Satellite Modular and Reconfigurable Thermal System (SMARTS)

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D. Bugby (ATK Space Systems)
W. Zimbeck (Technology Assessment & Transfer)
E. Kroliczek (B&K Engineering)
A. Williams (Air Force Research Laboratory)
**Introduction**

**SMARTS is an SBIR program funded by the AFRL Space Vehicles Directorate, Kirtland AFB, New Mexico**

- AFRL program manager: Mr. Andrew Williams
- Small business prime: Technology Assessment & Transfer (TA&T)
- Small business PI: Mr. Walter Zimbeck
- Program status: Phase II kickoff held on 7/25/08

**SMARTS is a new thermal management approach to help achieve the three ORS tiers, including the Tier 2 goal of "six day" satellite**

**Traditional approach -- cold-biasing plus heater power, involving judicious MLI/coating coverage and component placement on/near radiators -- not acceptable for RS:** Due to: (1) lengthy design/test process; (2) significant heater power; and (3) inadaptability.

**RS Need:** Thermal architecture that **intrinsically:** (a) minimizes design/test time and heater power; (b) enables quick assembly by eliminating the need for judicious MLI/coating coverage and component placement; and (c) assures on-orbit thermal control.
Background... traditional thermal design approach vs. RS needs

Traditional Spacecraft Thermal Design Approach

- Radiators sized for HOT CASE
- Heaters sized for COLD CASE
- Requires optimization of
  - component arrangement
  - MLI coverage
  - external coatings
- Limitations
  - lengthy design/test process
  - high survival heater power
  - limited design flexibility
  - not readily adaptable

RS Needs That Traditional Approach Cannot Provide

- **Thermal Adaptability** ... to meet the Tier 1 requirement for redeployment of existing assets in **minutes**
- **Rapid Deployability** ... to meet the Tier 2 requirement to build and deploy a new asset in **days**
- **Design Flexibility** ... to meet the Tier 3 requirement to incorporate new payloads in **months**
Background

... fundamental elements of the SMARTS approach

(b) Maximum External Insulation
(e.g., MLI blanket or alternative)

(c) Internal Heat Collection/Sharing System
(e.g., heat piped-embedded honeycomb panel)

(d) Heat Flow Modulating Capability
(e.g., fluid loop or thermal switch)

Radiator depicted as deployable, but does not have to be so, just external.

(a) Sufficient Radiator Area
(e.g., oversized external radiator)
Concept implementation of the SMARTS approach

Initial SMARTS Idea: "Equipment Rack" Satellite

Above IDEA based on SBIR that developed a cooling system for SERVERS on NAVY SUBS/SHIPS
Revised SMARTS Idea: Externally Paneled Satellite

Isothermalization Features

Insulation/Radiators/Variable Conductance
(Top View)

One option for integrating heat pipes, wiring, PCBs into panels
Concept

... implementations of the SMARTS approach

**Insulation / Radiator / Variable Conductance:** Single-Panel Module
Panel-to-Panel Coupling: Configuration / Conductance (Estimate)

Example of a Structure with Axial Longerons and Bolt-on Side Panels

- **Longeron Dimensions**: 0.5 cm x 5 cm x 100 cm
- **Longeron Conductance (6061 Al)**: $1.5 \times 0.5 \times 100 / 5 = 15 \text{ W/K}$
- **Joint Heat Transfer Coef.**: 0.5 W/cm² K
- **Joint Surface Area**: 100 cm x 2.5 cm
- **Joint Conductance**: $0.5 \times 100 \times 2.5 = 125 \text{ W/K}$
- **Panel-to-Panel Conductance**: $1 / (2/125 + 1/15) = 12 \text{ W/K}$
Modeling

... external heat input for 1 m cube in LEO

Properties Used: \( q_{SOLAR} = 1354 \, \text{W/m}^2 \), albedo = 0.35, \( q_{EARTH\,IR} = 225 \, \text{W/m}^2 \)

Cases Run:
1. \( \alpha = 1.0, \ \psi = 1.0 \), Beta 90° nadir pointing (w/ 45° yaw to increase projected area by 1.4):
2. \( \alpha = 1.0, \ \psi = 1.0 \), Beta 90° nadir pointing:
3. \( \alpha = 1.0, \ \psi = 1.0 \), Beta 0° nadir pointing:
4. \( \alpha = 0.2, \ \psi = 0.8 \), Beta 90° nadir pointing (w/ 45° yaw to increase projected area by 1.4):
5. \( \alpha = 0.2, \ \psi = 0.8 \), Beta 90° nadir pointing:
6. \( \alpha = 0.2, \ \psi = 0.8 \), Beta 0° nadir pointing:

CONCLUSION: External environment/surface coating effects can be modeled by applying a heat flux of 100-400 W/m² to the cube exterior and multiplying that flux by the total cube area \( A_S \) and a panel-dependent heat load factor \( f_{Q_E} \). The Beta = 0° orbit has a time-varying heat load factor as shown. The Beta = 90° orbit has a steady, highly non-uniform heat load factor:

Cold:
\( q_1 = 100 \, \text{W/m}^2 \)

Nominal (white):
\( q_2 = 175 \, \text{W/m}^2 \)

Hot (white):
\( q_3 = 250 \, \text{W/m}^2 \)

Hot (black):
\( q_4 = 400 \, \text{W/m}^2 \)

Approach to Calculate Absorbed Power:
\( Q_E, (t) = A_S \cdot q_{Q_E}, (t) \)  
\( i = \text{cube face}, \ j = \text{environment case}, \ A_S = \text{total surface area} \)

\begin{align*}
\text{Beta 0° (Case 6) Normalized Heat Load on Each Face (f_{Q_E})} \\
(1.0) &= \frac{f_{Q_{E1}} + f_{Q_{E2}} + f_{Q_{E3}} + f_{Q_{E4}} + f_{Q_{E5}} + f_{Q_{E6}}}{dU/C} \quad f_{Q_E} = Q_E / 650 \, \text{W} \\
\text{Time (sec)} & \quad f_{Q_{E1}} \quad f_{Q_{E2}} \quad f_{Q_{E3}} \quad f_{Q_{E4}} \quad f_{Q_{E5}} \quad f_{Q_{E6}} \\
3.00 \times 10^{-5} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.14 \quad 0.14 \quad 0.14 \\
4.48 \times 10^{-5} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.13 \quad 0.13 \quad 0.13 \\
8.51 \times 10^{-5} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.12 \quad 0.12 \quad 0.12 \\
1.52 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.11 \quad 0.11 \quad 0.11 \\
1.52 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.10 \quad 0.10 \quad 0.10 \\
1.52 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.09 \quad 0.09 \quad 0.09 \\
2.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.08 \quad 0.08 \quad 0.08 \\
2.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.07 \quad 0.07 \quad 0.07 \\
3.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.06 \quad 0.06 \quad 0.06 \\
3.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.05 \quad 0.05 \quad 0.05 \\
3.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.04 \quad 0.04 \quad 0.04 \\
3.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.03 \quad 0.03 \quad 0.03 \\
3.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.02 \quad 0.02 \quad 0.02 \\
4.48 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.01 \quad 0.01 \quad 0.01 \\
4.48 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.01 \quad 0.01 \quad 0.01 \\
5.00 \times 10^{-4} & \quad 0.30 \quad 0.30 \quad 0.30 \quad 0.00 \quad 0.00 \quad 0.00 \\
\end{align*}
Modeling

... simplified model of externally paneled satellite

Notes: The external radiator is shown linked to panel 3 (and 4). The radiator could be linked to any other panel, or single/multiple radiator(s) could be linked to multiple panels. Also, value of variable conductance link \( G_{VAR} \) is based on a single 20" (length) evaporator with a 1" wide mounting flange and interface heat transfer coefficient of 2.5 W/K-in\(^2\) (50 W/K) in series with typical evaporator conductance value of 12 W/K (two-phase loop vapor conductance assumed infinite and condenser conductance assumed much larger than the evaporator conductance).
### Results

... parameter sensitivity study results

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**SMARTS Approach vs. Traditional Approach (Non-SMARTS)**

Comparison of Prospective "Universal" ORS Thermal Designs ... Thermal Design Goal: $263 \, K < T < 313 \, K$

<table>
<thead>
<tr>
<th>CASE</th>
<th>HOT</th>
<th>COLD (No heaters)</th>
<th>COLD (Surv. heaters)</th>
<th>NOMINAL (400 kg)</th>
<th>NOMINAL (40 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta = 30 , W$, $\alpha = 25 , W/m^2$</td>
<td>$\beta = 30 , W$, $\alpha = 100 , W/m^2$</td>
<td>$\beta = 30 , W$, $\alpha = 100 , W/m^2$</td>
<td>$\beta = 200 , W$, $\alpha = 175 , W/m^2$</td>
<td>$\beta = 200 , W$, $\alpha = 175 , W/m^2$</td>
</tr>
<tr>
<td>SMARTS</td>
<td>$\Delta T_{\text{max}}$, $T_{\text{min}}$, $\Delta T^*$</td>
<td>$\Delta T_{\text{max}}$, $T_{\text{min}}$, $\Delta T^*$</td>
<td>$\Delta T_{\text{max}}$, $T_{\text{min}}$, $\Delta T^*$</td>
<td>$\Delta T_{\text{max}}$, $T_{\text{min}}$, $\Delta T^*$</td>
<td>$\Delta T_{\text{max}}$, $T_{\text{min}}$, $\Delta T^*$</td>
</tr>
<tr>
<td>SMARTS</td>
<td>313, 290, 24</td>
<td>263, 263, 0.4</td>
<td>263, 263, 0.4</td>
<td>291, 274, 16</td>
<td>295, 269, 27</td>
</tr>
</tbody>
</table>

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Satellite Modular and Reconfigurable Thermal System (SMARTS)
### Results

...additional modeling of intra-satellite isothermality

**Heat Source**

10 cm x 10 cm x 1 W/cm² = 100 W

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**LHP Evaporator Interface**

Boundary Node at 273 K

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<table>
<thead>
<tr>
<th>Case</th>
<th>Panel Construction</th>
<th>Heat Pipe Configuration on Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Al isogrid</td>
<td>no heat pipes</td>
</tr>
<tr>
<td>1b</td>
<td>Al-APG isogrid</td>
<td>no heat pipes</td>
</tr>
<tr>
<td>2a</td>
<td>Al isogrid</td>
<td>1 circumferential thermal bus heat pipe</td>
</tr>
<tr>
<td>2b</td>
<td>Al-APG isogrid</td>
<td>1 circumferential thermal bus heat pipe</td>
</tr>
<tr>
<td>3a</td>
<td>Al isogrid</td>
<td>1 circumferential thermal bus heat pipe, 6 spreader heat pipes</td>
</tr>
<tr>
<td>3b</td>
<td>Al-APG isogrid</td>
<td>1 circumferential thermal bus heat pipe, 6 spreader heat pipes</td>
</tr>
<tr>
<td>4a</td>
<td>Al isogrid</td>
<td>6 spreader heat pipes</td>
</tr>
<tr>
<td>4b</td>
<td>Al-APG isogrid</td>
<td>6 spreader heat pipes</td>
</tr>
</tbody>
</table>

* 1C = 1 circumferential HP per panel
  6S = 6 spreader HP per panel
Demonstrate SMARTS intra-panel and inter-panel isothermalization and variable conductance to external sink using existing water heat pipes/loop.
Phase I testing de-scoped to dual heat pipe panel simulation (two-phase water loop eliminated from test bed).

**Steady-State Results (Htrs. @ 1 W/cm²)**

\[ G_{pp} = 20 \text{ W/K}, \ A = 50 \text{ cm}^2, \ h = 0.4 \text{ W/cm}^2 \text{ K} \]

<table>
<thead>
<tr>
<th>TC Position</th>
<th>Plate 1, 1W/cm²</th>
<th>Plate 2, 1W/cm²</th>
<th>Plate 1, 0W/cm²</th>
<th>Plate 2, 0W/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1/#8</td>
<td>23.22</td>
<td>22.81</td>
<td>20.59</td>
<td>20.54</td>
</tr>
<tr>
<td>#2/#9</td>
<td>25.61</td>
<td>22.57</td>
<td>20.63</td>
<td>20.46</td>
</tr>
<tr>
<td>#3/#10</td>
<td>25.24</td>
<td>22.47</td>
<td>21.09</td>
<td>20.58</td>
</tr>
<tr>
<td>#4/#11</td>
<td>29.68</td>
<td>21.51</td>
<td>21.21</td>
<td>20.48</td>
</tr>
<tr>
<td>#5/#12</td>
<td>33.20</td>
<td>22.43</td>
<td>20.88</td>
<td>20.77</td>
</tr>
<tr>
<td>#6/#13</td>
<td>24.96</td>
<td>22.11</td>
<td>20.88</td>
<td>20.59</td>
</tr>
<tr>
<td>#7/#14</td>
<td>26.17</td>
<td>22.65</td>
<td>20.95</td>
<td>20.60</td>
</tr>
</tbody>
</table>

Chiller set temperature was 20°C

*Only heaters A and B were powered - 2 x 5.3 W = 10.6 W*
**Plans ... for SMARTS Phase II**

**Externally-Paneled Satellite Variable Conductance Test Bed**

- **Isogrid Panel 1** (Top Panel Simulator)
  - Heater Block
  - Insulation (e.g., MLI, Aerogel, etc.)
- **Isogrid Panel 2** (Side Panel Simulator)
  - Heater Block
  - Circumferential Thermal Bus Heat Pipe
- **Isogrid Panel 3** (Bottom Panel Simulator)
  - Heater Block
  - Condenser/Radiator
  - Aluminum Blocks with Kapton Heaters (simulates components)
  - Bolted Joints
  - TEC
  - Thermal Strap
  - Spread Heat Pipes in Panel 2 Only
  - LHP with TEC Thermal Control

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Conclusions

SMARTS is a new thermal management approach to help achieve the three ORS tiers, including the Tier 2 goal of developing a "six day" satellite.

SMARTS thermal design principles – (1) modestly oversized radiators, (2) maximum external insulation, (3) internal isothermalization, and (4) variable conductance link to space – are implemented as follows:

- **inter-panel heat transfer**
  - each panel has a single circumferential "thermal bus" heat pipe
  - panels bolted together along seams (should provide sufficient conductance)
  - one or more heat removal links to variable conductance subsystem

- **intra-panel heat transfer**
  - several panel-embedded "spreader" heat pipes
  - enhanced thermal conductivity material such as Al-APG

- **insulation, variable conductance, and radiator area**
  - combinations of body-mounted or deployable radiator modules.

SMARTS Phase I has analytically demonstrated the superiority of the approach (for RS) over the traditional satellite thermal design approach.

SMARTS Phase II will provide laboratory test verification of the above.

SMARTS thermal design principles will, in the very near term, be incorporated into future ATK small satellites.