Launch Vehicle Avionics for Passive Thermal Management

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Advanced Cooling Technologies, Inc.

Presented By
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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

<table>
<thead>
<tr>
<th>Temperatures</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseplate Allowable Temperature Range</td>
<td>-6.6 to 25.5°C</td>
</tr>
<tr>
<td>Purge Duct Nitrogen Sink</td>
<td>19.4 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Purge Duct</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum, wall thickness:</td>
<td>1.6 mm (0.063 in.)</td>
</tr>
<tr>
<td>Purge Duct Diameter</td>
<td>10 to 25 cm (4 to 10 in.)</td>
</tr>
<tr>
<td>Purge Duct Length</td>
<td>20 to 96 cm (12 to 48 in.)</td>
</tr>
<tr>
<td>Purge Duct Flow</td>
<td>8.5 to 51 m³/min (300 to 1800 cfm)</td>
</tr>
<tr>
<td>Purge Flow Pressure Drop in Fin Stack</td>
<td>690 Pa (0.1 psid)/per shelf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Avionics Shelf</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power per shelf</td>
<td>500 W</td>
</tr>
<tr>
<td>Shelf Length</td>
<td>152 cm (60 in.)</td>
</tr>
<tr>
<td>Shelf Width</td>
<td>46 cm (18 in.)</td>
</tr>
<tr>
<td>Shelf Thickness</td>
<td>3.8 cm (1.5 in.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Avionics Boxes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power per box</td>
<td>175 W</td>
</tr>
<tr>
<td>Maximum (Width x Depth x Height)</td>
<td>50 x 30 x 30 cm (20 x 12 x 12 in.)</td>
</tr>
<tr>
<td>Average</td>
<td>30 x 30 x 30 cm (12 x 12 x 12 in.)</td>
</tr>
<tr>
<td>Minimum</td>
<td>15 x 25 x 15 cm (6 x 10 x 6 in.)</td>
</tr>
</tbody>
</table>
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

Radiator Panel (w/ Embedded Heat Pipes)

Finned HEX Assembly

CCHP Header

PCM (“Blue”)

Hi-K Plate (w/ Fully Embedded Heat Pipes)
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.
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
**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

<table>
<thead>
<tr>
<th>TC</th>
<th>Temperature (°C)</th>
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<tbody>
<tr>
<td>1</td>
<td>43.87</td>
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<tr>
<td>2</td>
<td>43.67</td>
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<td>3</td>
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<td>7</td>
<td>40.89</td>
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<td>8</td>
<td>41.98</td>
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<td>9</td>
<td>43.41</td>
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<td>10</td>
<td>43.32</td>
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<td>14</td>
<td>29.35</td>
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<td>15</td>
<td>30.35</td>
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<tr>
<td>16</td>
<td>30.05</td>
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<td>17</td>
<td>24.91</td>
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<td>40.74</td>
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<td>19</td>
<td>42.08</td>
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<tr>
<td>20</td>
<td>24.27</td>
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<tr>
<td>ambient</td>
<td>21.41</td>
</tr>
<tr>
<td>power</td>
<td>95.10</td>
</tr>
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</table>

**AP0104 Case 6**

Time (Seconds) vs. Temperature (°C) and Power (W)
Hi-K Plate Thermal Analysis

Hi-K Plate Module Geometry
- 18”x20”x0.25”
- Cu/H₂O heat pipes (51)
  - OD = 0.25”
  - Wall thickness = 0.02”
  - Average Length = 11.25”

ΔT calculated between heat source and CCHP vapor
Results of Hi-K Plate Thermal Analysis

Worst Case: $\Delta T \sim 2^\circ C$

Medium Case: $\Delta T \sim 1.4^\circ C$

Best Case: $\Delta T \sim 1.1^\circ C$

Thermal interface between flange and plate not considered.
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)
  - $\Delta P < 230 Pa$ ($0.033\text{ psid}$) 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
Fin pitch iterations were carried out for 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
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)

$T_{\text{sink}} = 19.4 \, ^\circ\text{C}$

$\Delta T_{300\text{CFM}} = 3.5 \, ^\circ\text{C}$

$\Delta T_{1800\text{CFM}} = 3.1 \, ^\circ\text{C}$

$\Delta T \approx 1.0 \, ^\circ\text{C}$

$\Delta T = 2.0 \, ^\circ\text{C}$

$Q = 175 \, \text{W}$

Heat Source (175W)

Finned HEX

CCHP Header

Embedded Heat Pipes

PCM
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 -

$\Delta T_{\text{melt,avg}} = 25 \, ^\circ\text{C}$

$Q = 175 \, \text{W}$

$\Delta T = 1.7 \, ^\circ\text{C}$

$\Delta T$ based on steady-state 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”x48”x0.568”
- 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)

$T_{\text{sink}} = -40^\circ \text{C}$

$\Delta T = 1.98^\circ \text{C}$

$\Delta T \sim 1^\circ \text{C}$

$\Delta T = 2^\circ \text{C}$

$Q = 175 \text{ W}$
Summary of Thermal Stack-Up

\[ T_{\text{PCM}} = 25 - 27^\circ \text{C} \]

- \( T_{\text{avionics}} \) increased from 25.5°C to 28.7°C (During Launch)
- \( T_{\text{avionics}} \) reduced from 25.5°C to 23°C (Pre-Launch)
- \( T_{\text{sink}} \) reduced from 19.4°C to 16.9°C (Pre-Launch)
- \( T_{\text{sink}} = -40^\circ \text{C} \) (During Orbit)

Avionics operate at \( T_{\text{avionics,max}} = 25.5^\circ \text{C} \) (During Orbit)
# System Mass/Shelf

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

<table>
<thead>
<tr>
<th>Avionics HiK™ Shelf</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load</td>
<td>175 W</td>
</tr>
<tr>
<td>Avionics Max. Heat Flux Density</td>
<td>0.51 W/cm² (3.3 W/in²)</td>
</tr>
<tr>
<td>Maximum Avionics Surface Temperature</td>
<td>26°C</td>
</tr>
<tr>
<td>Avionics Shelf</td>
<td>50.8 x 45.7 cm (20 x 18 in.)</td>
</tr>
<tr>
<td>Bolt hole pattern for avionics boxes</td>
<td>2 in. x 2 in. bolt hole pattern</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat Sink</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate</td>
<td>8.5 m³/min (300 scfm)</td>
</tr>
<tr>
<td>Purge Flow Temperature</td>
<td>18 C</td>
</tr>
<tr>
<td>Duct Diameter</td>
<td>10.2 cm (4 inch)</td>
</tr>
<tr>
<td>Maximum pressure drop</td>
<td>690 Pa (0.1 psid)</td>
</tr>
<tr>
<td>Heat Exchanger (Duct Length)</td>
<td>Less than 30.5 cm (12 in.)</td>
</tr>
<tr>
<td>Vertical Distance for Heat Transport</td>
<td>122 cm (48 in.)</td>
</tr>
</tbody>
</table>
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/cm²) 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

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiK™ Plate to Heat Pipe</td>
<td>5.87°C</td>
<td>5.58°C</td>
</tr>
<tr>
<td>Heat Pipe Length</td>
<td>2.69°C</td>
<td>2.56°C</td>
</tr>
<tr>
<td>Heat Pipe to Air</td>
<td>6.58°C</td>
<td>6.34°C</td>
</tr>
<tr>
<td>Overall, Plate Surface to Air</td>
<td>15.13°C</td>
<td>14.40°C</td>
</tr>
</tbody>
</table>
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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