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DYNAMIC RPS PATH TO FLIGHT

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NASA Glenn Research Center has been pursuing the development of dynamic power conversion for several decades. Candidate NASA missions involve mutli-year travel to far away destinations, or to extreme environments where sunlight does not exist. Human-base mission studies also show that power needs would be beyond the capabilities of solar energy conversion, and instead would require nuclear reactor energy sources, for which the thermal energy must be converted to electricity. Dynamic power conversion technology has developed sufficiently to make a sound engineering argument that it is suitable for these NASA missions. Dynamic conversion power sources have yet to be flown in space, and thus suffer a disadvantage owing to their lack of heritage data on flight missions. One of the largest obstacles for adoption is the uncertainty in reliability of a device with moving parts. However, significant progress has been made toward demonstrating the technology capable in all relevant environments, with the necessary long life. Another hurdle for adoption is the lack of mission, which would drive specific requirements, and provide a solid timeline for technology development endpoint. Until a mission is identified, an alternative approach is necessary to advance a dynamic power conversion system towards flight.

I. BACKGROUND

Despite the cancellation of the Advanced Stirling Radioisotope Generator (ASRG) project in 2013, NASA in still investing in the development of power systems that utilize dynamic energy conversion. Significant progress has recently been made on this latest chapter of development, and prototype hardware from ongoing contracts will begin arriving in late 2019 (Ref. 1). Dynamic conversion offers several advantages over the status-quo, solid-state option that is thermoelectrics. In the case of systems using radioisotope heat sources, the availability of Pu-238 leads one to pursue higher conversion efficiency. Dynamic conversion can offer up to 40% thermal to electric efficiency, compared to the 6% efficiency provided by thermoelectric conversion. The higher efficiency also results in less waste heat for the spacecraft to accommodate, which could be an advantage for some compact designs. Dynamic power convertors have designed for a wide range of environmental chemistries, so a common design could be used for a range of missions, such as Mars, Titan, or Triton. Dynamic energy conversion is also extensible to much higher power levels than Radioisotope Power Systems (RPS). This technology would be viable for a multi-kilowatt power system necessary for human exploration missions. Such a system is attractive for a lunar base, as it would provide high conversion efficiency, long maintenance-free life, and operate regardless of the presence of solar energy. The technology has also demonstrated degradation-free performance over timespans representative of lengthy science missions. With this, mission designers would only have to anticipate power loss over time due to the Pu-238 fuel half-life decay itself, which amounts to approximately 15% over a 17 year mission.

II. REQUIREMENTS DEFINITION WITHOUT A SPECIFIC MISSION

In the absence of a defined mission, an alternative approach was employed by NASA to guide dynamic RPS. The RPS Program has chartered a Surrogate Mission Team (SMT) comprised of RPS community parties, NASA, DOE, and flight centers (JPL, APL, GSFC). The purpose of the team is to provide a stand-in for an actual mission. The team adopted a philosophy that the dynamic RPS should be applicable to as many missions as possible, to encourage adoption. Tailoring the requirements to one particular mission would constrain the design and perhaps disqualify its use unnecessarily. The method for this exercise was to examine all candidate destinations, and then choose the most important requirements where possible. For example, the thermal environment requirements encompass the wide spectrum of situations, including operation on the ground for qualification testing, deep space vacuum, lunar surface, and planetary protection processes. Similarly, the range of possible launch vehicles was examined, and the requirement set on the RPS to sustain the worst case random vibration. Life requirement was set at 12 years to cover the longest outer planets mission, and requirements for static acceleration were imposed to support a mission with entry, descent, and landing stages. A summary of the dynamic RPS requirements formulated by the SMT is shown in Table I. At first glance, this philosophy may look untenable, as it is attempting to prescribe a one-size-fits-all generator, which is atypical for spaceflight. However, these requirements were decomposed down to the convertor level, for the recent convertor development contracts, and found to be achievable. In their proposals, the contractors were given the freedom to choose which of these requirements would be imposed on their designs. The vast majority were adopted and contractors indicated such design work was within their engineering capabilities, bolstering the idea that dynamic conversion technology is widely applicable. In some regards, these designs are more ambitious than those from previous dynamic RPS projects (notably the thermal environment range). However, other performance targets were relaxed to open the design space. For example, the conversion efficiency target has been relaxed relative to previous technology development efforts, and emphasis has been placed on robustness. The contractors were encouraged to trade specific power for elements of robustness. System engineering estimates show that the convertor specific power need not be better than 20 W_e/kg to enable a reasonable RPS mass.

TABLE I. Summary of surrogate mission team's dynamic RPS requirements.

Item	Description
Design Life	12 years
Power	200 to 500 W_e
Efficiency	18% min.
Atmospheric compatibility	Earth, vacuum, Mars, Titan, Triton
Thermal environment	4K vacuum to 120°C air
Static acceleration	20g 1 minute
Random vibration	10.4 g_{rms}, 1 minute
Radiation	300 krad

III. ENCOURAGING DYNAMIC RPS ADOPTION

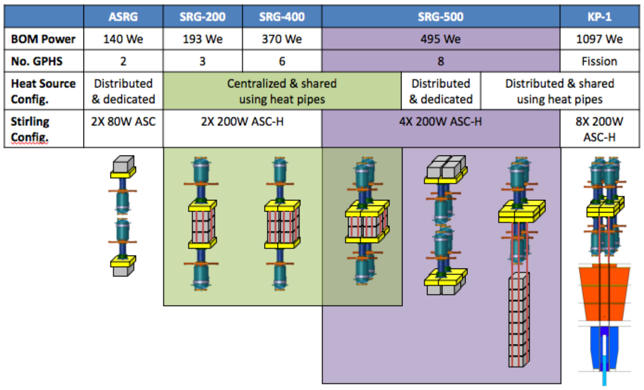
The life requirements associated with RPS are atypical in the realm of spaceflight qualification. Demonstrating margin on life via experiment is not possible. Any use of a new conversion technology must accept some level of risk. The first mission to use a dynamic RPS must either have it prescribed by mission requirements, or be significantly compelled to do so by the advantages offered by dynamic conversion. The goal of the dynamic RPS project at NASA Glenn is to raise the dynamic convertor technology readiness level to 6. This would be focused on demonstrating the technology in an environment relevant to the requirements, which would provide a confident starting point for flight generator development to begin. This effort will comprise independent test and analysis activities. Examples include, thermal vacuum operation, performance mapping, operation during launch-level random vibration and static acceleration, and long-term continuous operation. Efforts will also focus on independent model validation and development of unique dynamics models. Specific risk mitigation is also being pursued. The ongoing convertor contracts consisted of a 6-month design phase, and are currently in an 18-month prototype fabrication phase. This leaves little time to supplement the engineering knowledge with the data necessary to support a 20-year design life. Many materials simply do not yet have sufficient long-term data to determine design life with known confidence. In these cases the data must either be extrapolated, or additional margin must be designed into the component to encompass uncertainties. The dynamic RPS project is formulating plans to mitigate risks of important failure modes, in parallel with the contractor's work. Long-term material property data, to support a 20-year analysis, is nonexistent. Additional data for high-temperature metallic creep behavior is required. Similarly, any organics, such as epoxy, do not have sufficient data at the temperatures of interest. Demonstrations of robustness and margin would also bolster the case for these devices. For example, a random vibration test well above the qualification level would demonstrate the capability of the convertor to withstand much more than the expected environment, rather than be only marginally capable of enduring that mission phase.

Risks can also be mitigated at the generator level. The uncertainty in convertor reliability can be mitigated by implementing convertor redundancy. Such an arrangement would permit failure of one or more convertors while still providing the required power to the mission. These arrangements have been shown feasible by system studies (Ref. 2). In-house work is being formulated to address generator risks. This may include experimental validation of likely generator designs, including redundancy and radiant coupling of the heat source to the convertors. An ongoing controller development effort is making progress towards desirable designs that can be picked up by system integrators when that process begins. This effort builds on previous work completed during the ASRG project, which successfully demonstrated system-level engineering unit hardware via operational experiments.

IV. THE PERFECT DYNAMIC RPS

When one is first tasked with designing a spaceflight system, it is often useful to ask the question what a perfect design would look like, even if implausible. In the case of outer planets mission, the power source would have the following traits: reliable (always providing power), consistent power output throughout every mission phase, high power density and specific power, no disturbance to the spacecraft, and no upkeep required from the spacecraft or ground. These traits are possessed by RTG, which have paved its way onto many successful spacecraft. In this regard, a dynamic RPS appears to have a disadvantage compared to the simplicity of a thermoelectric generator. An RTG need not worry about startup, shutdown, or complicated con-ops during fueling. An RTG appears as a battery to the electrical bus, and outputs DC natively. There are no telemetry commands necessary to adjust for changes in the thermal environment, or fuel decay. However, it is the stance of the project that these desirable traits can be achieved in a dynamic RPS, such that there would be no extra burden on the spacecraft design. Reliability can be achieved by well-established convertor designs, and convertor redundancy. Convertor operation in the laboratory has surpassed the 12-yr mark on several units. The controller can be designed to provide a constant voltage power source to the spacecraft's bus, and manage all generator tasks autonomously. Despite the presence of oscillating components, the mechanical disturbance can be reduced to negligible levels. Design choices can be made such that the convertors provide nominal power at every mission stage regardless of the environment. Adjustments to convertor operation can be handled internally to the controller, eliminating any need for the spacecraft to monitor the RPS. With this, there would be no perceivable difference from the spacecraft's perspective, between a DRPS and an RTG, and only the DRPS advantages would remain.

System concepts have also been studied by the project to ascertain the most effective generator arrangements. During the Nuclear Power Assessment Study (NPAS) varying heat source and convertor arrangements were studied (Figure 1). There are two options for placement of the radioisotope fuel that drive concepts into two categories. The first has the radioisotope module(s) dedicated to a single convertor similar to the ASRG arrangement. This is in contrast to a centralized heat source arrangement where the heat source modules can distribute heat amongst multiple convertors (such as MMRTG). The obvious advantage for the centralized heat source configuration is that if a single convertor fails the heat from this GPHS module is not lost and can be processed by the remaining redundant convertors and converted to electricity. The other heat source placement option is the distributed arrangement. One of the advantages of a distributed heat source system is that convertor failures do not propagate to other convertors in the system. The benefits of redundant convertors must be weighed against the other complexities that come with a centralized heat source generator design.



	ASRG	SRG-200	SRG-400	SRG-500			KP-1
BOM Power	140 We	193 We	370 We	495 We			1097 We
No. GPHS	2	3	6	8			Fission
Heat Source Config.	Distributed & dedicated	Centralized & shared using heat pipes			Distributed & dedicated	Distributed & shared using heat pipes	
Stirling Config.	2X 80W ASC	2X 200W ASC-H		4X 200W ASC-H			8X 200W ASC-H

Fig. 1. NPAS heat source and convertor arrangement options.

By combining Stirling convertor and GPHS dimensions, we can make some general observations about the dimensions of future DRPS depending on the number of GPHS modules. Figure 2 shows an example of a single GPHS/Stirling convertor generator with a distributed heat source arrangement. The height of the generator can be found by laying out the known dimensions for the various components. Most Stirling convertors operate around 100 hz. This leads to a length between the Stirling acceptor and rejector of about 8 cm in the power range from a few watts to hundreds of watts per convertor. Stirling convertors grow in diameter as peak power output increases. The current lowest thermal conductivity high temperature insulation available will require about 3.8 cm if the generator is required to operate in the Martian atmosphere. Diameter of the housing is set by balancing the temperature drop and mass in the attachment between the heat rejection zone of the convertor, and the housing. The thickness of the insulation and finally the housing length. Above the rejection zone sits the alternator housing and above that a dynamic balancer along with a shunt which protects the generator from an inadvertent loss of load. Total height from a single GPHS/Stirling convertor should be from 45 to 50 cm with some variations due to alternator design selections. The housing width is set by GPHS width added with both the housing thickness and the insulation thickness. The housing can be decoupled from the insulation thickness if a lower thermal conductivity insulation is found but this may require a separate structure to hold the insulation in place. Total width of the housing will be about 20 to 25 cm. These dimensions are important because these generators must fit within the DOE shipping cask. The shipping container provides for the RPS to be moved from DOE's Idaho National Laboratory (INL) to the launch site. The existing 9904 shipping cask is approximately 86 cm in diameter and approximately 144 cm in height. The cask itself is actively cooled but has limited capacity for electrical feedthrough and no capacity for direct generator cooling.

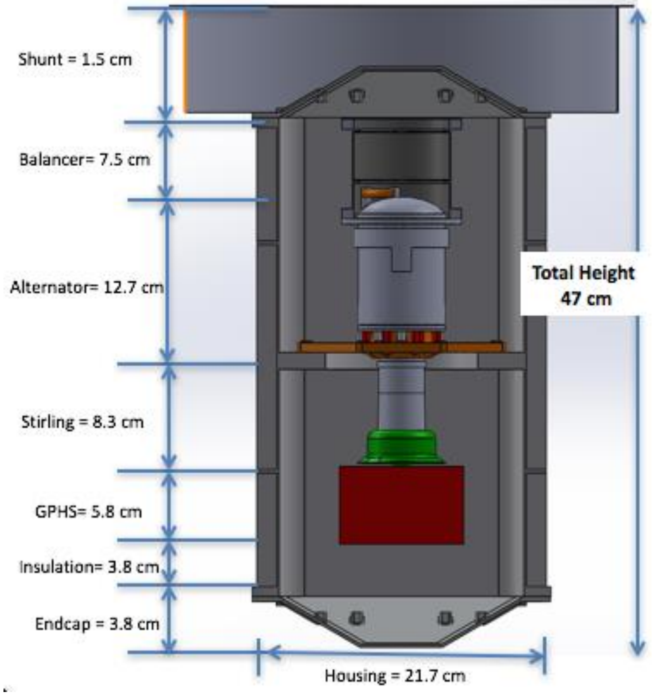


Fig. 2. Generator with single heat source, and single convertor with balancer.

The second example shown in Figure 3 is a 2-GPHS centralized heat source generator which results in dimensions and arrangement that are quite distinct from its distributed counterpart. Width totals for this configuration are about 50 cm with a height of about 27 cm.

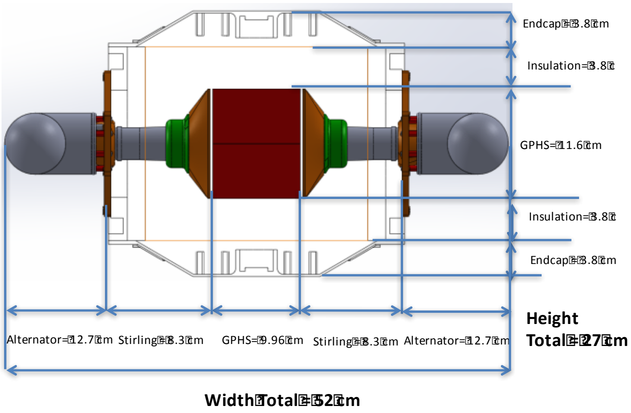


Fig. 3. Plan view of a dynamic RPS concept with four GPHS and four Stirling convertors.

NASA has developed DRPS system models to understand how these various configurations scale with both number of GPHS modules and number of Stirling convertors. Figure 4 shows both distributed and dedicated DRPSs for varying number of GPHS modules, along with a scaled outline of the shipping container. In general, dedicated convertor configurations have lower specific power than centralized heat source arrangements. The reason for this is twofold. First, the thermal efficiency of a centralized heat source is higher because there is less insulation loss as the number of GPHS grows. Second these systems are able to decouple the insulation thickness from the housing diameter and therefore, can be better optimized for the trade between insulation mass and specific power. NASA is currently considering a wide range of power outputs from generators. The smaller the unit size of the generator, the more closely a missions' needs can be met with a single generator. However, the higher the generator power output, the higher the specific power. One idea being explored is a smaller power output per generator but designing the generator building block to be coupled together with other generators and accepting the lower specific power. While this does not achieve the very high specific power of single larger generators, it does allow greater redundancy in number of generators and does decouple any single generator failure from impacting the working generators.

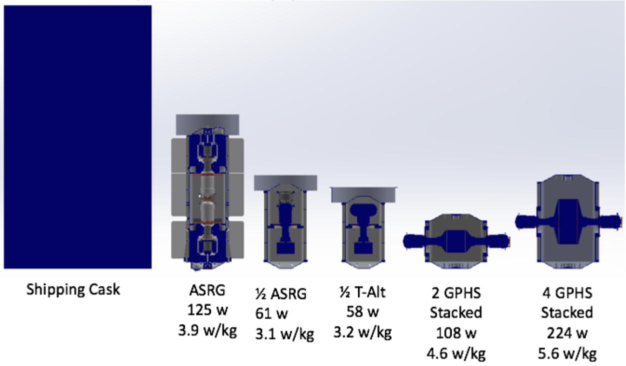


Fig. 4. Comparison of DRPS arrangements.

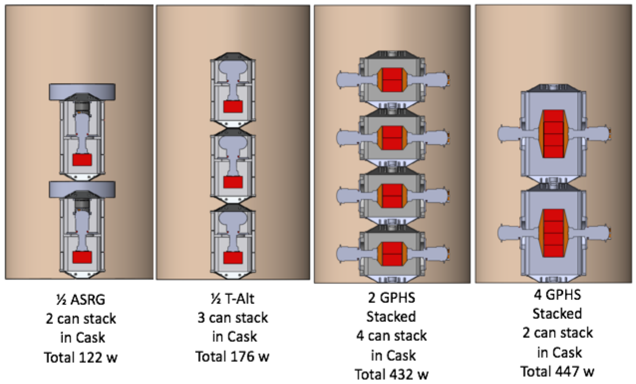


Fig. 5. Stacked DRPS generators in a shipping cask.

II. CONCLUSIONS

NASA is funding the development of dynamic power conversion for the advantages it offers in the area of conversion efficiency, and it's applicability to future higher power systems. A strategy has been formulated to drive these systems towards flight, for use in RPS on science missions. The strategy has included a stand-in surrogate mission team to drive requirements. A philosophy has been adopted to make the conversion technology and generators as attractive as possible, by tailoring them for use on a wide range of NASA missions. The first use of any new technology in space is a large hurdle, and the mission must accept some known risk. The dynamic RPS project and NASA Glenn has formulated plans to mitigate these risks.

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