Multi-Evaporator Hybrid Two-Phase Loop Cooling System for Small Satellites

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21st Annual AIAA/USU Conference on Small Satellites
Where do things stand today with respect to two-phase loop cooling of spacecraft?

Is there an alternative to a CPL or an LHP?

Single-Evaporator CPLs
... A Few Flying (e.g., HST/NCS)

Single-Evaporator LHPs
... 100+ Flying on Commsats

Multiple-Evaporator Hybrid Loop Heat Pipe (ME-HLHP)

Ground Testing of ME-HLHP Based Cooling Systems for...
- Smallsats (NASA ST-8)
- Five Additional Applications
  > Laser Diode/Crystal
  > Compact Laser
  > Large Spacecraft
  > Electronics
  > Instruments

Multiple-Evaporator CPLs
... CAPL-3 Flew in 2001, None flying

Multiple-Evaporator LHPs
... None have flown
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Ed Kroliczek
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Dave Wolf
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OUTLINE

- INTRODUCTION
- BACKGROUND
- RATIONALE
- CONCEPT
- DESIGN
- TESTING
- APPLICATIONS
- CONCLUSION
**OBJECTIVE:** Develop two-phase loop thermal management system (TMS) to replace the traditional "cold-biasing plus heater power" approach, to enable ...

- Flexibility in component placement
- Reduced mass / heater power / volume
- Improved power resource efficiency
- Scalability from 150 kg, 200 W nominal size

... NASA ST-8 requirements
(for future missions especially those with extended eclipses and limited power)

**PAPER / BRIEFING:** Describes a two-phase loop based cooling system for smallsats developed during a 6-month ST-8 study and 5 subsequent ground tested cooling systems for lasers, spacecraft, electronics, and instruments.
**BACKGROUND**

An advanced weapon and space systems company

- **Requirements (ST-8)**
  - enable component placement flexibility
  - minimize power/mass/volume
  - improve power resource efficiency
  - scalable from 150 kg, 200 W nominal size

- **Needed Functionalities**
  - multi-evaporator bus
  - heat load sharing (HLS)
  - miniaturized components
  - thermal diode action
  - multiple condensers
  - set-point controllability
  - high conductance

- **Two-Phase Loop Architectures**
  - capillary pumped loop (CPL)
  - loop heat pipe (LHP)
  - hybrid loop heat pipe (HLHP)

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**CPL**
- controllability
- expandability

**LHP**
- instant-on
- metal wicks

**HLHLP**
- CPL advantages
- LHP advantages
# RATIONALE

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>WHAT IT DOES</th>
<th>WHY IT’S GOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multi-Evaporator Bus</strong></td>
<td>Decouples structure and thermal design process so component placement is more flexible</td>
<td>Simplifies Design, Reduces Mass</td>
</tr>
<tr>
<td><strong>Heat Load Sharing</strong></td>
<td>Keeps environmentally exposed instruments warm when not &quot;ON&quot;</td>
<td>Reduces Heater Power, Improves Efficiency</td>
</tr>
<tr>
<td><strong>Miniaturized Components</strong></td>
<td>Reduces weight</td>
<td>Expands Packaging Options</td>
</tr>
<tr>
<td><strong>Thermal Diode Action</strong></td>
<td>Isolates payload/components from extreme environments</td>
<td>Expands Mission Options</td>
</tr>
<tr>
<td><strong>Multiple Condensers</strong></td>
<td>Reduces need to adjust attitude for thermal control</td>
<td>Increased Time Available for Science</td>
</tr>
<tr>
<td><strong>Set-Point Controllability</strong></td>
<td>Reduces payload/component temperature fluctuations</td>
<td>Minimizes Temperature Cycling, Lengthens Life</td>
</tr>
<tr>
<td><strong>High Conductance</strong></td>
<td>Enables centralized component mounting configurations</td>
<td>Shorter Electrical Harnessing, Simpler Structure, Reduced Mass</td>
</tr>
</tbody>
</table>
Multi-Evaporator Hybrid Two-Phase Loop Cooling System for Small Satellites
Multi-Evaporator Hybrid Two-Phase Loop Cooling System for Small Satellites
• **RESULTS:** With ammonia as the working fluid, 21 tests were carried out with the ST-8 ME-HLHP test loop resulting in:

- quad-evaporator transport of 8-280 W
- single-evaporator transport of 2-100 W
- power cycling from 50-200 W
- maximum heat flux of 30 W/cm²
- conductance of 5-8 W/K per evaporator
- heat load sharing greater than 95%
- condenser switching
- freeze-tolerant condenser
- set-point control to +/- 0.25 K
- rapid start-up
- sweepage evaporator power of 4W
- diode action/loop isolation
- Teflon evaporator 233-353 K cycling

• **STATUS:** All 21 tests successful ... key accomplishment was the development of a 5 μm miniaturized Teflon wick evaporator. Despite success, dual-evaporator LHP with TEC reservoir cold-biasing selected for flight experiment. Concerns ...

  - the risk of expanding beyond two evaporators
  - the impact of TEC failure on loop temperature controllability

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**Diode Action**

**Power Cycling**

**Heat Load Sharing**

**Set-Point Control**

**Miniaturized Al Body Teflon Wick Evaporator**

Wick 0.63 cm OD
5 micron pore size
**LASER DIODE/CRYSTAL COOLING**
Quad-Evap., Diode 50 W/cm², Crystal 30 W/cm² (tested w/ laser)

**COMPACT LASER COOLING**
Dual-Evap., Two-Sided Heat Input, 50 W/cm², Mechanical Pump

**APPLICATIONS**
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**Multi-Evaporator Hybrid Two-Phase Loop Cooling System for Small Satellites**

1. Mechanical Pump
2. Filter
3. Calorimeter
4. Evaporator 1
5. Evaporator 2
6. Evap 1-2 Liquid Line
7. Vapor Line
8. Condenser
9. Reservoir
10. Sweepage Valve
11. Reservoir Chiller/Shunt
12. Chiller Path 2
13. Chiller Path 2
14. Chiller Path 1
15. Chiller Path 1
16. DP Transducer
17. Fill Tube
**APPLICATIONS**

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**HIGH POWER SPACECRAFT COOLING**
6-Evap., 10 kW, Mech./Capillary Pumping ... AFRL DUS&T

**RACK ELECTRONICS COOLING**
Navy SBIR with TA&T, 3-Evap. ME-HLHP, 300 W, Water

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**3 Evaporators 2m Above Condenser**

**Elevation Control Hinges/Flex Lines**

**3 Evaporators 1m Below Condenser**

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**Multi-Evaporator Hybrid Two-Phase Loop Cooling System for Small Satellites**

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INTERMITTENT-POWER INSTRUMENT COOLING

Dual-Cascaded Loop, 0-400 W 4-Evap. Instrument Side ME-HLHP, 100 W Avg. 1-Evap./2-Condenser Radiator Side HLHP

APPLICATIONS

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ADDITIONAL TECHNOLOGIES DEMONSTRATED ON THIS PROJECT
1. Integral Condenser/TSU
2. DTE-TSW Reservoir Shunt
3. Liquid Cooled Shield (LCS)
4. TEC Reservoir Cold-Biasing
5. Parallel or Series Plumbing

Multi-Evaporator Hybrid Two-Phase Loop Cooling System for Small Satellites
# SUMMARY OF ME-HLHP GROUND TESTING

<table>
<thead>
<tr>
<th>Loop Feature</th>
<th>1a</th>
<th>1b</th>
<th>2</th>
<th>3a</th>
<th>3b</th>
<th>4</th>
<th>5a</th>
<th>5b</th>
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<tr>
<td>Number of Evaporators</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>1</td>
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<tr>
<td>Wick OD (cm)</td>
<td>0.64</td>
<td>1.2</td>
<td>1.2</td>
<td>1.9</td>
<td>1.9</td>
<td>1.3</td>
<td>0.8</td>
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<tr>
<td>Saddle Width (cm)</td>
<td>2.5</td>
<td>n/a</td>
<td>1.0</td>
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<td>2.5</td>
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<tr>
<td>Evaporator Length (cm)</td>
<td>5</td>
<td>23</td>
<td>7.5</td>
<td>46</td>
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<td>2.5</td>
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<td>Wick Material</td>
<td>Teflon</td>
<td>Ti</td>
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<td>Ti</td>
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<tr>
<td>Max Loop Heat Load (W)</td>
<td>280</td>
<td>2000</td>
<td>600</td>
<td>880</td>
<td>2000</td>
<td>10000</td>
<td>300</td>
<td>400</td>
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<tr>
<td>Max Evap Heat Load (W)</td>
<td>100</td>
<td>500</td>
<td>150</td>
<td>440</td>
<td>1500</td>
<td>2800²</td>
<td>100</td>
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<tr>
<td>Max Heat Flux* (W/cm²)</td>
<td>30³WA</td>
<td>50³IS</td>
<td>30²IS</td>
<td>55²A</td>
<td>17³WA</td>
<td>32³WA</td>
<td>30³WA</td>
<td>14³WA</td>
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<tr>
<td>Transport Length (cm)</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
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<td>Adverse Elevation (m)</td>
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<td>Evaporator Body Material</td>
<td>Al</td>
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<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Cu</td>
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<td>Working Fluid</td>
<td>NH3</td>
<td>NH3</td>
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<td>Water</td>
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</table>

* Heat flux based on: saddle area (SA) at max evap. heat load, projected wick area (WA) at max evap. heat load (2 = 2-sided heating), or heat source (HS) heat flux.

**P = parallel, S = Series, TSW = thermal switch, TSU = thermal storage unit, TEC = thermoelectric cooler, LCS = liquid cooled shield, MP = mechanical pump.
CONCLUSION

- **OVERALL:** This briefing has described the development and testing of a multi-evaporator two-phase loop based cooling system for small satellite thermal control.

- **TECHNOLOGY BASIS:** Multi-evaporator hybrid loop heat pipe (ME-HLHP), a two-phase loop cooling system with CPL and LHP underpinnings, but with key advantages over each.

- **PRIMARY APPLICATION:** Cooling system designed/built/ground-tested as part of the NASA ST-8 Phase A study from Jan-Jun 2004. At that time, it was the first-ever ground test of a miniatuized ME-HLHP cooling system.

- **ADDITIONAL APPLICATIONS:** The design and successful ground testing of five subsequent ME-HLHP based cooling systems -- in the areas of laser, spacecraft, electronics, and instrument cooling -- were also described.

- **FLIGHT EXPERIMENT:** The ME-HLHP architecture has clearly been proven through extensive ground testing for a variety of applications ... to fully validate it for future smallsat missions, an ME-HLHP flight experiment is needed!

**NOTE:** Paper Was Originally a Backup for Session X, so its file name on the Proceedings CD is SSC07-X-11.pdf