Pulsating Heat Pipe based Electronics Cooling System

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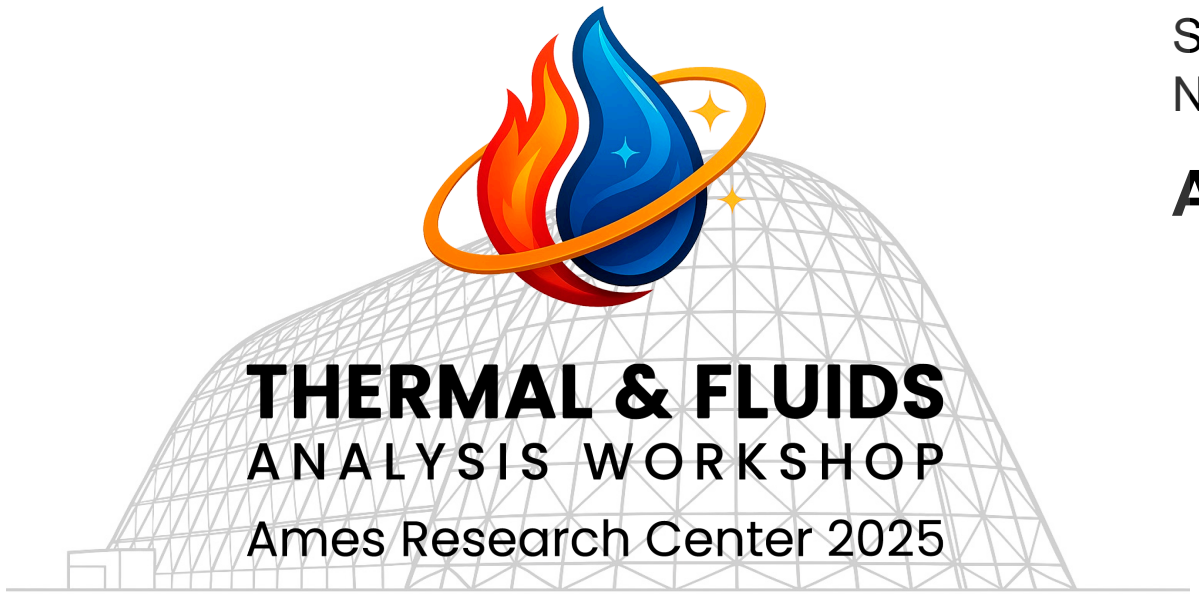

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Advanced Cooling Technologies, Inc.

Thermal & Fluids Analysis Workshop 2025
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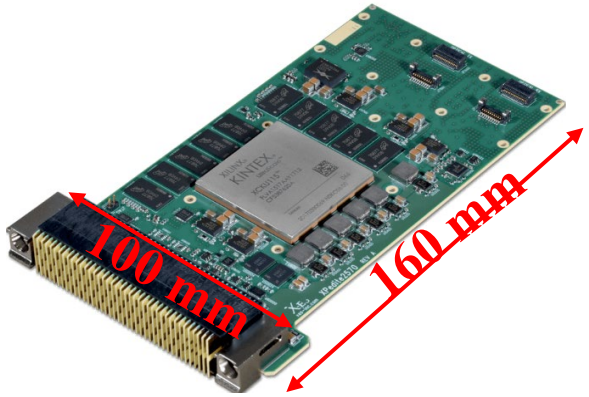
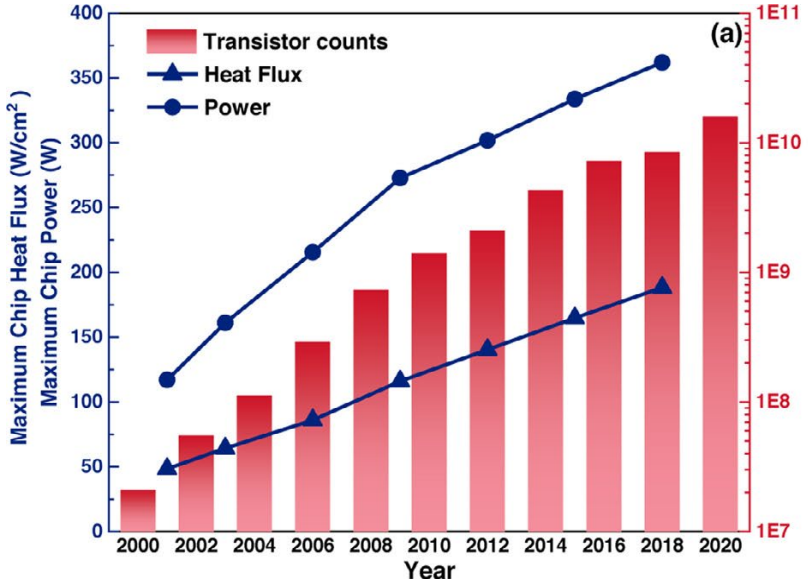
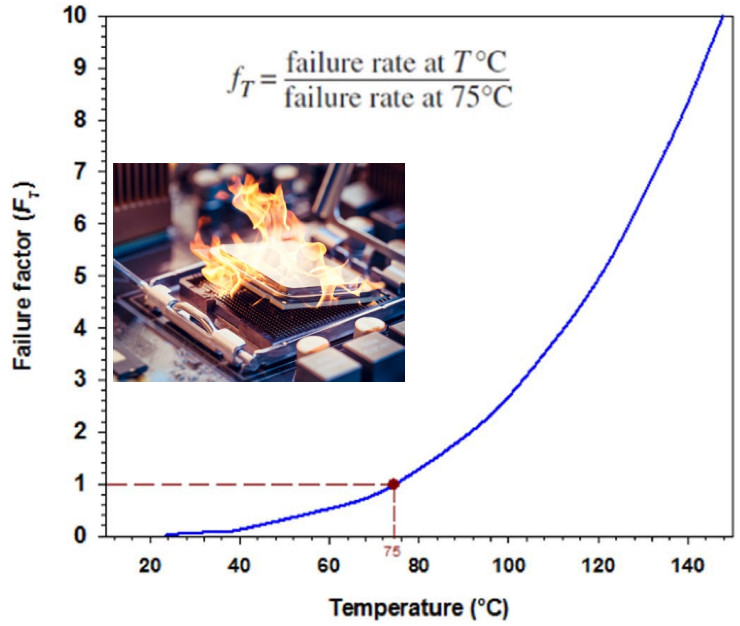
Electronics Waste Heat Management for Safe & Reliable Operation

Existing

- Modular electronics following VITA-VPX Standards (3U, 6U, etc.) have higher compute power requirements
- High Heat flux from the cards must be effectively dissipated to maintain them under 75-85°C range
- Embedded cards using two-phase heat transfer principles like pulsating heat pipes enable high heat load dissipation capability

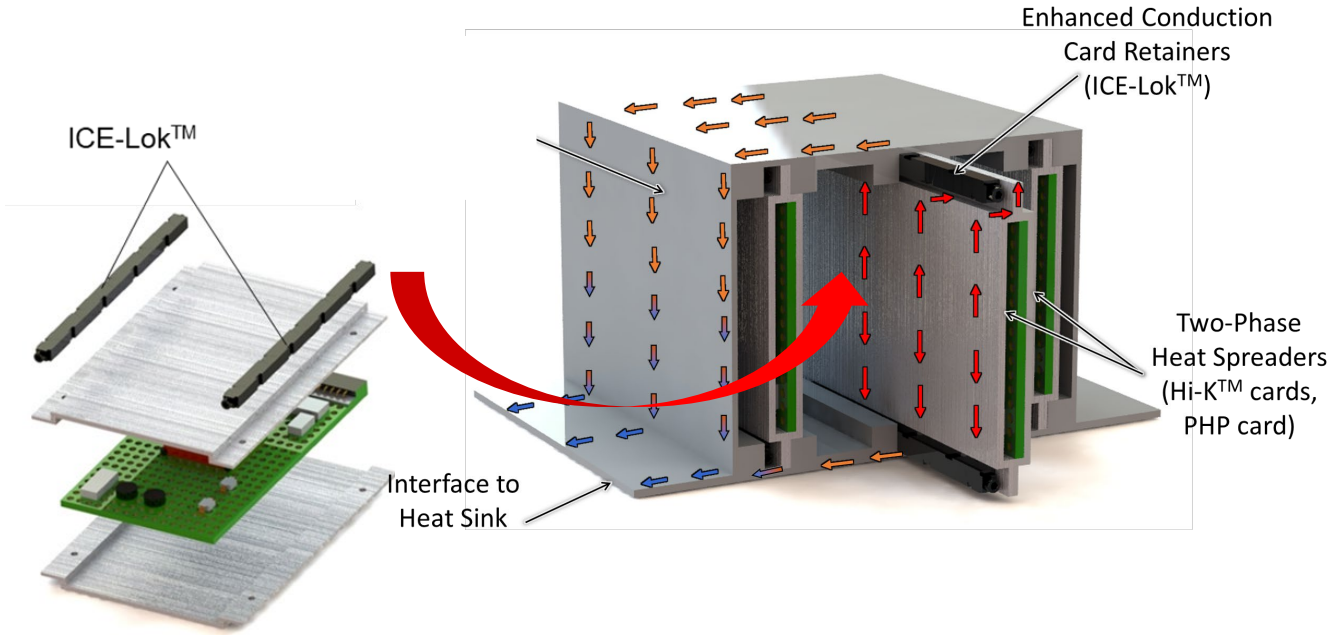


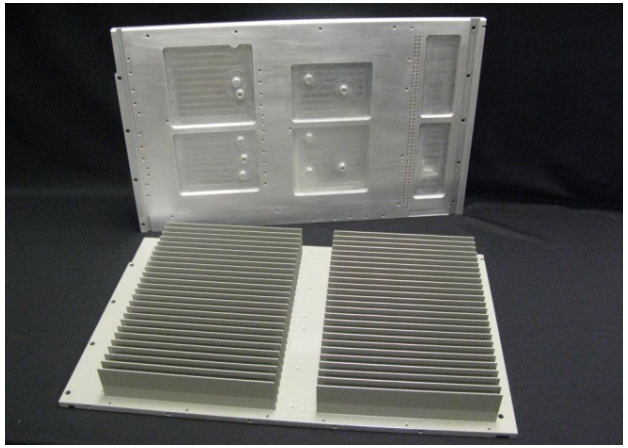


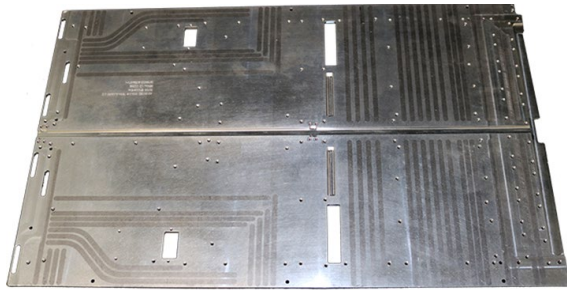


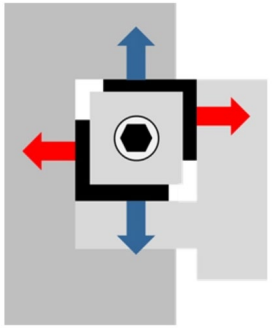
High Performance Heat Transfer Devices for Electronics Cooling

- Electronics heat is rejected from the source to the sink through multiple thermal links
  - Source to thermal spreading plane
  - Electronics enclosure (chassis) card retainer
  - Ultimate heat sink like a cold plate
- ACT's Two-phase Solutions
  - Embedded heat pipe (HiK™ plate)
  - Vapor chambers
  - Pumped-two phase cooling
  - Pulsating heat pipe (R&D)
  - Isothermal Card Edge (ICE-Lok®)



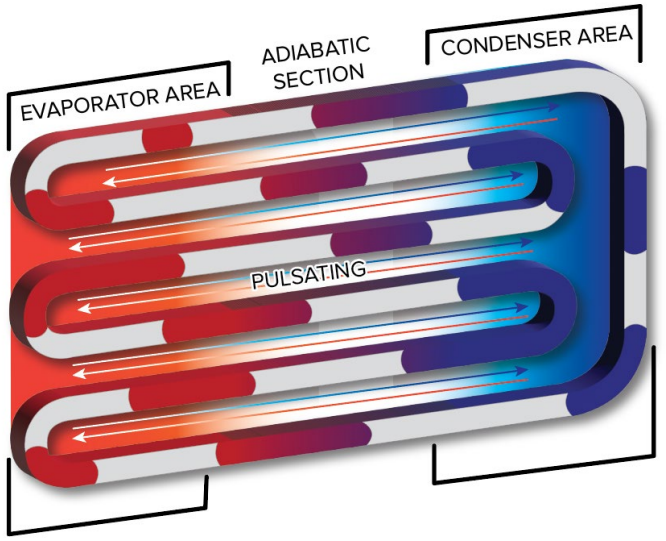






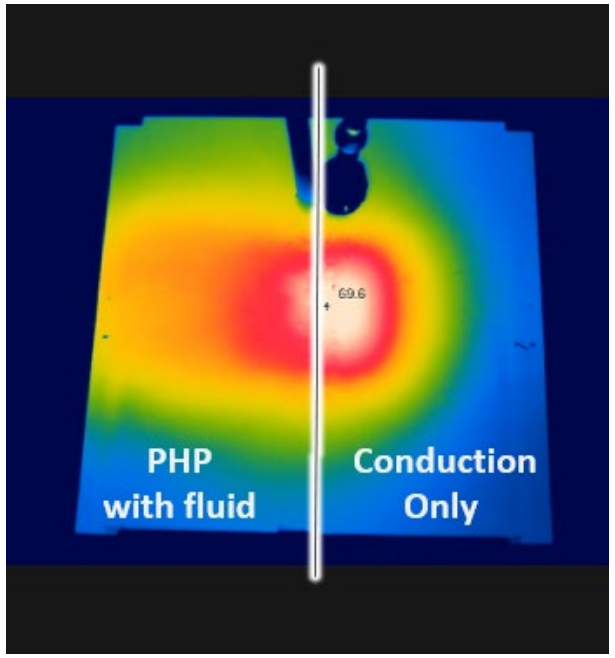
Pulsating Heat Pipe

- A Pulsating Heat Pipe (PHP) is a two-phase heat transfer device
- PHP is formed by meandering capillary sized fluid channels, typically connected end-to-end
- When a working fluid is introduced, it naturally distributes into liquid slugs and vapor lungs within the fluid volume



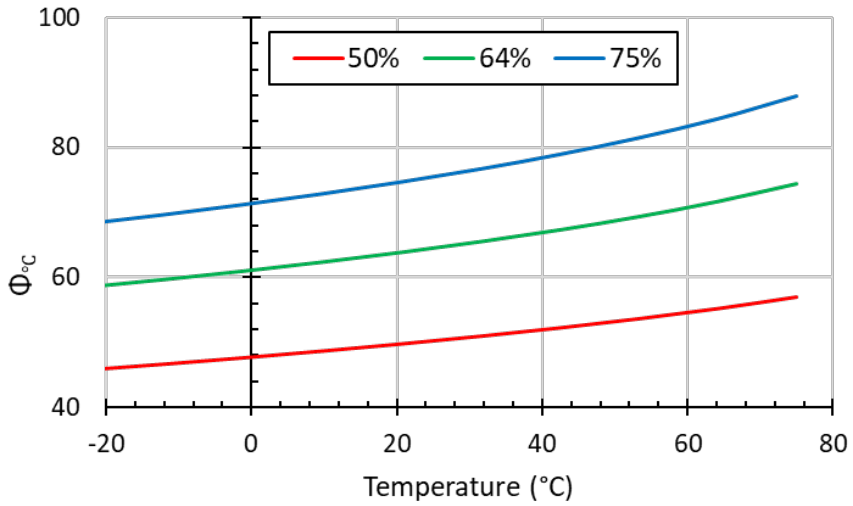
Operation Principles:

- Heat applied at the receiving section (evaporator) vaporizes the liquid, thereby, increasing the vapor pressure
- Heat delivered at the rejection section (condenser) causes the vapor to shrink or condense, thereby, reducing the vapor pressure
- The driving force ensued from the vapor pressure difference sustained by various hydraulic forces acting on the liquid slug results in the pulsation of the working fluid

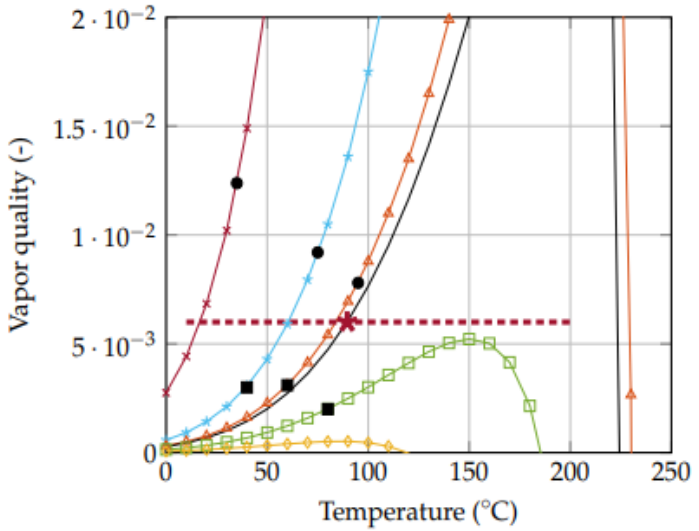


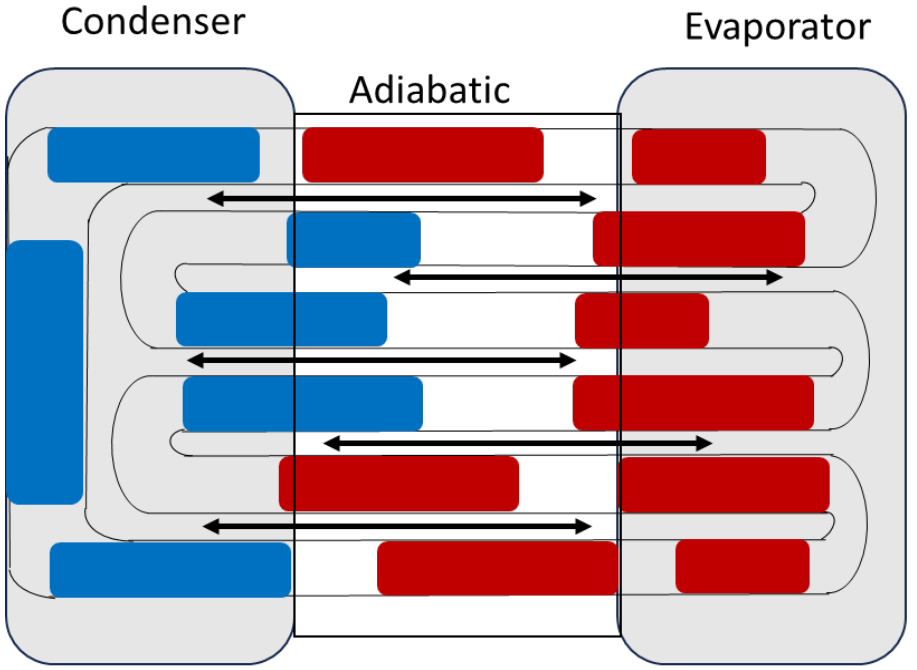
Notes: Considerations for Fluid Selection <Non-Merit Number Identities>

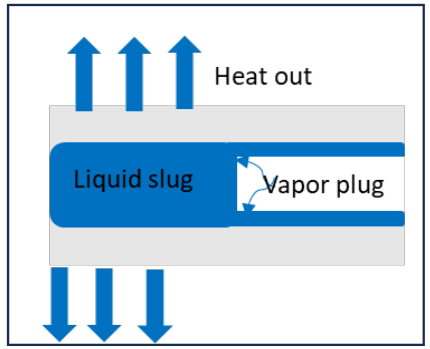
- Fluid selection: High dP/dT as driving force for ~isothermal operation
  - Fluid motion balanced by thermo-physical properties
  - Liquid density
  - Viscosity
  - Surface tension
  - Vapor contraction/ expansion

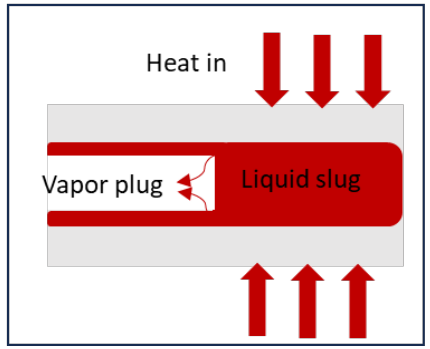


Ref: Schwarz F. et al., energies, 2020



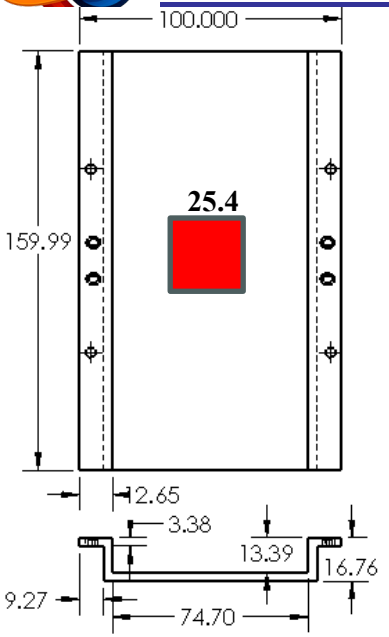


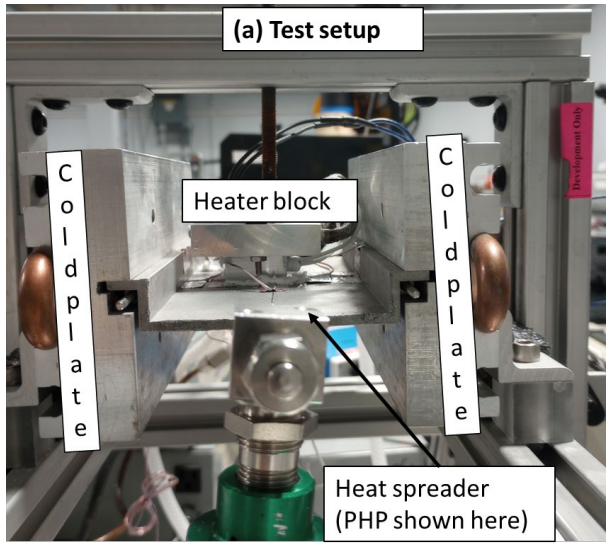


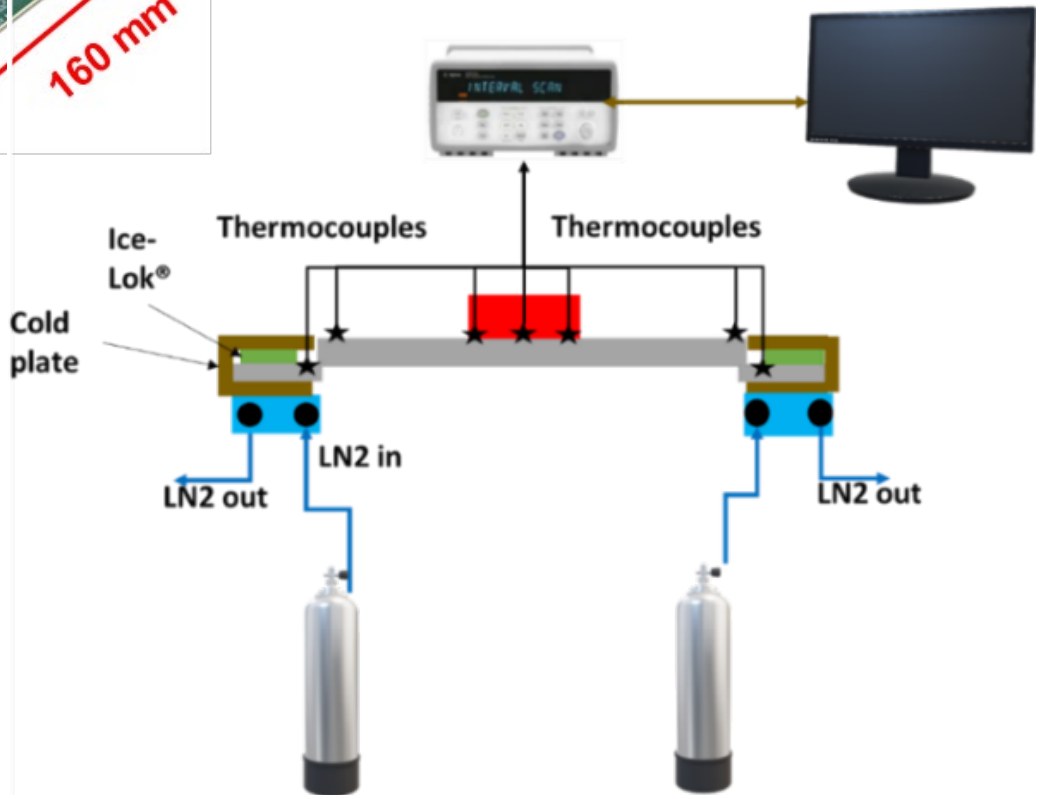


- Instantaneous fill ratio changes with temperature
- Vapor quality is associated with temperature
- Ensuring slug-plug pair is critical for efficient operation
- High “operational loads” sometime result in unstable fluid movement, approaching dry-out
- Fill ratio influence is critical. In general, ~60% fill ratio is reasonable

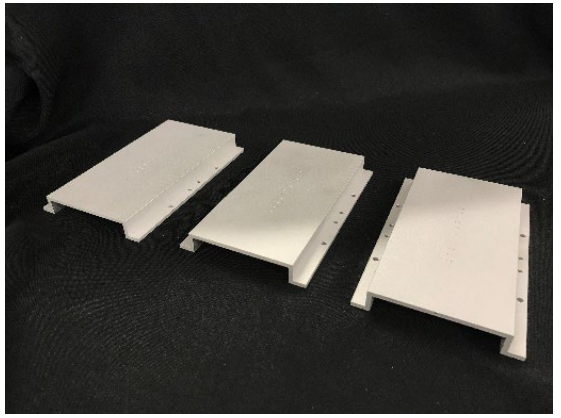
Description of Heat Spreader & Test Methodology: 3U Form Factor



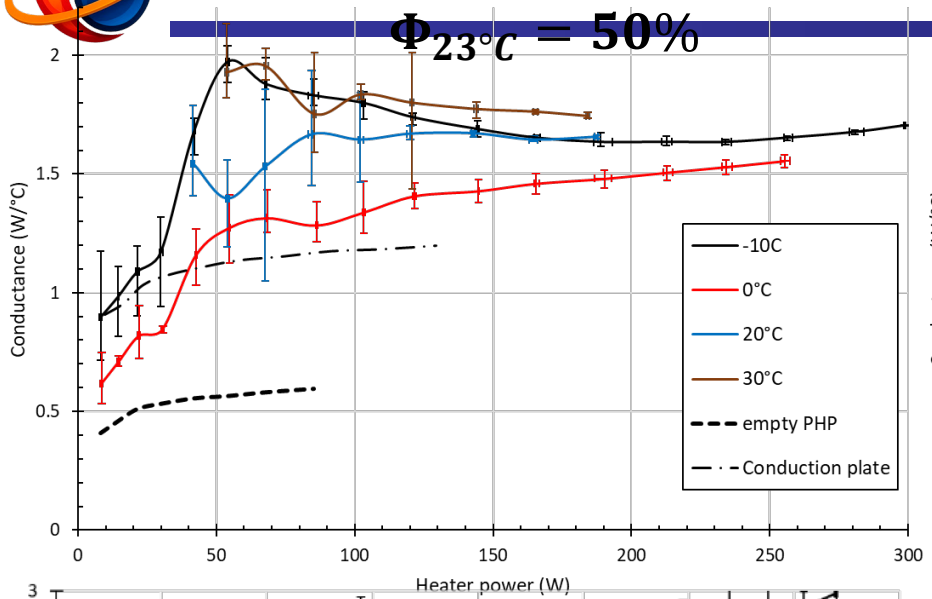


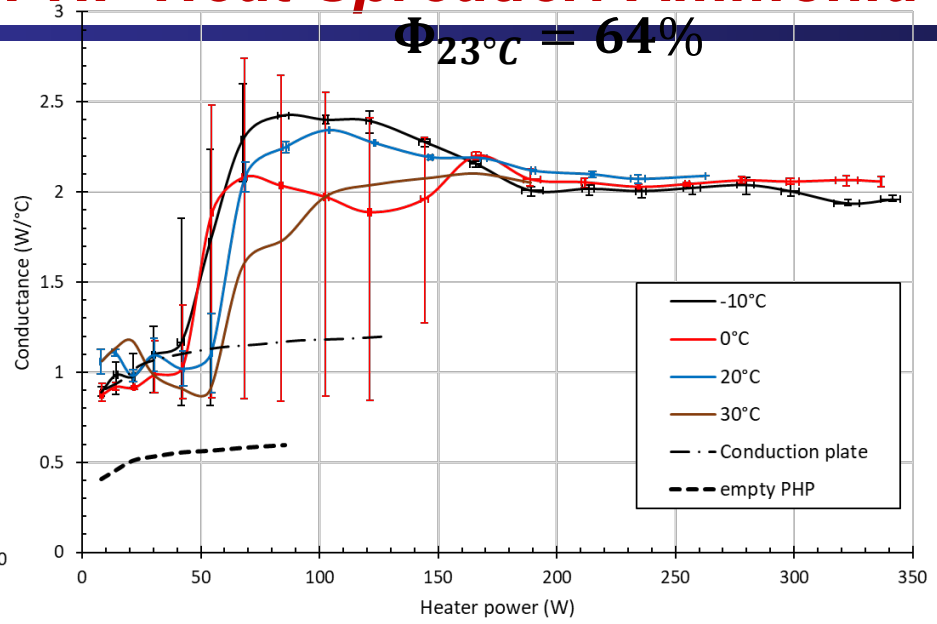


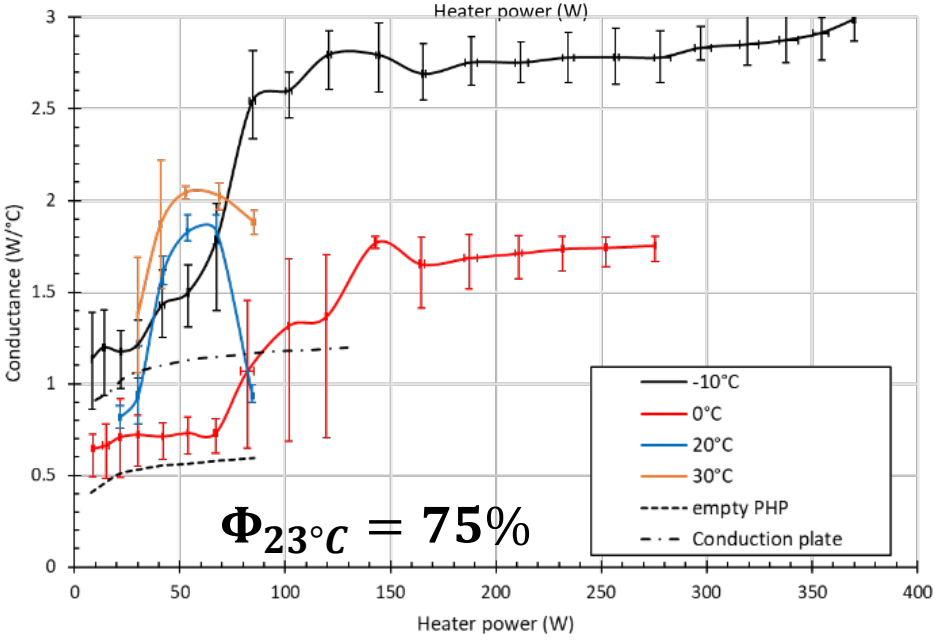
- Geometry: 3U form factor (SpaceVPX compliant)
- Conduction plate heat spreader: CNC machined
- PHP Heat spreader: Additive Manufacturing
- Heat rejection: Cold plates through card retainer
- Condenser section: maintained at constant temperature



Thermal Performance of PHP Heat Spreader: Ammonia PHP (Horizontal)







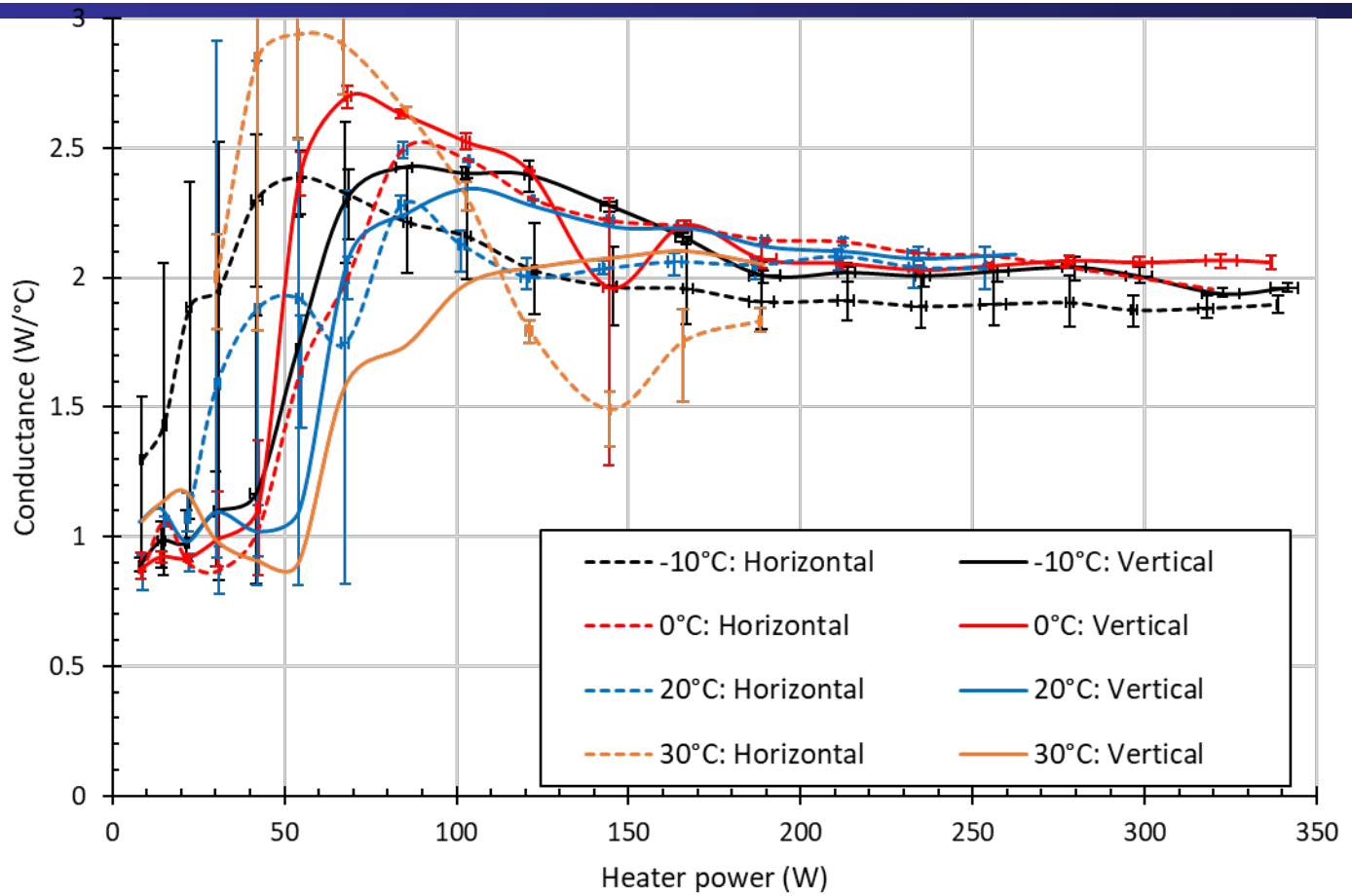
Fill ratio (%)	50%		64%		75%	
Condenser set point (°C)	-10	20	-10	20	-10	20
Evaporator temperature (°C)	81	83	80	78	80	88
Power or heat rate (W)	300	210	340	230	350	102

- Thermal conductance of PHP heat spreader shown

$$C = \frac{T_{evap} - T_{flange}}{Q}$$

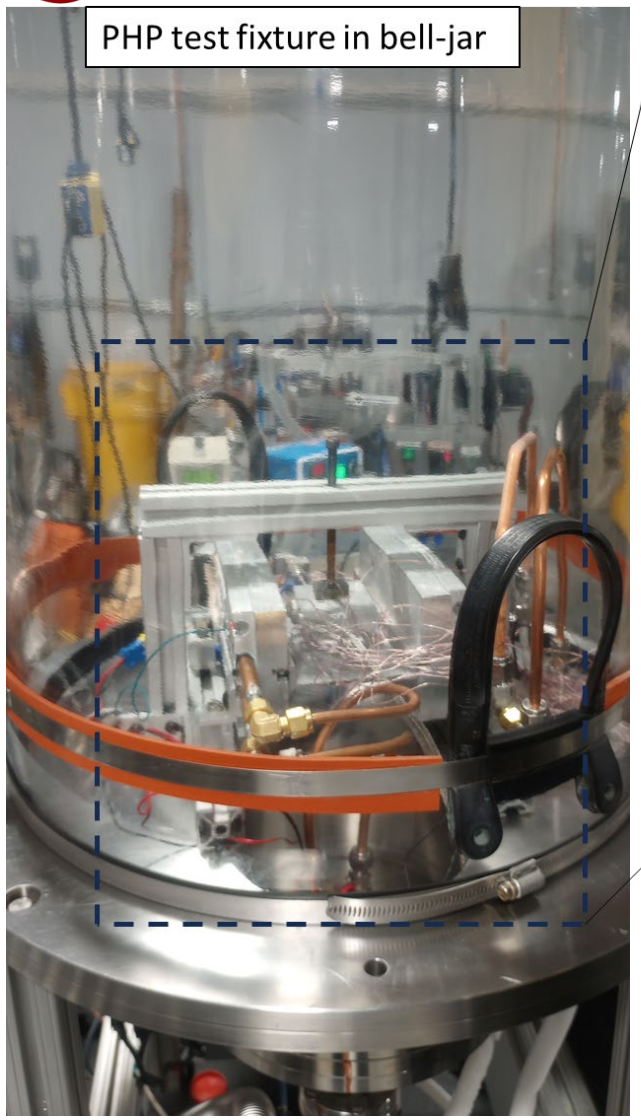
- Increasing performance with increasing heater power
  - Until 50-75W heater power, PHP operation stabilizes
  - Above 100W, consistent thermal conductance observed
- Varying fill ratios:
  - 50% fill ratio operated from -10° C to +30 ° C
  - Peak conductance: < 2W/° C
  - 64% fill ratio operated from -10° C to +30 ° C
  - Conductance ~2.4 W/° C
  - 75% fill ratio had conductance > 2.5 W/° C at -10° C
  - Did not operate at condenser above 20° C

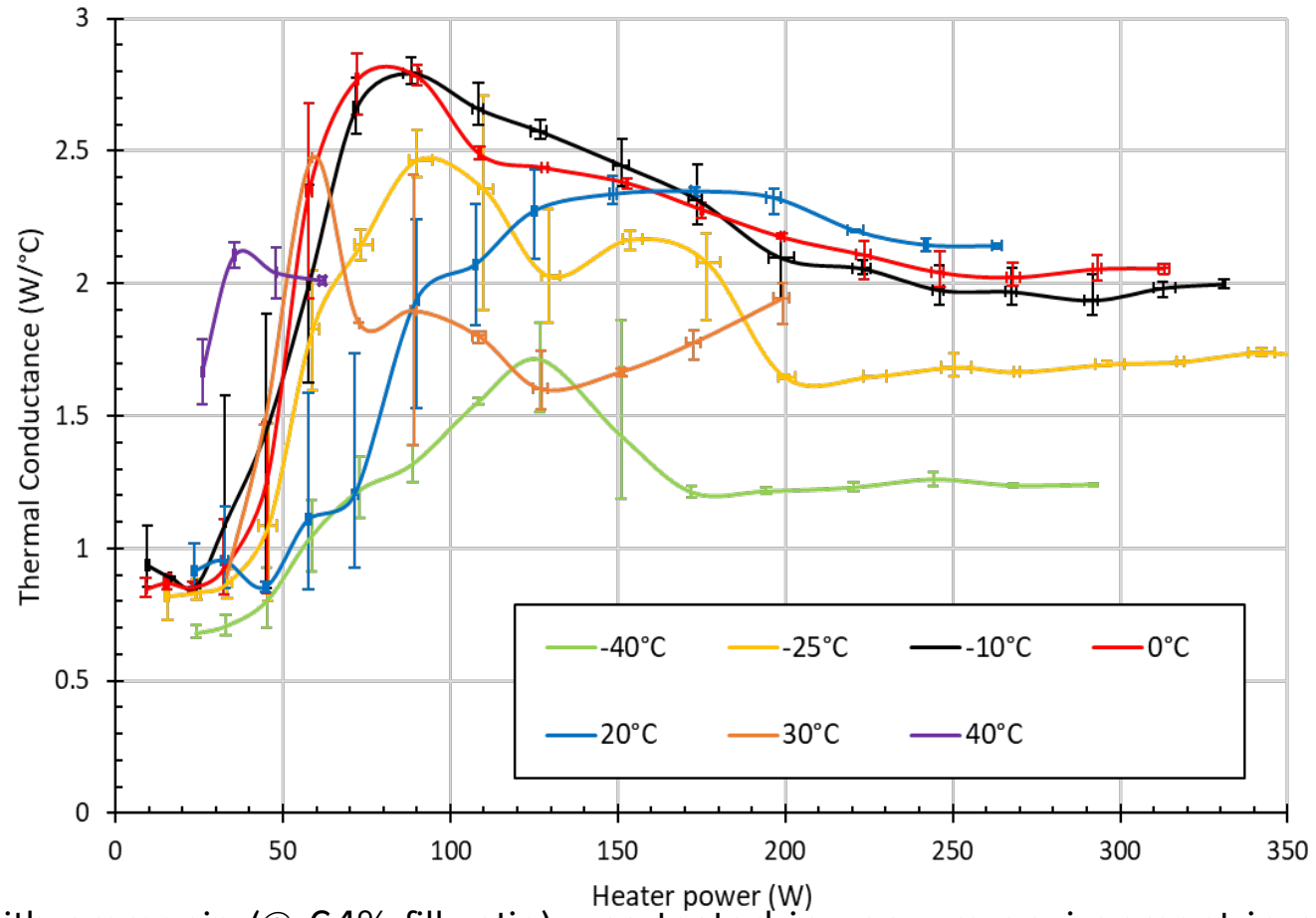
Orientation Influence on PHP Heat Spreader Thermal Performance



- PHP Heat spreader was tested in both horizontal & vertical orientation
- The thermal performance of the PHP heat spreader stayed largely independent of orientation after PHP operation was fully developed

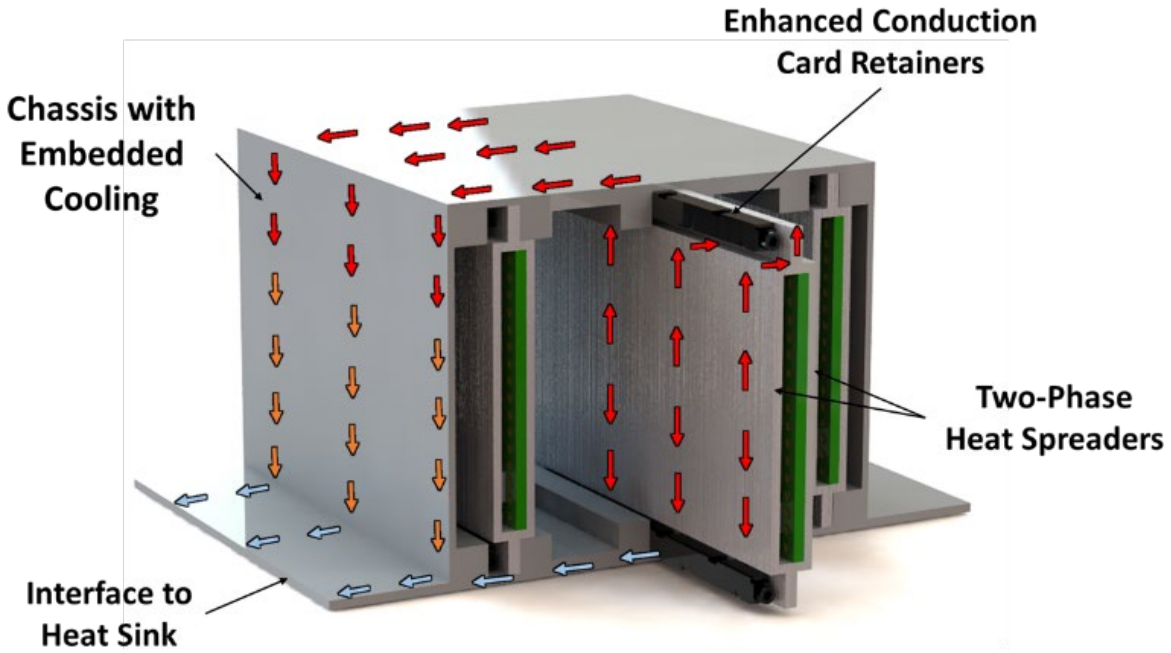
Performance Testing of PHP Heat Spreader in Vacuum Environment

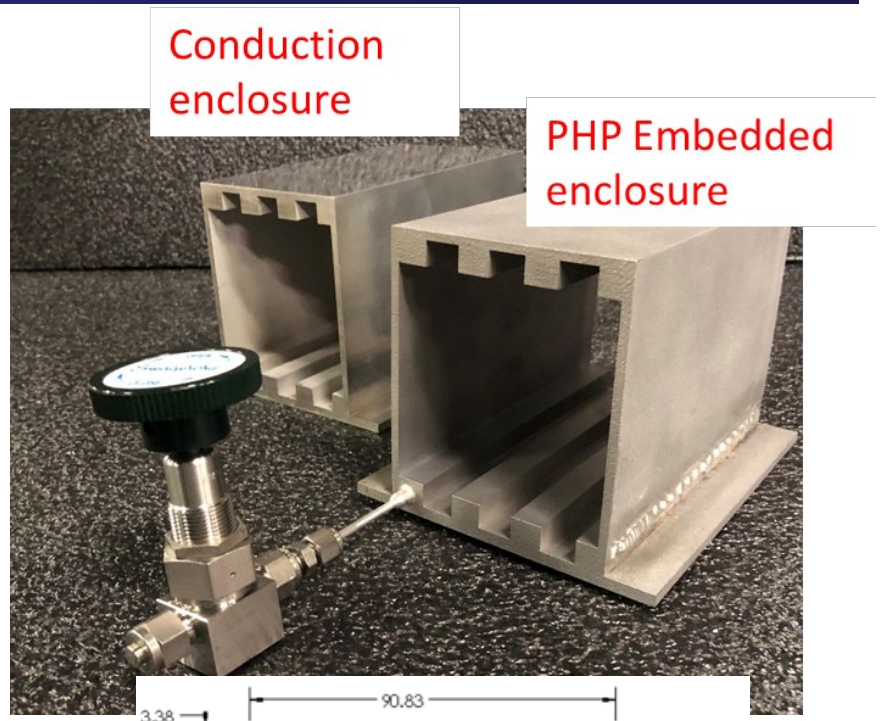


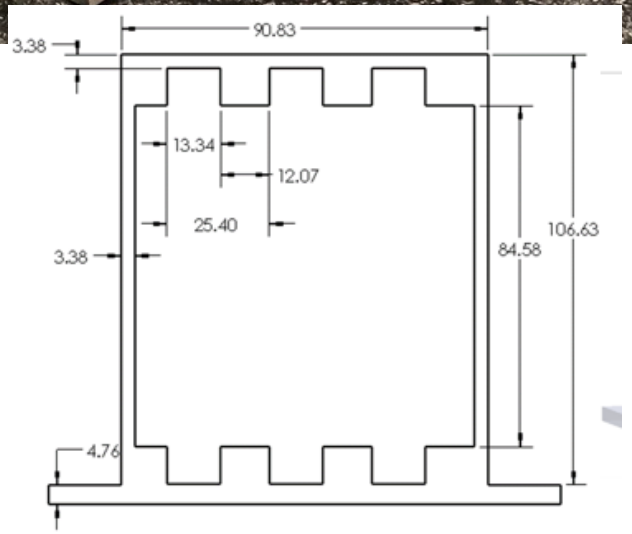


- PHP heat spreader with ammonia (@ 64% fill ratio) was tested in vacuum environment in a bell jar @vacuum < 0.04 Torr; MLI insulation was applied on the heat spreader
- From -40° C to -10° C upward trend in peak performance was observed
- Thermal performance curves stayed almost consistent at -10° C and 0° C
- At above 0° C, deterioration in thermal performance was observed

Advanced PHP Concept Demonstration: Embedded Enclosure Chassis



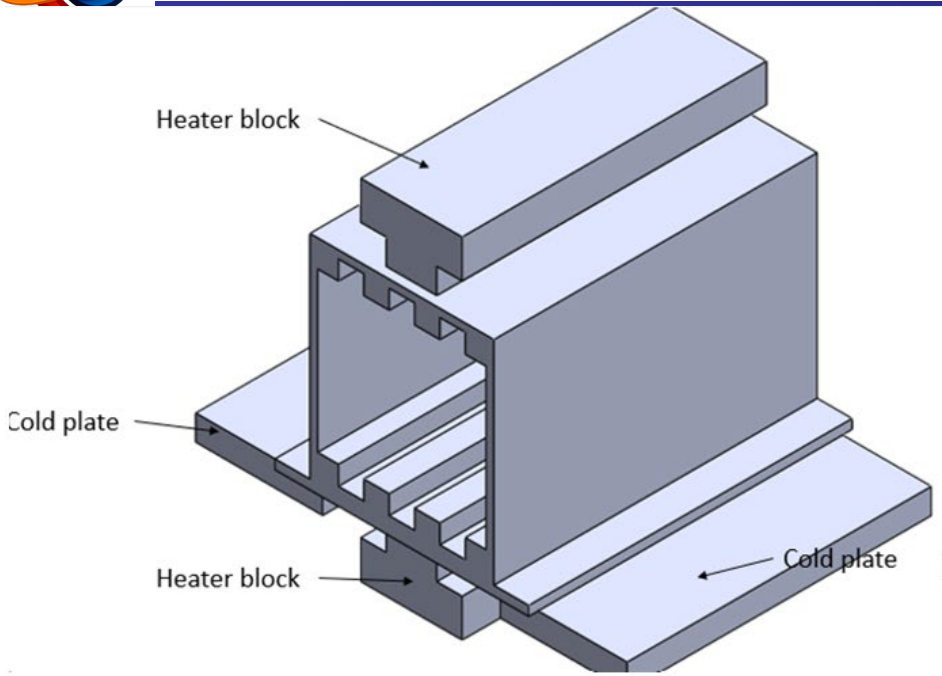




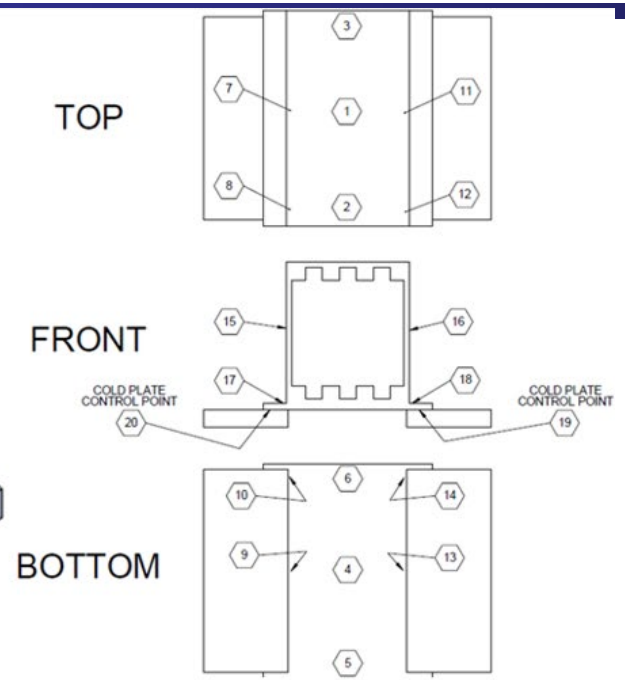
(a) Dimensions of the chassis

- Embedded PHP-enclosure module enable high performance heat dissipation from the card to the heat sink
- An enclosure module: conduction type (standard machining) and PHP-embedded (Additively manufactured) fabricated and tested
- Geometric specifications: VITA 48.2 (dimensions in mm)
- PHP embedded enclosure charged with propylene @ 60% volume fill ratio

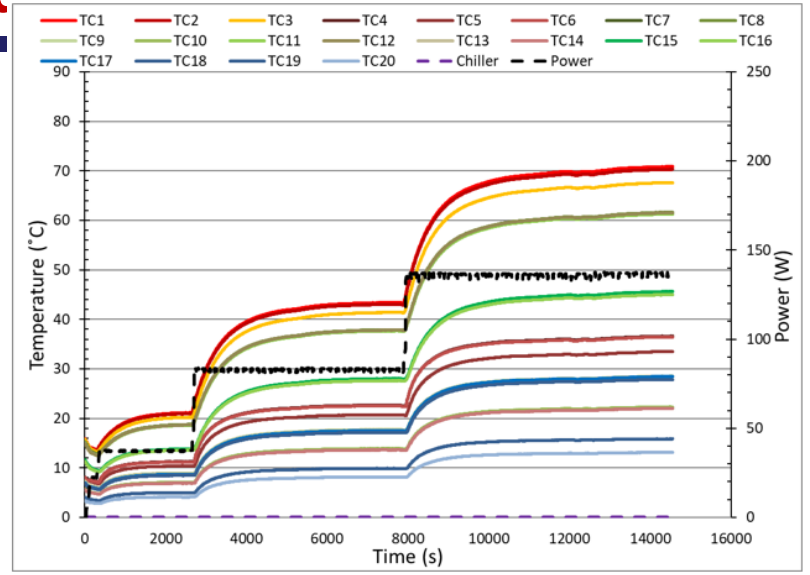
Thermal Performance of PHP Embedded Enclosure



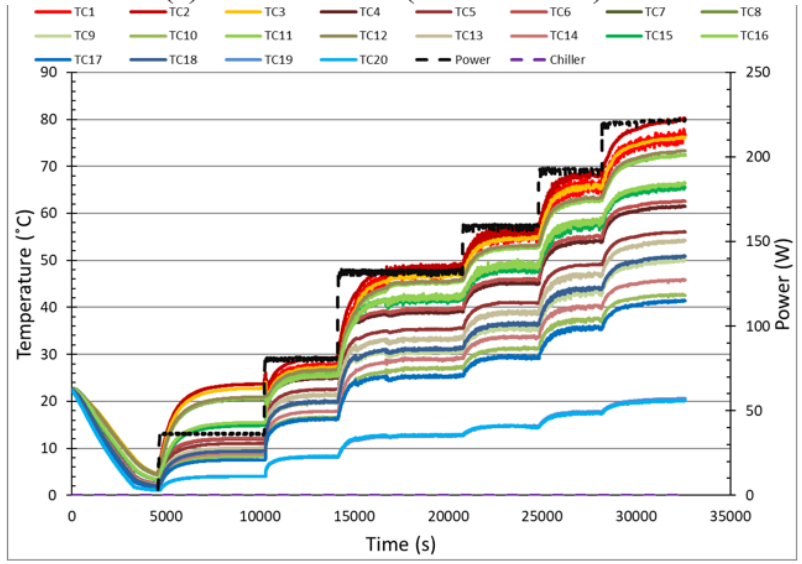
(a) Test setup configuration



(b) Thermocouples' layout



(a) Baseline case (Solid chassis)



(b) PHP Chassis (FR=60% propylene)

- Enclosure chassis tested with two heater blocks on the top and bottom sides
- Cold plate attached to the flanges and maintained at 0° C
- Temperature profile labels (in order of contrast)
  - Red: Evaporator/ heat source
  - Blue: Condenser & Heat sink
- PHP embedded chassis delivered almost 2X higher power compared to conduction chassis
- Mass savings obtained with PHP embedded enclosure chassis

Key Takeaways

- Thermal Performance of PHP embedded electronics cooling system was undertaken

PHP heat spreader

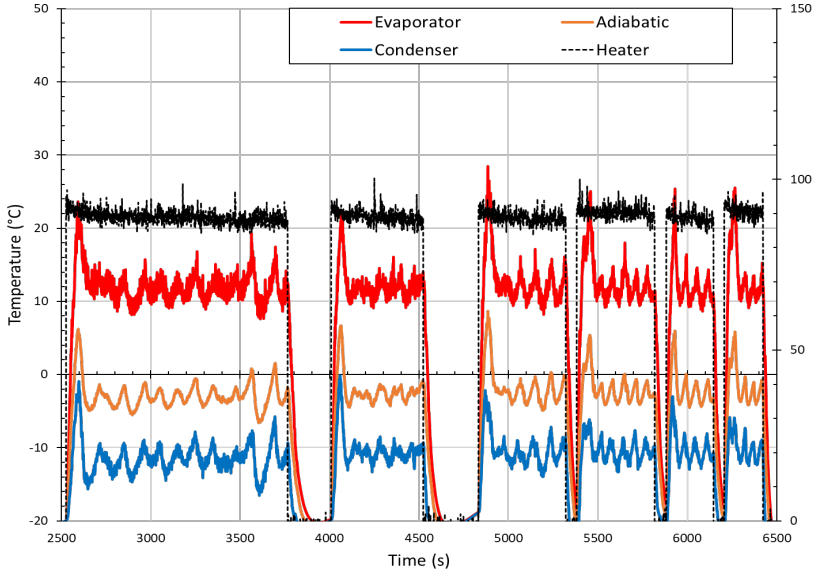
- Ammonia as working fluid: Below table shows maximum heat removal rates for 3U form factor heat spreader

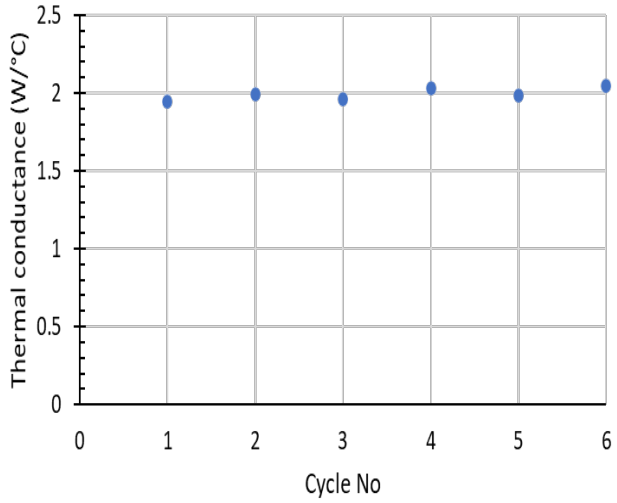
Fill ratio (%)	50		64		75	
Condenser set point (°C)	-10	20	-10	20	-10	20
Evaporator temperature (°C)	81	83	80	78	80	88
Power or heat rate (W)	300	210	340	230	350	102

- Orientation had minimal influence on the PHP thermal performance
- PHP heat spreader was tested in vacuum conditions at varying sink conditions. Performance was similar to ambient testing
- Cyclic testing of PHP @100W ON/OFF mode showed repeatable performance (curve shown here)

PHP Enclosure Chassis

- Embedded enclosure chassis fabricated via additive manufacturing
- Propylene (@60% fill ratio) used as working fluid
- About 40% higher heat transfer capability obtained with PHP-embedded chassis enclosure





Thank you for your time

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