Satellite Modular and Reconfigurable Thermal System (SMARTS)

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Introduction

... overview of the SMARTS SBIR program

- ***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*

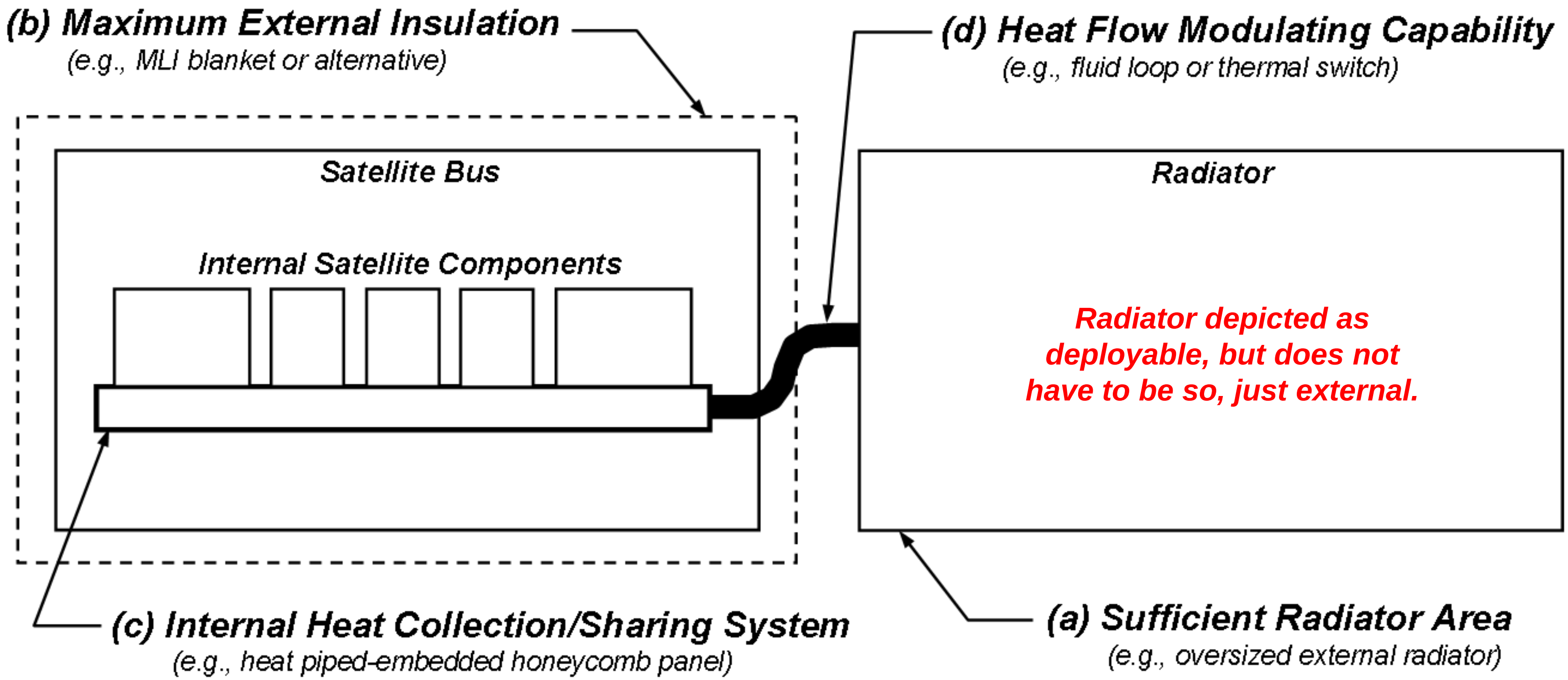
RS Needs That Traditional Approach Cannot Provide

- ***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***

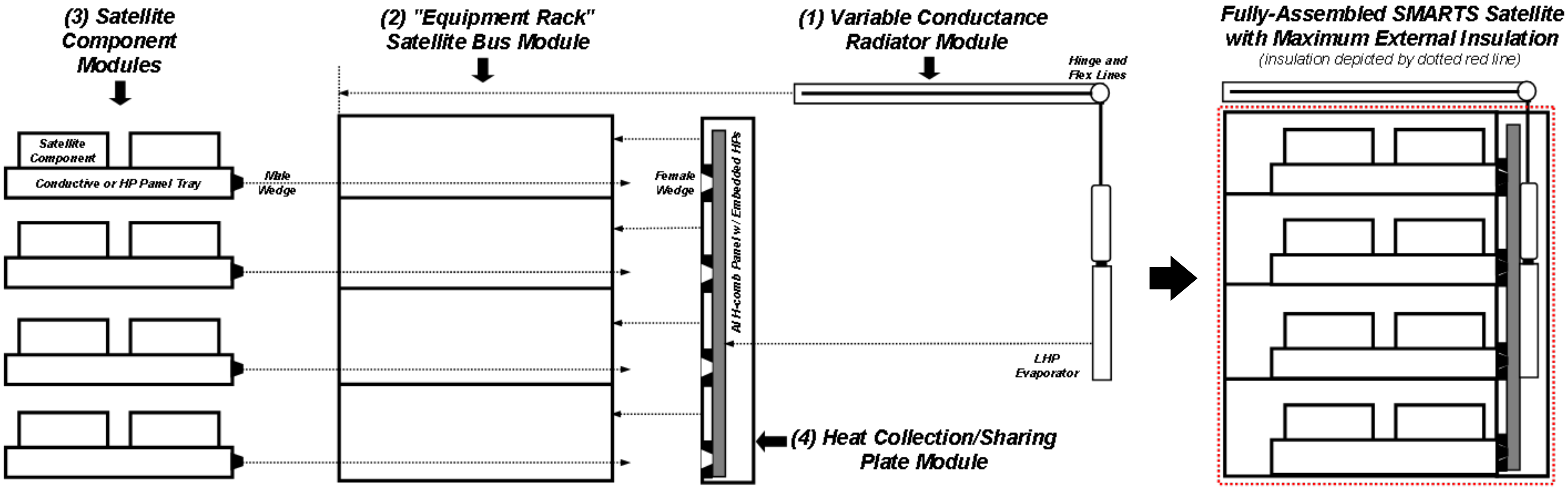
Background ... *fundamental elements of the SMARTS approach*



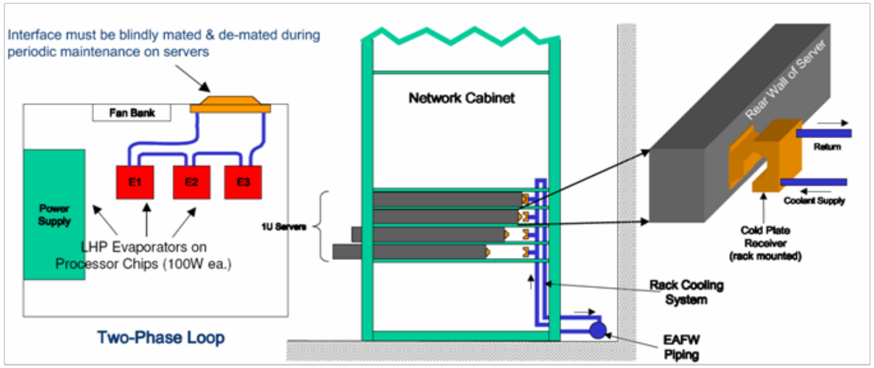
Radiator depicted as deployable, but does not have to be so, just external.

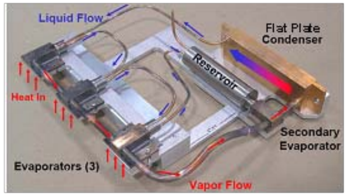
Concept … *implementations of the SMARTS approach*

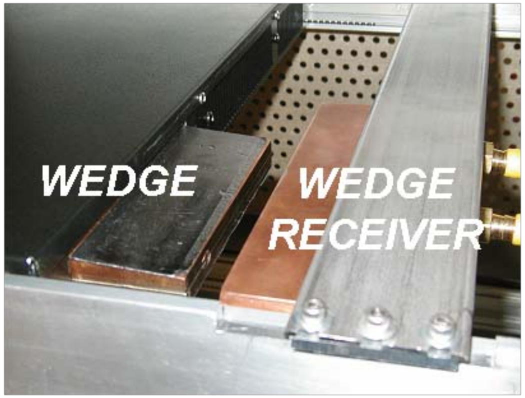
Initial SMARTS Idea: *"Equipment Rack" Satellite*



Above IDEA based on SBIR that developed a cooling system for SERVERS on NAVY SUBS/SHIPS



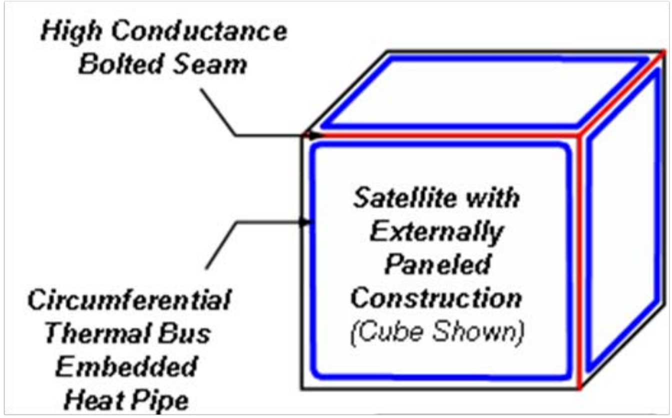


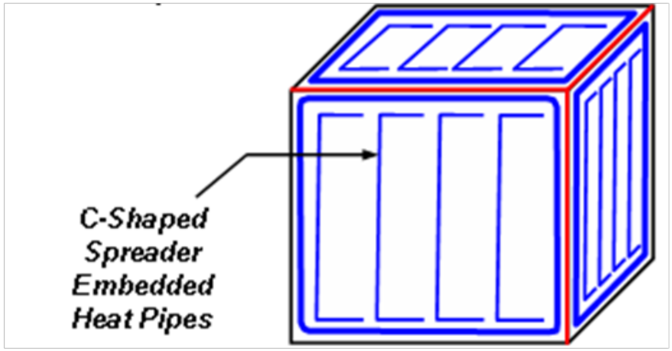


Concept ... *implementations of the SMARTS approach*

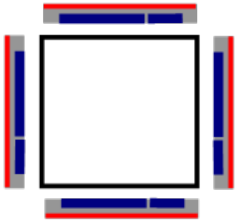
Revised SMARTS Idea: *Externally Paneled Satellite*

Isothermalization Features

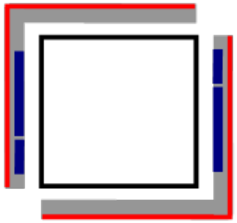




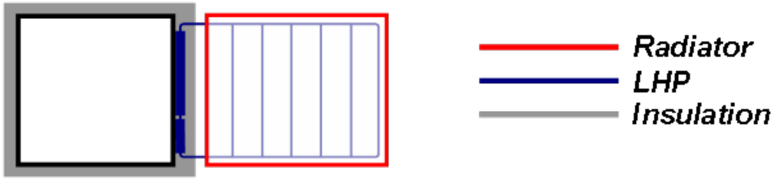
Insulation/Radiators/Variable Conductance (Top View)



Single-Side Modules with LHP/Insulation/Radiator

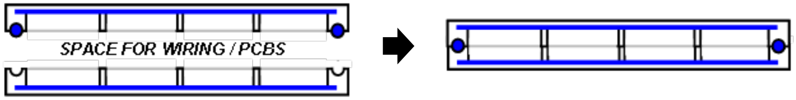


Dual-Side Modules with LHP/Insulation/Radiator



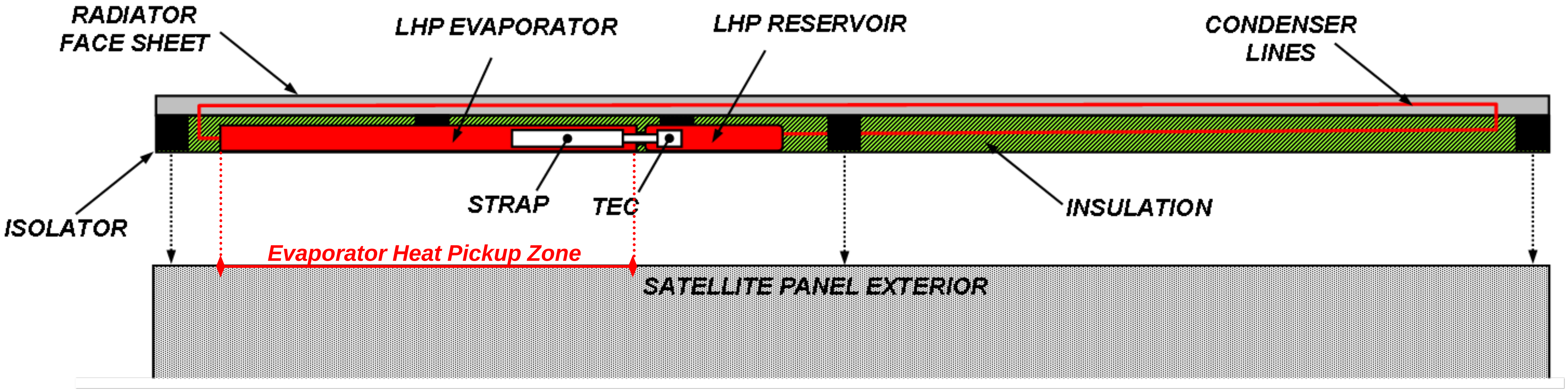
Deployable Module with LHP/Insulation/Radiator

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

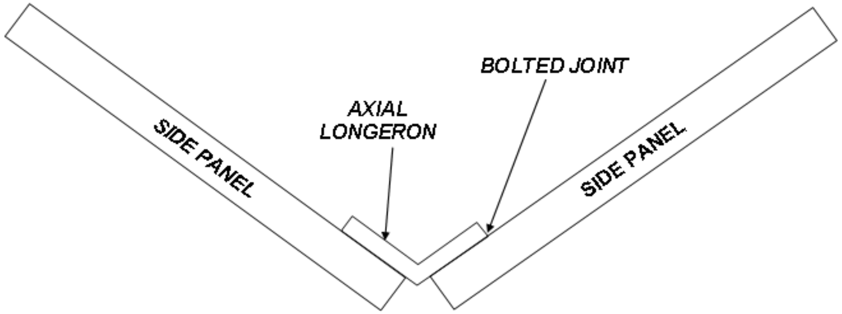


Concept ... *implementations of the SMARTS approach*

Insulation / Radiator / Variable Conductance: *Single-Panel Module*

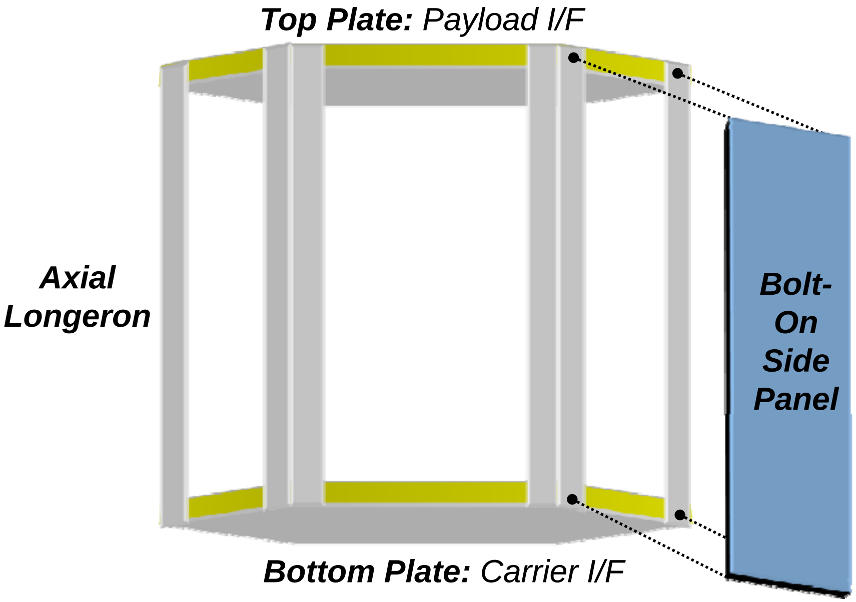


Panel-to-Panel Coupling: *Configuration / Conductance (Estimate)*



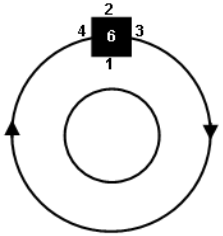
Longeron Dimensions = 0.5 cm x 5 cm x 100 cm
Longeron Conductance (6061 Al) = 1.5*0.5*100/5 = **15 W/K**
Joint Heat Transfer Coef. = 0.5 W/cm^2 K
Joint Surface Area = 100 cm x 2.5 cm
Joint Conductance = 0.5*100*2.5 = **125 W/K**
Panel-to-Panel Conductance = 1/(2/125 + 1/15) = 12 W/K

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

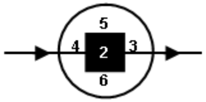


Modeling ... *external heat input for 1 m cube in LEO*

1 - NADIR
2 - ZENITH
3 - VELOCITY
4 - ANTI-VELOCITY
5 - ANTI-SUN (FOR BETA90)
6 - SUN POINTING (FOR BETA90)



Beta = 90°



Beta = 0°

Black	*White*
1 m cube	*1 m cube*
$\alpha = 1.0$	*$\alpha = 0.2$*
$\varepsilon = 1.0$	*$\varepsilon = 0.8$*
■	□

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

Cases Run:

(1) α=1.0, ε=1.0, Beta 90° nadir pointing (w/ 45° yaw to increase projected area by 1.4):	*total energy absorbed 2459 W ~ 410 W/m^2*
(2) α=1.0, ε=1.0, Beta 90° nadir pointing:	*total energy absorbed 1894 W ~ 315 W/m^2*
(3) α=1.0, ε=1.0, Beta 0° nadir pointing:	*total energy absorbed 1840 W ~ 305 W/m^2*
(4) α=0.2, ε=0.8, Beta 90° nadir pointing (w/ 45° yaw to increase projected area by 1.4):	*total energy absorbed 802 W ~ 135 W/m^2*
(5) α=0.2, ε=0.8, Beta 90° nadir pointing:	*total energy absorbed 690 W ~ 115 W/m^2*
(6) α=0.2, ε=0.8, Beta 0° nadir pointing:	*total energy absorbed 680 W ~ 115 W/m^2*

CONCLUSION: *External environment/surface coating effects can be modeled by applying a heat flux of 100-400 W/m^2 to the cube exterior and multiplying that flux by the total cube area (A_S) and a panel-dependent heat load factor (f_{QEi}). 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 W/m^2*
Nominal (white):	*q_2 = 175 W/m^2*
Hot (white):	*q_3 = 250 W/m^2*
Hot (black):	*q_4 = 400 W/m^2*

Approach to Calculate Absorbed Power: *$QE_i\,(t) = A_S\, q_j\, f_{QEi}\,(t)$*
(i = cube face, j = environment case, A_S = total surface area)

Beta 0° (Case 6) Normalized Heat Load on Each Face (f_{QEi})

$(1.0 = \int(f_{QE,1} + f_{QE,2} + f_{QE,3} + f_{QE,4} + f_{QE,5} + f_{QE,6})d(t/\tau)$ … $f_{QEi} = QE_i / 680$ W)

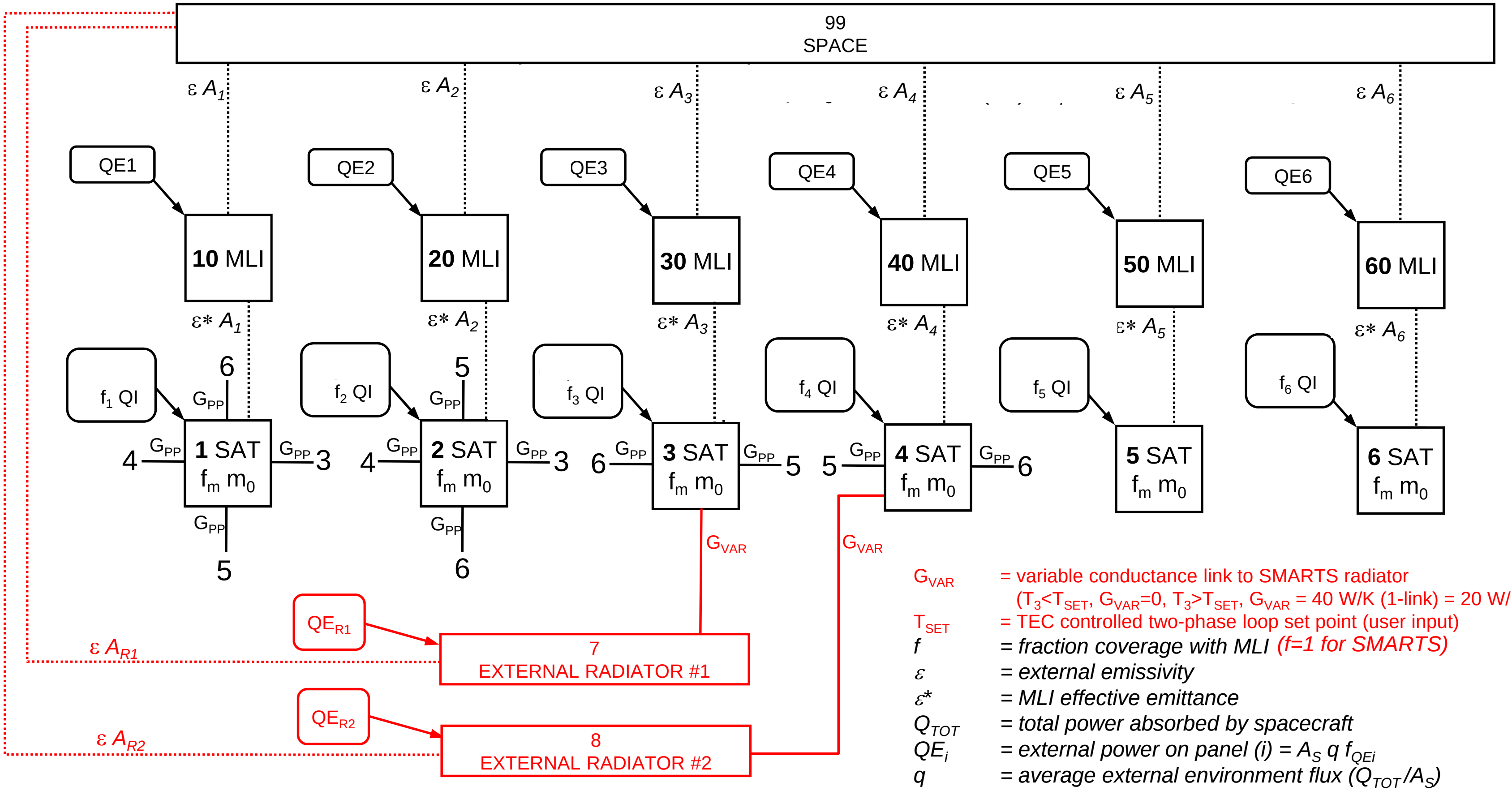
Time (sec)	f_{QE1}	f_{QE2}	f_{QE3}	f_{QE4}	f_{QE5}	f_{QE6}
0.0000E+00	0.38	0.40	0.14	0.14	0.14	0.14
4.4098E+02	0.36	0.34	0.13	0.33	0.13	0.13
8.8196E+02	0.31	0.20	0.11	0.46	0.12	0.12
1.3229E+03	0.25	0.00	0.09	0.49	0.09	0.09
1.5219E+03	0.34	0.00	0.09	0.48	0.09	0.09
1.5250E+03	0.25	0.00	0.09	0.09	0.09	0.09
1.7639E+03	0.25	0.00	0.09	0.09	0.09	0.09
2.2049E+03	0.25	0.00	0.09	0.09	0.09	0.09
2.6459E+03	0.25	0.00	0.09	0.09	0.09	0.09
3.0868E+03	0.25	0.00	0.09	0.09	0.09	0.09
3.5278E+03	0.25	0.00	0.09	0.09	0.09	0.09
3.7667E+03	0.25	0.00	0.09	0.09	0.09	0.09
3.7699E+03	0.34	0.00	0.48	0.09	0.09	0.09
3.9688E+03	0.25	0.00	0.49	0.09	0.09	0.09
4.4098E+03	0.31	0.20	0.46	0.11	0.12	0.12
4.8508E+03	0.36	0.34	0.33	0.13	0.14	0.13
5.2917E+03	0.38	0.40	0.14	0.14	0.14	0.14

Beta 90° (Case 5) Normalized Heat Load on Each Face (f_{QEi})

f_{QE1}	f_{QE2}	f_{QE3}	f_{QE4}	f_{QE5}	f_{QE6}
0.244	0.000	0.091	0.090	0.090	0.484

Modeling

... simplified model of externally paneled satellite



G_{VAR} = variable conductance link to SMARTS radiator
(T_3<T_{SET}, G_{VAR}=0, T_3>T_{SET}, G_{VAR} = 40 W/K (1-link) = 20 W/K 2-links

T_{SET} = TEC controlled two-phase loop set point (user input)

f = *fraction coverage with MLI* *(f=1 for SMARTS)*

ε = *external emissivity*

*ε** = *MLI effective emittance*

Q_{TOT} = *total power absorbed by spacecraft*

QE_i = *external power on panel (i) =* $A_S\ q\ f_{QEi}$

q = *average external environment flux* (Q_{TOT}/A_S)

QI = *total internal power*

f_i = *fraction of QI on panel (i)*

f_{QEi} = *fraction of total external power on panel (i) ...* QE_i/Q_{TOT}

G_{PP} = *panel-to-panel conductance (all* $G_{ij} = G_{PP}$*)*

f_m = *fraction of total mass* (m_0) *on panel (i)*

A_S = *total satellite external area*

A_i = *panel area =* $A_S/6$

A_{RAD} = *radiator area*

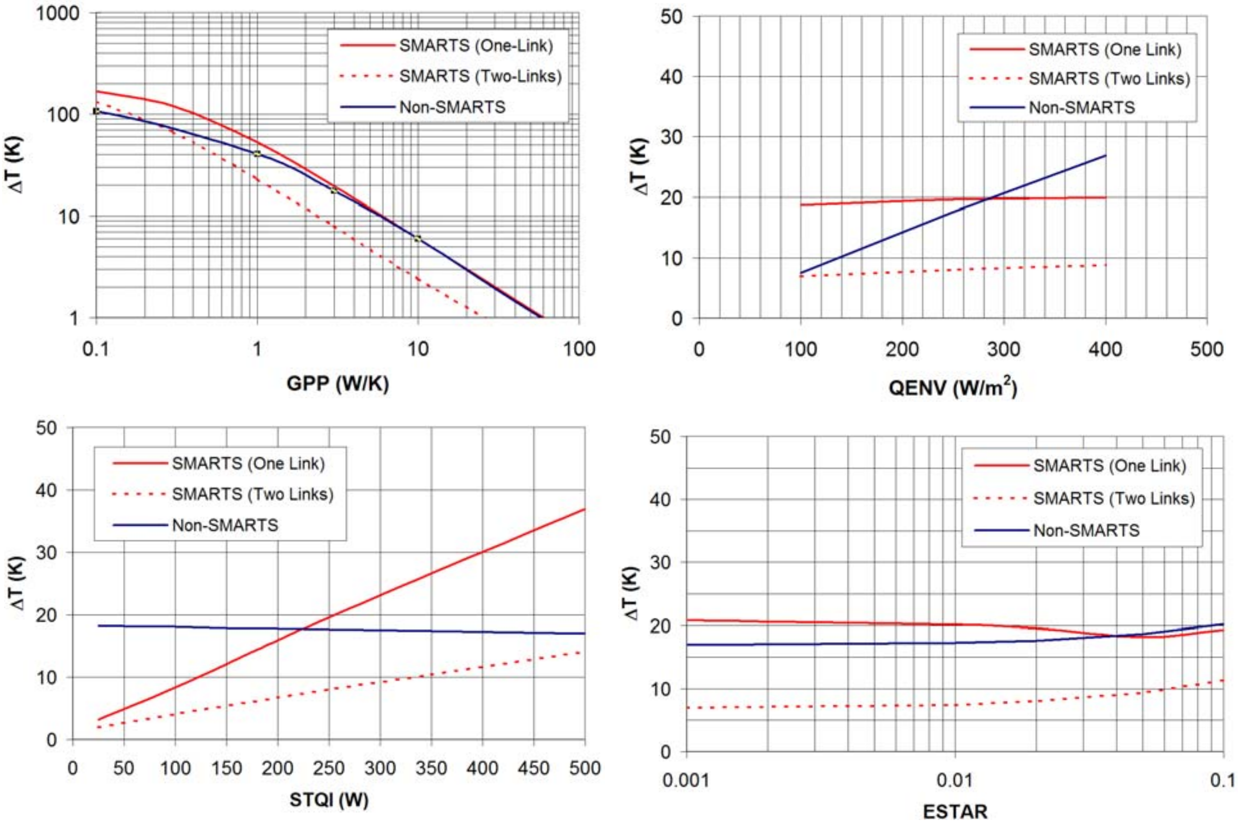
QE_R = *external power on radiator =* $(A_{RAD}/A_3)\ A_S\ q\ f_{QE3}$

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-in (240 W/K) yielding about 40 W/K (two-phase loop vapor conductance assumed infinite and condenser conductance assumed much larger than the evaporator conductance).*

Results

... parameter sensitivity study results

SMARTS Approach vs. Traditional Approach (Non-SMARTS)



SMARTS Basline Inputs

TINIT	300	INITIAL TEMPERATURE (K)
TSPAC	3	SPACE SINK TEMPERATURE (K)
STMS	400	SATELLITE TOTAL MASS (KG)
STQI	250	SATELLITE TOTAL POWER (W)
QENV	250	ENVIRONMENT FLUX (W/M2)
FMAS	0.167	FRACTION OF STMS IN EACH PANEL
FQI	0.167	FRACTION OF STQI IN EACH PANEL
CPAL	900	HEAT CAPACITY OF PANEL MATERIAL (J/KG K)
GPP	3.00	CONDUCTANCE PANEL-TO-PANEL (W/K)
FMLI	0.999999	FRACTION COVERAGE WITH MLI
EMIS	0.80	EMISSIVITY OF SPACE FACING SURFACES
ESTAR	0.02	MLI EFFECTIVE EMITTANCE
SAREA	6	SATELLITE EXTERNAL SURFACE AREA (M2)
NBETA	90	NBETA = 90 (BETA=90), OTHERWISE BETA=0
NORBT	100	NUMBER OF ORBITS IN SIMULATION
ARDT	2	RADIATOR AREA (M2)
RHOR	5	RADIATOR AREAL DENSITY (KG/M2)
TSET	263	SATELLITE SET POINT (K)
GVAR	40	VARIABLE CONDUCTANCE LINK TO RAD. (W/K)

Non-SMARTS Baseline Inputs

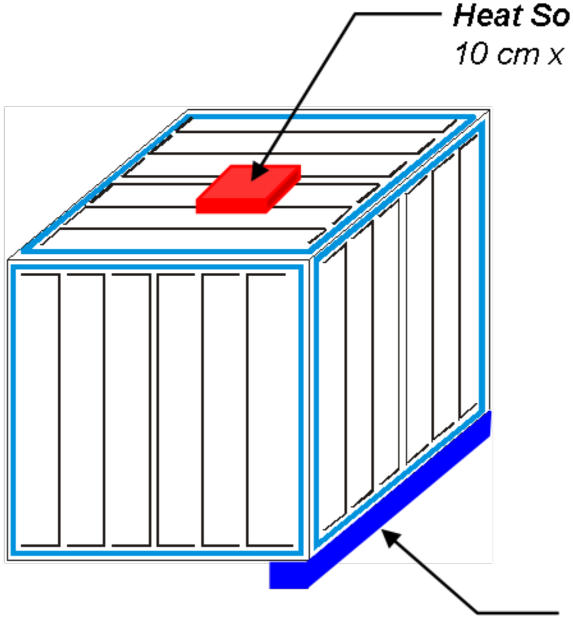
TINIT	300	INITIAL TEMPERATURE (K)
TSPAC	3	SPACE SINK TEMPERATURE (K)
STMS	400	SATELLITE TOTAL MASS (KG)
STQI	250	SATELLITE TOTAL POWER (W)
QENV	250	ENVIRONMENT FLUX (W/M2)
FMAS	0.167	FRACTION OF STMS IN EACH PANEL
FQI	0.167	FRACTION OF STQI IN EACH PANEL
CPAL	900	HEAT CAPACITY OF PANEL MATERIAL (J/KG K)
GPP	3.00	CONDUCTANCE PANEL-TO-PANEL (W/K)
FMLI	0.67	FRACTION COVERAGE WITH MLI
EMIS	0.80	EMISSIVITY OF SPACE FACING SURFACES
ESTAR	0.02	MLI EFFECTIVE EMITTANCE
SAREA	6	SATELLITE EXTERNAL SURFACE AREA (M2)
NBETA	90	NBETA = 90 (BETA=90), OTHERWISE BETA=0
NORBT	100	NUMBER OF ORBITS IN SIMULATION

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

CASE	HOT			COLD (No heaters)			COLD (Surv. heaters)				NOMINAL (400 kg)			NOMINAL (40 kg)		
	β90, 500 W, q_{ENV} 250 W/m^2			β90, 25 W, q_{ENV} 100 W/m^2			β90, 25 W, q_{ENV} 100 W/m^2				βZero, 250 W, q_{ENV} 175 W/m^2			βZero, 250 W, q_{ENV} 175 W/m^2		
	T_{MAX}	T_{MIN}	ΔT*	T_{MAX}	T_{MIN}	ΔT*	T_{MAX}	T_{MIN}	ΔT*	Q_{SURV}	T_{MAX}	T_{MIN}	ΔT*	T_{MAX}	T_{MIN}	ΔT*
SMARTS	313	290	24	263	263	0.4	263	263	0.4	0	291	274	16	295	268	27
n-SMARTS	314	291	23	227	216	11	272	262	10	575	271	262	9	283	253	30

Results

... additional modeling of intra-satellite isothermality



Heat Source

10 cm x 10 cm x 1 W/cm² = 100 W

LHP Evaporator Interface

Boundary Node at 273 K

Case	Panel	Heat Pipes*	ΔT (K)
1a	Al	None	162
1b	Al-APG	None	43
2a	Al	1C	88
2b	Al-APG	1C	25
3a	Al	1C, 6S	16
3b	Al-APG	1C, 6S	10
4a	Al	6S	64
4b	Al-APG	6S	22

* 1C = 1 circumferential HP per panel

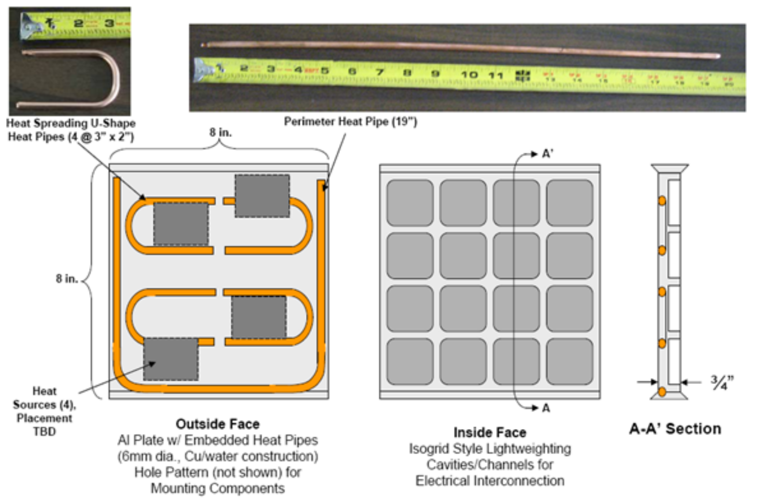
6S = 6 spreader HP per panel

Case	Panel Construction	Heat Pipe Configuration on Panel
1a	Al isogrid	no heat pipes
1b	Al-APG isogrid	no heat pipes
2a	Al isogrid	1 circumferential thermal bus heat pipe
2b	Al-APG isogrid	1 circumferential thermal bus heat pipe
3a	Al isogrid	1 circumferential thermal bus heat pipe, 6 spreader heat pipes
3b	Al-APG isogrid	1 circumferential thermal bus heat pipe, 6 spreader heat pipes
4a	Al isogrid	6 spreader heat pipes
4b	Al-APG isogrid	6 spreader heat pipes

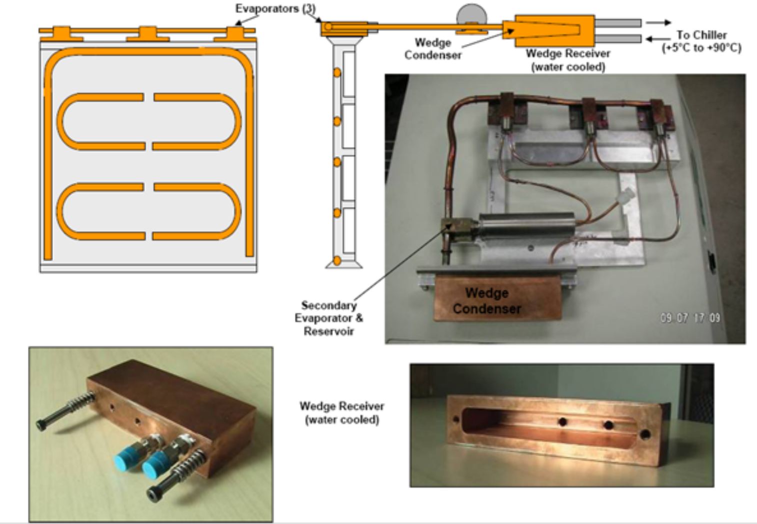
Testing

... SMARTS Phase I testing -- initial plan

Intra-Panel Heat Spreading

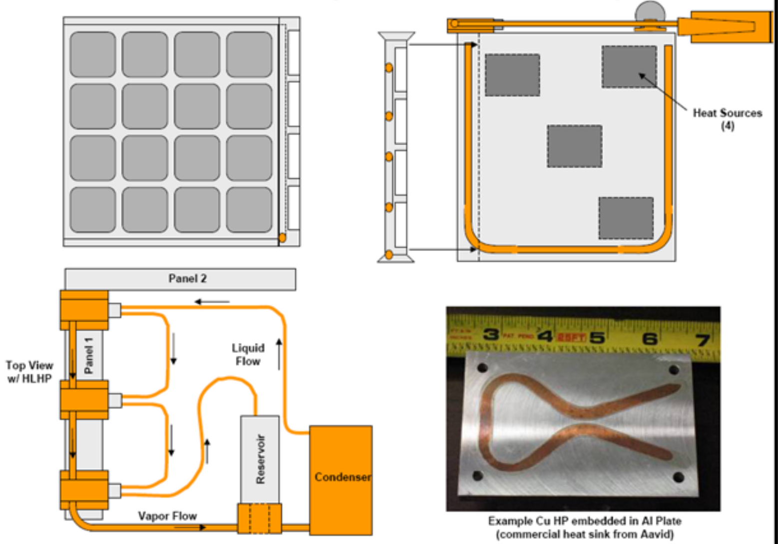


Three Evaporator Hybrid Loop Heat Pipe (Variable Conductance link to Radiator)



Demonstrate SMARTS intra-panel and inter-panel isothermalization and variable conductance to external sink using existing water heat pipes/loop.

Inter-Panel Heat Sharing (2nd Panel w/ Perimeter HP only)

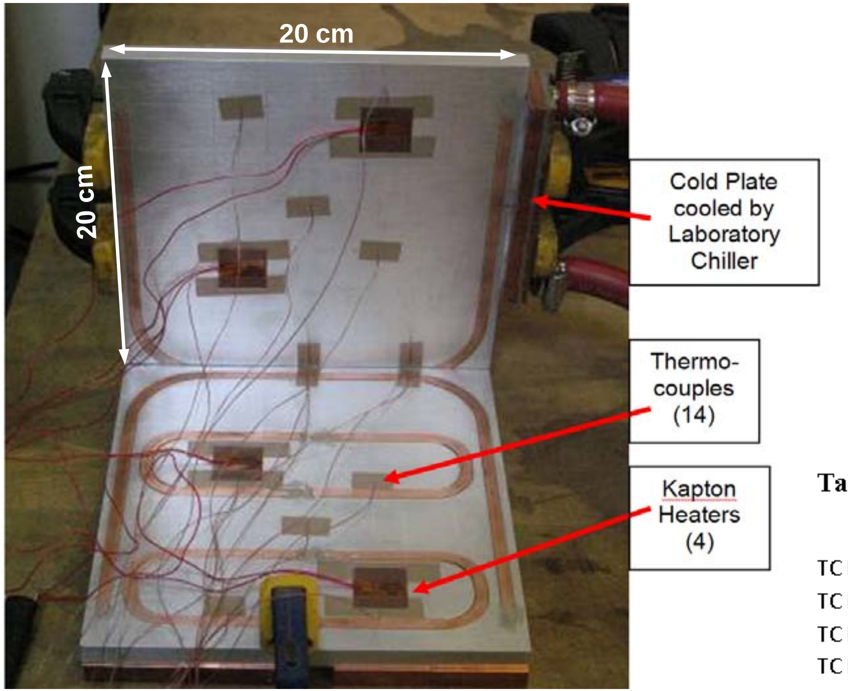


Testing ... SMARTS Phase I testing -- actual test unit

Phase I testing de-scoped to dual heat pipe panel simulation (two-phase water loop eliminated from test bed).

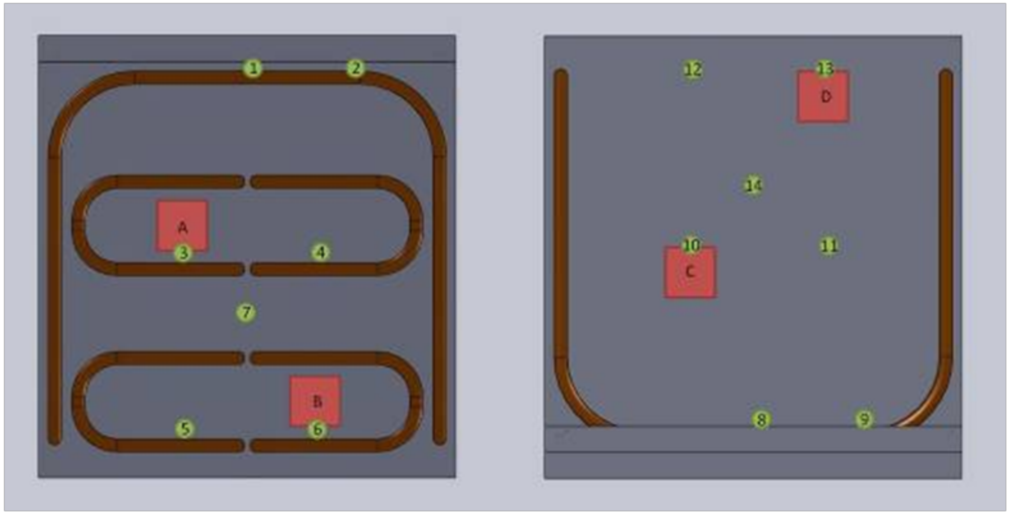
Steady-State Results (Htrs. @ 1 W/cm^2)

G_{PP} = 20 W/K, A = 50 cm^2, h = 0.4 W/cm^2 K



20 cm x 20 cm Al Isogrid Panels

(Lightweighting on Reverse Side Not Shown)



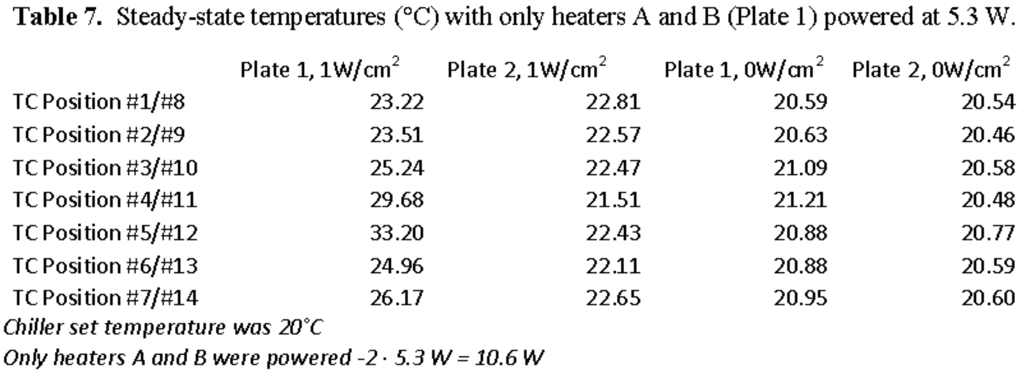


Table 7. Steady-state temperatures (°C) with only heaters A and B (Plate 1) powered at 5.3 W.

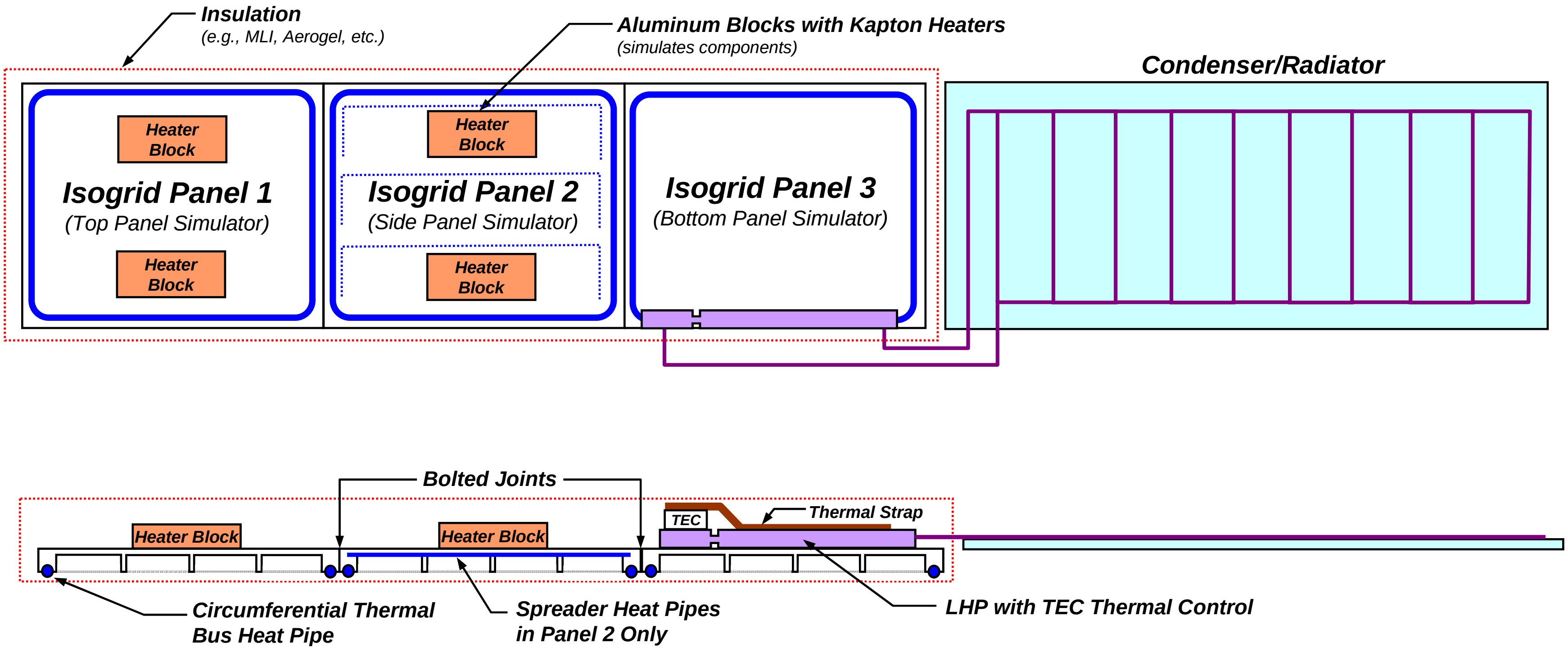
	Plate 1, 1W/cm^2	Plate 2, 1W/cm^2	Plate 1, 0W/cm^2	Plate 2, 0W/cm^2
TC Position #1/#8	23.22	22.81	20.59	20.54
TC Position #2/#9	23.51	22.57	20.63	20.46
TC Position #3/#10	25.24	22.47	21.09	20.58
TC Position #4/#11	29.68	21.51	21.21	20.48
TC Position #5/#12	33.20	22.43	20.88	20.77
TC Position #6/#13	24.96	22.11	20.88	20.59
TC Position #7/#14	26.17	22.65	20.95	20.60

Chiller set temperature was 20°C

Only heaters A and B were powered -2 · 5.3 W = 10.6 W

... for SMARTS Phase II

Externally-Paneled Satellite Variable Conductance Test Bed



Conclusions ... *viability of SMARTS for RS thermal control*

- ***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***