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Parametric System Model for a Stirling Radioisotope Generator

Paul C. Schmitz
Vantage Partners, LLC, Brook Park, Ohio

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Vantage Partners, LLC, Brook Park, Ohio

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Parametric System Model for a Stirling Radioisotope Generator

Paul C. Schmitz
Vantage Partners, LLC
Brook Park, Ohio 44142

Abstract

A Parametric System Model (PSM) was created in order to explore conceptual designs, the impact of component changes and power level on the performance of the Stirling Radioisotope Generator (SRG). Using the General Purpose Heat Source (GPHS ~ 250 W_{th}) modules as the thermal building block from which a SRG is conceptualized, trade studies are performed to understand the importance of individual component scaling on isotope usage. Mathematical relationships based on heat and power throughput, temperature, mass, and volume were developed for each of the required subsystems. The PSM uses these relationships to perform component- and system-level trades.

1.0 Introduction

The Radioisotope Power Systems (RPS) Program Office commissioned a study to help understand how Stirling Radioisotope Generators (SRGs) scale in power from the current 140-W Advanced Stirling Radioisotope Generator (ASRG) up to 1 kWe. The motivation to consider higher power systems is twofold. First in that it may reduce the integration burden placed upon future high-power spacecraft that would require many of the lower power ASRGs, and second that higher power levels and optimization of a SRG might enable higher specific power (w/kg). A Microsoft Excel-based Parametric System Model (PSM) was created to model the individual components associated with a SRG and determine how each of these component's characteristics affects the system. In order to understand these interactions some assumptions are needed to relate how the overall system will be arranged. For this study the ASRG (see Figure 1) was used as a typical physical arrangement for all of the SRGs considered in this analysis. The ASRG layout is a dual-opposed Stirling convertor system with the General Purpose Heat Source (GPHS) modules placed near the heater heads and located on the outboard side of each housing end. Surrounding the GPHS is thermal insulation that defines the minimum internal dimension of the housing/radiator. For all of the cases considered in this study, a cylindrical radiator was assumed, which is different from the rectangular block shape housing of the ASRG. The housing/radiator in the ASRG as well as for the SRG studied in this paper serves to contain the insulation, provide structural rigidity to the entire assembly, and contain an inert cover gas required during launch.

Figure 2 shows a heat flow diagram representing the SRG's analyzed. The heat flows and/or allowable temperature drops are used to size the components. By making material substitutions, an assessment can be made on the impact each substitution would have on overall system performance. Heat is generated in the GPHS module(s), which is surrounded by thermal insulation to reduce the heat losses to the surroundings. The remaining heat is sent via a conductive interface called the hot-side attachment (HSA) to the Stirling convertor. The Stirling convertor produces electrical power and the cycle waste heat is rejected to the cold-side adapter (CSA). The waste heat passes through the CSA and is then rejected to the environment via the housing/radiator.

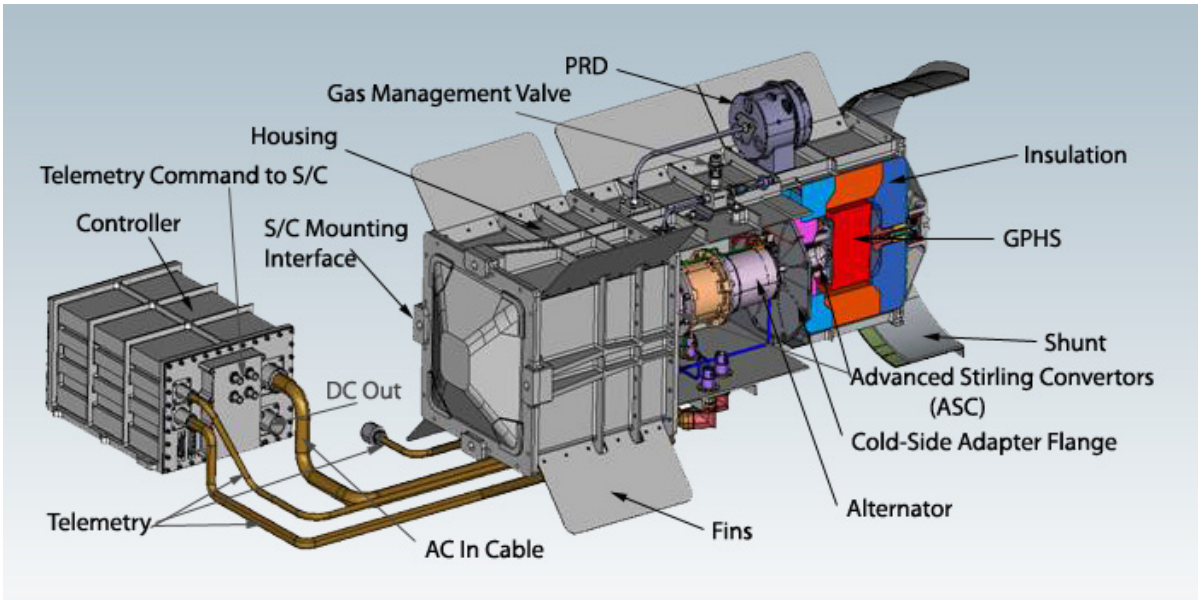


Figure 1.—Advanced Stirling Radioisotope Generator.

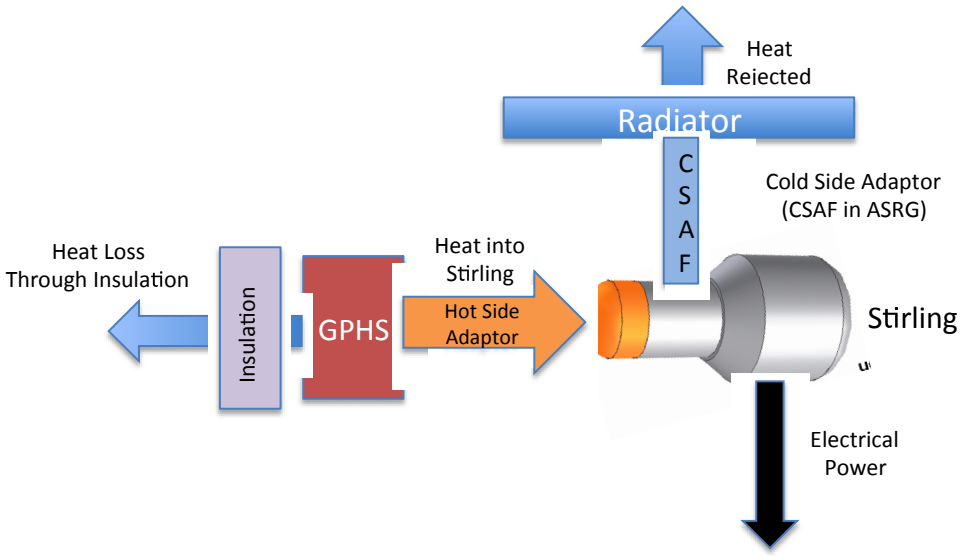


Figure 2.—Heat and power flows in a Stirling Radioisotope Generator (SRG).

2.0 Modeling Overview

Assuming a Stirling convertor temperature ratio (TR) (Eq. (1)), the Carnot efficiency (Eq. (2)) is used to calculate the ideal efficiency of a heat engine. Next, a representation of how close the Stirling engine is to ideal cycle (fraction of Carnot efficiency) is used to estimate the overall heat engine efficiency (Eq. (3)). The fraction of Carnot efficiency can either be a fixed value or dependent upon heat flow and acceptor/rejector temperature. The ASRG operating near a TR of 3.0 that has a fraction of Carnot is about 63 percent. Next, using an estimate of the alternator efficiency, one can find an overall efficiency of the engine/alternator combination (called a convertor) (Eq. (4)). The fraction of Carnot including the alternator for ASC is about 56 percent. Equation (5) is then used to calculate the heat into the heat engine. GPHS modules are specified as producing ~250 W at the beginning of life (BOL) (an assumed 3 years before mission launch). By selecting the electrical power output and the desired time (i.e., isotope decay) in the life of the GPHS, one can calculate the minimum number of GPHS modules required. The GPHS thermal input subtracted from the Stirling required heat input is the allowable losses through the insulation. With the insulation losses now fixed an estimate can be made for the surface area of the insulation and in turn the insulation thickness can be calculated. As the insulation thickness increases so does the minimum radiator/housing size and the radius of the CSA. All of these components coupled together are evaluated over a wide range of TRs within the PSM to achieve the required electrical power output.

$$\text{Temperature Ratio (TR)} = \frac{T_H}{T_C} \tag{1}$$

$$\text{Carnot Efficiency} = 1 - \frac{1}{\text{TR}} \tag{2}$$

$$\text{Heat engine efficiency} = \text{Carnot efficiency} * \text{Fraction of Carnot} \tag{3}$$

$$\text{Overall efficiency} = \text{Heat engine efficiency} * \text{Alternator efficiency} \tag{4}$$

$$Q_{IN} = \frac{\text{Electrical power}}{\text{Overall efficiency}} \tag{5}$$

3.0 Components

All of the components described below are modeled in the PSM. A brief overview of the characteristics of each component and the user-selected options that are available in the PSM are discussed.

3.1 General Purpose Heat Source

Reference 1 discusses the Department of Energy (DOE) GPHS, which is the heat source building block used for this analysis and is used in all current NASA RPS. The GPHS contains Pu-238 in the form of PuO_2 in four interior iridium capsules. The GPHS Pu-238 fuel has a half-life of approximately 87 years that leads to relatively constant heat flux out of the GPHS module during a typical NASA mission. The current GPHS in the form of a Step 2 GPHS are used for all space missions. Dimensions of a Step 2 GPHS module are 5.3 by 9.32 by 9.72 cm. Using the largest face (9.32 by 9.72 cm), the maximum

heat flux out of a single GPHS module at BOL with insulation is 2.69 W/cm^2. In contrast to the low heat flux from the GPHS modules is that required by a Stirling convertor. A typical SRG developed for high specific power requires an input heat flux of about 15 W/cm^2.

The GPHS module temperature limits are set by the iridium cladding around the Pu-238 fuel whose temperature must be maintained between 1335 °C (1608 K) and 900 °C (TE1173 K). The effective maximum surface temperature of the GPHS graphite shell is 1100 °C (1373 K) in vacuum. This temperature is well above the 840 °C Stirling convertor upper limit that is allowed by the Stirling heater head superalloy (MarM-247). This temperature combined with the temperature drop through the HSA sets the temperature of the Stirling convertor heater head.

Finally, the PSM allows variations in the GPHS initial heat output. The user may select either the BOL 250 W nominal value or other values based on lower or higher initial heat loading. Additionally, the user may select some future time for the SRG to produce its required power by allowing for the decay of the isotope.

3.2 Heat Source Attachment

A component called the HSA is used to conductively couple the GPHS module(s) to the Stirling convertor. In the ASRG, the HSA is made of nickel and sits over the acceptor dome of the Stirling convertor. As electrical power requirements increase and/or efficiency decreases it becomes necessary to add additional GPHS. One option that does not require changing the HSA is to stack the GPHS modules (Figure 3). This approach can be at best extended to two GPHS modules (see Ref. 2) as analysis has shown the temperature drop from most distant GPHS to the Stirling reduces safety margin of the heat source. The arrangement used in this study (see Figure 4) is to place the GPHS modules radially outward from the Stirling heater head. The advantage is that all of the GPHS modules are operating at the same temperature. The disadvantage of this arrangement is that the insulation plus multiple GPHS modules are driving the minimum diameter of the SRG. This in turn increases the mass penalty and/or temperature drop through the CSA. It is shown in Reference 3 that as power levels increase, GPHS orientation with the shortest GPHS dimension (5.32 cm) going radially outward from the centerline axis of the convertor is preferred and is used for the remainder of this analysis.

The mass of the HSA can be found by using the material properties, Stirling and HSA heat flux requirements and the distance between the heater head and the GPHS. A comparison between a nickel and graphite HSA mass is shown in Figure 5 for various numbers of GPHS modules arranged as shown in Figure 4.

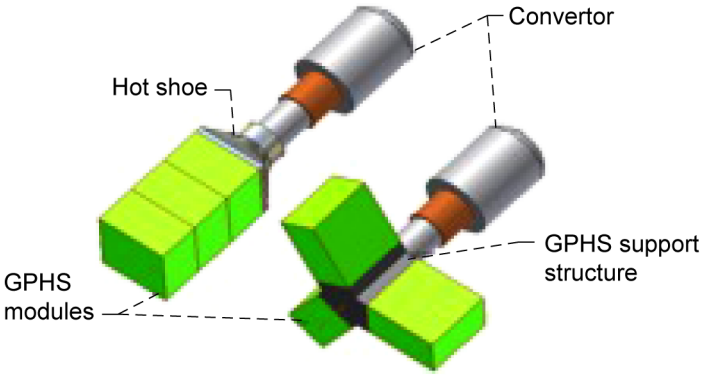


Figure 3.—General Purpose Heat Source (GPHS)/Stirling arrangements.

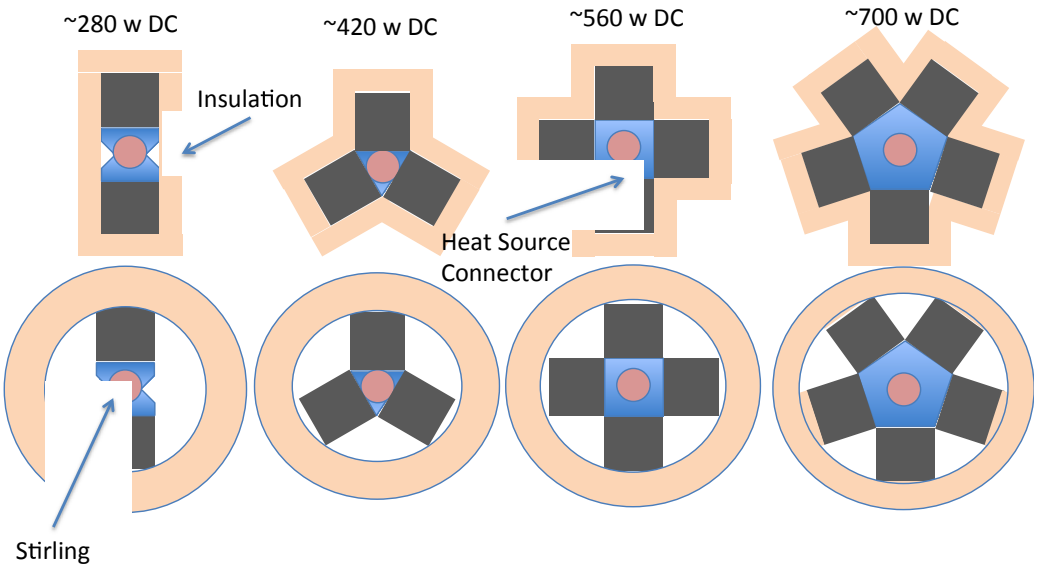


Figure 4.—General Purpose Heat Source (GPHS) arrangements.

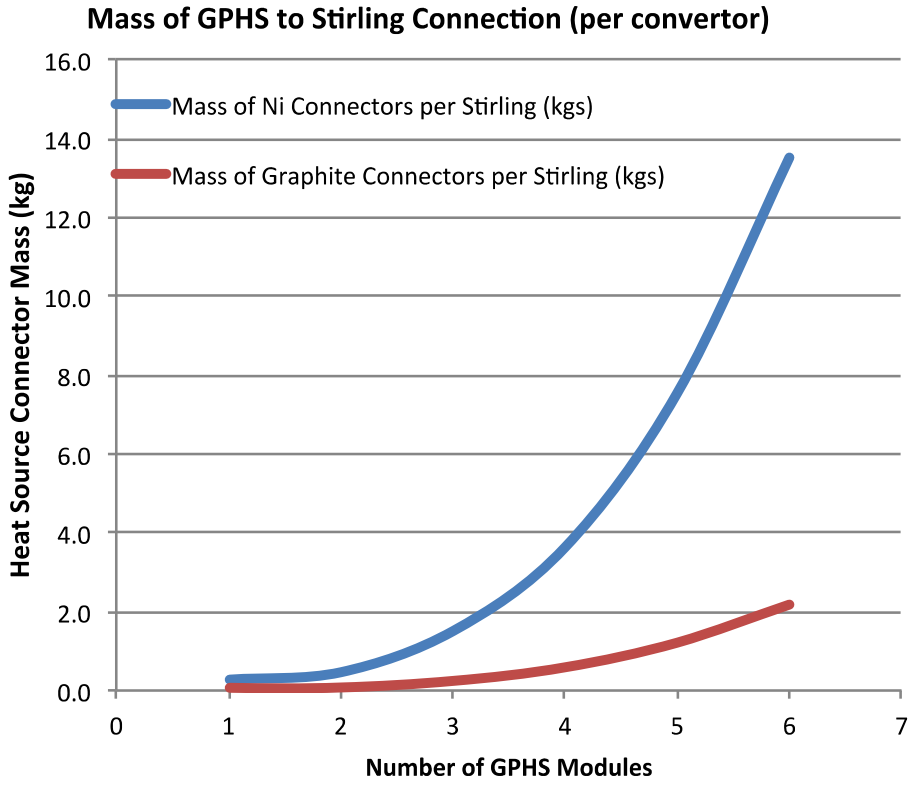


Figure 5.—Hot-side attachment (HSA) adapter as a function of the number of General Purpose Heat Source (GPHS) modules and connection material.

3.3 Insulation

Multilayer insulation (MLI) is considered as a possible replacement for the MicrothermHT solid thermal insulation currently used in the ASRG. High-temperature MLI was the thermal insulation used in the GPHS radioisotope thermoelectric generator (RTG), which was used on Cassini, Galileo, and New Horizons. The change from a solid insulation to a MLI, which requires a vacuum to be effective, would eliminate the SRGs use on planetary bodies with an atmosphere but should provide a higher specific power system when used in vacuum. The ASRG is a modified version of the SRG–110 generator discussed in Reference 4. The primary difference between the ASRG and the SRG–110 is that the ASRG replaced the Infinia Stirling convertors with Sunpower ASCs. Because the housing was a carryover from the SRG–110 program, its size and dimensions were set to optimize the SRG–110 that had a Stirling hot end temperature of 640 °C. During the development of the ASC there was a material change from the SRG–110's Stirling convertor Inconel heater head to the ASRG's MarM-247. This gave the ASRG the potential to have heater head temperatures in excess of 840 °C. Unfortunately, since the maximum insulation thickness was set by the original SRG–110 beryllium housing dimensions the optimal temperature based on balancing heat loss through the insulation and heat into the Stirling convertor resulted in a generator peak power temperature of 760 °C. It is desirable from a system perspective to explore variations in insulation and/or higher performing insulation to decouple the housing/radiator size. Figure 6 shows conceptually the trade between coupling the insulation thickness to the radiator diameter and by decoupling the insulation size from the insulation. Case A shows the blue radiator/housing diameter set at the thickness of insulation. This requires that the radiator must increase the cylindrical height in order to increase its surface area. Case B shows a decoupling of the radiator/housing diameter from the insulation thickness. This requires a larger CSA but results in a shorter effective fin length (when defined from the CSA housing attachment point to the end). Case B also requires additional support structure to contain the insulation and this was modeled as a thin-walled aluminum shell. The PSM allows the user to select MLI, MicrothermHT in a vacuum, and MicorthermHT in a Mars environment as well as consider coupling the housing diameter and the insulation diameter.

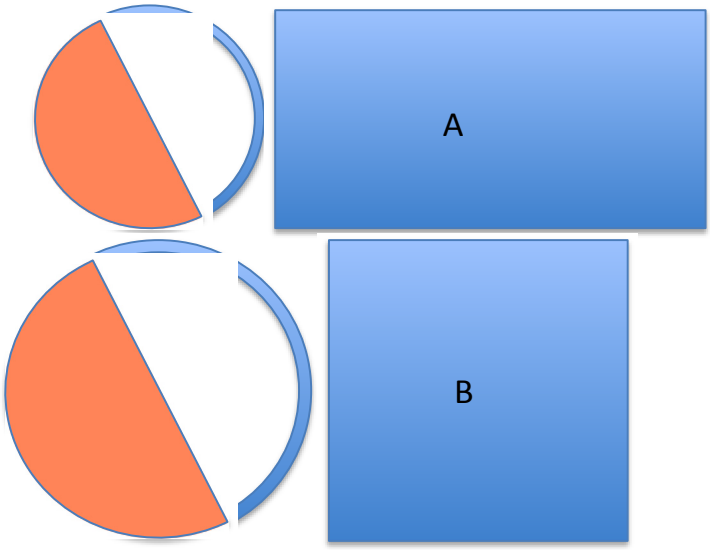


Figure 6.—Insulation sizing and scaling.

3.4 Stirling Convertor Performance

As was discussed earlier in this paper the performance of a Stirling convertor is related to both the Carnot efficiency and the fraction of Carnot efficiency. Stirling development at NASA Glenn Research Center and in industry has shown continuous improvements in both efficiency and mass. In 2004 during the SRG–110 program, the Stirling Technology Company (STC) created the Technology Demonstration Convertor (TDC) and was able to achieve approximately 47 percent of Carnot efficiency at a TR of 2.86. With the switch to the Advanced Stirling Convertor (ASC) and the intervening 8 years Sunpower was able to demonstrate 56.5 percent of Carnot at a TR of 3.3. Internal differences between the two convertors and materials changes resulted in the increased fraction of Carnot performance. It is important to understand the impact of higher performance on the overall performance of SRGs in general. The Novikov engine represents a semi-ideal heat engine operating at maximum power output in which heat transfer is irreversible but other components are ideal. In practice this represents a practical upper bound for engine efficiency and is useful to compare with the results currently being achieved in modern Stirling convertors. The Chambadal-Novikov efficiency is calculated by

$$\text{Novikov heat engine efficiency} = 1 - \sqrt{\frac{T_c}{T_H}} \tag{6}$$

The PSM allows user inputs of either a fixed fraction of Carnot, the Novikov efficiency along with other models of engine efficiency as a function of TR. At a TR of 3.3 the Novikov efficiency prediction is 56 percent of Carnot (including a 87 percent efficient alternator). Comparing this with the achieved 56 percent of Carnot for the ASC suggests it is very near the practical limits of what can be achieved with a heat engine.

3.5 Cold End Interface/Housing

The CSA moves heat from the Stirling to the housing. The CSA is attached to the Stirling convertor cold end and extends radially out to the radiator/housing. Figure 7 shows both a conventional solid CSA on the left and a heat pipe CSA under development at NASA Glenn on the right. The housing/radiator is a cylinder whose inner diameter is set by the housing of the GPHS modules and length set by the required area. Temperature drops in the CSA are measured from the outer heat rejection wall of the Stirling convertor cold end to the inner surface of the cylindrical radiator. Attachment points to the radiator/ housing are assumed to be ¼ of the distance from either end of the final height of the cylinder to make each of the ¼ radiator sections reject similar amounts of heat. The interconnect tube, which joins the two convertors together is sized based upon Stirling convertor length, radiator length, and the ¼ point attachment distance.

The PSM will either calculate the thickness of the CSA based on allowable temperature drop or the thickness can be set with the resulting temperature drop calculated. The greater the temperature drop allowed in the flange, the lighter the CSA mass but the lower the overall effective temperature of the radiator. This in turn leads to a larger radiator size and higher housing mass. One technology option under consideration is the replacement of the solid CSA with a water heat pipe, which would provide both a lower mass connection from the Stirling to the housing and also reduce the temperature drop over this same distance. Temperature drops into and out of the heat pipe CSA is based upon evaporator and condenser heat flux, heat pipe wall thickness, and working fluid selected. The obvious disadvantage in using a heat pipe CSA is the potential reliability penalty paid for this new heat transport device.

Just as in the CSA, the housing can be a solid conductive piece (as the Be housing of the ASRG), or it can have heat pipes embedded on the interior surface to augment heat transfer. Trade can be made using different materials (i.e., beryllium vs. aluminum) with or without the addition of heat pipes. Fin thickness of the housing/radiator can be set by fixing the temperature drop from the outer cold end flange to the

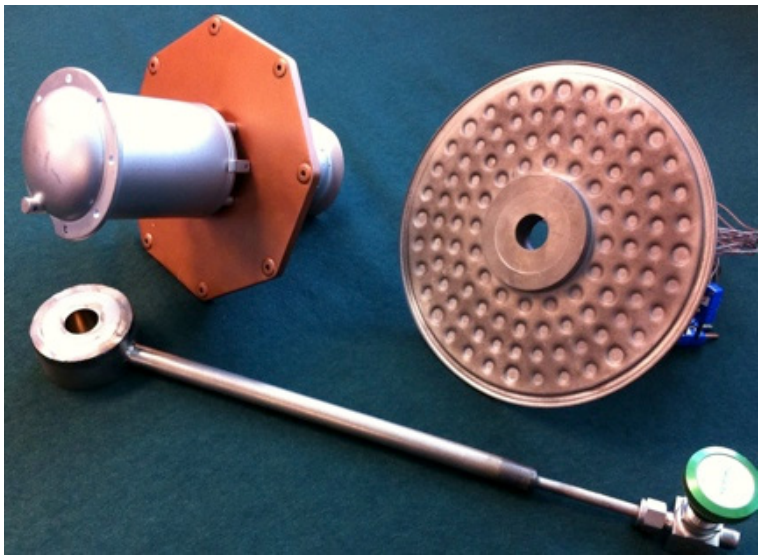


Figure 7.—Heat pipe cold-side adapter under test at NASA Glenn Research Center.

average radiator surface temperature. Increasing housing thickness or embedding heat pipes in general allows the surface area of the housing to be a more effective radiator by decreasing the temperature drop from the CSA to the average radiator temperature. The PSM allows the user to select either a solid (a variety of material properties are included) or heat pipe CSA. Additionally, the heat pipe material and working fluid may be selected.

4.0 Results

Table 1 shows a number of trades that were performed over the last year using the PSM. Below are some details of a few of these to illustrate the outcome of these studies.

The PSM was exercised to look at how its projected results compare with the ASRG. Figure 8 shows a plot of component and system mass as a function of Stirling cold end temperature. Each cold end temperature is associated with a 140-W generator. Each cold end temperature represents different convertor efficiency and therefore a different heat input and heat rejection requirement. Several of the larger components mass variations are included to help illustrate how the various systems are interacting. Notice that as the cold end temperature rises the mass of the radiator drops due to its T^4 dependence on heat rejection. As the cold end of the cycle rises the efficiency is dropping. In order to produce 140 W, the heat input to the Stirling convertors must increase. This additional heat is obtained by increasing the thickness of the insulation surrounding the GPHS modules. This can be clearly seen when looking at the insulation mass rapid rise around 360 K. The consequences of this increase in insulation thickness are a larger radius and more massive CSA and a larger more massive housing/radiator. It is this interplay that results in the step change at around 360 K and forces the system to add an additional GPHS module to meet the 140 W requirement while maintaining the 760C/97 °C (1033/360 K) TR. Although the cylindrical housing assumption will create a somewhat different system optimization than the rectangular block housing with fins of the ASRG, the overall results should be similar. Note that the PSM predicted maximum power occurs at a Stirling cold end temperature of 320 K while the ASRG maximum power point is 311 K.

In future plots when considering a range of power outputs one could make general conclusions about technology insertion trends. These future plots will only relate best specific power points. Each point shown in Figure 9 through Figure 12 is obtained by running an optimization similar to that shown in Figure 8.

TABLE 1.—TRADE STUDY COMPARISON EXAMPLES

Trade Study Space
PSM Results vs. ASRG Design
General Power Scaling Results
Comparison of Single Convertor with and w/o Balancer
Hot End Temperature Variations
Beryllium vs. Aluminum Housing
Variable Stirling Convertor Performance
Space Only vs. Multi-Mission Capable SRG
Single Convertor Systems

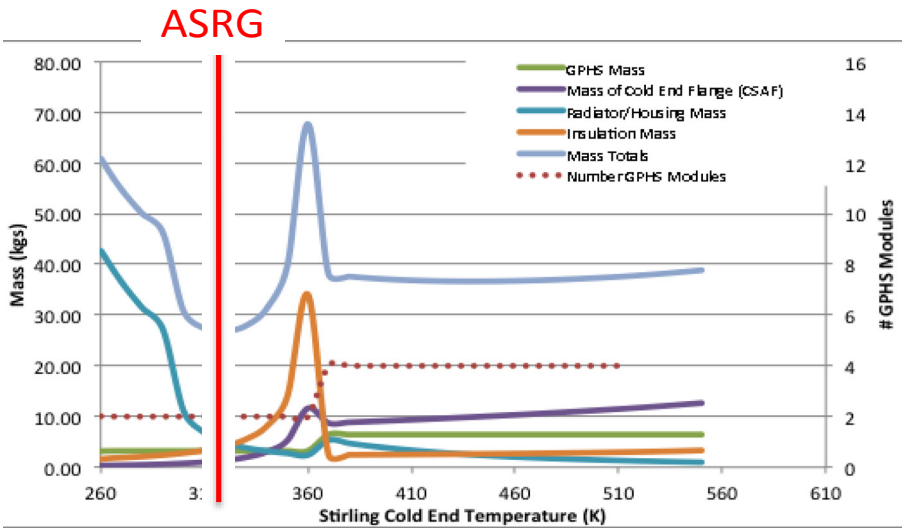


Figure 8.—A 140-W SRG system mass and number of GPHS modules as a function of cold end temperature.

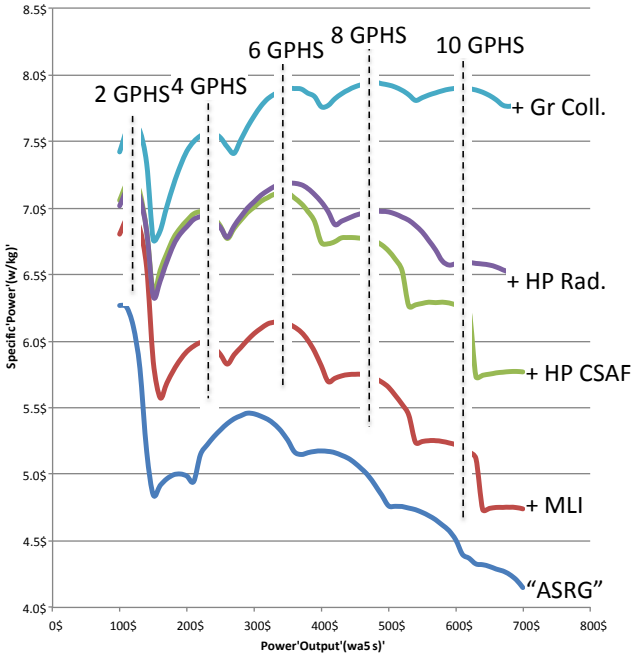


Figure 9.—Five technology insertion options for SRGs.

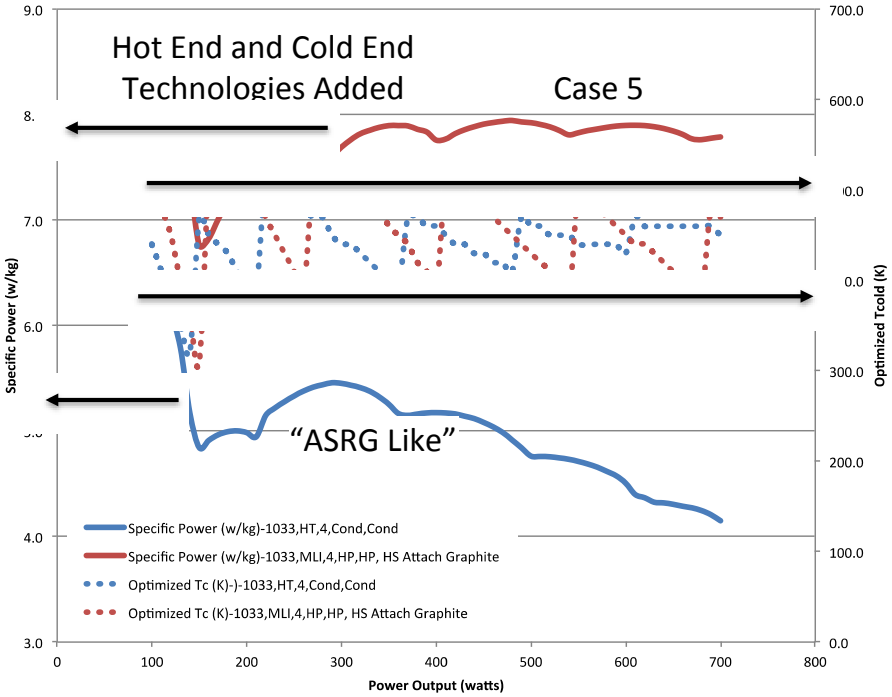


Figure 10.—Best specific power cold end temperature.

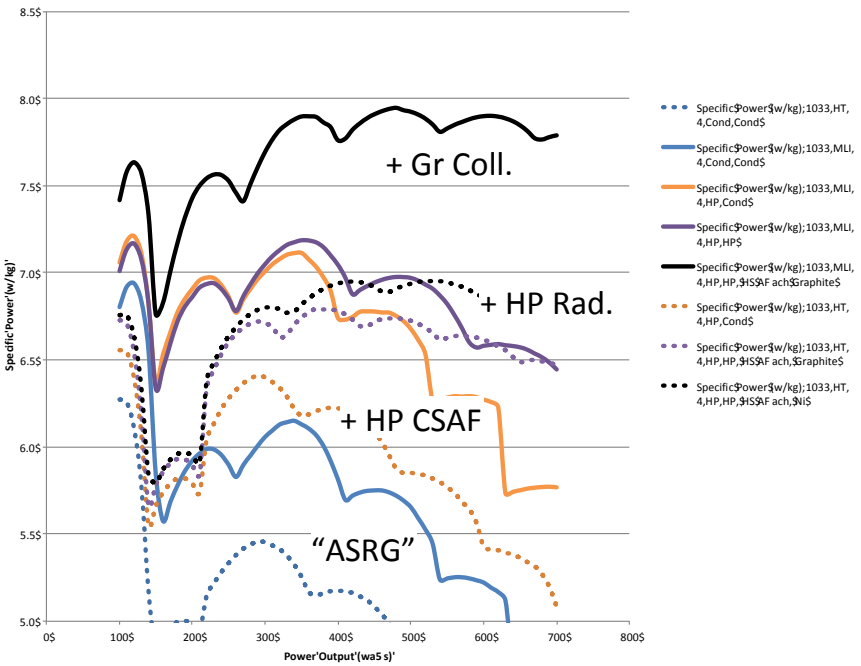


Figure 11.—Multimission capability.

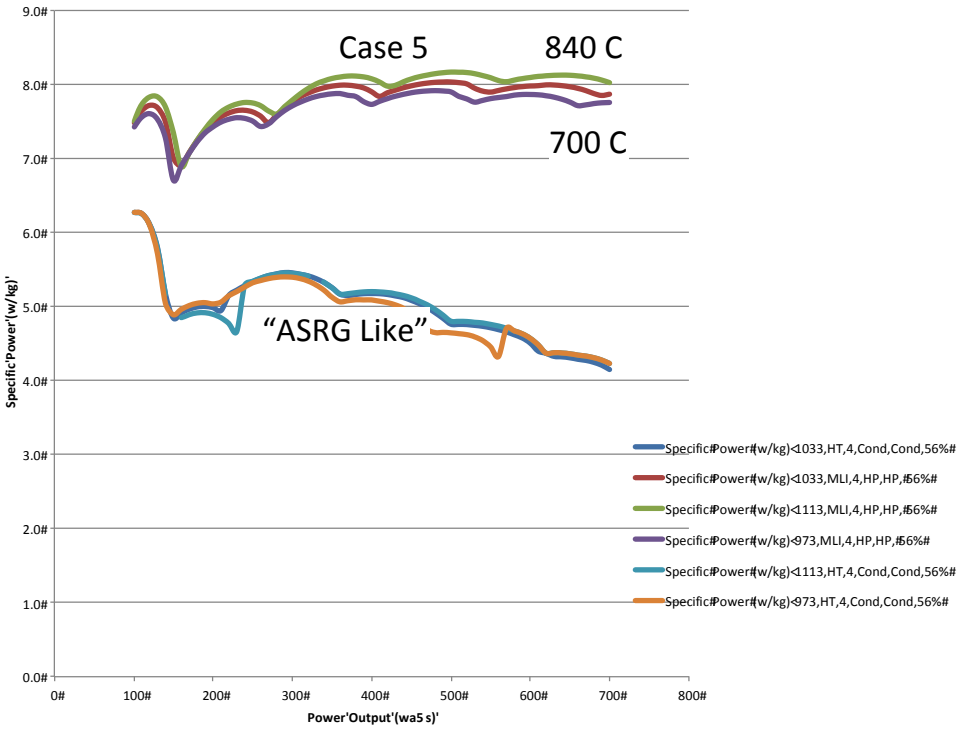


Figure 12.—Heater head temperature.

4.1 System Trade Space

In order to quantify each of the material/configuration options available in the PSM impact, the system five different combinations were considered as starting points for this analysis and then an additional parameter was varied in order to see its impact on specific power.

The five cases are as follows:

1. An "ASRG-like" system is used that has similar conductive interfaces with the same materials used in the ASRG as well as in solid insulation around the GPHS modules
2. A space-only system where the solid insulation around the GPHS modules is replaced with MLI
3. A space-only system with the replacement of the solid CSA with a heat pipe CSAF
4. A space-only system where in addition to the heat pipe CSA heat pipes are added to the radiator
5. A space-only system where a highly conductive graphite heat collector is added to join the GPHS modules to the Stirling convertor (4 + graphite)

These five different cases span a range of possible technology insertions into SRG systems, which should have a meaningful impact into how these systems scale. Figure 9 shows the five options inserted in order serially from 1 to 5. In general, peak specific power occurs in 120- to 130-W increments that correspond to best specific power points associated with each pair of GPHS added to the system. MLI and both heat pipe systems add approximately 1 w/kg to specific power over the range of power considered. Above 400 W specific power decreases unless all technology insertions are implemented. The lumpy nature of the specific power plot is a result of the interplay between insulation thickness, CSA thickness, and radiator area. Figure 10 shows cold end optimal temperature for both Cases 1 and 5 that further illustrate this interplay. Optimal cold end temperature in all but the two GPHS cases occurs between about 400 and 500 K, which is significantly higher than the ASRG's 311 K. The reason for this change is because of the increasing importance of radiator area, HSA, and CSA to the overall mass of the system. Notice that peak

specific power always occurs about halfway between the maximum and minimum optimized temperature range for any given number of GPHS modules. As an example let us look at Case 5 for a SRG producing 450 W. Optimal specific power of just about 8 w/kg occurs at a cold end temperature of about 450 K. This SRG uses eight GPHS modules to generate this power but the actual range of an eight-GPHS SRG is from 400 to 550 W. At 400 W the insulation can be very thin and thus the heat losses through the hot end are large and still achieve the 400 W required output. Additionally, the Stirling convertor does not have to be very efficient and the heat rejection temperature can be high (low Carnot efficiency). As power requirement rises above 400 to 550 W, efficiency becomes more important as well as requiring thicker insulation and then the optimal cold end temperature drops.

Multimission capability, which is the ability to operate on the surface of Mars or other planets/moons with an atmosphere, is not possible with MLI. Just like in the GPHS RTG, the superior performance of MLI allows higher specific powers to be achieved at the expense of Mars surface operation. The vast majority of RPS have been used as either orbiters to the outer planets or as vehicles that flyby another body. From a SRG design point the superiority of the MLI allows some decoupling of the housing diameter from the number of GPHS modules. This decoupling then allows the size (diameter and length) of the housing/radiator to be less influenced by the GPHS arrangement and diameter. Figure 11 shows comparisons of Cases 1 through 5 and the specific power changes due to the addition of MLI. The solid lines are associated with MLI, while the dotted line of the same color use MicrothermHT. In general, about 1 w/kg increase in specific power is found when using MLI versus MicrothermHT. The additional mass is a direct result of the increased thickness of the insulation and the downstream consequences of a larger CSA, higher temperature drops to the radiator, and therefore larger radiator. Case 5 MLI (with the other additions) does allow nearly constant specific power with power that is not possible using the MicrothermHT solid insulation. The flexibility in decoupling the specific power scaling from the absolute power level allows the design of a future SRG to be based on projected spacecraft requirements.

Just like fraction of Carnot efficiency can decrease isotope consumption, raising the hot end temperature can also increase efficiency by raising the Carnot efficiency of the engine. However, the higher temperatures lead to reduced material margins and increased heat losses through the insulation and/or thicker insulation. Figure 12 shows specific power as a function of power level and heater head temperature. For the ASRG-like systems, the range of heater head temperatures explored shows little difference between the 700 and 840 °C temperatures. This is due to the balance between hot end losses and efficiency gains of the system. This is exactly what is seen in the ASRG as it is fully capable of higher temperature operation but peak power occurs at 760 °C at BOL. With MLI and the other heat transfer enhancements for Case 5, one can see some advantages by going to higher heater head temperatures with the peak difference being about 0.25 w/kg.

5.0 Conclusions

A computer tool was developed to help understand how power output, material substitutions, and technology changes impact a Stirling Radioisotope Generator (SRG) mass and volume. The Parametric System Model (PSM) has shown that in order to increase specific power at higher power levels than the current Advanced Stirling Radioisotope Generator (ASRG), improvements must be made in insulation and heat transport systems within the SRG. Additionally, future SRG systems when optimized for highest specific power most likely require higher cold end temperatures than that found in the ASRG. Results from this analysis show that peak specific power using components similar to those used in the ASRG occur at around 6 w/kg and in about 120-W increments. The components, which made the system “similar” to the ASRG, were solid insulation and conductive heat input and heat rejection from the Stirling convertor. Projecting the insertion of technology advances such as higher performance materials and heat pipe heat transport allows the system to have improved specific power with increasing power and provide about 8 w/kg above 500 W.

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