The Use of Redundancy to Improve Reliability of Deep Space Missions Using Stirling Radioisotope Generator Power Sources

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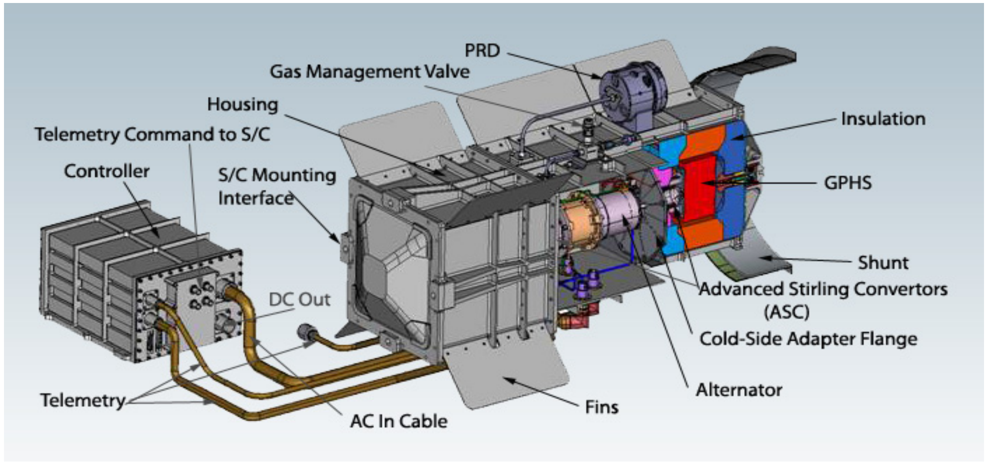
Advanced Stirling Radioisotope Generator background

- ASRG was a 140-W flight radioisotope power system being designed and built by Lockheed Martin, under contract to the Department of Energy
- Assembly of the ASRG Qualification Unit was to have begun in 2014
- Significant flight development completed of the Stirling convertors, controller, and generator housing
- Termination of the ASRG flight contract announced late 2013
- Contract closeout in process
- NASA has proposals in place that, if funded, would allow this hardware to go on test at the NASA Glenn Research Center (GRC).



ASRG Flight Unit

Advanced Stirling Radioisotope Generator Future Work

- The Advanced Stirling Radioisotope Generator (ASRG) was funded by NASA as a candidate for the next generation of radioisotope thermal to electrical converters for use by future NASA missions.
- Considering the current budget-constrained environment, and with an adequate supply of plutonium dioxide NASA has decided to discontinue procurement of ASRG flight hardware.
- The hardware procured under this activity will be transferred to the Glenn Research Center to continue development and testing of the Stirling technology.
- <u>It is in the context of this continued Stirling development that the work presented in this paper is presented</u>

Advanced Stirling Radioisotope Generator Path Forward

- The proposed path forward for the RPS program is to complete the engineering unit of the ASRG and continue to verify key reliability and life requirements through a combination of specific requirement tests and extended operational life testing.
- It will also survey mission needs in the next decade for RPS mission opportunities. Initial study results show mission power needs in the 100 We to 1000 We regime. Based on these projected needs the RPS program is looking at how the legacy ASRG design can meet these needs along with looking at potentially larger size generators.
- This work will describe how the cost of reliability to a mission in terms of added spares is optimized and accounted for

Purpose of Study

- This paper describes the application of a simple reliability tool to determine the minimum number of generator units needed to comply with a power generation system reliability requirement.
- The tool accounts for the use of fuel and the increase in system weight due to the addition of spare units. The tool can be used by system designers to trade power, mass, fuel and reliability and explore optimum solutions.

Overview of Study

- This study will look at the 140 We class generator as originally envisioned for the ASRG and a larger generator that is scaled up to use four times the fuel.
- The results discussed below quantify the effect of the use of smaller generators and indicates that a scheme that makes use of several smaller generators enhances the system reliability and allows for more graceful degradation.

Goals of this work

- Illustrate the concept of enhancing reliability by adding spares
- Ensure that the system can be adapted to missions with different power requirements and reliability goals;
- Develop a simple tool to facilitate the work for future RPS technology planners.
  - This tool will optimize the use of spares to meet overall reliability goals, and ensure that the required mass and fuel impacts of spares necessary to meet overall goals are accounted for.

Building Blocks

140 We Building Block		
Output Power @ end of life	113	We
Reliability @ end of life	0.9	
GPHSs	2	GPHSs
Mass	32	Kg
GPHS Heat @ end of life	219	Wth

500 We Building Block		
Output Power @ end of life	408	We
Reliability @ end of life	0.9	
GPHSs	8	GPHSs
Mass	75	Kg
GPHS Heat @ end of life	219	Wth

- To illustrate simply the impact of reliability on mass and fuel usage, our building blocks were limited to 140We and 500 We class generators.
- This allows us to illustrate key points without complicating the argument.
  - The method we used is applicable to the inclusion of other generators, and was developed in a modular method to streamline their inclusion.

Theory

- We defined the following:
  - r (unit) = the reliability of a single unit at end of life
  - r (system) = the reliability of a power generation system
  - Number Spares = total numbers of spares in system
  - Number Required = total number of operation units required
- If a system is constructed without any spares, all units are required to meet the reliability requirement. The reliability of this system is given by the following formula:
  - $r\ (\text{system}) = r\ (\text{unit})^{\text{Number of Required Units}}$

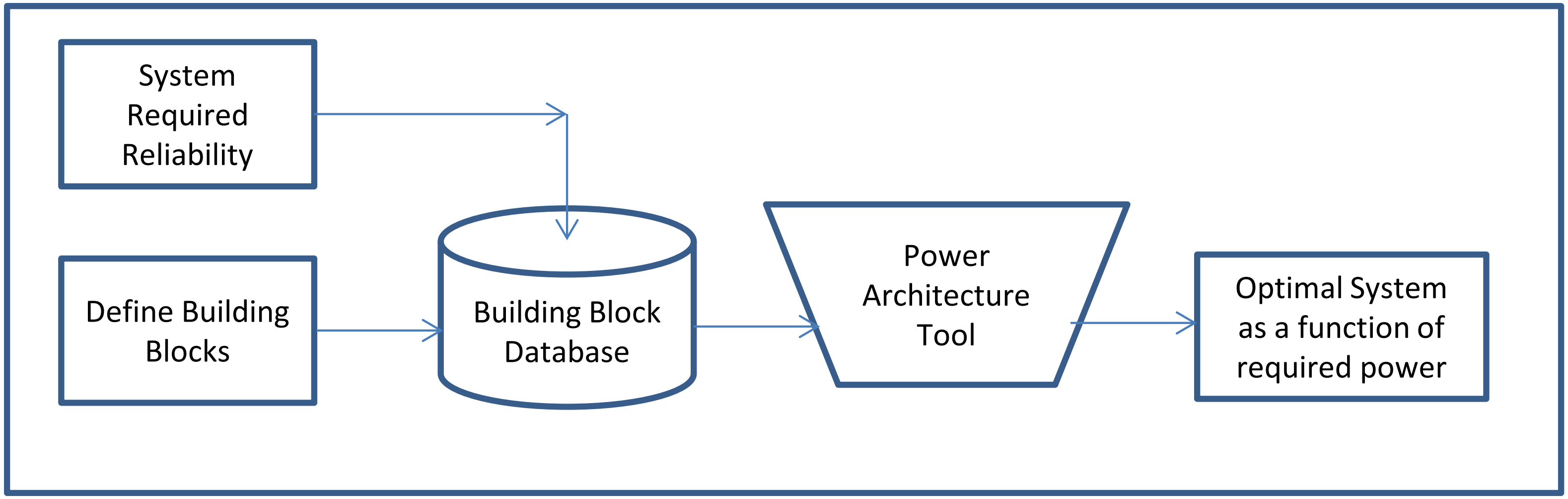
Theory – Effect Of Spares

- The reliability of a system can be improved through the use of spares. This allows for units to fail and still meet the reliability requirement. There are many combinations that can lead to an acceptable amount.
- We define the following:
  - M = the total number of building blocks in a system
  - N = the total number of building blocks whose failure can be tolerated within the constraint imposed by the reliability requirement (note that if there is no spare, P_1 reduces to the previous formula).
  - P_1= r (system) = the reliability of a power generation system
- The calculation we used is given by the following formula: The probability of success, P_1, is:

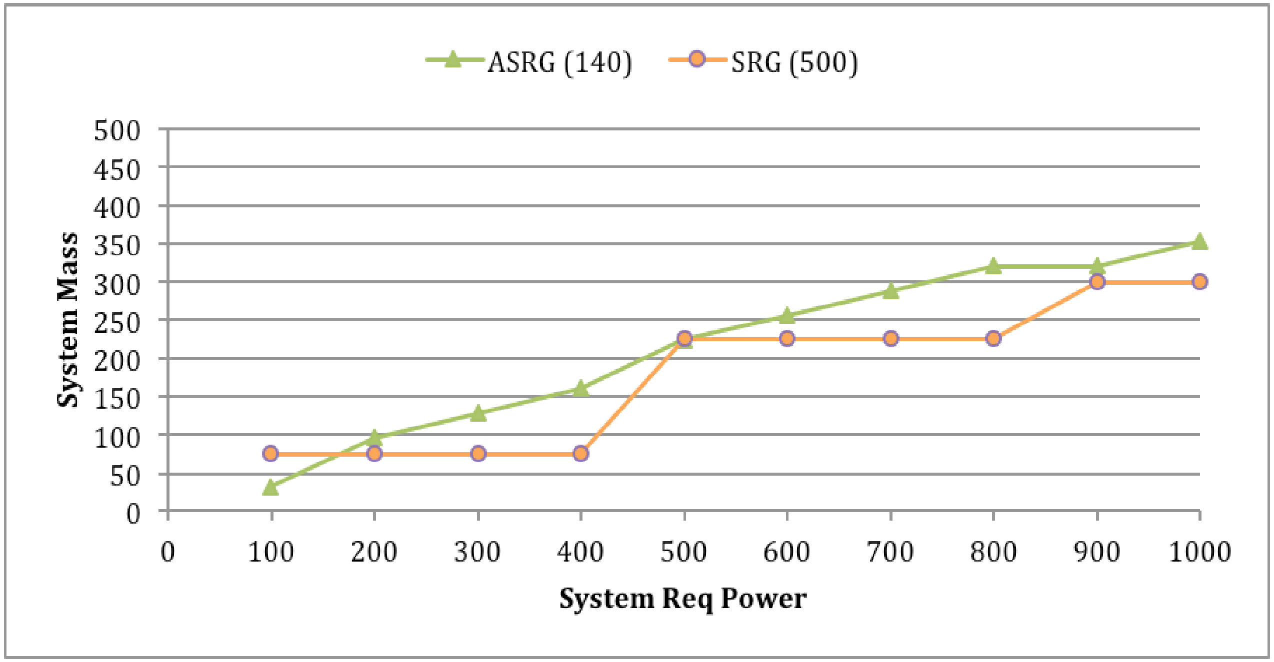
$$P_1 = \sum_{n=0}^{N} \binom{M}{n} (1 - \mathrm{r})^n r^{(M-n)}$$

Power Generation, Reliability based Architecture tool

- A tool was developed to optimize a power generation system across multiple system required power levels and reliability goals.
- The tool uses a database of standard building blocks as specified in the figure below. The tool can be run across the required power levels at the system level at various reliability goals.

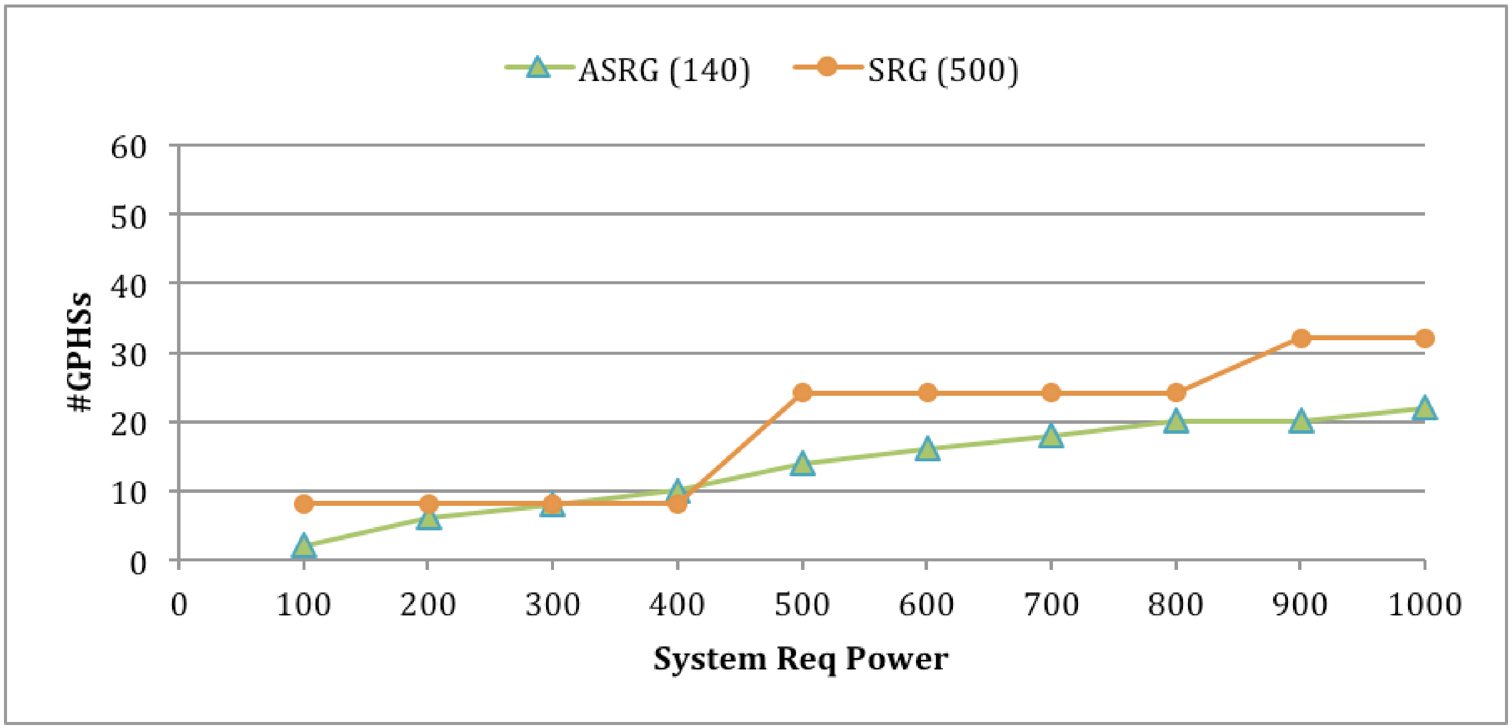


Results – 1 of 4



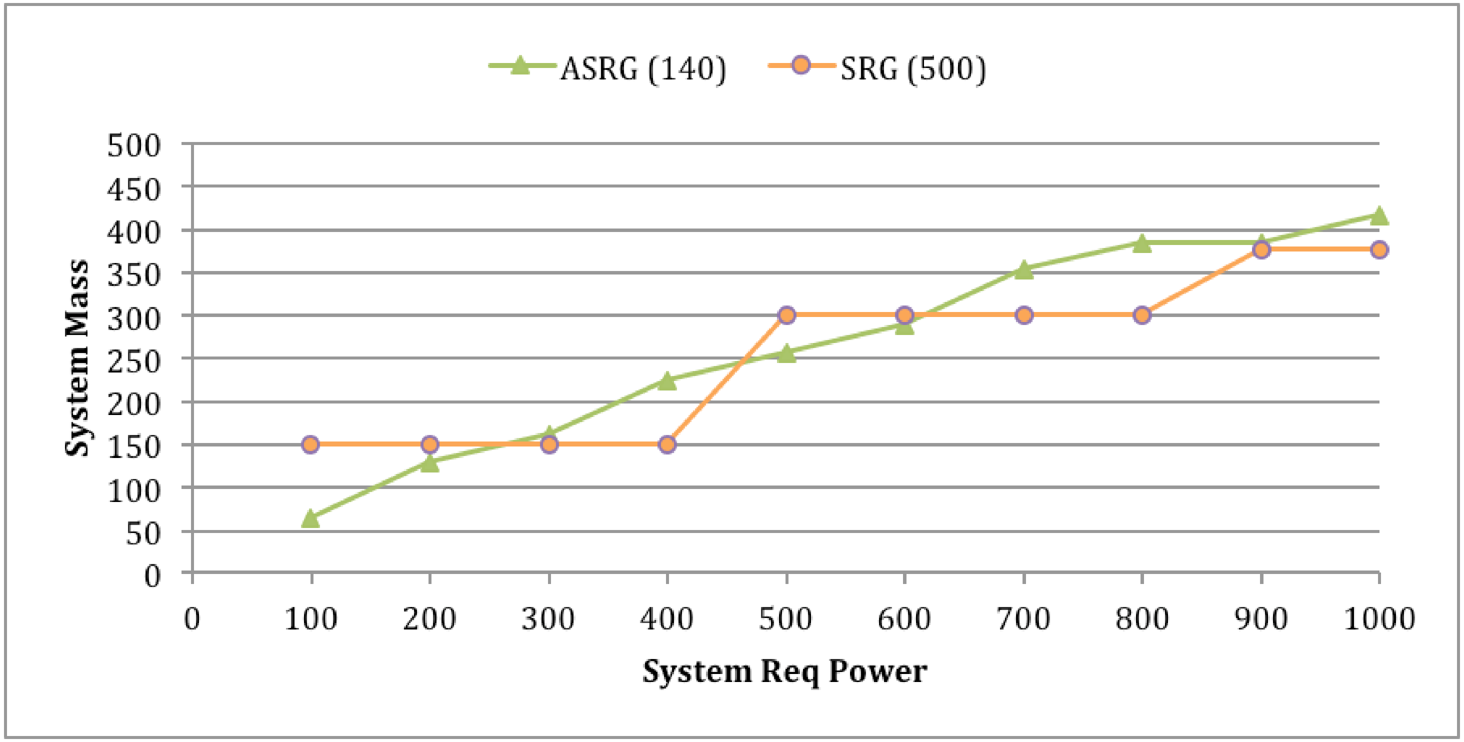
- Total system mass vs total system required power to meet system reliability goal of 90 % at EOL

Results– 2 of 4



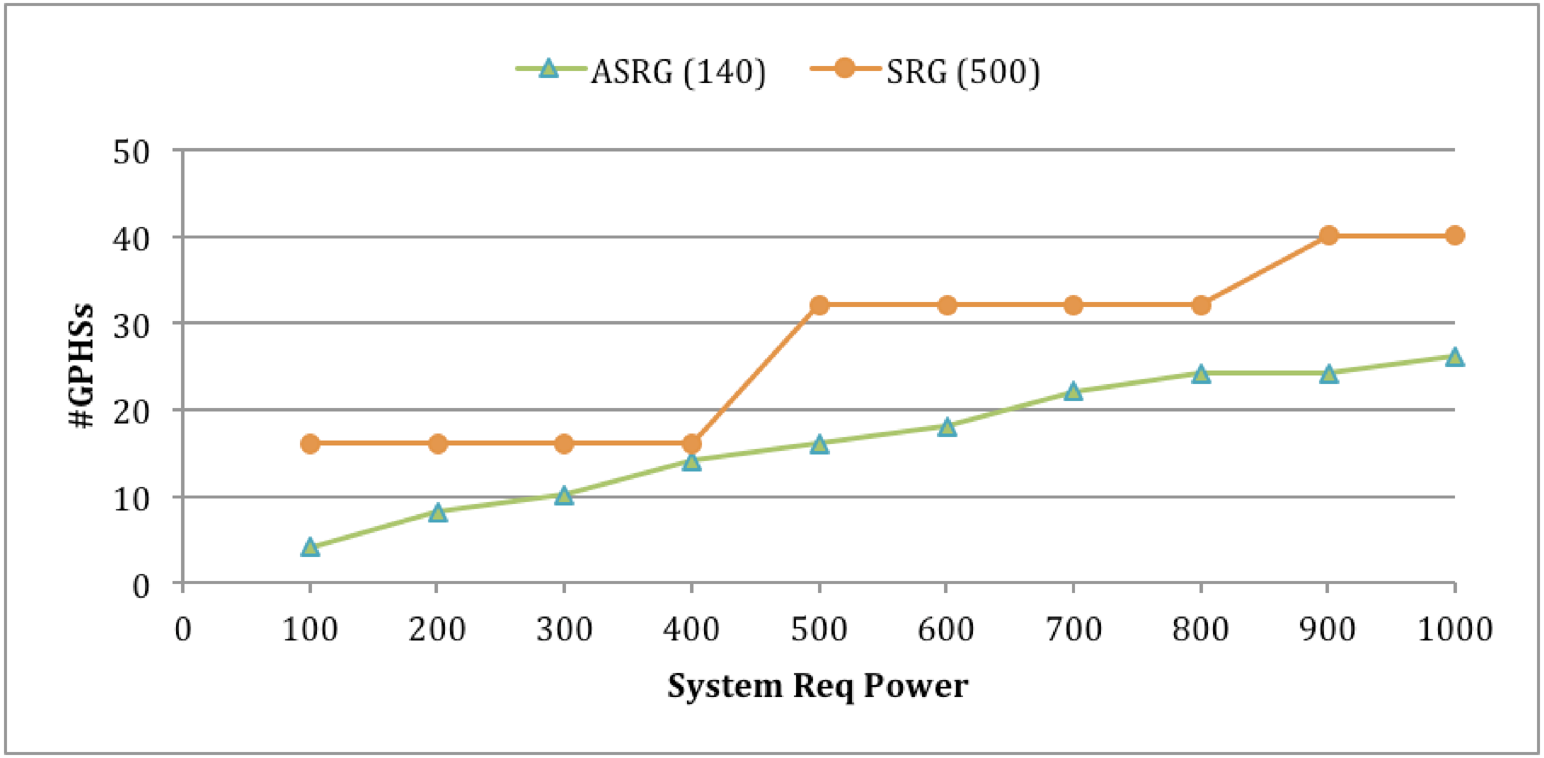
- GPHSs required to meet system-required power with a reliability goal of 90 %.

Results– 3 of 4



- Total system mass vs total system required power to meet system reliability goal of 99 % at EOL

Results– 4 of 4



- GPHSs required to meet system-required power with a reliability goal of 99 %

Results

- Our analysis clearly shows the effect of the redundancy on both total system mass and GPHS fuel used.
  - For the 90 % reliability requirement contrasting the two building blocks, one can see a system made up of smaller ASRGs will not be as mass efficient but it does allows for more graceful degradation.
  - For the 99% reliability requirement the mass penalty of redundant units is comparable, but the use of fuel is minimized when smaller building blocks are used.
- Reliability in both cases is achieved through redundancy. This redundancy has a cost in both mass and GPHSs used.
  - The systems made up of smaller generators compare favorably when this additional mass to meet system level reliability requirements is counted. In addition the graceful degradation afforded by the smaller building blocks can come into play, if the system were to experience additional failures.
  - The power will only incrementally decrease (by the amount provided by one unit). This demonstrates the concept of graceful degradation of a system made up of smaller components.

Conclusions

- Redundancy is a powerful method to achieve reliability.
- Redundancy, together with the use of smaller generators allows for graceful degradation at lower overall expense.
- This needs to be traded against the higher mass efficiencies of larger generators.
- Our tool and method allows one to quantify this and for system designers to find the optimal generator size as a function of overall reliability and power generation goals.

- ***As we mentioned initially proposals are in place to continue work in Stirling generators at GRC. Our analysis results are offered in the context of improving power Stirling power system reliability in the future should funding continue.***