Validation Database Based Thermal Analysis of an Advanced RPS Concept

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Abstract. Advanced RPS concepts can be conceived, designed and assessed using high-end computational analysis tools. These predictions may provide an initial insight into the potential performance of these models, but verification and validation are necessary and required steps to gain confidence in the numerical analysis results. This paper discusses the findings from a numerical validation exercise for a small advanced RPS concept, based on a thermal analysis methodology developed at JPL and on a validation database obtained from experiments performed at Oregon State University. Both the numerical and experimental configurations utilized a single GPHS module enabled design, resembling a Mod-RTG concept. The analysis focused on operating and environmental conditions during the storage phase only. This validation exercise helped to refine key thermal analysis and modeling parameters, such as heat transfer coefficients, and conductivity and radiation heat transfer values. Improved understanding of the Mod-RTG concept through validation of the thermal model allows for future improvements to this power system concept.

Keywords: RPS, ARPS, ARTG, Small RPS, thermal analysis, numerical model, validation.
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INTRODUCTION

The Vision for Space Exploration identified the Mars exploration pathway as one of the three major pathways [The White House, 2004]. Over the past fiscal year NASA's Advanced Planning and Integration Office (APIO) establish two teams to refine these pathways. One set of teams addressed strategic and one capability objectives. These activities concluded by May 2005. Furthermore, for the request of NASA's administrator, a so called "60 day study" was performed to establish plans for the lunar exploration program as a stepping stone for future solar system exploration. The study results from this were released in September 2005, and the next phases of preplanning of the various programs are underway. It includes the Mars Exploration Program, which is governed by four goals established by the Mars Exploration Program Analysis Group (MEPAG) [MEPAG, 2005]. These goals are: (1) Determining if life ever arose on Mars; (2) Understanding the process and history of climate on Mars; (3) Determining the evolution of the surface and interior of Mars; and (4) Preparing for human exploration. The first three goals are science driven, while the fourth goal is primarily technology oriented. The goals could translate to a number of robotic missions over the next decade and beyond, including smaller missions which may require advanced Radioisotope Power Systems (ARPS), generating power in the multi-ten watts power level. For Mars exploration small RPS enabled missions could include a multi-lander network or MER class rovers [Balint & Jordan, 2005]. The sequence of these missions is not yet established, and could change from the one reported in [3]. However, it is anticipated that similar mission types will be required to address the four MEPAG defined goals, cross referenced with NASA programmatics and budgetary considerations. The lunar program could also benefit from such missions, where long lived robotic exploration – related to prospecting for in-situ resources in permanently shadowed craters at the Polar Regions – would require RPS [Balint, 2005].

At present NASA, DoE and their industry partners are developing two RPSs, both generating ~110We at BOL. The first one is a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) using static power conversion and the second is a Stirling Radioisotope Generator (SRG) utilizing dynamic power conversion. An MMRTG uses 8

General Purpose Heat Source (GPHS) modules, while an SRG is designed with 2 GPHS modules. Smaller power sources were also envisioned with a single GPHS module and static or dynamic power converters [Abelson et al., 2004]. Analytical work has been performed at JPL, addressing the thermal environment of a multi-lander network element concept throughout all mission phases [Balint & Emis, 2005]. These identified mission phases are Earth storage, launch, cruise, entry-descent-landing (EDL) and in-situ operations phases. The thermal analysis by Balint and Emis provided insight into the phenomena, but without a validation database the numerical results could not be confirmed.

In order to advance our knowledge on small RPS designs, an experimental work has been performed at Oregon State University during the summer of 2005 [Woods, Arnold & Balint, 2006]. These measurements provided a validation database for the numerical analysis reported here.

METHODOLOGY AND ASSUMPTIONS

The primary goal for this study is to validate the thermal model that was developed for a mock-up of a small RPS unit that was tested to replicate storage in an earth atmosphere [Woods, 2006]. The test assembly that was developed by Oregon State University simulated some of the major components of the RPS system. To mimic the 250 Wt that would be generated by the four plutonium pellets within a single GPHS module, a resistance heater (operated between 28 and 30 Vdc to produce 250 Wt) was used. The heater was located inside of a graphite block, which approximates the casing of the GPHS module. The heat generated by the heater was conducted through the graphite block and radiated to eight graphite shoes, which acted as the representative hot side of the thermoelectrics (TE). A single tungsten rod was attached on each of the graphite shoes to simulate the thermoelectrics and the temperature drop between its hot and cold sides. This assembly (GPHS module and TE mock-up) is encased in ceramic insulating boards (κ=0.1 W/m-K). Finally, an aluminum housing with 8 radial fins was used to encase the test unit. Table 1 summarizes the materials and the associated property values that were employed. The fins and the bottom plate were be welded to the cylindrical case, while the top plate was bolted (see Figures 1 and 2(a)). Based on the test results from OSU, the thermal model and assumptions used could be validated for operation in an earth storage configuration.

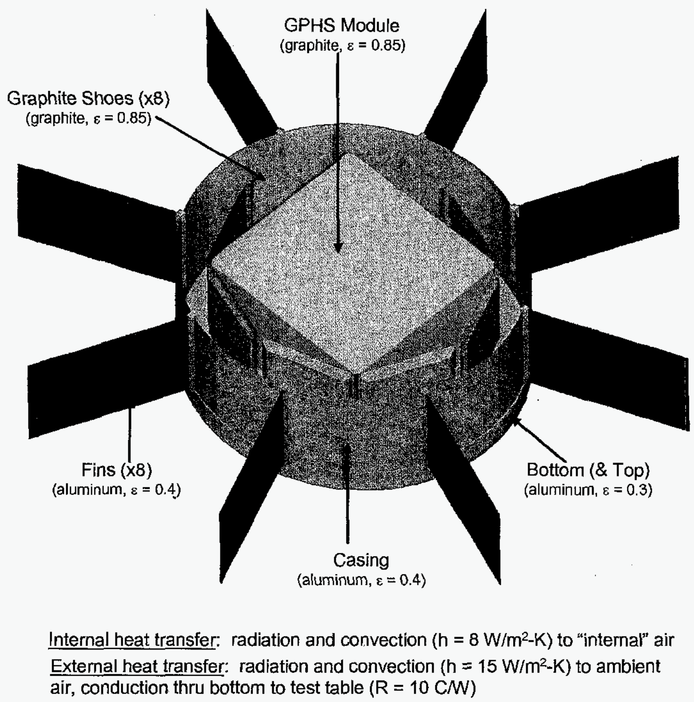


FIGURE 1. Internal layout and radiative properties of small RPS test unit (for clarity, the top plate and insulation are not shown).

TABLE 1: Material Properties Used in the Thermal Model.

Material	Conductivity (W/m-K)	Density (kg/m^3)	Specific Heat (J/kg-K)
Aluminum	150	2770	1033
Graphite	30	2210	1650
Insulation	0.1	241	1047

The thermal modeling effort for this task followed the methodologies that were established and used to analyze the Mars NetLander Network Mission [Balint & Emis, 2005]. The reference geometry for the present configuration was imported into I-DEAS (as a STEP file) from the CAD model that was developed by OSU. Then each of the relevant components was discretized (meshed) using finite element modeling (FEM) with MAYA's I-DEAS TMG Thermal Analysis software [MAYA, 2004]. A summary of the type and number of elements is shown in Table 2. The exterior casing and fins were allowed to radiate (ε=0.4) and convect (h=15 W/m^2-K) to ambient air at 20°C. There were conductive couplings between the casing and insulation and between the insulation and GPHS module. There were both radiative and convective couplings between the GPHS module and the graphite shoes. Typical values were initially used for these couplings as a first-cut analysis, but were then updated and verified once test data was available. A correlation effort was then made to more closely match the thermal modeling results with the test data. The test set-up and thermal model were optimized for conditions assumed for an earth storage phase (Figure 2). It is anticipated, however, that the numerical model will provide additional insight into other phases of the mission (i.e., launch, cruise, EDL, and in-situ landed operations). Each of these phases will have a different external environment, but the internal configuration for each case will be the same. Therefore, the data provided by the testing performed by OSU will be helpful for modeling the thermal behavior of conceptual small RPSs.

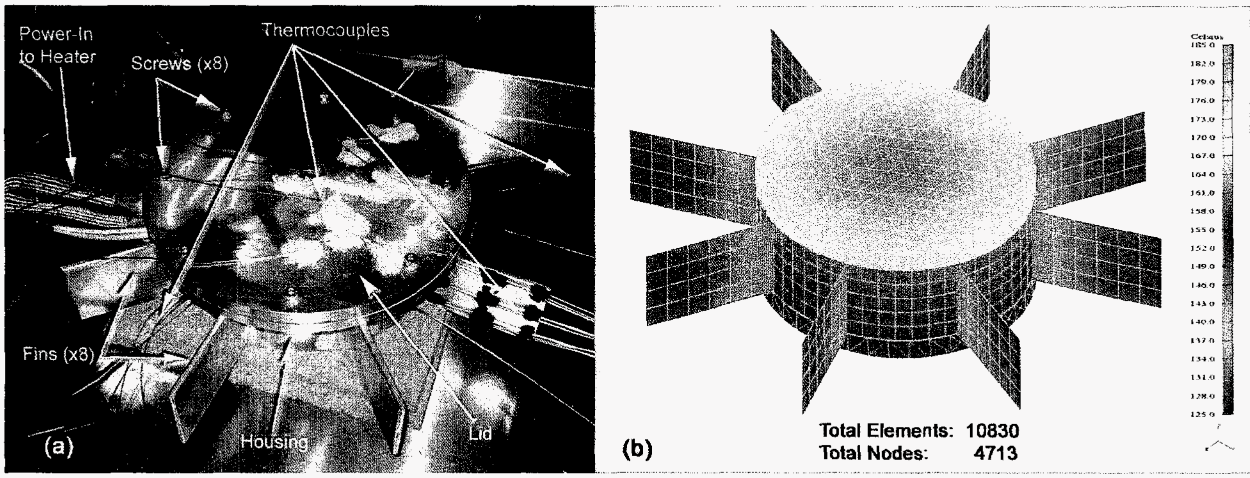


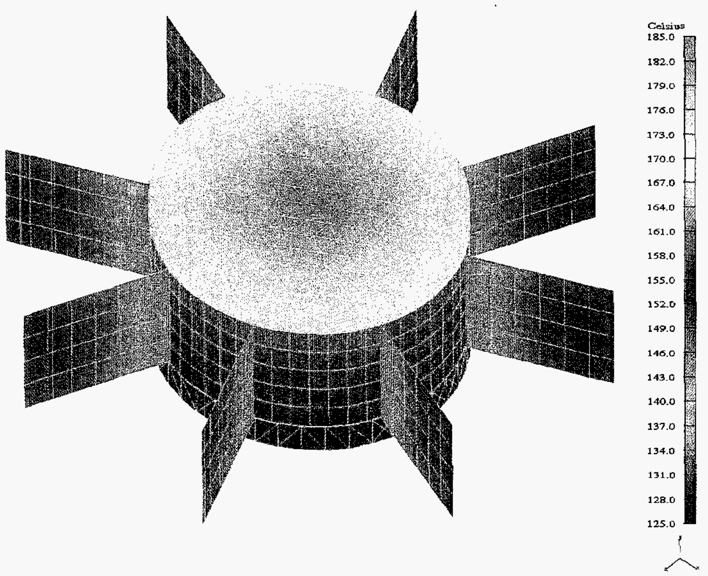
FIGURE 2. Comparison of the experimental (a) and numerical (b) models.

TABLE 2: Thermal Model Element and Nodal Details.

Description	# of Elements/Nodes
Solid Element	8910
Thin Shell Element	1888
Beam Element	32
Total Elements	10830
Total Nodes	4713

RESULTS AND DISCUSSIONS

By comparing test data obtained from OSU with the simulation results from a numerical thermal model of the small RPS developed at JPL, additional insights may be gained about the heat transfer mechanisms at work. The small RPS mock-up was tested at several input powers and the data was compared to the TMG model that was developed to approximate the small RPS concept. The correlation effort was optimized for the 250 Wt case, which would simulate an actual GPHS module, where the other low powered cases were used as additional data points to provide confidence in the numerical model. Figure 3 shows the temperature distribution of the external surfaces of the small RPS mock-up, with a table summarizing the temperature ranges seen after the validation step. The validation consisted of the adjustment of key variables for the 250 Wt input power case, in order to approximate the experimental data. Once the correct material properties were entered, the various thermal connections could be manipulated. Since the test was performed in ambient conditions, convection as well as radiation and conduction, would have to be correctly accounted for.



Summary Temperature Ranges (degC)	
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

FIGURE 3. Temperature mapping and values from analytical model of small RPS (250 Wt dissipation).

The validation step, that is the adjustment of the numerical model, can be separated into two parts. One addresses the internal parts and another the external parts. The external parts included the aluminum components of the small RPS test unit, namely the casing, cooing fins, and the top/bottom plates (Figure 4). It was assumed that there was good heat transfer through the welded joints between the case and the bottom plate and between the eight fins and the casing. There was a slightly less efficient joint between the top plate and case, where a resistance of 50 C/W was used to simulate a bolted connection. The top plate was approximately 20°C warmer that the case and bottom plate which had a good thermal path to the heat rejecting fins. As shown in Figure 2(a), the aluminum components were untreated without applied coatings. For these components an emissivity of 0.4 was assumed during the radiation calculations, which corresponds to oxidized aluminum. The ambient air temperature was assumed at 20°C. Since the test was performed at ambient conditions, convection was found to be the dominant form of heat transfer. By using a heat transfer coefficient of 15 W/m^2-K, approximately 75% of the heat was rejected by convection. The rejected heat could be further increased by the use of high emittance coating, such as black paint with an emissivity of 0.9.

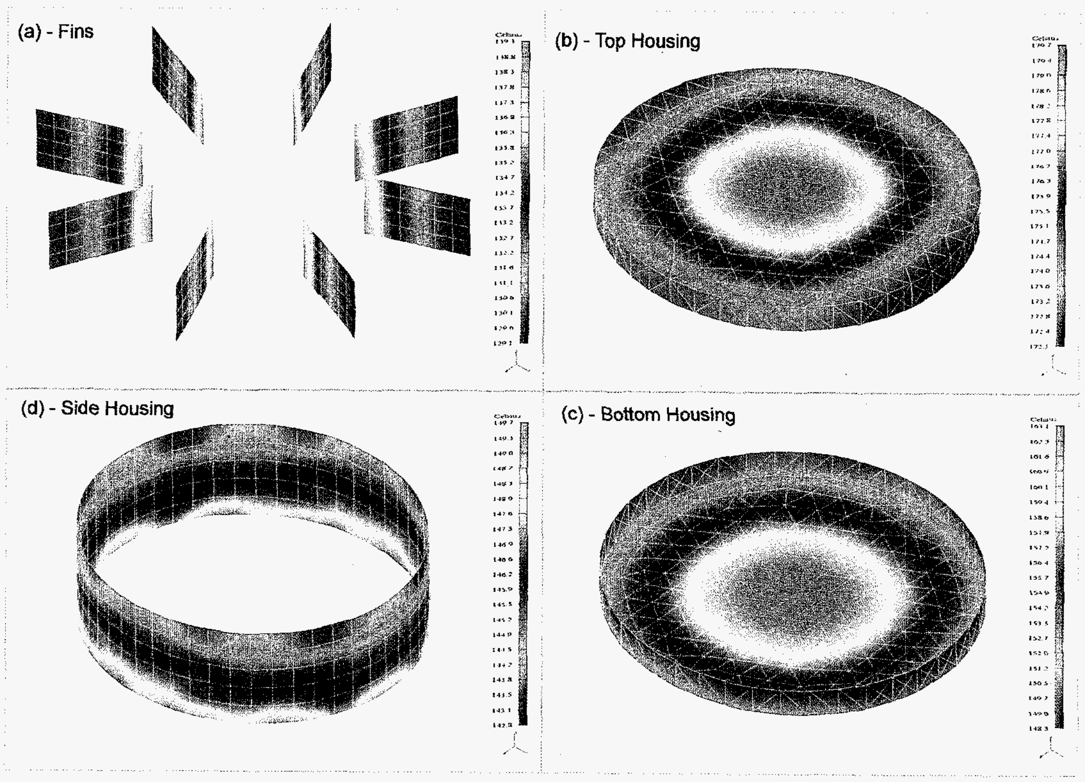


FIGURE 4. Temperature mapping for external housing and fins.

The internal components of the test unit (i.e., the GPHS module and the graphite shoes) were chosen to approximate the operational functions of an actual small RPS unit (see Figure 5). These parts were made of graphite, which were assumed to have a high emissivity (e = 0.85) to facilitate moving the heat from the heater and GPHS module to the graphite shoes and cold legs. Convection inside the unit was also accounted for, although the heat transfer coefficient for the internal convection was smaller (h = 8 W/m2-K), due to the enclosed space and limited amount of recirculated air. The GPHS module and graphite shoes were encased in insulation with a conductivity of 0.1 W/m-K, with a thickness of 5/8 inch around the sides and 1/8 inch on the top and bottom. The top and bottom sections of insulation were thinner [Woods, Arnold and Balint, 2006]. Due to the limited space and the slightly compressive nature of the insulation, it was assumed that the contact resistance between the GPHS module and the top and bottom insulation pieces was 400 W/m^2-K. This still forced most of the heat to be transferred from the GPHS module to the graphite shoes and through the tungsten rods to the case before being rejected to the ambient by the fins. There was a weak resistive link of 5 C/W to generate the temperature drop across the tungsten rods, which would simulate the thermoelectrics.

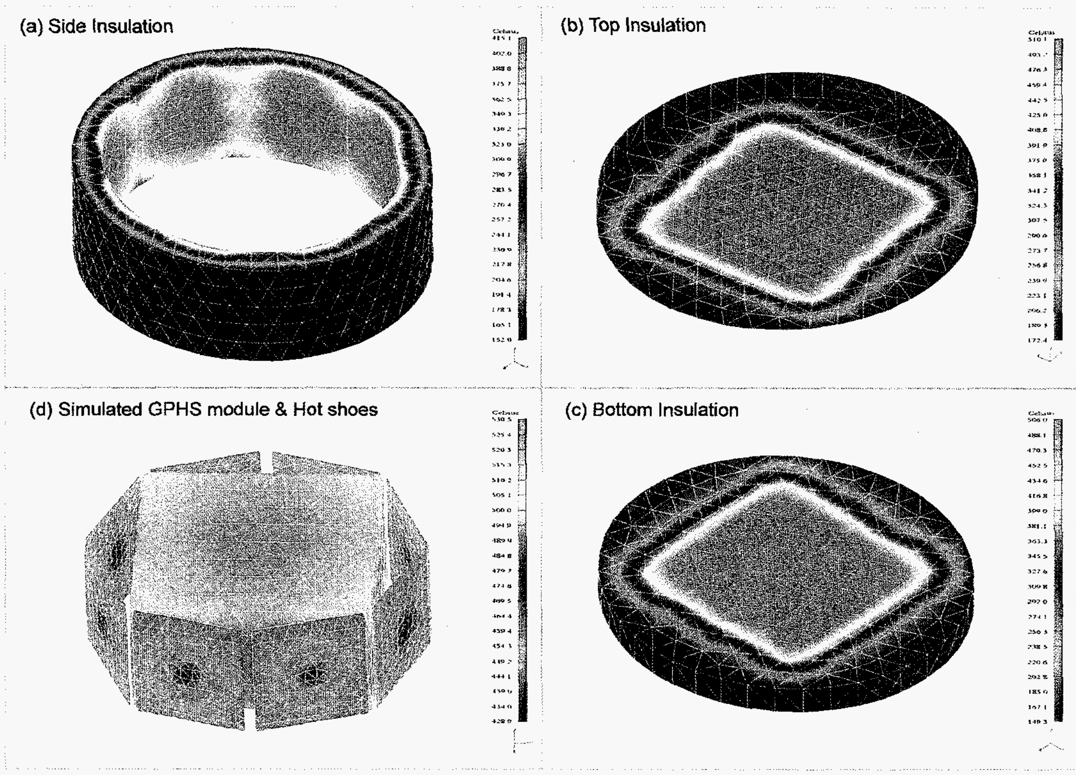


FIGURE 5. Temperature mapping for internal components and insulation.

A comparison of the test data along with the predicted temperatures is shown in Table 3. The external aluminum parts showed the greatest agreement and these areas were also the most heavily instrumented. The internal graphite parts showed larger degree of discrepancies, but that area also included the largest amount of unknowns in terms of contact area and contact pressure. Furthermore, the test set-up pictures provided by OSU showed that the spacing and layout (particularly the graphite shoes) was not as uniform as what was modeled. Finally, a balance between the test data for the heater and GPHS module had to be made. The larger temperature difference was due to the limited test data and location of the thermocouples compared to the analytical thermal model, which provided more calculation points throughout the GPHS module. The thermal model showed a much closer temperature between these two components compared to the test data.

TABLE 3. Summary of test data and predicted temperatures for the small RPS thermal mock-up.

	Test Data		**Predicted**		delta T	
	Min	Max	**Min**	**Max**	Min	Max
Casing	145	146	**143**	**150**	-2	4
fins	122	141	**129**	**139**	7	-2
Top Plate	173	178	**172**	**180**	-1	2
bottom plate	148	155	**148**	**163**	0	8
GPHS*	408	410	**511**	**531**	103	
graphite shoes*	324	327	**429**	**459**	105	132
heater*		637		**531**		-106
casing insulation**	NA	NA	**152**	**415**		
top insulation**	NA	NA	**172**	**510**		
bottom insulation**	NA	NA	**149**	**506**		

* The GPHS and graphite shoes are modeled with solid elements and showed a larger variation in expected temperatures compared to test data

** There were no thermocouples on the insulation

CONCLUSIONS

The analysis reported in this paper addressed the validation of the numerical model of a small-RPS. The thermal validation database provided for the study was generated at Oregon State University, where the experimental program was performed during the summer of 2005 on a thermal model of a small-RPS. One of the greatest benefits of comparing the results from an analytical thermal model with actual test data was to highlight the critical areas that will need to be defined for any flight unit. It was seen that the external environment and conditions of the external case (radiation properties of the case and the amount of convection present) play an important role in the amount of heat that can be rejected. While the welded joints between the casing and the bottom plate and fins were efficient, the bolted interface between the top plate and casing showed a larger resistance, which reduces the effectiveness of using the heat rejection fins. For space based applications, radiation which is usually the dominant heat transfer mechanism can be maximized with the appropriate surface coating (high emittance coating such as black paint) and configuration (the placement and orientation of the small RPS on the spacecraft). The RPS location would be chosen to optimize its view factor to a cold sink such as deep space, and by choosing the appropriate area to be used for heat rejection. The area is controlled by the number and size of fins. This test article used eight radial fins to increase the total area available for heat rejection, which was effective for both radiation and convection. The test set-up showed that convection could also be an efficient means of heat rejection. For landed missions with an available atmosphere or for storage conditions, convection can be maximized by allowing good air flow between the heat rejection surfaces. If additional heat needs to be rejected, forced convection such as a pumped fluid loop could also be used to cool the RPS fins. For some mission phases, such as the cruise phase where the RPS may be encapsulated inside an aeroshell, this may be the only practical method of heat rejection.

With the preliminary test data, some of the trends inside the RPS could be seen and the thermal control of it be optimized. The appropriate choice of insulation material (by picking the correct thickness and conductivity) will help isolate the heat in the GPHS module and hot side of the graphite shoes. This will maximize the efficiency of the thermoelectrics (approximated by the tungsten rods in these tests) which are used to convert the thermal heat to electrical power. A preliminary look at the calculated optical properties showed that graphite, which naturally has a high emittance, is an efficient material for radiative heat transfer. Since the test unit was not hermetically sealed, there was available air inside the model which assisted the heat transfer from the GPHS module to the hot shoes. In the absence of sufficient atmosphere, radiation would be the dominant mechanism. Depending on the configuration of the GPHS module and the location/shape of the thermoelectrics, heat will more easily be transferred directly by conduction from the GPHS module to the thermoelectrics (such a configuration, using Close Packed Arrays, were discussed in [Abelson et al., 2004]). The results and trends presented here will be helpful for the future characterization of a small RPS that utilizes actual thermoelectrics and a GPHS module.

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