TFAWS Passive Thermal Paper Session

TFAWS23-PT30

Copper/Water Heat Pipe Qualification Testing for Spaceflight Hardware

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THERMAL & FLUIDS ANALYSIS WORKSHOP
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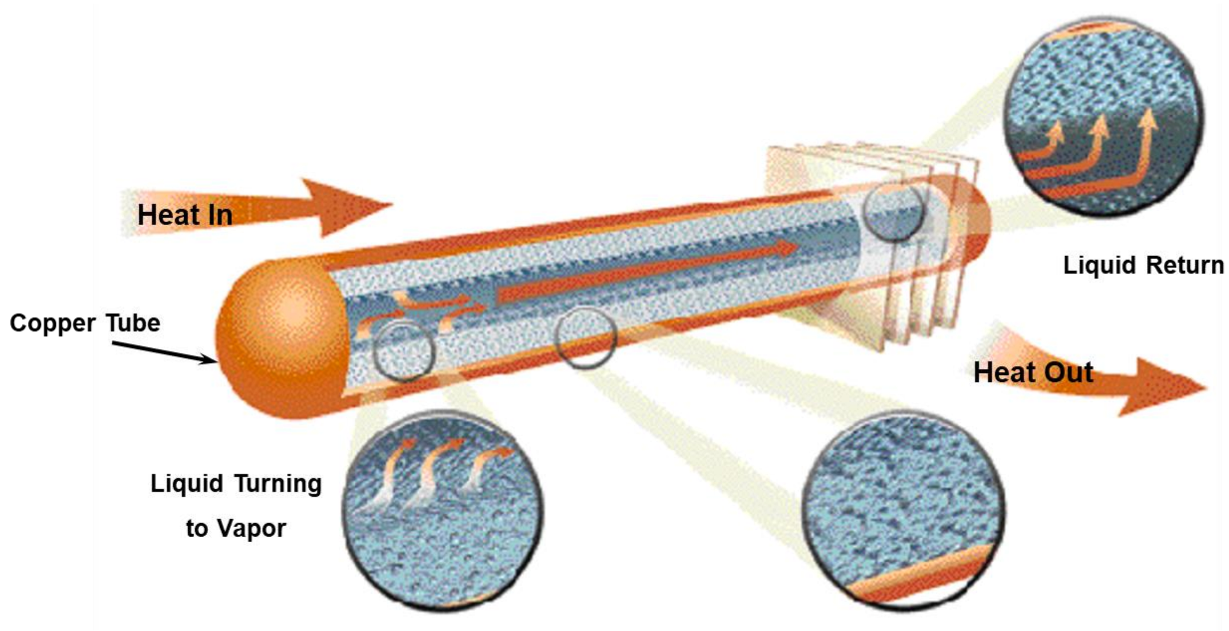
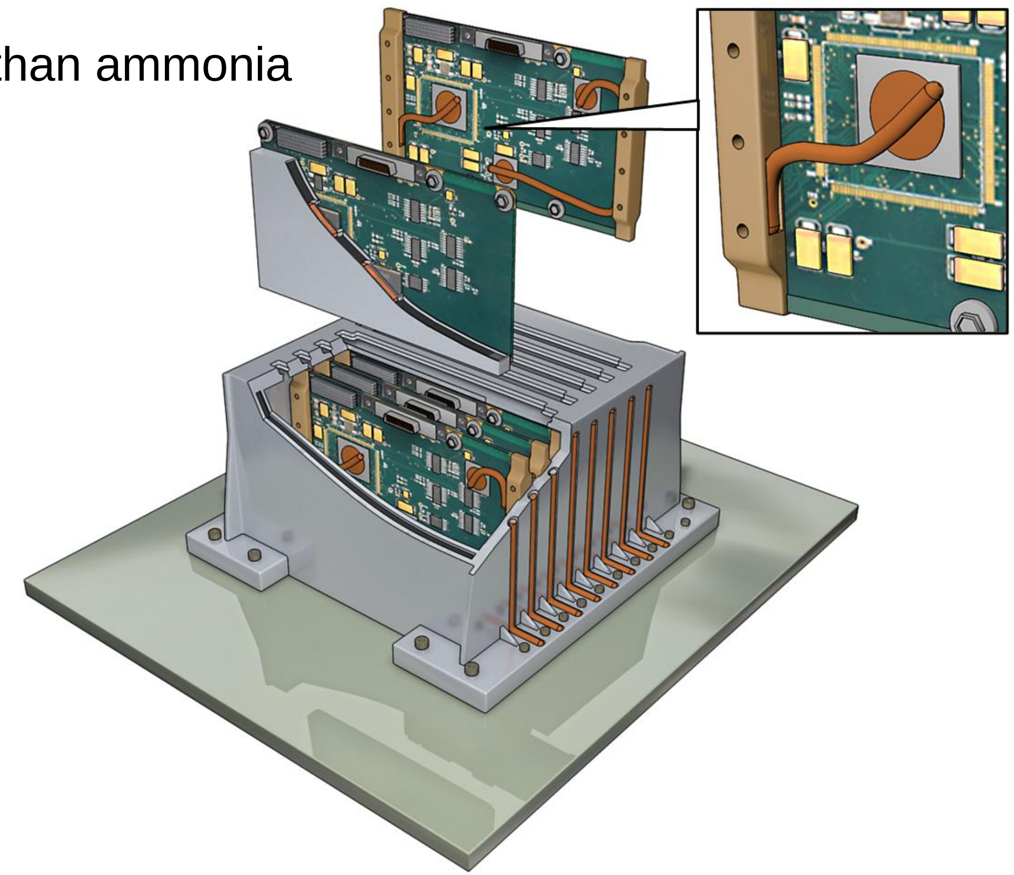
- Copper/Water heat pipes are widely used in the electronics cooling world.
  - By the tens of millions
- Can water heat pipes really survive freeze-thaw cycles?
- How is water heat pipe function effected by thermal cycling?
- How are these heat pipes tested?
  - Passive thermal cycles
  - Active thermal cycles
    - Heat input to the evaporator while the condenser cycles back and forth across 0C.

- Copper/Water heat pipe design characteristics
  - Phase change heat transfer
    - Wick – porous structure rather than grooves
    - Working fluid is water, which has better properties than ammonia

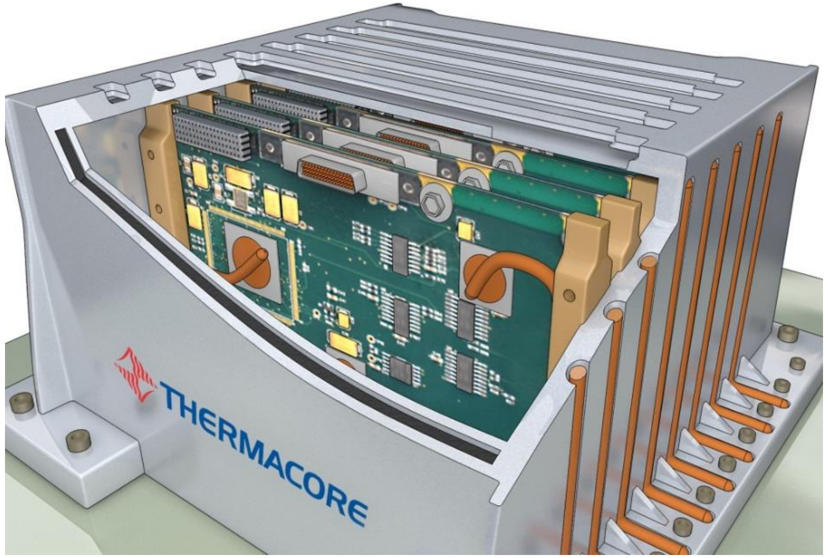




- Copper/Water heat pipe design characteristics
  - Compliant wick
    - Sintered copper powder
      - ~50% porosity, like a metal sponge
    - Copper wire mesh

  - Careful metering of the quantity of working fluid
    - All liquid should be contained in the wick
    - Avoid any pools of liquid spanning the space between the walls of the tube
  - As the water freezes during passive, unheated conditions
    - The heat pipe is nearly isothermal
    - Granules of ice form, contained inside the wick
    - The wick flexes, accommodating the volume increase of the ice
    - Over 1,500 passive freeze/thaw cycles have been performed

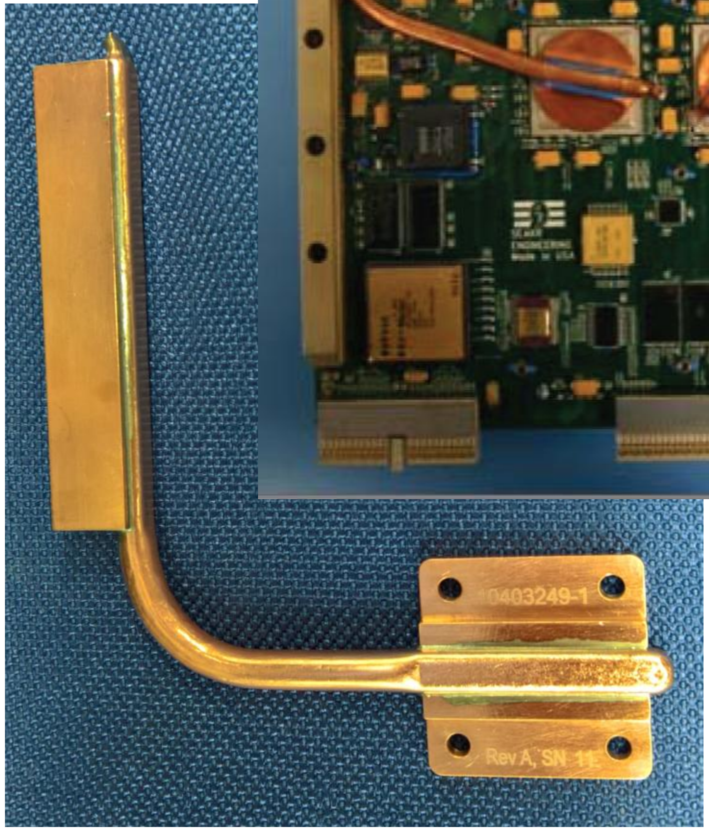
- Typical Applications
  - Virtually every laptop uses copper/water heat pipes to cool the CPU/GPU
    - Components are linked to air-cooled heat sinks
  - Many applications attach high powered components to a cold rail
    - Most common space application
  - Embedded in an aluminum structure to increase the conductance
    - Payload chassis
      - Link the cold rail to the thermal ground plane
    - Cold Plates
    - Large heat sinks
    - Heat sinks with a complex mechanical structure

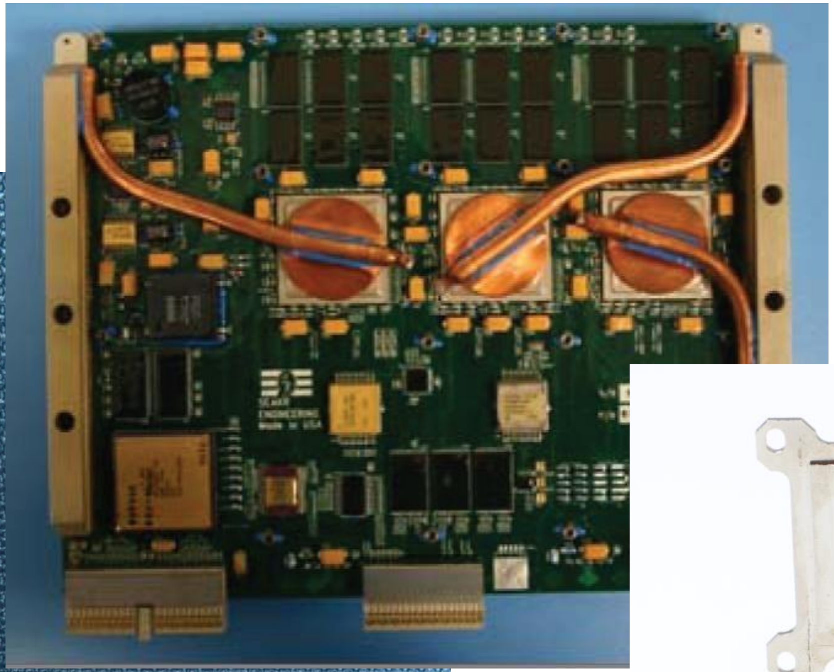


Copper/Water Heat Pipe Qualification Testing for Spaceflight Hardware

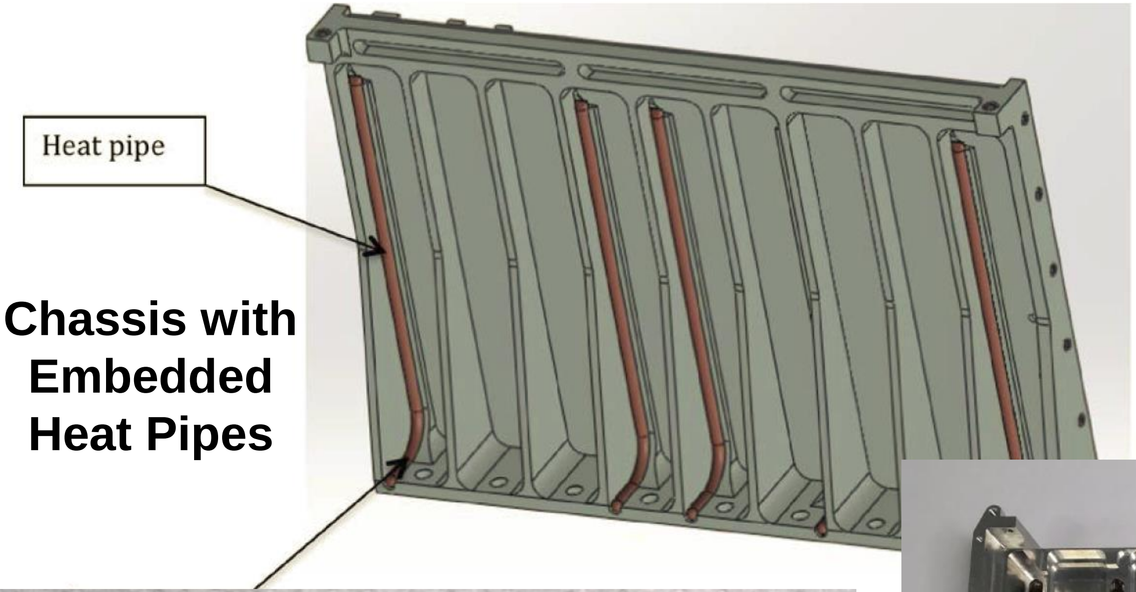
- Copper/Water heat pipe design characteristics
  - Diameter 3mm to 8mm
  - Length 10cm to 30 cm
  - Heat Load 5W to 25W
  - Heat Flux $10W/cm^2$ to $25W/cm^2$
- Evaporator and/or Condenser Blocks are often attached
  - Soldered or epoxied
- Bent and flattened to accommodate the design
  - Annealed copper is very soft
- Vapor Chambers
  - Same phase change heat transfer
  - 2D structure from welded copper plates
  - Sintered wick on one plate

- Copper/Water Heat Pipe Design Characteristics
  - “Chip Coolers”





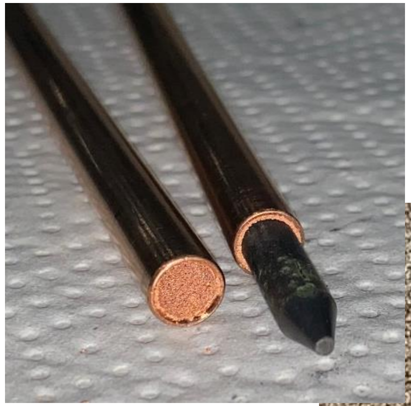
- Copper/Water Heat Pipe Design Characteristics



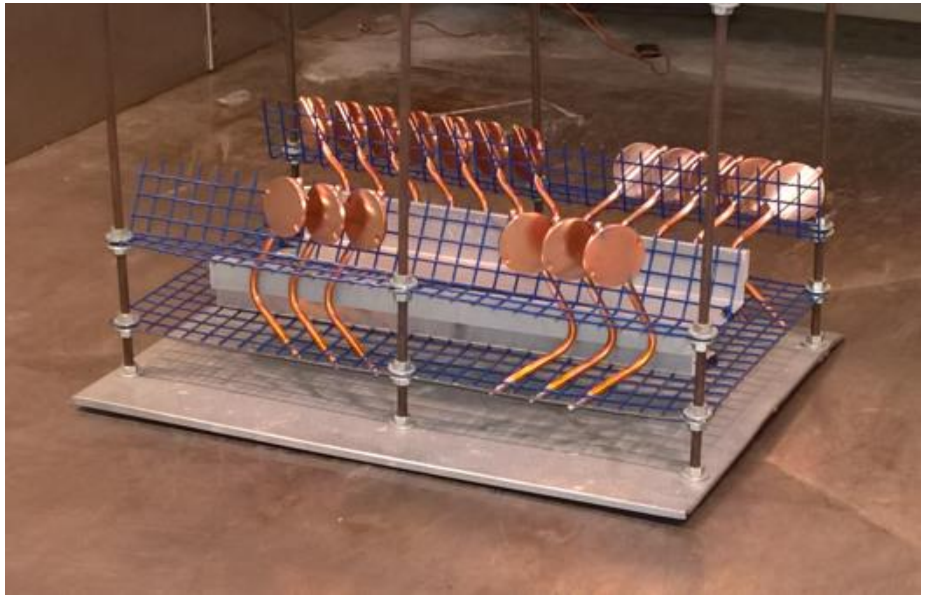
Chassis with Embedded Heat Pipes

Cold Plate with Embedded Heat Pipes

- Copper/Water heat pipe fabrication process
  1. Cut & clean copper tubing
  2. Spin one end of tube into a hemisphere
     1. Braze the spun end
  3. Powder fill the tube
     1. Center cylindrical mandrel to create hollow vapor space
     2. Vibration to settle powder
  4. Sinter the powder in a high temperature furnace
  5. Swage the open end to a smaller diameter
  6. Evacuate air & add fluid charge
  7. Burn-In & circulate
  8. “Burp” NCG and excess fluid from the heat pipe
  9. Pinch-seal and braze the open end
  10. Bend and/or flatten the heat pipe
  11. Attach evaporator and/or condenser blocks


- Copper/Water heat pipe Quality Assurance steps
  1. First Article Inspection / Material Certs
  2. Process controls
     a. Cleaning
     b. Sintering
     c. Fluid charge
  3. Sintering inspection
     a. After sintering
     b. After freeze/thaw test
  4. Leak Check
  5. Go/NoGo Gauge
     a. Bent heat pipes
     b. Soldered assemblies
  6. Burn-In & NCG Test
  7. Thermal performance tests
     a. Various heat loads, temperatures, orientations
  8. Passive Freeze/Thaw tests
     a. Stand-alone heat pipes
     b. Soldered assemblies
  9. Active freeze/thaw tests
     a. Cold Start test
     b. Powered Freeze/Thaw test



- Historical data for freeze-thaw tolerance has primarily been passive thermal cycles
  - Fluid is largely retained in the wick structure during passive thermal cycling

- Design, test and missions can significantly impact the fluid/ice distribution
  - System utilization may induce freeze-thaw cycles during test at cold dwells
  - On-orbit environments may drive freeze events for units with continuous operation
  - Powered events will drive non-uniform fluid/ice distribution along the length of the pipe
    - Vapor will condense and then freeze in place in the condenser in these conditions, leading to dry-out in the evaporator

- Several areas of interest influenced definitions of qualification test
  - Freeze/thaw tolerance for passive and actively powered freeze conditions
  - Restart capability during aforementioned freeze conditions
  - Impact to EOL performance

- Three tests developed to address the various cases
  - Standard passive freeze-thaw
    - Uniform freeze and thaw
  - Powered freeze-thaw (power applied continuously)
    - Non-uniform freeze and thaw
  - Cold start (power applied only during ramp from cold dwell through hot dwell)
    - Uniform freeze, non-uniform thaw

- Pre, mid, and post test performance verification
  - BOL performance
  - Mid cycle verification of appropriate restart
  - EOL Performance

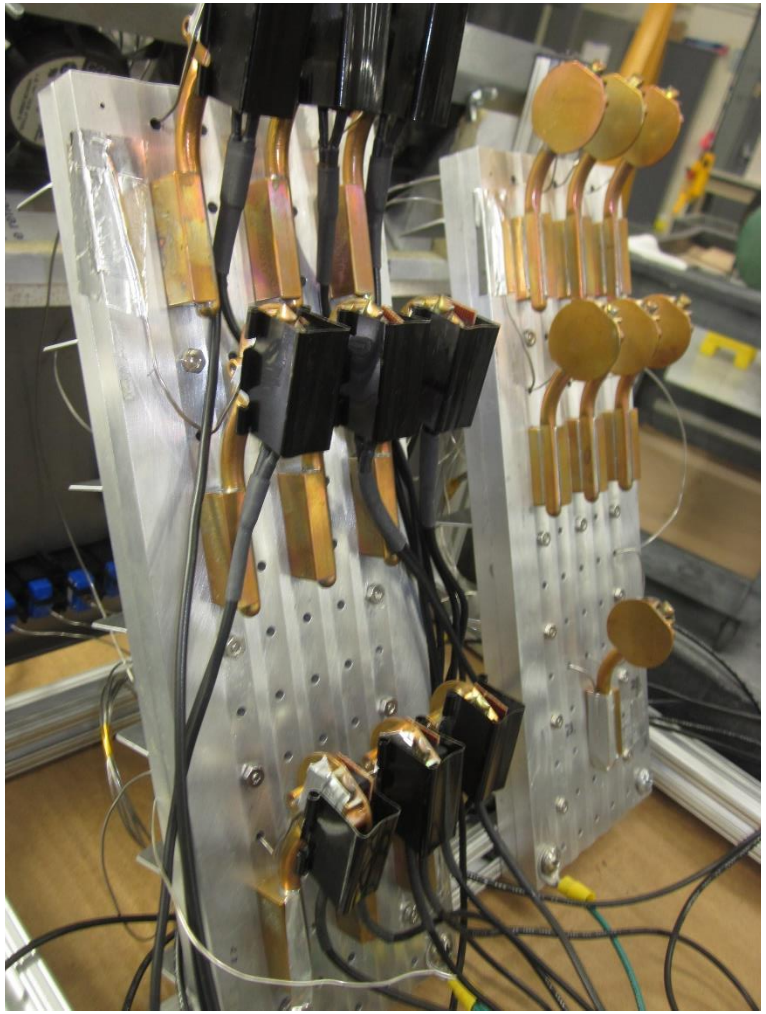
Copper/Water Heat Pipe Qualification Testing for Spaceflight Hardware

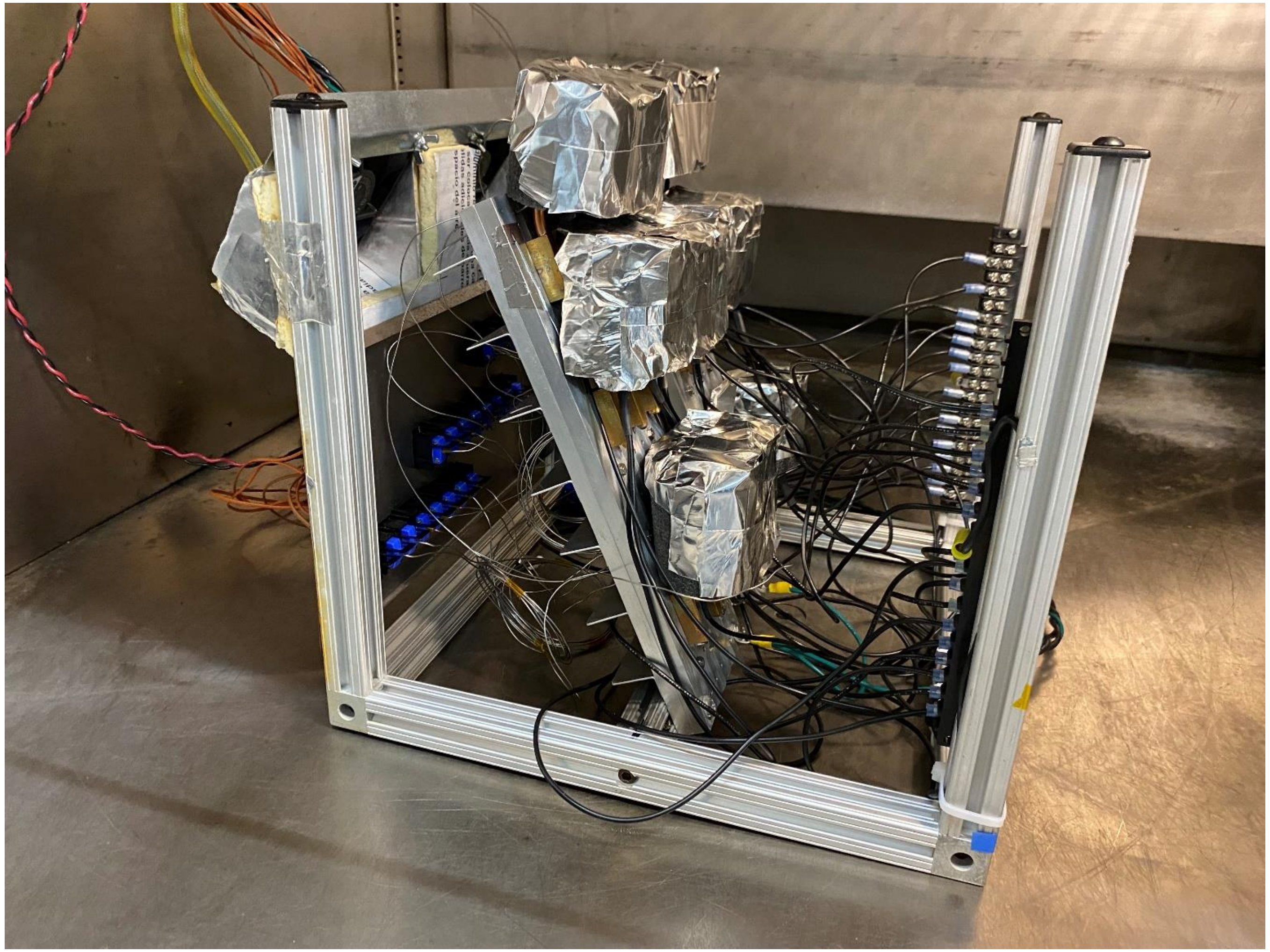
- Copper/Water heat pipe Acceptance Test Protocol
  1. Thermal Performance
     a. Performed at Acceptance Hot
     b. 50% max load, max load
     c. Adverse gravity & Gravity neutral
  2. Passive Freeze/Thaw
     a. Above and below 0C
     b. Over 30 cycles
        i. Gravity Aided
        ii. Adverse Gravity
  3. Powered Freeze/Thaw
     a. Above and below 0C
     b. Over 10 cycles, max heat load
        i. Heat applied continuously
        ii. Adverse gravity
  4. Cold Start
     a. Above and below 0C
     b. Over 10 cycles, max heat load
        i. Heat applied only during the up-ramp and hot dwell
        ii. Adverse gravity
  5. Thermal Performance Test
     a. Performed at Acceptance Hot
     b. 50% max load, max load, 125% max load
     c. Adverse gravity & Gravity neutral

- Copper/Water heat pipe Qualification Test Protocol
  1. Thermal Performance
     a. Performed at Acceptance Hot
     b. 50% max load, max load
     c. Adverse gravity & Gravity neutral
  2. Passive Freeze/Thaw
     a. Above and below 0C (same as acceptance)
     b. Over 120 cycles in various orientations
        i. Gravity aided
        ii. Adverse gravity
        iii. Gravity neutral
  3. Powered Freeze/Thaw
     a. Above and below 0C (same as acceptance)
     b. Over 450 cycles in various orientations, max heat load
        i. Heat applied continuously
        ii. Adverse gravity
        iii. Gravity neutral
  4. Cold Start
     a. Above and below 0C (same as acceptance)
     b. Over 30 cycles, max heat load
        i. Heat applied only during the up-ramp and hot dwell
        ii. Adverse gravity
  5. Thermal Performance Test
     a. Performed at Acceptance Hot
     b. 50% max load, max load, 125% max load
     c. Adverse gravity & Gravity neutral

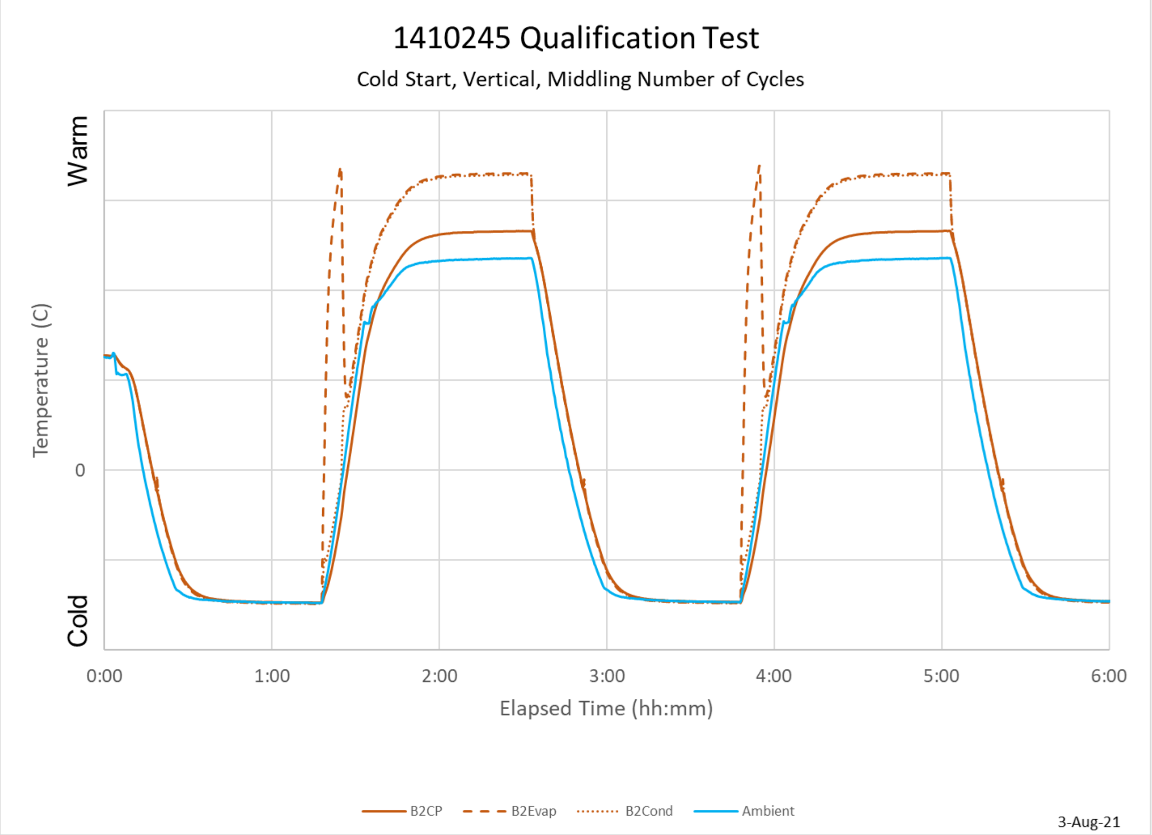
Copper/Water Heat Pipe Qualification Testing for Spaceflight Hardware

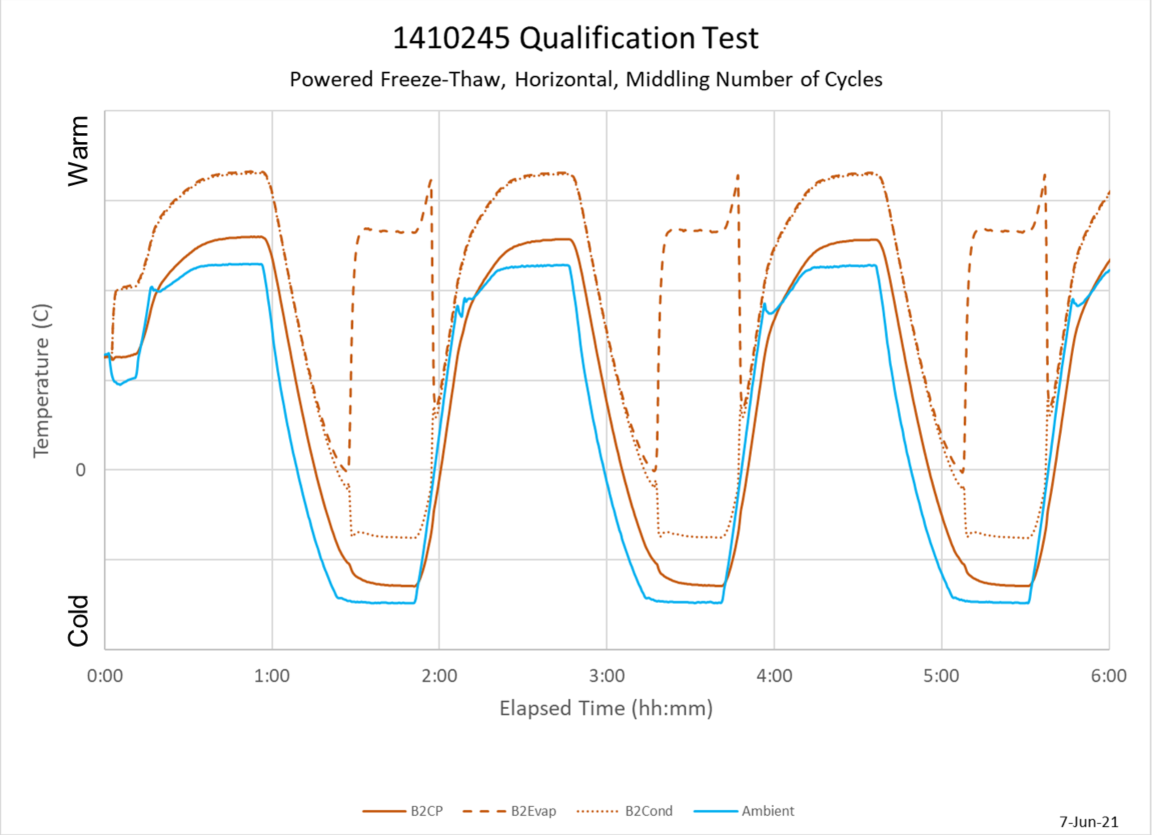
- Cold Start and Powered Freeze/Thaw





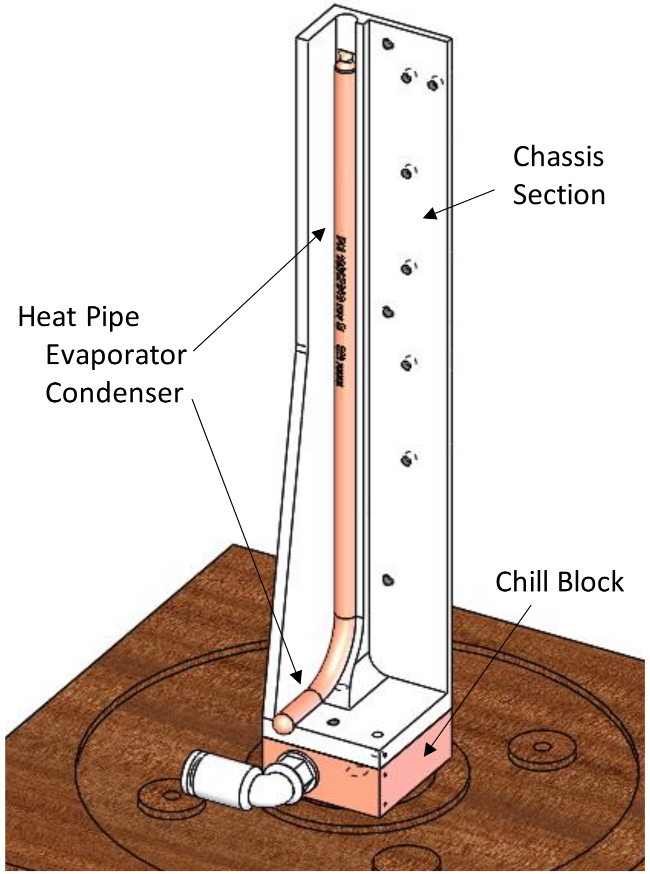
- Cold Start and Powered Freeze/Thaw

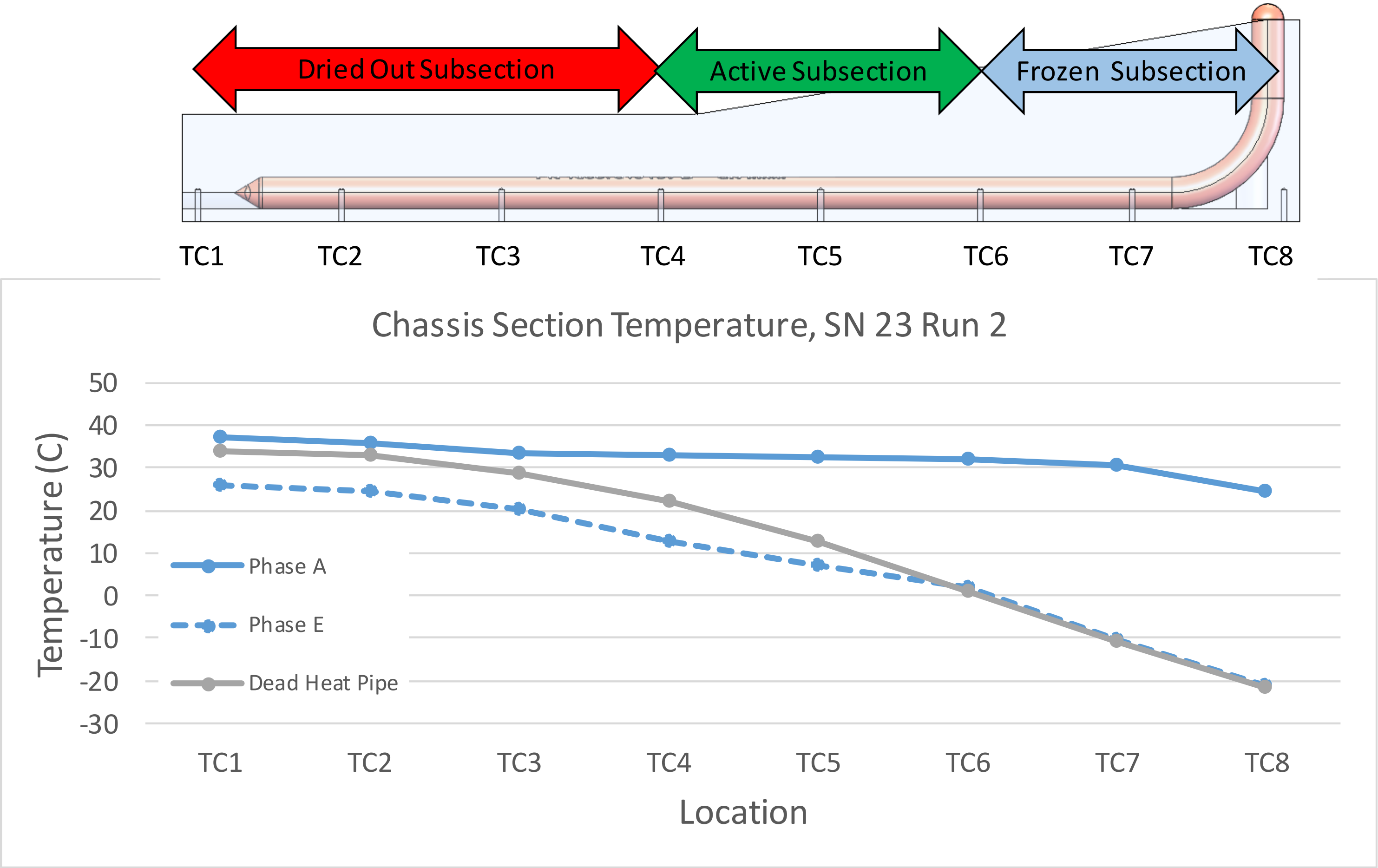




- Conclusions from qualification test
  - Restart demonstrated for subject designs with passive as well as actively powered conditions
  - Freeze/thaw tolerance demonstrated for over 650 combined cycles
  - EOL performance verified in adverse gravity and gravity neutral conditions
    - Demonstrated no detrimental degradation of wick structure

- What's going on inside a Copper/Water heat pipe during Freeze/Thaw?





- Approximate quantities of Copper/Water Heat Pipes and Vapor Chambers in space
  - Boyd US
    - Heat Pipes
      - >1000 in space
      - > 8 years heritage
      - Several major satellite vendors
      - NASA
        - » TESS
        - » SWOT
    - Vapor Chambers
      - >20 in space
      - ~2 years heritage
      - Satellite prime
  - Boyd UK
    - Heat Pipes
      - >3000 in space
      - > 8 years heritage
      - Chip Coolers & Chassis
      - Several European satellite primes plus some smaller vendors