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# Power for Science and Exploration: Upgrading the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG)

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**The General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) has been the workhorse nuclear power source of the space science community for over 20 years having powered such challenging missions as Galileo, Ulysses, Cassini and New Horizons. At ≥300 We beginning of life (BOL) power, the GPHS-RTG is the highest-powered radioisotope power source (RPS) ever flown with the highest specific power (5.3 We/kg). However, recent changes in the design of the GPHS fuel modules would reduce the number of modules that could be emplaced in the GPHS-RTG thereby reducing the power. This paper explores several options including modifications to the converter housing and the insulation that could reclaim the advantages of the GPHS-RTG even with the new thicker, heavier GPHS modules. Coupled with the existence of over 3,100 GPHS-RTG thermoelectric elements ("unicouples") it would be possible to power future outer planet missions with the performance advantages of the original GPHS-RTG.**

## 1. Introduction

The General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG), which was originally designed and developed as a substitute RTG for the International Solar Polar Mission (now called Ulysses, see Figure 1), became the most successful U.S. nuclear power source (NPS) by powering such challenging missions as the Galileo mission to Jupiter (Figure 2), the Cassini mission to Saturn (Figure 3) and the New Horizons mission to Pluto (Figure 4). At ≥300 We beginning of life (BOL) power, the GPHS-RTG is the highest-powered radioisotope power source (RPS) ever flown with the highest specific power (5.3 We/kg).[1,2] Originally planned successors to the GPHS-RTG such as the Modular RTG (MOD-RTG) which could be assembled to provide a range of powers (19 We to 340 We) and the higher-powered (1-10 kWe) Dynamic Isotope Power System (DIPS) did not materialize even as the manufacturing and assembly lines for the GPHS-RTG were closed.[3-9]

(To aid the reader a list of key acronyms used in this paper is presented in Appendix A at the end of the paper.)

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**Figure. 1. Ulysses spacecraft in tail of Comet Hyakutake.** The single GPHS-RTG is shown at the bottom**.** (ESA)

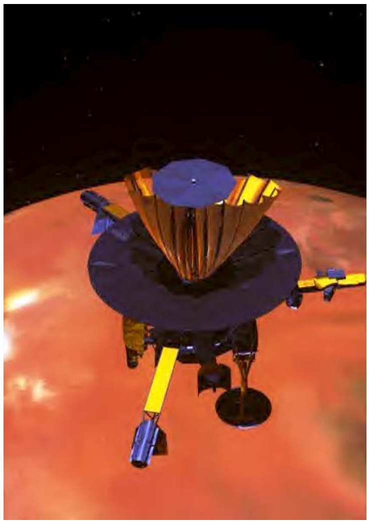

**Figure 2. Galileo spacecraft over Io.** One of the two GPHS-RTGs is shown at the bottom. (JPL)

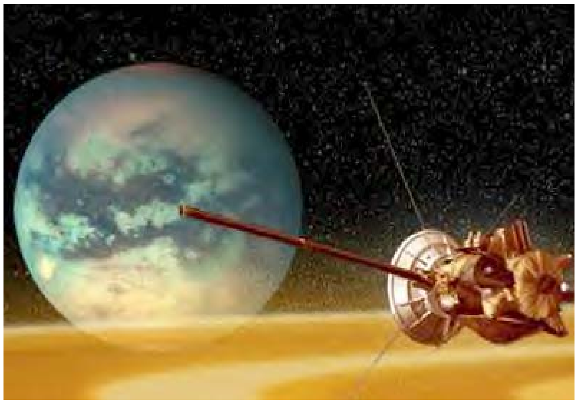

**Figure 3. Cassini spacecraft over Saturn's rings with Titan, Saturn's largest moon.** One of the three GPHS-RTGs is shown near the top of the spacecraft. (NASA/JPL)

**Figure 4. New Horizons spacecraft shown flying by Pluto with satellite Charon in the background.** The single GPHS-RTG is shown mounted on the left side of the spacecraft. (JHU/APL and SwRI)

In the world of "faster, cheaper, better" and smaller, U.S. radioisotope power source (RPS) efforts naturally have focused on the lower powered (~125 We BOL) Multi-Mission RTG (MMRTG) for the Mars Science Lander (MSL) and the Advanced Stirling Radioisotope Generator (ASRG) (~140 We BOL).[10,11] In parallel, there has been some technology development aimed at producing a higher power (~250 We - 270 We) Advanced RTG (ARTG).[12,13,14] (It should be noted that with work both the MMRTG and ASRG technologies could be upgraded to produce higher powers.) However, for certain flagship missions such as orbiters of the outer planets and their satellites, the higher-powered GPHS-RTG with its off-the-shelf technology still offers some attractive features especially when the decision has been made to use RTG power. This paper will discuss some options for rebuilding the GPHS-RTG in light of current constraints. Mission information has been taken from the Web sites maintained by NASA, the Jet Propulsion Laboratory (JPL), the Johns Hopkins University Applied Physics Laboratory (JHU/APL), the European Space Agency (ESA), and the National Space Science Data Center <http://nssdc.gsfc.nasa.gov/>.

## 2. Outer Planet Flagship Mission (OPFM) Studies

Over the past several years NASA has sponsored pre-Phase A studies of four candidate outer planet flagship (OPF) missions (with life cycle costs on the order of ≥$1 B), including a mission to Jupiter's moon Europa ("Europa Explorer"), a mission to the Jovian system ("Jupiter System Observer"), a mission to Saturn's moon Enceladus, and a mission to Saturn's moon Titan ("Titan Explorer").[14-17] The purpose of these studies was to inform near-term strategic decisions for the next Flagship mission.[16] Because of the lack of sunlight, the low temperatures and the presence of severe ionizing radiation, each of these missions required RPS for power. In addition, the periodic "decadal surveys" conducted by the Space Studies Board (SSB) of the National Research Council (NRC) have identified candidate outer planet missions that would require RPS. One such recommended Flagship mission relevant to this paper was the Europa Geophysical Explorer (EGE). In addition the SSB has recommended development of advanced RPSs and an "in-space fission reactor power source".[18] The recently released National Space Policy states that "The United States shall develop and use space nuclear power systems where such systems safely enable or significantly enhance space exploration or operational capabilities".[19] The National Space Policy enjoins the Secretary of Energy to "Maintain the capability and infrastructure to develop and furnish nuclear power systems for use in United States Government space systems".[19]

In 2009, NASA and the European Space Agency (ESA) announced plans for a joint Europa-Jupiter-System Mission (EJSM) that would involve two spacecraft to be launched separately in 2020: Jupiter Europa Orbiter (JEO) to be built by NASA and Jupiter Ganymede Orbiter (JGO), called "Laplace", to be built by ESA.[20,21] Other systems (e.g., Russian-built Europa lander) could be part of EJSM. JEO would carry either five MMRTGs or five ASRGs to provide at least 540 We[20] (although recent statements by NASA officials indicate a focus on the RTG option[22]). As in most of the OPFM studies, a lithium ion battery would be provided on JEO for peak power management.[20]

## 3. Radioisotope Power Source (RPS) Options

In 2001, in response to the "faster, cheaper, smaller" mandate and a desire to have a multipurpose RPS, a joint NASA/DOE team was formed to study the RPS options. The team issued a report recommending the Stirling Radioisotope Generator (SRG) for a range of space and surface missions in the 100-We class. The MMRTG was recommended as a backup.[23] The Mars Science Laboratory (MSL) project selected the MMRTG. The SRG development was later redirected to the ASRG program. In 2007, NASA directed that the new OPFM would use the MMRTG.[11] Separately, NASA's Jet Propulsion Laboratory (JPL) pursued development of an Advanced Radioisotope Thermoelectric Generator (ARTG) with plans to provide BOM powers in the range 250 We to 270 We at a system efficiency of 8% to 9% and a specific power of about 7 We/kg.[12,13,14] Table 1, whose first three rows have been taken without change from Ref. 14, summarizes the attributes of the three RPS options (MMRTG, ASRG, ARTG) under OPFM consideration. For comparison purposes the original GPHS-RTG attributes are also shown.[1]

**Table 1. RPS System Performance Comparison**[1,14]

| Radioisotope Power Source | Power (BOL)[1] | Mass | Specific Power BOL | Efficiency | Number of GPHS Modules | Estimated TRL[2] |
|---|---|---|---|---|---|---|
| MMRTG | 125 We | 44 kg | 2.9 We/kg | 6.3 % | 8 | 6 |
| ASRG | 143 We | 20.2 kg[3] | 7.0 We/kg | 28% | 2 | 5 |
| ARTG | 250 We | 40 kg | 7 We/kg | 8.3% | 12 | 3 |
| GPHS-RTG[4] | 300 We | 55.9 kg | 5.3 We/kg | 6.8% | 18 | 9 |

[1] Beginning-of-life (BOL) power is defined at the time of RPS fabrication by DOE.
[2] TRL = Technology Readiness Level (the higher the number the more mature the technology is).
[3] The mass does not include the additional mass to shield ASRG electronics from the radiation environment.
[4] The GPHS-RTG performance parameters are for the original Galileo/Ulysses-class GPHS-RTG.

Given the reported shortage of plutonium-238 ($^{238}$Pu) for future missions[22], the emphasis in performance parameters naturally gravitates toward the higher efficiency ASRG. Even though the listed specific power of 7 We/kg for the ASRG is the same as that proposed for the ARTG and only a third greater than the original GPHS-RTG, in terms of power per mass of Pu-238, the ASRG is three to four times better than the other options. This would clearly compensate for the added mass of the controller and radiation shielding. Moreover, in the general push for ever higher specific powers, it should be borne in mind that RPS specific powers greater than 10 We/kg appear "unlikely" from basic thermodynamic considerations.[24]

In the four OPFM studies completed in 2007-2008, two (Enceladus and Titan Explorer) selected the ASRG and two (Europa Explorer and Jupiter System Observer) selected the MMRTG for power.[14,15,16,17] None of the studies selected the ARTG. The study teams were not allowed to consider the GPHS-RTG even though there were reports than some of the teams were interested in including the GPHS-RTG in the trade space.

For future missions, the ASRG clearly has the preferred attributes: (1) high specific power which means it is the lowest mass RPS option and (2) high efficiency which means it uses almost one-fourth of the nation's precious supply of plutonium-238 ($^{238}$Pu) radioisotope fuel. However, the two teams which did not select the ASRG cited several issues including lifetime, radiation tolerance, final design definition, use of excess waste heat, and interactions of the ASRG-generated environments (e.g., vibration and electromagnetic interference, EMI) particularly in off-nominal cases (e.g., one failed ASRG engine).[14,15]

NASA and DOE are pursuing an aggressive program to address these issues, including a flight test to provide added confidence in the ASRG.[11]

The ARTG, which has attractive performance goals, was not selected because it was "judged too risky and immature for the either the 2015 or 2017 launch opportunities" evaluated in the Europa Explorer study.[14] It was estimated to have a "longer development schedule and higher development risk" and to be "still in its infancy in concept development".[14]

The Europa Explorer team judged that the higher (~4X) use of plutonium-238 by the MMRTG compared to the ASRG was not an issue, citing a DOE commitment to support eight MMRTGs by 2015.[14] Eight MMRTGs would have 64 GPHS modules which are more than enough to fuel three GPHS-RTGs.

According to trade press reports, one issue affecting the cited more mature MMRTG is power decay as a function of time.[25,26] The two study teams which selected the MMRTG cited a power degradation rate of approximately 1.6% per year[14,15] although a graph in a 2009 paper from the manufacturer indicated the degradation rate could approach 2.2% per year.[10] While changes in the MMRTG thermoelectric elements and operating temperature from those used in the Pioneer SNAP-19 RTGs require care in making comparisons, the Pioneer SNAP-19 RTG power averaged over 10 years indicates a decay rate on the order of 3.3% per year.[27] This could be the basis for the published concerns about the EOM performance of the MMRTG on MSL.[25,26] For reference, the power decay rate for the GPHS-RTG is usually taken to be 1.6% per year, of which approximately half comes from the natural decay of the plutonium-238 radioisotope fuel; however, the power decay of the two Galileo GPHS-RTGs averaged over the 14 years of that mission was ~1.1% per year.[28]

[In fairness, it must be noted that RTGs typically do not have a "constant" power decay rate. The plots of RTG power as a function of time often show a more rapid degradation in the first year or two, the "burn-in" phase, followed by a lessening of the decay over the subsequent several years to be succeeded by a lower, more "linear" decay for the longer term that tracks the fuel decay.[29] As noted in the preceding paragraph, a major contributor to the power decay is the decay of the radioisotope fuel, something outside the control of designers. Other factors contributing to RTG power decay include changes in the properties of the thermoelectric elements and, for sealed RTGs such as the MMRTG, changes in the thermal conductivity of the cover gas resulting from the helium buildup produced by the alpha particle ($^{4}$He) decay of the $^{238}$Pu fuel.[29] The GPHS-RTG, which was designed for use in space, is vented so there is no cover gas hence no buildup of helium.[1]]

Outer planet flagship missions typically require electrical power in the range of 360 We to 1 kWe or more which would make them candidates for a high-powered RPS such as the 300-We GPHS-RTG. Just the ease of spacecraft assembly would make a higher-powered RPS very attractive (attaching two or three GPHS-RTGs to a spacecraft as was done for Galileo and Cassini versus attaching four to eight RTGs of the 125-We variety). Another constraint is redundancy. For example, in the Enceladus mission study it was assumed that four ASRGs would be carried (one being a backup) to meet the maximum steady-state load of 362 We. The mass for these four ASRGs was listed as 80.8 kg. The study also considered using three MMRTGs which would provide an estimated 288 We at end-of-life (EOL) for a total mass of 132 kg. The study judged the use of MMRTGs to provide insufficient power at EOL and to be heavy. Both the ASRG and the MMRTG options required the addition of a rechargeable 40-Ah lithium-ion battery to meet occasional higher power demands such as 746 We during orbital insertions.[16] Based on the Galileo, Ulysses and Cassini experiences, three fully fueled GPHS-RTGs of the original design could provide a total of 900 We at launch and over 640 We after 16 years (the Enceladus mission studied had a worst-case mission life of 18.8 years) all within a total mass of 169 kg without the need for a battery. Just 1.5 GPHS-RTGs (essentially one 300-We GPHS-RTG and the GPHS-RTG equivalent of one 155-We Voyager-class Multi-Hundred Watt Radioisotope Thermoelectric Generator, MHW-RTG) could provide more than the required RPS power listed in the Enceladus study with a mass of about 94 kg while reducing battery requirements.

One concern expressed during the search for alternatives to the GPHS-RTG was that it was not "designed to withstand the higher launch loads associated with the newest launch vehicles being used by NASA".[30] Reportedly a major part of this concern had to do with acoustic shock which can be mitigated by special blankets as was done for the Cassini launch. As to other "launch loads", spacecraft designers have dealt with them in the past for both nuclear and non-nuclear missions. There are techniques to reduce the launch loads experienced by the payload. To date, seven GPHS-RTGs have successfully survived real "launch loads".[1,2]

Two issues stand in the way of using the GPHS-RTG on these outer planet flagship missions: (1) the production line for silicon-germanium thermoelectric elements ("unicouples") has been shut down and (2) the GPHS module has been redesigned limiting the existing GPHS-RTG to 16 GPHS fuel modules instead of the original 18 modules thereby reducing the power below 300 We BOL. These issues will be addressed in this paper following the description of the GPHS-RTG given in the next section.

## 4. GPHS-RTG Description

The General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS), shown in cutaway in Figure 5, is composed of two principal elements: the general-purpose heat source (GPHS) assembly and the converter. The original GPHS assembly as used on Galileo, Ulysses, Cassini and New Horizons consisted of 18 GPHS fuel modules, each containing four fueled clads that combined (using fresh fuel) produce about 245 Wt per module for a total of about 4410 Wt. This thermal power is converted into at least 285 We at beginning of mission (BOM) by the converter with its 572 silicon-germanium (Si-Ge) alloy thermoelectric elements ("unicouples"). (At the time of fueling, BOL, the GPHS-RTG is capable of producing ≥300 We. The data from the Galileo and Cassini GPHS-RTGs suggest that 300 We can be achieved at BOM if desired.[1] For the New Horizons mission, the BOM power was 245.7 We because 21-year-old plutonium-238 had to be used in 52 of the 72 fueled clads.[1])

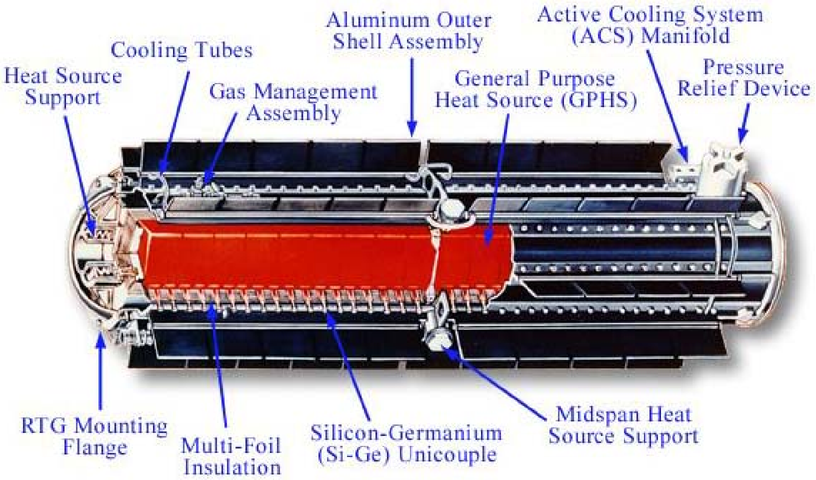

**Figure 5. Cutaway of the General-Purpose Heat Source Radioisotope Thermoelectric Generator as used on the Galileo and Ulysses spacecraft.**
The original GPHS-RTG had an overall diameter of 0.422 m and a length of 1.14 m with a mass of about 55.9 kg. The GPHS-RTG is capable of producing 300 We at BOM from ~4410 Wt of thermal power from the 18 fuel modules of the GPHS. (DOE/NASA/JPL)

### 4.1 GPHS-RTG Converter

The GPHS-RTG converter consists of a thermopile inside an outer shell. The thermopile consists of 572 thermoelectric elements termed "unicouples", multifoil insulation, and an internal frame. The design of the GPHS-RTG thermopile is based on the design of the thermopile used in the Multi-Hundred Watt RTGs (MHW-RTGs) that powered the USAF Lincoln Experimental Satellites 8 and 9 (LES-8/9) and Voyagers 1 and 2.[1,29] The GPHS-RTGs are smaller in diameter than the MHW-RTGs; however, the GPHS-RTGs are about twice as long as the MHW-RTGs and they have almost twice the number of unicouples such that they generate almost twice the power of the MHW-RTGs.[1]

The hot junction temperature averages about 1273 K at BOM and the cold junction temperature averages about 566 K. The corresponding nominal hot shoe temperature is about 1308 K.[1]

The multifoil insulation assembly, which serves as a thermal barrier, consists of 60 layers of molybdenum foil and 60 layers of Astroquartz cloth. The support frame for the insulation system is made of molybdenum. The outer shell assembly, which is made of a type 2219-T6 aluminum alloy forging, consists of a flanged cylinder with eight radial fins and four midspan bosses. Other components such as the electrical power connector, four resistance temperature devices (RTDs), gas management system (GMS), and pressure relief device (PRD) are mounted to the outer shell and sealed by the use of C-seals. The inboard flange has four barrel nuts mounted on the four main load carrying ribs to mount the GPHS-RTG to the spacecraft. A silicone coating applied to the outer shell raises its emissivity to about 0.9. To limit the heat radiated from the converter surface to the launch vehicle (e.g., Space Shuttle), an active cooling system (ACS) consisting of tubular passages near the base of each fin permits water circulation to remove approximately 3,500 Wt. (The ACS was not activated for the launches of Cassini or New Horizons which were accomplished with expendable launch vehicles.)[1]

Following the completion of the GPHS-RTGs for the Cassini mission, the GPHS-RTG production line was shutdown. (The F-8 GPHS-RTG used on the New Horizons spacecraft was built from a spare converter from the Cassini program.) Estimates of the time and cost to reestablish the GPHS-RTG production line (particularly the unicouple production line) have apparently led decision-makers to not consider the GPHS-RTG for future missions where RTG power is required. This paper will consider some options to reconstitute the GPHS-RTG production line, showing that the GPHS-RTG is an attractive power source for future RTG-powered space missions.

### 4.2 General-Purpose Heat Source (GPHS)

The thermal power provided to the converter comes from the general-purpose heat source (GPHS) assembly, which consists of a stacked column of 18 individual fuel modules each providing about 245 Wt from the natural decay of encapsulated plutonium-238 ($^{238}$Pu) oxide fuel, which has a half-life of 87.7 years. Nominally, the plutonium is enriched to about 83.5% Pu-238, although this has varied with later generators (for example, reports on the Cassini GPHS-RTGs cited a lower nominal enrichment of about 82.2%). The reduction of thermal power from the natural decay of $^{238}$Pu is only approximately 0.8 percent per year which makes $^{238}$Pu ideal for long-duration missions. (Various changes in the properties of the unicouple materials can add to the electrical power decay with time.)[1]

A cutaway view of a single GPHS module is shown in Figure 6. Safety was the principal design requirement for the GPHS. The main safety objective was to keep the fuel contained or immobilized to prevent inhalation or ingestion by humans in the event of postulated accidents (e.g., atmospheric reentry and impact). The modules are composed of five main elements: the fuel; the fuel cladding (iridium alloy); the graphite impact shell (GIS); the carbon-bonded carbon fiber (CBCF) insulation; and the Fine-Weave Pierced Fabric (FWPF™) aeroshell. Each module contains four fuel pellets made of a high-temperature ceramic (plutonia) with a thermal inventory of approximately 62.5 Wt per pellet. This translates into about 151 grams of plutonia ($PuO_2$) or about 111.6 grams of $^{238}$Pu. Each module has a total mass of about 1.43 kg (except for F-8, see below). Nominally (and allowing for tolerances on the fuel loading of the individual pellets), the total thermal power for the GPHS assembly is about 4410 Wt at beginning of life (BOL) which translates into about 8.1 kg of Pu-238 per generator. (Because of the plutonium-238 decay, the actual thermal inventories vary depending on when the fuel was made; thus, different thermal inventories will be reported for different missions. For example, for New Horizons, because of the over 21-year-old fuel in 52 of the 72 fueled clads, the estimated thermal power at launch was only 3948 Wt.)[1]

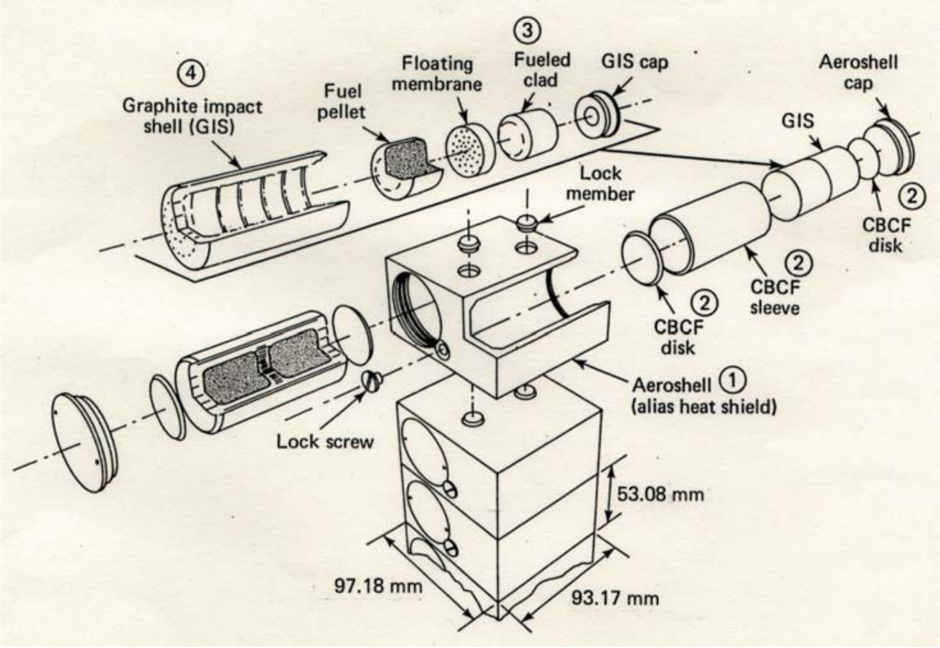

**Figure 6. Cutaway of a general-purpose heat source (GPHS) module. (DOE/LMA/APL)**
The aeroshell and graphite impact shells are made of Fine-Weave Pierced Fabric (FWPF).
CBCF stands for the thermal insulator carbon-bonded carbon fiber.

Following the launch of the Cassini spacecraft in 1997, the U.S. Department of Energy (DOE) embarked on a two-phase program to add more FWPF to the existing GPHS fuel module as part of a safety improvement program. Figure 7 shows the two new module designs ("Step 1" and "Step 2") compared to the original GPHS module (sometimes referred to as "Step 0") that was flown on the Galileo, Ulysses and Cassini missions. The New Horizons spacecraft used the Step 1 module design. The Step 1 module includes an internal web for increased aeroshell strength during postulated impacts and hyper-velocity reentries. The addition of the internal web raises the mass of the GPHS module from 1.435 kg (Step 0) to 1.514 kg (Step 1) but it still allows 18 modules to be placed inside the converter as was done for F-8, the New Horizons GPHS-RTG.

For future missions, DOE has moved to Step 2, which includes the internal web of Step 1 plus a thicker ablator (aeroshell) for improved safety margins during postulated reentries and impacts. The mass of the Step 2 module is 1.606 kg. Within the envelope of the existing GPHS-RTG converter, the increased thickness of the aeroshell limits the number of GPHS modules to 16. This reduces the thermal inventory (and hence the electrical power) by over 10%.

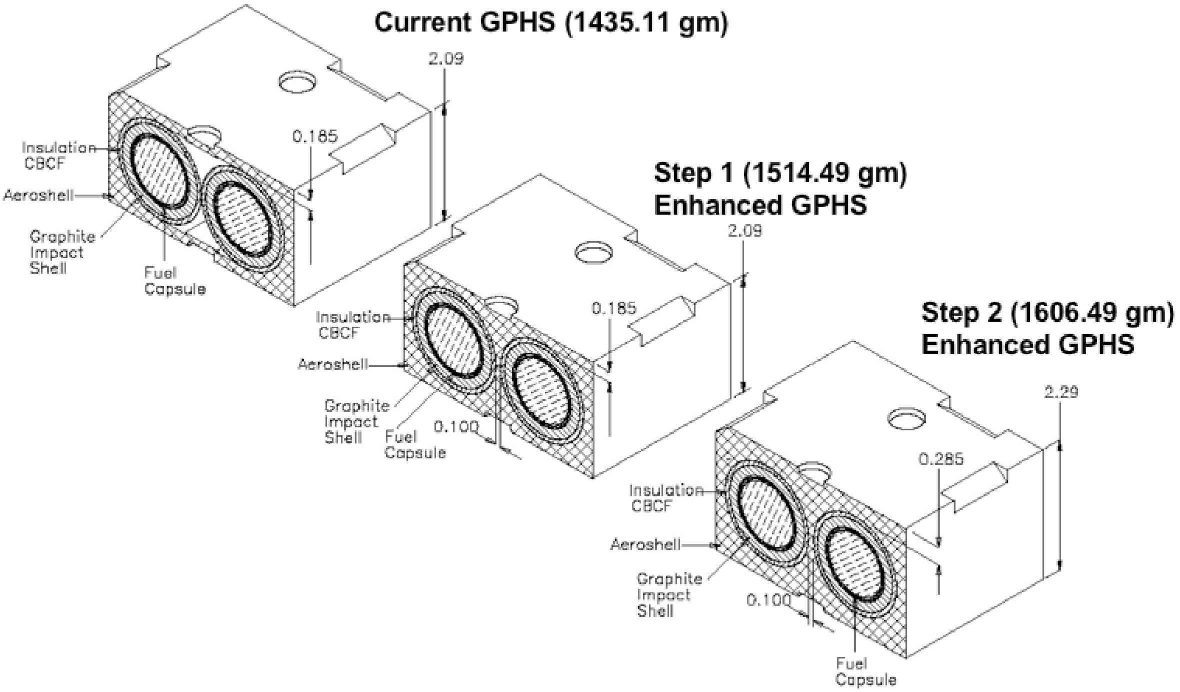

**Figure 7. Evolution of the General-Purpose Heat Source (GPHS) module. (DOE)**
The aeroshell and graphite impact shells are made of Fine-Weave Pierced Fabric (FWPF).
CBCF is an acronym for the thermal insulator carbon-bonded carbon fiber.

## 5. Recreating the GPHS-RTG for Future Missions

The advent of future space missions requiring more RTG power naturally lead to consideration of recreating the GPHS-RTG production line. As noted earlier, two key issues need to be addressed in planning to build new GPHS-RTGs: (1) production of the silicon-germanium alloy unicouples and (2) accommodation of the new heavier and thicker GPHS Step 2 module. The following sections address these two issues and describe some options for producing future GPHS-RTGs under these constraints along with a discussion of improvements that could be made in the GPHS-RTG to accommodate the heavier and larger Step 2 module.

### 5.1 Production of GPHS-RTG Silicon-Germanium Alloy Thermoelectric Elements ("Unicouples")

Following the production of the GPHS-RTGs for the Cassini mission, the production line for the silicon-germanium alloy thermoelectric elements ("unicouples") was shut down and disassembled. The estimated cost and effort required to recreate the unicouple production line have reportedly been major factors in causing decision-makers to turn to other RTG technologies for space missions. However, the discovery in 2007 that Lockheed-Martin had over 3100 unicouples means that two to three new GPHS-RTGs could be readily built without the time and expense of recreating the unicouple production line.

The available unicouples were reported to be distributed as follows:

| | |
|---|---|
| Cassini reserve unicouples | 293 |
| Unicouples from the E-5 converter | 572 |
| MHW-RTG unicouples (from 4 MHW-RTGs) | 1248 |
| Cassini qualification unicouples | 150 |
| MHW-RTG residual unicouples | 879 |
| TOTAL | 3142 |

Obviously each of these unicouples would have to be examined to determine if they meet specifications and some will no doubt require additional work to get them up to flight standards. But if only 36% of these unicouples were acceptable, there would be enough (1144) unicouples to build two GPHS-RTGs. Two GPHS-RTGs would provide 600 We (BOL), more than enough for many planned planetary missions. A yield of about 55% would provide enough (1716) unicouples to build three GPHS-RTGs, enough to provide almost 1 kWe of power!*

Looking beyond existing unicouples, there is clearly a need to maintain the unicouple option. One approach would be to have the GPHS-RTG system contractor subcontract with a company that already specializes in manufacturing thermoelectric devices or in the production of other solid-state devices. Avoiding the complexities of a large system organization could help reduce the cost, particularly the overhead.

Another approach would be to establish the unicouple production line at a government laboratory, much as the government maintains test facilities for industry and operates production facilities for certain national security operations. It would be easier for the government to maintain the unicouple production line in a standby mode during the period between missions than it would be for a for-profit corporation to do so.

### 5.2 Accommodation of the GPHS Step 2 Fuel Module

Within the internal length constraints (~95.5 cm) of the existing GPHS-RTG converter, only 16 of the thicker Step 2 GPHS modules can be accommodated. While having 16 nominally fueled GPHS modules would reduce the BOL thermal inventory to about 3920 Wt (from ~4410 Wt nominal) and the BOL electrical power to about 267 We (from 300 We), the mass would be essentially unchanged. (Sixteen Step 2 modules would have a mass of almost 25.70 kg versus 25.83 kg for 18 Step 0 modules. Adjusting for fewer lock members and the possible addition of a small carbon-based insert to accommodate a 23-cm gap for the 16-module stack would probably lead to a small mass increase for the Step 2 GPHS-RTG.)

Given the importance of and the commonality of the GPHS fuel module to all currently planned RPS, the RPS community should investigate whether there are improved aeroshell and GIS materials that might not require the added thickness of the Step 2 GPHS module. A module that has the dimensions of the original Step 0 module would benefit all currently planned RPS.

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*In practice, more than 572 unicouples per GPHS-RTG would have to be allocated to a build to allow for any losses that may occur during assembly.

### 5.2.1 Enriching the fuel

Usually, the $^{238}$Pu enrichment for the GPHS-RTG fuel pellets is reported as about 82.2 wt% to produce a nominal thermal inventory of approximately 62.5 Wt per pellet. However, if one looks at the GPHS-RTG with the largest thermal inventory (4479.1 Wt BOL for F-3, the GPHS-RTG used on the Ulysses spacecraft) one quickly calculates that the average thermal inventory was 62.2 Wt per pellet. Had the GPHS fuel pellets been enriched to the nominal 62.5 Wt per pellet the total BOL thermal inventory for the F-3 GPHS stack would have been 4500 Wt. Clearly there is margin for improvement within currently specified enrichments.

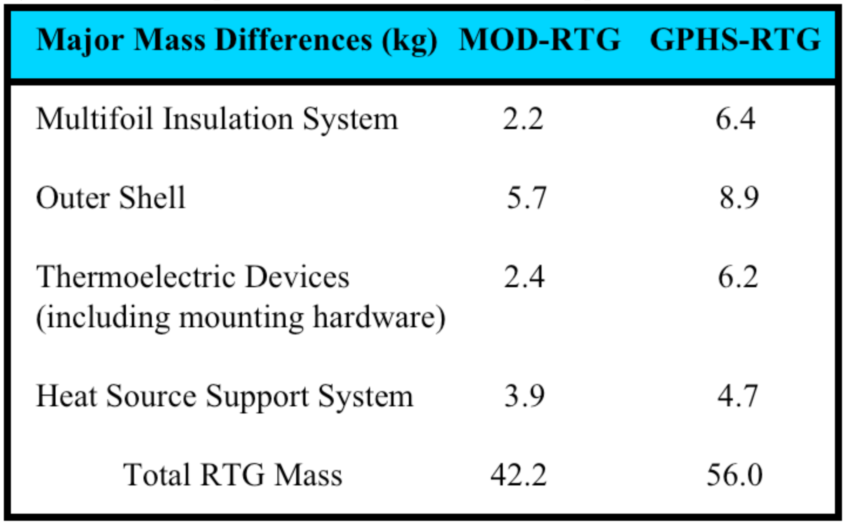
During the production of fuel pellets for the Galileo and Ulysses GPHS-RTGs, Savannah River had occasion to increase the thermal power (enrichment) of the fuel pellets to compensate for some earlier lower-powered (lower-enriched) pellets. Thus, the U.S. production complex had the capability to go above 82.2 wt% $^{238}$Pu. So-called "medical grade" plutonium as used in certain heart pacemakers was enriched to 90 wt% $^{238}$Pu.[31] Moreover, the Russians were reported to be able to enrich beyond 82.2 wt% $^{238}$Pu. [Using medical grade plutonium in a 16-module Step 2 GPHS-RTG would provide almost 4380 Wt BOL, very close to the original specified BOL thermal inventory (4410 Wt) for the original GPHS-RTG.]

Increasing the $^{238}$Pu enrichment from ~82 wt% to 86 wt% would increase the thermal inventory of the 16-module Step 2 GPHS stack to about 4195 Wt BOL. This in turn would yield about 285 We BOL. Coincidentally, 285 We is the BOM specification minimum power for the original Step 0 GPHS-RTGs.

### 5.2.2 Improving the converter

Research conducted during the MOD-RTG program identified a number of improvements that could be made to a converter (see Table 2).[3] For example, where the GPHS-RTG multifoil insulation system used 60 layers of molybdenum foil separated by 60 layers of silica-based Astroquartz separators, the MOD-RTG separated the 60 layers of molybdenum foil with a zirconia powder coating. This reduced the mass of the multifoil insulation system to about one-third of the GPHS-RTG value (~2.2 kg for the MOD-RTG versus ~6.4 kg for the GPHS-RTG).[3] While the specific insulation proposed for the MOD-RTG may not be applicable to the GPHS-RTG, the MOD-RTG work does suggest that with innovative design and development the mass of the insulation system can be reduced for the GPHS-RTG.

**Table 2. Major Mass Differences Between the MOD-RTG and the GPHS-RTG[3]**
(NOTE: Only those components with significant mass changes are shown which is why sums of the component masses shown do not add up to the listed total masses.)



| Major Mass Differences (kg) | MOD-RTG | GPHS-RTG |
|---|---|---|
| Multifoil Insulation System | 2.2 | 6.4 |
| Outer Shell | 5.7 | 8.9 |
| Thermoelectric Devices (including mounting hardware) | 2.4 | 6.2 |
| Heat Source Support System | 3.9 | 4.7 |
| Total RTG Mass | 42.2 | 56.0 |

The GPHS-RTG converter shell and fin assembly is composed of an aluminum alloy (2219-T6). If the aluminum alloy were replaced with beryllium as was used in the MHW-RTG and SNAP-27 converters, the mass of the GPHS-RTG converter shell and fin assembly could be reduced from about 8.9 kg to about 6 kg. (Beryllium is also in the design of the ASRG converter. Using beryllium would necessitate incorporating features to ensure that the converter would release the GPHS modules during a postulated atmospheric reentry.)

There are no doubt other improvements that could be made (e.g., the heat source support assembly) and the vibration/acoustic response of the GPHS-RTG would have to be assessed for the planned launch vehicles.

Table 3 presents summary of the various $^{238}$Pu fuel options and converter options, including as shown in the last two columns, increasing the length of the converter to accommodate the original 18 fuel modules (albeit now of the Step 2 variety). This zeroth order analysis shows that there are significant improvements that can be made to the GPHS-RTG that would make it a very attractive option for future RTG-powered space missions.

**Table 3. GPHS-RTG Options to Accommodate the Heavier Step 2 GPHS Module**
(NOTE: Rounding of the total masses in this table means the listed mass changes in the last row do not follow directly from these listed total masses.)

| GPHS-RTG Options<br>Characteristics | Step 0 (Baseline) | Step 1 | Step 2 | Step 2 (Enriched) | Step 2 Improved Converter | Step 2 Full Stack + Improved Converter | Step 2 Full Stack +Improv Conv + Enriched |
|---|---|---|---|---|---|---|---|
| BOL Electrical Power (We) | 300 | 300 | 267 | 285 | 267 | 300 | 315 |
| GPHS Type | Step 0 | Step 1 | Step 2 | Step 2 | Step 2 | Step 2 | Step 2 |
| Mass (kg) | 56 | 58 | 57 | 57 | 48 | 53 | 53 |
| BOL Specific Power (We/kg) | 5.3 | 5.2 | 4.7 | 5.0 | 5.5 | 5.6 | 5.9 |
| Number of GPHS Modules | 18 | 18 | 16 | 16 | 16 | 18 | 18 |
| Pu-238 Enrichment | 82% | 82% | 82% | 86% | 82% | 82% | 86% |
| Thermal Inventory (Wt) | 4410 | 4410 | 3920 | 4195 | 3920 | 4410 | 4625 |
| Mass Change (kg) | 0.0 | +1.4 | +0.1 | +0.1 | -7.6 | -3.3 | -3.3 |

## Conclusions

A top-level analysis of the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) shows that options exist to improve the performance of the GPHS-RTG under the constraints of the heavier and larger Step 2 GPHS fuel module. If these improvements are successful, the GPHS-RTG could once again be the RTG of choice for RTG-powered space missions. The existence of over 3,100 thermoelectric elements ("unicouples") means that production of the GPHS-RTG could be resumed almost immediately without rebuilding the unicouple production line. The space flight heritage of seven highly successful GPHS-RTGs [Galileo (2), Ulysses (1), Cassini (3), New Horizons (1)] argues strongly for including a modified GPHS-RTG option in the trade space for future RTG-powered space missions. As the space community moves forward with new missions and considers advanced power sources, we should remember the words of Admiral Hyman Rickover (see Appendix B): "… it is incumbent on those in high places to make wise decisions, and it is reasonable and important that the public be correctly informed. It is consequently incumbent on all of us to state the facts as forthrightly as possible."

## Appendix A

## List of Acronyms

ARTG = Advanced Radioisotope Thermoelectric Generator
ASRG = Advanced Stirling Radioisotope Generator
BOL = Beginning of Life
BOM = Beginning of Mission
CBCF = carbon-bonded carbon fiber (thermal insulator)
DIPS = Dynamic Isotope Power System
DOE = U.S. Department of Energy
EJSM = Europa-Jupiter-System Mission
EOL = End of Life
EOM = End of Mission
ESA = European Space Agency
FWPF = Fine-Weave Pierced Fabric
GPHS = General-Purpose Heat Source
GPHS-RTG = General-Purpose Heat Source Radioisotope Thermoelectric Generator
MHW-RTG = Multi-Hundred Watt Radioisotope Thermoelectric Generator
MITG = Modular Isotopic Thermoelectric Generator (later called the MOD-RTG)
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
MOD-RTG = Modular Radioisotope Thermoelectric Generator
MSL = Mars Science Laboratory
NASA = National Aeronautics and Space Administration
OPFM = Outer Planet Flagship Mission
RPS = Radioisotope Power Source (or System)
RTG = Radioisotope Thermoelectric Generator
SNAP = Systems for Nuclear Auxiliary Power
SRG = Stirling Radioisotope Generator (precursor to the ASRG)
USAF = U.S. Air Force
We = watts of electrical power
Wt = watts of thermal power

## Appendix B

## "Paper Reactors, Real Reactors"

### Admiral Hyman G. Rickover

An academic reactor or reactor plant almost always has the following basic characteristics: 1) It is simple. 2) It is small. 3) It is cheap. 4) It is light. 5) It can be built very quickly. 6) It is very flexible in purpose. 7) Very little development is required. It will use mostly off-the-shelf components. 8) The reactor is in the study phase. It is not being built now.

On the other hand, a practical reactor plant can be distinguished by the following characteristics: 1) It is being built now. 2) It is behind schedule. 3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. 4) It is very expensive. 5) It takes a long time to build because of the engineering development problems. 6) It is large. 7) It is heavy. 8) It is complicated.

The tools of the academic reactor-designer are a piece of paper and a pencil with an eraser. If a mistake is made, it can always be erased and changed. If the practical-reactor designer errs, he wears the mistake around his neck; it cannot be erased. Everyone can see it.

The academic-reactor designer is a dilettante. He has not had to assume any real responsibility in connection with his projects. He is free to luxuriate in elegant ideas, the practical shortcomings of which can be relegated to the category of "mere technical details." The practical-reactor designer must live with these same technical details. Although recalcitrant and awkward, they must be solved and cannot be put off until tomorrow. Their solution requires manpower, time and money.

Unfortunately for those who must make far-reaching decisions without the benefit of an intimate knowledge of reactor technology, and unfortunately for the interested public, it is much easier to get the academic side of an issue than the practical side. For a large part those involved with the academic reactors have more inclination and time to present their ideas in reports and orally to those who will listen. Since they are innocently unaware of the real but hidden difficulties of their plans, they speak with great facility and confidence. Those involved with practical reactors, humbled by their experiences, speak less and worry more.

Yet it is incumbent on those in high places to make wise decisions, and it is reasonable and important that the public be correctly informed. It is consequently incumbent on all of us to state the facts as forthrightly as possible.

[Reprinted from *The Energy Daily*, 15 March 1984, page 5, where it was reported that this appeared in the June 1953 edition of *The Journal of Reactor Science and Engineering*. According to Wikipedia (http://en.wikiquote.org/wiki/Hyman_G._Rickover), Admiral Rickover, stating that they were comments from the early 1950s, read some of these statements as part of his testimony before Congress, published in *AEC Authorizing Legislation: Hearings Before the Joint Committee on Atomic Energy* (1970), p. 1702. A slightly longer version of this article in the form of a letter dated 5 June 1953 may be found at http://www.ecolo.org/documents/documents_in_english/Rickover.pdf.]

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