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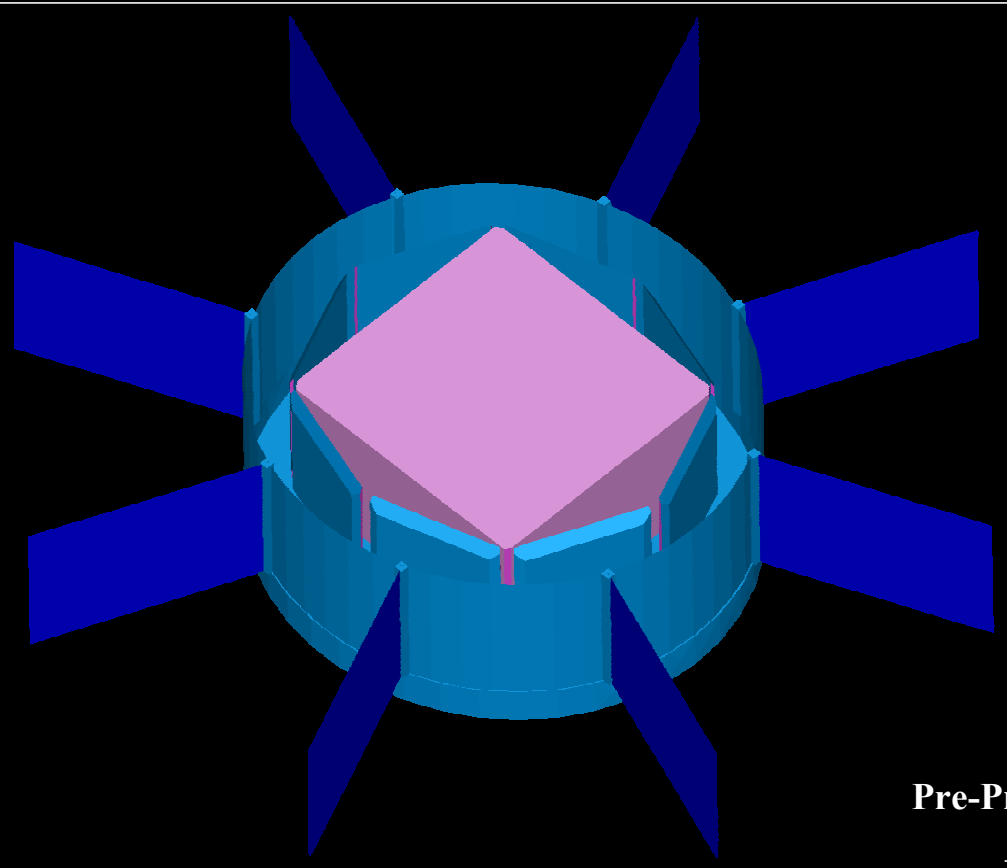
Validation Database Based Thermal Analysis of an Advanced RPS Concept



by
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Presented by Nickolas Emis at the
Space Technology & Applications International Forum (STAIF-2006), Albuquerque, NM, USA
February 16, 2005

Outline

- Acknowledgments
- Introduction
- Methodology and Assumptions
- Thermal Analysis Approach
- Results and Discussion
- Conclusions/Future Work

Acknowledgments

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- Special thanks to:
  - Dr. James F. Jordan: manager for Office-610, Mars Program Office, who funded this numerical study in connection with the Multi-Lander Network concept and mid-rover mission concept studies
  - Dr. Brian Woods: professor at Oregon State University, where the testing was performed, generating the validation database used in this thermal analysis
  - Dr. Samad Hayati: program manager for Mars Technology at JPL, who funded the testing at OSU

Background

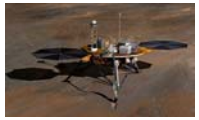
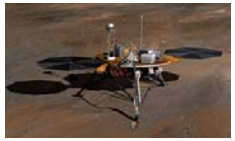
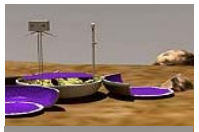
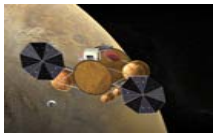
- Small-RPS power sources could enable smaller missions including and in addition to the ones identified in NASA's Mars and Solar System Exploration roadmaps

- Previous work under the Mars Program Office has identified several candidate missions, that considered small-RPSs as power trade options:
  - Mars Multi-Lander Network concept: integrated with a single GPHS module based unit (STAIF 2005, AGU 2005)
  - MER class Mid-Rovers concept: using 2 to 4 single GPHS module based small-RPS design concepts (STAIF 2005)

- Thermal testing of a small-RPS thermal mockup test unit was performed at Oregon State University to provide validation data for JPL's thermal models. The test were performed under atmospheric conditions (with simulated thermocouples and an electrically heated module). The present study uses this validation database.

Draft Mars Exploration Architecture (Approval Pending)

2009 - 2024

2009	2011 / 2013	2016	2018	2020	2022	2024
Mars Science Laboratory (MSL) Design Concept	Scout or Mars Science Orbiter with Telecom OR 	Midrovers or Astrobiology Field Laboratory (AFL) OR	Scout 	Planetary Evolution And Meteorology Network 	Mars Sample Return (MSR) Orbiter and Return Capsule 	Mars Sample Return (MSR) Mobile

Addressing MEPAG Goals I (life), II (climate) & III (geology)
"Follow the water" turns into "Follow the Carbon"

Ref: Hayati, S., Balint, T., "The Potential Benefits of Nuclear Power on the Surface of Mars: The Robotic Exploration Perspective", STAIF-06

Approved and Candidate Robotic Mars Missions

Selected & Potential Missions	Mission Class	Power System Option(s)
Orbiters (e.g., **MRO**[1])	Moderate/Large	Solar (typical for Mars orbiters)
Phoenix[1]	Scout	Solar selected
Mars Science Laboratory (MSL)[1]	Large	RPS (MMRTG) baselined (solar feasibility study in work)
Scouts (small missions)	Scout	Solar (RPS usage not allowed)
Multi-Lander Network	Moderate/Large	(Small-RPS or Solar)[2]
Astrobiology Field Lab (AFL) rover	Large	(To be determined)[2]
Mars Sample Return (MSR)	Flagship	(Solar or RPS)[2]
MSR Fetch rover (sub-MER class)	Scout-Large	(Small-RPS or Solar)[2]
Deep Drill	Large	(RPS or Solar)[2]

[1] **Funded** missions;
[2] **Based upon presumed mission requirements and preliminary power trade studies**

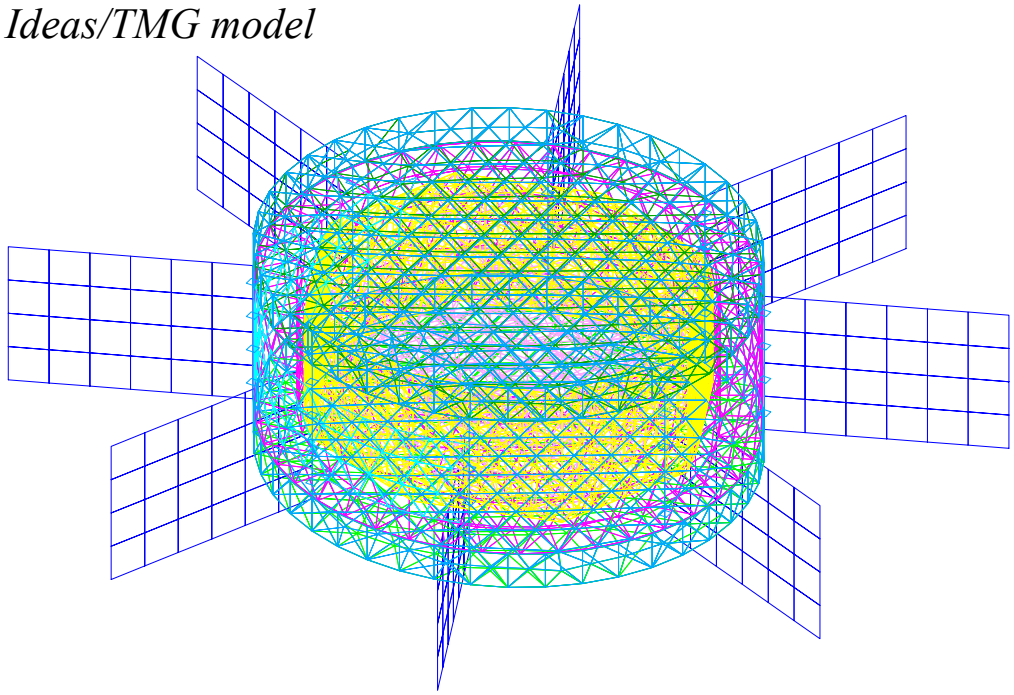
Ref: Hayati, S., Balint, T., "The Potential Benefits of Nuclear Power on the Surface of Mars: The Robotic Exploration Perspective", STAIF-06

Methodology and Assumptions

- Verification and Validation (V&V) represents an important and necessary step for numerical analysis of components.
- In this study we validated our small-RPS design concept against numerical data obtained from experimental testing of a small-RPS mock-up at OSU
  - Typical mission phases relevant to RPS enabled missions for a Mars in-situ exploration include: (1) Earth storage; (2) launch phase; (3) cruise phase; Entry/Descent/Landing (EDL) phase; and (4) landed in-situ operations.
  - Our numerical analysis focuses on the Earth storage phase.
- IDEAS/TMG was used to develop a geometric representation and a thermal model of the small-RPS experimental mockup unit.
- An initial numerical analysis methodology was developed for simulating the thermal environment of a small-RPS concept, and reported during STAIF-05
- This methodology was then applied for the current configuration and the numerical model was tuned using the validation database from OSU
- Consequently, the insights gained and the correlated values obtained from the resulting validated numerical thermal model could be now applied
  - To other mission phases and
  - To other small-RPS design concepts.

TMG Model of Small-RPS Test Unit

Ideas/TMG model

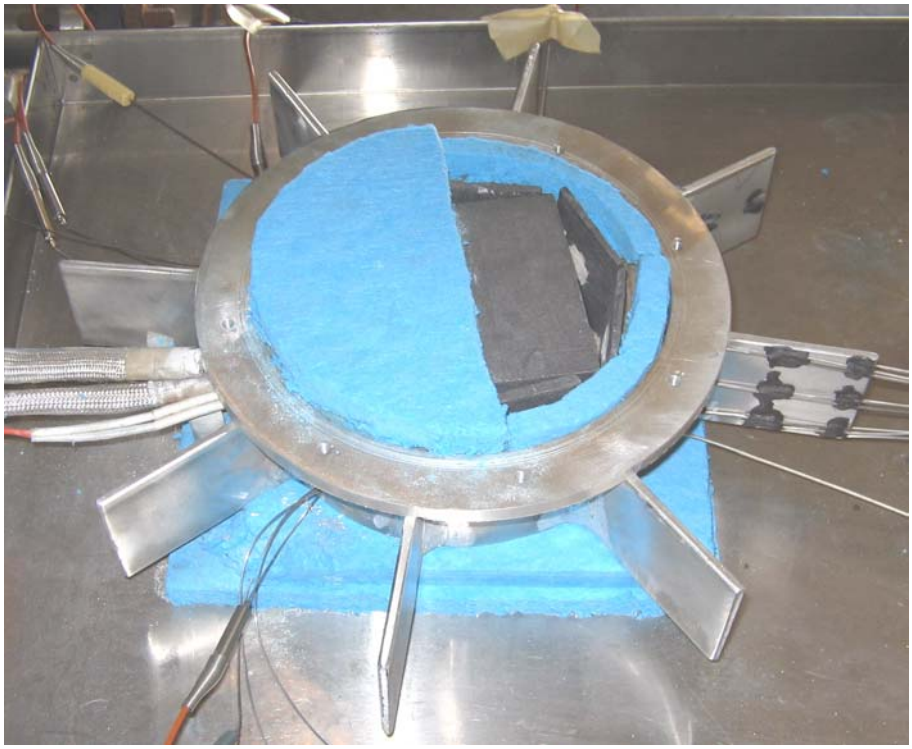


Description	# of elements/nodes
Solid Element	8915
Thin Shell Element	1668
Beam Element	32
Total Elements	**10615**
Total Nodes	**4515**

- Parts modeled in Unigraphics NX and imported into IDEAS/TMG
- Discretized (meshed) using a combination of solid, shell, and beam elements
- Material properties, boundary conditions, and thermal couplings supplied within TMG environment

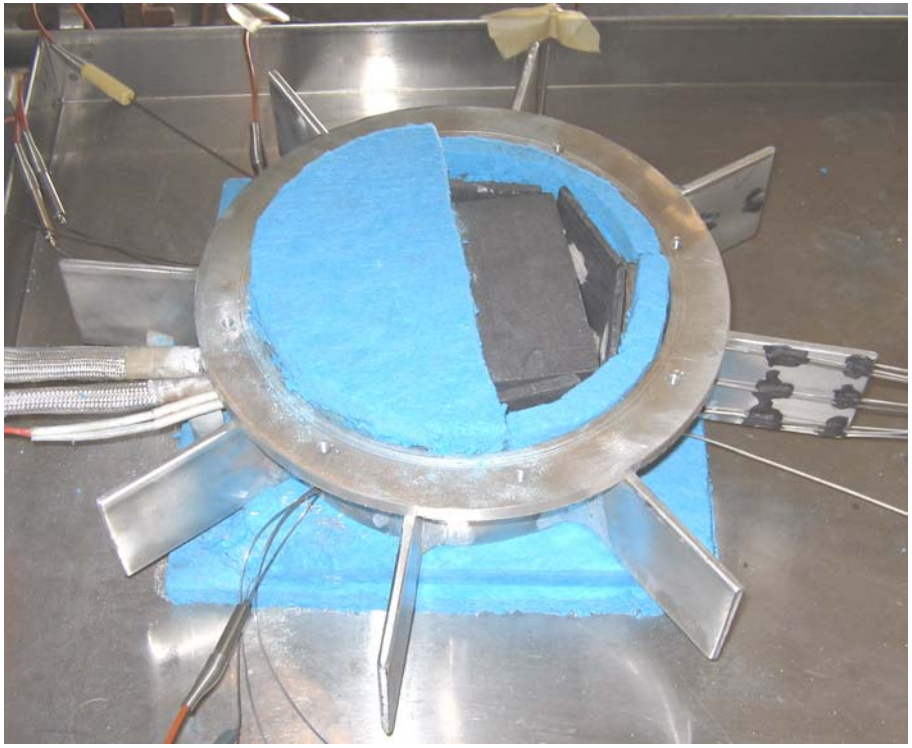
Test Unit Description

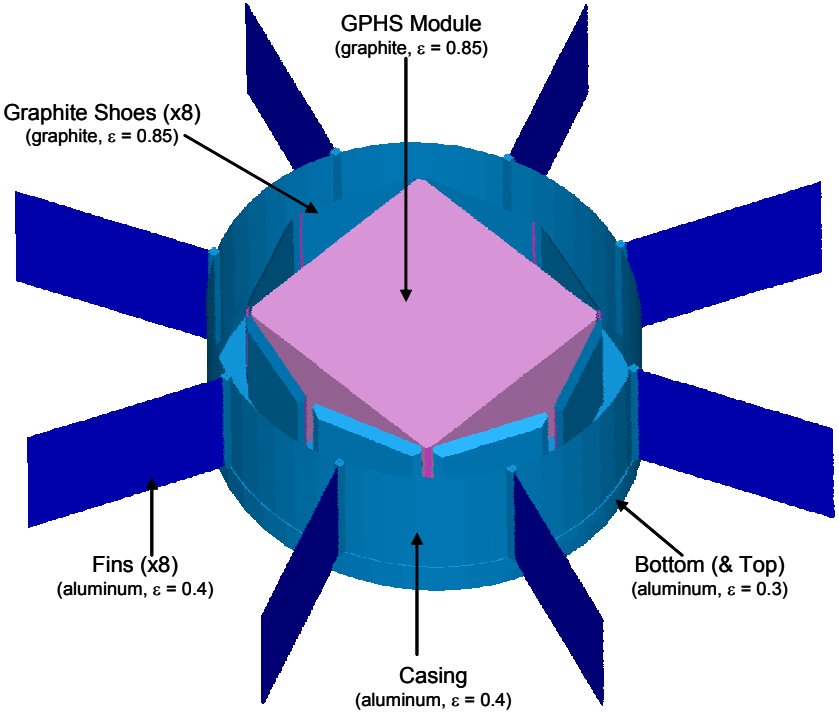
- The test unit was designed and built at OSU, based on specifications from JPL
- Power level: 250 W_t
- Heater: a resistance-heated graphite block, simulating a single GPHS module
- Heat radiated from the graphite block to 8 flat graphite "hot-shoes", representing the hot side of the thermoelectrics (TE)
- Each "hot-shoe" attached to a single tungsten rod, simulating the TE
  - Was chosen to simulate temperature drop from the hot side to cold side
- The GPHS module simulator and thermoelectric mock-up is encased in insulation and an outer aluminum casing, with 8 radial fins



Comparison of Test Unit and Analytical Model

- Small RPS unit is tested in ambient conditions to simulate a steady state, Earth storage phase
  - Other mission phases include: launch, cruise, EDL, and mission operation (not studied here)





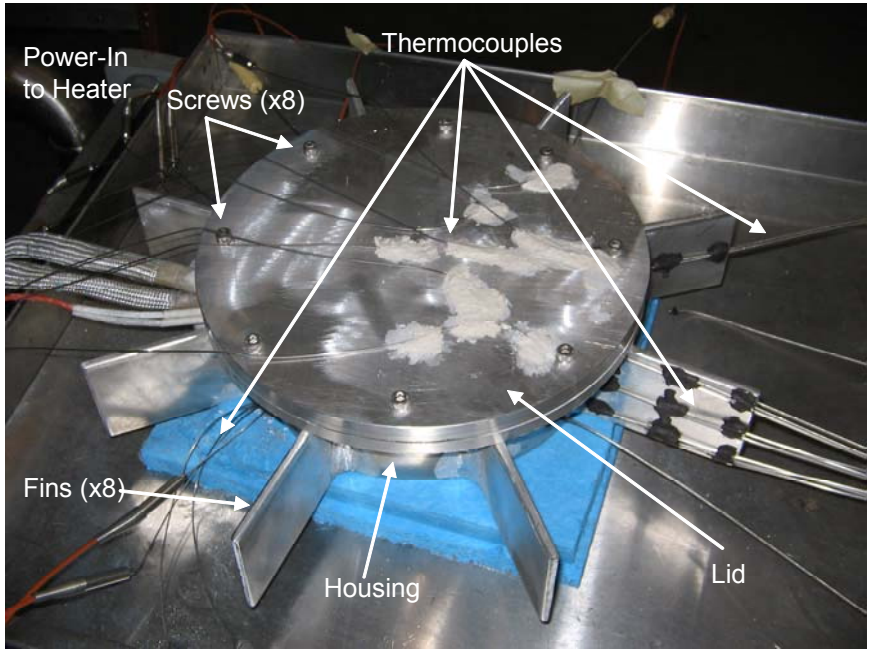
Internal heat transfer: radiation and convection (h = 8 W/m^2-K) to "internal" air

External heat transfer: radiation and convection (h = 15 W/m^2-K) to ambient air, conduction thru bottom to test table (R = 10 C/W)

Thermal Modeling Assumptions

- Convection used for storage on Earth
  - Inside casing: h = 8 W/m^2-K,
  - Outside casing: h = 15 W/m^2-K, with air temperature = 20 °C

- Radiation within internal cavity and external to case
  - Inside casing: Maximized by using "black" graphite (ε = 0.85)
  - Outside casing: Radiate heat externally from 8 fins, casing, and top lid to ambient conditions at 20 °C (with an ε = 0.4)

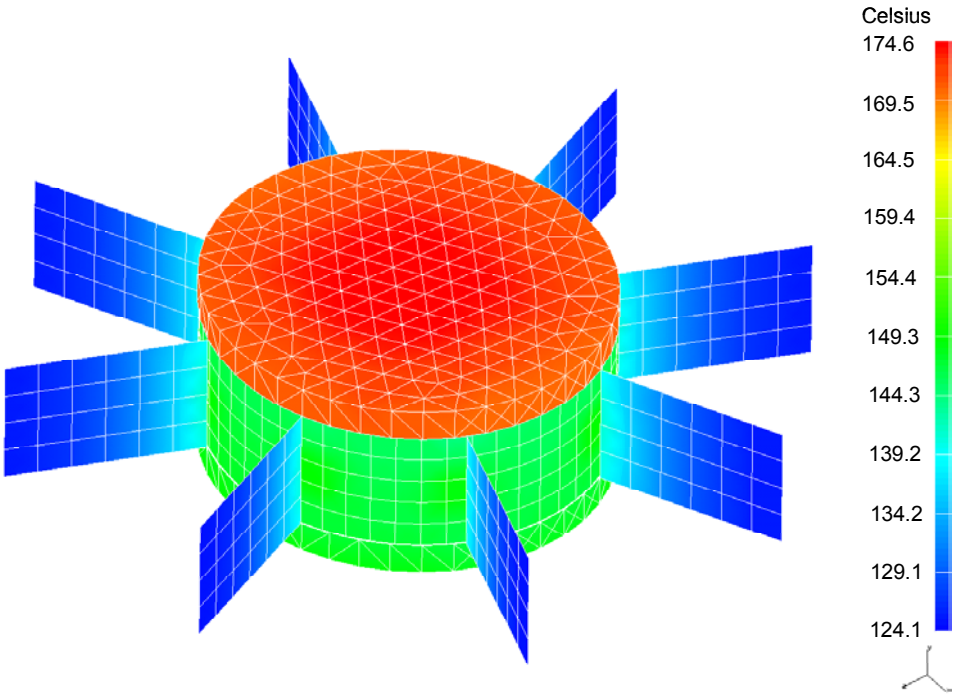


Thermal Model Adjustments – Validation Step

- Internal Correlation
  - Contact resistance between the top and bottom insulation with GPHS module is 600 W/m^2-K
  - A resistive link of 1.1 C/W was used to generate the appropriate temperature drop across the tungsten rods
  - A convection coefficient of 15 W/m^2-K was used to help transfer heat away from the GPHS module

- External Correlation
  - Good conduction path through welded joints (base and fins to casing)
  - Bolted top plate causes top plate to be ~20C warmer than case and bottom plate
  - 75% of heat lost by convection from fins and external casing
  - Additional heat could be radiated if fins and case were painted black ($\varepsilon = 0.9$)

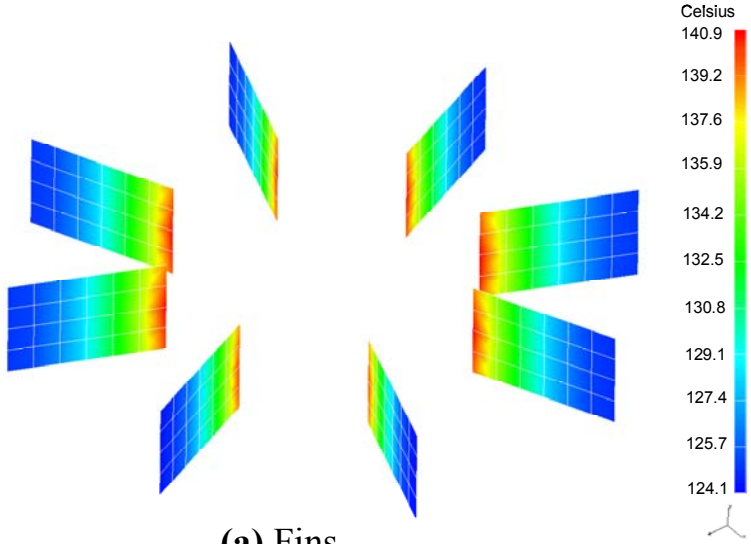
Summary of Temperature Results



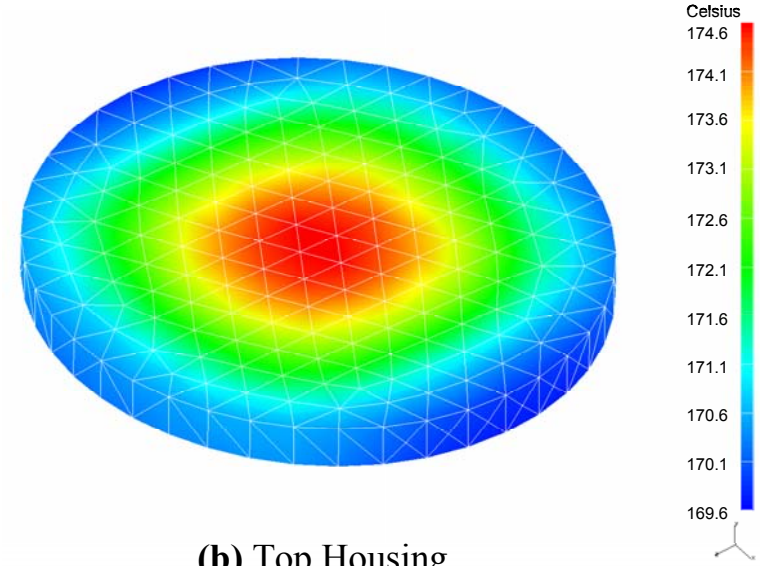
Summary Temperature Ranges (°C)	
Casing	143 - 150
Top Plate	172 - 180
Fins	129 - 139
Bottom Plate	148 - 163
Casing Insulation	152 - 415
Top Insulation	172 - 510
Bottom Insulation	149 - 506
GPHS Module	511 - 531
Graphite Shoes	429 - 459

Note: Temperature values from numerical analysis approximate experimental results. However, these are lower than the expected temperatures inside a future small-RPS. Future experiments and analysis is planned to refine the temperature ranges.

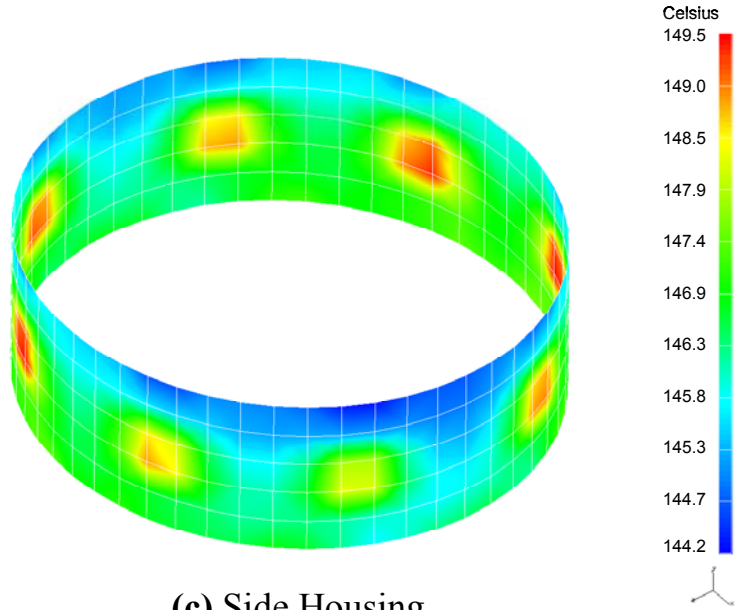
Temperature Mapping of External Housing and Fins



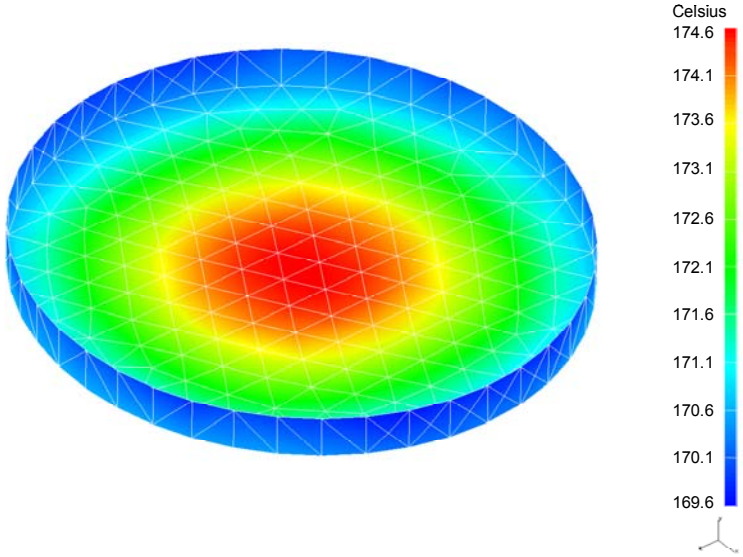
(a) Fins.



(b) Top Housing.



(c) Side Housing.



(d) Bottom Housing.

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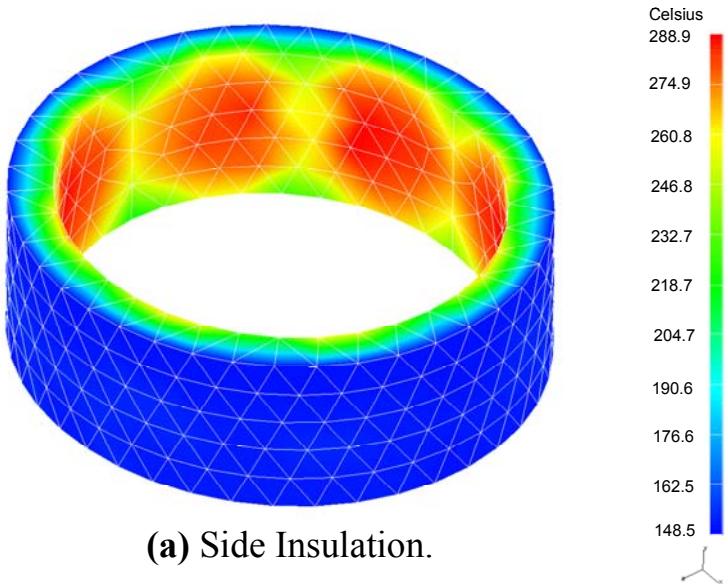
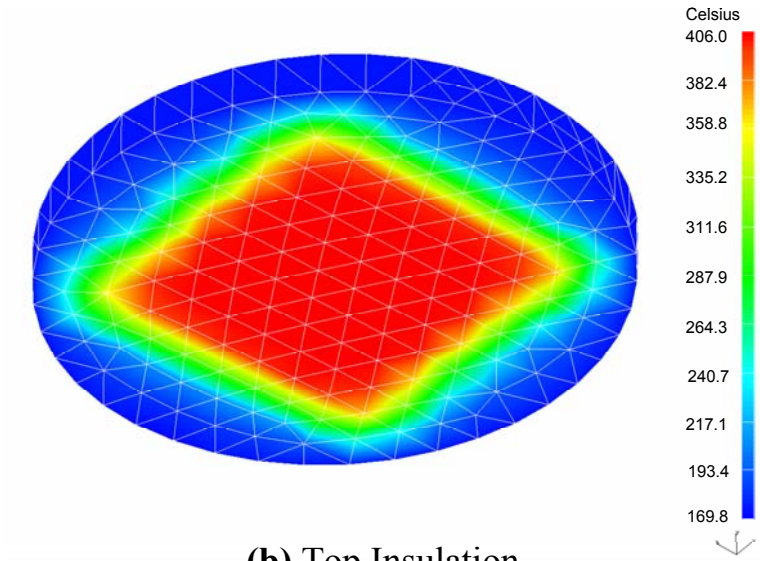
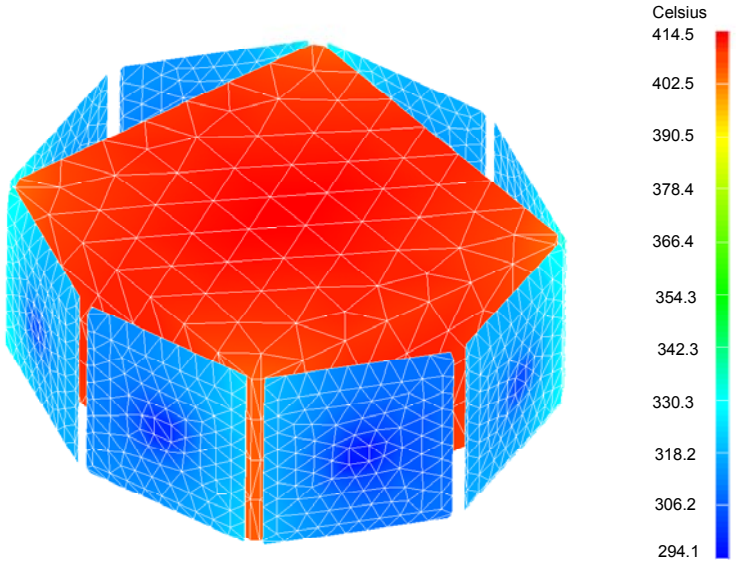
Temperature Mapping of Internal Components and Insulation



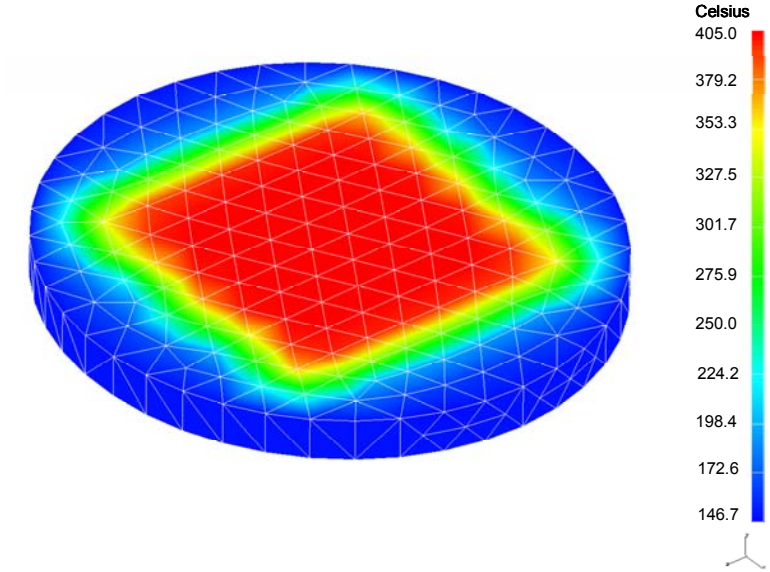
(a) Side Insulation.



(b) Top Insulation.



(c) Simulated GPHS Module and Hot Shoes.



(d) Bottom Insulation.

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Summary of Test Data and Predicted Temperatures

	Test Data (°C)		Predicted (°C)		% Error	
	Min	Max	Min	Max	Min	Max
Casing	145	146	144	150	-0.7	2.7
Fins	122	141	124	141	1.6	0.0
Top Plate	173	178	170	175	-1.7	-1.7
Bottom Plate	148	155	146	159	-1.4	2.6
GPHS	408	410	403	415	-1.2	1.2
Graphite Shoes	324	327	294	332	-9.3	1.5
Heater*		637				
Casing Insulation**	NA	NA	149	289		
Top Insulation**	NA	NA	170	406		
Bottom Insulation**	NA	NA	147	405		

* The heater was not modeled with thermal elements (heat was applied to inside of GPHS)

** There were no thermocouples on the insulation

The validated model predicted the temperature distribution both inside and outside of the small-RPS model within an acceptable error range. Further refinements are planned to reduce the error +/-5%

Conclusions

- A numerical model of a small RPS has been validated with test data provided by Oregon State University

- The temperature distribution was predicted within an acceptable range, and this validated methodology can be used for other small-RPS designs.

- Results indicate that critical areas affecting thermal performance include:
  - External environment (convection and radiation effects)
  - Outside casing properties (radiation and conduction effects)
  - Configuration and placement of RPS on spacecraft would be important to achieve a good radiating environment
  - Can maximize both convection and radiation rejection capability by increasing number and size of fins
    - Trade off of optimum thermoelectric operating temperature
  - Test unit was not hermetically sealed, which may have caused too high of an internal convection coefficient (compared to a future flight unit)

Future Work

- Additional testing could incorporate more accurate simulations of the thermoelectrics
  - 1 or 2 of the graphite hot shoes/tungsten rod pairs (that simulates hot and cold side of thermoelectrics) could be replaced by working thermoelectrics
  - This should provide a higher fidelity temperature distribution along the TEs
  - It would also demonstrate an initial power generation capability

- A redesigned test model could use an upgraded insulation material, consistent with a small-RPS concept (such as MinK-1400)

- Additional experiments could be performed in vacuum & low pressures to simulate other mission phases

Thanks for your attention

Any questions?