# Next-Generation RTGs for NASA

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**NASA has used Radioisotope Thermoelectric Generators (RTGs) for nearly five decades to power planetary science missions where solar arrays or other power systems were impractical or ineffective. The Multi-Mission RTG (MMRTG) is the only type of RTG available for spaceflight today and it relies on technology used for the Pioneer and Viking missions of the 1970s. The MMRTG's distant-relative, the General-Purpose Heat Source-RTG (GPHS-RTG), went out of production shortly after the turn of the twenty-first century. The thermoelectric technology it relied upon is several decades old and was first flown on the Voyager missions in 1977. While the GPHS-RTG could theoretically be brought out of mothballs, many advances have been made in thermoelectric materials, advances that warranted a clear-eyed review and study of the optimal properties of a "next-generation" RTG. This paper summarily describes the outcome of the study.**

## Nomenclature

BOM = Beginning of Mission
CTE = Coefficient-Of-Thermal-Expansion
eMMRTG = Enhanced MMRTG
EOM = End of Mission
GPHS = General Purpose Heat Source
GPHS-RTG = GPHS Radioisotope Thermoelectric Generator
GRC = Glenn Research Center
GSFC = Goddard Space Flight Center
HSMRTG = Hybrid-Segmented RTG
INL = Idaho National Laboratory
JPL = Jet Propulsion Laboratory
LV = Launch Vehicles
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
PbSnTe = Lead-Tin-Telluride
PbTe = Lead-Telluride
PSD = Planetary Science Division
RTG = Radioisotope Thermoelectric Generator
TC = Thermoelectric Couple
SKD = Skutterudite
SRTG = Segmented RTG
SMRTG = Segmented-Modular RTG
TAGS = Tellurium-Silver-Germanium-Antimony
$T_{cj}$ = Cold-Junction Temperature
TE = Thermoelectric
TRL = Technology Readiness Level
UDRI = University of Dayton Research Institute
W = Watts electric

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# I. Introduction

In July 2016, NASA's Radioisotope Power Systems (RPS) Program set down the objective for a study [1] to explore what possible options exist for a next generation of Radioisotope Thermoelectric Generators (RTGs) that could be produced in the late 2020s and would be useful throughout the following 20 years. The objective of the study was:

> …to determine the characteristics of the next RTG that would "best" fulfill NASA's Planetary Science Division (PSD) mission needs. This study is limited to systems that convert heat to electricity using thermoelectric couples. "Best" is defined as a confluence of the following factors:
>
> - An RTG that would be useful across the solar system
> - An RTG that maximizes the types of missions: flyby, orbiter, lander, rover, boats, submersibles, balloons
> - An RTG that has reasonable development risks and timeline
> - An RTG value (importance, worth and usefulness) returned to PSD for investment is warranted, as compared with retaining existing baseline systems

The scope and breadth of the study were tailored to target a wide variety of potential destinations within the solar system, from the Sun to the Kuiper Belt, to trade a variety of RTG system architecture options, and to rate the risk of a variety of thermoelectric (TE) materials and couple configurations useful in new RTG concepts. Requirements were defined for the conceptual RTGs, TE materials were evaluated to find those that were most mature, and performance was estimated for each RTG concept using the new materials. A database was developed to ease the burden of storing, analyzing, categorizing, and correlating the number of parameters and data employed in this study. No such capability existed before this study was initiated. The database may now be useful in future RTG studies and mission analyses as a knowledge base and repository.

This study was chartered to draw on the talent and experience at three NASA centers: Goddard Space Flight Center, Glenn Research Center, and the Jet Propulsion Laboratory/California Institute of Technology, as well as the US Department of Energy, the John Hopkins University's Applied Physics Laboratory, and the University of Dayton Research Institute.

The study used mission analyses of concepts detailed in the latest Planetary Sciences Decadal Surveys [2,3], other mission studies completed throughout the agency, and recent analyses of potential Ocean Worlds to identify requirements that might be needed for Next-Generation RTGs. In addition, many of the possible destinations within the solar system were analyzed against a list of mission types including flyby, orbiter, atmospheric probe, aerial, lander (static, roving, floating, submersible), melt probe, and sample return missions to identify new requirements. Lastly, requirements were drawn from previously flown and available RTGs. The requirements were identified using this "top-down" engineering approach and then documented in the study report.

A "bottom-up" engineering approach was used to identify the most promising TE materials. Those findings were documented in a matrix after careful review of products available in the market and research papers from laboratories around the world. A matrix of 67 candidate materials was reduced to those "at hand," meaning those that had been given at least modest long-term testing and were made in the USA. Thermoelectric couple configurations were conceived using this reduced set of materials. Some couple configurations would use a single material in each leg., others would use legs composed of two or more segments. The mixing and matching of materials for the couples was based upon several factors, such as Coefficient-Of-Thermal-Expansion (CTE) matches, power compatibility [4], and allowable operating temperature ranges. This activity further winnowed the list of TE materials useful for RTGs destined for the Next-Generation RTG concepts. Power conversion efficiency was estimated for each couple over its operating temperature range, and a detailed scorecard for each couple was prepared so the couples could be compared, further winnowing the working list of 21 couples. Eight thermoelectric couples survived this process.

Figure 1 is an example of two TE couples: one from the MMRTG (left) that shows one leg composed of a single material and the other leg being segmented with two materials; in comparison, the skutterudite material-based legs of the TE couples proposed for the potential enhanced MMRTG (eMMRTG) would be composed of a single segment each.

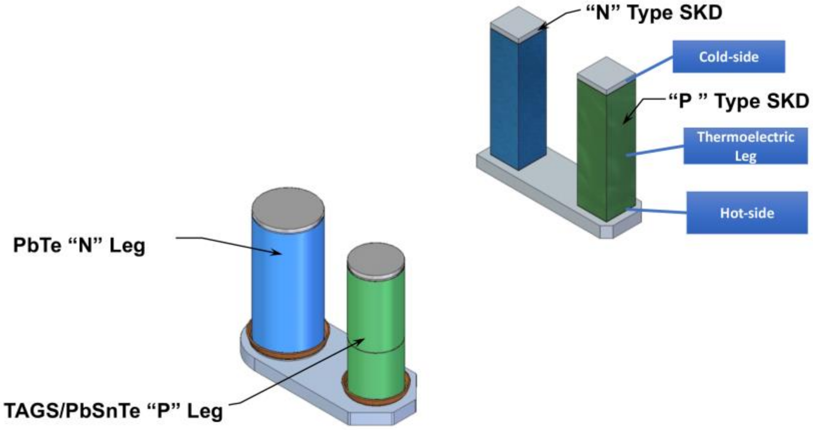

Figure 1. Two examples of thermoelectric couples: the MMRTG thermoelectric couple (left) and the skutterudite (SKD) couple being developed for the potential eMMRTG (right).

Next, the bottom-up TE couple configurations were combined with the top-down requirements to allow specific Next-Generation RTGs concepts to be modeled and reviewed.

The study team settled on Next-Generation RTG concepts with several distinguishing architectural characteristics based upon the requirements and thermoelectric couples. RTG concepts were created that included single-point designs, modular (scalable) systems, systems designed with lower housing temperatures (primarily for very cold environments), systems that would operate only in the vacuum of space, systems capable of operation in planetary atmospheres, and a hybrid architecture that would allow a single type of RTG to operate in both vacuum and in planetary atmospheres. Those architectural choices led to the conceptualization of well over one hundred RTG concepts.

Those choices led to system-level hardware differences that affected mass, volume, and power. For example, designing an RTG to operate at lower housing temperature than has been traditionally achieved requireed that fin area and thickness be increased. This led to mass growth, which then had an effect on specific power.

Power estimates for each Next-Generation RTG concept were made. The concepts were then evaluated against one another and the usefulness of each architecture was then evaluated against the requirements. RTG concepts that maximized utility per the objective of the study were identified and the top three RTG concepts were noted in the final report along with a catalog of all the RTG concepts.

The final results are summarized below with an emphasis on the RTG concepts, along with a discussion of the ways in which these new concepts might aid NASA in developing effective missions concepts in 2030-2040s, which are likely to be much more challenging than in the past.

## II. Requirements for Next-Generation RTGs

Recently flown RTGs, related mission studies, and potential destinations within the solar system were reviewed to develop requirements. The requirements for the GPHS-RTG, MMRTG, and the potential eMMRTG formed a basis for the requirements captured in the report. As such these generators became the reference generators for the study. These rich sources provided foundational requirements and in-flight data (in the case of the GPHS-RTG and MMRTG) that did not and could not come from a review of mission studies or mission types. For example, a next generation of RTGs has to clearly be compatible with Launch Vehicles (LVs) available to NASA both at the time one of these new RTG would complete flight development, and years beyond that, when new and unknown LVs may become available. And while the mission studies reviewed for this effort made use and mention of a LV, most did not include LV environments that could form a useful basis set of requirements on new RTG concepts. Instead, the reference RTGs stood in. This pattern was true for other functional requirements, such as spacecraft power bus voltages, fuel thermal inventory, storage life for these generators, internal redundancy, structural requirements, and factors of safety, and so on.

A total of 249 mission studies were used to identify a great many different requirements such as power, mass, design lifetime, operation in atmospheres or not, Entry, Descent, and Landing loads, and more. Seven types of missions were defined, some with sub-classes so the mission studies could be binned for further analyses; see Table 1. Combinations of destinations and mission types not yet flown or studied were found by combining the list of potential destinations within the solar system with the targets and mission type found in the studies. This enhanced the numerical basis for ascribing "fit" to any one of the Next-Generation RTG concepts as then not just studies were included but potential and unstudied destinations across the solar system. The numerical fit included studied missions, unstudied destinations, and mission types; see Figure 2.

Table 1. Types of missions.

| Class | Flyby | Orbiter | ATMO Probe | Aerial | | | Surface | | | | Subsurface | | | Sample Return |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sub-class | | | | Balloon | Fixed Wing | Helicopter | Impact | Lander | Rover | Boat | Liquid | Soil & Regolith | Ice | |

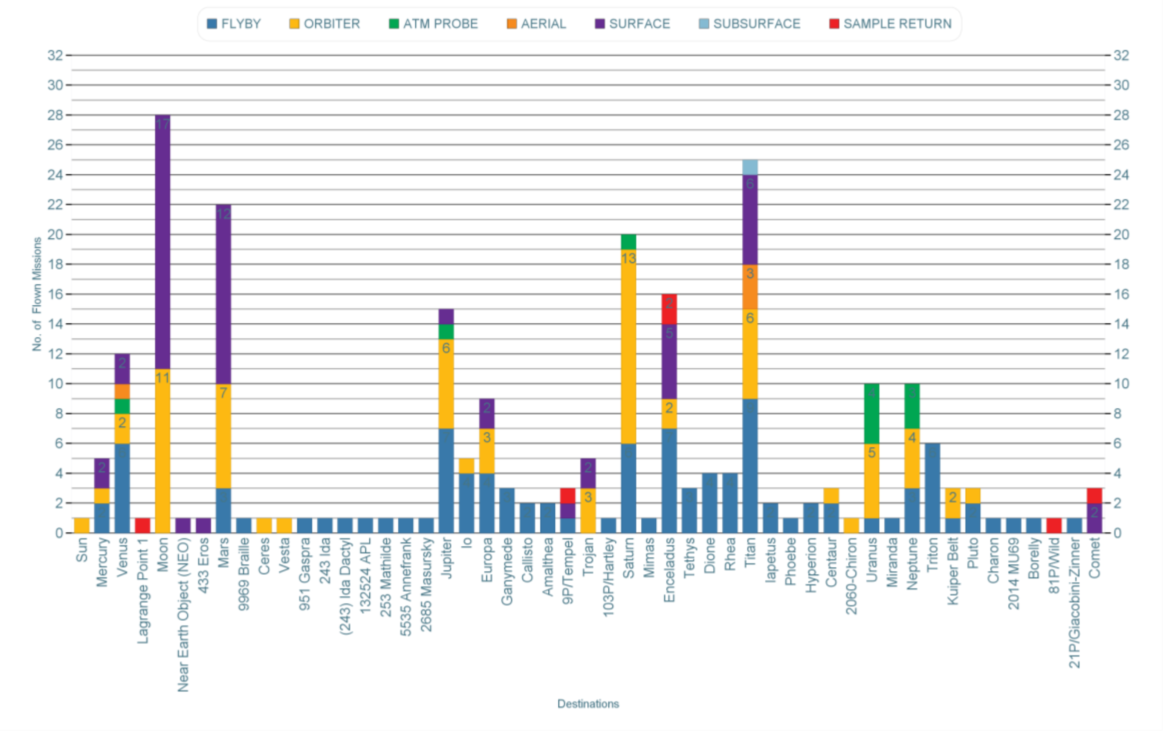

Fig. 2. 249 mission studies were binned by target and mission type.

Additional insights were illuminated when searching the database by binning power requirements by mission classes used by NASA's PSD for scientific exploration. Figure 3 bins power needs by the mission classes: Flagship, New Frontiers, and Discovery. The Flagship class consists of the most ambitious and costly missions, with Discovery the least and New frontiers in between; see references [2,3] for more information.

Figure 3 shows Discovery-class missions need power systems producing less than 300 W at End of Mission (EOM), and even lower, to below 150 W, and Flagship missions need power above 600 W. For example, the Cassini mission to Saturn launched with ~900 W. A generator producing 150W could satisfy the needs of some Discovery missions but would be impractical for use on a Cassini-class mission as it would require flying six of those RTGs. Analysis of the information in Figure 3 strongly suggests a scalable or modular RTG is needed to suit the needs of the three mission classes. A modularized system would allow users to select RTGs from a series of RTGs with different lengths, power estimates, and masses. Length, power, and mass would vary with the amount of radioisotope fuel in a variant of the Next-Generation RTG. Many other parameters would have to be constrained or prevented from changing to preserve the value of a modularized RTG. This requirement maximized the utility of Next-Generation RTG concepts at destinations across the solar system and has the potential to serve a large range of power needs across the Discovery, New Frontiers, and Flagship class missions, a range from ~130 W to ~1,000 W.

The requirement also provides a potential means to use RTG fuel more efficiently and reduce spacecraft integration issues. Hence, a requirement for modularity was documented.

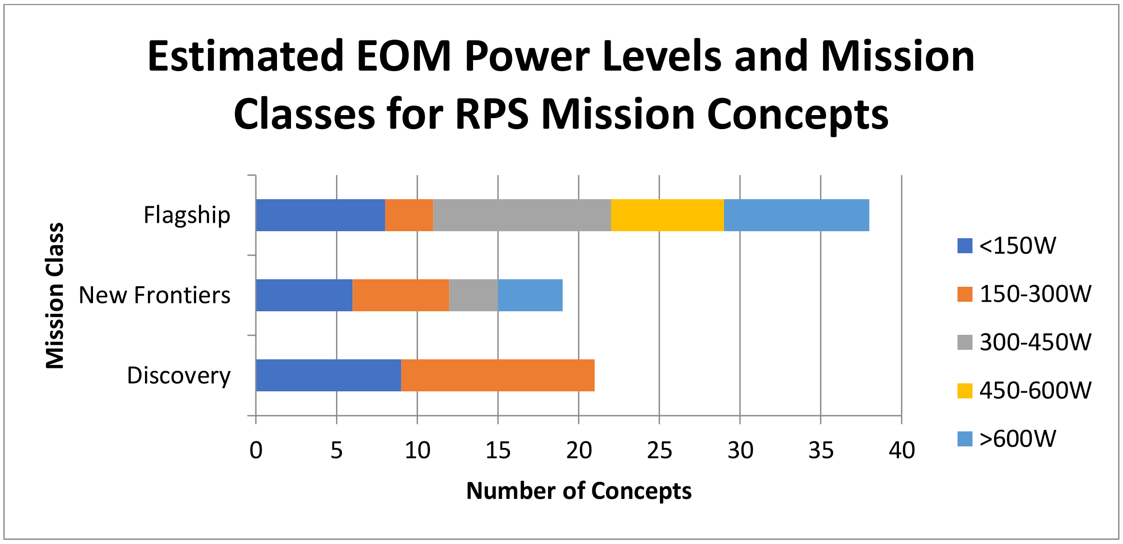

Fig. 3. The RPS mission studies, sorted by mission class and End of Mission (EOM) power level.

Niche requirements for specialized RTG concepts were also noted. A requirement was categorized for Specialized RTGs if the requirement was meant for a likely minority of missions. These requirements might also be burdensome to the majority of potential missions; that is, they might lower the utility of an RTG's architecture rather than increase it when applied across the potential missions within the solar system. For example, exploration in the ice sheets and oceans on other worlds or on the surface of Venus would require any RTG to have a housing that is a pressure vessel, due to hydrostatic and hydrodynamic pressures. This type of vessel adds tens to hundreds of kilograms to the mass of an RTG, making this type of RTG potentially unusable by many of the mission concepts studied. However, a pressure vessel could enable a set of potential and—as yet—unattempted missions, so a balance must be sought.

## III. Thermoelectric Materials and Couples for RTGs

The bottom-up engineering approach found a significant level of global research has been performed over the last decade to develop novel, advanced TE materials. These advanced materials range from Zintl, skutterudite, chalcogenide, and half-Heusler materials to nanostructured materials, such as nanowires, quantum dots, quantum wells, thin film superlattices, combinatorial sputtered deposits, and many others. The University of Dayton Research Institute (UDRI) was engaged to lead this effort and provide a fresh review of recent research. However, UDRI's findings reinforced the understanding that many of these novel thermoelectric material systems, as published, are not suitable for incorporation into an RTG design intended for space applications. UDRI further found that the efforts undertaken by JPL over the last few decades to identify novel thermoelectric materials that are potentially suitable for terrestrial and space RTGs is noteworthy. Those efforts, coupled with an ability to conduct research to mature potential materials to higher technology readiness levels (TRLs) where they can be thoroughly assessed, enables NASA to have the ability to validate whether future investments are merited.

TE couple efficiencies ranging from approximately 11-17% may be achievable by employing segmented thermoelectric couple architectures. Segmentation could be used to improve the efficiency of TE couples by constructing one or both legs of a couple from two or more segments, each composed of a different material that has a peak figure of merit (ZT) at a different temperature. This effectively designs a thermoelectric leg to provide a large average figure of merit over a specific temperature range. Segmentation has been used in thermoelectric couple designs such as the MMRTG couples. Segmentation for the identified thermoelectric materials is innovative however, and many significant technical challenges must be addressed before for any of the segmented configurations might be flown.

Twenty-one thermoelectric couples were originally conceived. From those, eight TE couples were selected as viable candidates for a Next-Generation RTG. One, two, or three segments could be used for a couple's legs.

However, adding segments was viewed as increasing risk. In fact, no three-segment couples have ever been flown in an RTG. The study team chose to recommend couples composed of one and two segments. The eight candidate couples for the Next-Generation RTG concepts were given distinct labels, the concatenation of "TC" with a couple's number in the list of 21 candidates originally conceived. The concatenation of those two identifiers resulted in the eight couples being labeled TC-1, TC-2, TC-3, TC-4, TC-10, TC-11, TC-14, and TC-21. The resultant RTG performance estimates using these eight thermoelectric couples will be discussed in the next section.

These eight candidates represented the lowest risk couples for further development.

This study has identified a strong need for a closely coordinated and parallel research and development effort focused on developing and validating methods and materials to bond the TE materials identified as segmented configurations, to mitigate material diffusion across the segmented interfaces, and to develop protective coatings to reduce sublimation. If the research and development efforts are not conducted in parallel and in a coordinated manner, then by default, the most mature configuration will become the baseline technology in Next-Generation RTG concepts.

## IV. RTG Concepts

The derived requirements for a Next-Generation RTG, combined with the candidate TE couples identified, resulted initially in six RTG concepts. Three candidates were quickly discarded after it was realized they violated critical requirements. The three concepts that remained are: the Segmented[2] RTG (SRTG), the Segmented-Modular[3], RTG (SMRTG), and the Hybrid[4]-Segmented Modular RTG (HSMRTG). While none of the remaining three were dropped from the study, they were prioritized as SMRTG, SRTG, and HSMRTG. An analysis of the reviewed spacecraft and mission studies amplified this prioritization. It showed that about 80% of the spacecraft concepts would operate in vacuum-only environments. Hence 80% of the spacecraft studied could fly an SRTG or SMRTG.

The SRTG is a single-point design concept that would use 16 General-Purpose Heat Sources (GPHSs)[5] and segmented TE couples. The SMRTG is a modular (hence the 'M' in the acronym) or scalable design concept using segmented TCs and could be produced in eight variants using between 2 and 16 GPHSs. The HSMRTG is a modular design concept using segmented TCs and adding a sealed vessel for the couples so as to protect them from harmful gasses or vapors in atmospheres on planets and moons. The HSMRTG also was conceived with eight variants. Figure 4 depicts the SMRTG variants. The SRTG is a single-point design and would be very similar to the right-most generator in Fig 4.

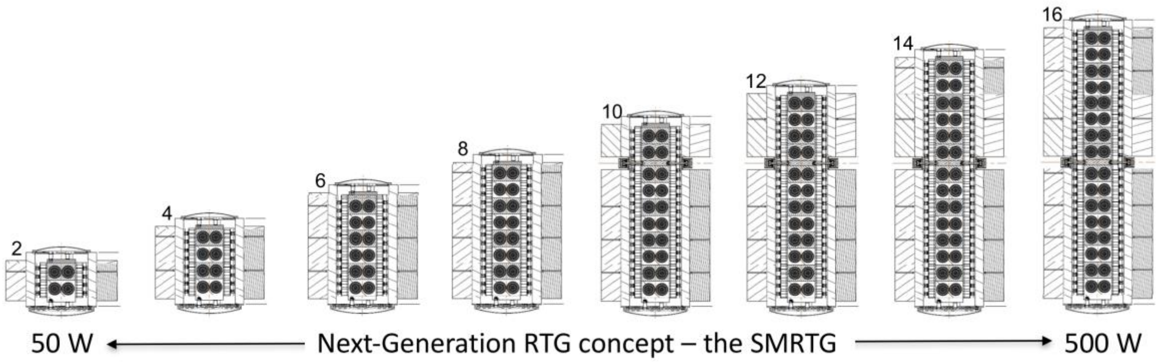

Figure 4. The SMRTG concepts in cutaway view.

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[2] "Segmented" refers to the segments in the thermocouple.

[3] "Modular" refers to the number of modules per RTG. In this study, the smallest module was an RTG fueled by 2 GPHSs. A modular RTG can therefore be fueled with 2, 4, 6, 8, 10, 12, 14 or 16 GPHSs; these modular RTG concepts would provide users the opportunity to select from 8 variants of the same model of Next-Generation RTG.

[4] "Hybrid" denotes that the RTG housing is sealed, and that it can operate in both vacuum and in an atmosphere (e.g., Titan).

[5] A GPHS is the package for the plutonium oxide used in RTGs. It comes in one size and no other heat source is used in RTGs at this time.

The SRTG and SMRTG would operate in only vacuum. The HSMRTG would be able to operate in both the vacuum of space and in an atmosphere (e.g., Titan). Because of this, the study teams regards it as a more complex system and hence riskier to develop than either the SRTG or SMRTG.

RTGs using the selected eight TE couples have the potential to deliver the same amount of power as a GPHS-RTG using just 44% of the fuel. This can be seen in Figure 5. The GPHS-RTG power at Beginning of Mission (BOM) is shown on the left side of the plot. Reading horizontally across the plot from that data shows clearly that there is more than one SMRTG variant listed on the x-axis that nears or exceeds the GPHS-RTG power estimate. The comparison of these power estimates indicates the SMRTGs can produce the power of the GPHS-RTG using 44% of the fuel; a GPHS-RTG used 18 GPHSs, many of the SMRTG variants in the same power class need only eight.

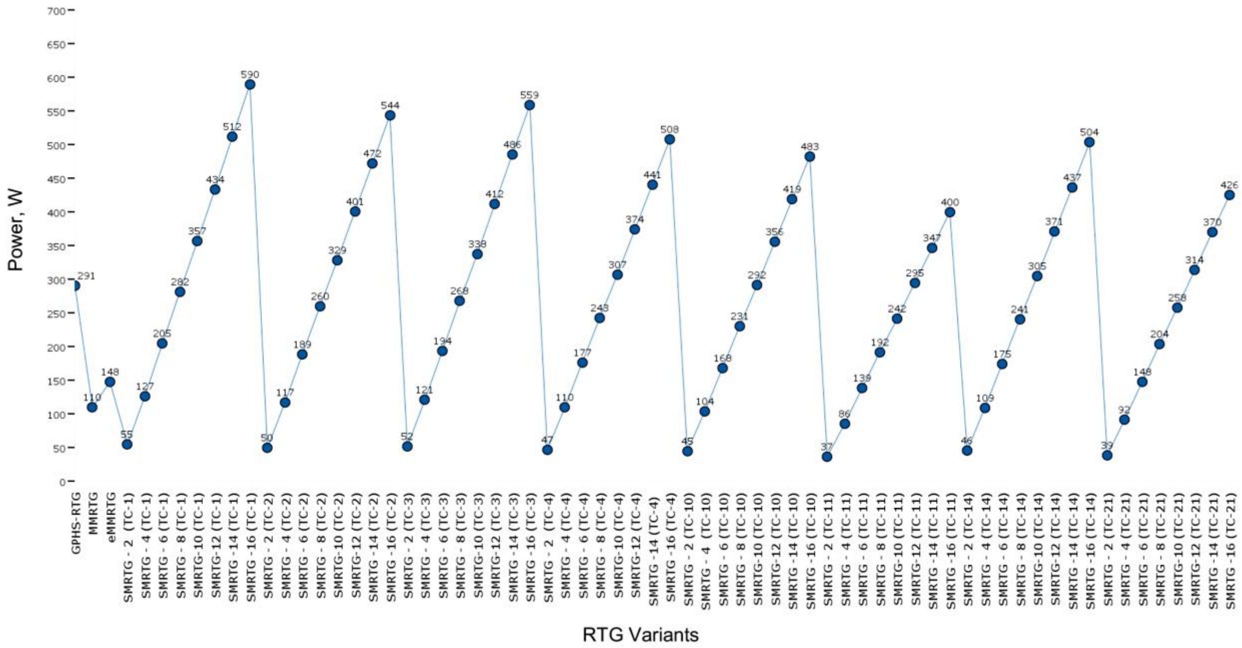

Figure 5. SMRTG power is identified for each variant and TE couple. Electrical power is in Watts on the y-axis. The reference RTGs are listed on the left of the graphic, and the remainder of the x-axis labels can be read as SMRTG-N (TC-x), where N is the number of GPHS in each variant and x is the configuration number of the couple used to estimate power.

Power estimates for the SMRTG and HSMRTG concepts are estimated within an envelope of 50 W and 600 W for the smallest and largest variants and using the various TCs. The HSMRTG and SMRTG variant were estimated to produce the same amount of power. That range is the current best estimate. A mid-point for performance to be conservative, and so the power estimates range from 50 to 500W in accord with the embryonic state of the concepts. That power range could make it possible for a Next-Generation RTG to support the power needs of both small and large spacecraft. including the entire range of Discovery, New Frontiers, and Flagship mission classes. A conservative envelope of power estimates for the three Next-Generation RTG concepts and all their variants is plotted in Figure 6. The power is plotted as a function of the number of GPHS used in each variant. At the low-end of the power estimates are the two-GPHS generators using the eight different couples to produce between 50 and 60 W. At the high-end of the power estimates are the SRTG, SMRTG-16, and HSMRTG-16, all using 16 GPHSs and the eight TE couples from this study to produce between 400 and 500 W. Spacecraft requiring 2 kW of power could use four SMRTG-16s, SRTGs, or HSMRTG-16s. That is more than enough power to adequately power a large Cassini-like spacecraft or a potential Radioisotope Electric Propulsion system. At the other extreme, a Discovery-class mission might only need a single 50W Next-Generation RTG.

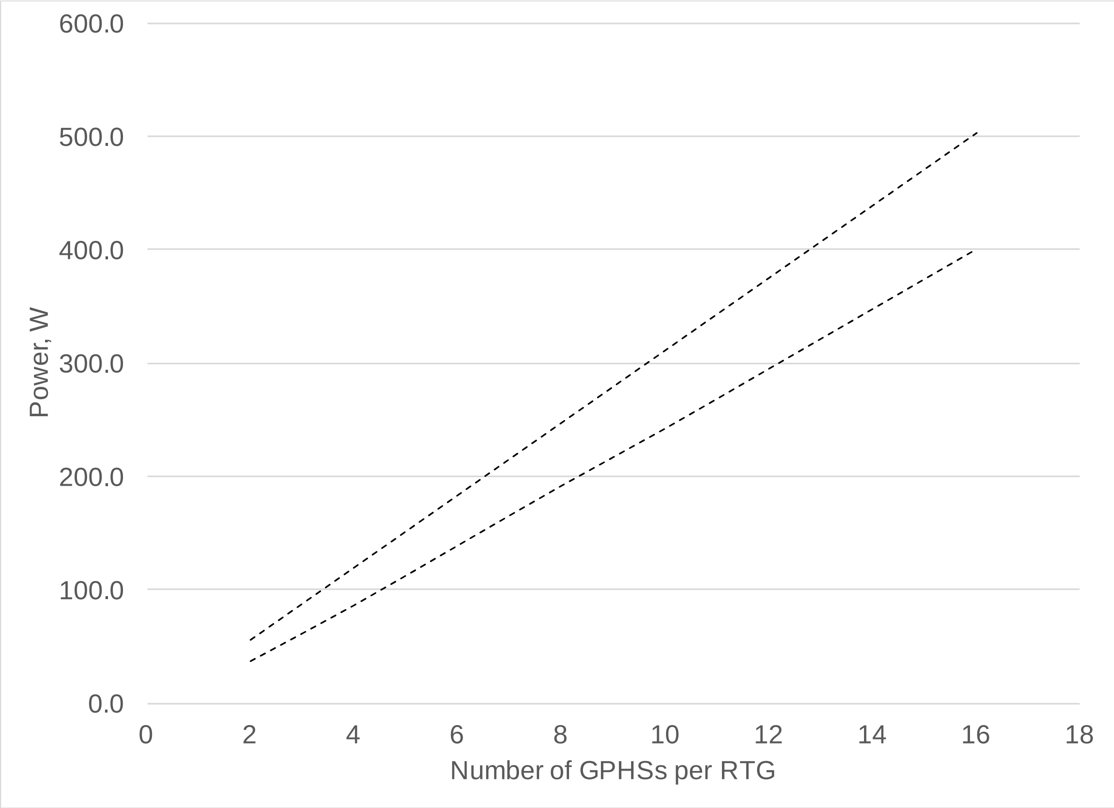

Figure 6. The envelope of power estimates of Next-Generation RTG concepts. The envelope of power estimates for Next-Generation RTG concepts for minimum to maximum power.

## V. Conclusions

A total of eight candidate thermoelectric couple configurations were identified for the three Next-Generation RTG concepts. These new concepts have the potential to deliver the same amount of power as a GPHS-RTG using just 44% of the radioisotope fuel. The study determined that the strongest candidates for Next-Generation RTGs are the SRTG, the SMRTG, and the HSMRTG; all other concepts studied failed to meet critical requirements. Table 3 provides a brief description of the three top candidate designs.

Table 3. Summary descriptions of candidate RTG concepts.

| | |
|---|---|
| SRTG: | Segmented RTG. A generator with segmented thermoelectric couples. No modularity. Vacuum only operations. Optimized for specific power. TC efficiency calculated at Cold Junction Temperature ($T_{cj}$): 450K. |
| SMRTG: | Segmented-Modular RTG. A modularized generator with segmented thermoelectric couples. Vacuum only operations. TC efficiency calculated at Cold Junction Temperature ($T_{cj}$): 450 K. |
| HSMRTG: | Hybrid Segmented-Modular RTG. A modularized generator with segmented thermoelectric couples relying upon a hybrid housing to allow operations in atmospheres and vacuum. TC efficiency calculated at Cold Junction Temperature ($T_{cj}$): 450 K. |

Power estimates for these generators range from 50-60 W up to the 400-500 W upper limit per RTG.

The value of modularity outweighed the perceived lower risk of a point design, as in the SRTG. The hybrid feature would add more development risk over the other two generator concepts, but is still an attractive candidate. While none of these three were eliminated from the study, they were prioritized as SMRTG, SRTG, and HSMRTG.

In summary:

1. Eight-candidate thermoelectric couple configurations were found to be of modest risk and sufficiently efficient to warrant further RTG concept development.
2. The Next-Generation RTG concepts have the potential to provide considerable mass and fuel savings while boosting power by a factor of 1.5–2.0 over previous RTGs. The power from one Next-Generation RTG is equal to one GPHS-RTGs using just 44% of the fuel.
3. Three Next-Generation RTG concepts could be linked to requirements from flown RTGs and flown missions, mission concepts studied, and mission concepts prioritized in the most recent Planetary Science's Decadal Surveys from the National Research Council. These three candidates for Next-Generation RTGs were found to "best" fulfill these broad planetary science mission needs.

## VI. Acknowledgements

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## VII. References

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