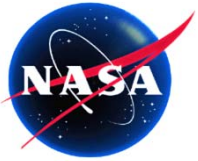


Experimental Investigation of Heat Pipe Startup Under Reflux Mode

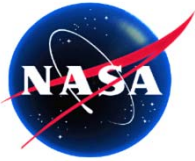
**Jentung Ku
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA**

**2018 Spacecraft Thermal Control Workshop
El Segundo, California, March 20-22, 2018**



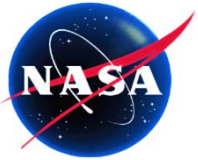
Outline

- **Introduction/Objectives**
- **Technical Approach**
- **Test Article**
- **Test Setup and Instrumentation**
- **Tests Performed**
- **Test Results**
- **Summary and Conclusions**



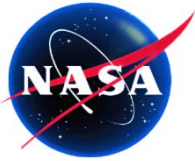
Introduction/Objectives

- **During instrument-level or spacecraft-level ground testing, heat pipes onboard the flight hardware may be placed in a non-planar position and have to operate under the reflux mode.**
- **A superheat is required in order for the heat pipe to start successfully and operate properly.**
 - **The required superheat for boiling incipience is affected by the pressure differential imposed on the vapor bubbles.**
 - **The gravity head is expected to affect the pressure differential imposed on the bubble.**
- **An experimental investigation was conducted to find ways to start a heat pipe under the reflux mode effectively and efficiently.**



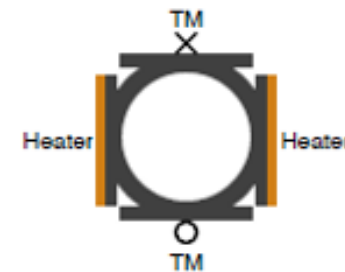
Technical Approach

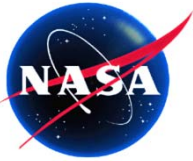
- **An L-shaped axially grooved aluminum/ammonia heat pipe was used for this experimental study.**
- **The heat pipe was placed in an upright position so that liquid puddle was formed at the bottom of one leg of the heat pipe. The liquid-filled part is designated as the evaporator section where heat was applied.**
- **The end of the other leg was designated as the condenser section where a coolant flow was circulated.**
- **Tests were conducted by tilting the evaporator leg 90 degrees and 30 degrees relative to the horizontal plane.**
- **The liquid-filled evaporator section was divided into 7 equal-length segments where various heat load distributions and heat fluxes were applied.**
- **The study consisted of employing different sequences of applying the heat load distributions and heat fluxes.**



Test Article

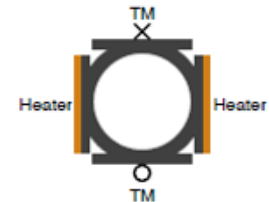
- The test article was a spare unit from the LRO flight project.
- The heat pipe:
 - Two legs with lengths of 1168 mm and 1016 mm, respectively.
 - Outer diameter: 15 mm
 - Vapor core diameter: 11 mm
 - Four flanges on the outer surface along the axial direction, each 111 mm wide.
 - Working fluid: ammonia
 - Fluid inventory: 52.5 grams
 - When the entire liquid inventory accumulates at the bottom of the heat pipe under gravity, the liquid puddle length is 714 mm at 298K.



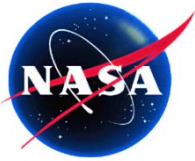


Test Setup And Instrumentation (1/2)

- The end of the 1168 mm leg was designate as the evaporator.
 - Evaporator length: 714 mm
 - The evaporator was divided into 7 segments of equal length, 102 mm each.
 - On each segment, two tape heaters were attached to the flanges on the opposite sides. One on each flange.
 - On each segment, four thermistors are attached to the flanges on the opposite sides. Two on each flange and were staggered in the axial direction.
 - A total of 28 thermistors on the evaporator segments.

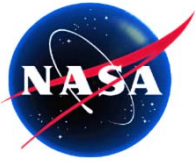


- The end of the 1016 mm leg was designated as the condenser.
 - Condenser length: 305 mm
 - A cold plate was attached to the condenser. A recirculating chiller was used to circulate the coolant through the cold plate.
 - Four thermistors were attached to the condenser.
- Four thermistors were attached to the adiabatic section.

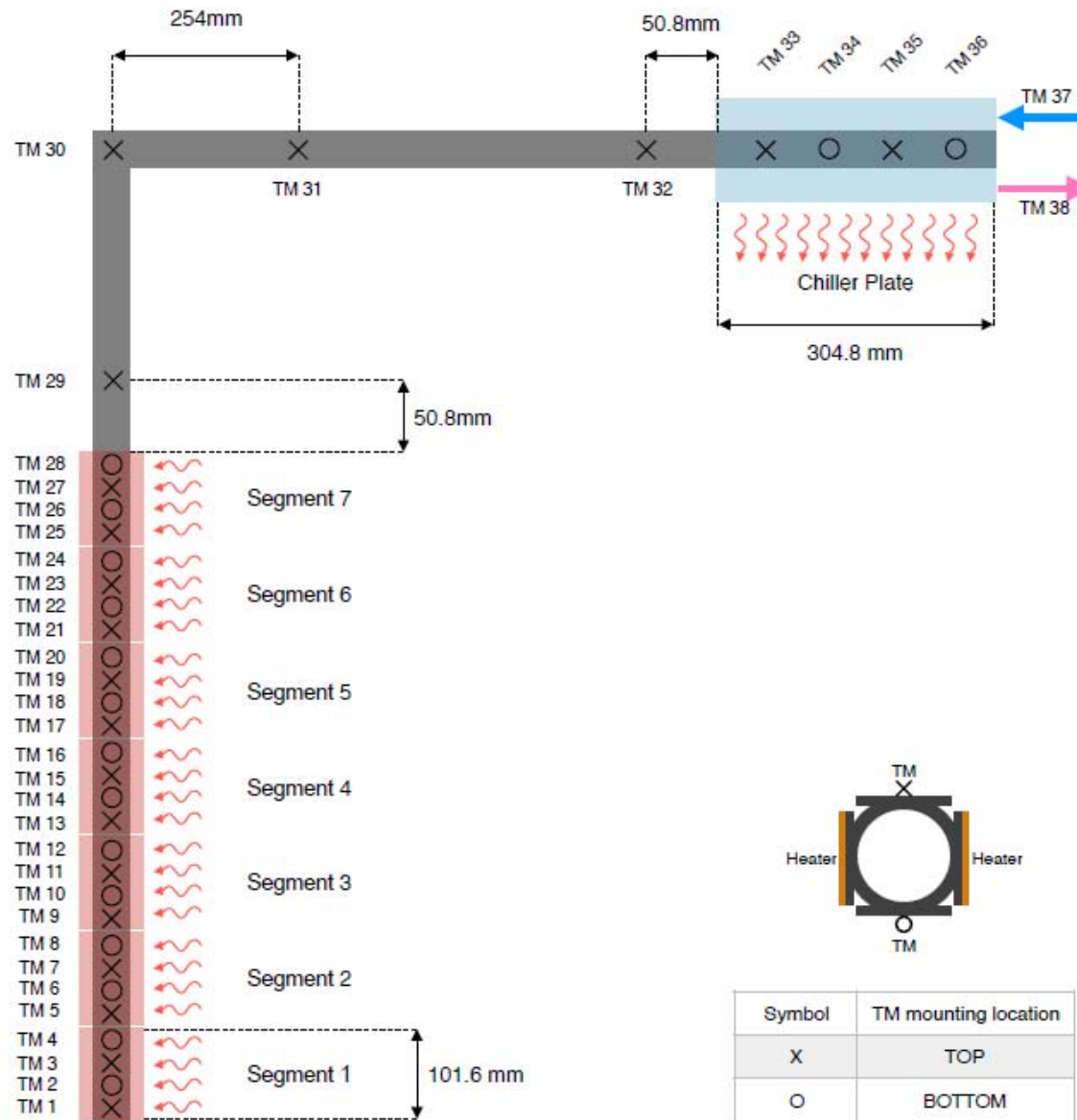


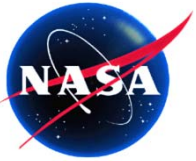
Test Setup and Instrumentation (2/2)

- **A power supply was used to provide the heat load to the evaporator segments.**
- **All heaters were connected in parallel. The two tape heaters on each segment were connected to the same relay, which turned the heaters on or off.**
- **The maximum heat load to each segment 15W due to the tape heater's flux capability.**
- **The entire heat pipe was covered with polyolefin insulation.**
- **There were two test configurations**
 - **V90 configuration: the 1168-mm leg was in a vertical position and the 1016-mm leg was horizontal.**
 - **V30 configuration: the 1168-mm leg and the 1016-mm leg formed 30-degree and 60-degree angles, respectively, relative to the horizontal plane.**

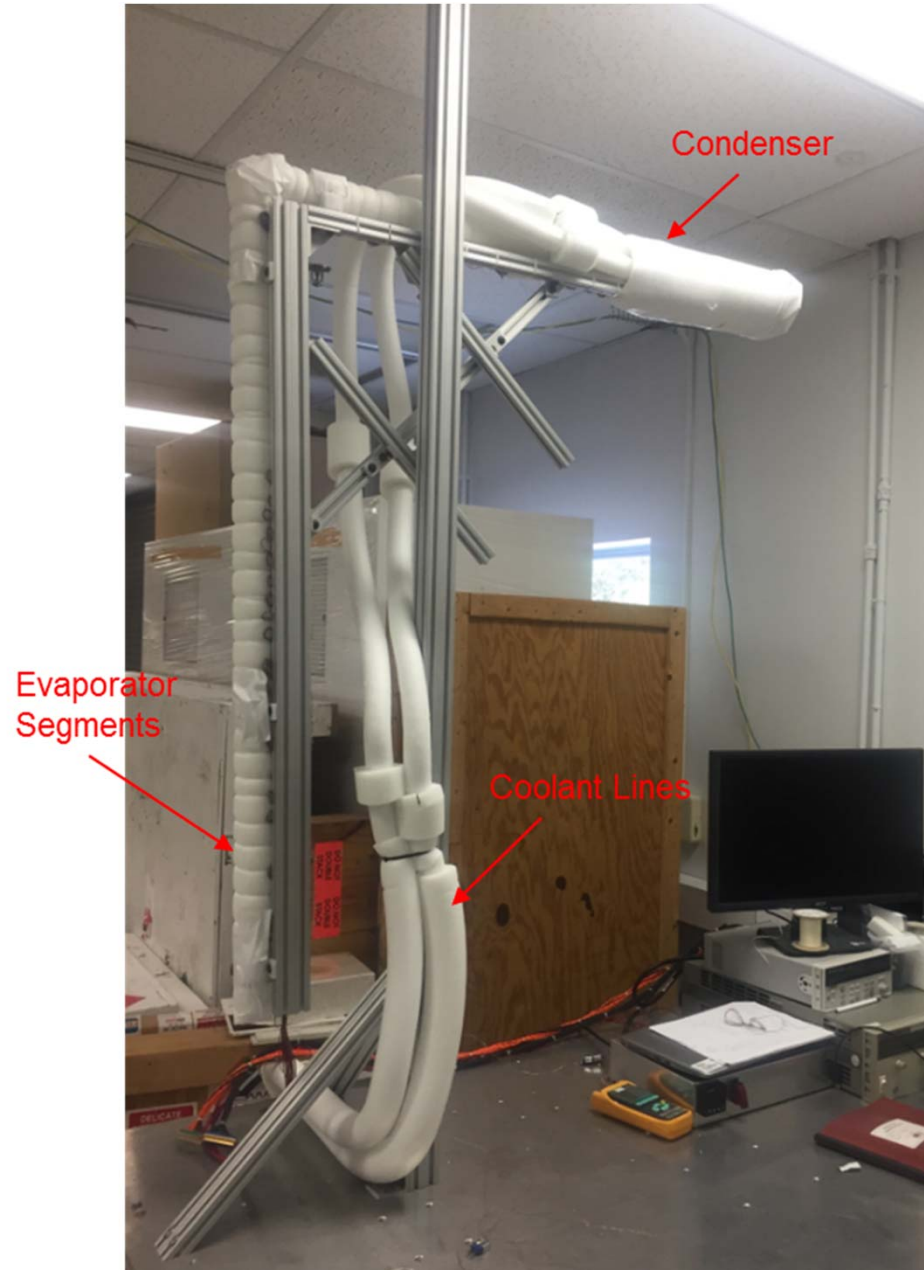


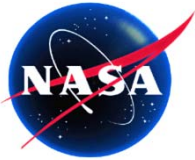
Thermistor Locations





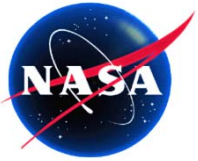
Heat Pipe in V90 (Vertical) Configuration





Tests Performed

- **Tests were performed under the V90 configuration first. Most of the tests were then repeated under the V30 configuration.**
 - **The gravity head under the V30 configuration is half of that under the V90 configuration.**
- **Tests were performed with various combinations of heat load distributions and heat fluxes.**
- **Heat load distributions**
 - **Uniform: same heat load to all 7 segments simultaneously**
 - **Top down: heat load was applied to Segment 7 first. Additional heat was then added to the next segment below in steps until all segments received heat**
 - **Bottom up: heat load was applied to Segment 1 first. Additional heat was then added to the next segment above in steps until all segments received heat**
 - **Heat load to Segment 1 only**
- **Heat fluxes**
 - **Heat load to each segment varied between 2.5W and 15W.**
 - **The corresponding heat fluxes are 2.2 kW/m² and 13.3 kW/m².**



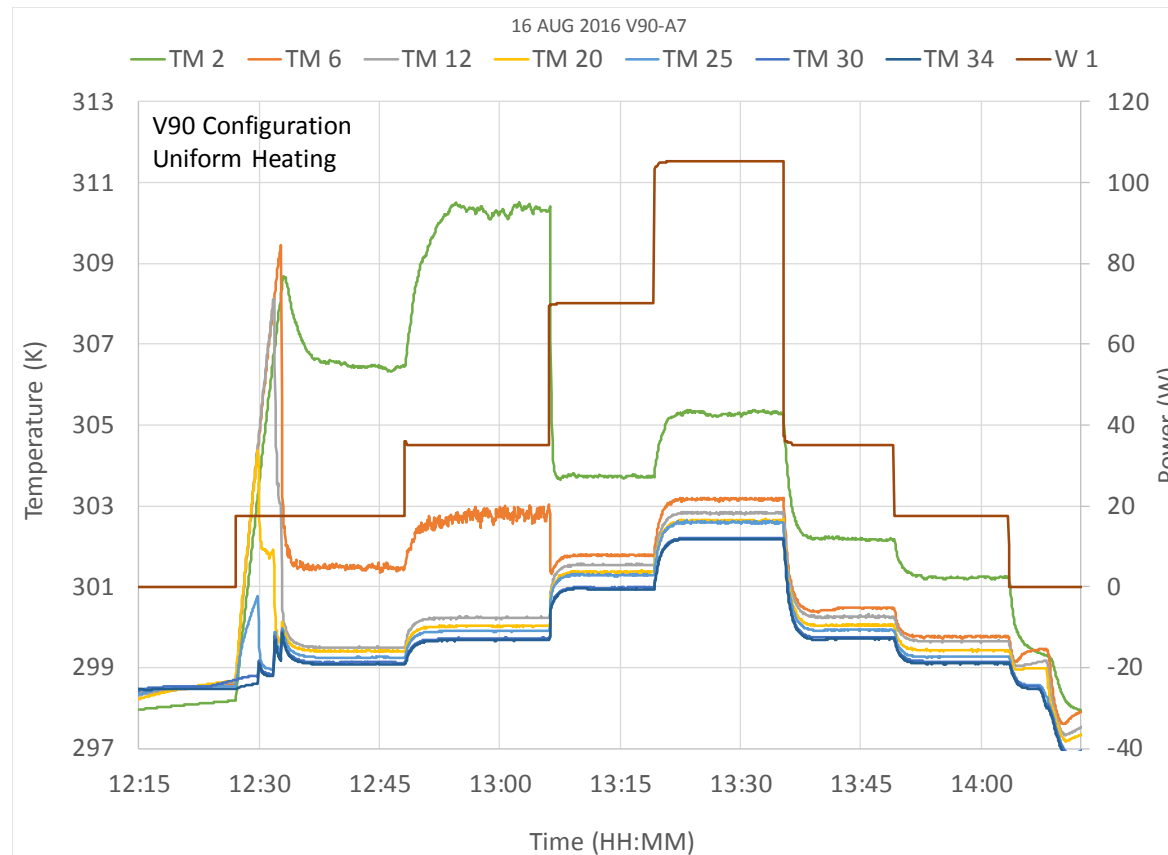
Data Plots

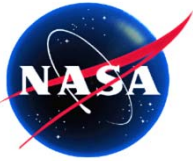
- **In the following data plots, relevant segments and their thermistor temperatures are plotted to show the sequence of events during heat pipe startup and operation.**
 - **Each segment had 4 thermistors. The segment represented by the thermistor(s) can be easily identified.**
- **Two plots may be presented for the same test in order to show the overall long term heat pipe operation and the detailed startup transients.**
- **Only the total heat load to all 7 segments are shown, no individual heat load to each segment are plotted (too many curves otherwise). The heat load distribution can be found from the type of the test performed.**
- **Each test is associated with a test number.**
 - **For example, V90-A7 refers to test under the V90 configuration. A7 simply means the test number without any particular significance.**



V90-A7: Uniform Heating with 2.5W and Higher

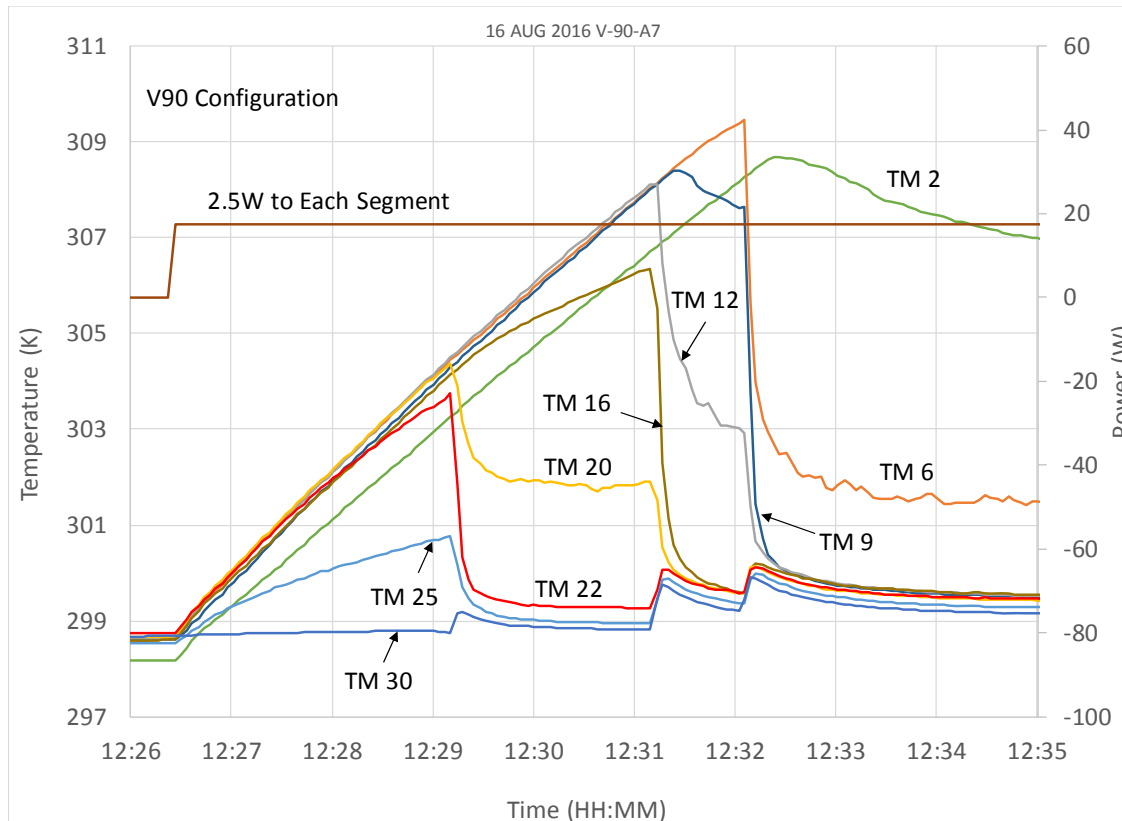
- Startup test were conducted by applying uniform heat load of 2.5W, 5W, 10W, and 15W to each segment.
- Nucleate boiling is characterized by a sudden increase of the condenser temperature and a sudden decrease of the evaporator segment temperature to near the saturation temperature.
- Segments 3 to 7 started with 2.5W. Segment 2 started with 10W.
- Segment 1 did not start even with 15W.

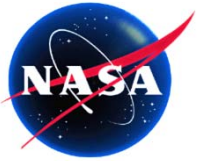




V90-A7: Uniform Heating with 2.5W (Detail)

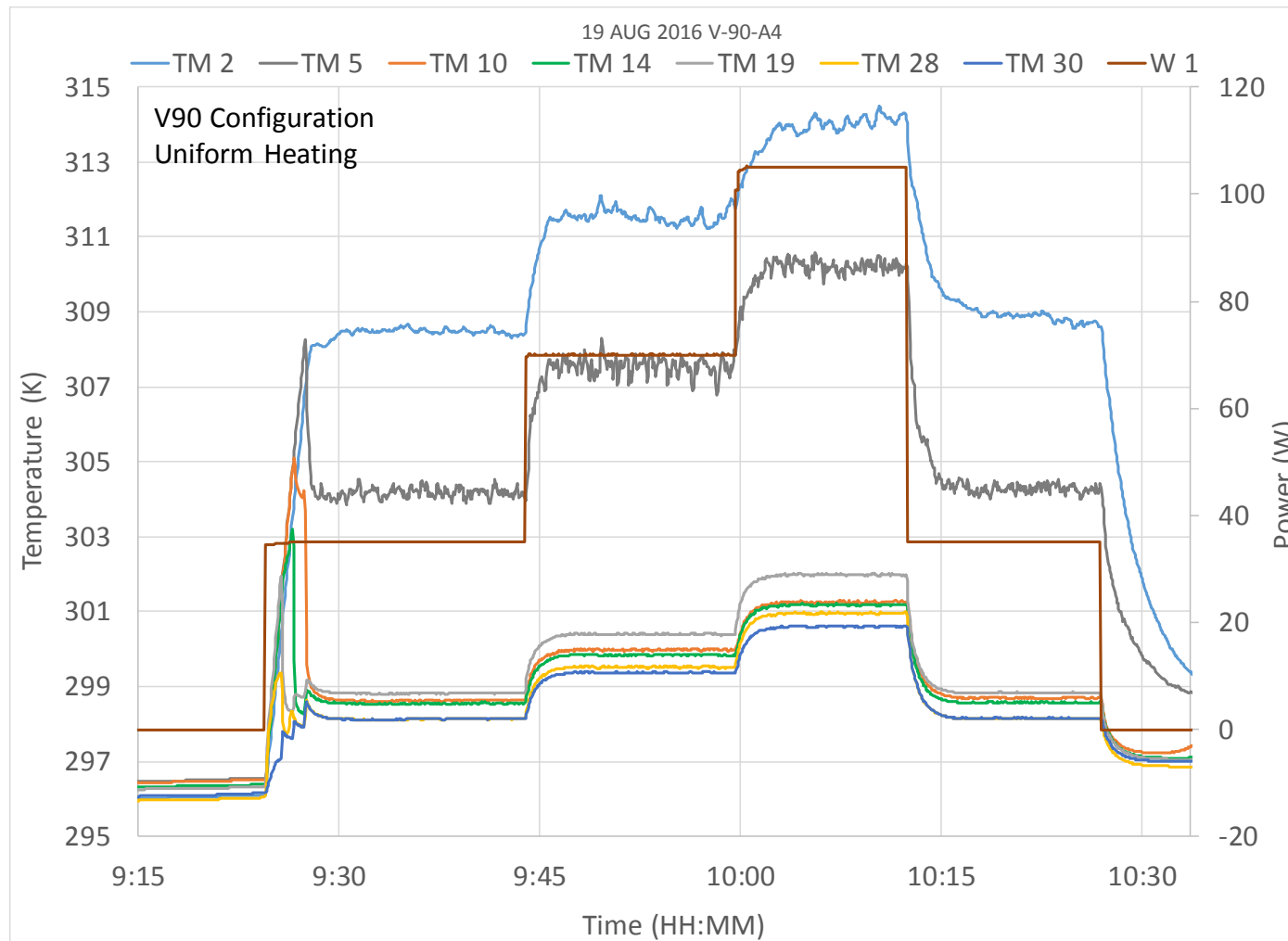
- 3 distinct temperature rises of condenser temperature, corresponding to nucleate boiling at three different times and locations.
- Segments 6 and 7 started at 12:29. Segments 4 and 5 started at 12:31. Segment 3 started at 12:32:30.
- Temperature gradient existed within each segment prior to nucleate boiling(TM 9 & 12).
- Segment 2 did not start with 2.5W, but started at 13:06 with 10W (previous slide).
- Segment 1 did not start even with 15W (previous slide). Heat was conducted to Segment 2 during SS and the required superheat could not be attained.

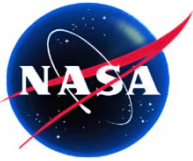




V90-A4: Uniform Heating with 5W and Higher

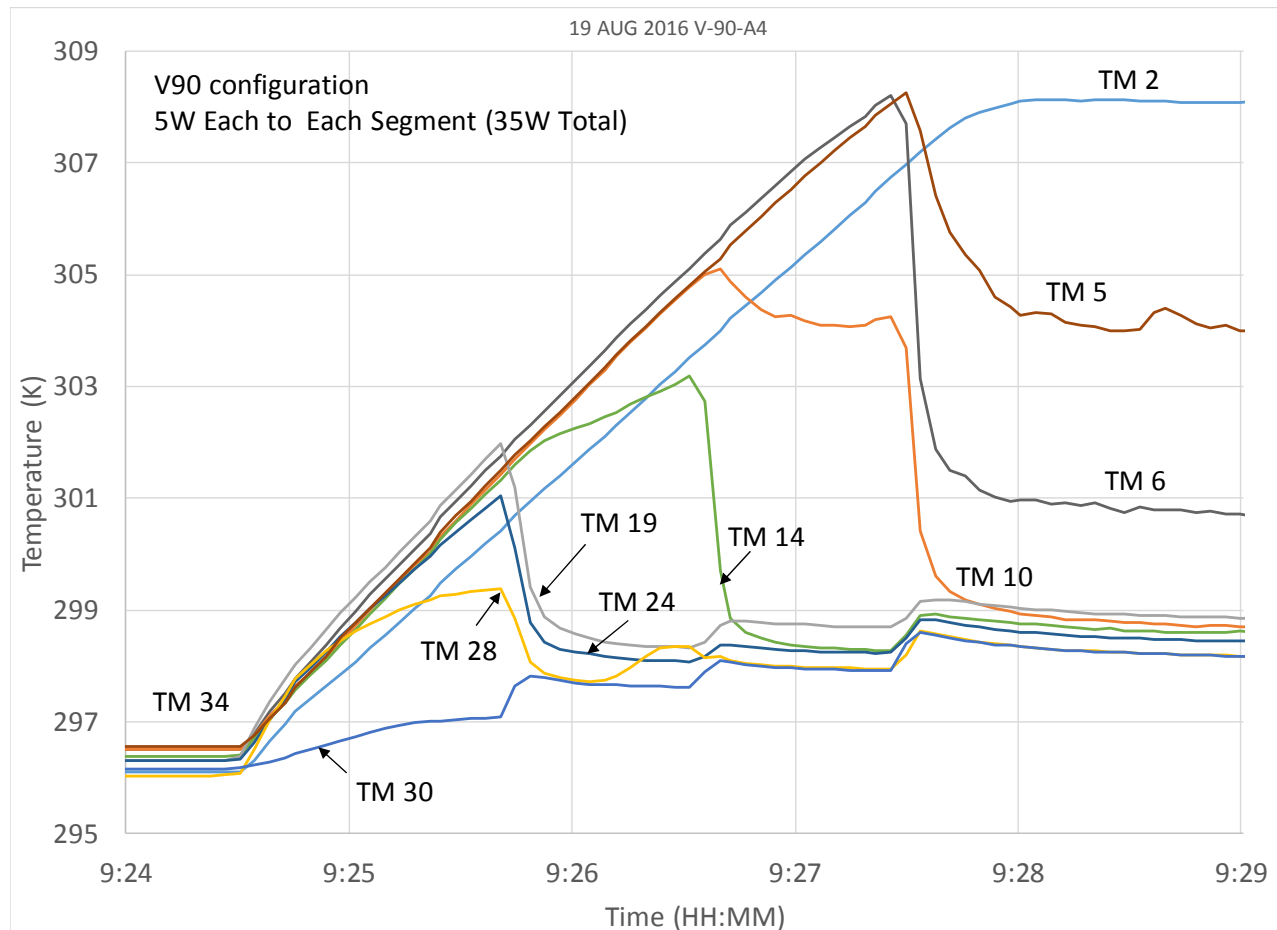
- Segments 3 to 7 started with 5W. Segments 1 and 2 did not start even with 15W.
- Segments 1 and 2 had superheat of 13K and 10K at 15W, still not enough to initiate nucleate boiling.

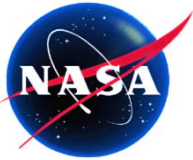




V90-A4: Uniform Heating with 5W (Detail)

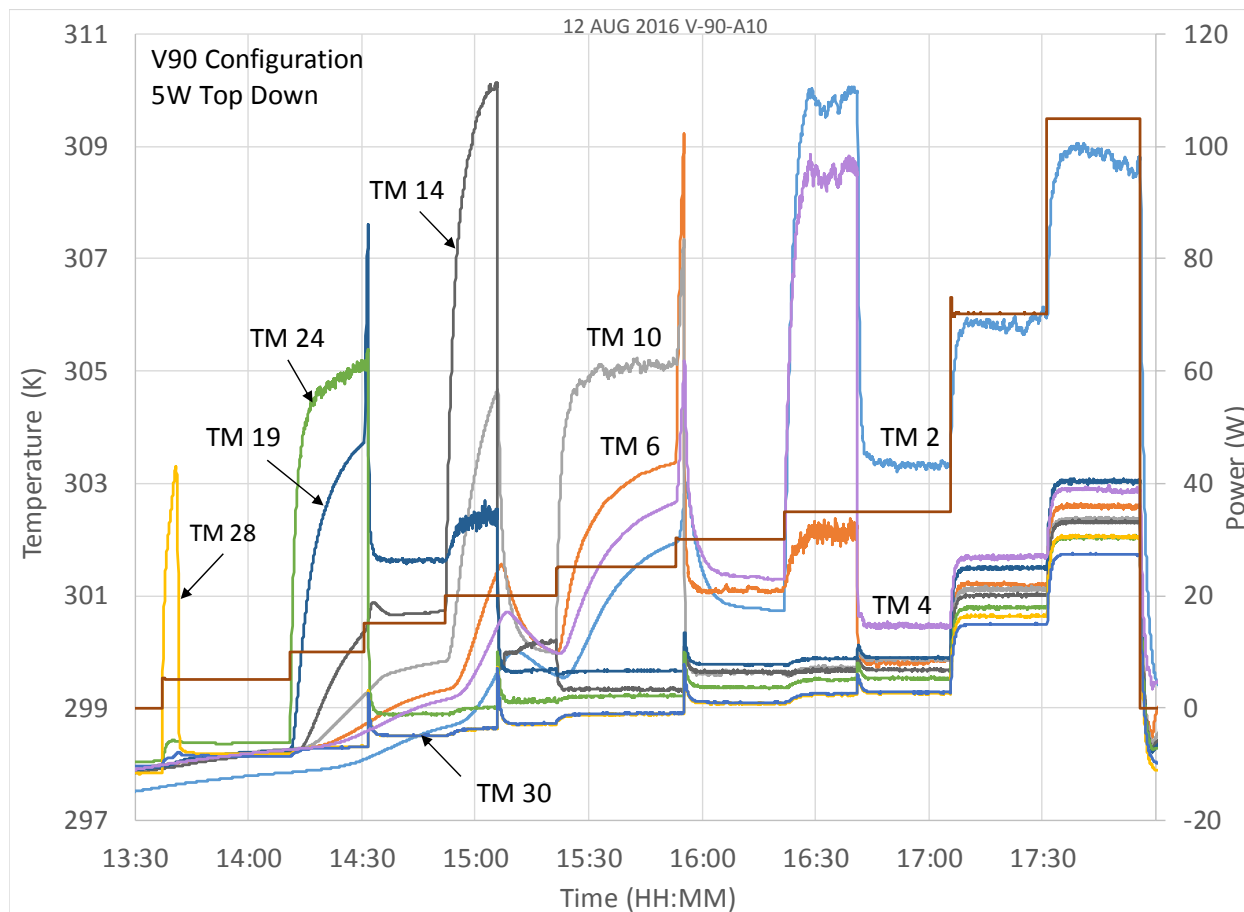
- The top segment required smallest superheat and the bottom segment required largest.
- Segments 7, 6, and 5 started first, followed by Segment 4, and then Segment 3.
- Segments 1 and 2 did not start even with 15W to each (previous slide).
- Segment 1 and 2 reached SS through heat conduction to the next segment above.
- Temperature gradient existed within each segment prior to nucleate boiling (TM5, TM6).

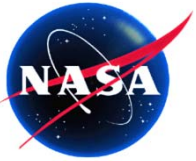




V90-A10: 5W Top Down)

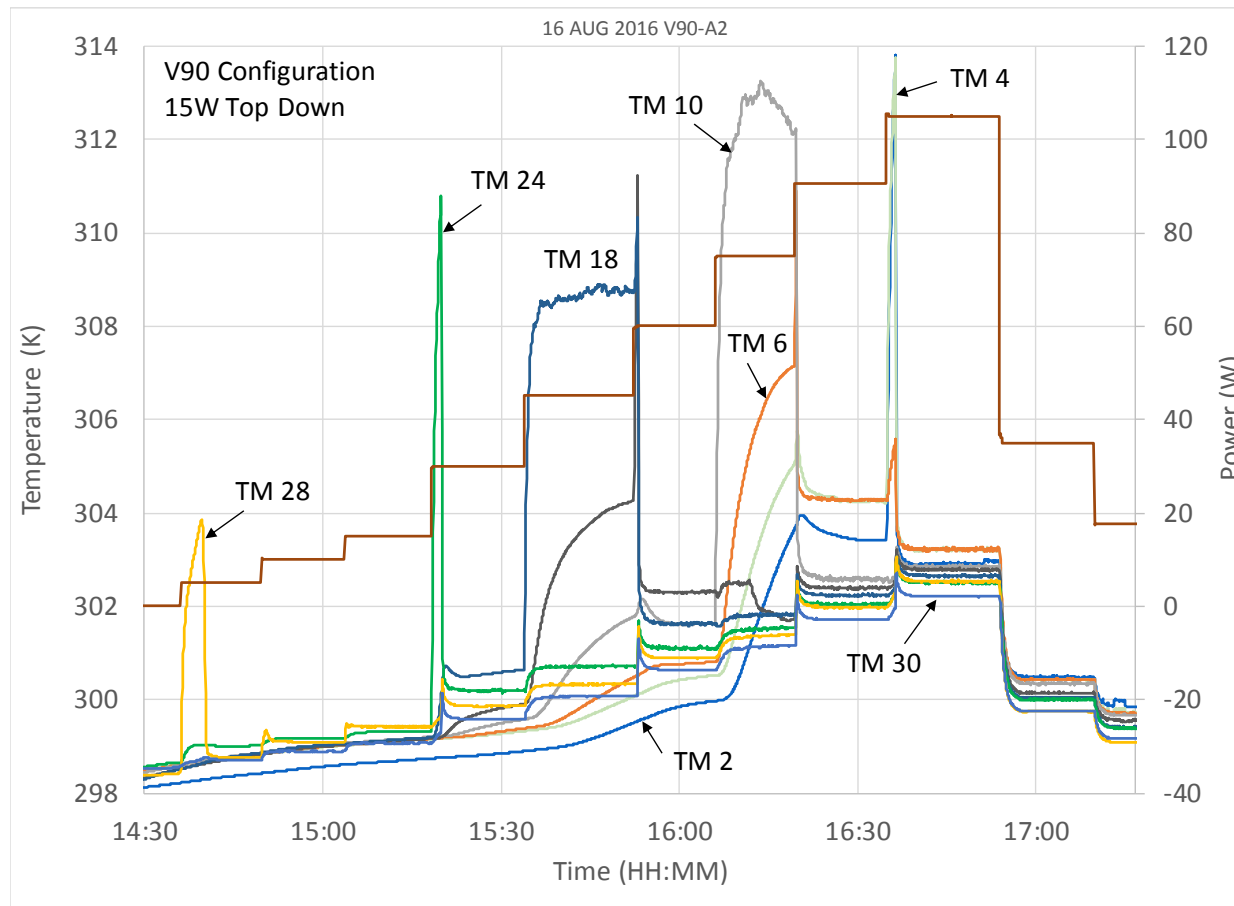
- 5W was applied to Segment 7 first. An additional 5W was then added to the next lower segment in steps. Segments 6 to 2 started one by one as 5W was added to respective segments.
- Segment 1 did not start even with 15 W. Heat was conducted to Segment 2 during SS. The required superheat could not be attained.

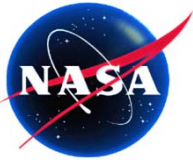




V90-A2 (15W Top Down)

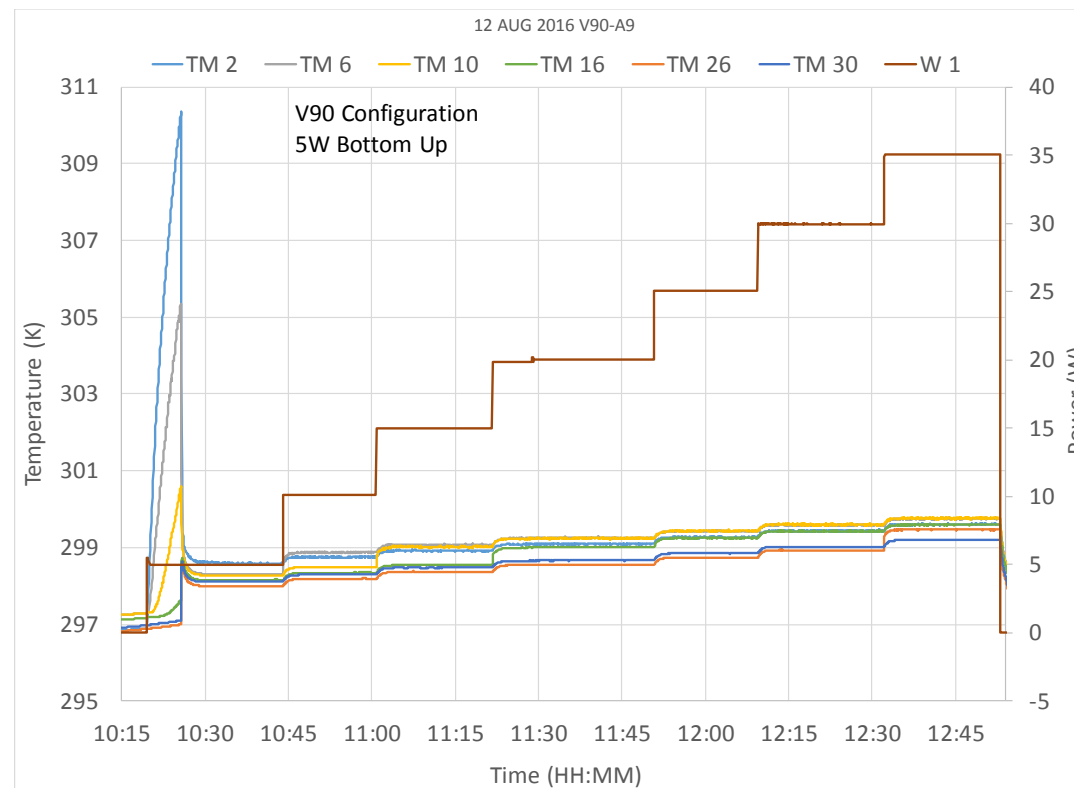
- 5W/10W/15W to Segment 7 only, then top down with 15W additional heat to each segment below in steps. A superheat was required for every segment.
- Compared to V90-A10 (top down with 5W, Segment 1 did not start with 15W): a higher heat flux was needed to attain the required superheat if the segment above had started. Again, this was due to heat conduction to the upper segment that had started.





V90-A9 (5W Bottom-up)

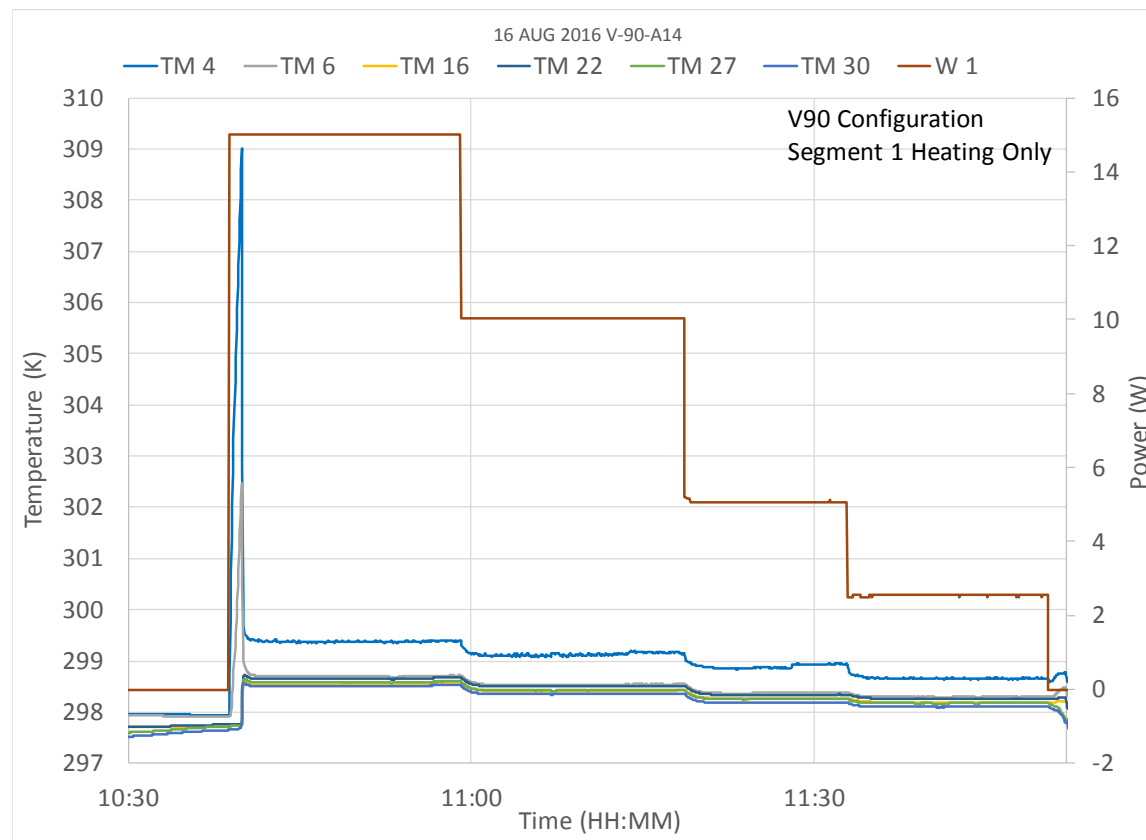
- 5W to was applied to Segment 1 first. Various superheats for all segments (due to heat conduction from Segment 1). All segments were filled with liquid prior to onset of nucleate boiling in Segment 1.
- At 10:25, segment #1 started with 13K superheat. All segments above showed a sudden temperature decrease, indicating liquid in the core was cleared.
- An additional 5W was added to the next segment above in steps.
- No superheat was required for any segment above Segment 1. Liquid simply evaporated.

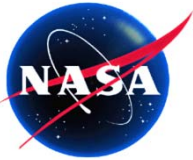




V90-A14: Heat Load to Segment 1 Only

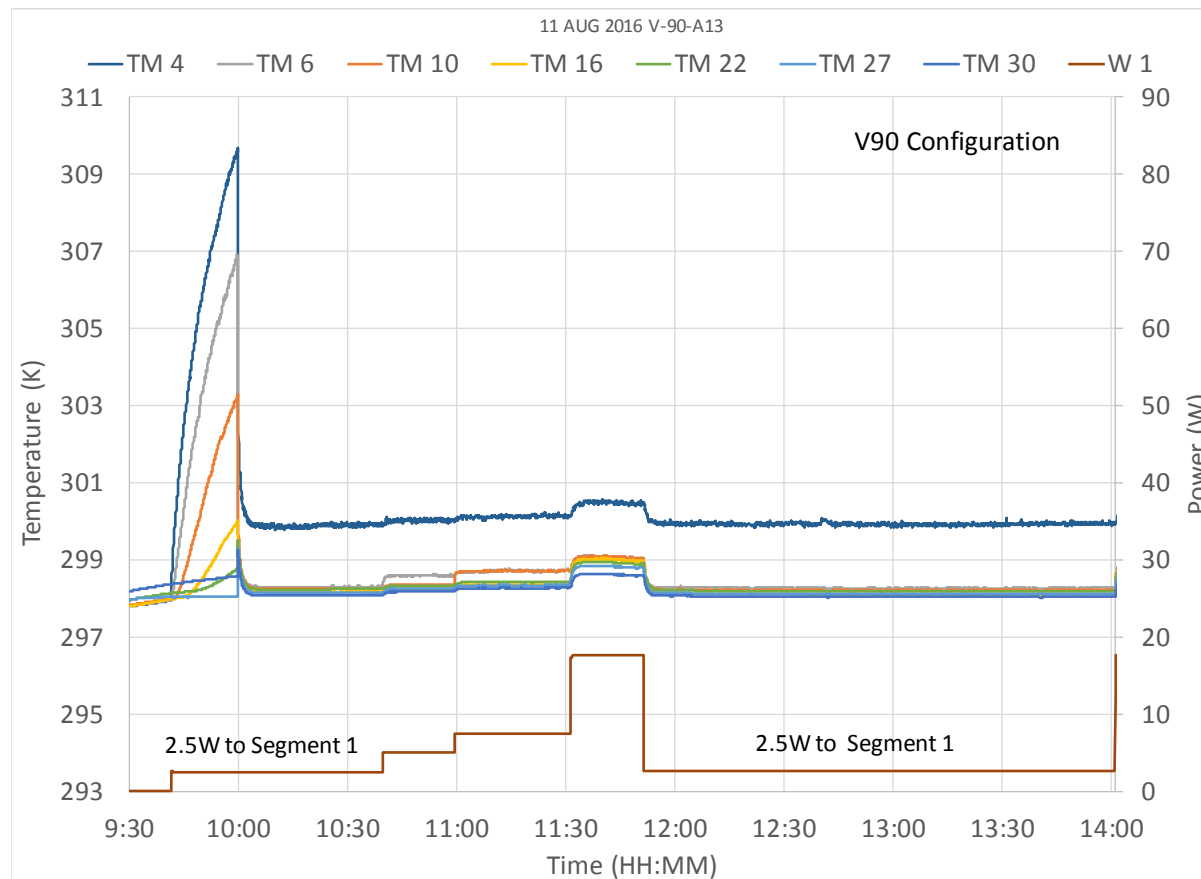
- 15W was applied to Segment 1 only. Temperature gradient existed among segments due to heat conduction from Segment 1.
- Segment 1 started when the superheat reached 11K.
- Temperatures of all segments above Segment 1 dropped to saturation temperature, indicating liquid was cleared from the core.
- HP could operate with heat load of 2.5W to Segment 1 alone. No percolator effect.

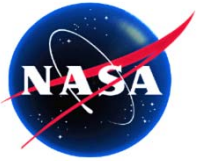




V90-A13: 2.5W Heater 1 Only for Startup

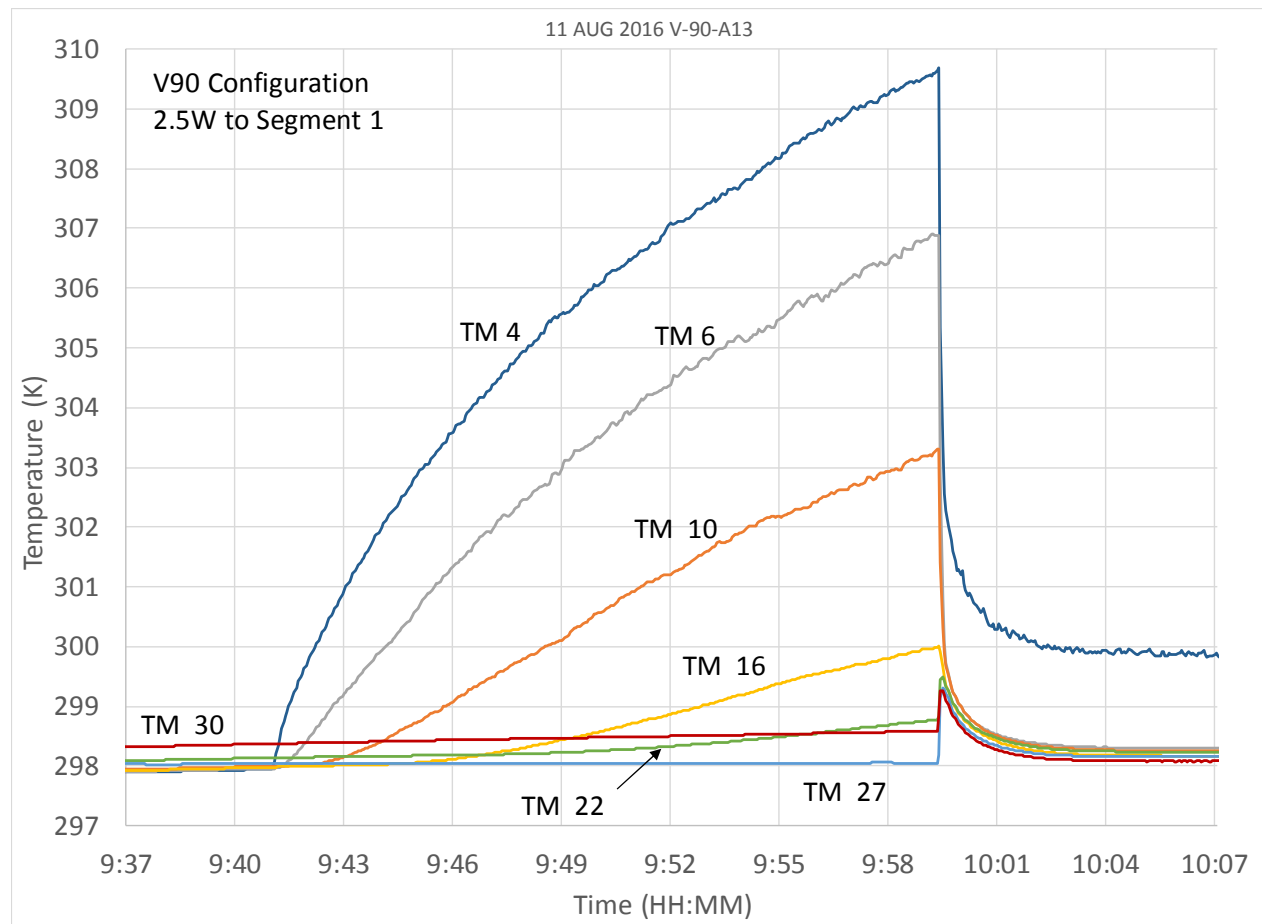
- When 2.5W was applied to Segment 1, heat was conducted to segments above.
- Superheat of 13K for nucleate boiling in Segment 1 with 2.5W. All segments above were cleared of liquid in the core. No superheat was required when additional heat was added to Segment 2, and then to Segment 3, and then to all segments.
- HP could operate with 2.5W applied to Segment 1 alone for two hours without percolator effect.

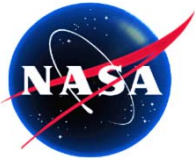




V90-A13: 2.5W Heater 1 for Startup (Detail)

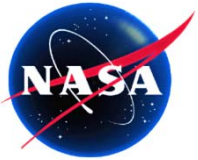
- When 2.5W was applied to Segment 1, heat was conducted all the way to Segment 6 prior to nucleate boiling. Segment 7 was unheated.
- Right after onset of nucleate boiling, Segment 7 was heated to the saturation temperature.





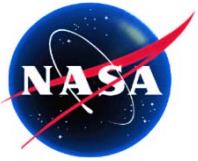
Summary of Tests Under the V90 Configuration (1/3)

- **If a heated zone is completely covered by liquid, a superheat is required to initiate nucleate boiling in that zone.**
- **If the required superheat cannot be achieved, that zone will remain liquid filled and no vapor will be generated there. The referred zone can be the entire evaporator segment or a part it.**
- **Once a segment has initiated nucleate boiling, the center core of all segments above it will be cleared of liquid because of the buoyancy force. Any subsequent power application to these segments will result in immediate liquid evaporation and no superheat is required.**
- **On the other hand, all segments below that segment will still have the center core filled with liquid due to gravitational force. A superheat is required in order to initiate nucleate boiling for subsequent power application to any of these segments.**



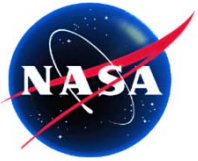
Summary of Tests Under the V90 Configuration (2/3)

- **Uniform heating of all segments and top down heating will lead to nucleate boiling from the top segment to segments below in sequence, and a superheat is required for all segments. At low heat fluxes, however, the segments near the bottom may not attain the required superheat and will remain liquid filled.**
 - **Most of the heat applied to these segment is conducted to the adjacent upper segment where nucleate boiling has occurred.**
 - **A high heat flux will ensure that all segments achieve nucleate boiling.**
- **The required superheat for nucleate boiling is a function of the gravity head.**
 - **The bottom segment requires the largest amount of superheat and the top segment requires the smallest amount.**
 - **In general, the higher the gravity pressure head, the larger the required superheat.**



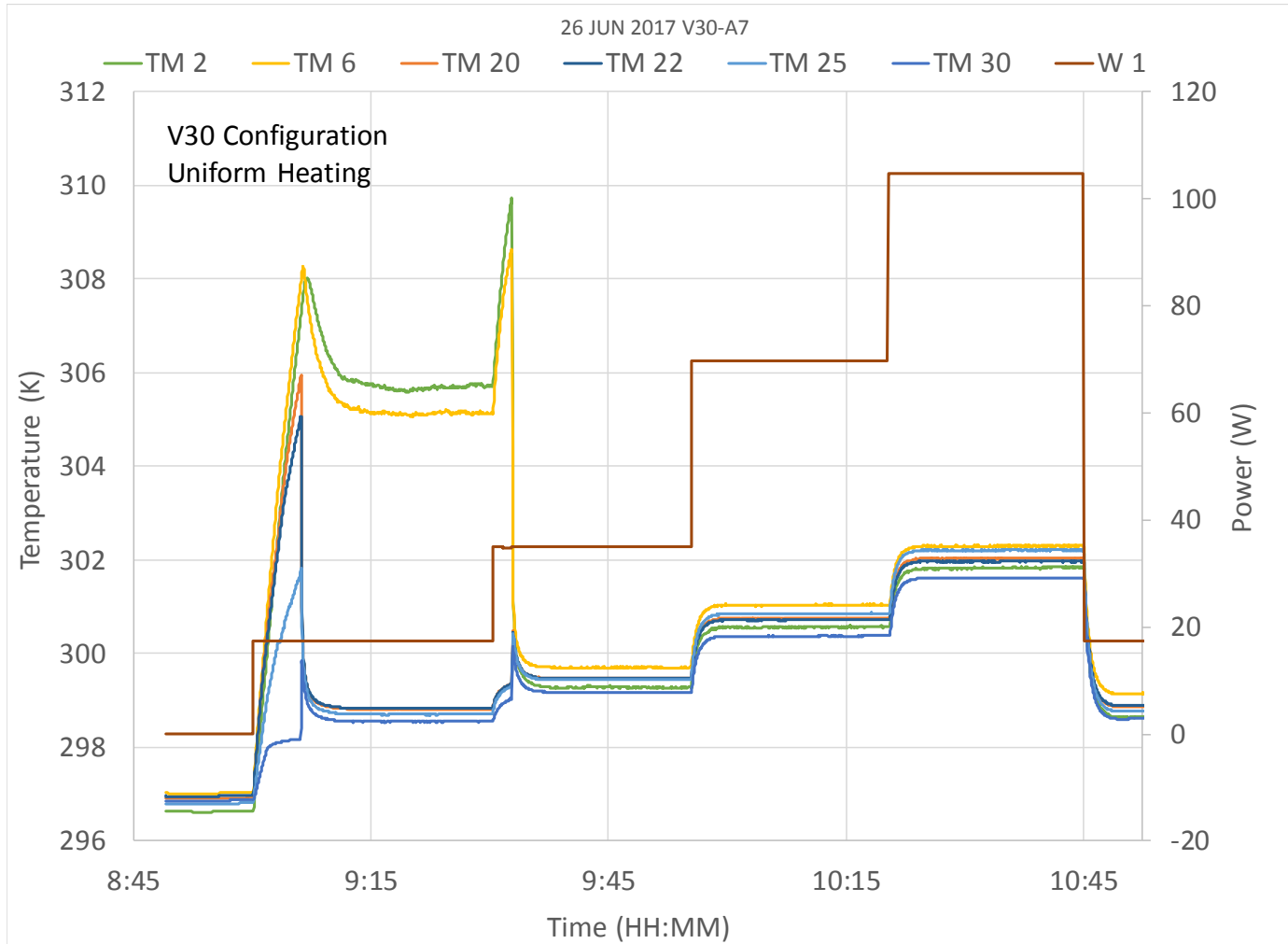
Summary of Tests Under the V90 Configuration (2/3)

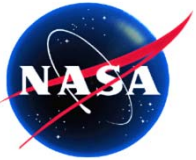
- **The required superheat is only a weak function of the heat flux. However, a higher heat flux leads to a short time for achieving the required superheat for nucleate boiling.**
- **The heat pipe can start and operate with a very low heat load even when the bottom segment alone receives the power, and there is no percolator effect during the low power operation.**



V30-A7: Uniform Heating with 2.5W and Higher

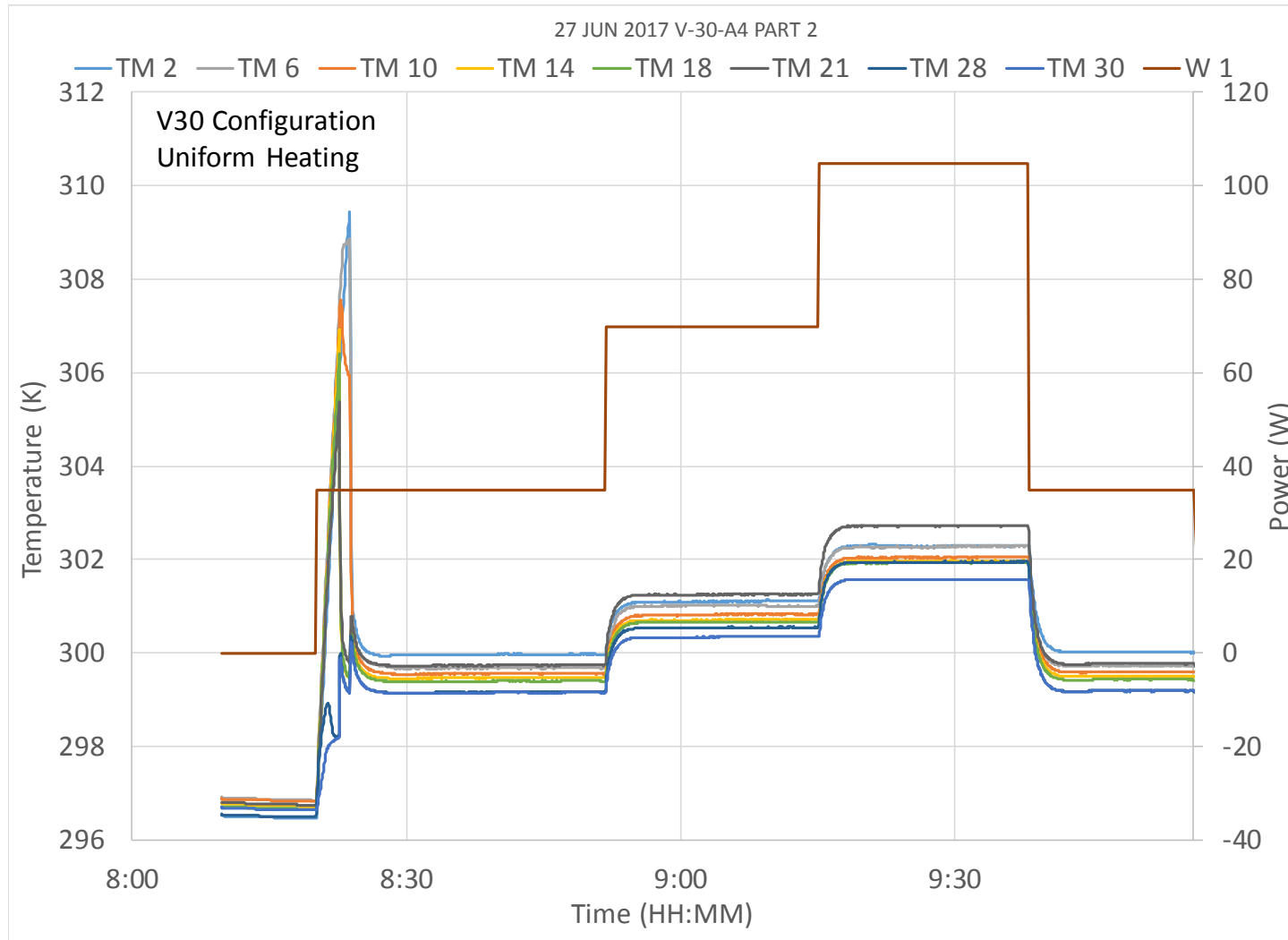
- Segments 3 to 7 started with 2.5W
- Segments 1 and 2 started with 5W, consistent with V30-A4 (next slide).

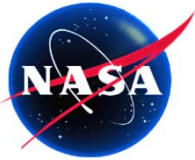




V30-A4: Uniform Heating with 5W and Higher

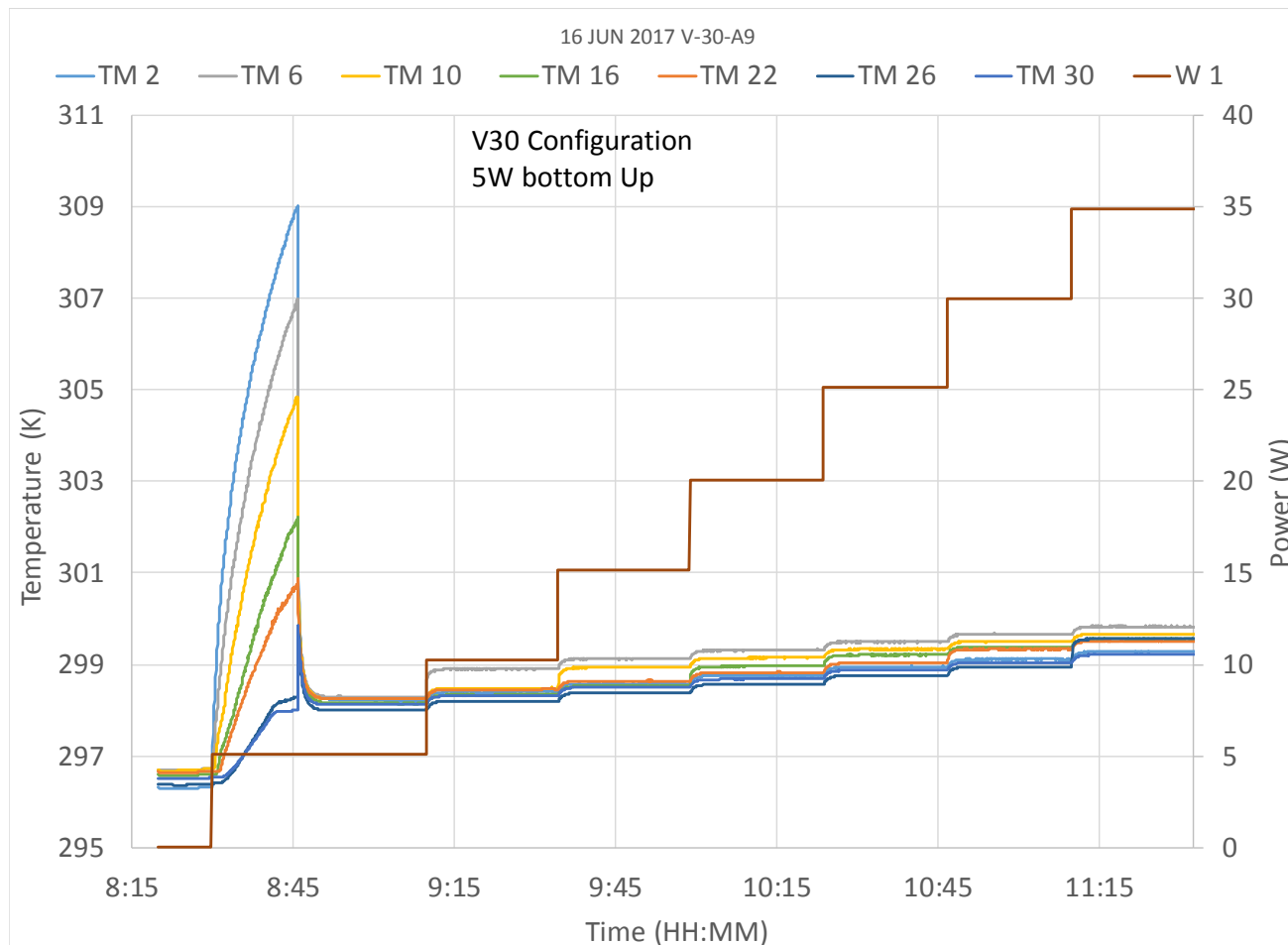
- Segments 3 to 7 started with 5W.
- Segments 1 and 2 could also start with 5W, consistent with V30-A7 (previous slide).

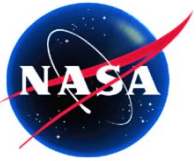




V30-A9: 5W Bottom-up

- The startup transient was similar to that of V90-A9.
- The required superheat for nucleate boiling was 11K.
- It took a longer time to achieve the required superheat. The temperature gradient prior to nucleate boiling extended further into Segment 6.

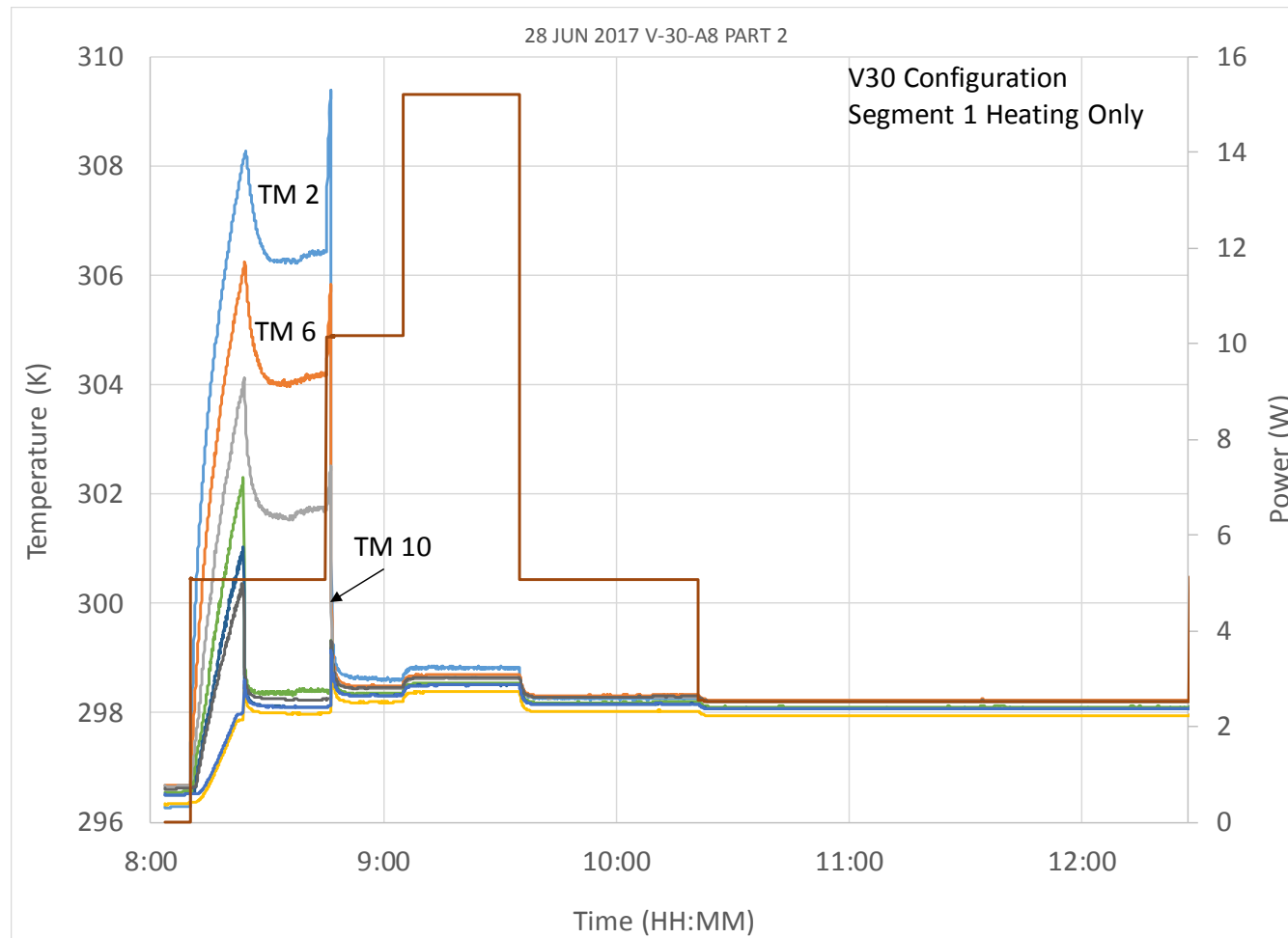


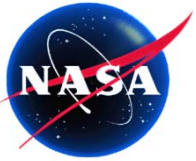


V30-A8: 5W to Segment 1 Only

5W to Segment 1 only. Segments 4, 5, 6, 7 started at 5W. Quite unusual.
Segments 1, 2, 3 started at 10W.

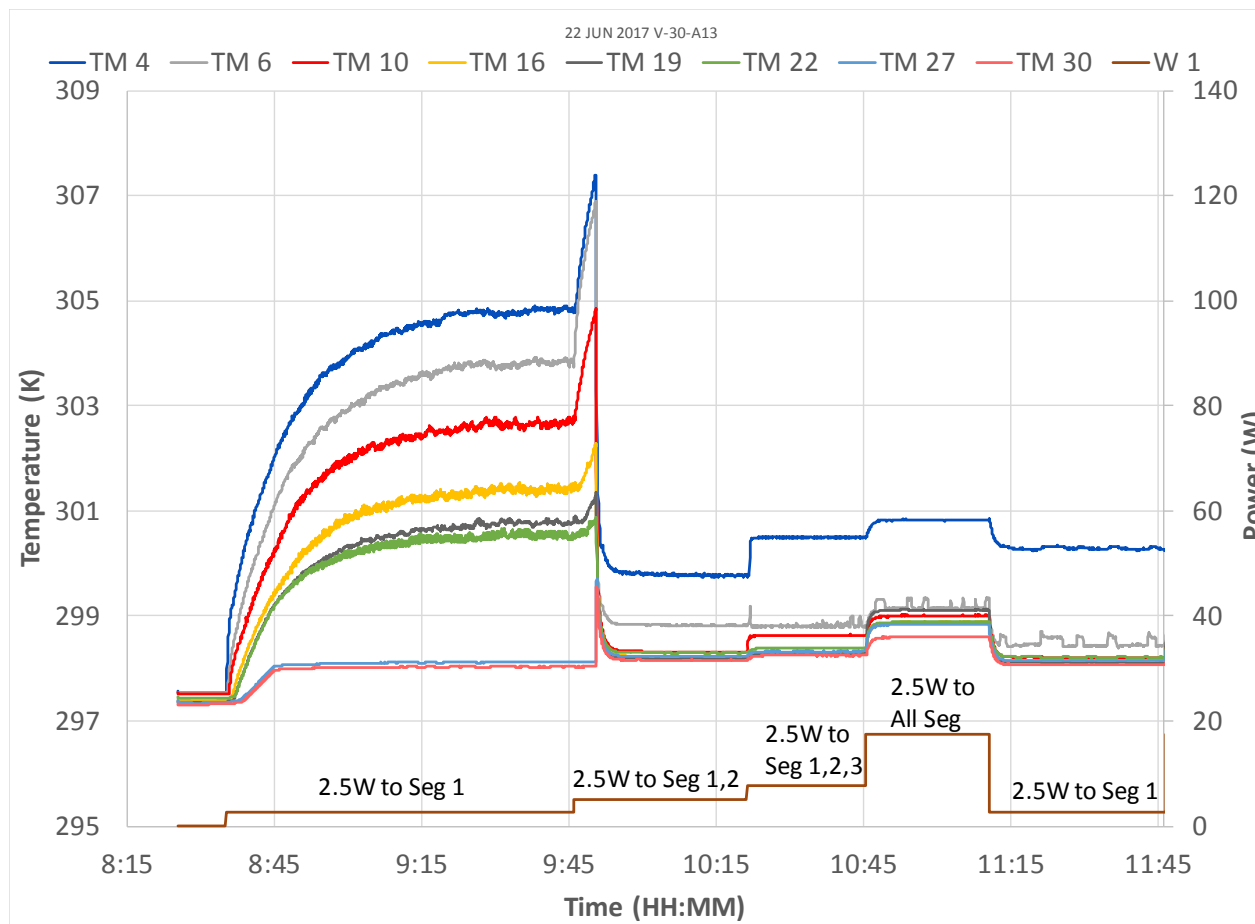
Heat pipe operated at 2.5W for 2 hours with 2.5W to Segment 1 only, no percolator effect.

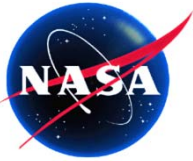




V30-A13: 2.5W Bottom Up

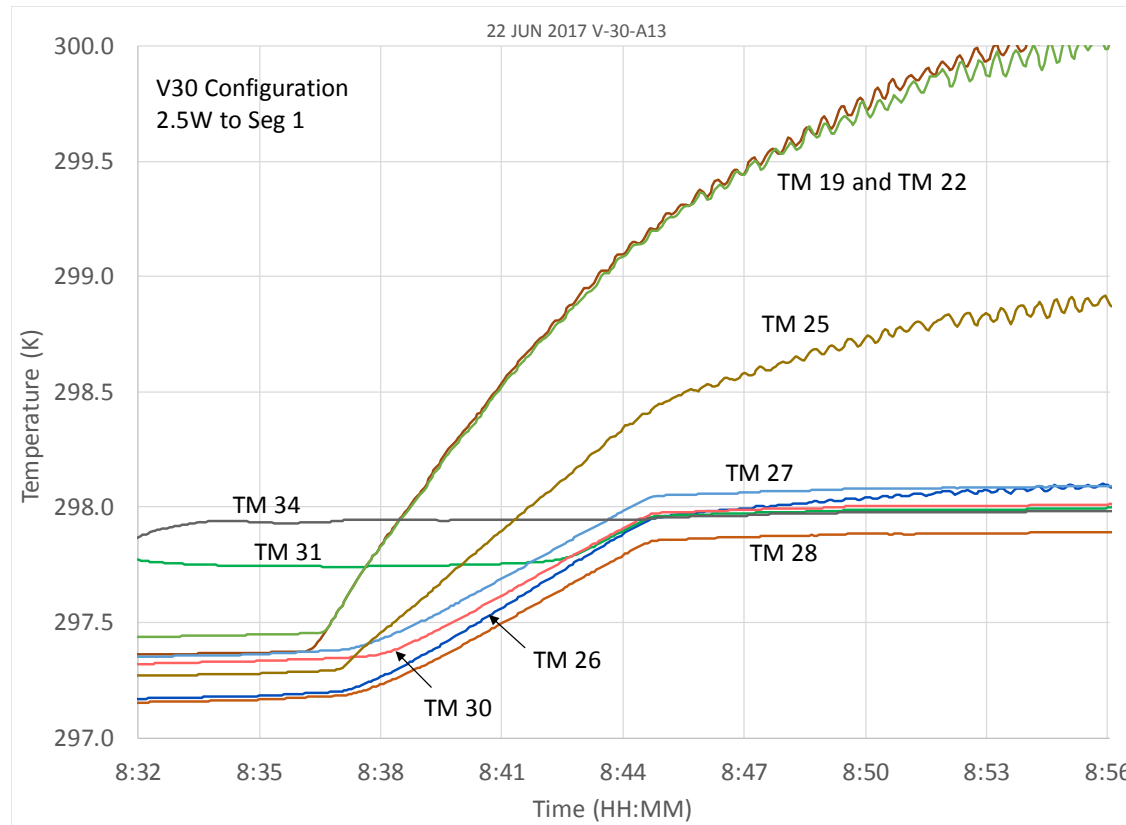
- Heat pipe did not start with 2.5W to Segment 1 (superheat at 7K, not sufficient to initiate nucleate boiling). Heat conducted to Segment 2 during SS.
- 5 minutes after 2.5W was added to Segment 2, nucleate boiling occurred.
- HP could operate with 2.5W applied to Segment 1 alone. No percolator effect.

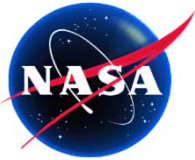




V30-A13: 2.5W to Segment 1 Only (Detail)

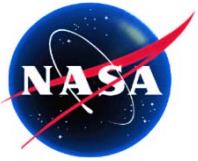
- This phenomenon that the heat pipe could reach a SS with 2.5W to Segment 1 without any sign of startup was not seen in V90 configuration and is puzzling.
- This was clearly due to the tilt of 30 degrees instead of 90 degrees (vertical). Further studies are needed.
- Look at TM 25, 26, 27, 28, 30, 31 and 34
- Heat conduction or free convection from 8:37 to 8:45?
- Liquid evaporation in Segment 7 after 8:45?





Summary of Tests Under the V30 Configuration

- **The pressure head imposed on the liquid puddle under the V30 configuration is about half of that under the V90 configuration.**
 - **The required superheat for nucleate boiling for each segment is lower under the V30 segment.**
- **The summary described under the V90 configuration also holds true for the V30 configuration except that some additional phenomena were observed.**
- **For bottom up and Segment 1 heating only, it took a longer time to reach the required superheat under the V30 configuration with the same heat flux.**
 - **Part of the heat load was transmitted to upper segments by conduction and possibly by free convection also.**
 - **Under very low heat flux, the heat pipe reached a steady state with all the heat load being transmitted away from Segment 1 and no nucleate boiling would occur.**
 - **Only with relatively high heat fluxes could Segment 1 reach the required superheat and initiate nucleate boiling.**
 - **Further investigation of this phenomenon is needed**



Conclusions

- **The most effective and efficient method to start a heat pipe under the reflux mode is to apply a high heat flux to the bottom segment where liquid puddle resides.**
 - It is effective because a high heat flux will ensure that the required superheat for nucleate boiling can be reached and that heat pipe will start successfully.
 - It is efficient because it requires the least total power consumption.
- **When the heat pipe is tilted at an angle other than the vertical position, some other factors affect the heat pipe startup.**
 - It is speculated that free convection plays a role.
 - Further studies are needed.
- **In instrument-level or spacecraft-level ground testing, multiple heat dissipating components may be attached to the adiabatic section of the heat pipe. Further studies are needed to find the minimum power required for heat pipe startup and its subsequent operation in order to maintain these components within their specified temperature ranges.**