TFAWS Active Thermal Paper Session

Launch Vehicle Avionics for Passive Thermal Management

William G. Anderson, Cameron Corday, Mike DeChristopher, John Hartenstine, Taylor Maxwell, Carl Schwendeman, and Calin Tarau
Advanced Cooling Technologies, Inc.

Presented By
William G. Anderson

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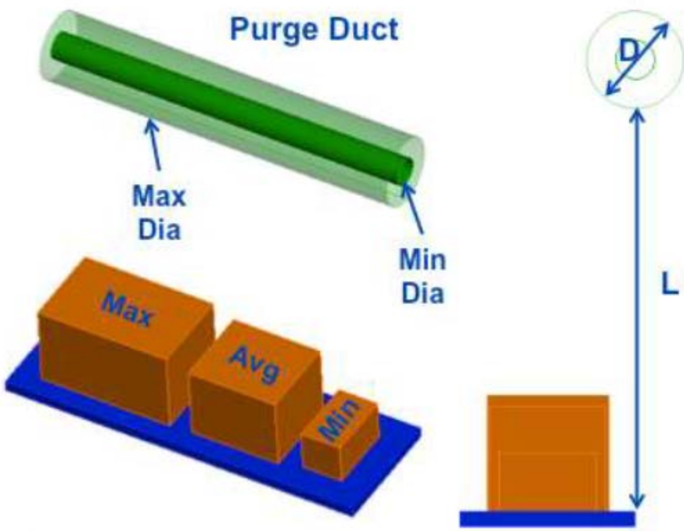
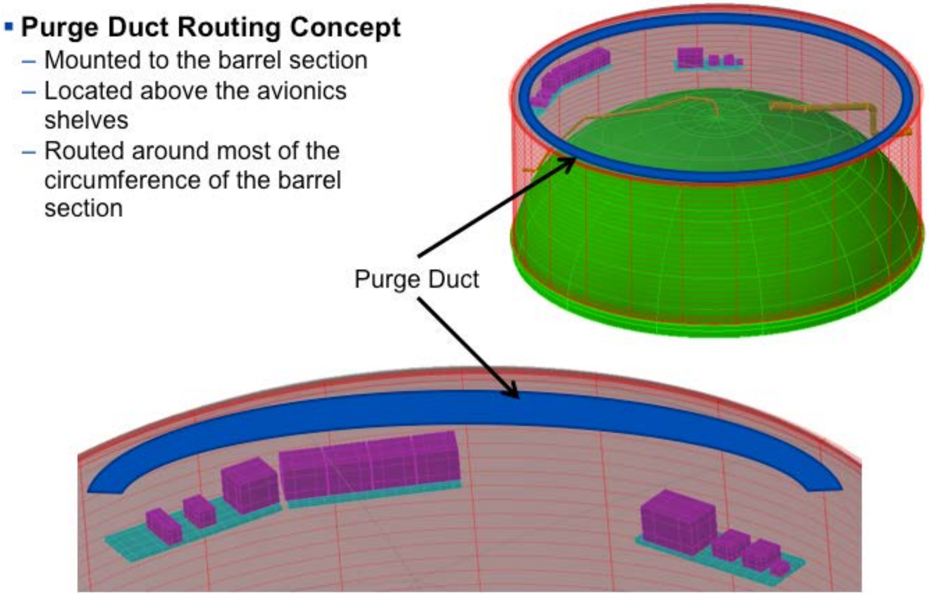
Design Objectives

- Develop a Launch Vehicle Avionics Passive Thermal Management System
  - Series of aluminum shelves with avionics boxes
  - Arbitrary location and size of the avionics boxes
- Provide cooling for avionics
  - On ground prior to launch (indefinitely) – Purge duct
  - During launch (~10min) – Thermal storage
  - Avionics cooling on orbit (indefinitely) – Radiator
- Heat Source
  - 175 Watts per box (Max.)
  - 500 Watts per shelf (Max.)
  - 1-4 boxes per shelf



Pre-Launch Heat Sink

- Heat Sink
  - Purge duct nitrogen sink: 67°F (~19.4°C)
  - Purge flow pressure drop cannot exceed 0.1 psid per shelf
  - Flow rates vary between 300 and 1800 scfm
  - Distance between shelf and duct ranges from L = 12”-48”
  - Duct diameter, D = 4”-10”
  - Baseplate allowable max: +78°F (~25.5°C)
  - Baseplate allowable min: +20°F (~6.7°C)
  - Purge duct is above all of the shelves



Design Constraints

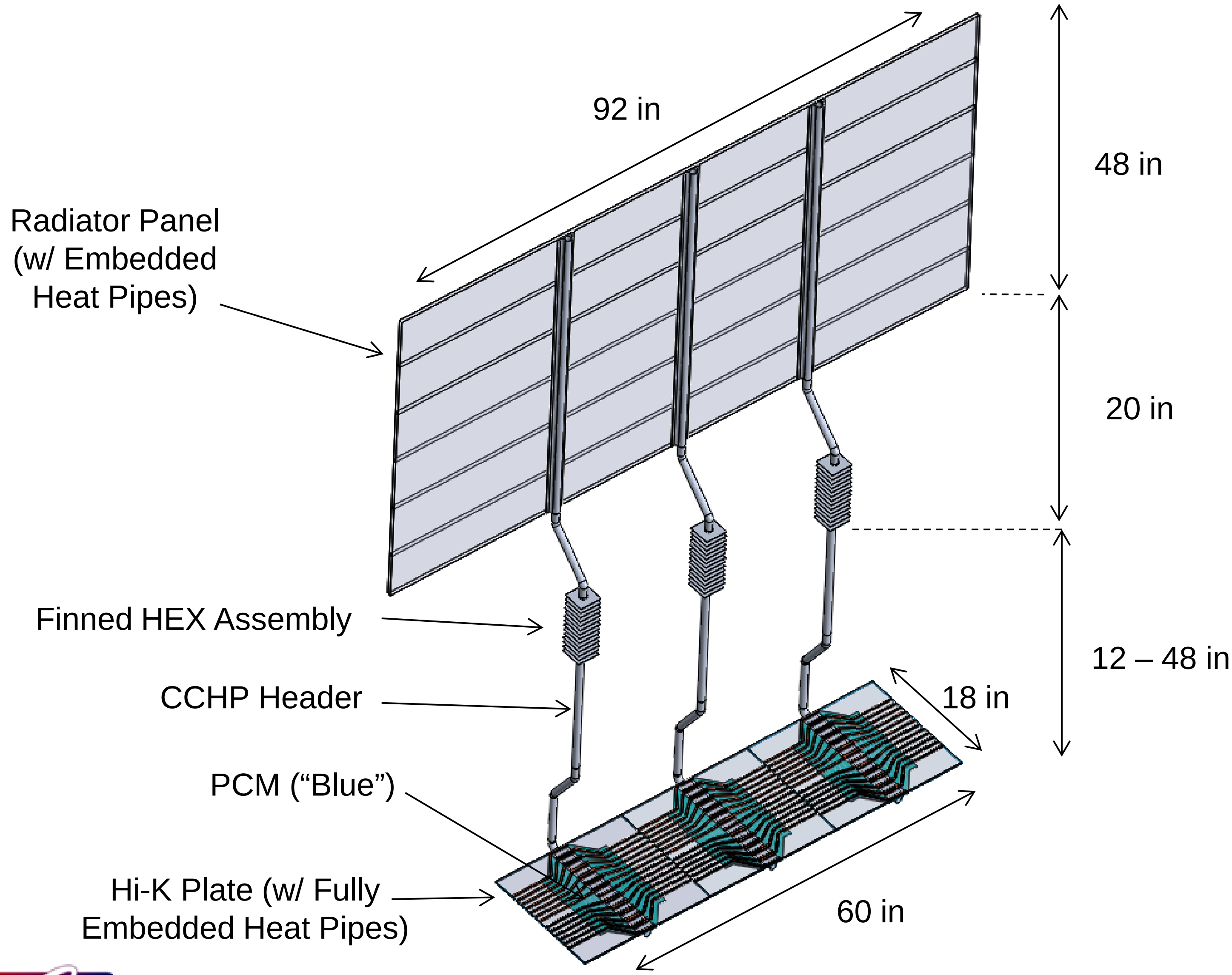
Temperatures	
Baseplate Allowable Temperature Range	-6.6 to 25.5°C
Purge Duct Nitrogen Sink	19.4 °C
Purge Duct	
Aluminum, wall thickness:	1.6 mm (0.063 in.)
Purge Duct Diameter	10 to 25 cm (4 to 10 in.)
Purge Duct Length	20 to 96 cm (12 to 48 in.)
Purge Duct Flow	8.5 to 51 m^3/min (300 to 1800 cfm)
Purge Flow Pressure Drop in Fin Stack	690 Pa (0.1 psid)/per shelf
Avionics Shelf	
Maximum power per shelf	500 W
Shelf Length	152 cm (60 in.)
Shelf Width	46 cm (18 in.)
Shelf Thickness	3.8 cm (1.5 in.)
Avionics Boxes	
Maximum Power per box	175 W
Maximum (Width x Depth x Height)	50 x 30 x 30 cm (20 x 12 x 12 in.)
Average	30 x 30 x 30 cm (12 x 12 x 12 in.)
Minimum	15 x 25 x 15 cm (6 x 10 x 6 in.)

Thermal Management System

The thermal management system has 5 components

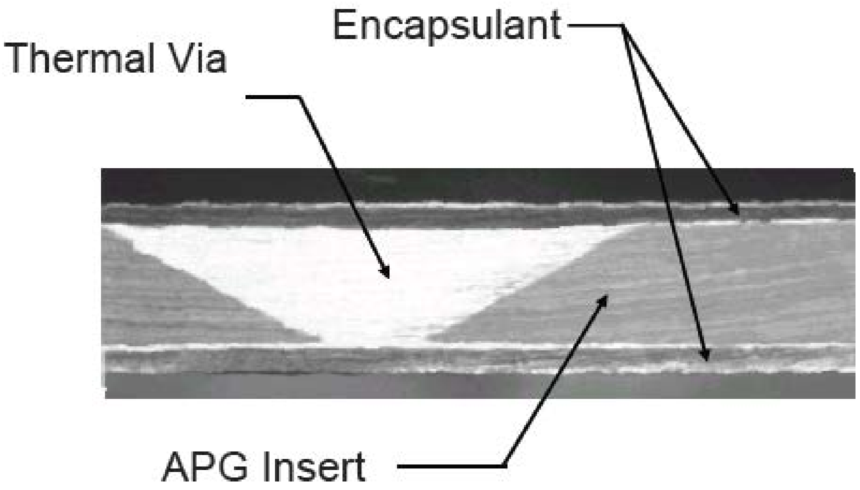
1. A heat collection system to collect the heat from the electronics boxes, and deliver it to a heat pipe
2. A heat transport system, consisting of riser heat pipes that transfer heat from the avionics shelf to the heat sinks.
   – Thermosyphon on the ground
   – CCHP in space
3. A finned heat sink to reject the heat to the purge duct flow on the ground
4. A radiator to reject heat on orbit.
   – While CCHPs are discussed here, VCHPs would be necessary in certain orbit to maintain the minimum electronics temperature
5. A thermal storage system, to accept the heat generated during ascent

Thermal Management System Layout



Heat Collection System

- Avionics Shelf requires
  - High effective thermal conductivity
  - Arbitrary location of avionics boxes and heat sources
- Two possible solutions
  - Encapsulated pyrolytic graphite
  - High Conductivity (HiK™) plates with embedded heat pipes
- Encapsulated pyrolytic graphite rejected
  - Relatively low effective thermal conductivity, ~ 550 W/m K
  - Thermal vias required due to the very low conductivity in the Z direction
  - Location of vias is fixed during the fabrication process.

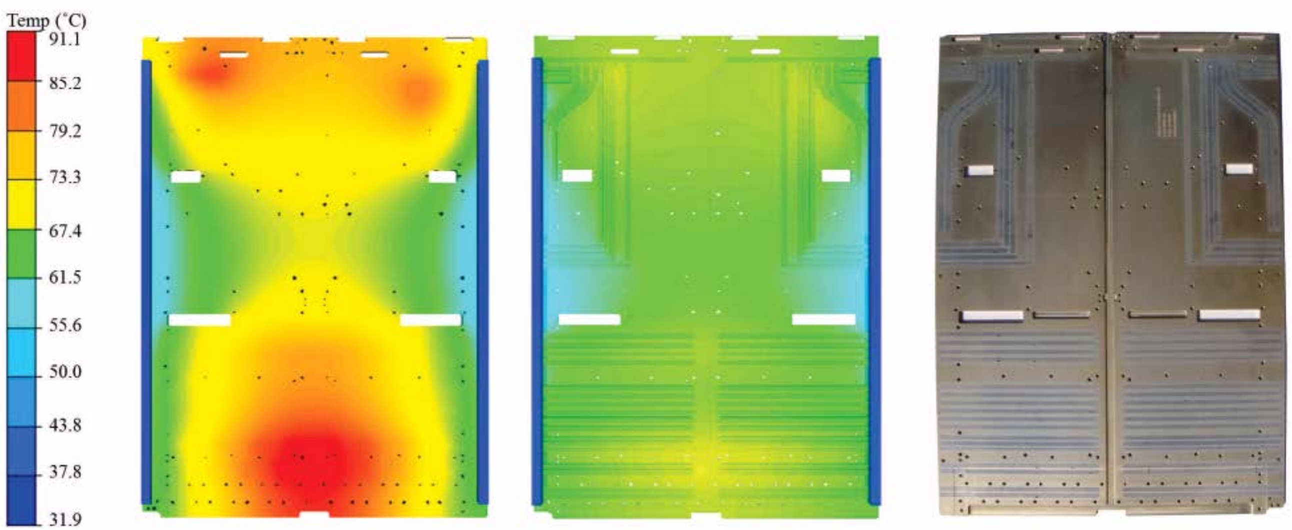


S. Kugler, "Aluminum Encapsulated APG High Conductivity Thermal Doubler" Spacecraft Thermal Control Workshop, El Segundo, CA, March 11-13, 2008

Embedded Heat Pipe Plates

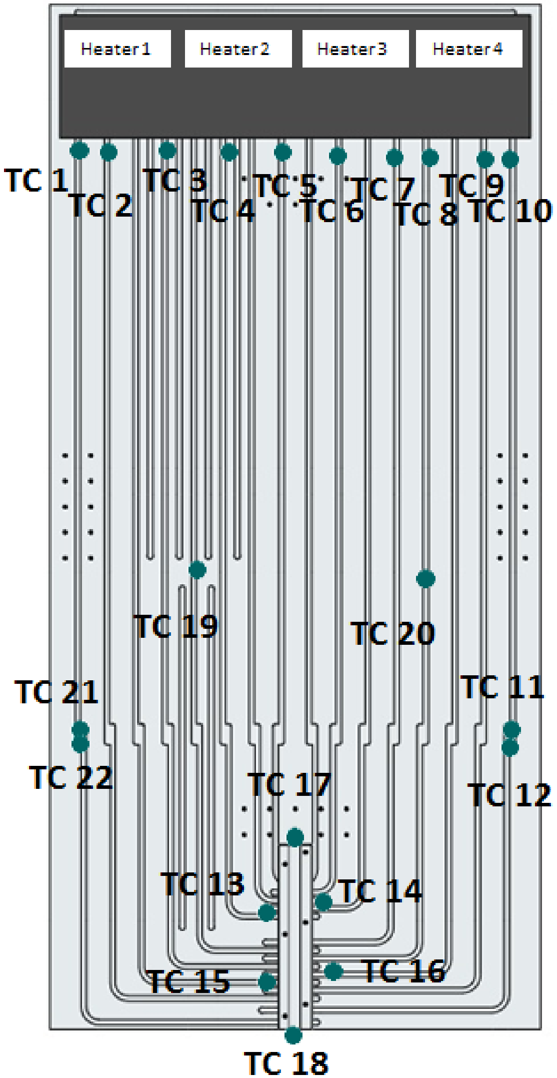
- HiK™ plates have copper/water or copper/methanol heat pipes
  - Flatten, solder in machined slots
  - Can withstand thousands of freeze/thaw cycles
  - Operate up to 12 inches against gravity (if water is used)
  - Effective thermal conductivity of 500 – 1200 W/m K for terrestrial applications, up to 2500 W/m K for spacecraft
- Identical Dimensions, 22°C Reduction in Peak Temperature Measured

Aluminum Plate **HiK™ Plate**



Embedded Heat Pipe Plate Example

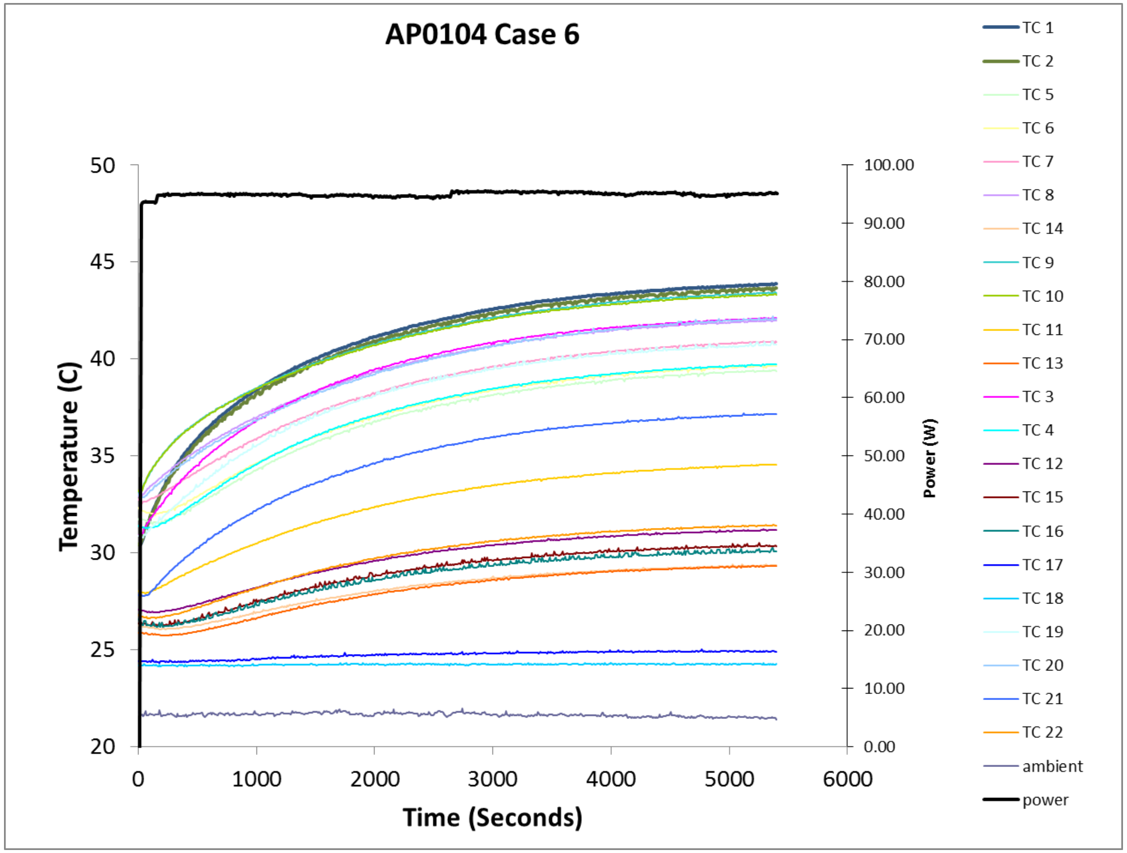
- HiK™ plate with copper/water and methanol/water heat pipes was fabricated
  - Heat supplied by heaters at one end of the plate
  - Removed by a 25°C cold plate simulating a VCHP at the other end
  - 127 cm (50 in.) by 61 cm (24 in.) by 0.79 cm (0.312 in.)
- Test case: 95 W applied to heaters 1 and 4
  - 50°C maximum allowable
- Maximum plate temperature for this case was 43.9°C



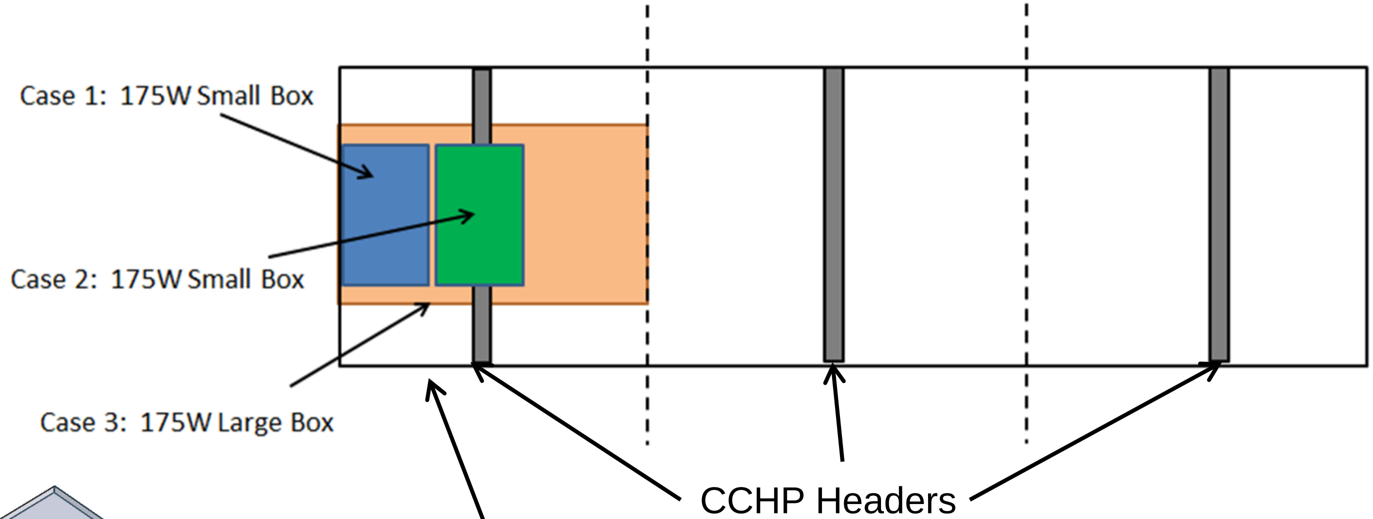
HiK™ Plate: 95 W total at Heaters 1 and 4

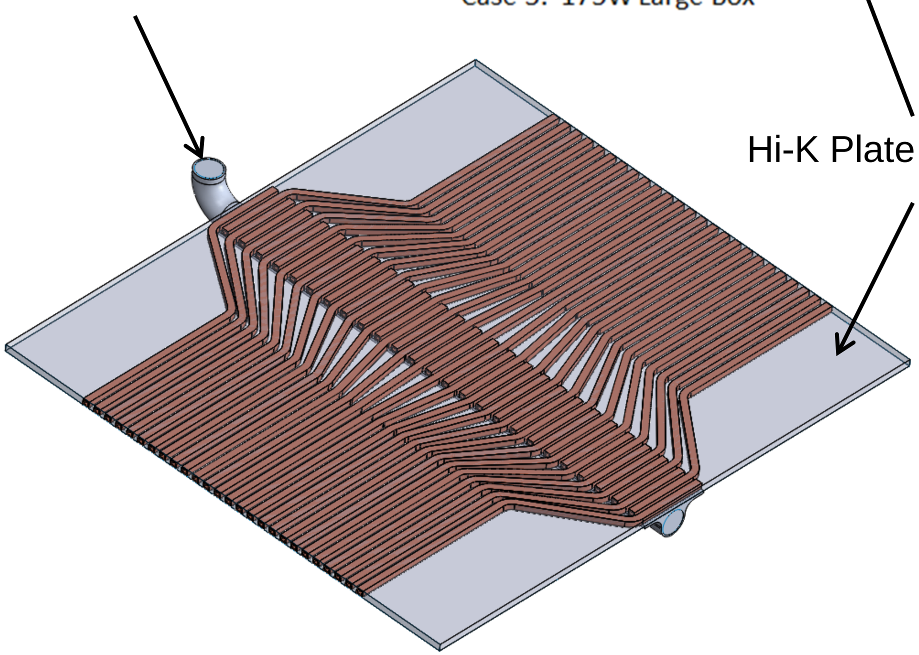
- Maximum plate temperature for this case was 43.9°C (18.9°C ΔT)
- Effective thermal conductivity of 2100 W/m K

TC 1	43.87
TC 2	43.67
TC 3	42.11
TC 4	39.73
TC 5	39.38
TC 6	39.66
TC 7	40.89
TC 8	41.98
TC 9	43.41
TC 10	43.32
TC 11	34.54
TC 12	31.17
TC 13	29.30
TC 14	29.35
TC 15	30.35
TC 16	30.05
TC 17	24.91
TC 19	40.74
TC 20	42.08
TC 21	37.17
TC 22	31.43
TC 18	24.27
ambient	21.41
power	95.10



Hi-K Plate Thermal Analysis

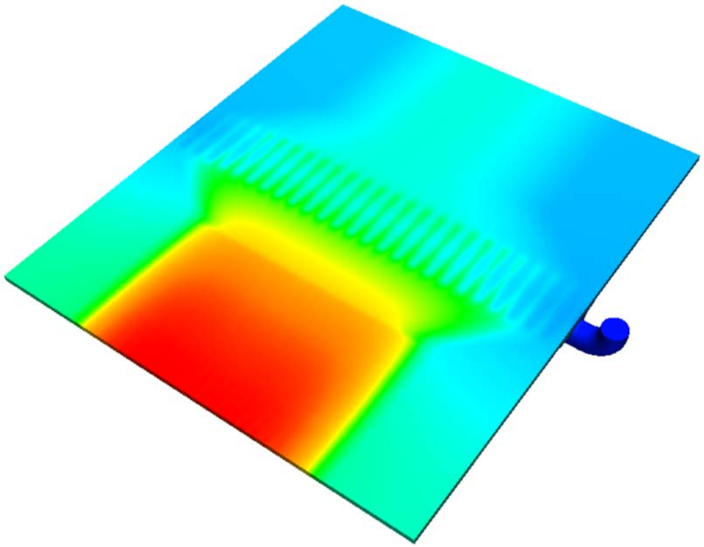




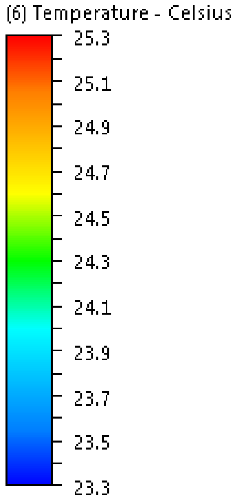
Hi-K Plate Module Geometry

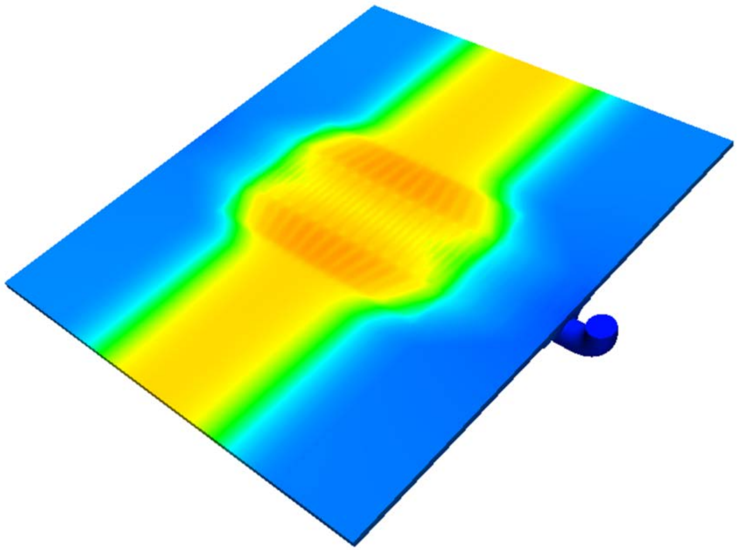
- 18”x20”x0.25”
- Cu/H_2O heat pipes (51)
  - OD = 0.25”
  - Wall thickness = 0.02”
  - Average Length = 11.25”

Results of Hi-K Plate Thermal Analysis



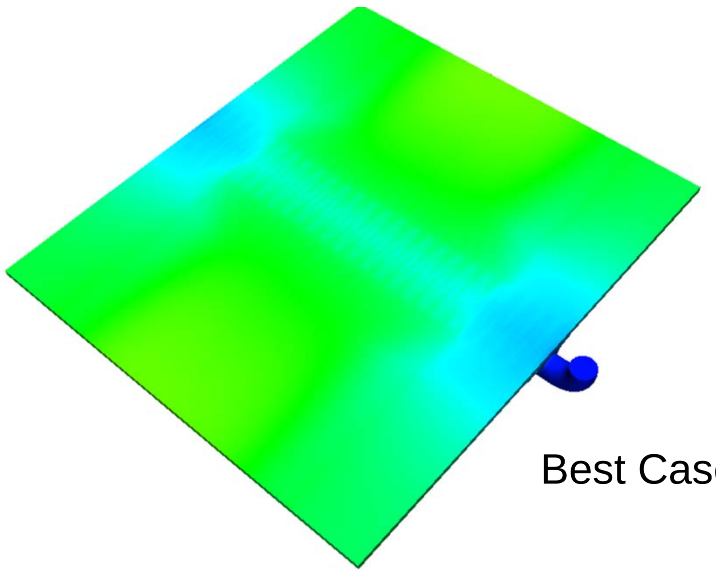
Worst Case: ΔT ~ 2°C





Medium Case: ΔT ~ 1.4°C

Thermal interface between flange and plate not considered

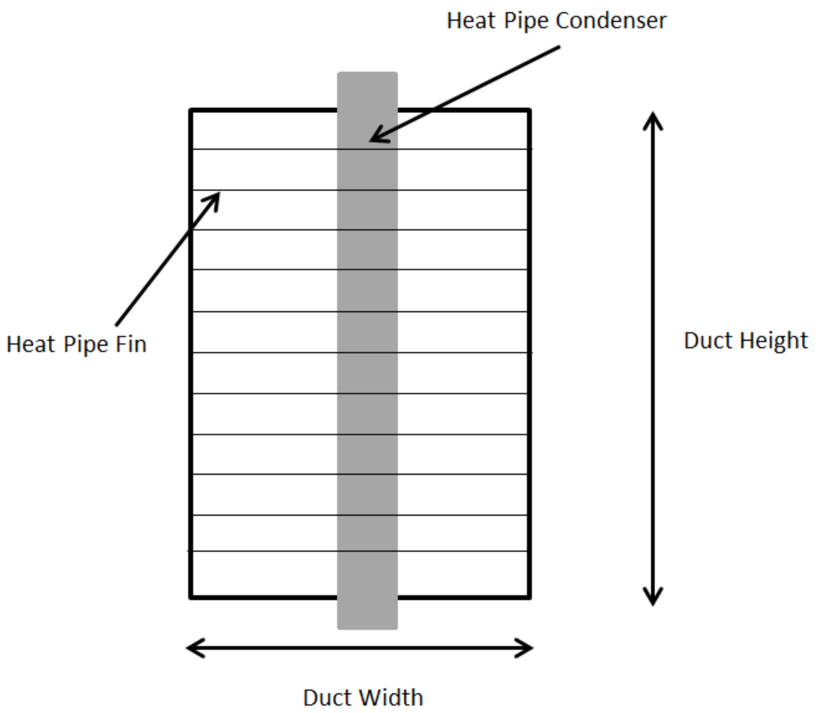


Best Case: ΔT ~ 1.1°C

Heat Pipes/Heat Sinks

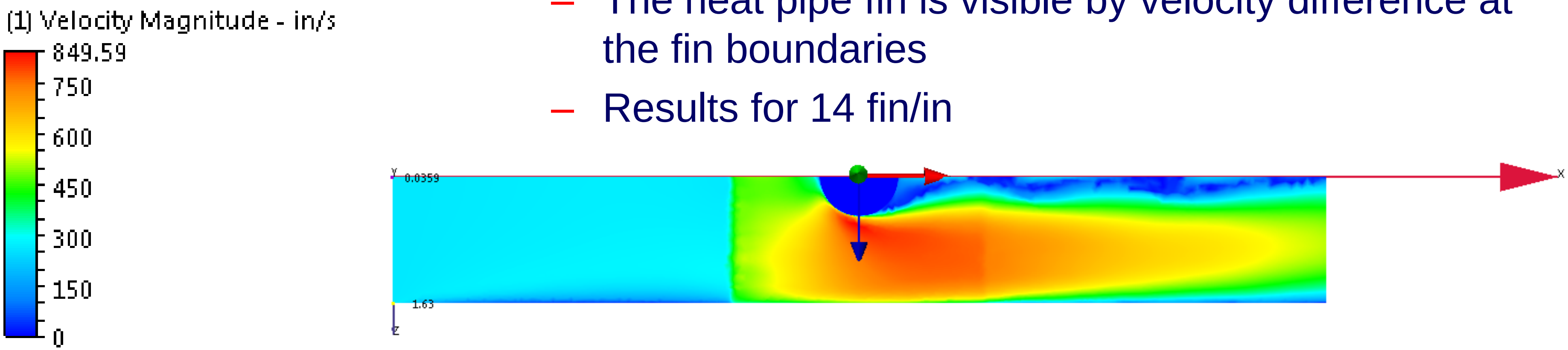
- Standard grooved aluminum/ammonia heat pipes
  - Evaporator located underneath shelf
  - Allows electronics boxes to be mounted anywhere
  - 3 heat pipes based on transport capability

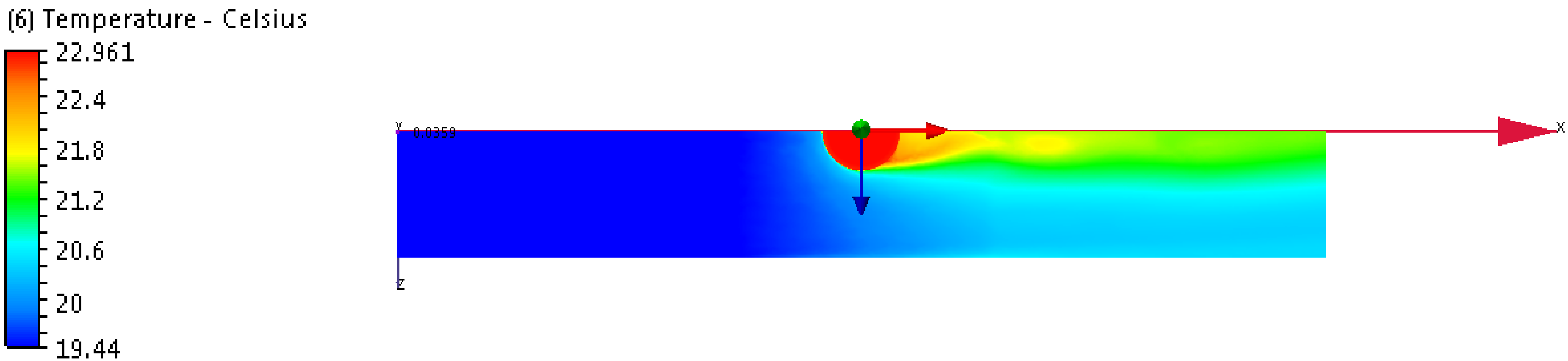
- Finned Heat Sink
  - Aluminum fins
  - Nitrogen Purge at 19.4°C (67°F)
  - ΔP < *230Pa* (*0.033 psid*) per header heat pipe
- Examine 300 and 1800 cfm cases
  - Vary fin geometry
  - CFD simulations



CFD Example Geometry

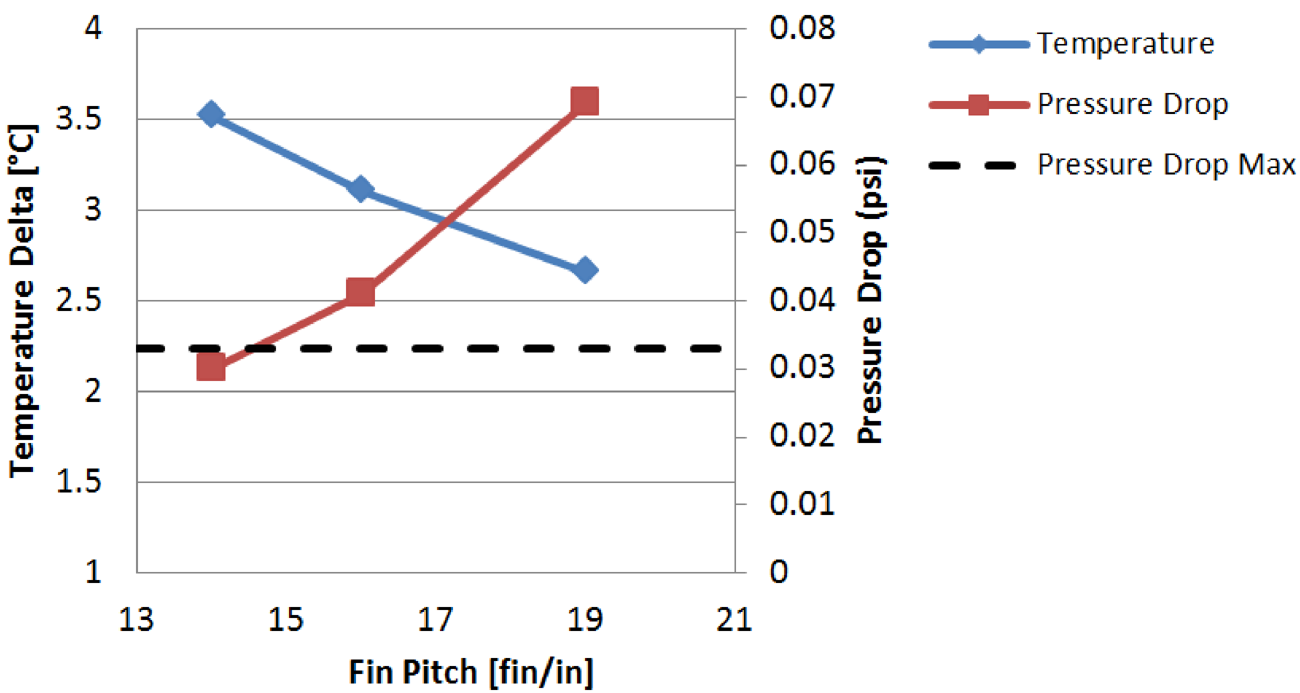
- Nitrogen is flowing left to right
- The heat pipe is the blue half circle (top picture)
- The heat pipe fin is visible by velocity difference at the fin boundaries
- Results for 14 fin/in





300CFM CFD Results

- Fin pitch iterations were carried out for a a fixed height of 10 in.
  - Higher fin pitch results in a higher pressure drop but lower temperature difference (as expected)
  - 14 fin/in was selected as it meets the pressure drop requirement

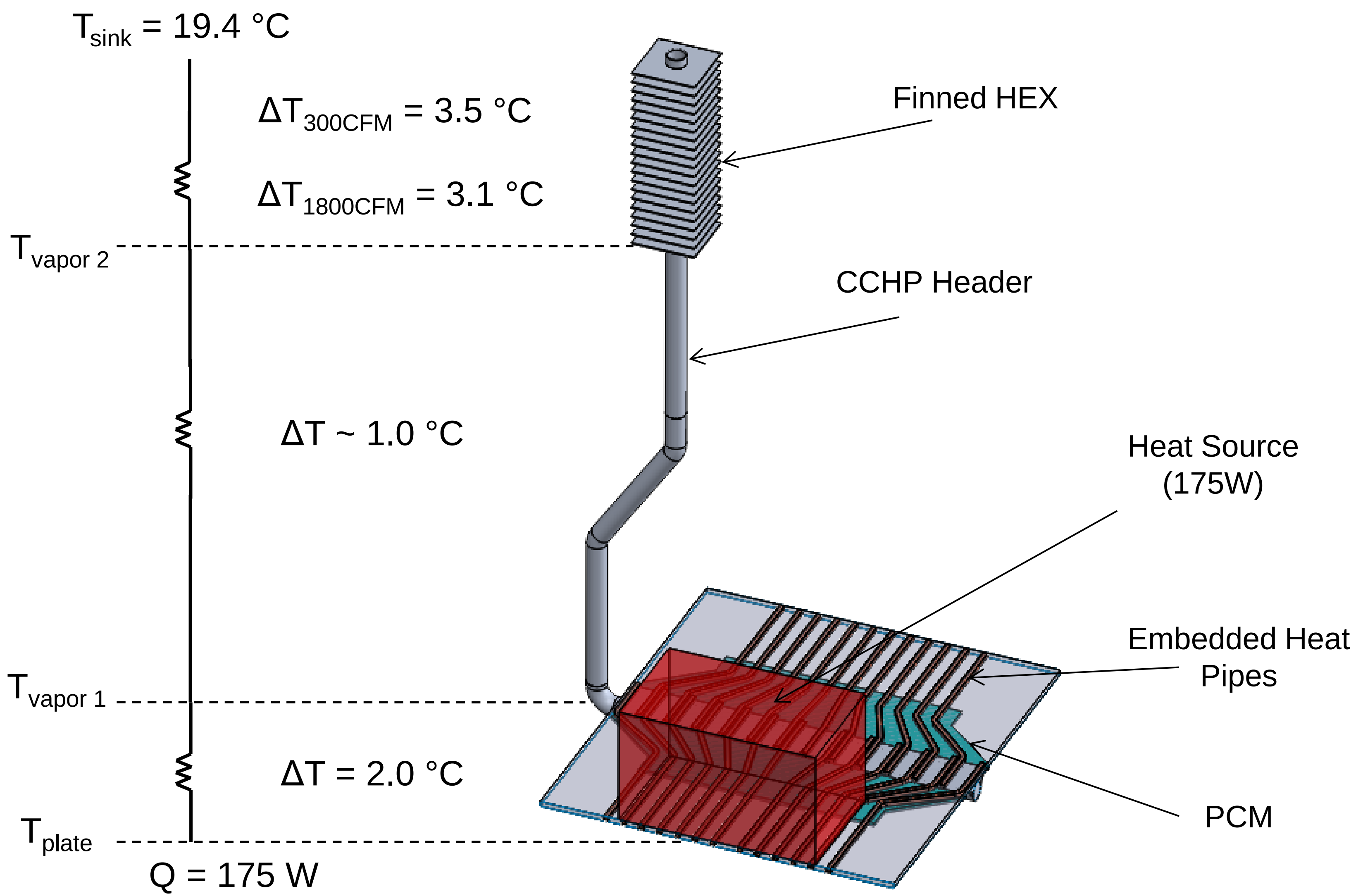


Pipe Height: 10", Fin Thickness: 0.02", Power: 200W

Fin Configurations

- To meet the 4.1°C ΔT and pressure drop requirements at 200W
- 300 CFM
  - 25.4 cm (10 in.) tall heat pipe condenser
  - 14 fins/in.
  - Fin width 8.3 cm (3.25 in.)
  - Duct width 8.3 cm (3.25 in.)
  - Fin thickness 0.51 mm (0.02 in.)
- 1800 CFM
  - 26.7 cm (10.5 in.) tall heat pipe condenser
  - 12 fins/in.
  - Fin width 9.5 cm (3.75 in.)
  - Duct width 22.9 cm (9.0 in.)
  - Fin thickness 0.51 mm (0.02 in.)

Thermal Stack-Up (Pre-Launch)

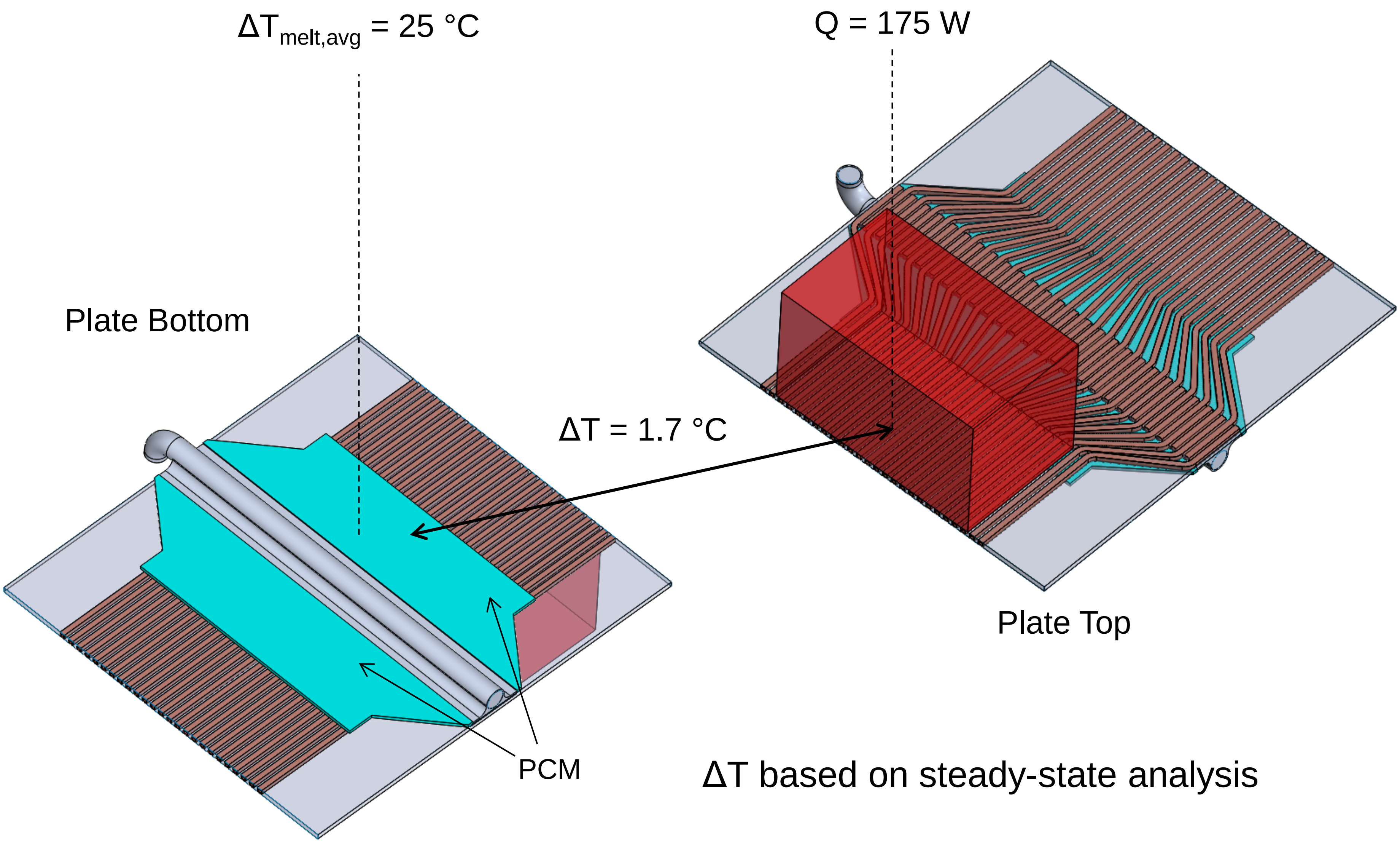


Thermal Storage During Launch

- Thermal storage for 500W of heat from a shelf for ~10 minutes (i.e. 300kJ).
  - Hydride and PCM thermal storage were considered
    - Hydrides rejected, since don't want to vent hydrogen
  - Rubitherm, (SP25A08) was selected as the PCM
    - Melts at 25°C
  - With this PCM, need to drop the purge temperature from 19.4 to 16.9°C, to keep the PCM frozen before launch
- PCM was spread over half of the bottom of each one-third of the shelf
  - PCM thickness of 2 mm (0.080 in.).
  - Conductivity enhanced with aluminum fins

Thermal Stack-Up (During Launch)

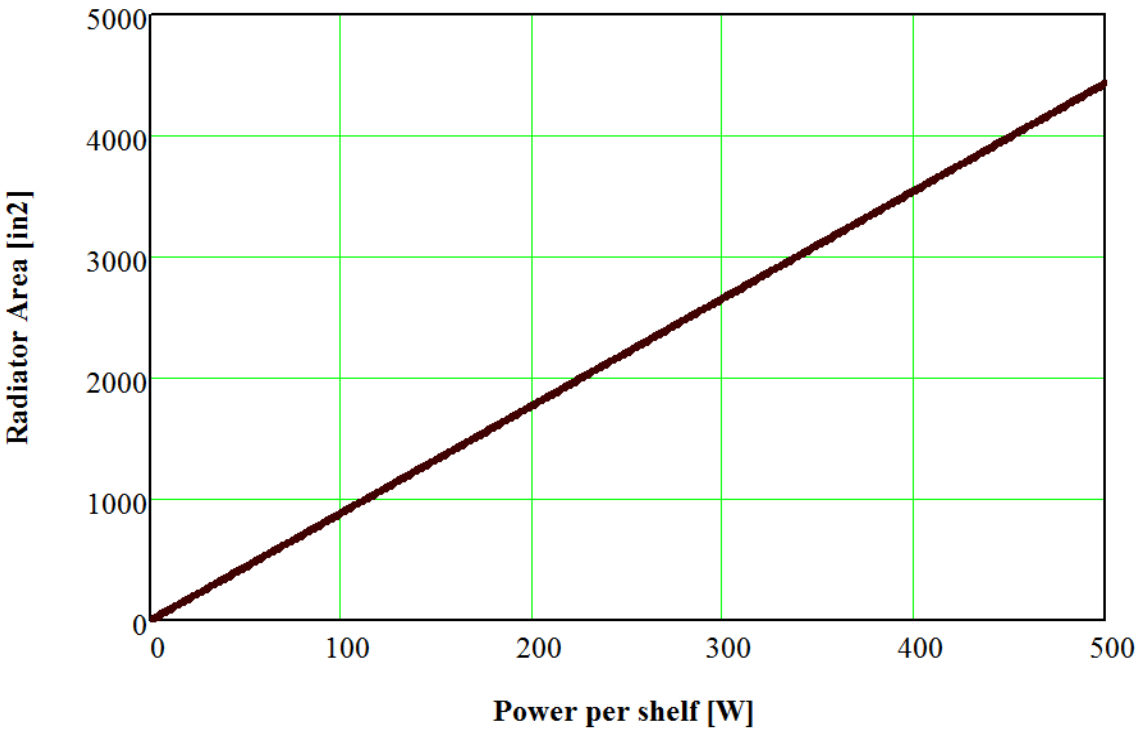
- Worst Case -



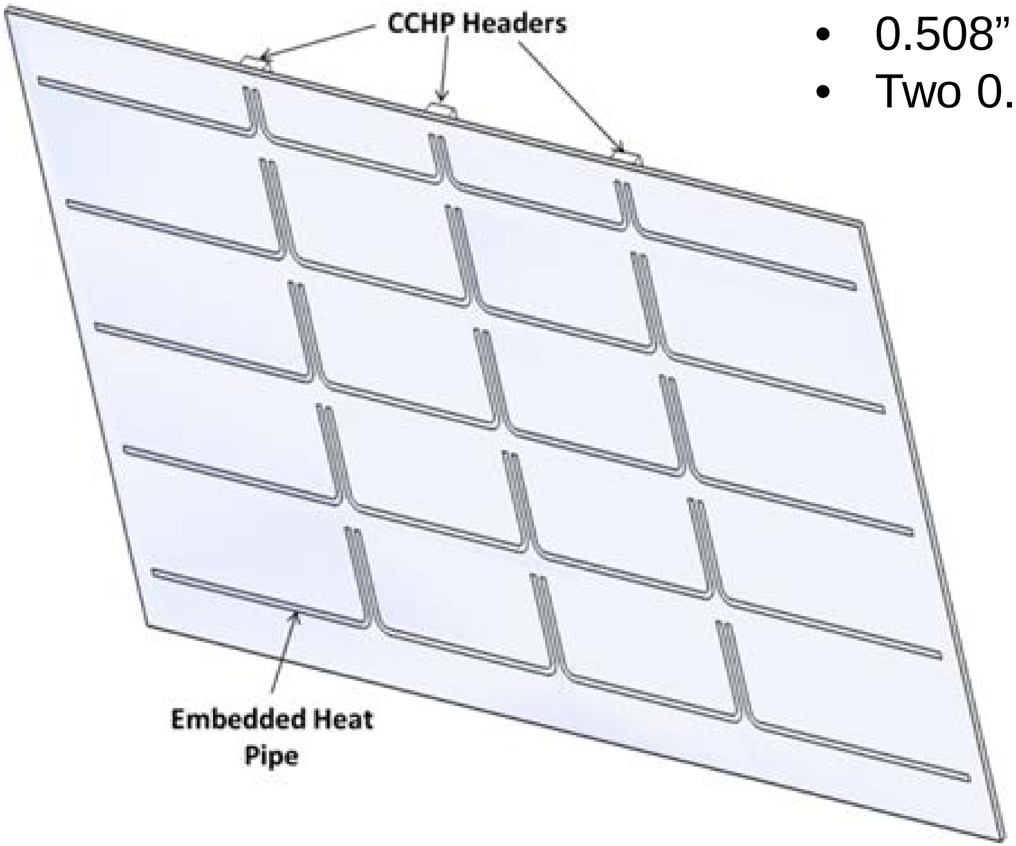
ΔT based on steady-state analysis

Radiator Analysis

- Heat pipe radiator
- Power is constant during mission at any value between 0 and 500W
  - Emissivity…0.85
  - View factor…0.9
  - Minimum Efficiency…0.9
  - Hottest sink…-40°C
  - Coldest sink…-84.5°C
  - Trans-lunar…-248.4°C



Radiator Analysis

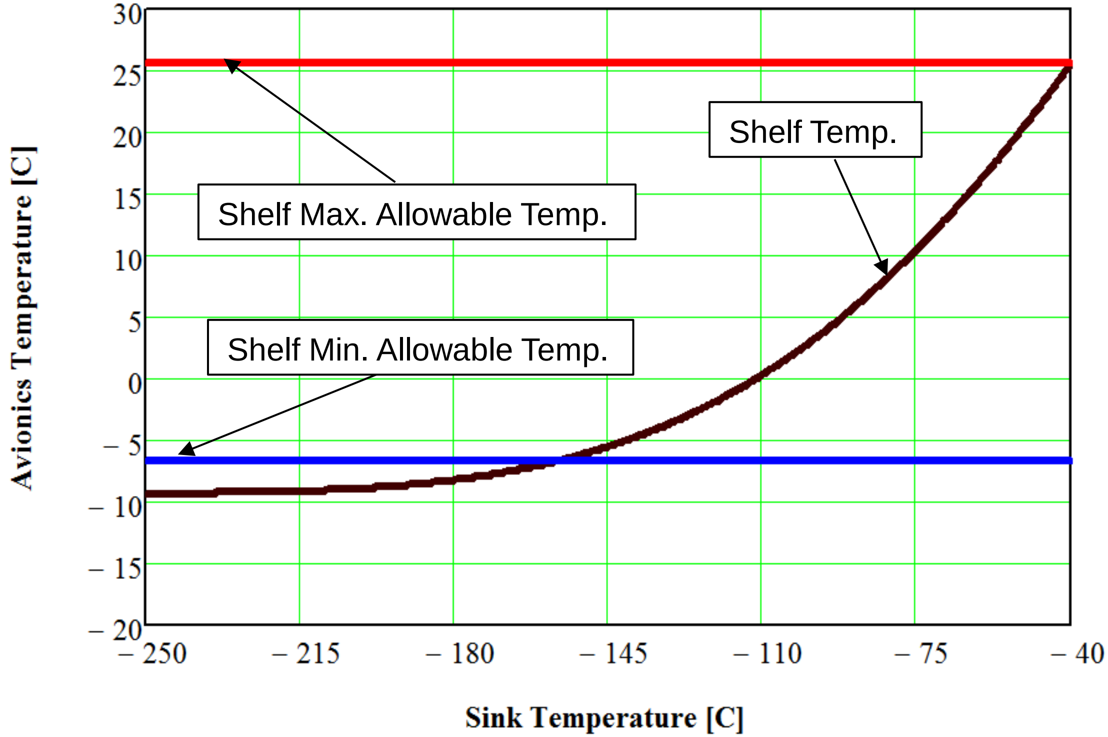


Radiator Geometry

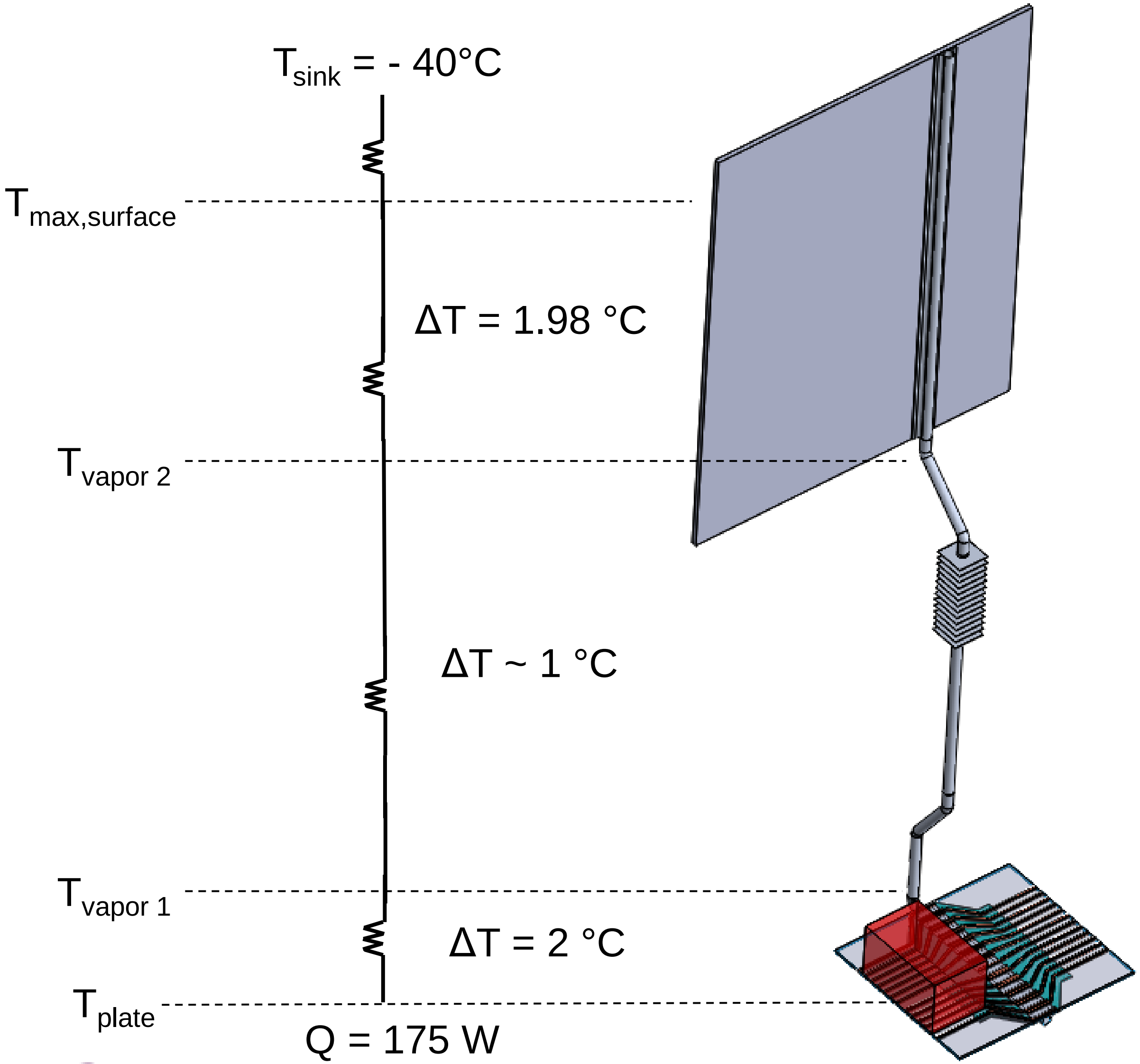
- Panel dimensions: 92”x48x”0.568”
- 20 Embedded Al/NH_3 heat pipes (0.5”)
- 0.508” thick Al honey-comb structure
- Two 0.03” Al face sheets

Radiator Analysis

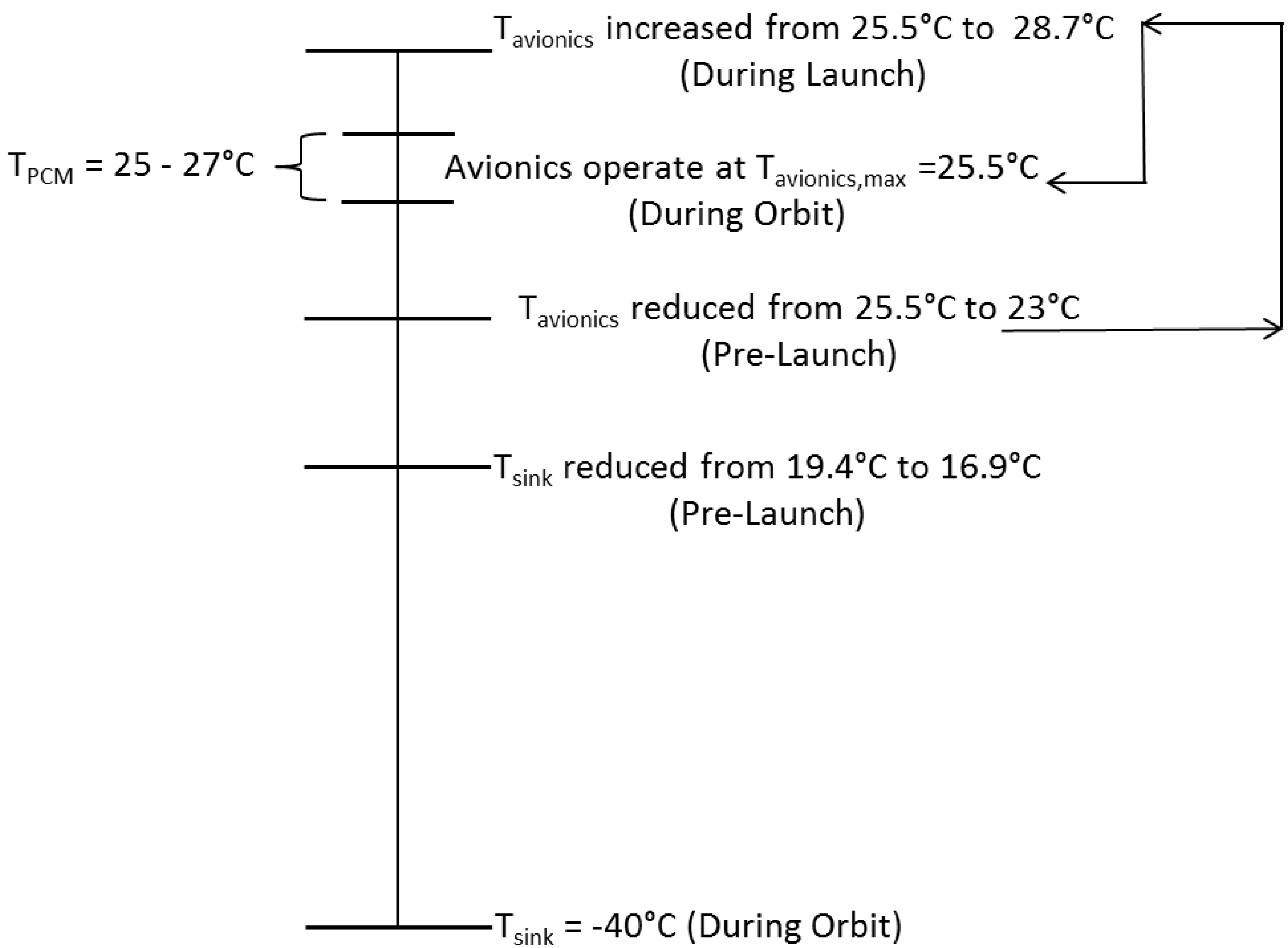
- Shelf temperature as sink temperature changes is evaluated
- Shelf max. allowable temp. 25.5°C
- Shelf max. allowable temp. -6.6°C
- VCHP may be needed for certain orbits



Thermal Stack-Up (During Orbit)



Summary of Thermal Stack-Up



System Mass/Shelf

Component Description	Component Mass (kg)	Quantity	Mass (kg)
Al Hi-K Plate (0.25")	7.38	1	7.38
Embedded Cu Pipes	0.06	153	9.18
Embedded Ti Pipes	0.02	153	3.06
Al/NH3 CCHP Header	1.09	3	3.27
Total PCM Package	0.93	3	2.80
Al Finned Stack (for duct) 300CFM	0.40	3	1.21
Al Finned Stack (for duct) 1800CFM	0.49	3	1.48
Radiator Panel	13.50	1	13.50
Embedded Al Pipes for Radiator	NA	20	3.60
Total Mass w/ Cu Pipes (kg)			42.42
Total Mass w/ Ti Pipes (kg)			36.30

Experimental System

- Low-cost, simplified version of the system was fabricated to verify the design during ground testing
- One-third of a compete shelf
- Three components:
  - High Conductivity Plate, or embedded heat pipe HiK™ plate.
  - Header heat pipe to purge duct
  - Removable Purge Flow Fin Heat Exchanger
    - Off-the-shelf heat sink

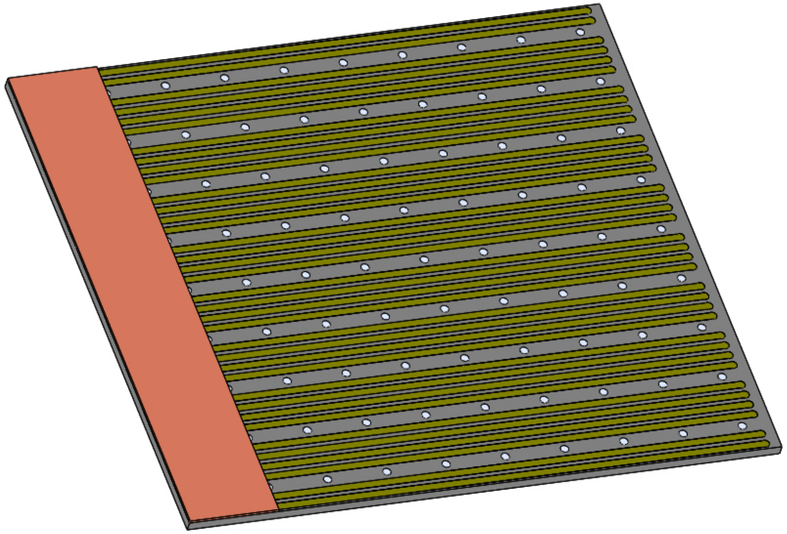
Experimental System Design Parameters

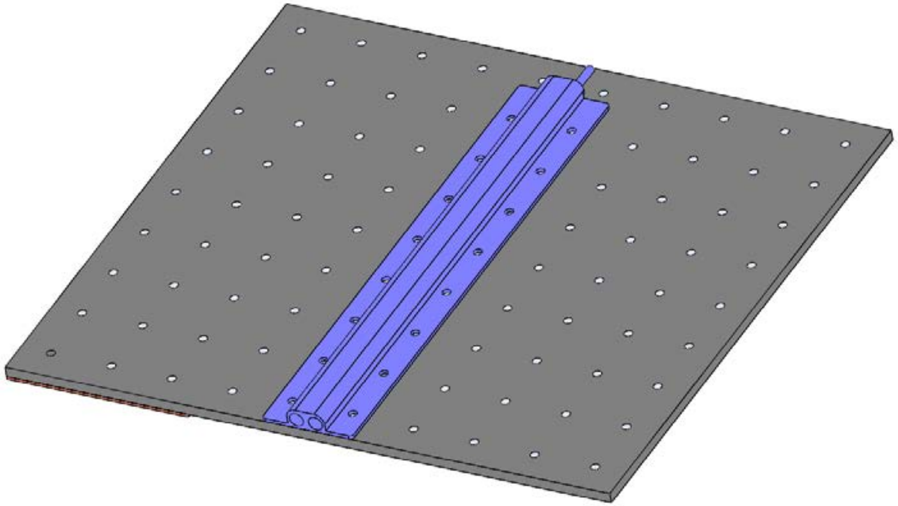
- System designed for easy disassembly, to swap out components
  - TIM was Nusil CV2-2646 for all the make/break joints

Avionics HiK™ Shelf	
Heat Load	175 W
Avionics Max. Heat Flux Density	0.51 W/cm^2 (3.3 W/in^2)
Maximum Avionics Surface Temperature	26°C
Avionics Shelf	50.8 x 45.7 cm (20 x 18 in.)
Bolt hole pattern for avionics boxes	2 in. x 2 in. bolt hole pattern
Heat Sink	
Flow Rate	8.5 m^3/min (300 scfm)
Purge Flow Temperature	18 C
Duct Diameter	10.2 cm (4 inch)
Maximum pressure drop	690 Pa (0.1 psid)
Heat Exchanger (Duct Length)	Less than 30.5 cm (12 in.)
Vertical Distance for Heat Transport	122 cm (48 in.)

HiK™ Plate Layout

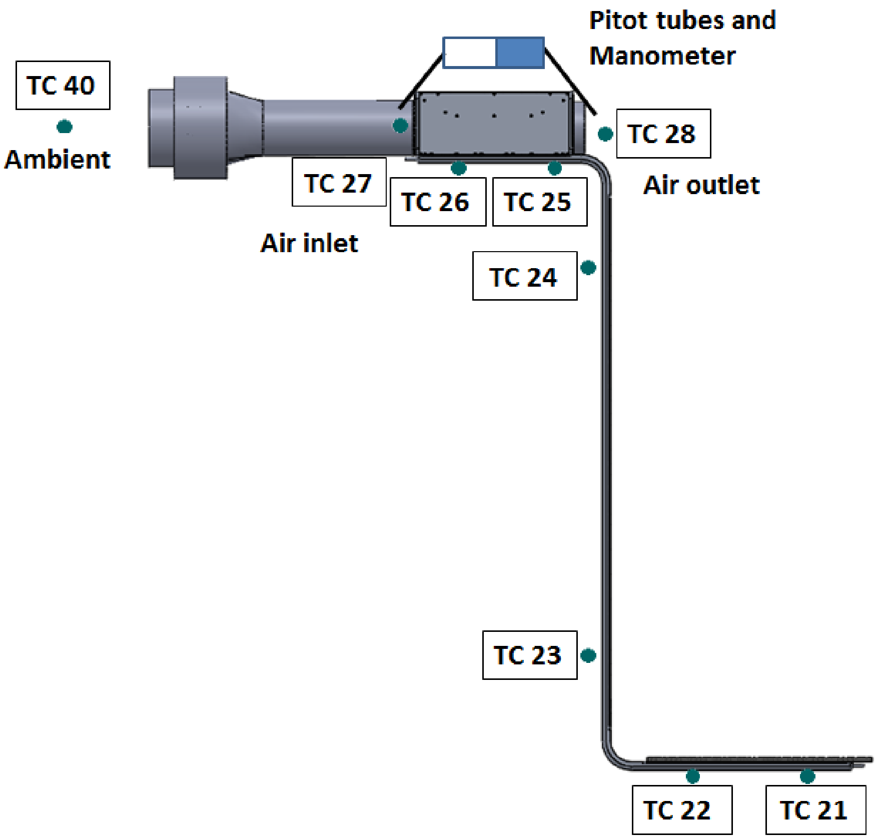
- 36 embedded copper/water heat pipes
- Initial O.D. of 6.35 mm (0.25 in.) flattened to fit the plate
- Heat pipes laid out to avoid the mounting bolt holes
- Electrical heaters applied 175 W (0.51 W/cm^2) over a 7.6 x 35.7 cm (3 x 18 in.) strip at the edge of the plates (worst case).





Experimental Setup

- Tests were conducted to verify basic functionality



Experimental Results – Basic Functionality Tests

- Measured ΔT of roughly 15°C was above the predicted value of 13.5°C.
  - Much of the overall ΔT is due to the thermal interface materials (TIMs), between the HiK™ plate and the CCHP, and the CCHP and the Heat Sink
  - Can improve with a better thermal interface material, or by bonding the components together
- High level goal is an avionics thermal management system with an overall thermal gradient of near 6°C.
  - Low-cost proof of concept system developed under this program demonstrated that the components are conducive to a 6°C system

	Test 1	Test 2
HiK™ Plate to Heat Pipe	5.87°C	5.58°C
Heat Pipe Length	2.69°C	2.56°C
Heat Pipe to Air	6.58°C	6.34°C
Overall, Plate Surface to Air	15.13°C	14.40°C

Conclusions

- A passive thermal management system was designed to cool avionics on a launch vehicle for 3 different thermal modes
  - Cooling for avionics while on ground prior to launch (indefinitely), dumping the heat to flow in a purge duct.
  - Cooling for avionics during launch (~10min), storing the heat in a PCM module
  - Cooling on-orbit (indefinitely), with a radiator.
- The system has the following components
  - High Conductivity (HiK™) Plate with embedded heat pipes, where the avionics are mounted
  - Three Constant Conductance Heat Pipe (CCHP) Header Heat Pipes, that transfer heat to the purge duct of the radiator
  - Finned Heat Exchangers, the designated heat sink during pre-launch.
  - PCM modules, the designated heat sink during ascent.
  - Radiator, the designated heat sink on orbit.

Conclusions

- Low-cost, simplified version of the system was designed and fabricated to verify the design during ground testing.
  - One-third of complete shelf
  1. HiK™ plate
  2. Al/ammonia heat pipe from the plate to the simulated duct
  3. Low-cost, off the shelf heat sink in the duct
- Functionality Testing
  - Measured ΔT of roughly 15°C
  - Above the predicted value of 13.5°C, due to the thermal interface material
  - Overall thermal performance can be improved with a better interface material
- Future Work
  - System currently being tested at NASA Marshall

Acknowledgements

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  - The Technical Monitor was Dr. Jeffery T. Farmer

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