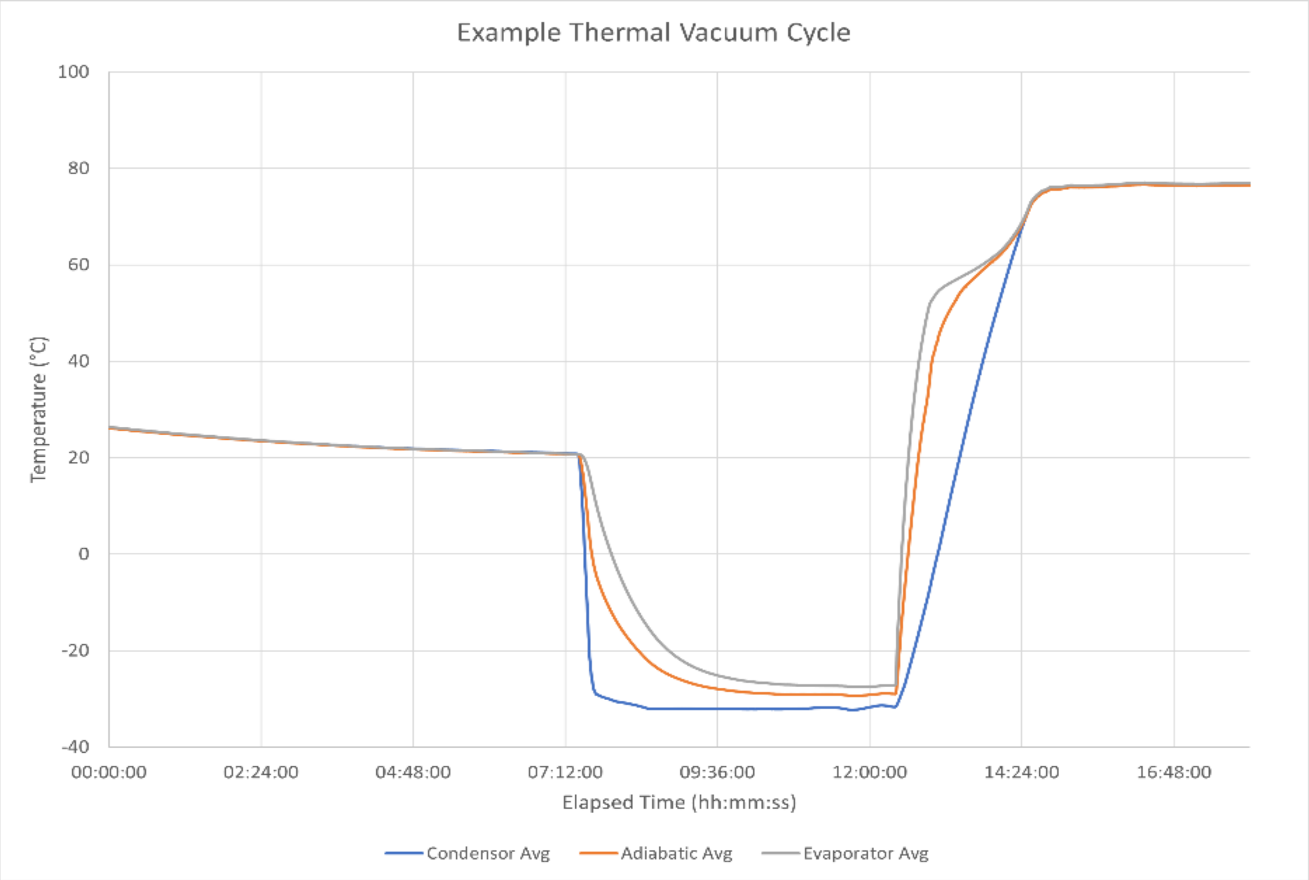
- Before thermal vacuum testing, the HR-VCHP went through random and sine vibration testing.
- Test cycles were performed without any visible failures for the HR-VCHP.
- A benchtop functional thermal test verified that the thermal performance of the HR-VCHP was nominal post-vibe.

Thermal Vacuum Testing

- HR-VCHP underwent a thermal vacuum test campaign guided by the Goddard Environmental Verification Standard (GEVS).
- Test temperatures of 10°C above and below the **allowable flight temperature** (AFT) range.
- AFT range was determined to be -22°C to 60°C, resulting in a test range of -**32°C to 70°C**.
- The vacuum pressure was always maintained below 10^{-5} Torr during the test.
- **F**our test cycles were performed at each temperature extreme, with a four-hour dwell period at each setpoint.
- Upon completion of the thermal cycling, a functional test was performed and verified that the HR-VCHP still operated as expected.



HR-VCHP in TVAC

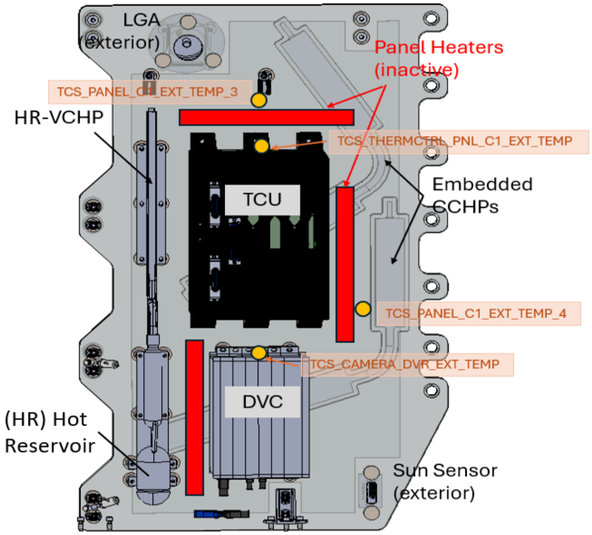


First TVAC cycle

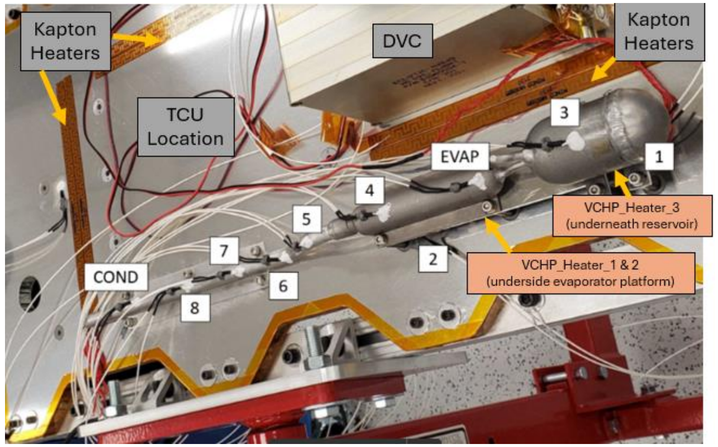
HR-VCHP Integration on Peregrine

Mission Details, HR-VCHP Integration and Instrumentation

Astrobotic Peregrine Mission 1 Lander (Enclosure Panel C1 hidden)



Enclosure Panel C1 viewed from the enclosure interior

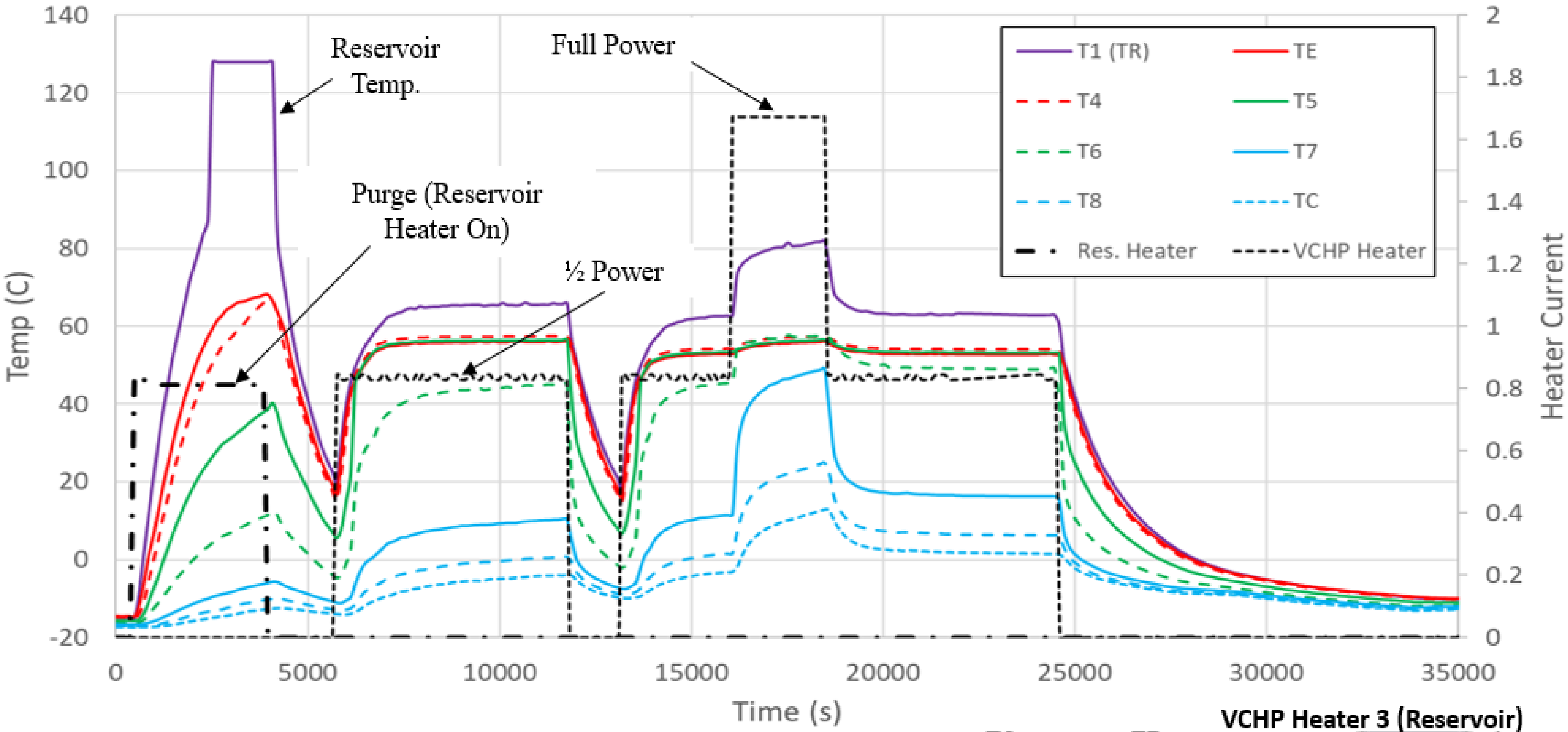


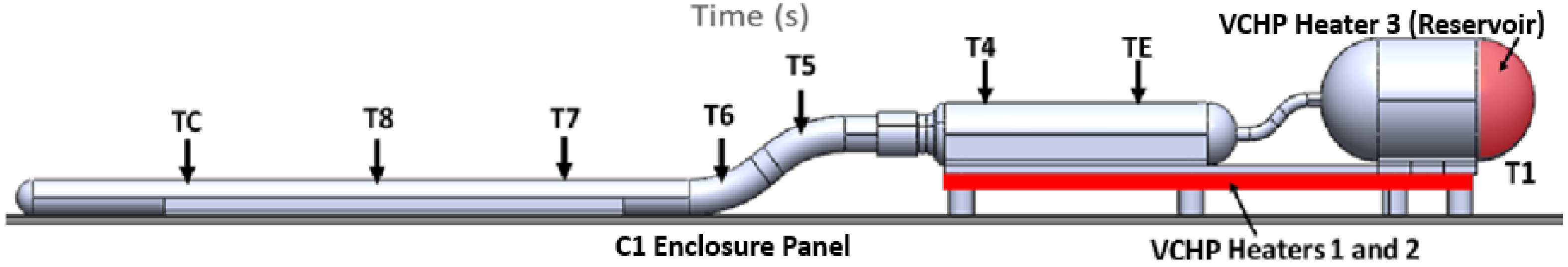
Instrumentation – Thermistors and Heaters

- ❑ HR-VCHP testing began on January 9, 2024, at 5:01 am ET and concluded approximately seven hours later at 12:00 pm.
- ❑ The testing occurred during the initial transit of PM1 to cis-lunar orbit, before reaching apoapsis beyond the Moon's orbit and returning to Earth.
- ❑ During this phase, the environmental conditions on the spacecraft and Enclosure Panel C1 were constant, with the solar vector pointing consistently on the PM1 solar panel and no measurable contributions of infrared energy from the Earth or Moon.
- ❑ The non-integrated HR-VCHP was mounted on Enclosure Panel C1, next to the Digital Video Controller (DVC) and a Thermal Controller Unit (TCU) on the interior surface of the panel
- ❑ Ten temperature sensors (thermistors) and three heaters were installed.

HR-VCHP Testing in Microgravity

Thermal Control Test

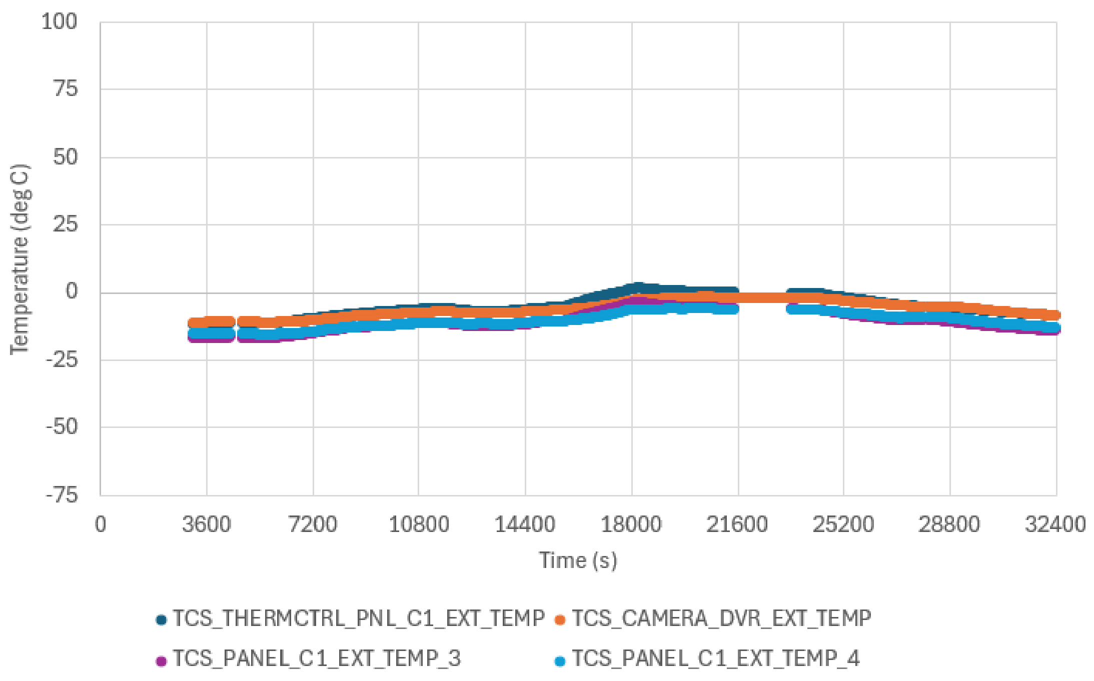




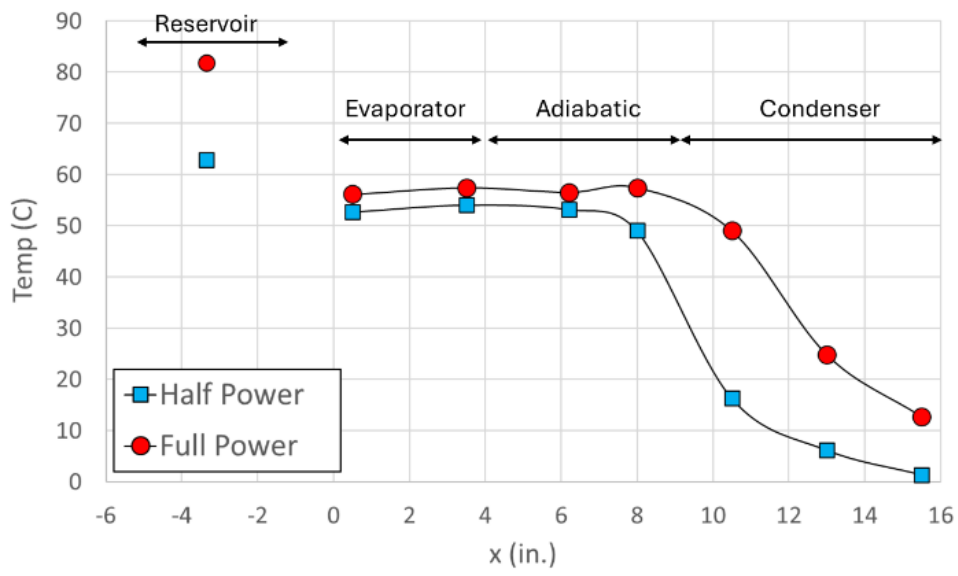
Three phases of thermal control testing:

- **Phase I – purging (0 – 5500 seconds)**
- **Phase II – constant power (5500 – 12000 seconds)**
- **Phase III – variable power (13000 – 24500 seconds**

Thermal Control Test

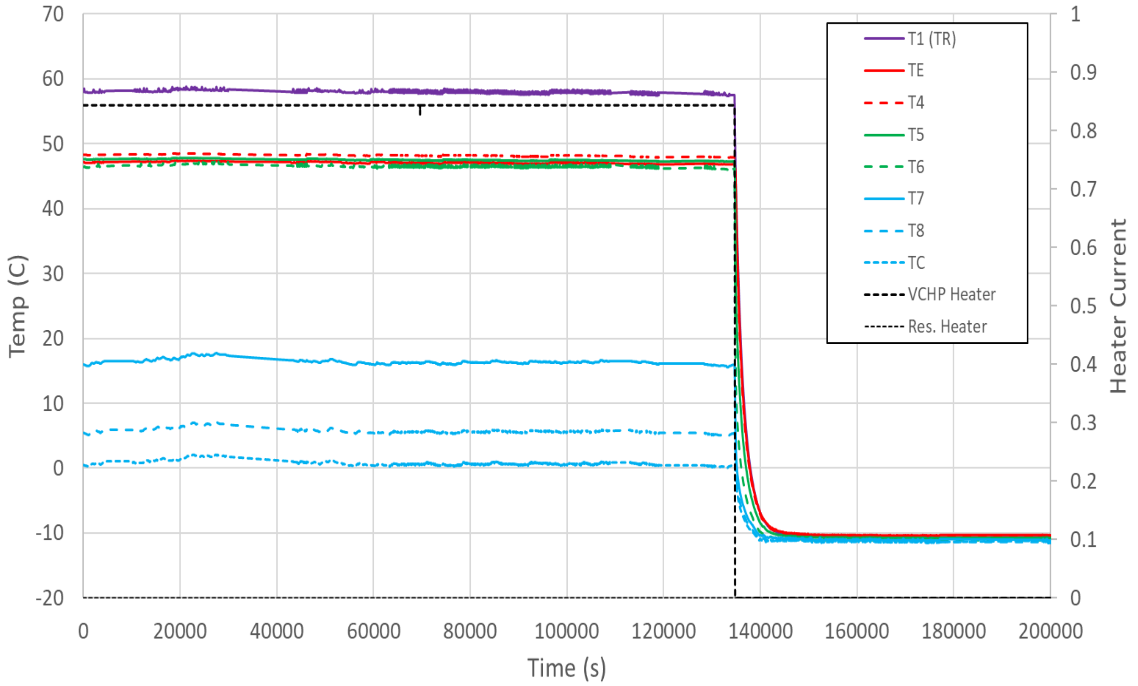


Thermal control testing: Enclosure Panel C1 (heat sink) temperatures

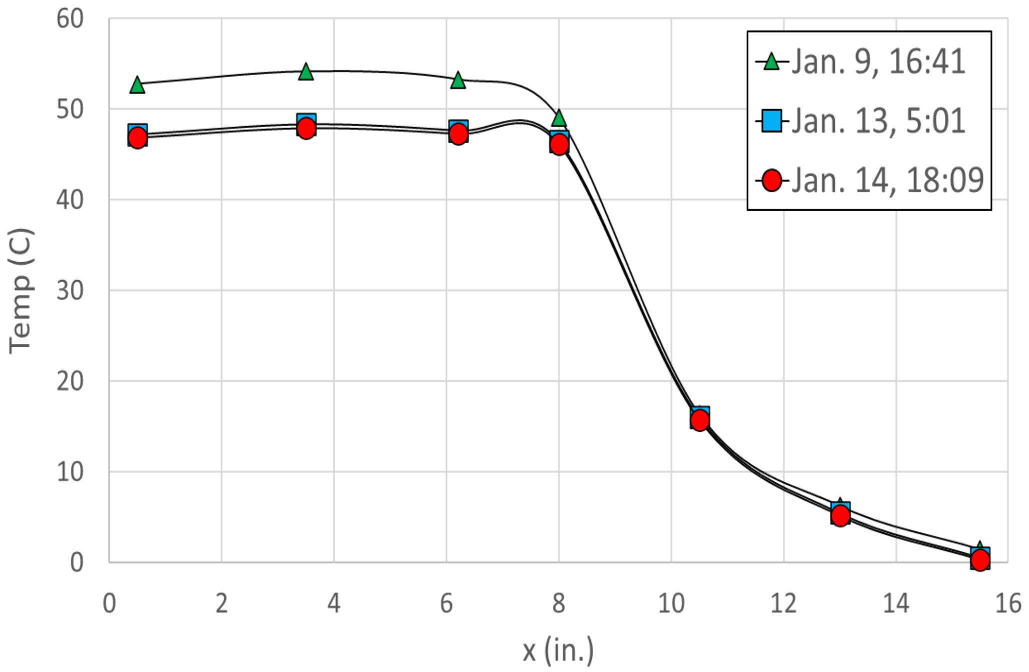


Instantaneous temperature profiles along the HR-VCHP for half-power and full power sequences

Reliability Test



Reliability test: Temperature vs. time



Reliability test: Instantaneous temperature profiles along the HR-VCHP

- ❑ **The reliability test is the most important, given the challenges from previous developments**
- ❑ **The results show no changes in the reservoir**

Summary and Conclusions

Summary and Conclusions

- The hybrid wick (screen or 3D printed porous structure in the evaporator and grooves or no wick in the adiabatic/condenser) prevented temperature spikes during startup in a gravity-aided orientation (during ground testing).
- The non-integrated HR-VCHP, which maintains the NCG reservoir at a warmer temperature than the evaporator, exhibits excellent passive temperature control.
  - Turndown ratio of 185:1 was estimated during ground tests at ACT
- The non-integrated NCG reservoir allows for independent heating of the reservoir which can be effectively used to purge working fluid from the reservoir.
- Microgravity testing results again showed that the thermal control capability of the non-integrated HR-VCHP is high (the same as the integrated reservoir version shown in previous papers)
- The reliability of the HR-VCHP was finally fixed and demonstrated by the non-integrated version that introduced independent purging (not significantly impacting evaporator temperature), allowing the reservoir to operate constantly at a higher temperature than the saturation point in the pipe. The conclusion is that as long as the reservoir is warmer than the saturation point in the HR-VCHP, no net accumulation of superheated vapor (increased humidity) occurs.
- The successful testing on Peregrine 1 in microgravity elevated the TRL of the non-integrated HR-VCHP to 8.