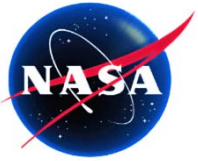


# **Thermal Performance of an Aluminum/Ammonia Heat Pipe under Reflux Mode**

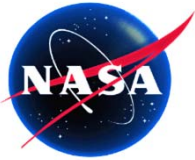
**Jentung Ku  
NASA Goddard Space Flight Center  
Greenbelt, Maryland, USA**

**2019 Spacecraft Thermal Control Workshop  
The Aerospace Corporation, El Segundo, California, March 26-28, 2019**



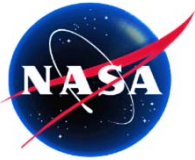
## Outline

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



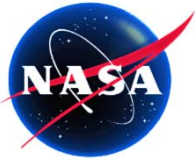
## Introduction/Objectives

- **During instrument-level or spacecraft-level ground testing, heat pipes may be placed in reflux mode, with condenser above evaporator. A liquid pool will form at the bottom of the heat pipe.**
- **If heat is applied to a site below the surface of the liquid pool in a vertical heat pipe, the heat pipe can work properly under reflux mode.**
  - **A superheat is required for startup.**
- **If heat is applied to a site above the liquid pool, the heat pipe is not expected to work unless additional heat is applied to the liquid pool to provide the needed flow circulation.**
  - **There are many reason to minimize the additional heater power.**
- **An experimental investigation was conducted to study the heat pipe behavior under this configuration.**



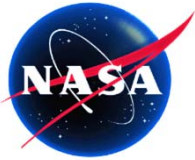
## Theoretical Background – HP Operation (1/3)

- For proper heat pipe operation, liquid must be present in the porous wick inside the heat pipe at the heating site.
- In the absence of any body forces, liquid will fill the porous wick throughout the entire heat pipe. The heat pipe can take heat from any location, making it an isothermalizer.
- Under reflux mode, a heated site below the liquid pool level will have continuous liquid supply. Vapor is formed when liquid in the pool is vaporized and flows upward to the condenser. Liquid drains from the condenser and flows downward along the capillary wicks due to the influence of gravity.
- Once this reflux flow is established, it is possible for the heat pipe to take heat at locations above the liquid pool. In this case evaporation occurs directly from the condensate film falling down the wall of the heat pipe.
- It is critical that at any heated location there remains sufficient flow of condensate so that dry-out does not occur.



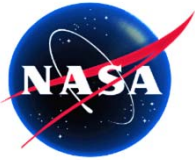
## Theoretical Background – HP Operation (2/3)

- For steady heat pipe operation, there must be sufficient condensate feeding the heated site to ensure that the heat load is dissipated solely by liquid evaporator at all times.
- As an example, consider two heated sites: the upper heated site is above the liquid pool and lower heated site is below.
- The lower heated site always has a continuous supply of liquid.
- Some liquid falling from the condenser will “leak” through the upper site regardless of heat loads to the two sites. Otherwise, the lower site will be depleted of liquid after a while.
- The system will eventually reach an equilibrium state – either at a steady or quasi-steady state.
- If there is ample liquid falling from the condenser, and the upper site can capture sufficient liquid to handle its applied heat load solely by evaporation, the heat pipe will have steady temperatures over its entire length.
-



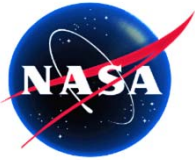
## Theoretical Background – HP Operation (3/3)

- **If the amount of falling liquid captured by upper site is insufficient to handle the heat by evaporation, the upper site will display temperature fluctuations due to its intermittent contact with liquid.**
  - **When in contact with liquid, its temperature drops. Immediately after liquid evaporation, the upper site dries out and its temperature rises until it captures the falling liquid again. This process repeats itself.**
  - **The amplitude and frequency of temperature fluctuation is a function of liquid vaporization in both upper and lower sites, vapor condensation in the condenser, the amount of liquid accumulated in the condenser before falling back toward the liquid pool.**
  - **The most important factor that characterizes the system performance is the relative heat loads to the upper and lower sites.**
  - **The magnitude of temperature fluctuation at the upper site decreases with an increasing heat load to the lower site, and vice versa.**
  - **The lower heating zone will always show steady temperatures because it has a continuous supply of liquid.**
  - **For a given power to the upper heater, there exists a threshold power to the lower site above which the temperature fluctuation disappears and the heat pipe reaches a true steady state.**



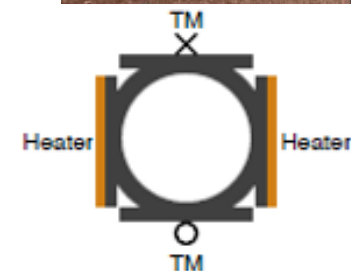
## Technical Approach of the Study

- **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 vertical leg of the heat pipe.**
- **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 at a site removed from 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.**

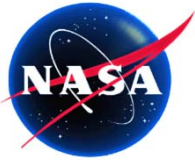


## Test Article

- **The test article was a spare unit from the LRO 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 111 mm wide.**
  - **Working fluid: ammonia**
  - **Fluid inventory: 31.2 grams**
  - **When the entire liquid inventory accumulates at the bottom of the heat pipe under gravity, the liquid pool length is 423 mm at 298K.**

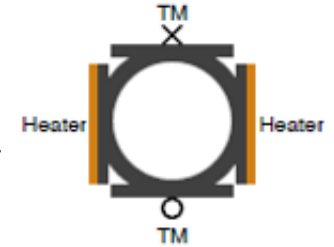


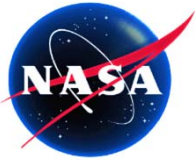




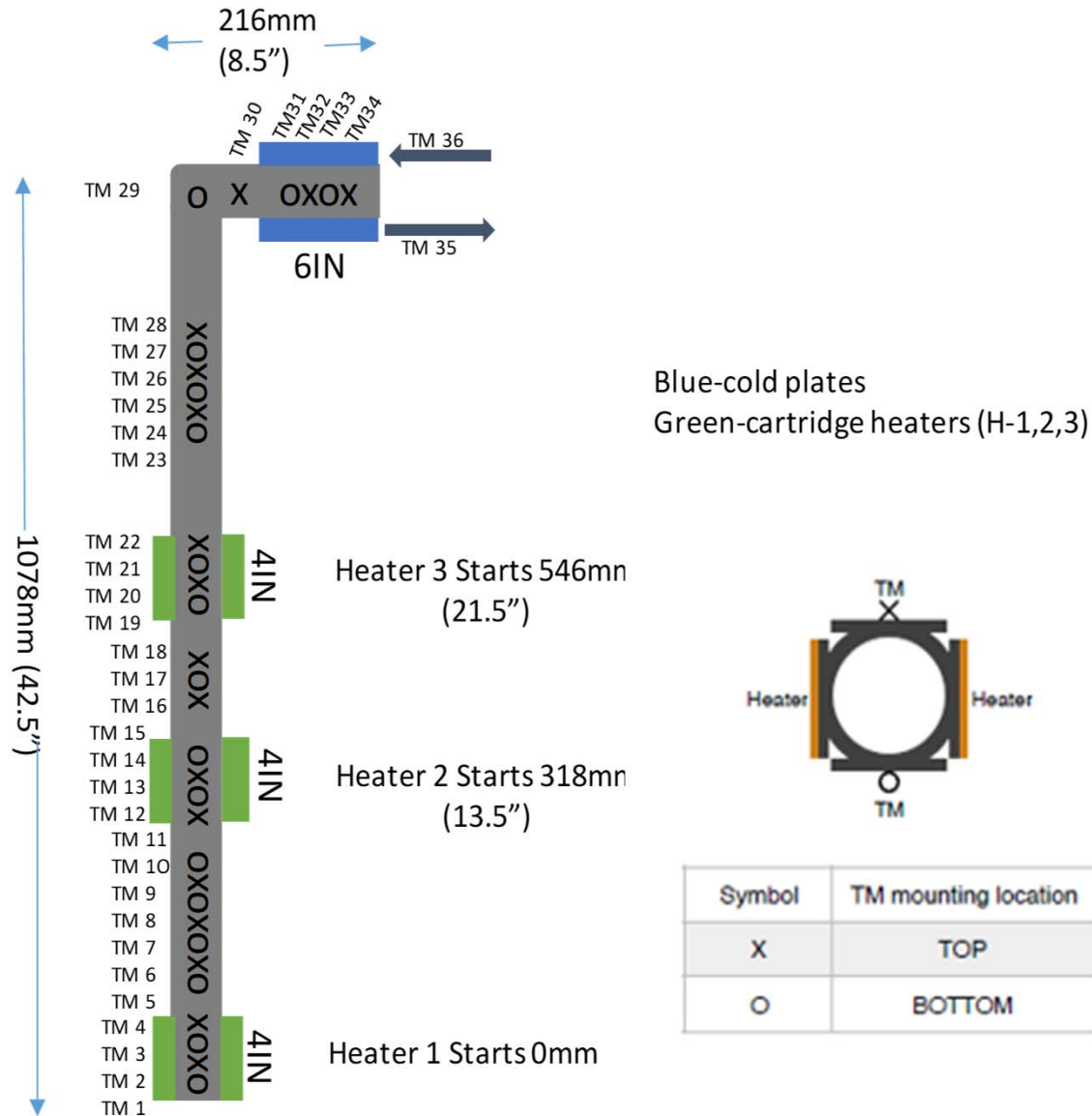
## Test Setup and Instrumentation (1/2)

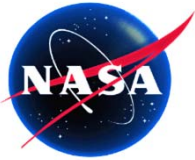
- **Three aluminum heater blocks were used with inserted cartridge heaters.**
  - Each 101.6mm long, and provided up to 300W of power.
- **The three heater blocks were attached to three sites on the 1068 mm vertical leg.**
  - Heater 1 was at the very bottom of the leg.
  - Heater 2 were 343mm from the 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 heating site had 4 thermistors.
- **The end of the 216 mm horizontal leg was used as the condenser.**
  - Condenser length: 153 mm
  - A cold plate was attached to the condenser. A recirculating chiller was used to circulate the coolant through the cold plate.
  - Four thermistors were attached to the condenser.
- **Eighteen thermistors were installed in the adiabatic sections in-between heater blocks and the condenser.**





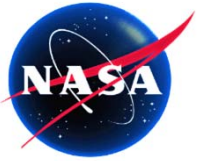
# Heater and Thermistor Locations



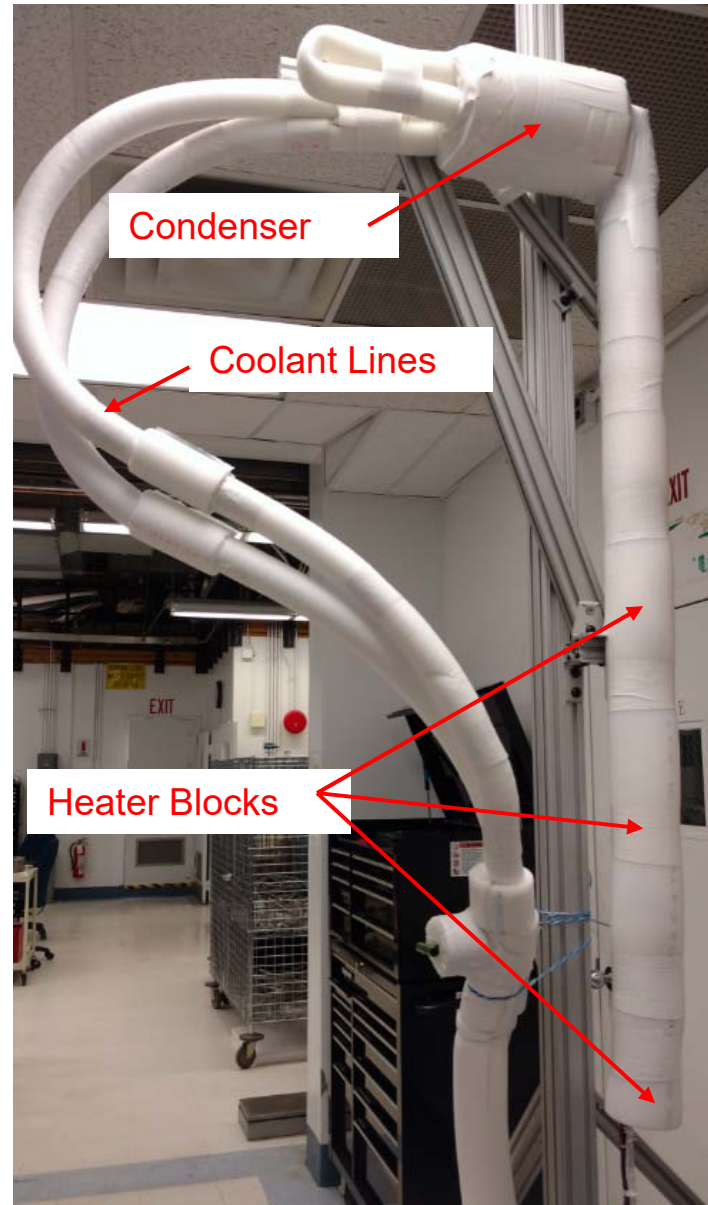


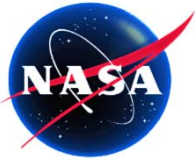
## Test Setup and Instrumentation (2/2)

- **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 displayed on the screen once every second, and stored in computer once every 5-10 seconds.**



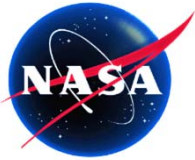
# Heat Pipe in Vertical Configuration





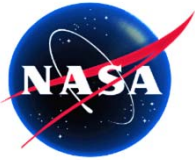
## Tests Performed

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



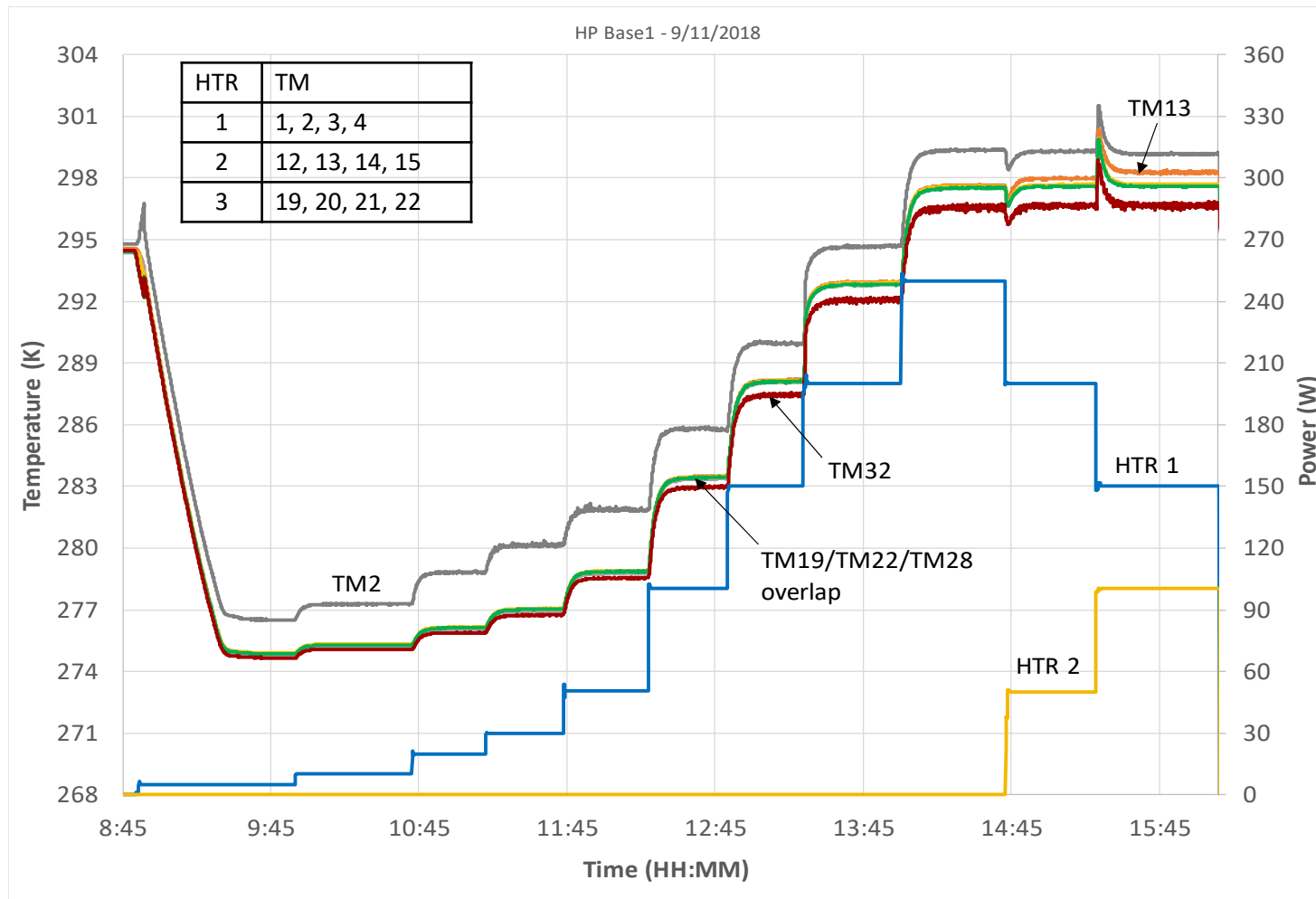
## Data Plot and Presentation

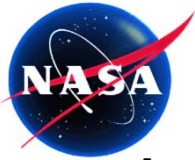
- **In each figure, relevant segments and their thermistor temperatures are plotted to show the temperature profiles of the heat pipe.**
  - **Each heater had 4 thermistors**
  - **A table is provided to show the heater and corresponding thermistors**
- **Each plot is assigned the test series and test number for easy reference during discussion.**
  - **A1, A2, B1, B2, etc.**



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

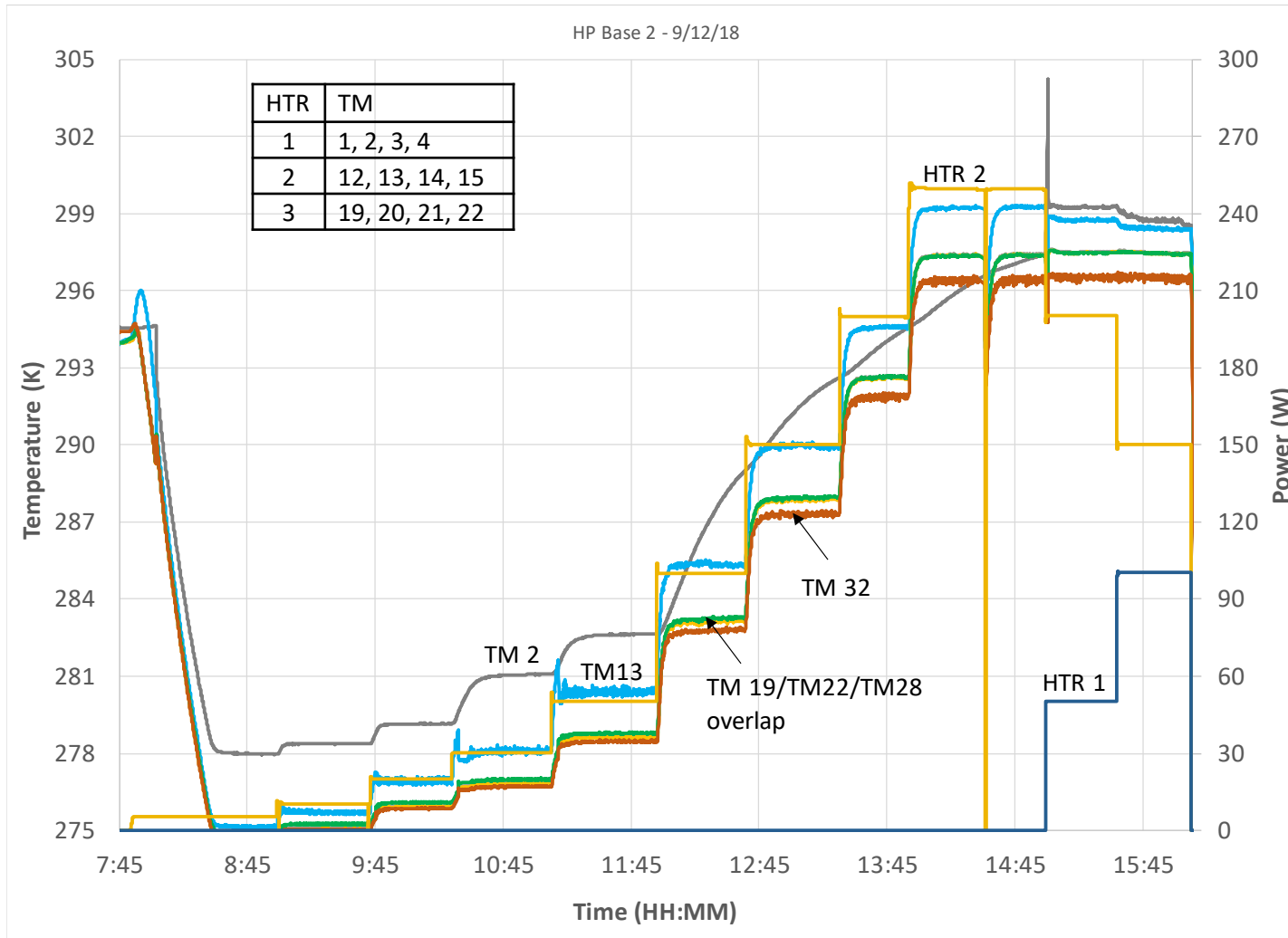
- Applied different heat loads to HTR 1 and HTR 2. Startup with 5K superheat (TM2). Steady operation. No temperature fluctuation. All thermistors above HTR 1 showed a uniform temperature except for heat source and heat sink.



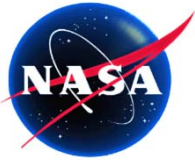


## A2 Baseline: HTR 2 Power from 5W to 250W

- Applied different heat loads to HTR 2 & HTR 1. Startup with 7K superheat (TM13). Steady operation. No temperature fluctuation. TM2 rose due to heat conduction from HTR 2. 8K superheat at boiling inception.







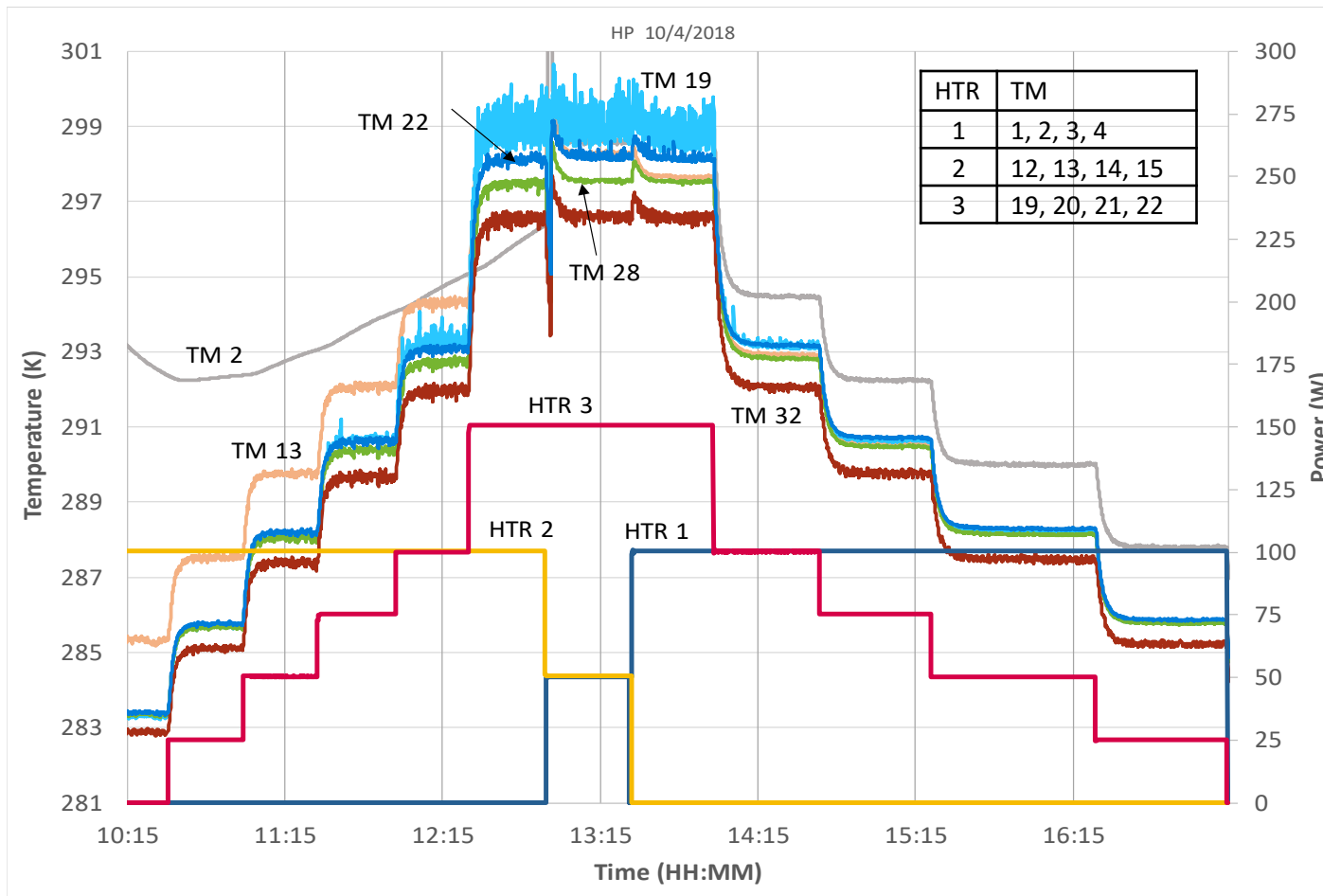
## Data Analyses and Discussions (1)

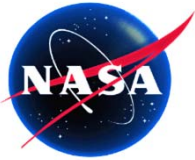
- **A superheat was required when heat was applied to a site completely covered by liquid – whether it was HTR 1 or HTR 2.**
- **After start-up, a uniform temperature was seen for all TMs above the heating site. The liquid pool still existed below the heating site.**
- **After startup, and the heat pipe operated similarly to that under a horizontal condition when the heat load and/or the sink temperature changed,**
- **A1 showed that after startup with the lower heater (HTR 1), no more superheat was required when HTR 2 power was added.**
- **A2 showed that after startup with HTR 2 heater, HTR 1 was still covered with liquid and a superheat was require when HTR 1 power was added.**
- **In subsequent plots of test results, the heat pipe was started by applying power to HTR 1 or HTR 2 before applying power to HTR 3. The startup was always accompanied by a superheat. The startup portion is not presented for most tests in order to show temperatures more clearly.**



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

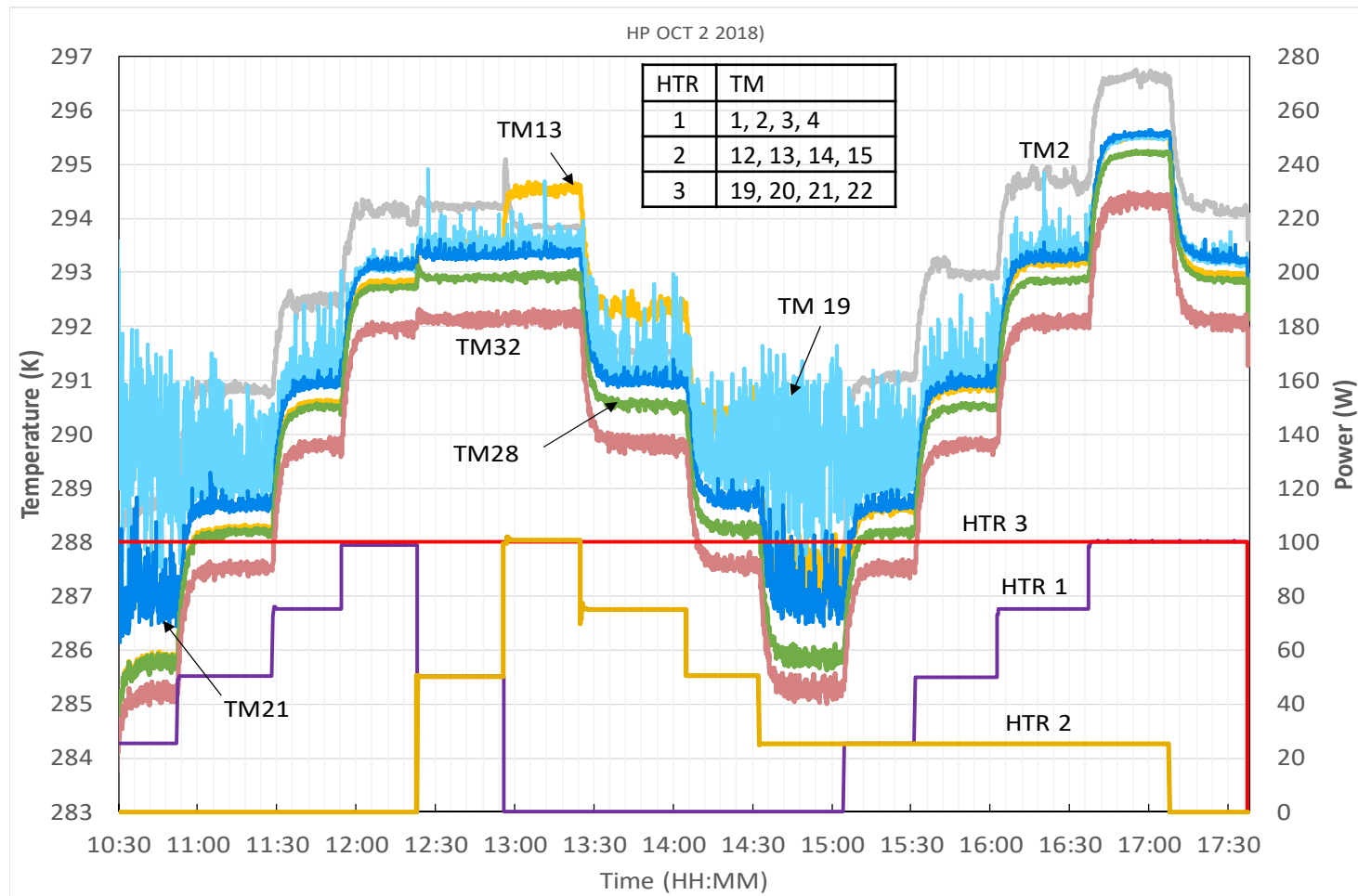
- A total power of 100W to HTR1/HTR2. HTR 3 power varied between 25W and 150W.
- No or small temperature fluctuation for HTR 3 power up to 100W. At 150W, temperature fluctuation was ~2K. At 12:55, HTR 2 was added, and TM2 rose to 311K (superheat = 14K) at nucleate boiling incipient (off scale).
- Using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

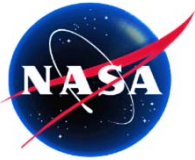




## D2a- 100W to HTR 3, (HTR 1 + HTR 2) Power Varied

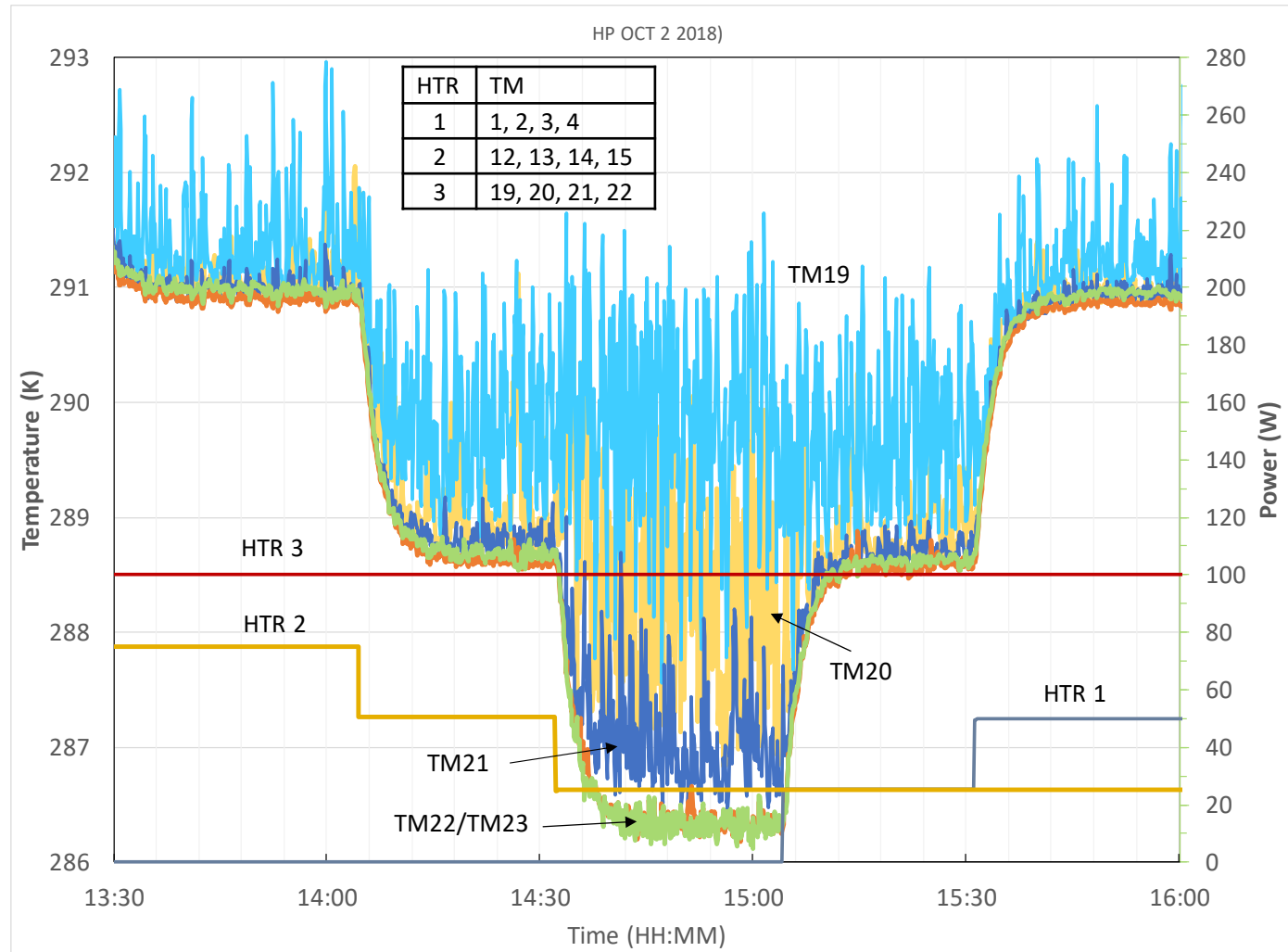
- HTR 3 showed temperature fluctuation when total power to (HTR 1 + HTR 2) was below 100W. Amplitude of temperature fluctuation decreased with increasing power to (HTR 1 + HTR 2).
- Using HTR 1 had a slight advantage over HTR 2 in reducing temperature fluctuation.

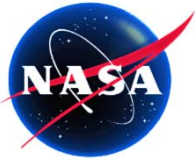




# D2b - 100W to HTR 3, (HTR 1 + HTR 2) Power Varied

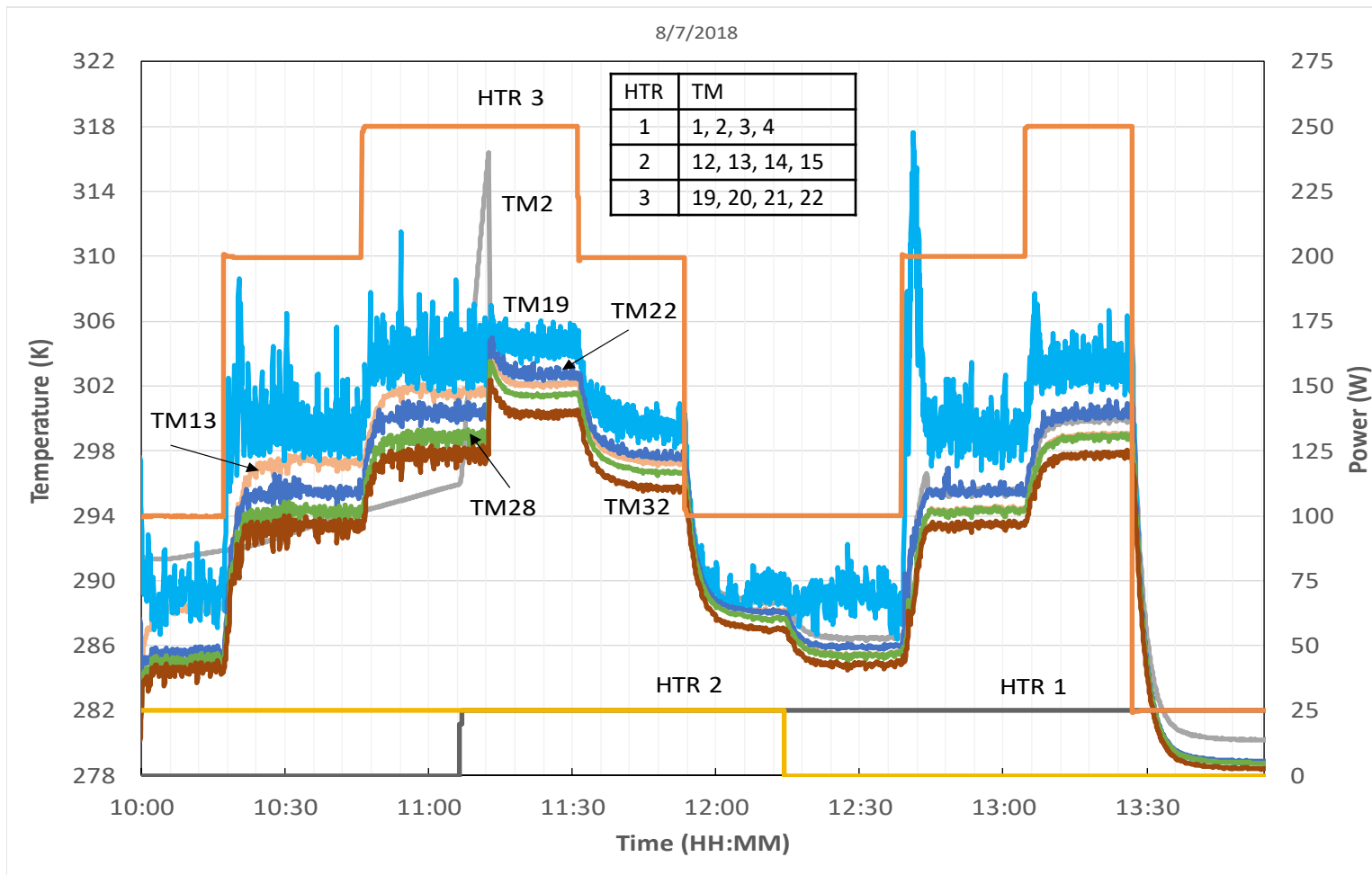
- This is a subset of the same test as shown in D2a. The amplitude of temperature fluctuation at the top of HTR 3 (TM22) was much lower than that at the bottom (TM19).

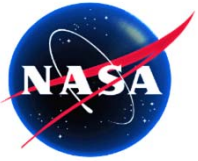




# D3 - Various Heat Loads to HTR 1, HTR 2, and HTR 3

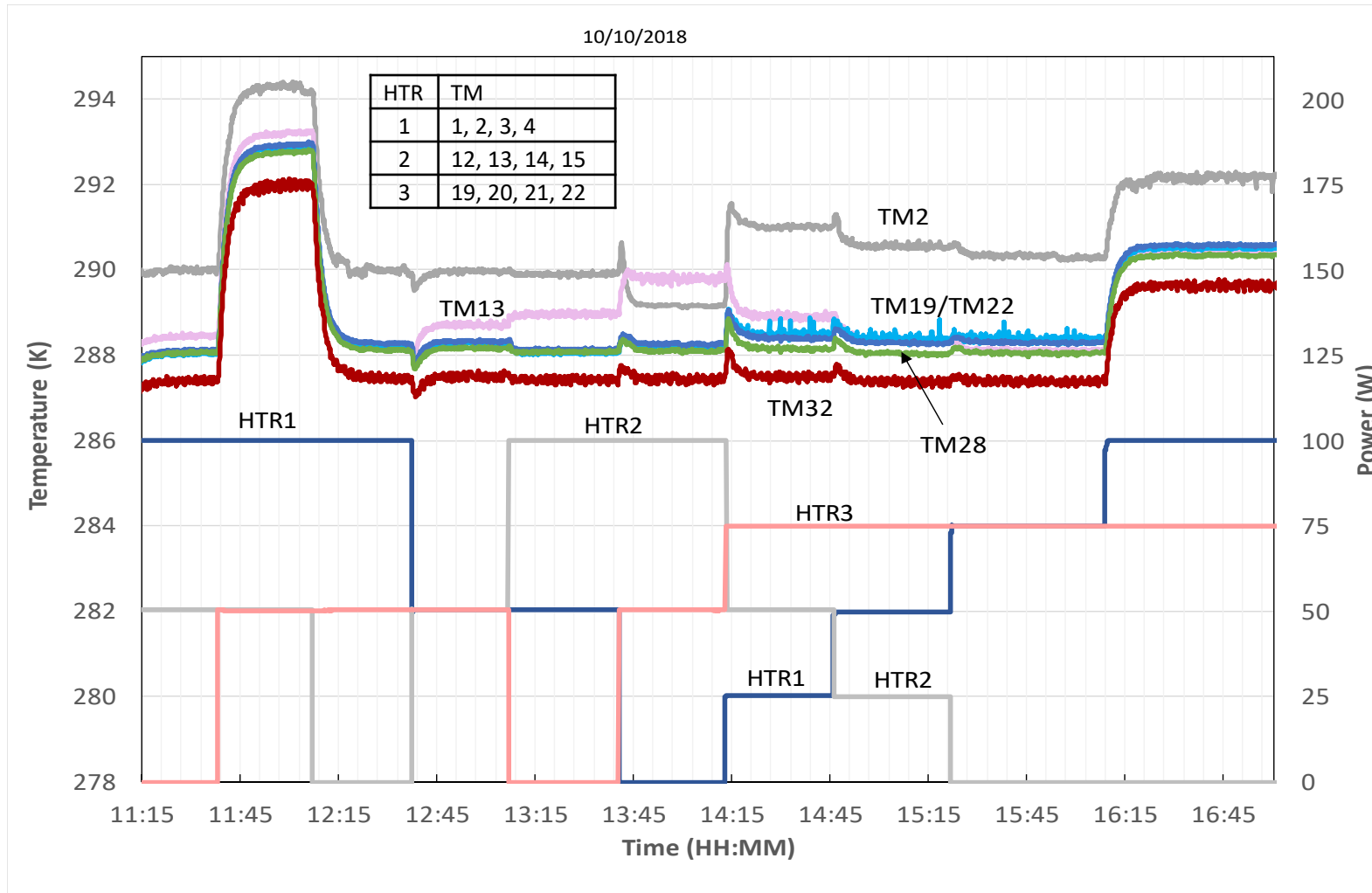
- 1<sup>st</sup> part - HTR 3 power: 100W/200W/250W, HTR 2 power: 25W
- 2<sup>nd</sup> part – HTR 3 power: 250W/200W/100W, HTR 1 power: 25W, HTR 2 power: 25W
- 3<sup>rd</sup> part – HTR 3 power: 100W/200W/250W/25W, HTR 1 power: 25W

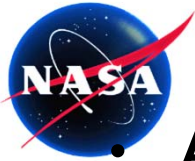




# D4 - Condition for Steady Operation

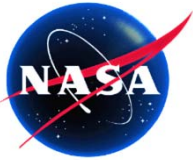
- As long as the total power to (HTR 1 + HTR 2) is greater than HTR3 power, there will be no or little temperature fluctuation.





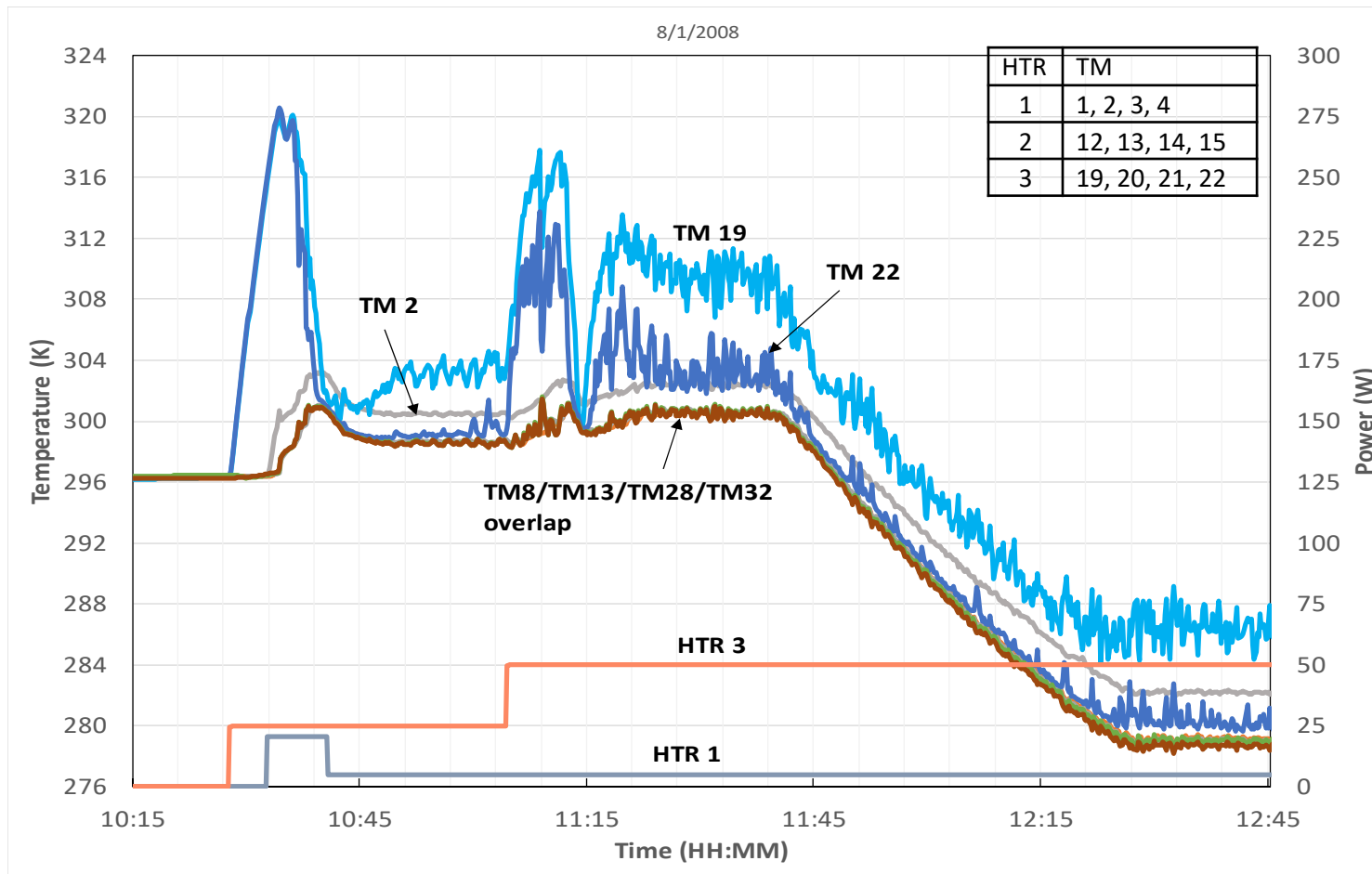
## Data Analyses and Discussions (2)

- Apparently, when liquid falling from the condenser passed through HTR 3, some liquid “leakage” occurred. Unless HTR 3 could capture sufficient amount of liquid, its temperature would fluctuate because of its intermittent contact with liquid.
- TM 21 and TM 22 were at the top of HTR 3, and could capture more liquid than TM19, which was at the bottom of HTR 3. This was manifested in the magnitude of temperature fluctuation on each sensor. This is more clearly shown in Plot D2b.
- The greater the total power to HTR 1 and HTR 2, the more falling liquid was available for HTR 3 to capture, and the smaller the amplitude of temperature fluctuation.
- As long as the total power to HTR 1 and HTR 2 is greater than HTR3 power, there will be no or little temperature fluctuation. This is valid for a given heat pipe, heater locations, and test setup.
- All test results shown above were those after the heat pipe had successfully started using HTR 1 or HTR 2.
- Other attempts for startup are presented next.

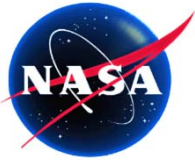


# B1 - Startup with HTR 1 Assist

- With 25W to HTR 3 alone, the HP did not start as TM19 rose to 316K. Then 20W was added to HTR 1, and the heat pipe started soon after.
- Right after HTR 3 power increase to 50W, HTR 3 temperatures rose sharply. Then a quasi-steady condition was reached and the temperatures decreased and fluctuated.
- At 11:40, chiller reset from 294K to 273K.

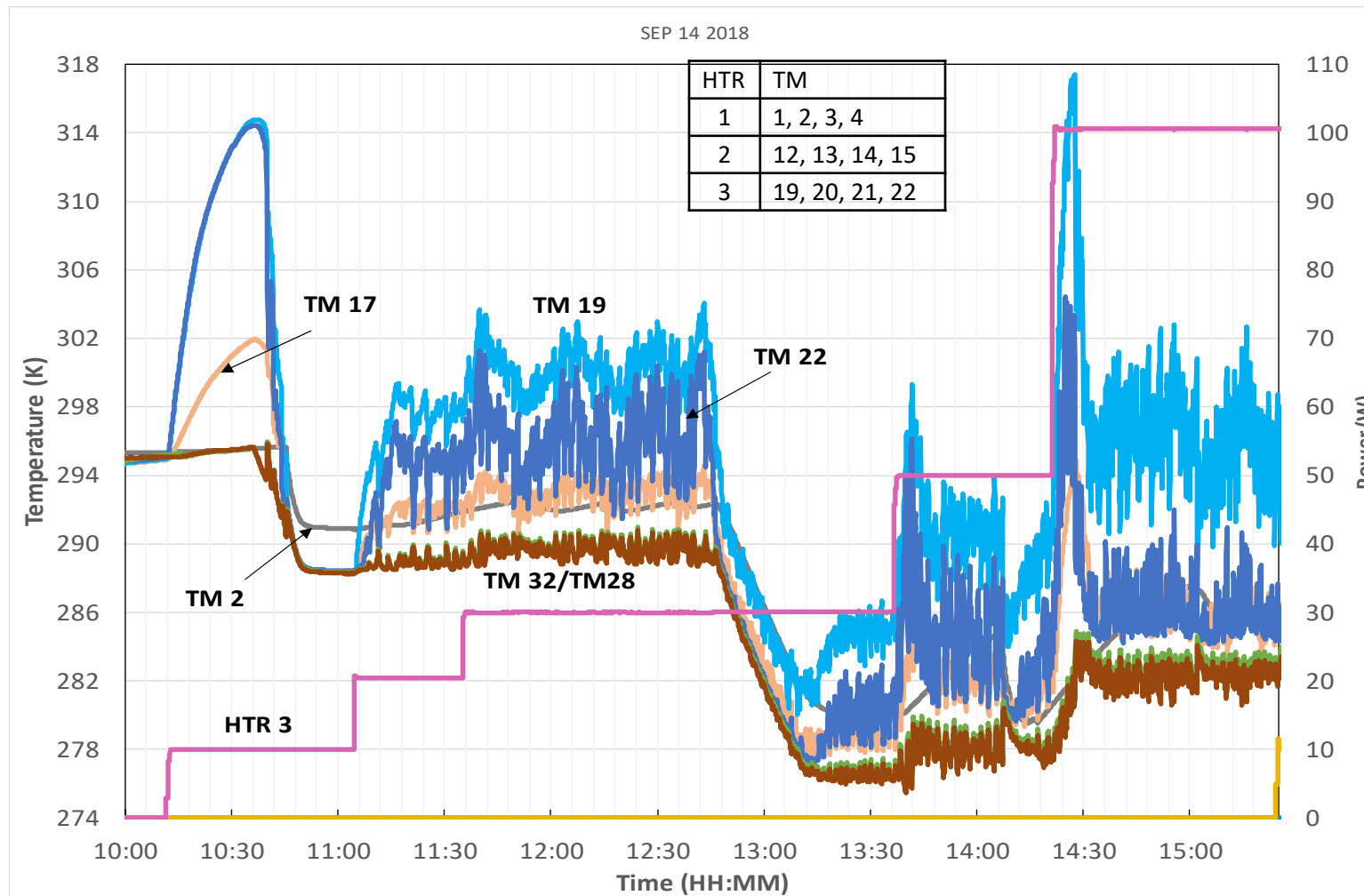


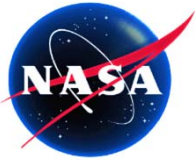




# E1 - Heat Load to HTR3 Only

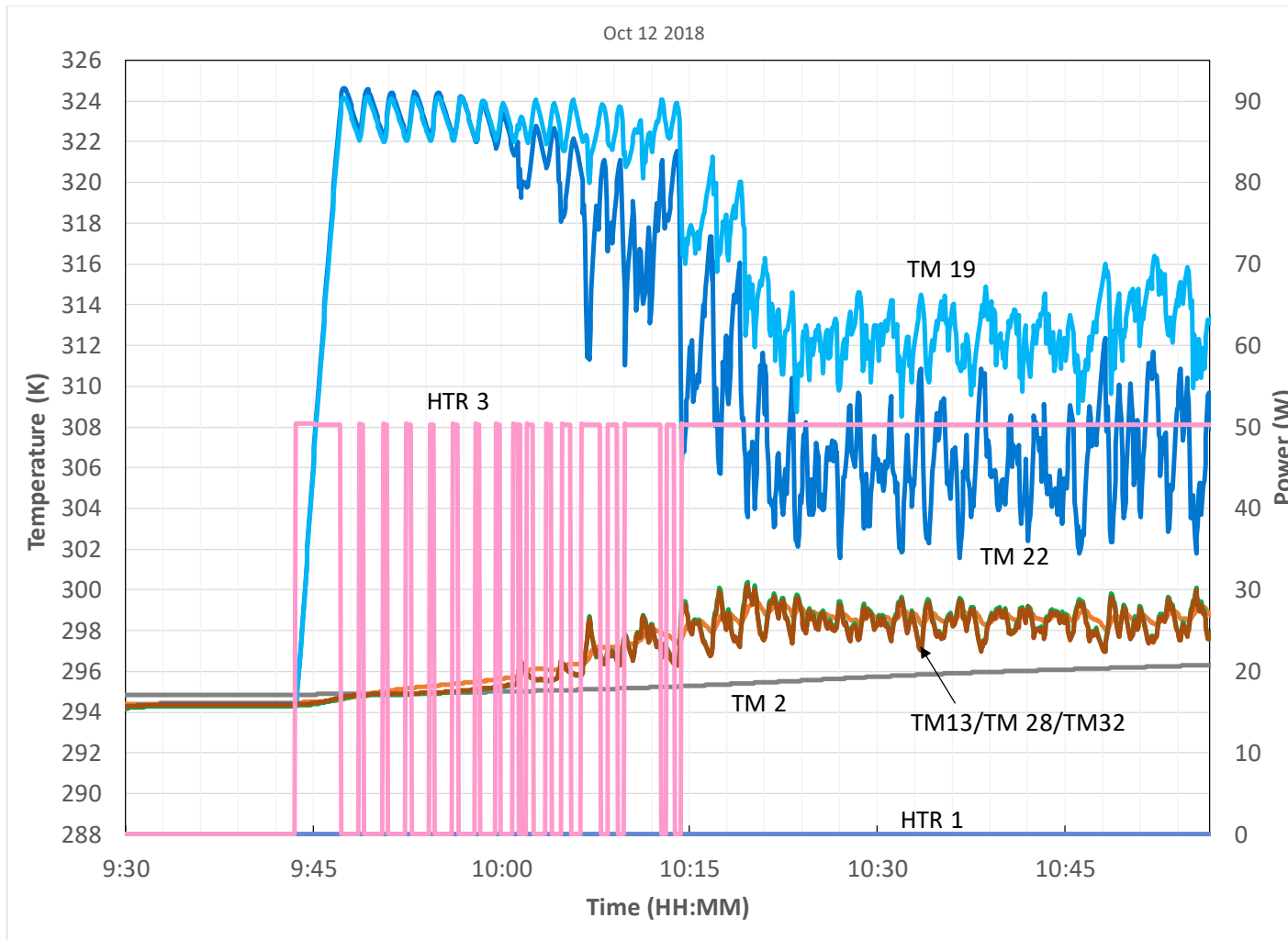
- The heat pipe did not start as TM19 rose to 314K. HP started when the sink temperature was reset from 294K to 283K.
- Different heat loads to HTR3 only after startup. HTR temperatures fluctuated.



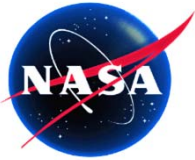


## E2 - Startup with 50W to HTR 3 Only 10/12/18 (done)

- HTR 3 cycled on and off for 30 minutes at thermostat set point of 325K. Vapor began to condense in the condenser.
- HTR 3 finally captured the falling liquid and stated.

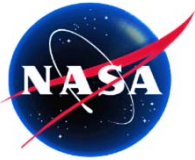


HTR	TM
1	1, 2, 3, 4
2	12, 13, 14, 15
3	19, 20, 21, 22



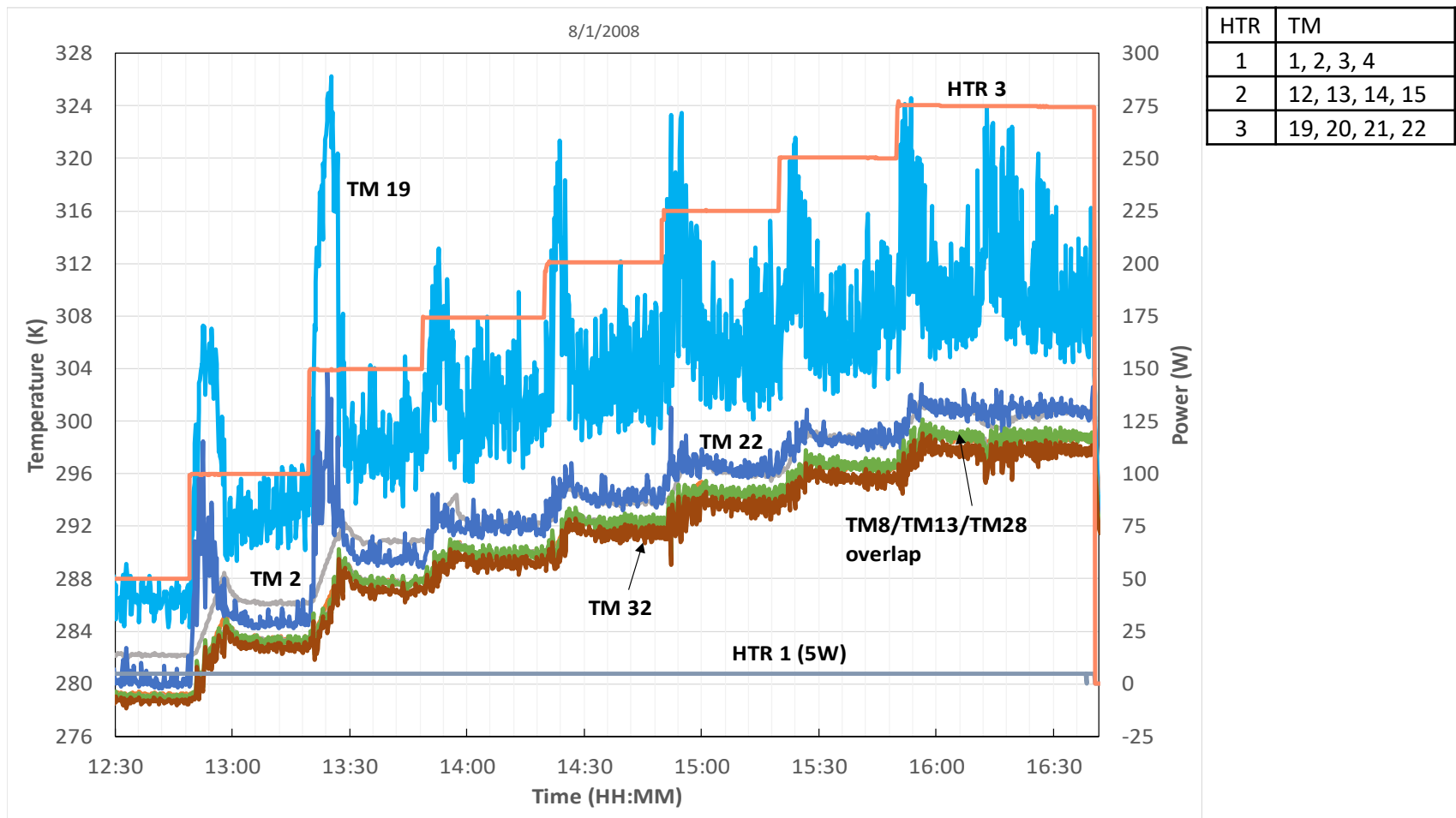
## Data Analyses and Discussions (3)

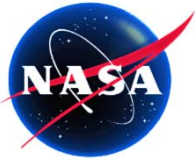
- **Although heat applied to HTR 3 could be transmitted to the condenser and liquid pool by conduction through the aluminum shell, the most efficient way to dissipate heat from HTR 3 was by way of liquid evaporation.**
- **The only liquid that could be captured by HTR 3 was the liquid falling from the condenser.**
- **When the condenser temperature was lower than the rest of the heat pipe, vapor resulting from liquid evaporation in the liquid pool could be slowly condensed in the condenser and would eventually fall back toward the liquid pool.**
- **The most effective way to provide sufficient amount of falling liquid for HTR 3 to capture was to apply heat to the liquid pool (either to HTR 1 or to HTR 2).**
- **Conclusion: the most effective way to start the heat pipe was to apply heat to HTR 1 or HTR 2, or both.**



## B2 - 5W to HTR 1 After Startup

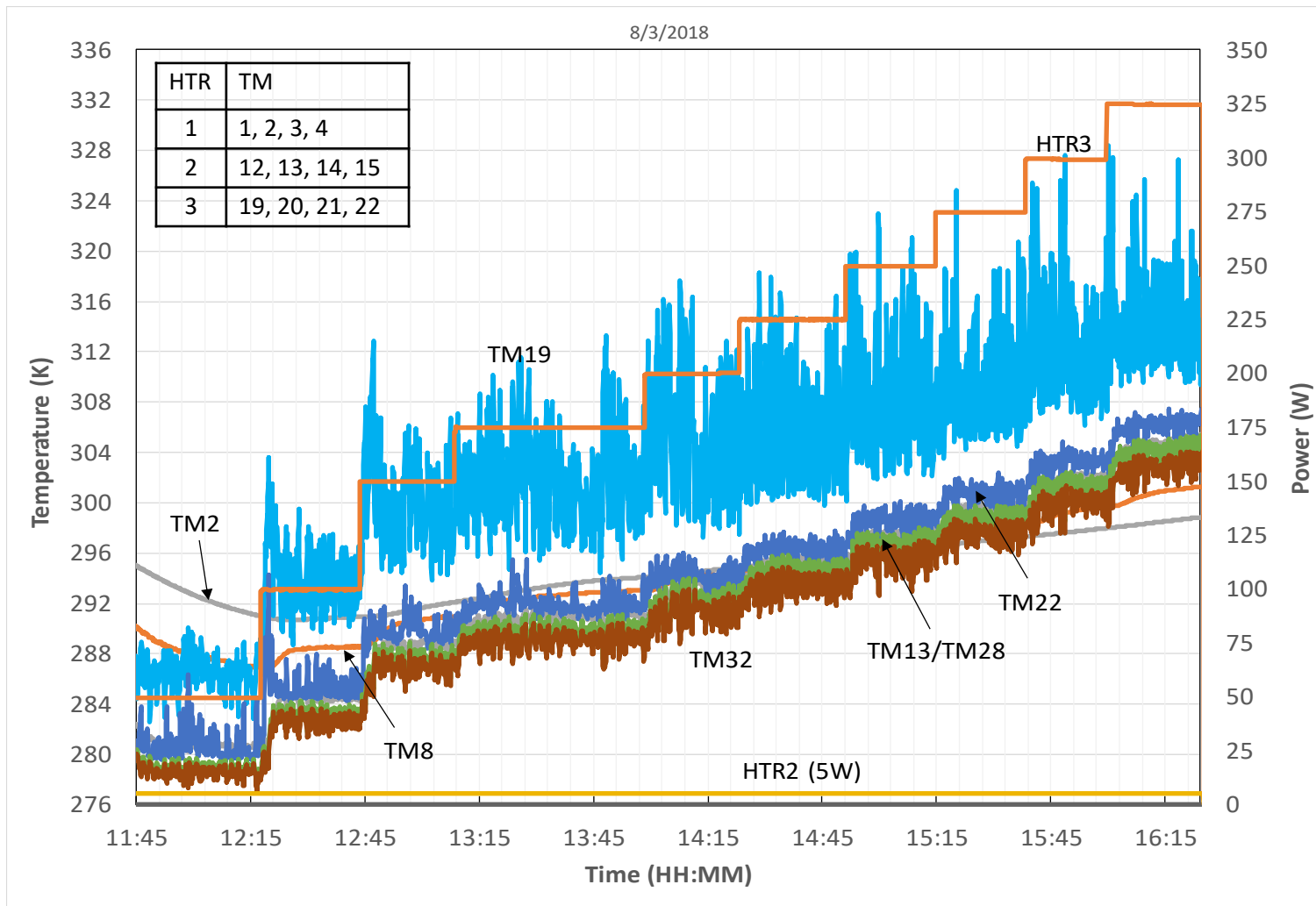
- 5W constant to HTR 1, variable heat load to HTR 3 from 50W to 275W.
- Immediately after each power increase, TM19 temperature rose sharply. As HTR 1 continued to supply vapor to the condenser, a quasi-equilibrium condition was eventually reached among HTR 1, HTR 3, and the condenser. The process repeated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

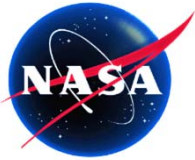




# C1 - 5W to HTR 2 After Startup

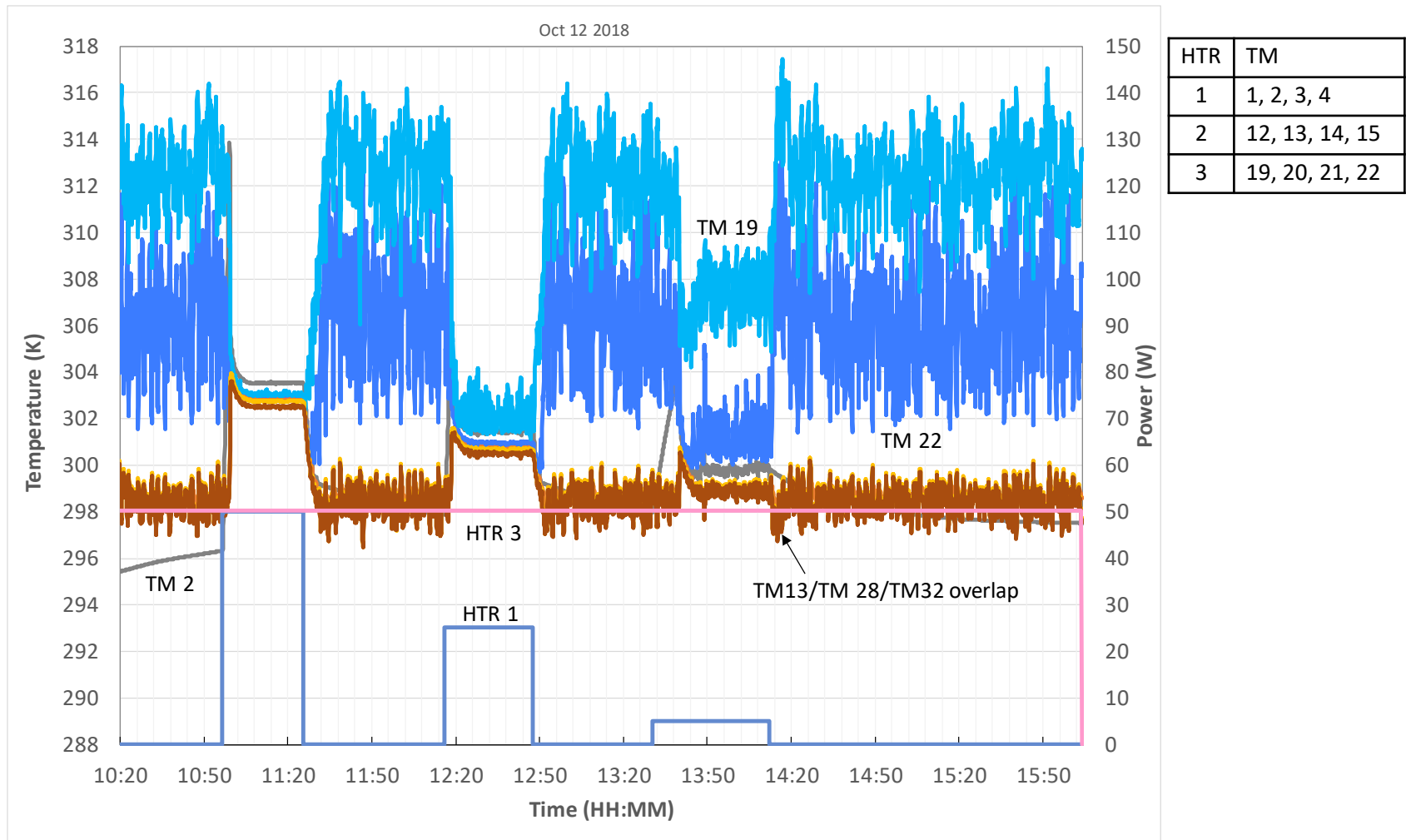
- 5W to HTR 2, variable heat load to HTR 3 from 50W to 325W.
- Operation was similar to when 5W was applied to HTR 1

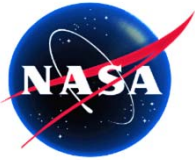




## B3 - Operation After Startup

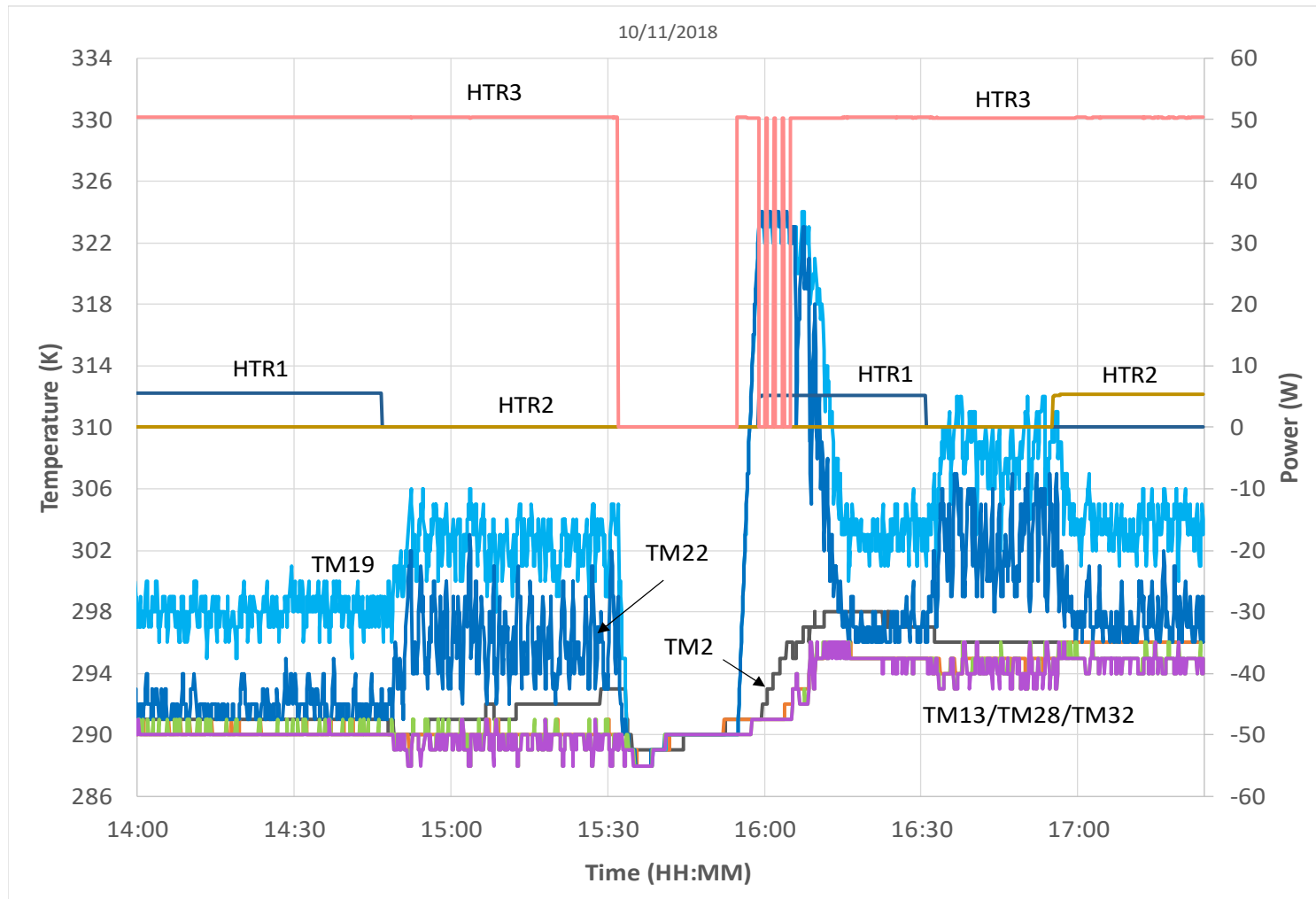
- Temperatures with HTR3/HTR1 = 50W/0W is independent of prior condition. The magnitude of temperature fluctuation is a function of HTR 1 power.
- Even a small power of 5W to HTR1 can significantly reduce temperature fluctuation.





# D5 – Restart with HTR 3 Only

- After all heaters were 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.



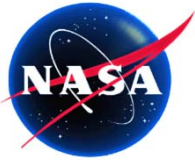
HTR	TM
1	1, 2, 3, 4
2	12, 13, 14, 15
3	19, 20, 21, 22



## Data Analyses and Discussions (3)

- Plots B2 and C1 showed that with 5W to HTR 1 or HTR 2, the heat pipe could operate under a quasi-steady condition for HTR 3 power up to 325W.
- Moreover, Plot C1 shows that the temperature difference between TM19 (average) and TM28 did not change much for HTR 3 power of 100W and 325W.
- It is postulated that, at each HTR 3 power, HTR 2 could continue to provide vapor to the condenser such that the resulting falling liquid allowed HTR 3 to capture the required amount of liquid to sustain the quasi-steady operation. At quasi-equilibrium, the “liquid leak” through HTR 3 was roughly equal to 5W provided by HTR 2.
- This postulate is further supported by Plot B3. As long as there was sufficient liquid in the condenser initially, a quasi-equilibrium condition could be sustained with 50W to HTR 3 alone. Under this condition, there was no “liquid leak.” The operation with 50W to HTR 3 alone was independent of prior condition of HTR 1 power.
- In Plot D5, the quasi-steady operation of 50W to HTR 3 alone was interrupted when all heaters were turned off. There was no liquid in the condenser. Operation of 50W to HTR 3 had to begin by adding 5W to HTR 1 for startup.





## Conclusions

- In ground testing of a heat pipe under the reflux mode, if the heat source was applied to a site remote from the liquid pool at the bottom, an additional heat must be added to the liquid pool for startup and proper operation.
- There are many reasons to minimize the additional heat to the liquid pool. If the additional heat is not large enough, temperature fluctuation will occur at the remote heating site.
- There is a threshold power for the liquid pool heater above which there is no temperature fluctuation.
- The proper amount of liquid pool heater power is a function of many factors:
  - The allowable amplitude of temperature fluctuation
  - Heat source power
  - Condenser sink temperature
  - Heat source location above the liquid pool
  - Condenser length
  - Etc.