# Operation of a Heat Pipe with Multiple Heat Loads under Reflux Mode

**Jentung Ku**
**NASA Goddard Space Flight Center**
**Greenbelt, Maryland, USA**

**ASME 2019 International Mechanical Engineering Congress & Exposition**
**Salt Lake City, Utah, November 11-14, 2019**

# Outline

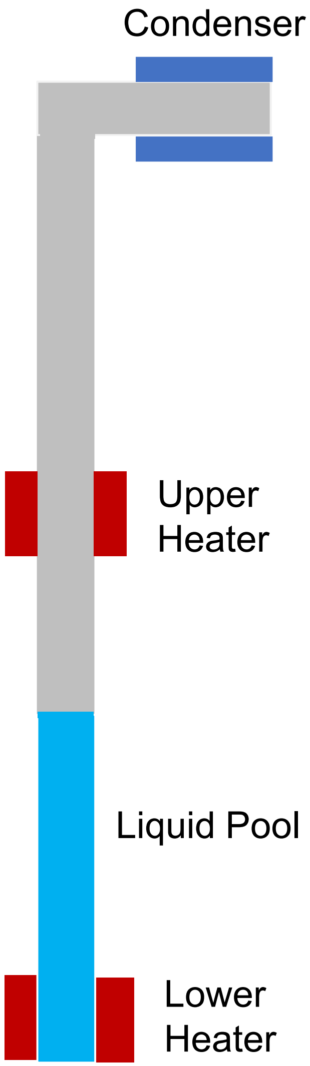
- Introduction/Objectives
- Theoretical Background
- Technical Approach
- Test Article
- Test Setup and Instrumentation
- Test Results And Data Analyses
- Conclusions

# Introduction/Objectives

- **For proper heat pipe operation, liquid must be present in the porous wick inside the heat pipe at the heated site.**
- **In ground testing, heat pipes may be placed in a reflux mode, with condenser above evaporator. A liquid pool will form at the bottom of the heat pipe.**
- **If the heated site is below the surface of the liquid pool in a vertical heat pipe, the heat pipe can work properly under reflux mode.**
- **If the heated site is above the liquid pool, the heat pipe is not expected to work unless a reflux flow has already been established.**
  - **The needed reflux flow can be provided by adding additional heat to the liquid pool.**
- **An experimental investigation was conducted to study the heat pipe behavior under this configuration.**

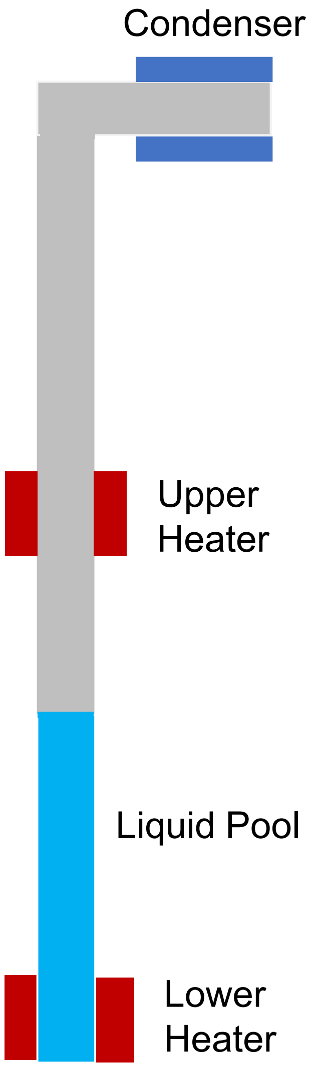
# Theoretical Background – Heat Pipe Operation (1/2)

- **Under reflux mode, a heated site below the liquid pool level will have continuous liquid supply. As liquid is vaporized, vapor flows upward condenses at the condense. The condensate falls down along porous wicks.**
- **Once this reflux flow is established, the heat pipe can take heat at locations above liquid pool. Evaporation occurs directly from the condensate film falling down the wall of the heat pipe.**
- **Some falling condensate will be captured by the upper site and the generated vapor will flow back to the condenser. Some falling condensate will "leak" through the upper site regardless of heat loads to the two heated sites.**
- **The system will eventually reach an equilibrium – either at a steady state or a quasi-steady state.**



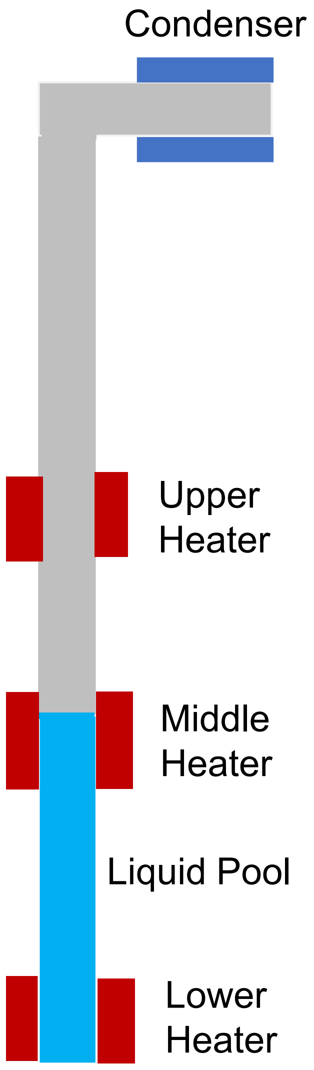
# Theoretical Background – Heat Pipe Operation (2/2)

- If the upper site cannot capture sufficient liquid to handle its heat load solely by evaporation, its temperature will fluctuate because it has only intermittent contact with liquid.
  - When in contact with liquid, its temperature drops. Immediately after liquid evaporation, its temperature rises due to temporary partial dry-out until it captures the falling liquid again. This process repeats itself.
  - The most important factor that characterizes the system performance is the relative heat loads between the upper and lower sites.
  - For a given power to the upper site, there exists a threshold power to the lower site above which the temperature oscillation disappears and the heat pipe reaches a true steady state.
  - The threshold power to the lower site increases with an increasing power to the upper site.
- The lower site always has a steady temperature.



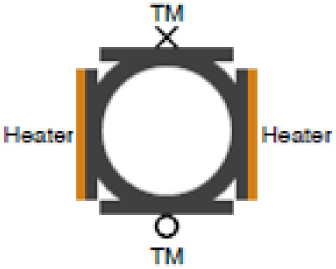
# Technical Approach

- **An L-shaped axially grooved aluminum/ammonia heat pipe was used for this experimental study.**
- **The heat pipe was placed in an upright position so that a liquid pool was formed at the bottom of its vertical leg.**
- **Three heaters were attached to the vertical leg of the heat pipe: two were at sites in contact with the liquid pool and the third was above the liquid pool.**
- **Cooling was provided to the end of the horizontal leg of the heat pipe where a coolant flow was circulated.**
- **The study consisted of applying various heat load distributions to the three heaters.**
    - **The amplitude of temperature oscillation as a function of the heat load distribution**
    - **Conditions for true steady operation of the heat pipe**

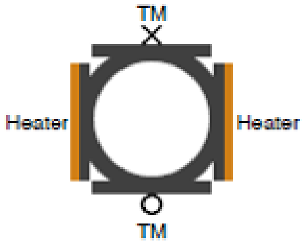


# Test Article

- The test article was a spare unit from the Lunar Reconnaissance Orbiter flight project.
- The heat pipe:
  - Two legs with lengths of 1080 mm and 216 mm, respectively.
  - Outer diameter: 15 mm
  - Vapor core diameter: 11 mm
  - Four flanges on the outer surface along the axial direction, each 11.1 mm wide.
  - Working fluid: ammonia
  - Fluid inventory: 31.1 grams
  - When the entire liquid inventory accumulates at the bottom of the heat pipe under gravity, the liquid pool height is 423 mm (16.7”) at 298K.



# Test Setup and Instrumentation (1/2)

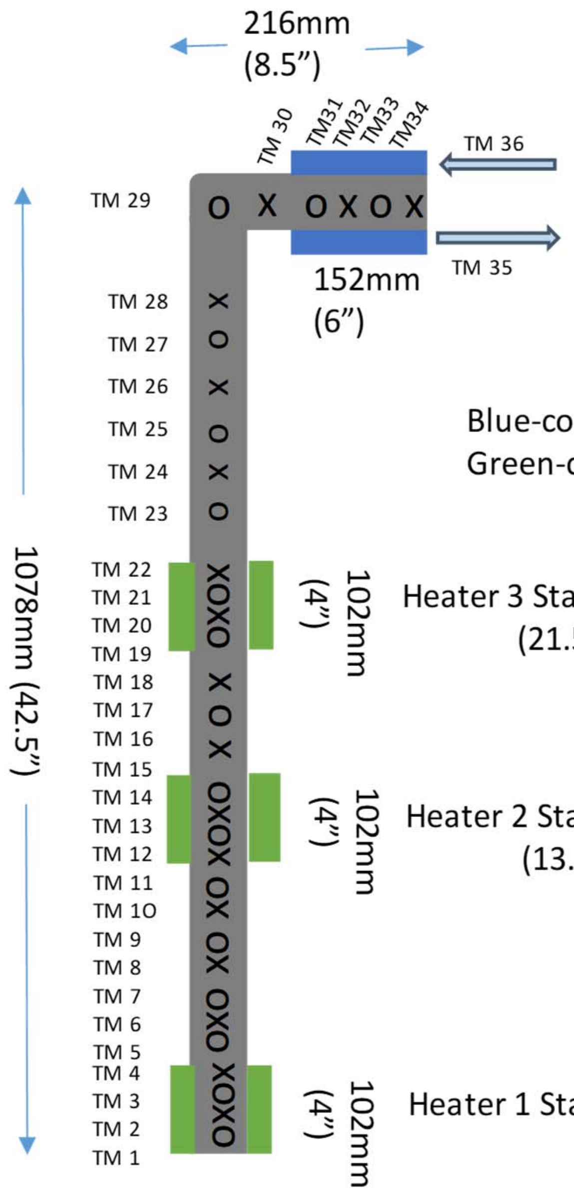


- Heater locations
  - Heater 1 was at the very bottom of the leg.
  - Heater 2 was 343mm from the bottom, and covered 81.3mm of liquid pool (partial coverage of the top of the liquid pool).
  - Heater 3 was 123mm above the liquid pool.
- Each heater has two aluminum blocks on opposite sides of flanges.
  - Each block was 101.6mm long
  - A cartridge heater inside each block provides up to 400W power
- The end of the 216 mm horizontal leg was used as the condenser.
  - Condenser length: 152 mm
  - Two cold plates were attached to the condenser. A recirculating chiller was used to circulate the coolant through the cold plates.
- Thermistor locations
  - Four thermistors on each heated site.
  - Four thermistors on the condenser
  - Eighteen thermistors on the adiabatic sections in-between heater blocks and condenser

# Test Setup and Instrumentation (2/2)

- Three power supplies were used – one for each heater. Heat load to each heater was independently controlled.
- The maximum power for each heater was 400W.
- The entire heat pipe was covered with polyolefin insulation.
- Test configuration: the 1080-mm leg was placed in a vertical position and the 216-mm leg was horizontal.
- Test data was collected, displayed, and stored once every 5 seconds.

# Heater and Thermistor Locations

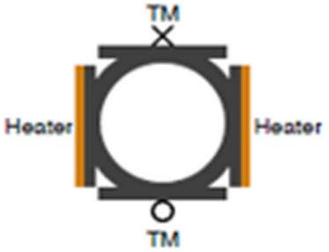


Blue-cold plates
Green-cartridge heaters (H-1,2,3)

Heater 3 Starts 546mm
(21.5")

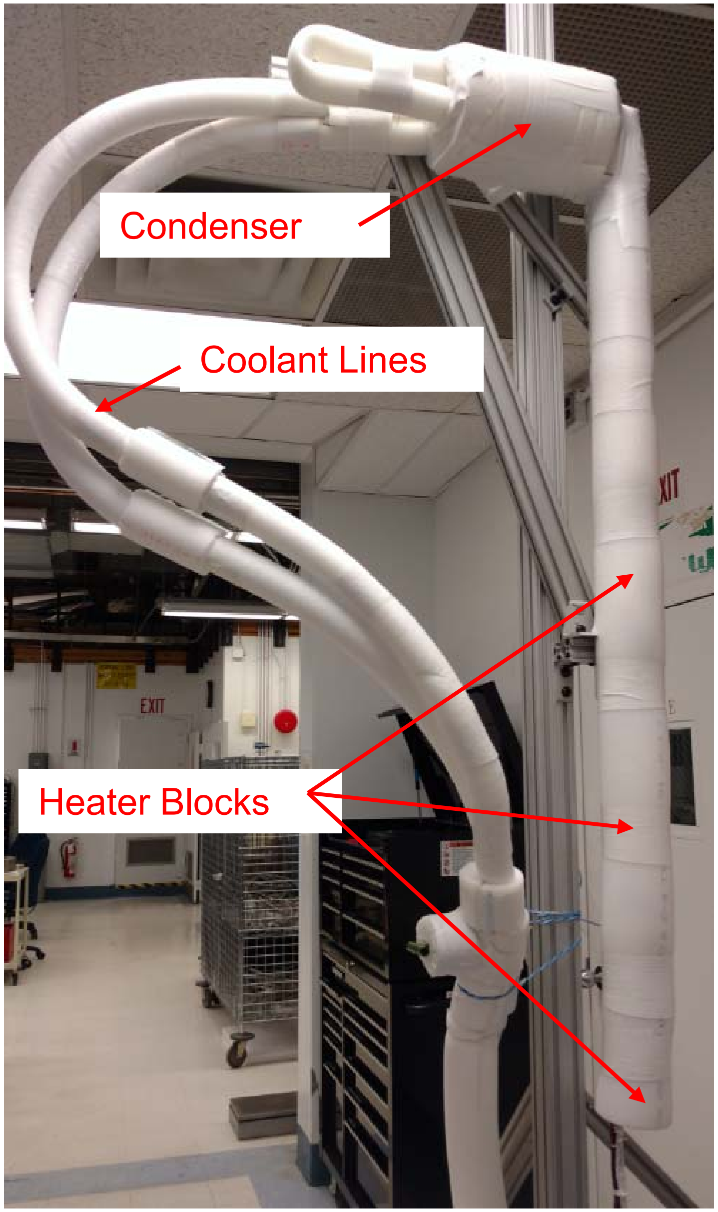
Heater 2 Starts 343mm
(13.5")

Heater 1 Starts 0mm



| Symbol | TM mounting location |
|---|---|
| X | TOP |
| O | BOTTOM |

# Heat Pipe in Vertical Configuration



# Test Objectives

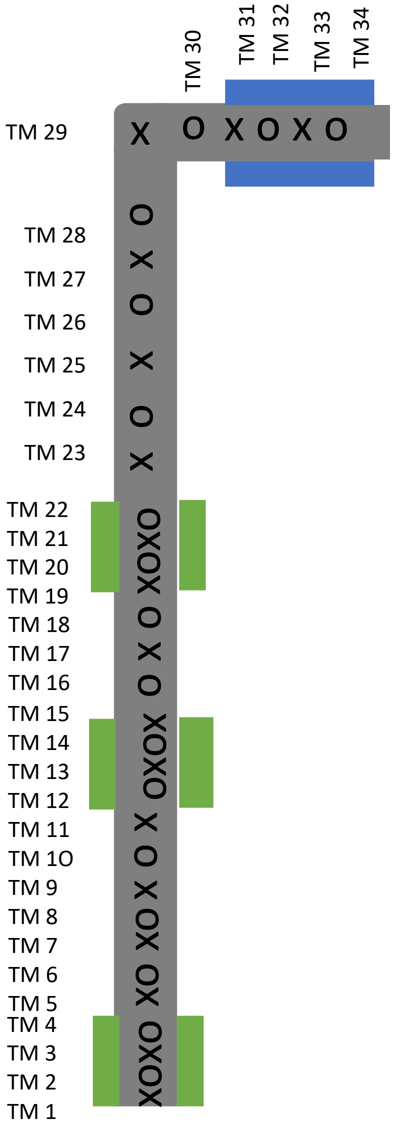
- Applying various heat load distributions to the three heaters to study the temperature oscillation as a function of the heat load distribution:
  - Amplitude of temperature oscillation
  - For a given HTR 3 power, whether a threshold power exists (HTR 1 and HTR 2) above which heat pipe operates stably without temperature oscillations
  - Whether there is a difference in applying power to HTR 1 or HTR 2
  - Whether a heat load to HTR 3 alone can sustain the heat pipe operation after a reflux flow has been established

# Tests Performed

- Baseline - Various heat loads to HTR 1 and/or HTR 2: to show the heat pipe performance when the heated site was in direct contact with the liquid (Group A)
- Various heat loads to HTR 1 and HTR 3 (Group B)
- Various heat loads to HTR 2 and HTR 3 (Group C)
- Various heat loads to HTR 1, HTR 2, and HTR 3 (Group D)
- Various heat loads to HTR 3 only (Group E)
- Startup
  - Heat load to HTR 1 or HTR 2
  - Heat load to HTR 3 only
- Most tests were performance at 273K sink temperature. Some tests were performed at 283K and 294K sink temperature.

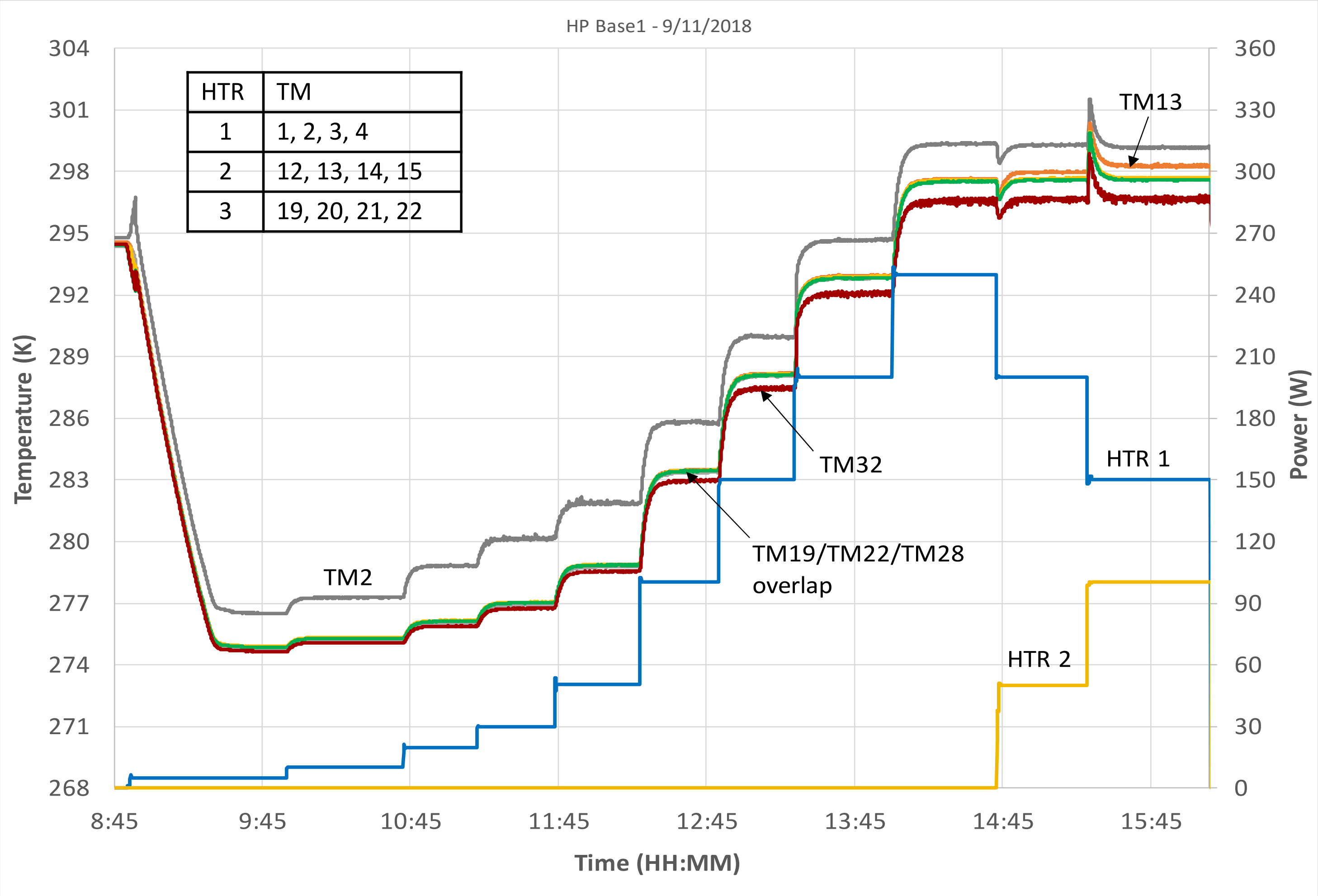
# Data Plot and Presentation

- In following data plots, relevant segments and their thermistor temperatures are selected to show temperature profiles of the heat pipe.
  - Each heated site had 4 thermistors.
  - A table is provided to show the heater and corresponding thermistors.
  - The adiabatic temperature (TM28) and the condenser temperature (TM32) are included in most plots.
  - The four thermistors on heated site 3 are TM19, TM20, TM21, and TM22
- Each plot is assigned a test number for easy reference during discussion.
  - A1, A2, B1, B2, etc.



# A1 - Baseline: HTR 1 Power from 5W to 250W

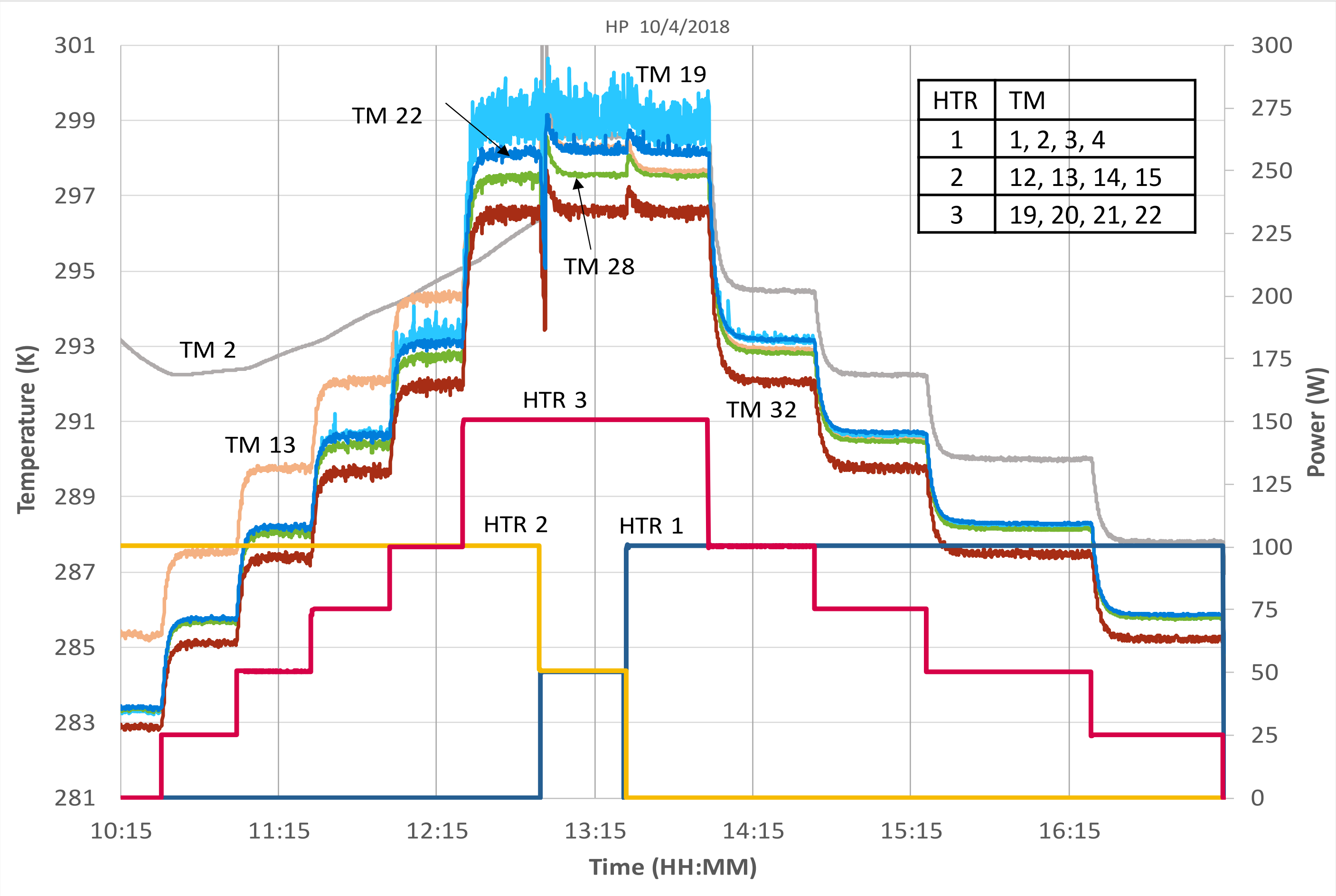
- **Applied different heat loads to HTR 1. Startup with 5K superheat (TM2). Power was added to HTR 2 near the end of test.**
- **Steady temperatures throughout the test. All thermistors above HTR 1 showed a uniform temperature except for heat source and heat sink.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# D1 - 100W to (HTR 1 + HTR 2), HTR 3 Power Varied

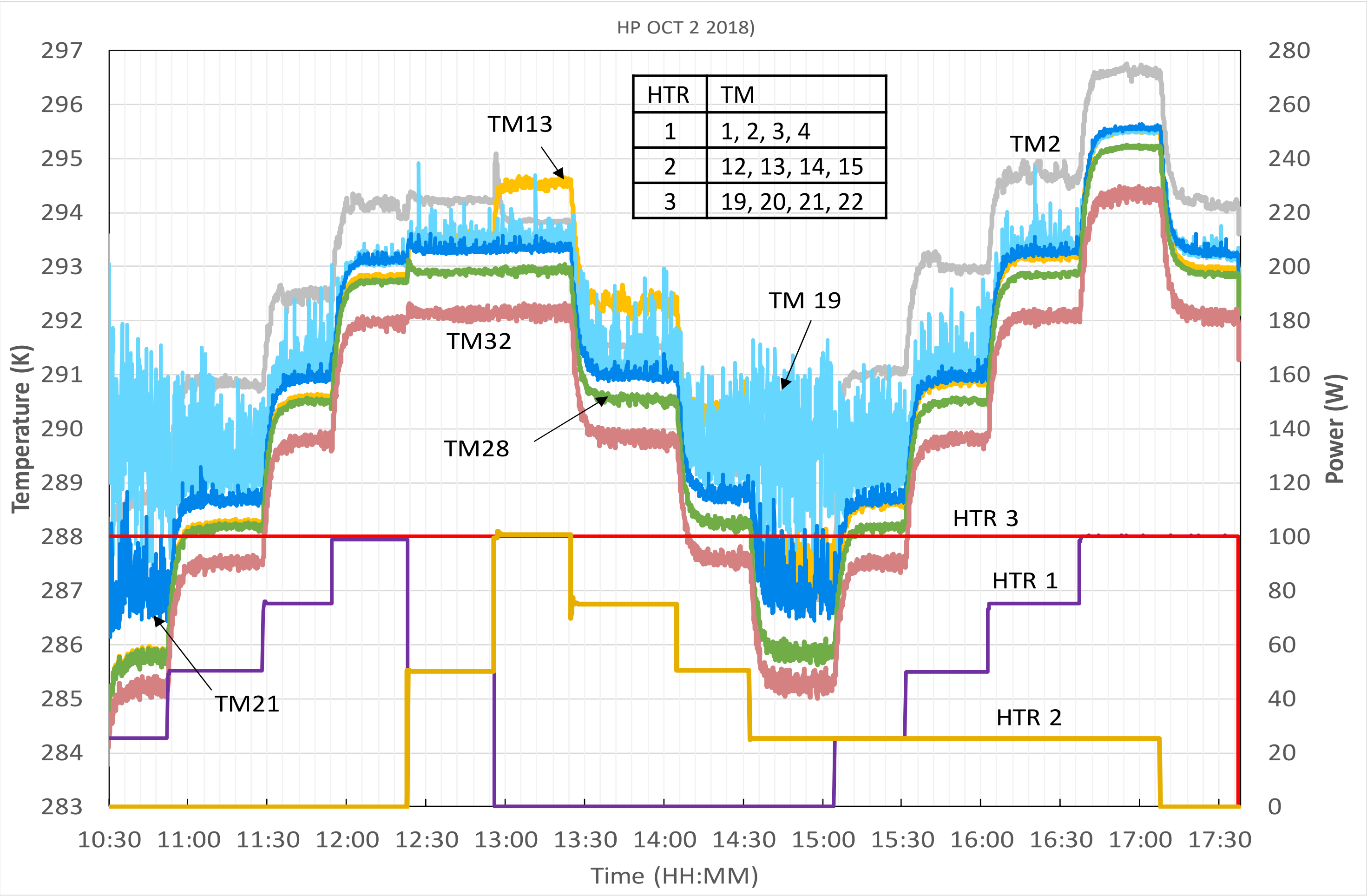
- **A total power of 100W to (HTR1 + HTR2). HTR 3 power varied between 25W and 150W.**
- **Small or no temperature oscillation for HTR 3 power up to 100W. At 150W, temperature oscillation was ~2K. At 12:55, HTR 1 was added, and TM2 rose to 311K (superheat = 14K) at boiling incipience (off scale).**
- **Using HTR 1 had a slight advantage over HTR 2 in reducing temperature oscillation.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# D2a - 100W to HTR 3, (HTR 1 + HTR 2) Power Varied

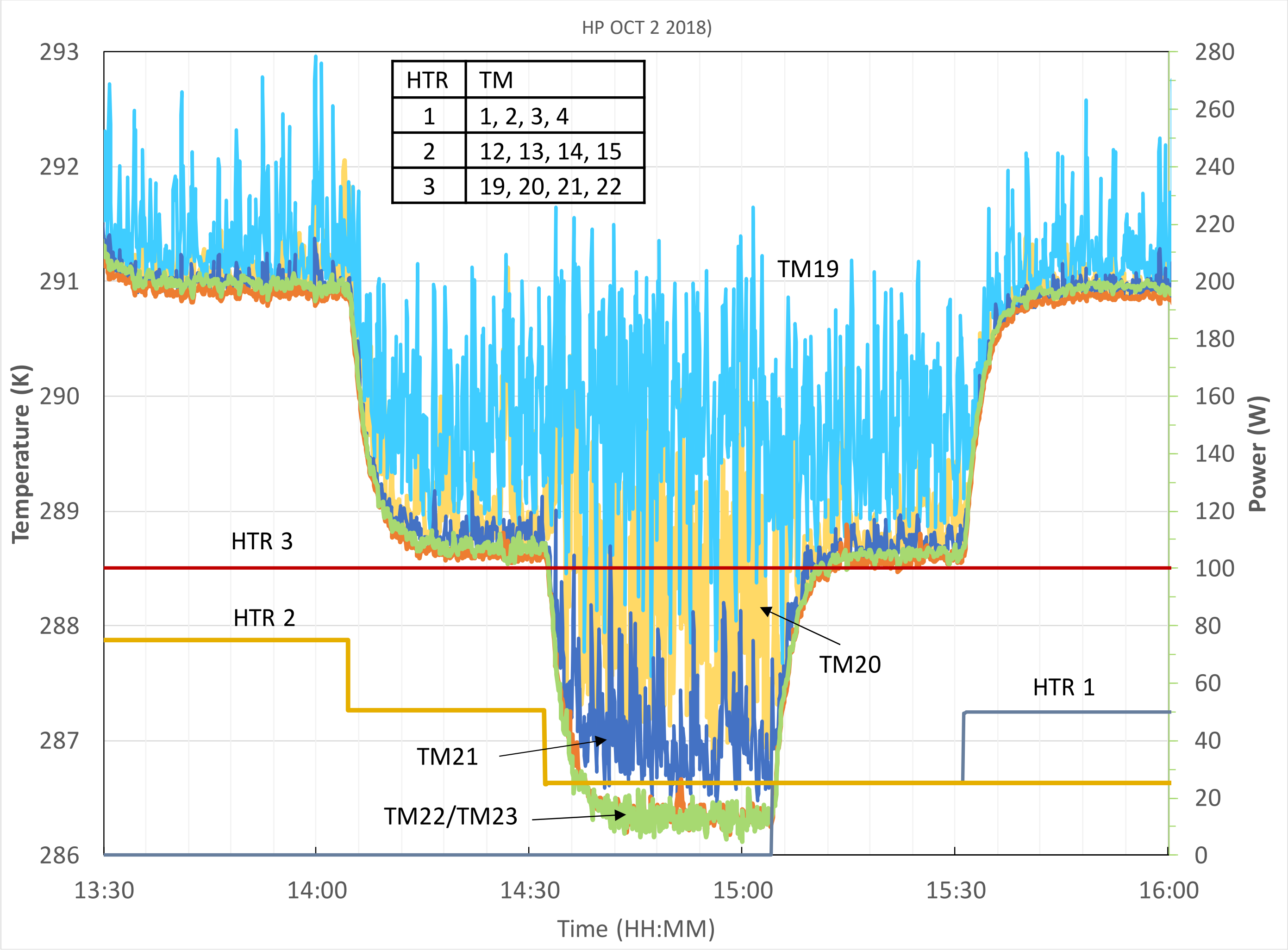
- **HTR 3 showed temperature when total power to (HTR 1 + HTR 2) was below 100W. Amplitude of temperature oscillation decreased with increasing power to (HTR 1 + HTR 2).**
- **Using HTR 1 had a slight advantage over HTR 2 in reducing temperature oscillation.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# D2b - 100W to HTR 3, (HTR 1 + HTR 2) Power Varied

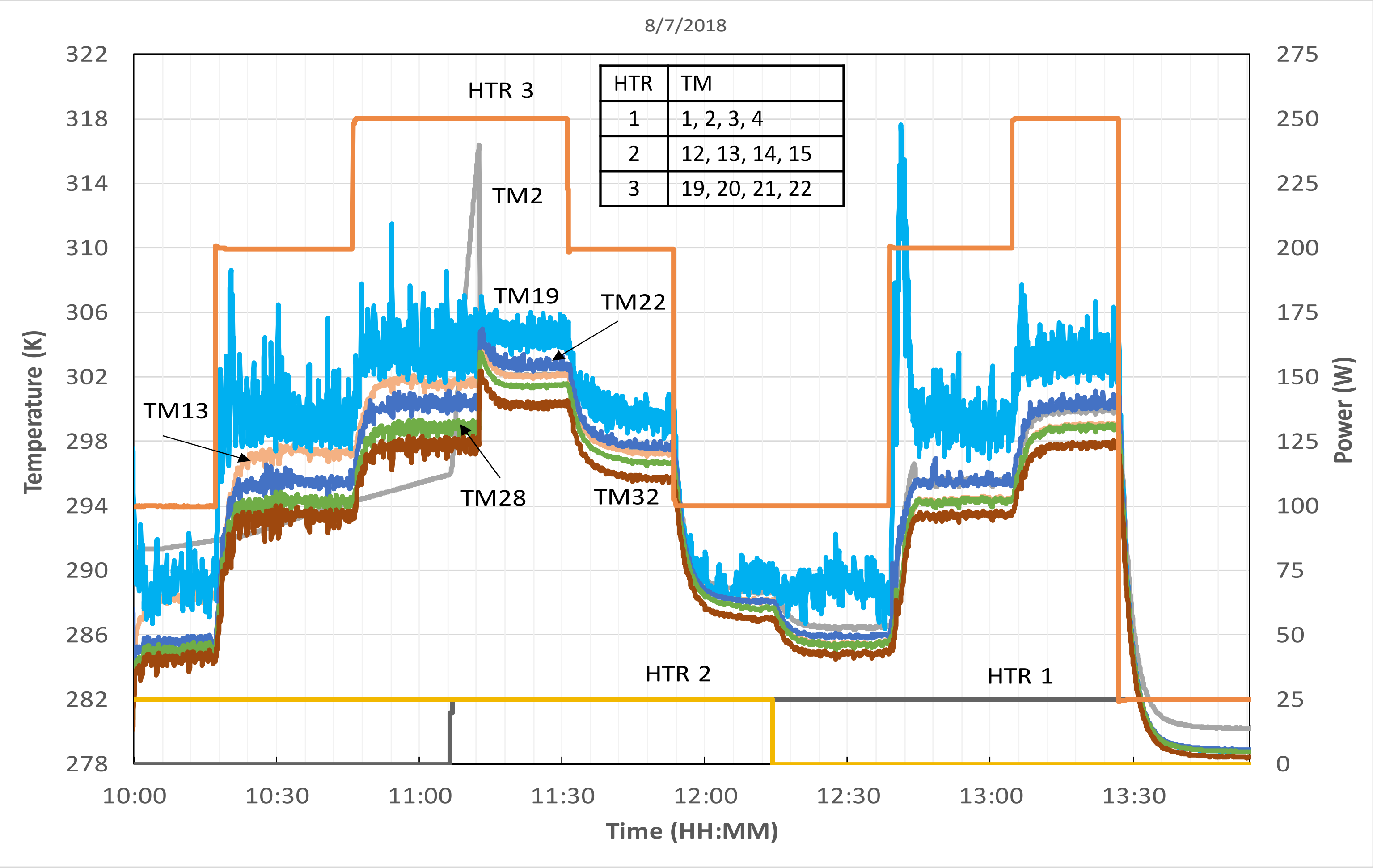
- This is a subset of the same test as shown in D2a. The amplitude of temperature oscillation at the top of Site 3 (TM22) was much lower than that at the bottom (TM19).



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# D3 - Various Heat Loads to HTR 1, HTR 2, and HTR 3

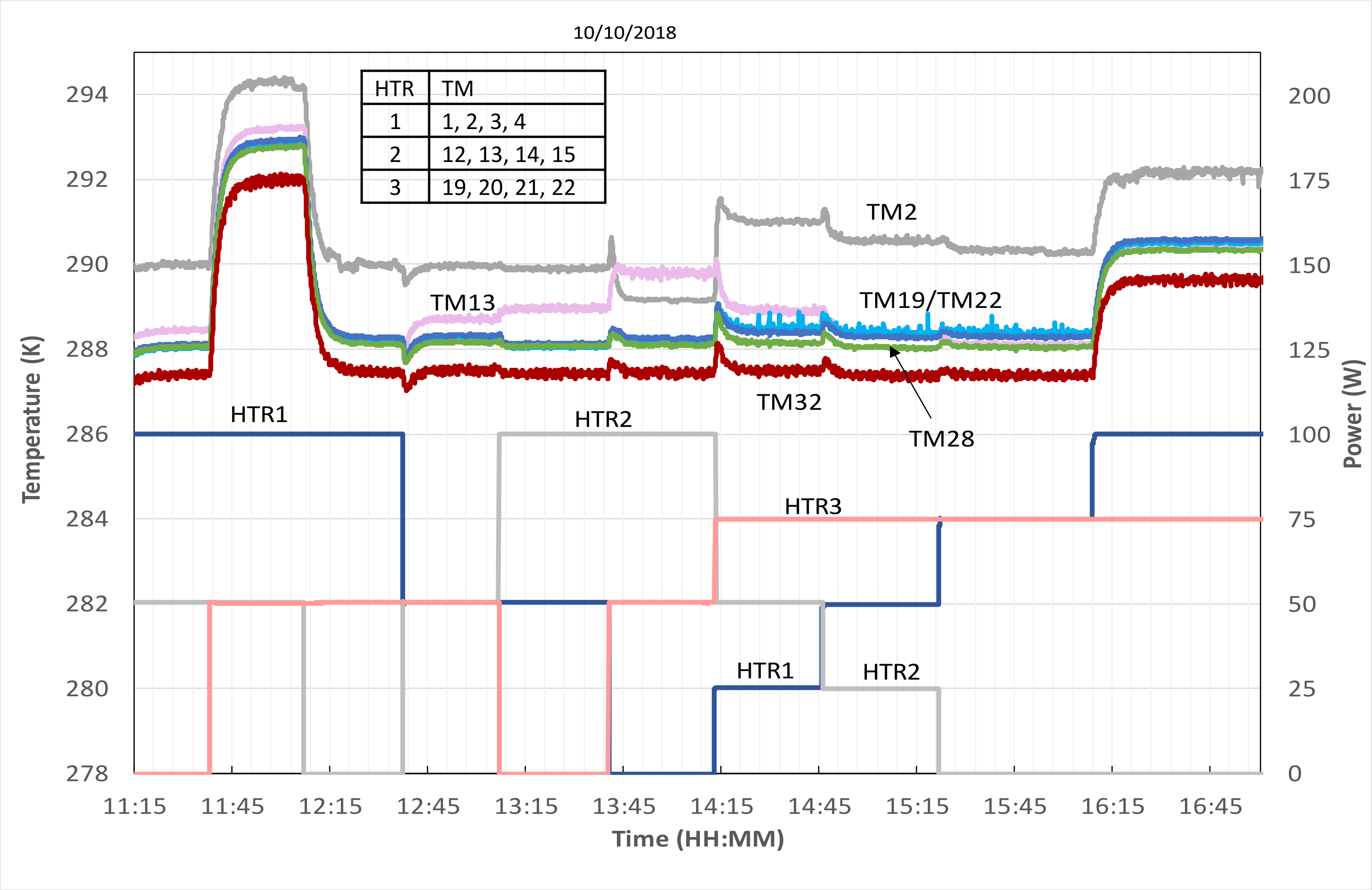
- 1st part - HTR 3 power: 100W/200W/250W, HTR 2 power: 25W
- 2nd part – HTR 3 power: 250W/200W/100W, HTR 1 power: 25W, HTR 2 power: 25W
- 3rd part – HTR 3 power: 100W/200W/250W/25W, HTR 1 power: 25W
- In all cases, (HTR 1 + HTR 2) < HTR 3, and temperature oscillation persisted.



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# D4 - Condition for Steady Operation

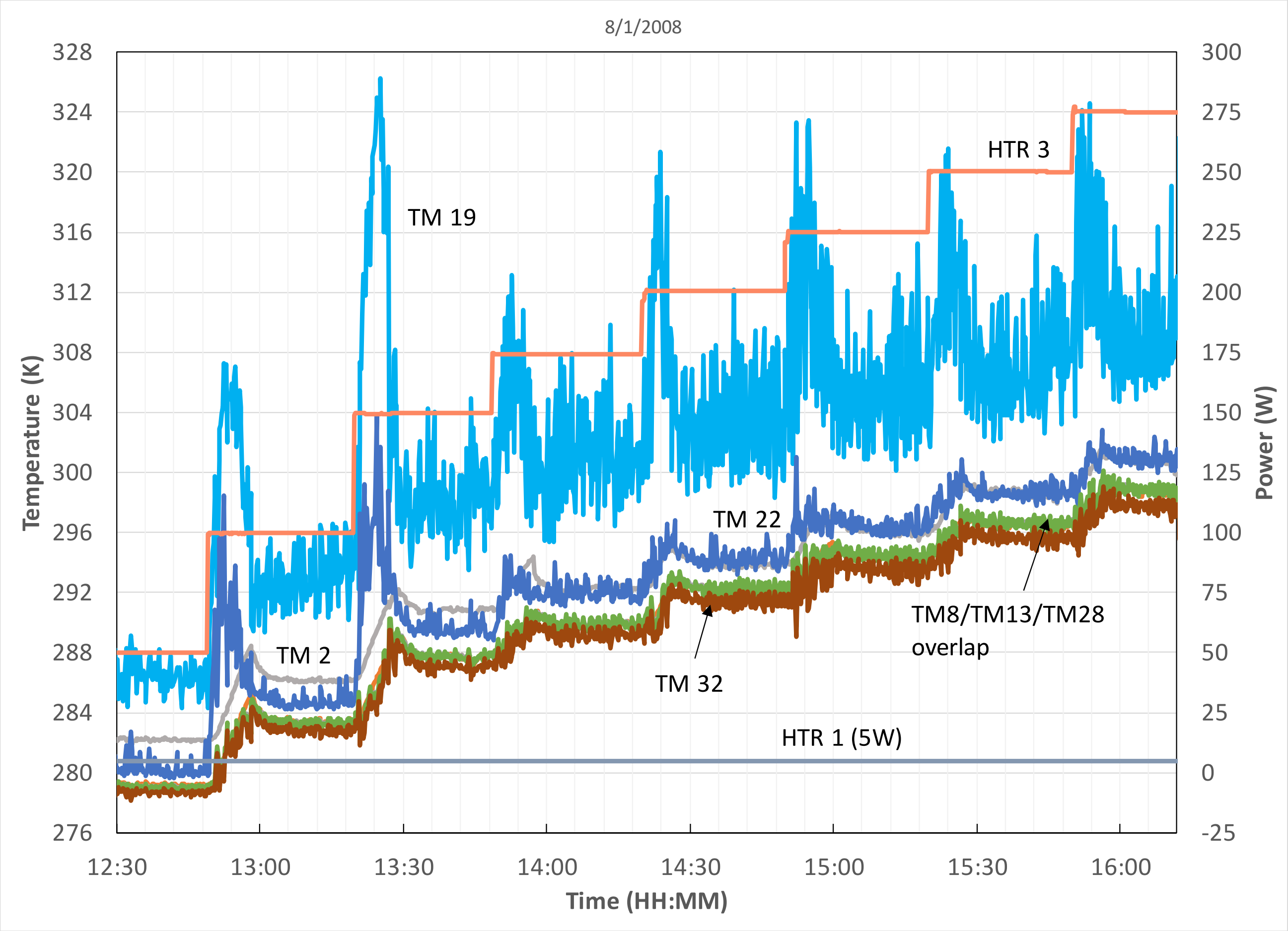
- **As long as the total power to (HTR 1 + HTR 2) was greater than HTR 3 power, there was no or little temperature oscillation.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# B2 - 5W to HTR 1 After Startup

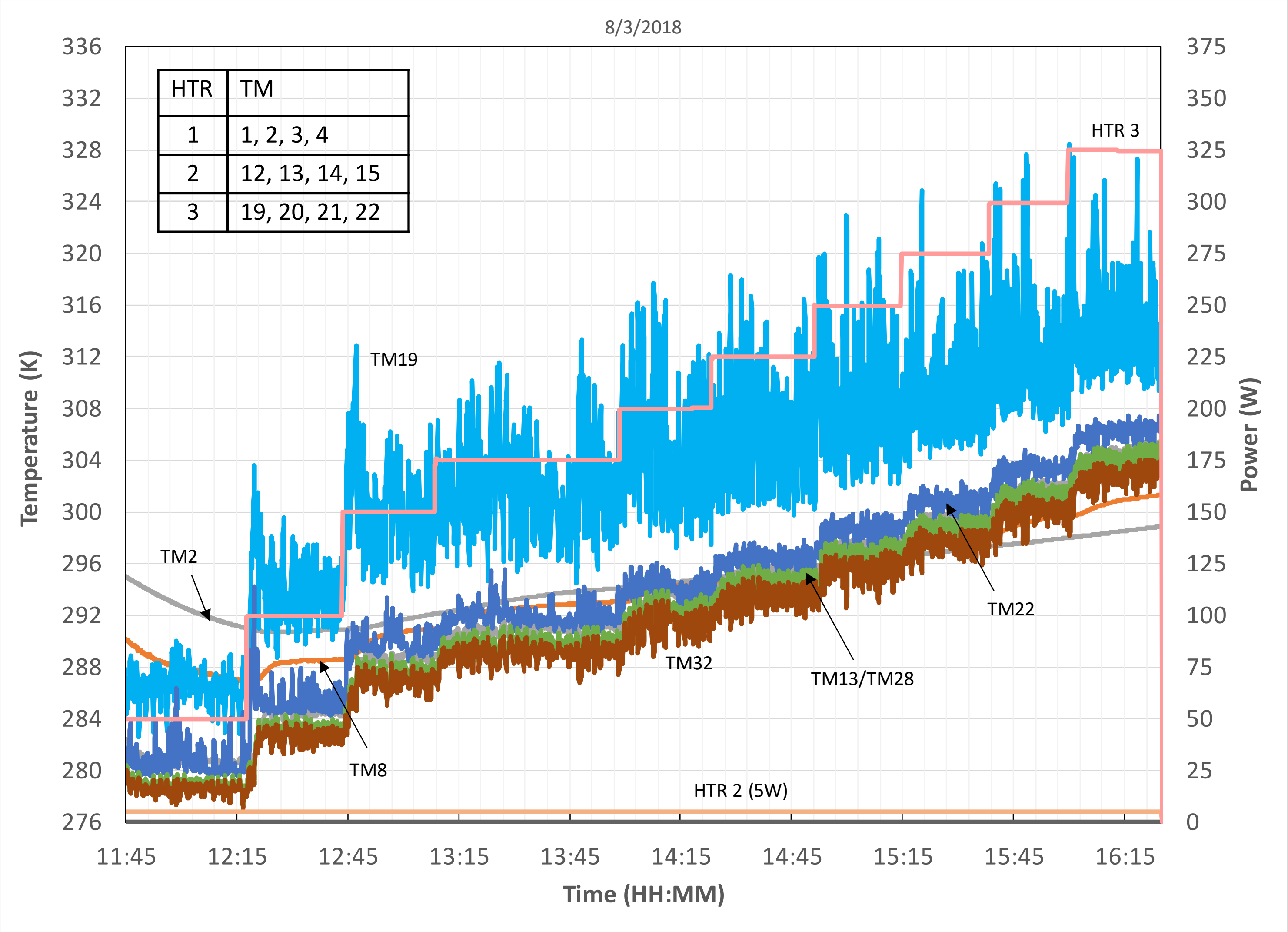
- **5W constant to HTR 1, variable heat load to HTR 3 from 50W to 275W.**
- **Immediately after each power increase, TM19 temperature rose sharply. As HTR 1 continued to supply vapor to the condenser, a quasi-steady condition was eventually reached among HTR 1, HTR 3, and the condenser. The process repeated after each HTR 3 power increase.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# C1 - 5W to HTR 2 After Startup

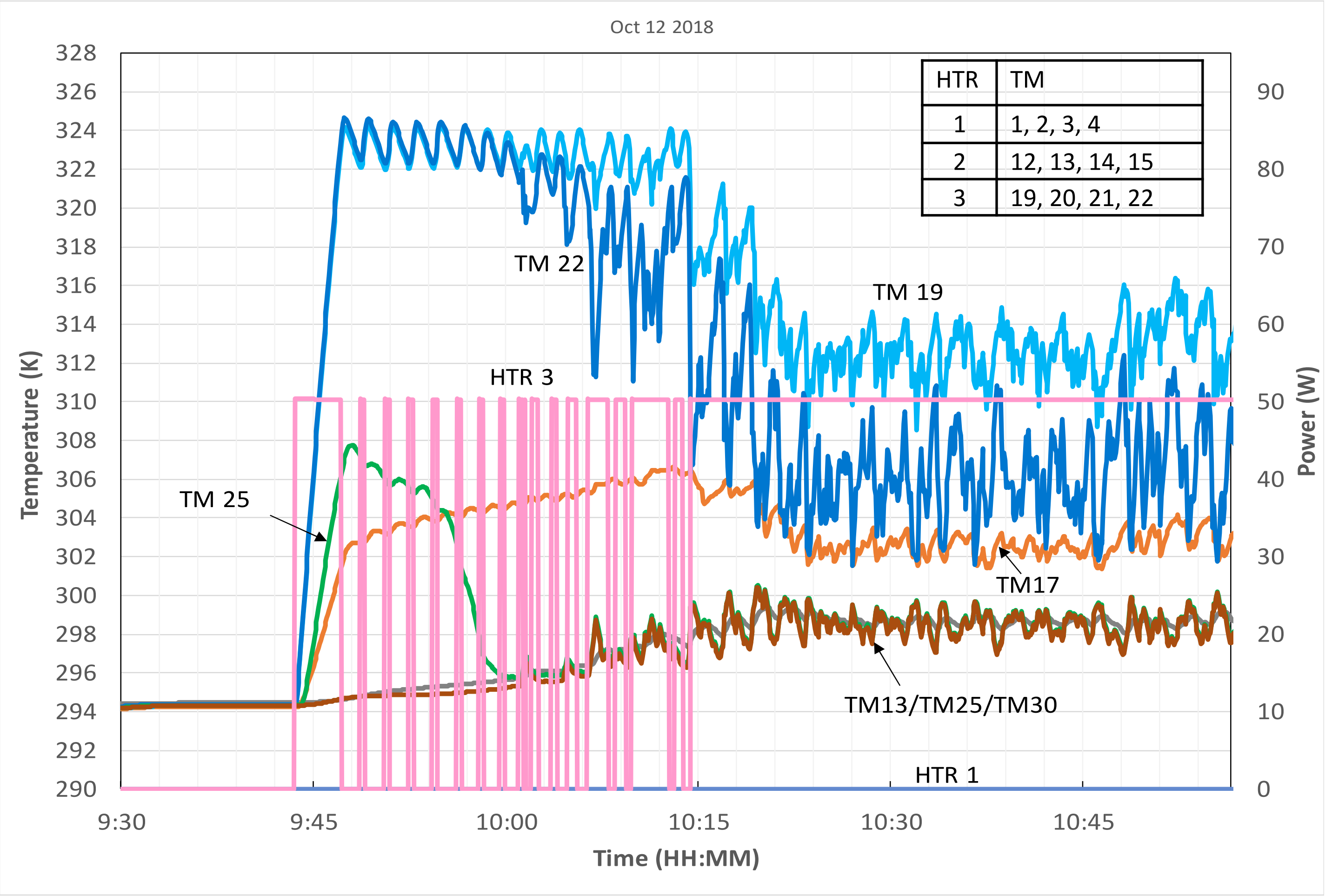
- **5W to HTR 2, variable heat load to HTR 3 from 50W to 325W.**
- **Operation was similar to that when 5W was applied to HTR 1. The amplitude of temperature oscillation did not vary much with HTR 3 power.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# E1 - Startup with 50W to HTR 3 Only

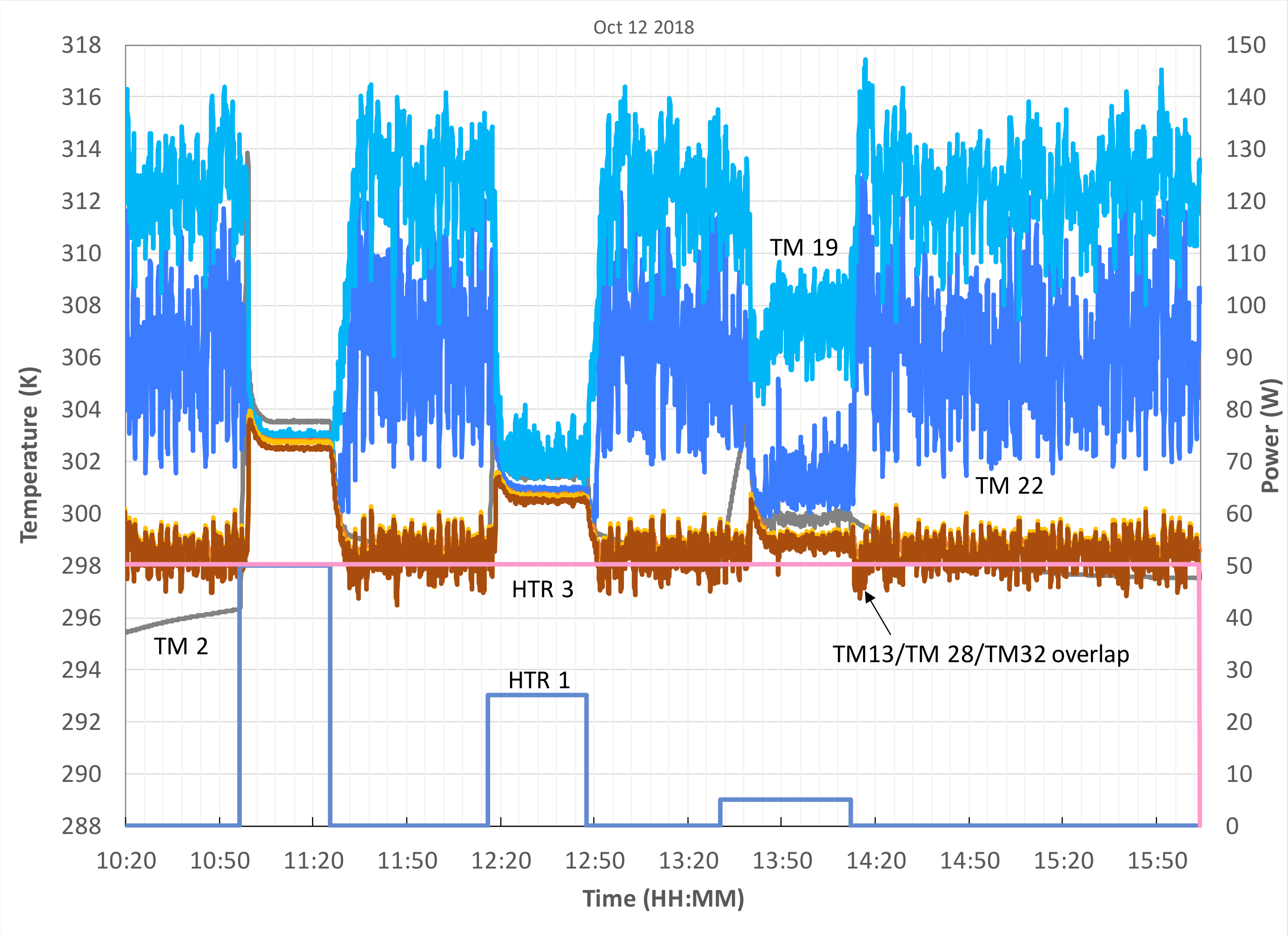
- HTR 3 cycled on and off for 30 minutes at thermostat set point of 323K. No startup. In theory, vapor in the condenser should condense slowly. Condensate began to built up in condenser.
- HTR 3 finally captured the falling condensate and the heat pipe started.



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# B3 - Operation After Startup (continued from E1)

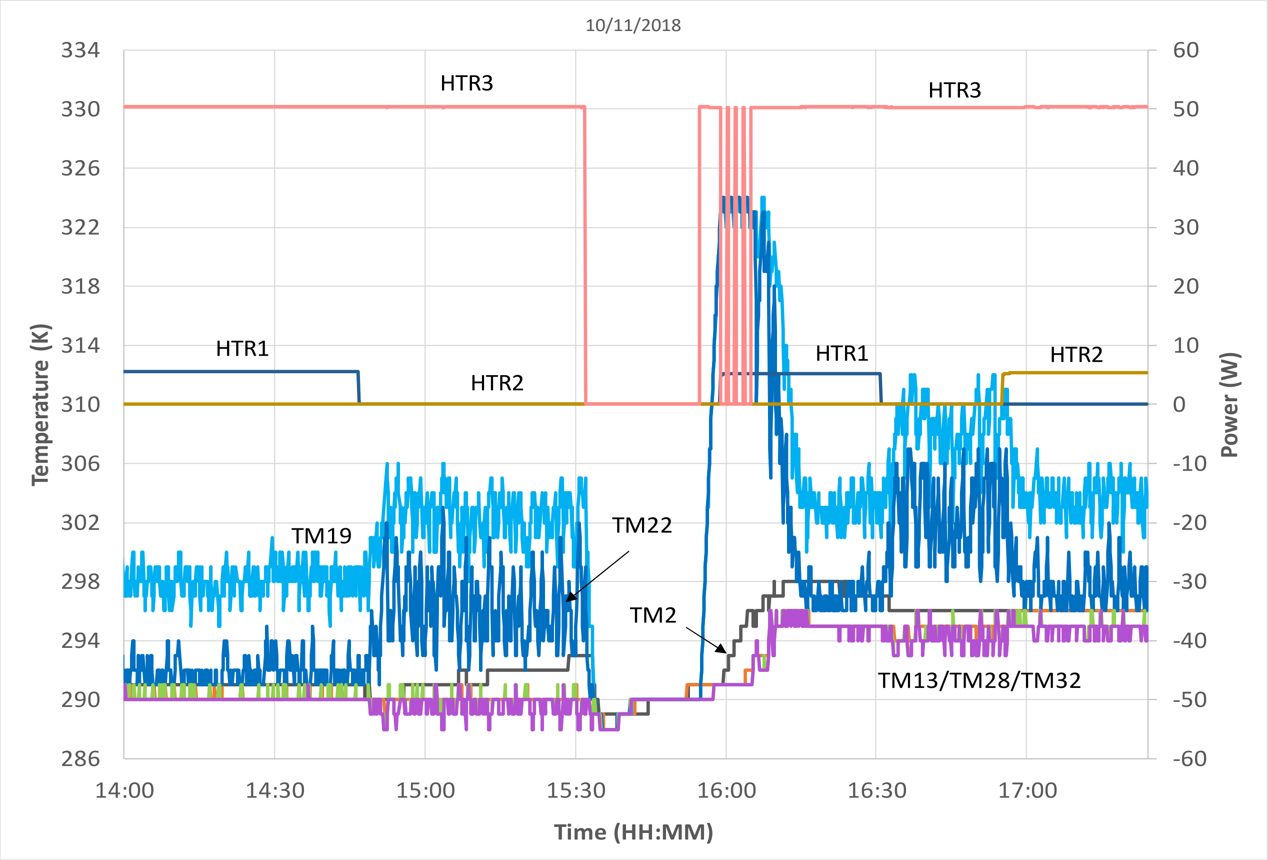
- After startup, heat pipe operated with 50W to HTR 3 alone. Amplitude of temperature oscillation with HTR3/HTR1 = 50W/0W was independent of immediate prior condition.
- Amplitude of temperature oscillation was a function of HTR 1 power when added.
- Even a small power of 5W to HTR1 could significantly reduce temperature oscillation.



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# D5 – Restart with HTR 3 Only

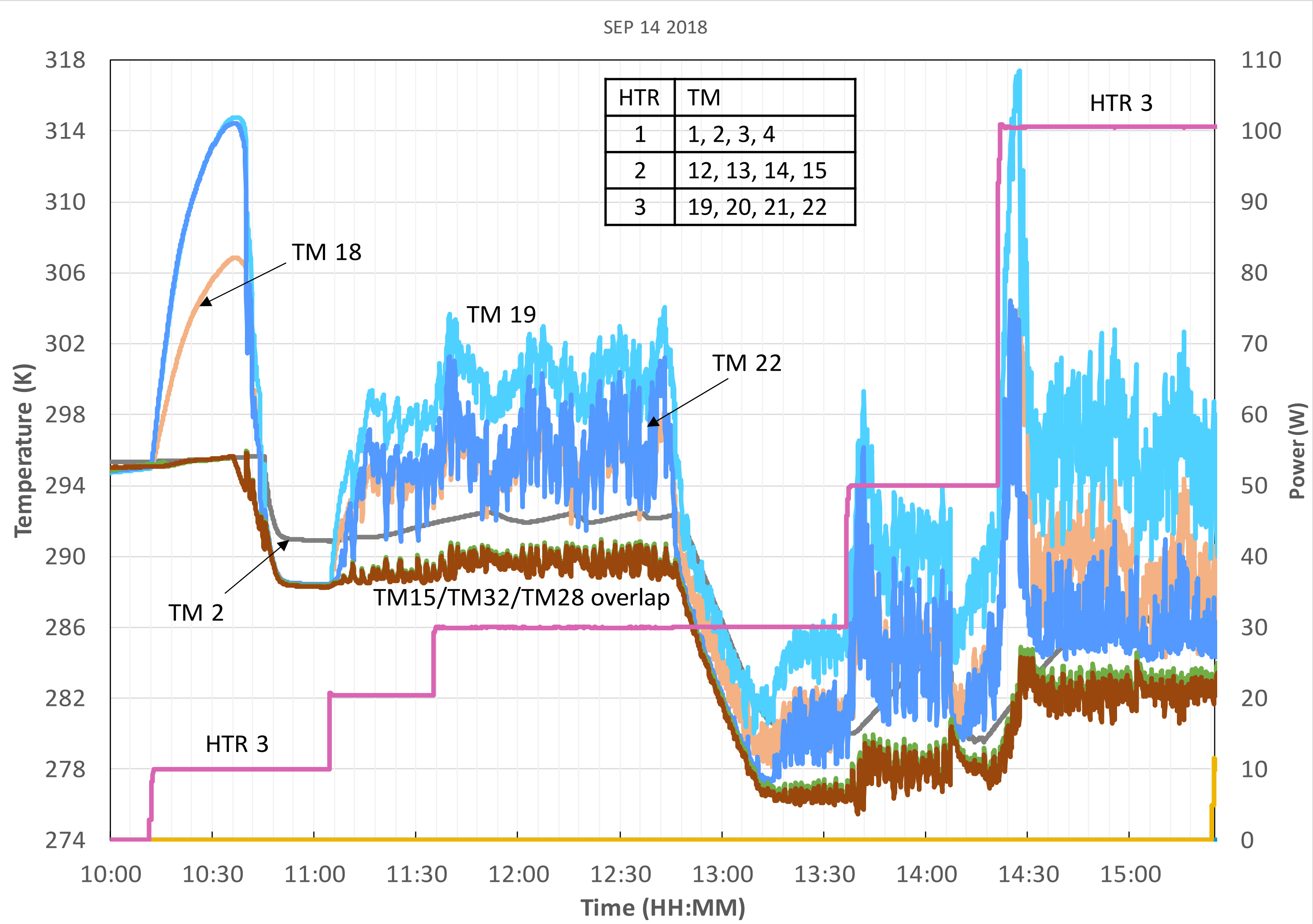
- **After startup, heat pipe operated quasi-steadily with 50W to HTR 3 alone.**
- **All heaters were turned off after quasi-steady operation, and there was no fluid flow.**
- **Applying 50W to HTR 3 raised HTR 3 temperatures, but no startup until 5W was added to HTR 1.**
- **Heat pipe operated quasi-steadily again with 50W to HTR 3 alone.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# E2 - Startup and Operation with Power to HTR 3 Only

- **The heat pipe did not start as TM19 rose to 314K. It started when the sink temperature was lowered from 294K to 283K.**
- **After startup, heat load applied to HTR3 only. HTR 3 temperatures fluctuated.**

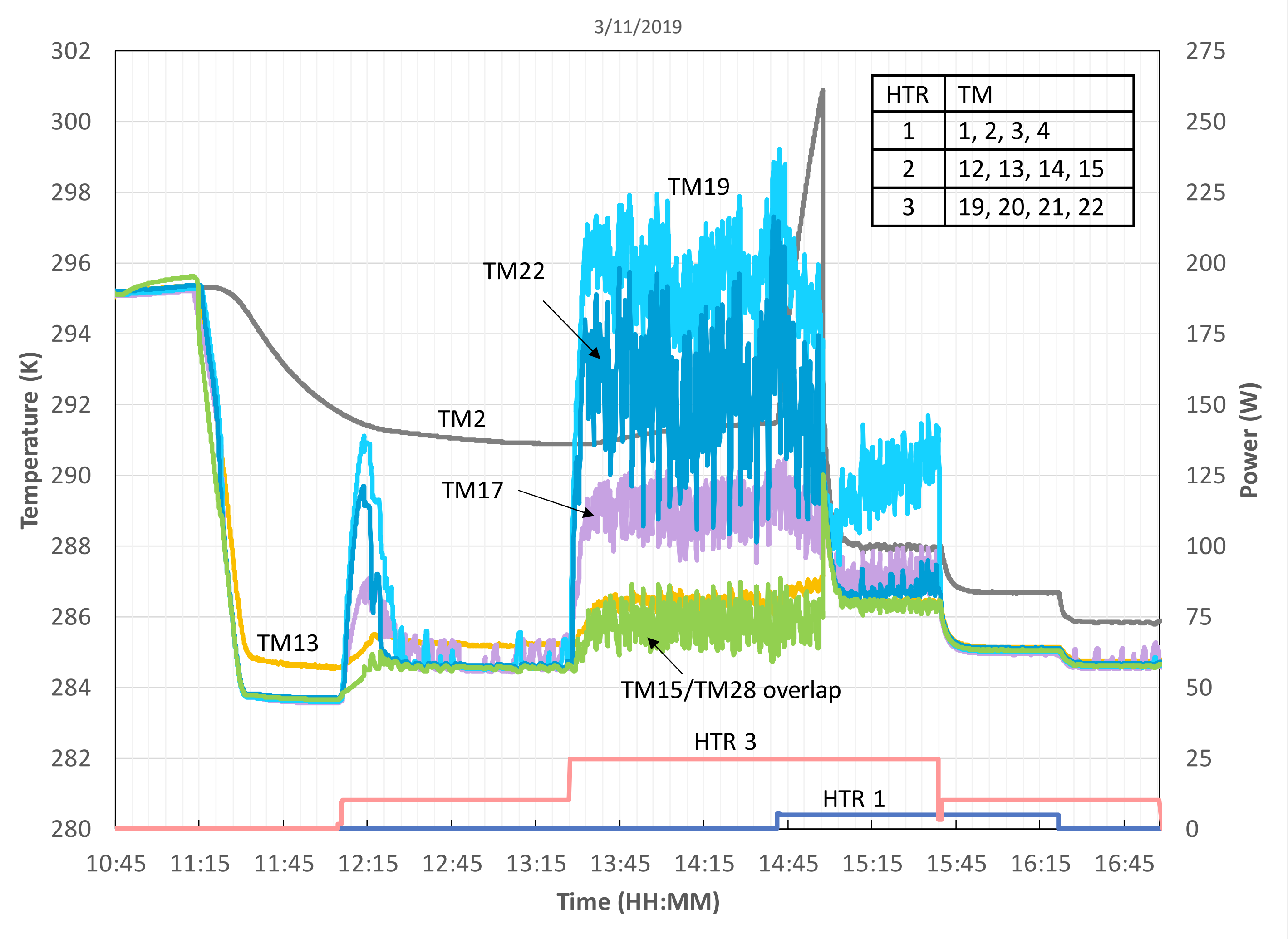


SEP 14 2018

| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# E3 – Startup and Operation with Power to HTR 3 Only

- **The heat pipe started when the sink temperature was lowered from 294K to 283K.**
- **After startup, 10W was applied to HTR 3 only – near steady state after transient. Large temperature oscillation when HTR 3 power increased to 25W.**



| HTR | TM |
|---|---|
| 1 | 1, 2, 3, 4 |
| 2 | 12, 13, 14, 15 |
| 3 | 19, 20, 21, 22 |

# Conclusions (1/2)

- **Under reflux mode, if the heated site is in contact with the liquid pool, the heat pipe can operate steadily.**
- **If the heated site is remote from the liquid pool, a reflux flow must be established before heat can be applied to that site.**
- **The most effective way to establish a reflux flow is to apply heat to a site in contact with the liquid pool. Another method is to reduce the condenser temperature rapidly before startup.**
- **After a reflux flow has been established, the temperature of the remote heated site is a function of its ability to capture the falling condensate.**
  - **If it can capture sufficient liquid to handle its entire heat load solely by evaporation, the heat pipe will reach steady operation.**
  - **Otherwise, temperature of the remote site will oscillate.**
- **For a given power to the remote site, there is a threshold power for the liquid pool heater above which temperature oscillation disappears.**
  - **The threshold power increases with an increasing power to the remote site.**

# Conclusions (2/2)

- The smaller the liquid pool power compared to the required minimum power, the larger the amplitude of its temperature oscillation.
- After a reflux flow has been established, the heat pipe can have self-sustained, quasi-steady operation with heat load to the remote site alone. At low heat load, the heat pipe may even reach self-sustained steady operation.
- This study used an L-shaped heat pipe and the condenser was placed in the horizontal leg. Liquid might have accumulated in the horizontal leg before it reached a critical volume and fell. It is suspected that the operating characteristic may be different if a straight heat pipe is used.
- In some flight applications, heat is applied to the middle and dissipated to both sides of the heat pipe. This case cannot be exactly simulated under reflux mode.