Experimental Investigation of the Effect of Gravity on Heat Pipe Startup

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Introduction/Objectives

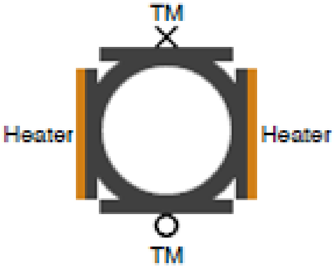
- During instrument-level or spacecraft-level ground testing, heat pipes onboard the flight hardware may be placed in a non-planar position and have to operate under the reflux mode.
- A superheat is required in order for the heat pipe to start successfully and operate properly.
  - The superheat is defined as the difference between the evaporator wall temperature and the adiabatic temperature.
  - 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.
  - The onset of nucleate boiling is characterized by a sudden increase of the adiabatic and condenser temperatures and a sudden decrease of the evaporator temperatures to near the adiabatic temperature.
- An experimental investigation was conducted to find methods 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 a liquid pool was formed at the bottom of one of the heat pipe legs. 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 heat load distributions and heat fluxes to the liquid pool.**

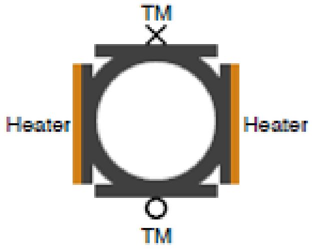
Test Article

- **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 pool length is 714 mm at 298K.**



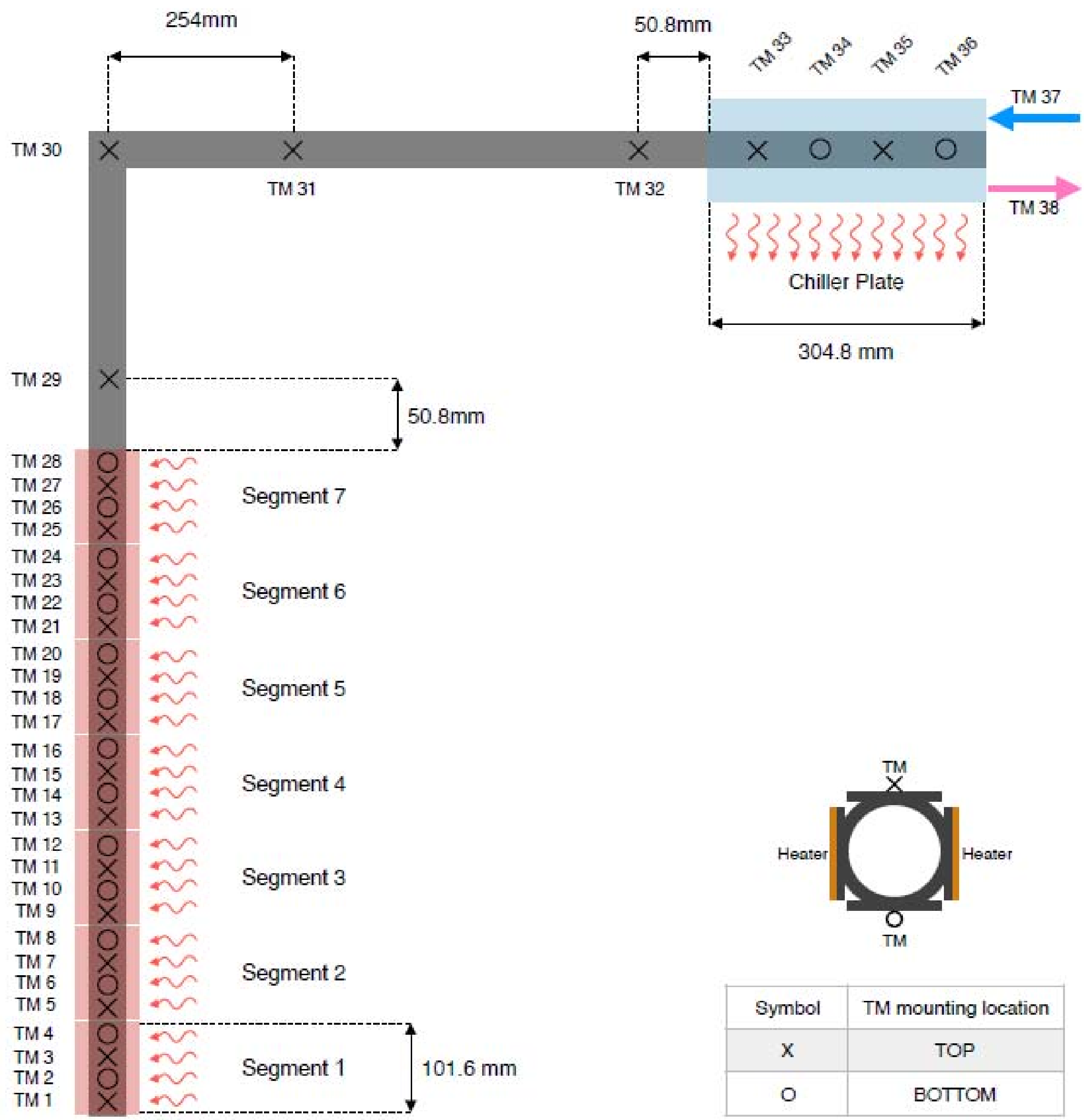
Test Setup and Instrumentation (1/2)

- The end of the 1168 mm leg was designated 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 evaporator segment, four thermistors are attached to the flanges on the opposite sides. Two on each flange and were staggered in the axial direction.
  - There were 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.

Heater and Thermistor Locations

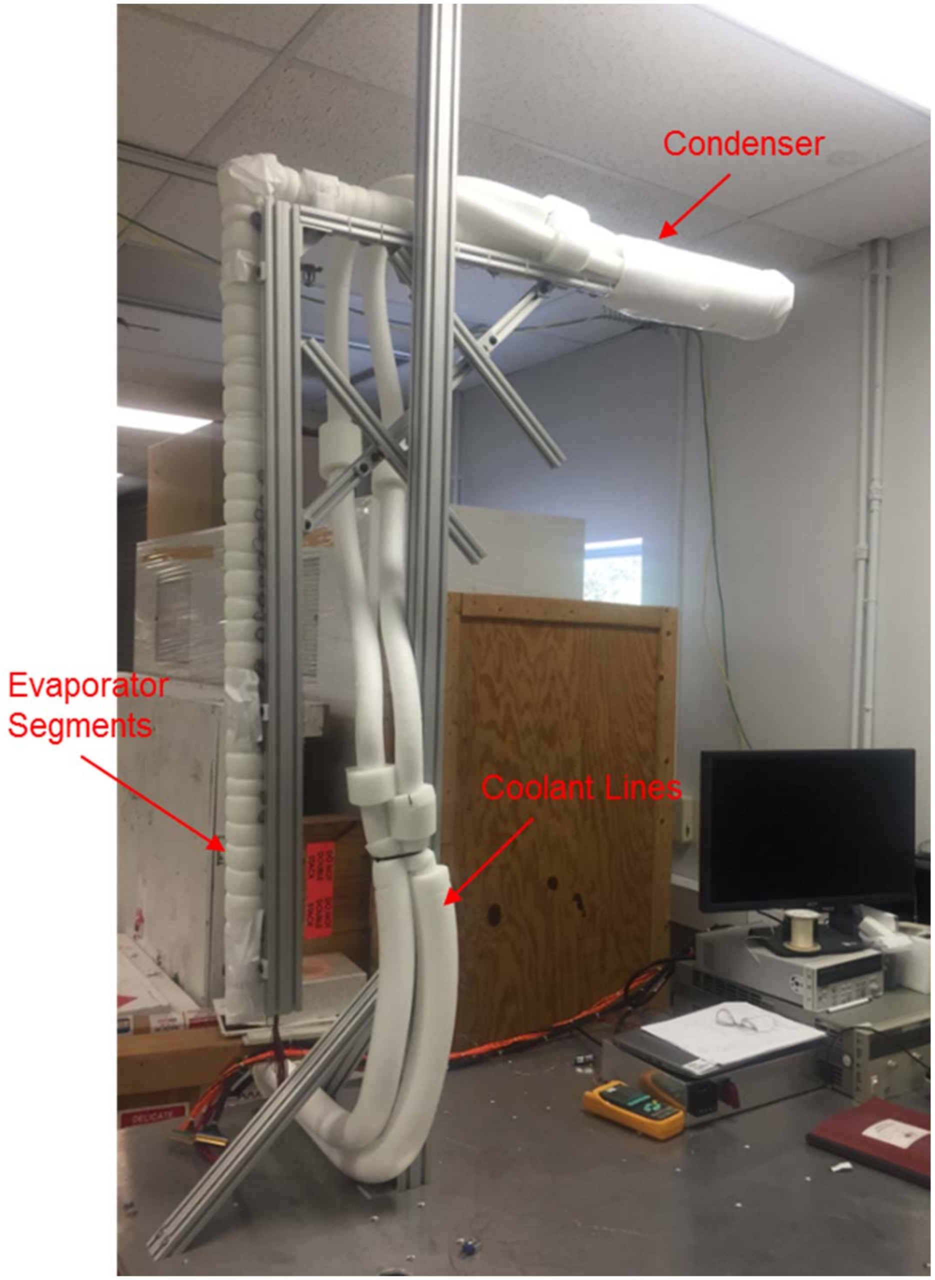


Symbol	TM mounting location
X	TOP
O	BOTTOM

Test Setup and Instrumentation (2/2)

- A single power supply was used to provide heat loads to all evaporator segments.
- All heaters were connected in parallel. The two tape heaters on each evaporator segment were connected to the same relay, which turned both heaters on or off.
- The seven relays were independently controlled.
- The maximum heat load to each evaporator segment was 15W due to the heat flux limit of the tape heater.
- The entire heat pipe was covered with polyolefin insulation.
- There were two test configurations.
  - V90 configuration: the 1168-mm leg was placed 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.
- Test data was displayed on the screen once every second, and stored in computer once every 10 seconds.

Heat Pipe in V90 (Vertical) Configuration



Tests Performed

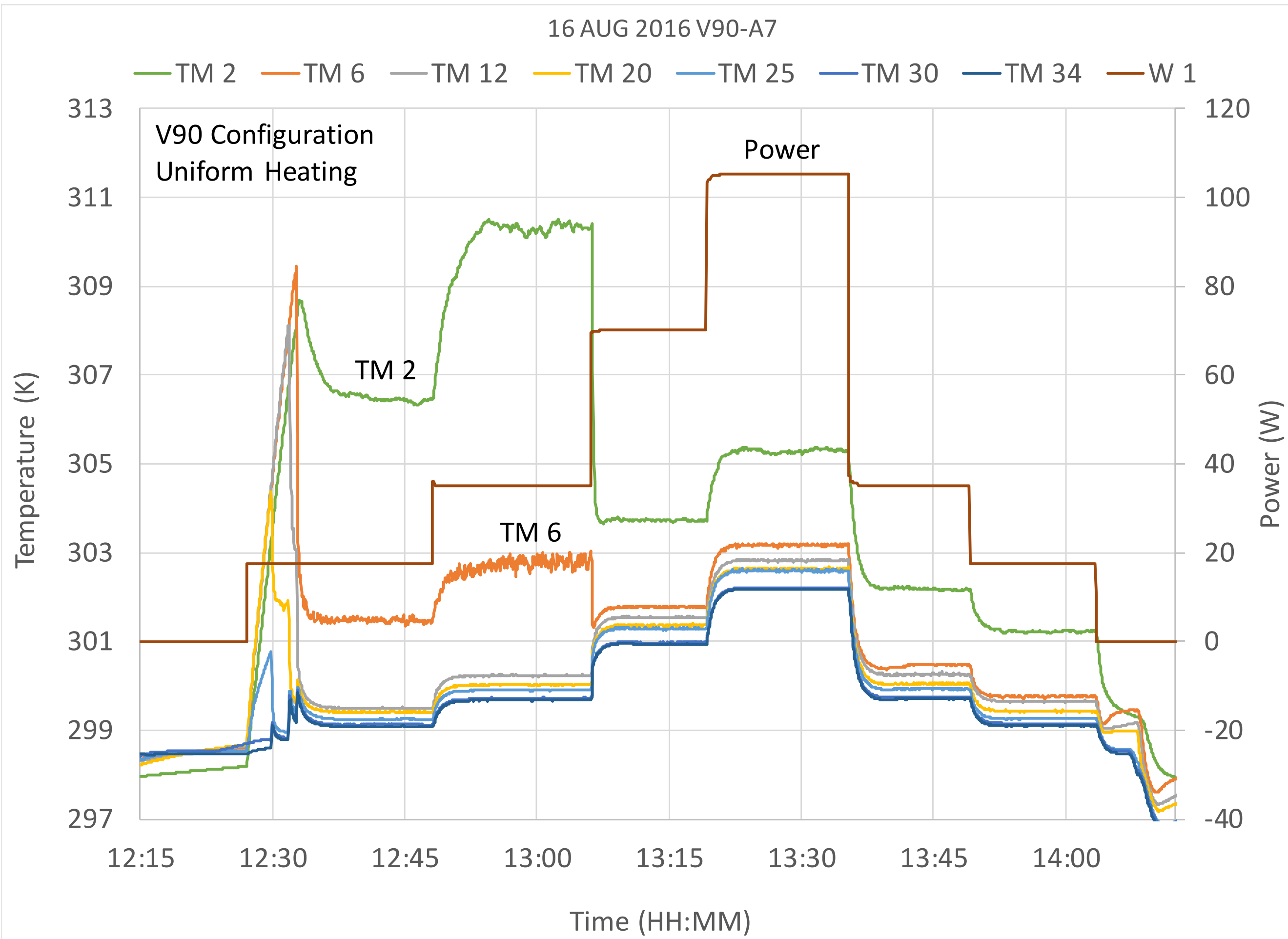
- **Tests were performed under the V90 configuration first. Most of the tests were then repeated under the V30 configuration.**
  - **The gravity head under the V30 configuration is half of that under the V90 configuration.**
- **Tests were performed with various combinations of heat load distributions and heat fluxes.**
- **Heat load distributions**
  - **Uniform: same heat load to all 7 evaporator segments simultaneously**
  - **Top down: heat load was applied to Segment 7 first. Additional heat was then added to the next lower segment 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 upper segment 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 were 2.2 kW/m^2 and 13.3 kW/m^2.**

Data Plot and Presentation

- The evaporator segment is referred to as "ES" or simply "segment".
- In each figure, relevant segments and their thermistor temperatures are plotted to show the sequence of events during heat pipe startup and operation.
  - Each ES had 4 thermistors.
  - A table is provided to show the ES and corresponding thermistors.
- Two figures may be presented for the same test in order to show the overall long term heat pipe operation and details of the startup transient.
- Only the total heat load to all 7 segments are shown, no individual heat load to each ES is plotted (too many curves otherwise). The heat load distribution can be found from the type of test performed.
- "The ES starts" means nucleate boiling has occurred in that ES.
- Each test is associated with a test number.
  - For example, V90-A7 refers to a test under V90 configuration. A7 simply indicates the test number without much significance.

V90-A7: Uniform Heating with 2.5W and Higher

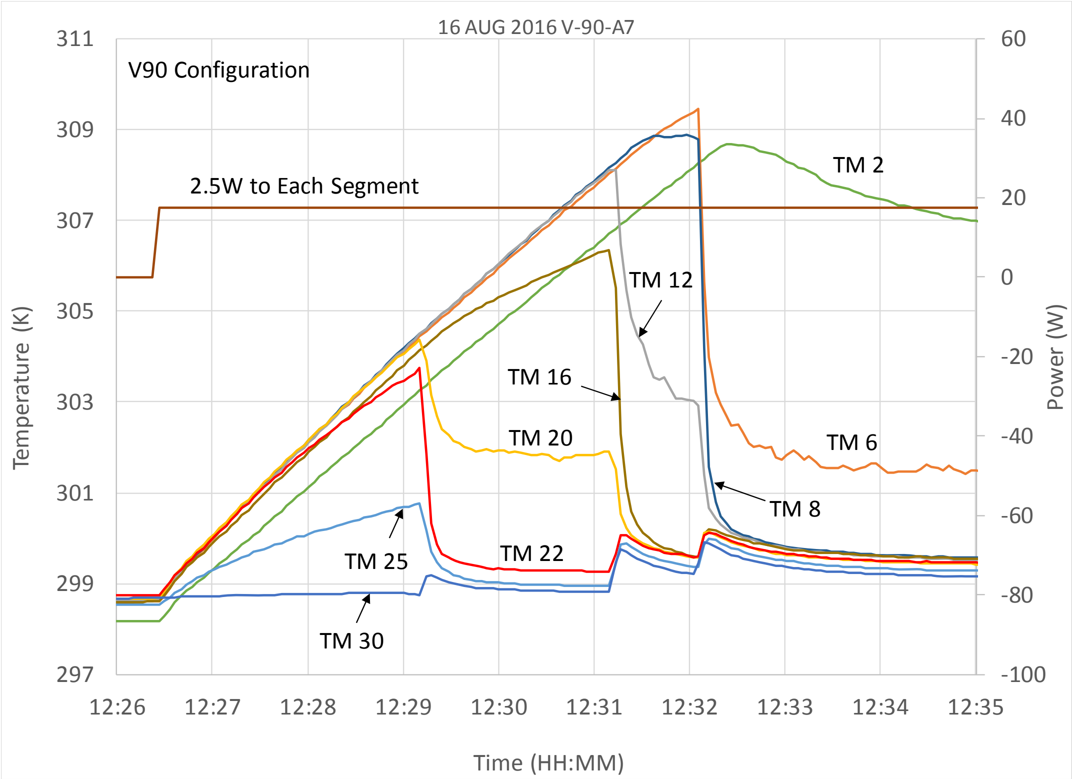
- Applied uniform heat load of 2.5W, 5W, 10W, and 15W to each ES simultaneously at each step.
- ES3 to ES7 started with 2.5W. ES2 started with 10W.
- ES1 did not start even with 15W.



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

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

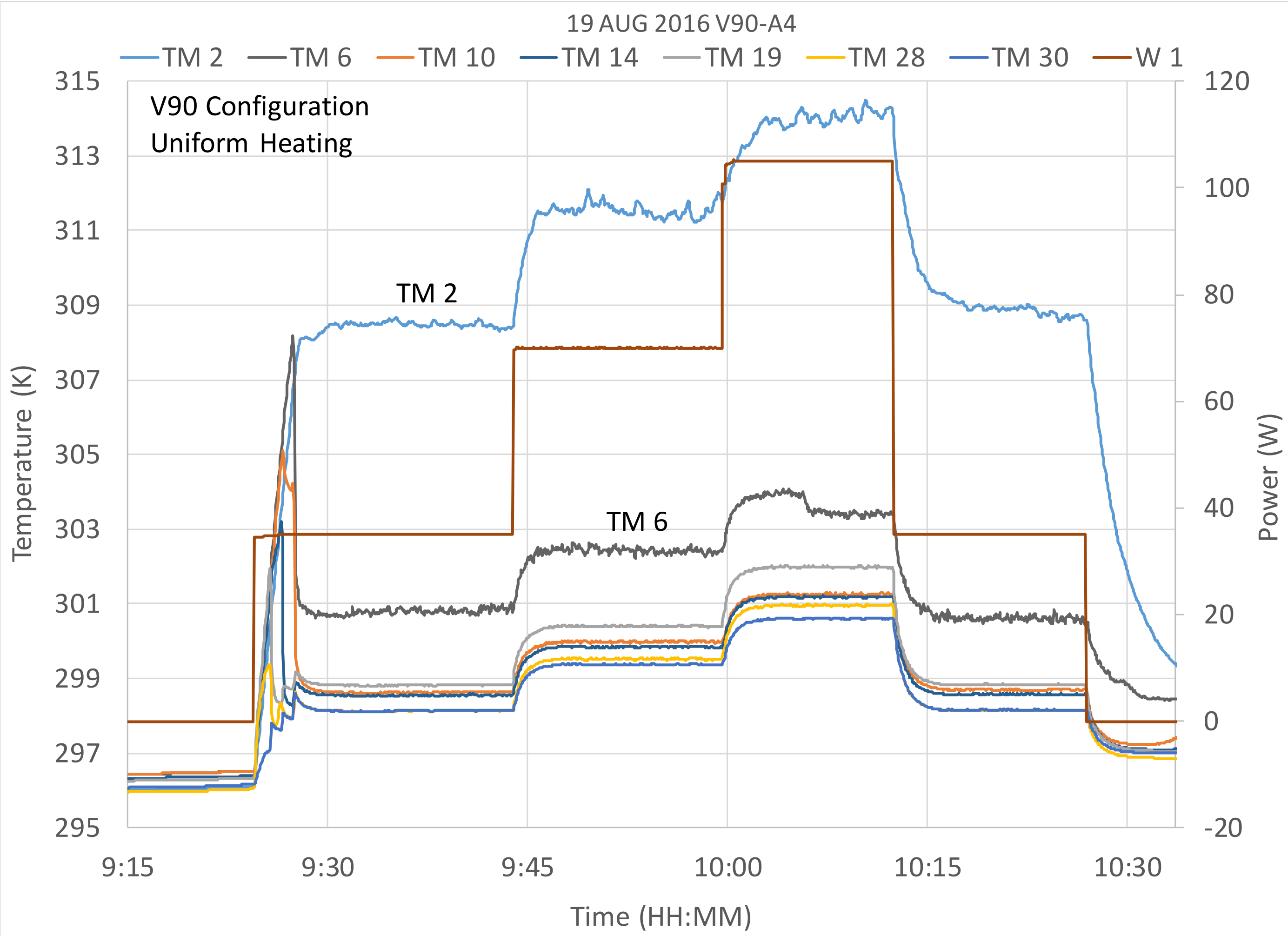
- Three distinct condenser temperature rises, corresponding to nucleate boiling at three different times and locations.
- Nucleate boiling in ES6 and ES7 at 12:29, in ES4 and ES5 at 12:31, and in ES3 at 12:32.
- Nucleate boiling might not occur over the entire ES (see TM6 & TM8 in ES3).
- ES2 did not start with 2.5W, but started at 13:06 with 10W (previous slide).
- ES1 did not start even with 15W (previous slide). Heat was transmitted to ES2 during SS and the required superheat could not be attained.



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V90-A4: Uniform Heating with 5W and Higher

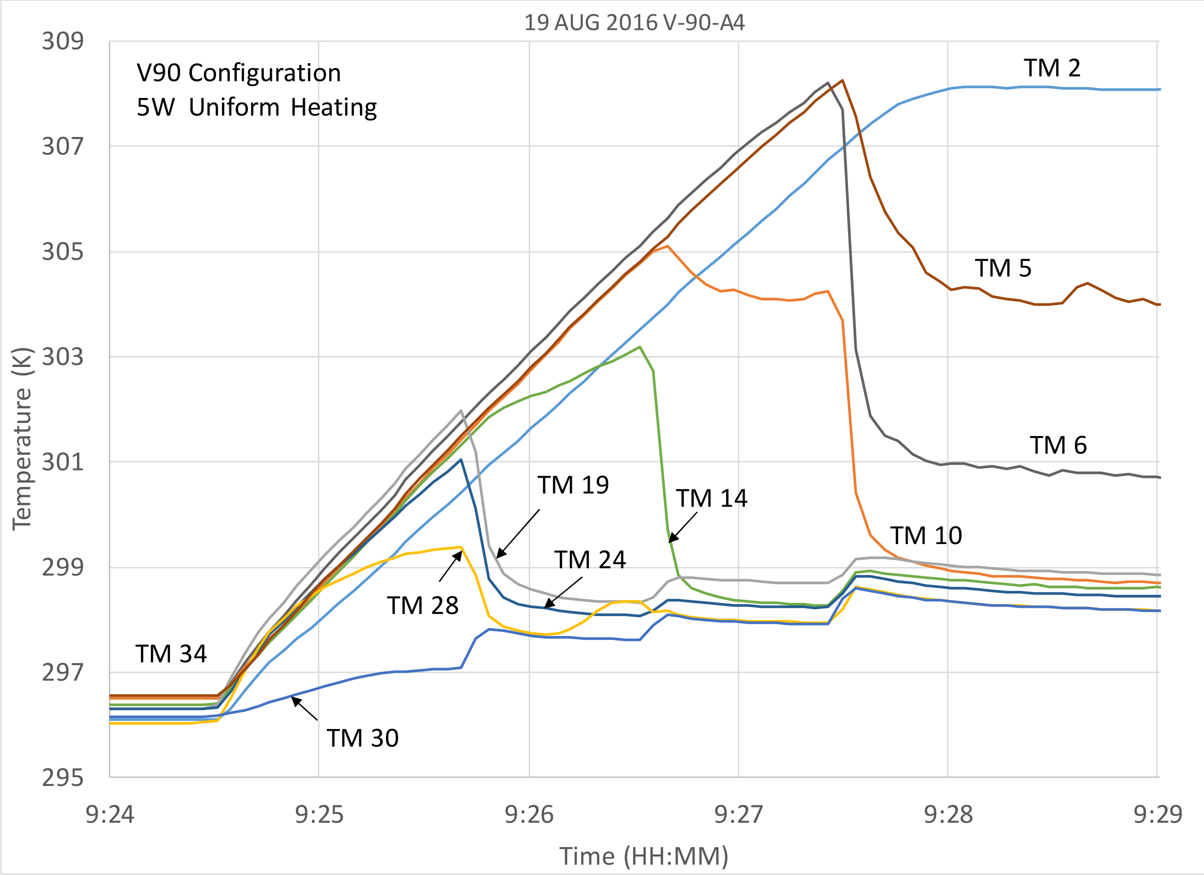
- **ES3 to ES7 started with 5W. ES1 and ES2 did not start even with 15W.**
- **ES1 and ES2 had superheat of 13K and 10K at 15W, still not enough to initiate nucleate boiling.**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

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

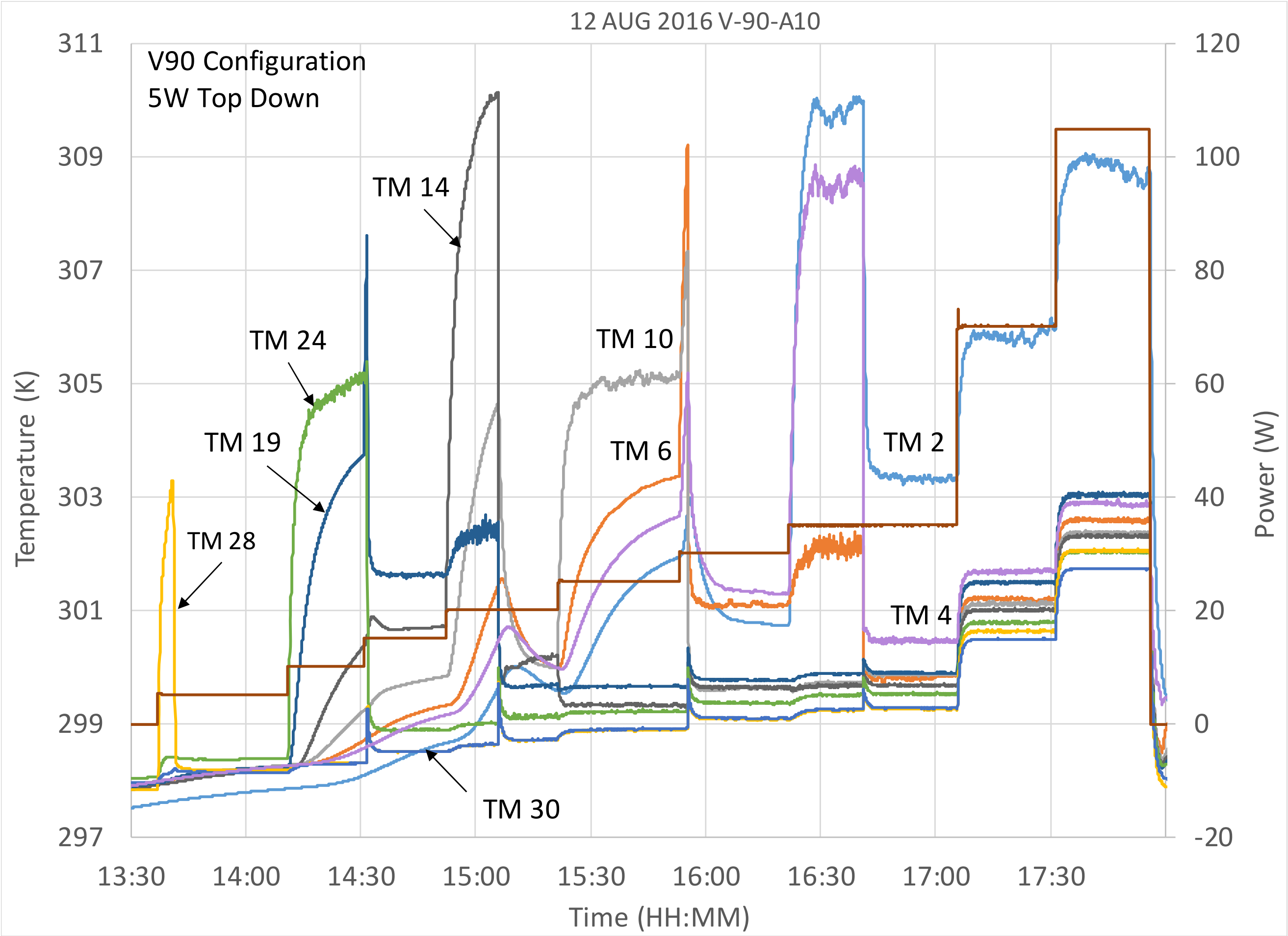
- **The top segment required smallest superheat and the bottom segment required largest.**
- **ES7, ES6, and ES5 started first, followed by ES4, and then ES3.**
- **ES1 and ES2 did not start even with 15W (previous slide).**
- **ES1 and ES2 reached SS through heat transmission to upper segments.**
- **Temperature gradient existed within each ES prior to nucleate boiling (see TM5, TM6).**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V90-A10: 5W Top Down

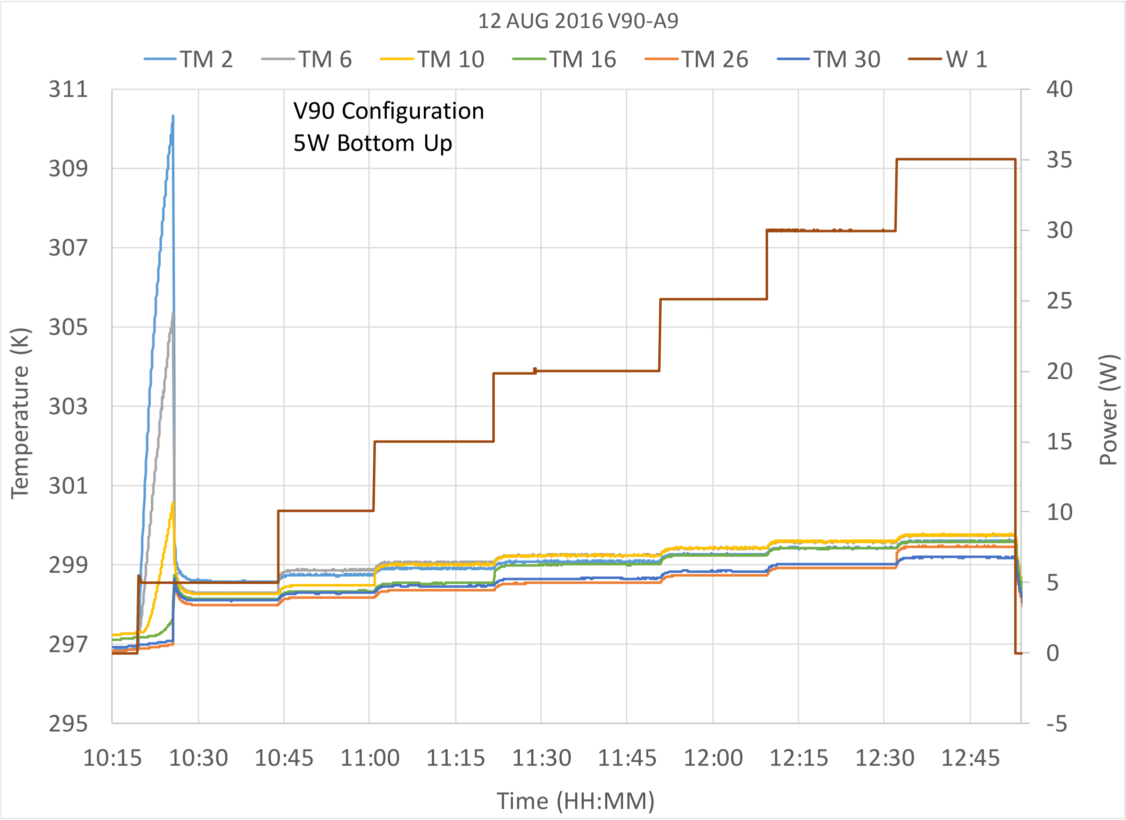
- 5W was applied to ES7 first. An additional 5W was then added to the next lower ES in steps. ES7 to ES3 started one by one as 5W was added to respective segments.
- ES2 did not start until 5W was added to ES1.
- ES1 did not start even with 15 W. Heat was transmitted to upper segments during SS. The required superheat could not be attained.



ES	Thermistors
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V90-A9: 5W Bottom-up

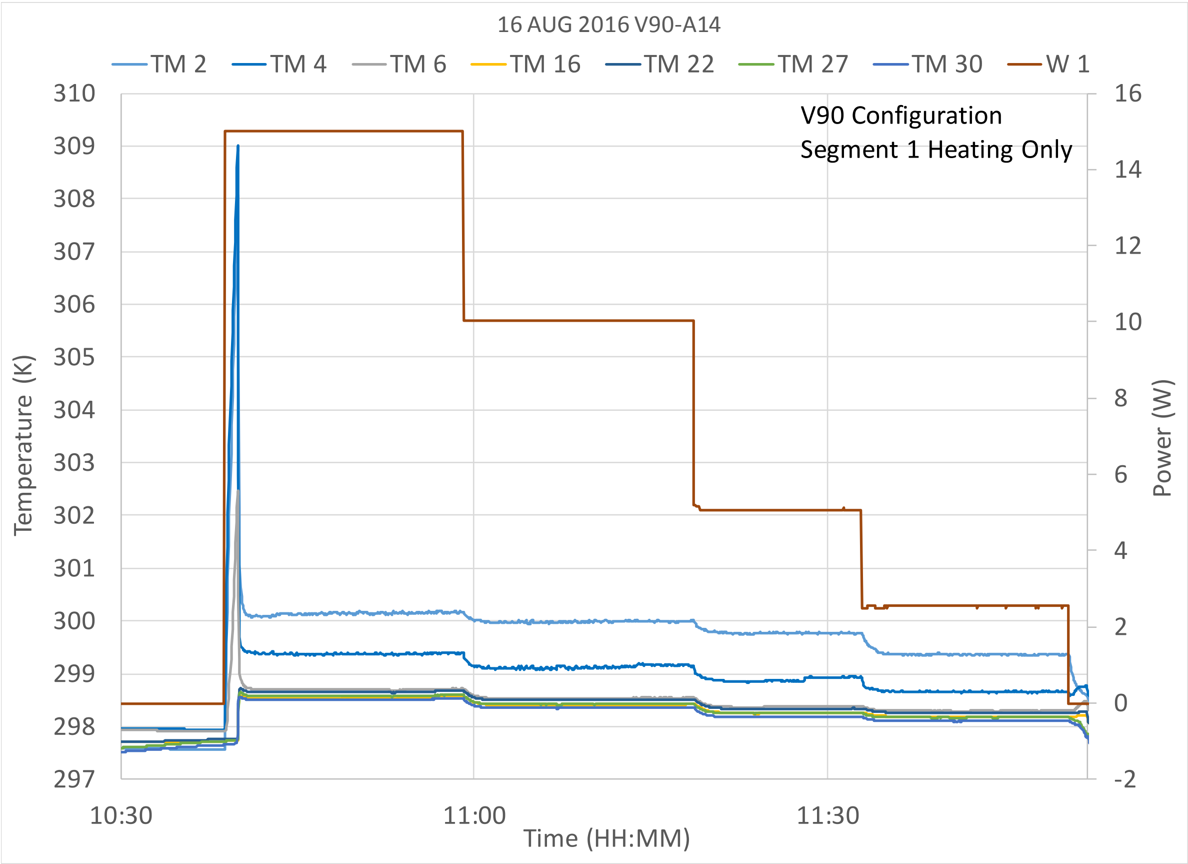
- **5W to was applied to ES1 first. A thermal gradient extended from ES1 to ES4 due to heat transmission from ES1. All segments were filled with liquid prior to onset of nucleate boiling in ES1.**
- **At 10:25, ES1 started with 13K superheat. All upper segments showed a sudden temperature decrease, indicating presence of vapor or two-phase fluid in the core.**
- **An additional 5W was added to the next upper segment in steps.**
- **No nucleate boiling and hence no superheat was required for any ES above ES1.**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V90-A14: 15W to ES1 Only

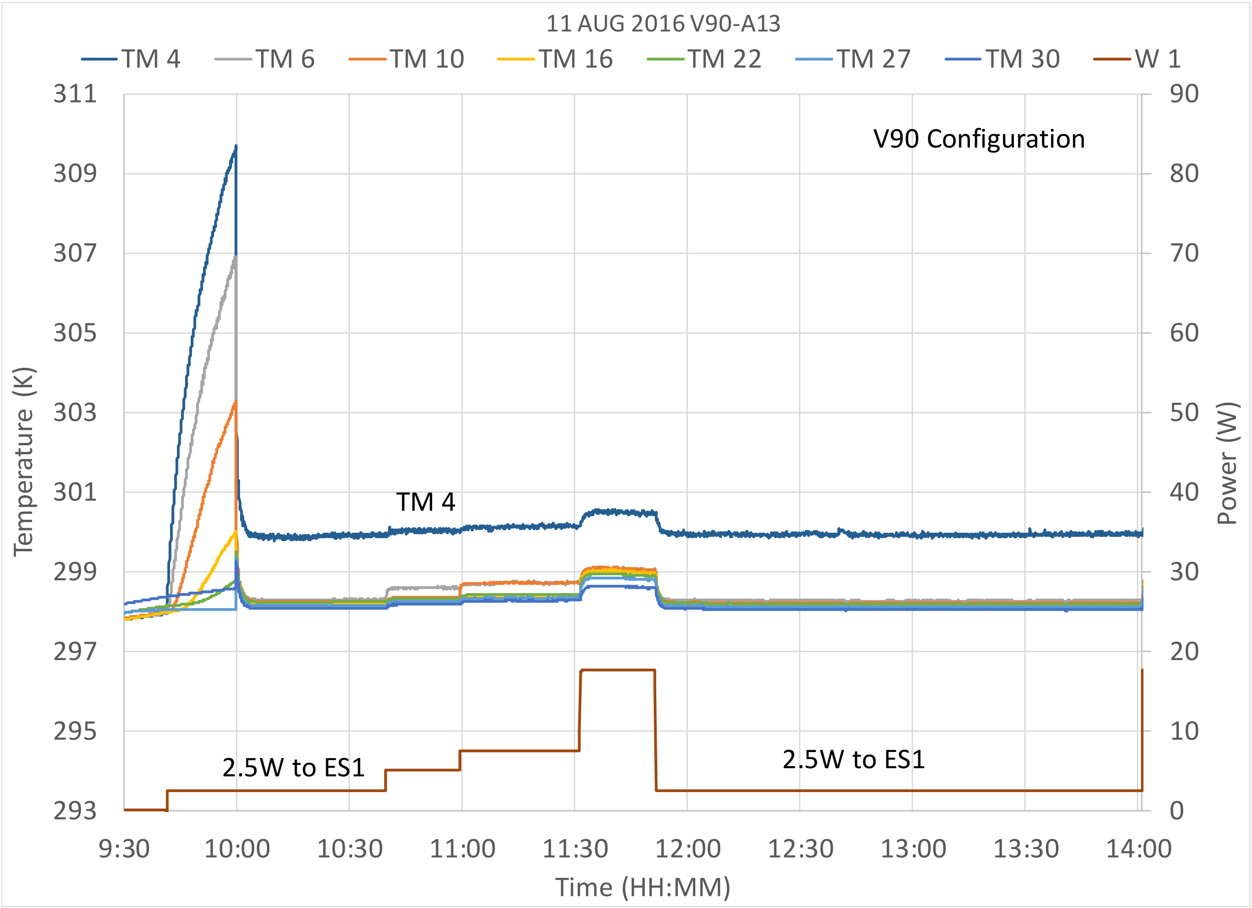
- **15W was applied to ES1 only. A temperature gradient existed among segments due to heat transmission from ES1 prior to onset of nucleate boiling.**
- **ES1 started when its superheat reached 11K.**
- **Temperatures of all segments above ES1 dropped to saturation temperature, indicating presence of vapor or two-phase fluid in the core.**
- **HP could operate with heat load of 2.5W to ES1 alone.**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V90-A13: 2.5W to ES1 Only

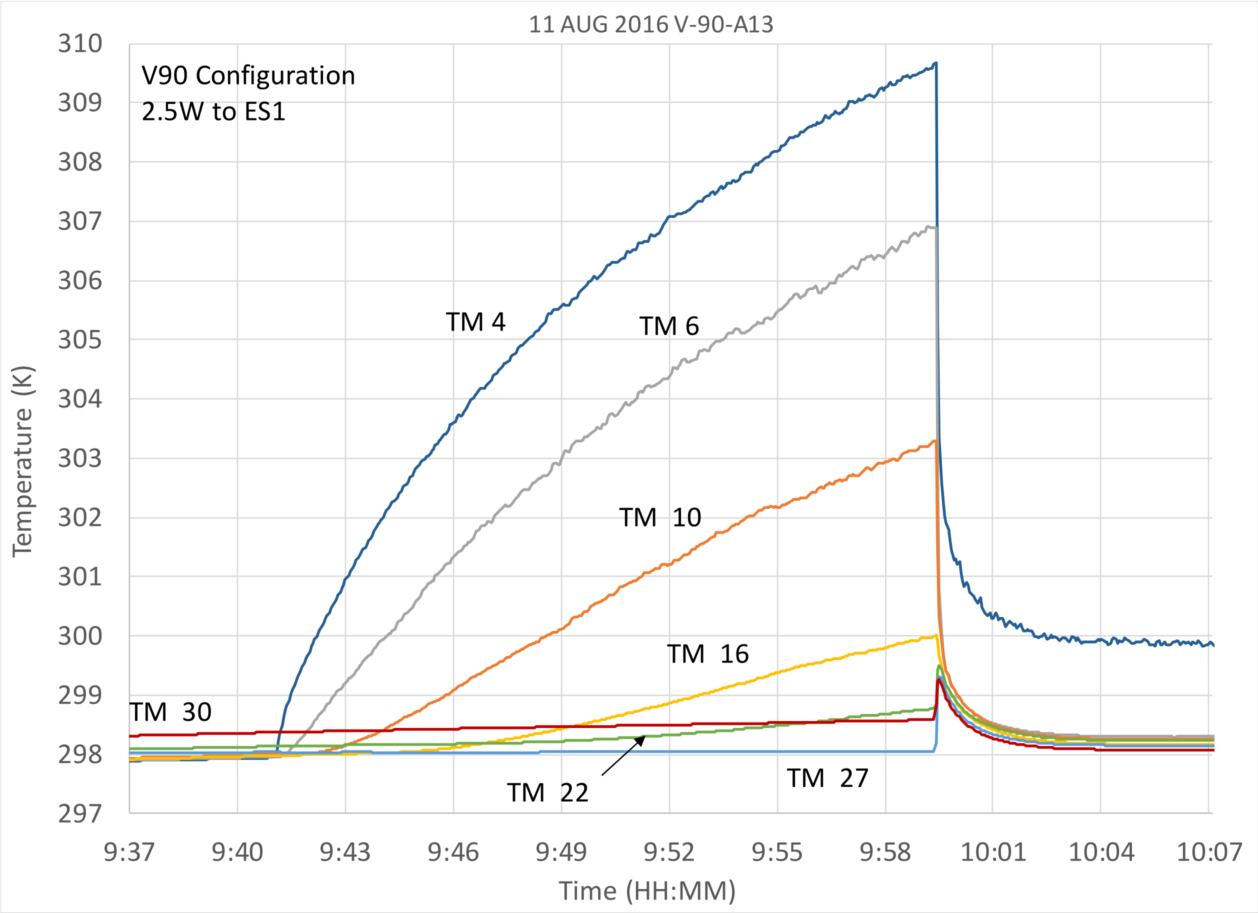
- All segments were filled with liquid prior to onset of nucleate boiling in ES1.
- After the onset of nucleate boiling in ES1, temperatures of all upper segments dropped to saturation temperature, indicating presence of vapor or two-phase fluid in the core.
- No superheat was required when additional heat was added to ES2, and then to ES3, and then to all segments.
- Heat pipe could operate stably with 2.5W applied to ES1 alone for two hours.



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V90-A13: 2.5W to ES1 Only (Detail)

- **When 2.5W was applied to ES1, heat was conducted to upper segments prior to nucleate boiling. The thermal gradient extended from ES1 to ES6.**
- **It took ES1 18 minutes to rise to 310K and achieve 12K of superheat for nucleate boiling.**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

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

- If a heated zone was covered by the liquid pool, a superheat was required to initiate nucleate boiling in that zone.
- If the required superheat could not be achieved, that zone would remain liquid filled and no vapor would be generated there. Such a zone could be the entire evaporator segment or a part it.
- Once a segment had initiated nucleate boiling, the center core of all segments above it would be occupied by vapor or two-phase fluid. Any subsequent power application to these segments would result in immediate liquid evaporation and no superheat was required.
- On the other hand, all segments below that segment would still be liquid-filled due to gravity. A superheat was 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)

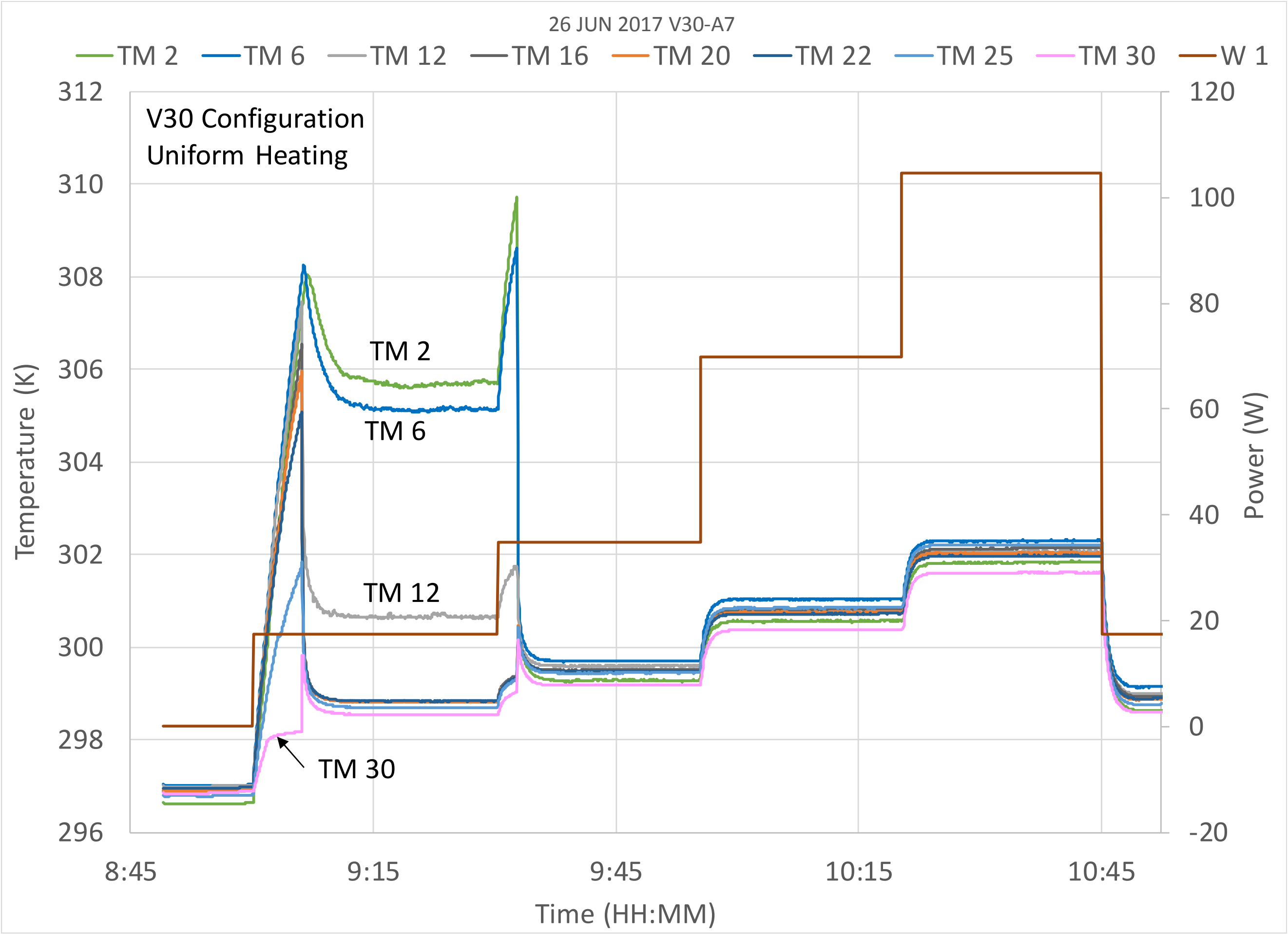
- **Uniform heating of all segments and top down heating would lead to nucleate boiling from the top segment to the next lower segment in sequence, and a superheat was required for all segments. At low heat fluxes, however, the segments near the bottom might not attain the required superheat and would remain liquid filled.**
  - **Most of the heat applied to these segments was transmitted to adjacent upper segments where nucleate boiling had occurred. Heat transmission occurred by heat conduction through heat pipe envelope and free convection within the liquid pool.**
  - **A high heat flux would enhance the possibility that all segments achieved nucleate boiling.**
- **The required superheat for nucleate boiling was a function of the gravity head.**
  - **The bottom segment required the highest superheat and the top segment required the lowest.**
  - **In general, the higher the gravity pressure head, the larger the required superheat.**

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

- **The required superheat showed no or very weak dependence on the heat flux. However, a higher heat flux led to a shorter time for achieving the required superheat for nucleate boiling.**
- **The heat pipe could start successfully and operate stably with a very low heat load even when the bottom segment alone received the power.**

V30-A7: Uniform Heating with 2.5W and Higher

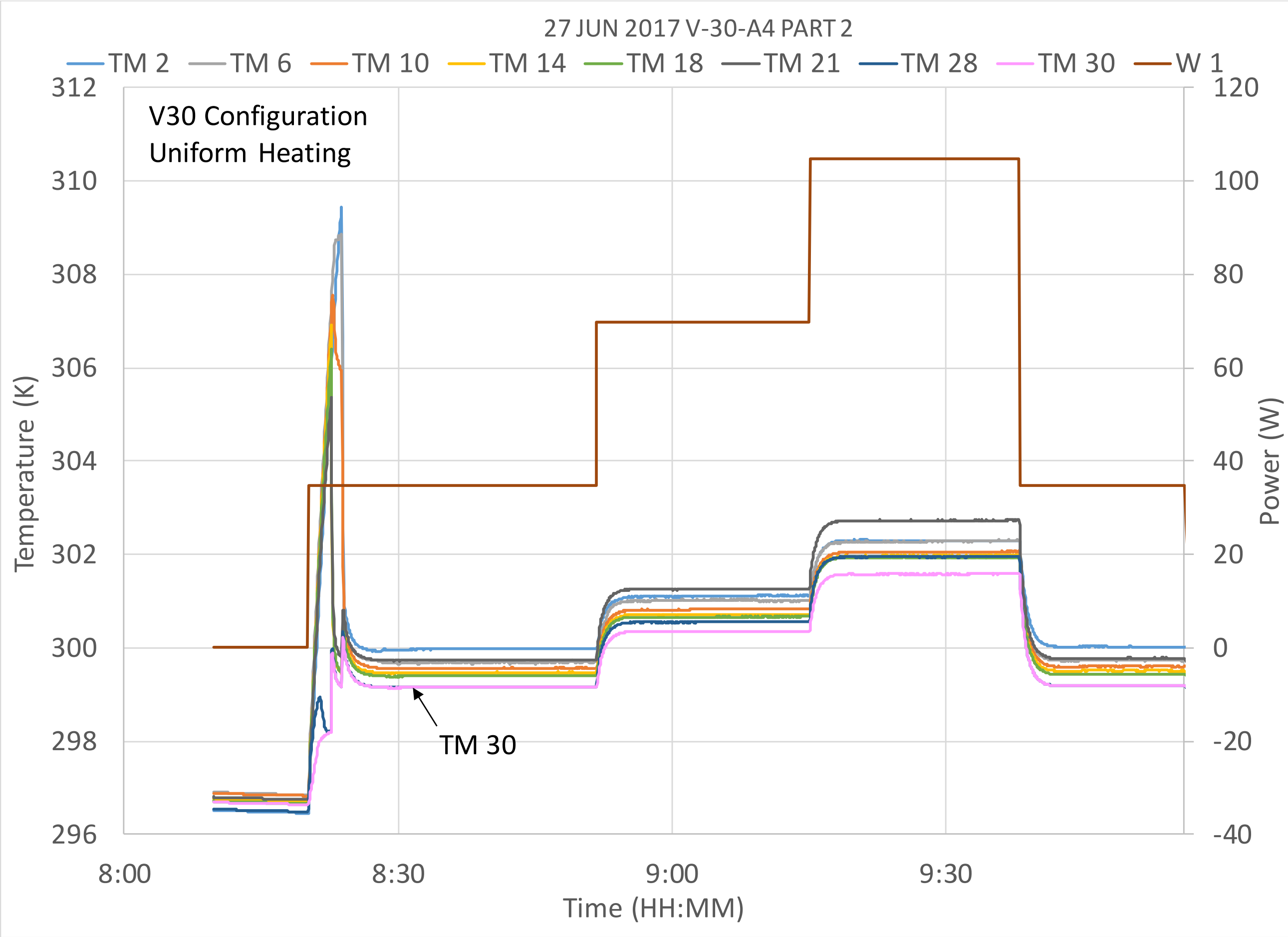
- **Applied uniform heat load of 2.5W, 5W, 10W, and 15W to each ES simultaneously in steps.**
- **ES4 to ES7 started with 2.5W (same as in V90 configuration)**
- **ES1, ES2, and ES3 started with 5W (ES1 did not start in V90 configuration).**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V30-A4: Uniform Heating with 5W and Higher

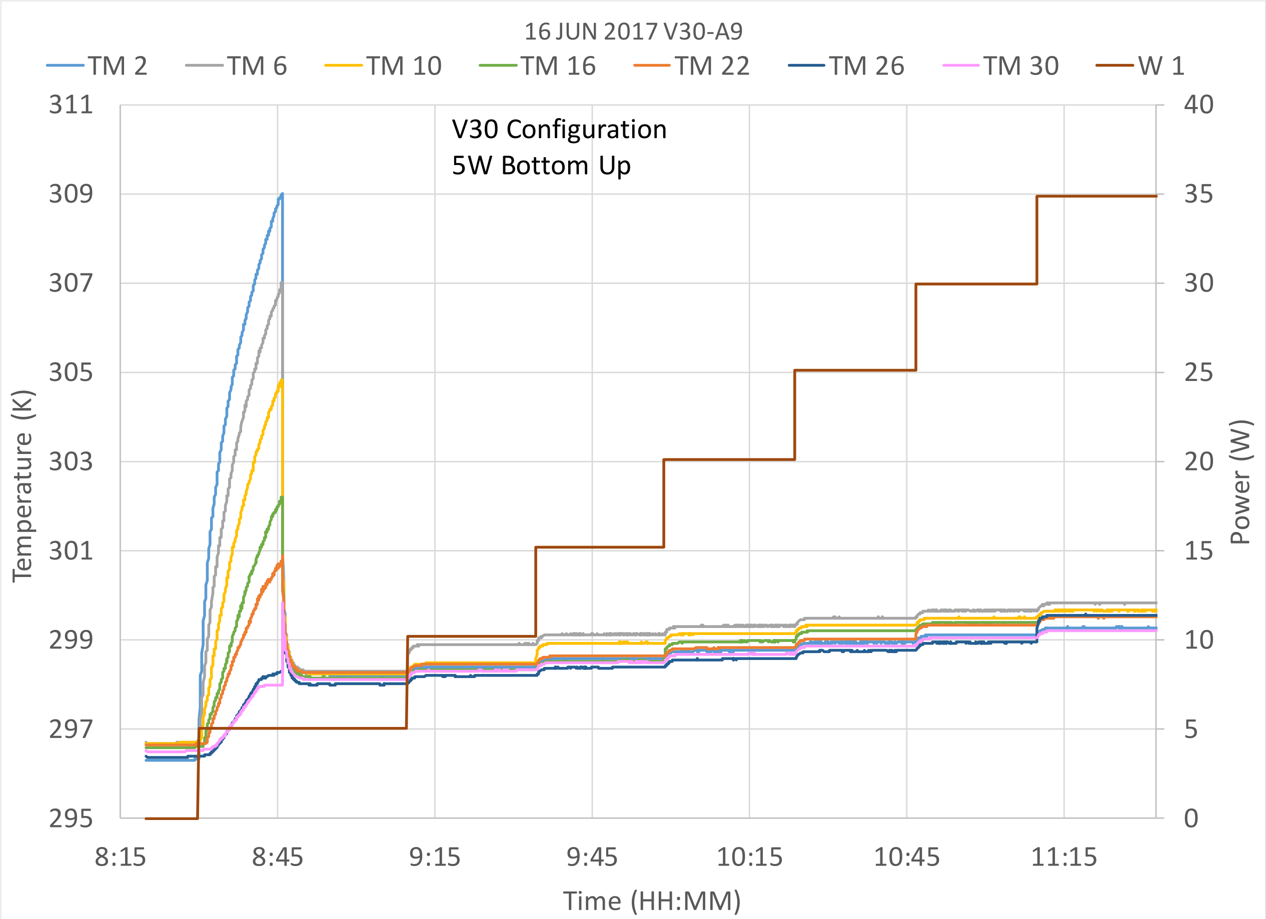
- **All segments started with 5W, including ES1, ES2, and ES3. This was consistent with the V30-A7 test (previous slide).**
- **ES1 and ES2 did not start with heat load up to 15W in V90 configuration.**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

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 for ES1 to achieve the required superheat. The temperature gradient prior to nucleate boiling extended further into ES6 (only to ES4 in V90 configuration).



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
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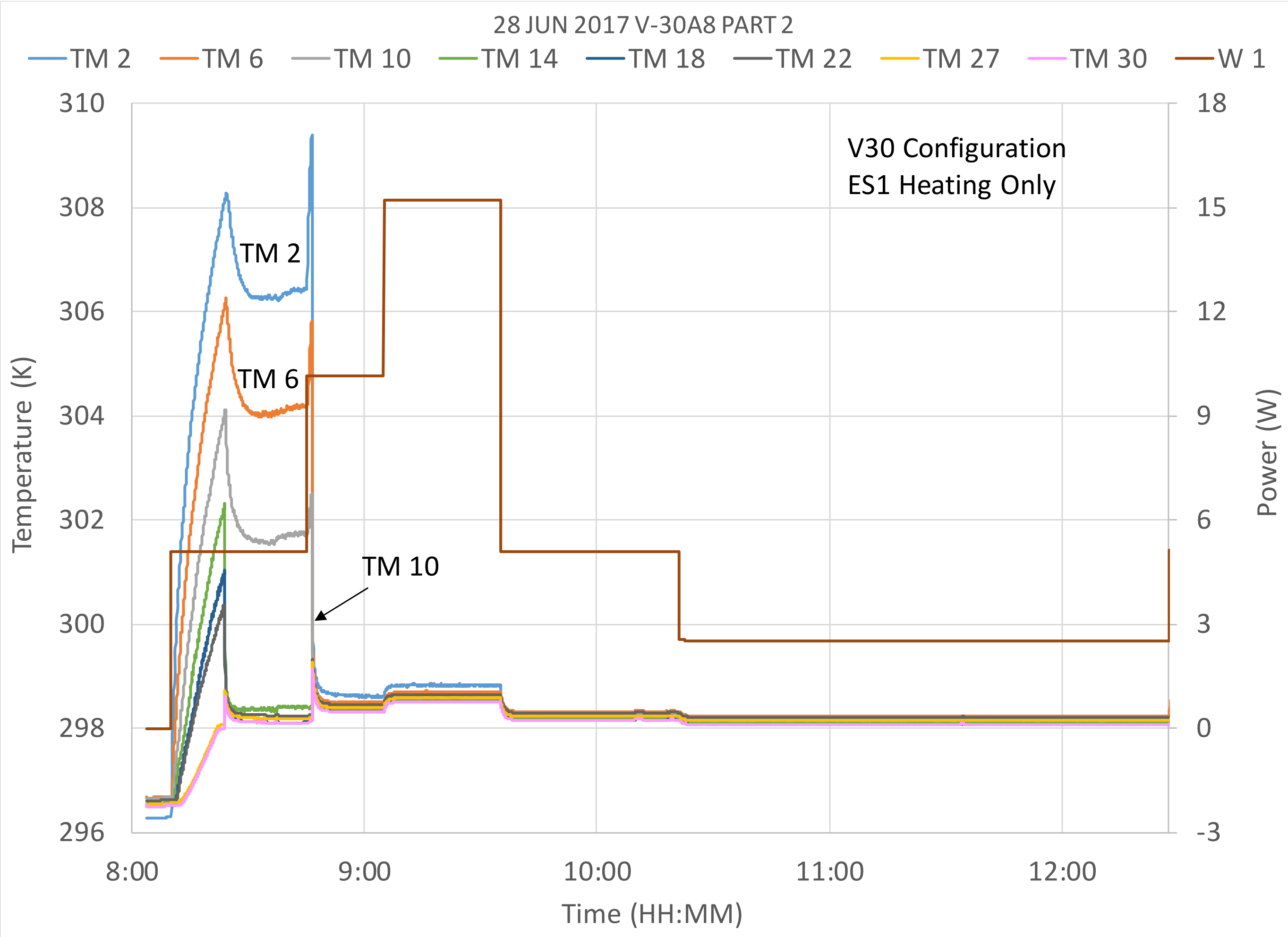
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V30-A8: 5W to ES1 Only

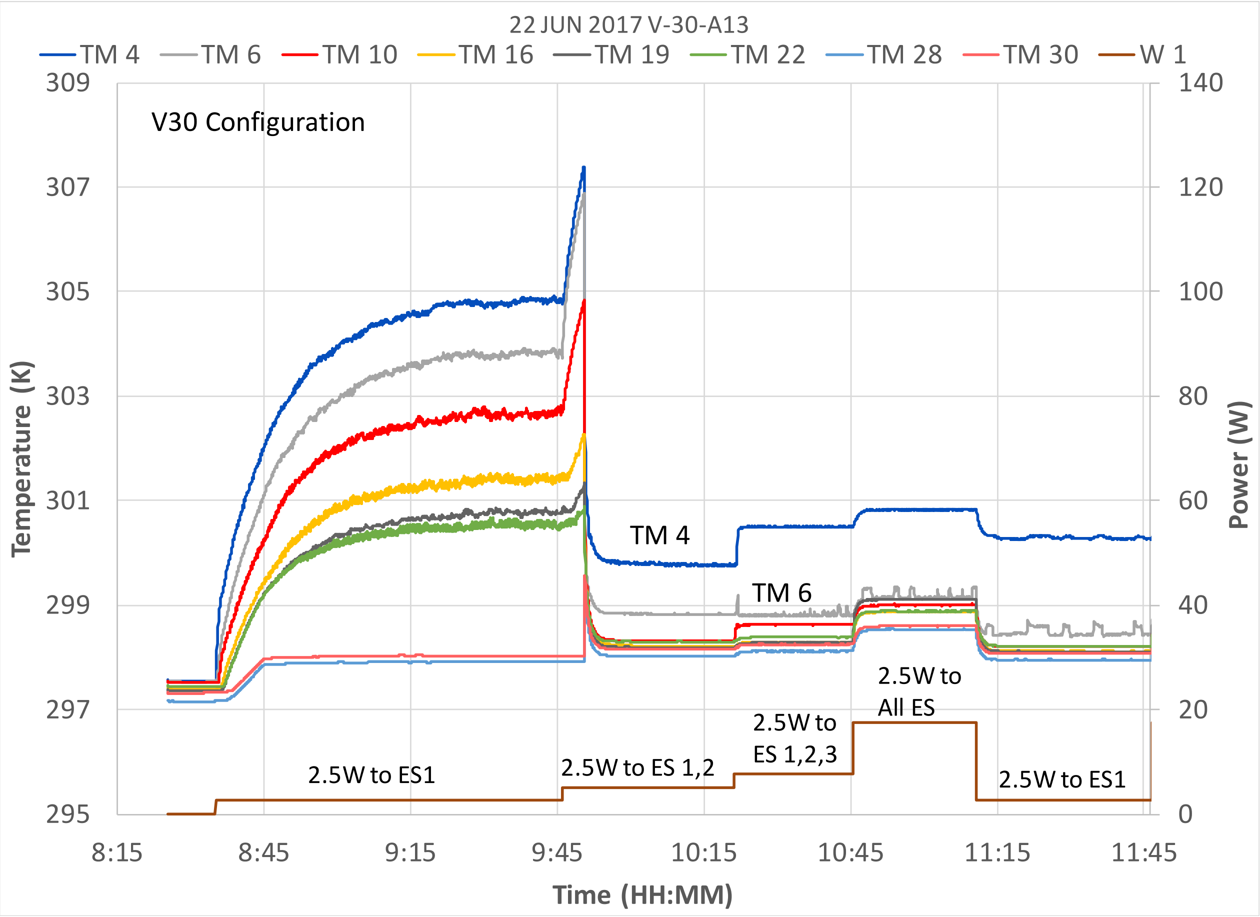
- 5W to ES1 only. ES4 to ES7 started at 5W. Quite unusual.
- ES1, ES2, and ES3 started at 10W.
- Heat pipe operated stably for 2 hours with 2.5W to ES1 only.



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V30-A13: 2.5W to ES1 only for Startup

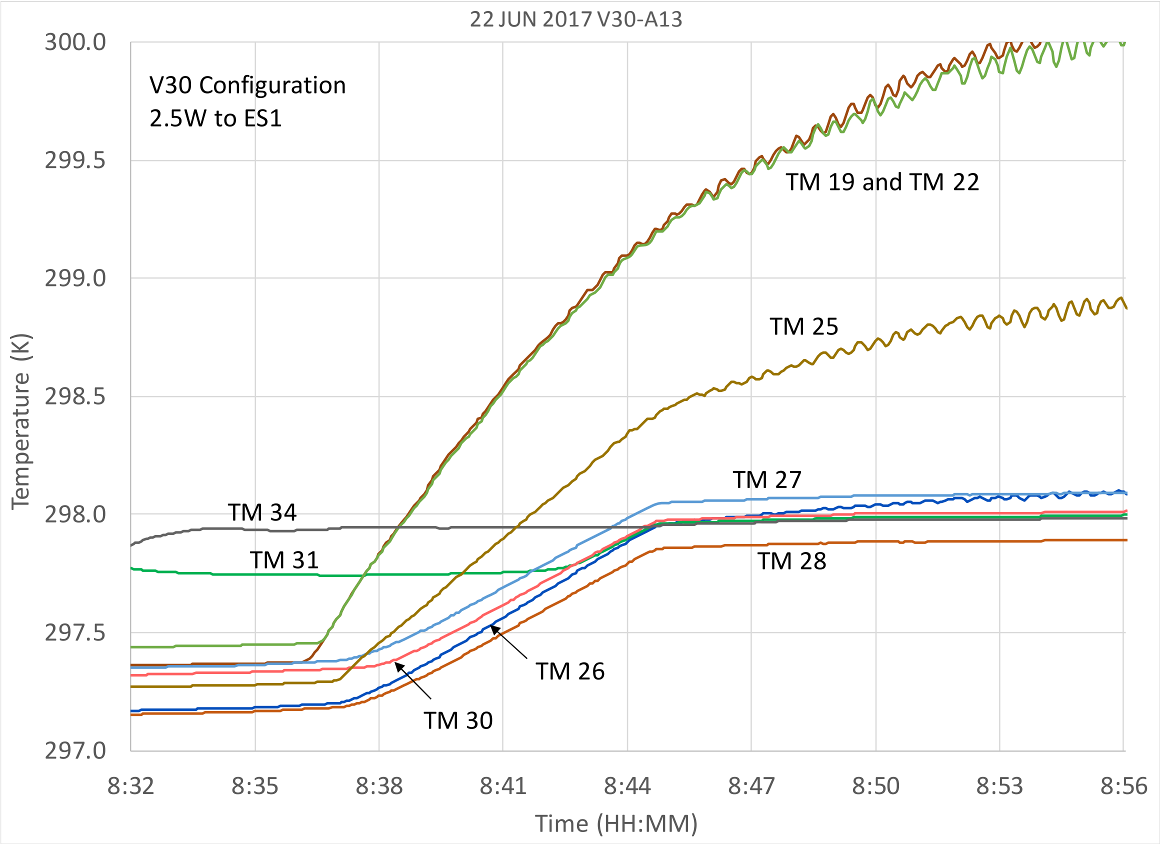
- **ES1 did not start with 2.5W (superheat at 7K, not sufficient to initiate nucleate boiling). Heat was transmitted to ES2 during SS. (ES1 started in V90 Configuration)**
- **5 minutes after 2.5W was added to ES2, nucleate boiling occurred.**
- **Heat pipe could operate with 2.5W to ES1 alone.**



ES	Thermistors (TM)
1	1, 2, 3, 4
2	5, 6, 7, 8
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28

V30-A13: 2.5W to ES1 Only (Detail)

- **The liquid seemed to mix better in the pool in V30 configuration than V90 configuration.**
- **From the temperature profiles:**
  - **Heat conduction and free convection from 8:37 to 8:45?**
  - **Liquid evaporation in ES7 began at 8:45?**
- **Vapor generated on the surface of the liquid pool could reach the condenser more easily under the V30 configuration.**



ES	Thermistors (TM)
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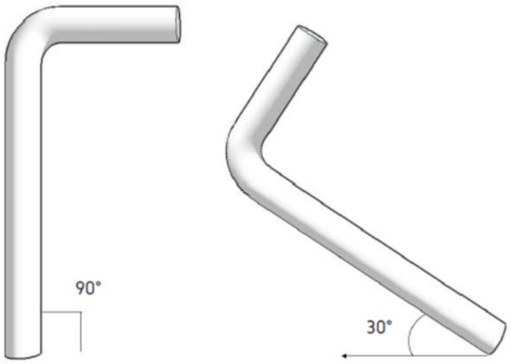
3	9, 10, 11, 12
4	13, 14, 15, 16,
5	17, 18, 19, 20
6	21, 22, 23, 24
7	25, 26, 27, 28



Summary of Tests Under the V30 Configuration

- **The pressure head imposed on the liquid pool under the V30 configuration was about half of that under the V90 configuration.**
  - **The required superheat for nucleate boiling for each segment was lower under the V90 segment.**
- **The observations summarized under the V90 configuration also hold true for the V30 configuration except that some additional phenomena were observed.**
- **For bottom up and ES1 heating only, it took a longer time for ES1 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 through heat pipe envelope and by free convection within the liquid pool.**
  - **With very low heat fluxes, the heat pipe reached SS with all the heat load being transmitted away from ES1 and no nucleate boiling occurred.**
  - **Only with high heat fluxes could ES1 reach the required superheat and initiate nucleate boiling.**
  - **Further studies of this phenomenon are 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 pool resides.**
  - **It is effective because a high heat flux will ensure that the required superheat for nucleate boiling can be reached, and nucleate boiling at the bottom can boil off the liquid pool more easily.**
  - **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.**
  - **Free convection within the liquid pool may play an important 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.**