A comprehensive review of Radioisotope Thermoelectric Generator. A B S T R C T

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Review article

A comprehensive review of Radioisotope Thermoelectric Generator.

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A B S T R C T

Given independent and flexible power supply requirements of space apparatus, radioisotope thermoelectric generators are currently playing an increasing role in space power systems. Radioisotope thermoelectric generators (RTGs) convert the decay energy of a radioisotope (^{238}Pu) into heat then into electricity. RTGs have been used to power space exploration missions. This review article studies several crucial features of the static RTGs and the radioisotope fuel and the applications of RTGs and many more. Radioisotope power systems have demonstrated numerous advantages over other types of power supplies for long-lived, unattended applications in space and in remote terrestrial locations. Many especially challenging power applications can be satisfied by proper selection, design, and integration of the radioisotope heat source and the power conversion technologies that are now available or that can be developed.

Contents

1. INTRODUCTION

Radioisotope power systems are nuclear power systems that derive their energy from the spontaneous decay of radionuclides, as distinguished from nuclear fission energy created in reactor power systems. The most commonly used radioisotopes are the alpha and beta emitters because they do not require the significant shielding as required for gamma emitters. The two major components of any radioisotope power system, or generator, are a radioisotope heat source and an energy conversion system. Heat is produced during the decay process within the heat source. This heat is partially transformed into electricity and the waste heat is transferred to space or the environment surrounding the generator. Such power systems are rugged, compact and highly reliable, and can be safely produced and used with minimal risk to operating personnel, the general public, and the Earth's environment. These systems started with general purpose heat source-radioisotope thermoelectric generators (GPHS-RTGs) then the multi-mission radioisotope thermoelectric generators (MM-RTGs). All types of radioisotope power systems have a number of common advantages for instance a long life, high power density and lighter weight compared with other power sources such as solar energy. Also, they still work well in bad weather conditions, various temperatures and pressures, dense atmosphere and vacuums. As a result of this, their applications are becoming wider. Their applications can range from micro-electromechanical systems (MEMS) which need low electrical power such as micro-sensors for measuring and monitoring purposes in the difficult accessible places such as bridges, undersea, building structures, biomedical devices, through to the space exploration missions which require up to a hundred watts during their work on the outer solar systems. The general-purpose heat source radioisotope thermoelectric generator (GPHS-RTGs), which was most recently flown on the New Horizons mission to Pluto, was originally conceived in 1979 and executed in a crash program to replace another RTGs for the planned International Solar Polar Mission (ISPM). ISPM would later morph into the Ulysses mission to explore the polar regions of the Sun. When the benefits of the GPHS-RTGs technology became apparent, the Galileo program also adopted the GPHS-RTGs as the power source for orbital exploration of Jupiter. The GPHS-RTGs then became the power source of choice for the Cassini mission to Saturn. The GPHS-RTGs was designed such that it could produce 300 watt at fueling with a mass of 55.9 kg, making the GPHS-RTGs the most powerful RTGs with the highest specific power ever flown.

2. RADIOISOTOPE FUEL

Selection of a suitable radioisotope, commonly referred to as fuel, for use in space radioisotope power systems is the key to their acceptance and use. The characteristics of an acceptable fuel include a long half-life, low radiation emissions, high power density and specific power and a stable fuel form with a high melting point. The fuel must be safely producible in useful quantities and at a reasonable cost and must be capable of being used safely in all normal and potential accident environments. The size and weight of a heat source are directly related to the half-life of the fuel. If the half-life is too long, the radioactive decay rate is slower and associated heat production rate is low. This results in a fuel loading that is too large and too heavy for space missions. If the half-life is too short, a great deal of heat may be produced initially, but the heat production rate will decay quickly. Because of this, excess fuel must be added to maintain the amount of heat required at the end-of-mission (EOM). The half-life of the radioisotope fuel should be at least as long as or longer than the mission lifetime to reduce the heat variation over the mission.

The levels of penetrating radiation (gamma, X-ray, and neutron) emissions must be inherently low for any radioisotope fuel used in space applications. This will reduce the burden required to protect workers and the spacecraft from the potential damaging effects of radiation. This is also important for protection of the public and the environment in the event of a launch accident. The radioisotope fuel must also be useable in a form with a high melting point that remains stable during postulated launch accidents. The fuel form must be chemically compatible with its containment material over the operating life of the heat source. It is also highly desirable that the fuel form have a low solubility rate in the human body and in the natural environment. Radioactive decay products must not adversely affect the integrity of the fuel form, and the decay process should not degrade its properties.

Any radioisotope fuel selected for space power applications must be producible in sufficient quantities and on a schedule to meet mission requirements. There are only two methods for obtaining radioisotopes in the quantities needed for space power applications. The first involves processing spent fuel from a nuclear reactor to isolate by products of interest. The other is the deliberate production of radioisotopes by irradiation of target materials in a nuclear reactor or a very high-powered accelerator facility. Both of these approaches require major investments in nuclear facilities capable of processing highly radioactive spent reactor fuel or irradiated targets. Chemical processing technology to produce the proper fuel compound with the necessary purity must also be available, along with fabrication processes and facilities to produce the final fuel form. These radioisotope fuel facilities must be operated under the strictest safety and environmental standards and take into account the ultimate disposal of any radioactive wastes generated.

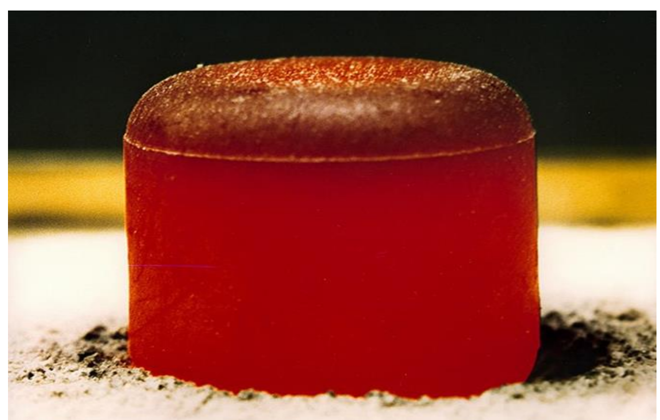


Fig.1 Plutonium-238 oxide pellet glowing from its internal generated heat.

The isotope which has been most used in such power systems is ^{238}Pu. However other isotopes were used in the past, for example polonium ^{210}Po was used by the United Soviet Socialist Republic (USSR) in 1961 and 1971. Their aim at that time was to generate 800W heat in Orion-1 and Orion-2 (RTGs) respectively. Researchers have been investigating a potential replacement isotope for ^{238}Pu. In spite of these efforts, it has been concluded that the most acceptable isotope for space missions is ^{238}Pu. There are a number of reasons for this, namely: a long half-life of around 87 years, high power density (heat/ volume), high specific power (heat/ mass) and pure alpha emission (100 % alpha decays). The fuel is formed in a ceramic oxide ($^{238}\mathrm{Pu}O_2$) to be used within the GPHS modules because this form has a very high melting point and very low solubility, among other features.

$$^{238}\mathrm{Pu} \xrightarrow{alpha\ decay} {}^{234}\mathrm{U} + 5.6MeV \text{(Half-life about 87.7 years)} \quad (1)$$

The, ^{238}Pu is created when neptunium targets are irradiated by neutrons in a laboratory or by other means.

$$^{237}Np + n \rightarrow {}^{238}Np \xrightarrow{\beta\ decay} {}^{238}\mathrm{Pu} \quad (2)$$

Firstly, targets are placed in a nuclear reactor, which utilizes enriched uranium such as light water reactors. During this process sometimes isotope ^{236}Pu is produced as well, which creates difficulties because it emits gamma rays that require significant shielding. Another method that can be used is to reprocess the spent fuels of a nuclear reactor.

3. ENERGY CONVERGION SYSTEM

The radioisotope heat source delivers its heat to some type of energy conversion system that converts part of the heat into useful electrical power. Static systems include thermoelectric, thermionic, and thermophotovoltaic conversion devices that can convert heat to electricity directly with no moving parts.

Efficiency is an important consideration in selecting an energy conversion system because of its effect on the radioisotope inventory and its impact on cost, availability, size and weight. System reliability is also important. Since mission success depends on having sufficient electrical power over the life of the mission, the selection of an energy conversion system must be consistent with mission power levels and lifetimes. Graceful power degradation over the life of a mission is acceptable as long as it is within predictable limits. Other characteristics important in selecting an energy conversion unit for a radioisotope space power system are weight, size, ruggedness to withstand shock and vibration loads, survivability in hostile particle and radiation environments, scalability in power levels, flexibility in integration with various types of spacecraft and launch vehicles, and versatility to operate in the vacuum of deep space or on planetary surfaces with or without solar energy inputs.

4. RADIOISOTOPE THERMOELECTRIC GENRATORS (RTGs)

RTGs are devices that convert the waste heat given off by radioactive decay processes into useable electrical energy and are often installed in space-bound objects that require energy and other remote structures/machines that cannot obtain energy efficiently by any other means. These include satellites, probes, and remote lighthouses. Ideally, RTGs are established in systems under some of the following circumstances:

1. Unable to be continually maintained and serviced
2. Incapable of generating solar energy efficiently
3. Need to remain operating without human aid for long durations of time
4. Minimal human interaction

Based on these circumstances, the chief usage of RTGs is in fully automated systems that will not experience human contact for periods of time longer than other sources of energy, such as batteries and fuel cells, can sustain and in environmental conditions that are not conducive to generating energy by natural means (solar, wind, etc.). The following provides an overview of radioisotope thermoelectric generators including descriptions of their designs and how they operate, some examples of modern applications, and a few comments on their general safety.

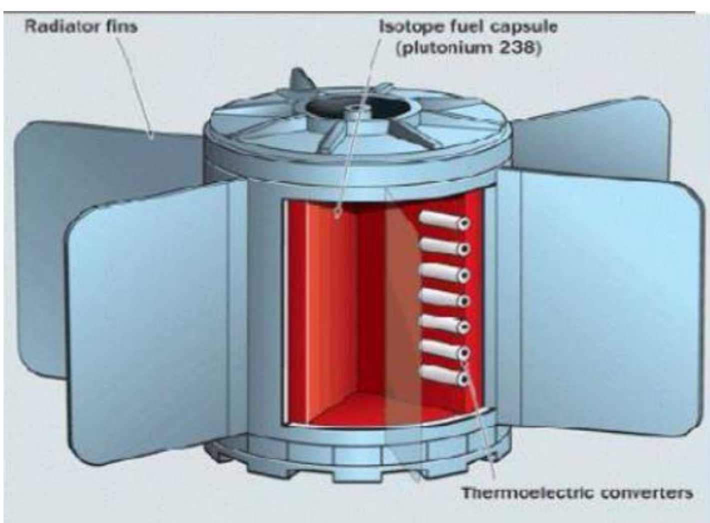


Fig.2 RTGs.

RTGs are currently the longest-lived sources of energy, it does not require any human maintenance or refueling. Isotopes of a given element are atoms with the same number of protons and electrons but different numbers of neutrons in the nucleus. They are unstable and undergo a process of decay during which they emit radiation the term radioisotopes. Radioisotope power generation is the process of generating electrical energy through an electrical generator that uses thermocouples to convert heat from the decay energy of a radioisotope material by the Seebeck effect. RTG's are mostly used in small-scale situations that need a few hundred watts of power or less. It is the most desirable energy source that is suitable for the unmaintained situation. They are mostly used in space exploration missions which require up to a hundred watts during their work on the outer solar systems. They are also used on earth where electrical power is needed for weather stations, navigation beacons, and other special installations like power for lighthouses.

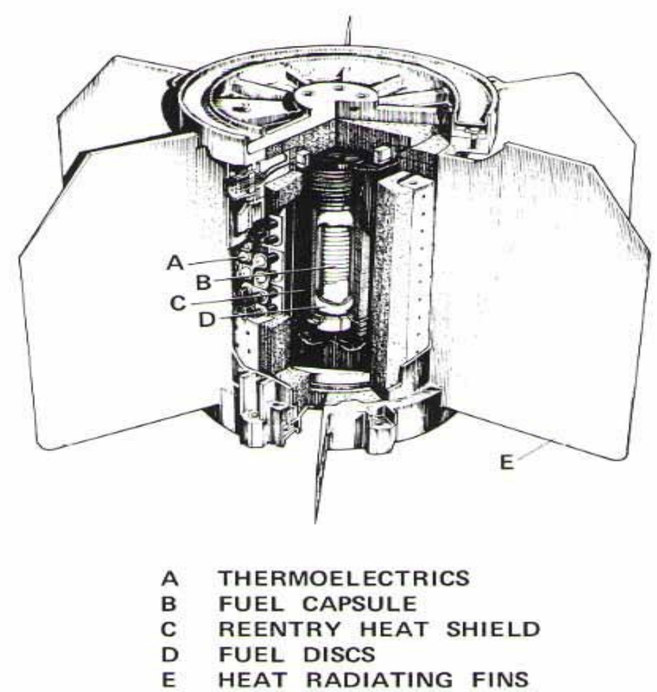


Fig.3 construction of the RTGs.

RTG's are static thermal to electric energy conversion devices, no electromagnetic interferences, no moving parts, no vibrations. Their freedom of maintenance makes it a very useful source of energy in the spacecraft sent off to the outer solar system and beyond where the intensity of sunlight decreases with distance. Although Radioisotope thermoelectric generators have advantages of reliability and mostly used in fully automated systems that will not experience human contact for periods of time longer than other sources of energy, they are rarely used compared to other sources of energy due to their Low efficiency, huge cost and only used in small-scale application.

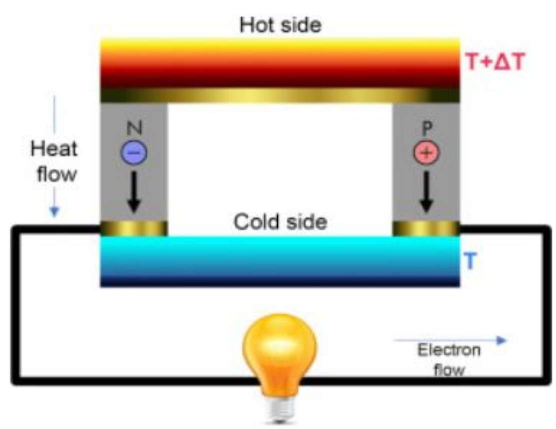
4.1. PERFORMANCE

Thermoelectric generator typically consists of two major components; the fuel capsule (energy source) that will decay radioactively, and several hundred thermoelectric elements to transform part of the isotope decay heat into electricity. The fuel is located behind the thermal insulation layer and thermocouples are lined in modules throughout the sides of the RTG. The fuel source produces the thermal output power from the kinetic energy of radioactive decay of the radioisotope, then sends the heat to sets of thermocouples that convert the heat into useful electricity based on a principle called the Seebeck effect.

The Seebeck effect states that electrical voltage can be generated in a loop, which consists of two different electrically conductive materials with a temperature differential across the junction. An applied temperature gradient causes charged carriers to diffuse from the hot to cold side in the material. This phenomenon was discovered by the German scientist Thomas Seebeck in 1821. Thermoelectric converters require no start-up devices to operate and begin producing electrical power as soon as the heat source is installed.

The converters are connected thermally in a parallel circuit to prevent system failure due to an open circuit or short circuit in a single thermocouple and electrically in a series circuit in order to increase the obtained voltage. Thermocouples are typically low voltage, high current devices so a number of them must be connected in series to produce normal load voltages. Thermocouple used in a radioisotope generator is composed of positive-P and negative-N type element. Electrons flow toward the hot junction in positive elements and flow away from the hot junction in negative elements.

Fig.4 shows a schematic of the thermoelectric generator, the hot side is heated from the energy source of radioisotopes.



$$dE_s \; \alpha \; dT \quad \rightarrow \quad dE_s = \pm\alpha dT$$

$$E_s = \pm\int_{T_1}^{T_2} \alpha dT \qquad (1)$$

E_s is the Seebeck voltage.

α is the Seebeck coefficient for material.

T is the temperature.

The Seebeck coefficient S is given by the potential-to-temperature difference ratio:

$$S = \frac{\Delta V}{\Delta T} \qquad (2)$$

Where ΔV is the potential difference across a piece of metal due to a temperature difference ΔT. The sign of the Seebeck coefficient represents the potential of the cold side with respect to the hot side. For electrons diffusing from hot to cold end, the cold side is negative with respect to the hot side, making S < 0.

Using the Fermi-Dirac distribution, the average energy E_{av} per electron in a metal is given by

$$E_{av} = \frac{3}{4}E_{F0}\left[1 + \frac{5\pi^2}{12}\left(\frac{kT}{E_{F0}}\right)^2\right] \quad (3)$$

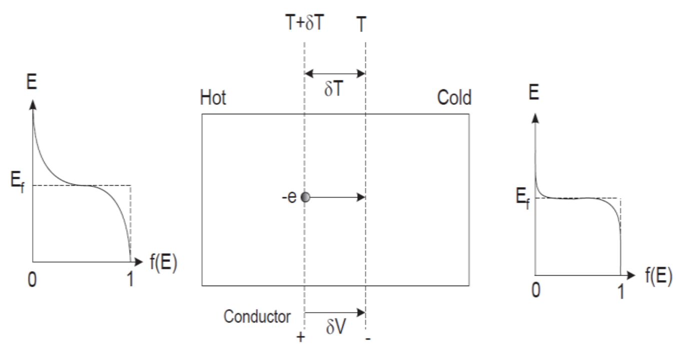


Fig.5 Seebeck effect diagram

Considering a small temperature difference δT produces a voltage δV between the accumulated electrons and exposed positive metal ions as it is shown in Fig.4 for electrons diffusing from the hot region to the cold part, the system would work against the potential difference δV, i.e. -eδV, decreasing the average energy of the electron byδE_{av}, yielding

$$-e\delta V = E_{av}(T + \delta T) - E_{av}(T) \quad (4)$$

Using Eq. (3) in (4), and expanding T+δT, neglecting δT^2 term we obtain,

$$-e\delta V \approx \frac{\pi^2 k^2 T}{2E_{F0}} \qquad (5)$$

The Seebeck coefficient

$$S \approx -\frac{\pi^2 k^2 T}{2eE_{F0}} \qquad (6)$$

The sign means that the electrons moves from cold to hot end of a copper rod.

Considering an aluminum rod heated at one end and cooled at the other end, the voltage difference reads

$$V_{AB} = \int_{T_0}^{T} (S_A - S_B)\, dT \qquad (7)$$

Where $S_A - S_B$ is the thermoelectric power for the thermoelectric couple given by both rods joined in a closed circuit. The voltage produced by the thermocouple pair depends on the metal used. Some conductor doped by the addition of impurities can produce deficiencies or an excess of electrons providing greater efficiency. The power extracted of the thermoelectric material is a function of its operating temperature. Elements with high enough thermal conductivity produce energy loses. Heat entering into the hot end would escape without much conversion to electricity. For a thermoelectric generator the thermoelectric rating,$Z = \frac{S^2}{RK}$ depends on the characteristic of the material, i.e. the voltage produced for the difference of temperature. Both R and K are electrical resistivity and thermal conductivity of the material, respectively. The thermoelectric generator will be more efficient with high Z values, i.e. high S, 1/R and 1/K. Ordinary metals like cooper are very good heat conductors.

4.2. APPLICATION OF RTGs.

The simple design of RTGs leads to their utilization in many applications fitting the parameters listed in the introduction, both on Earth and in space. On Earth, RTGs have been used in unmanned facilities such as hundreds of old, abandoned Russian lighthouses and various U.S. commissioned arctic monitoring sites. The keys to these terrestrial uses are that the RTGs have been placed in remote areas not frequently accessed by humans for maintenance and used in facilities that will remain at their locations for extended periods of time, lasting decades. This justifies the use of these potentially hazardous nuclear-powered RTGs on Earth, minimizing danger to human beings.

The most impactful usage of RTGs has been in a variety of interstellar projects including a fairly large variety of space probes sent to the Moon, flights to the outer planets of the Solar System such as Pioneer and Voyager, and most recently, the robotic rover Curiosity sent to Mars.

4.3. SAFETY

As with the implementation of any nuclear-based processes into functioning devices, there is always concern over human safety and radioactive contamination. Even though RTGs are designed to function in remote environments with sparse human populations, the worries are not totally unwarranted as there are plenty of questions regarding the event of RTG fuel leaks or possible explosions while launching space-bound RTGs. In the worst-case scenarios of these situations, there would be substantial radioactive contamination in the environment along with the potential for radiation damage to humans. This makes the use and launching of RTGs at least semi-controversial. However, in practice, there are safety measures applied to minimize the risks of radioactive contamination from RTGs. For instance, in the NASA mission to Saturn featuring the Cassini-Huygens probe, the RTGs isotope fuel was stored in high-strength blocks of graphite and surrounded by a layer of iridium metal in order to curb the risk of accidental explosions. These graphite blocks have proven to be successful in preventing radiation contamination as in the case of the famed failed Apollo 13 landing in 1970, which left its RTG in the ocean after its return to Earth, but with no detectable plutonium contamination. In the end, despite potential radiation risks, the advantages of RTGs use far outweigh all other factors.

5. GENRAL PURPOPSE 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 modules each providing about 245 Watt from the natural decay of encapsulated plutonium-238 (Pu-238) 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. As a result of the Pu-238 half-life, the reduction of thermal power is only approximately 0.8 percent per year which makes it ideal for long-duration missions. (Various changes in the properties of the unicouple materials can add to the electrical power decay with time.)

A cutaway view of a single GPHS module is shown in Figure 6. Safety was the principal design driver for the GPHS. The main safety objective was to keep the fuel contained or immobilized to prevent inhalation or ingestion by humans. The modules are composed of five main elements: the fuel; the fuel cladding; the graphite impact shell (GIS); the carbon-bonded carbon fiber (CBCF) insulation; and the Fine Weave Pierced Fabric (FWPF) aero shell. Each module contains four fuel pellets made of a high-temperature ceramic with a thermal inventory of approximately 62.5 Watt per pellet. Each module has a total mass of about 1.43 kg. Nominally (and allowing for tolerances on the fuel loading of the individual pellets), the total thermal power for the GPHS assembly is about 4410 Watt 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 Watt.)

The GPHS went through a number of exacting engineering tests to assess its performance under operating conditions, including vibration and operating temperature. An extensive safety testing and analyses program has been conducted to assess the GPHS performance under a range of postulated accident conditions such as launch pad explosions, projectile impacts, propellant fires, impacts, and atmospheric reentry. Separate, detailed safety analysis reports, independent safety evaluation reports, and environmental impact statements have been completed for each of the missions (Galileo, Ulysses, Cassini and New Horizons). The public and independent agencies such as the Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC) have been involved in these four separate reviews. Based upon independent assessments of this detailed work have come individual presidential launch approval decisions for each of the four missions.

The fuel pellets have a diameter of about 2.76 cm and a length of about 2.76 cm. Each fuel pellet within a GPHS module is individually encapsulated in a welded iridium alloy (DOP-26) clad that has a minimum wall thickness of 0.55 mm. The DOP-26 alloy is capable of resisting oxidation in a hypothetical post-impact environment while also being chemically compatible with the fuel and graphitic components during high temperature operation and postulated accident environments. The combination of fuel pellet and iridium cladding is referred to as a “fueled clad”.

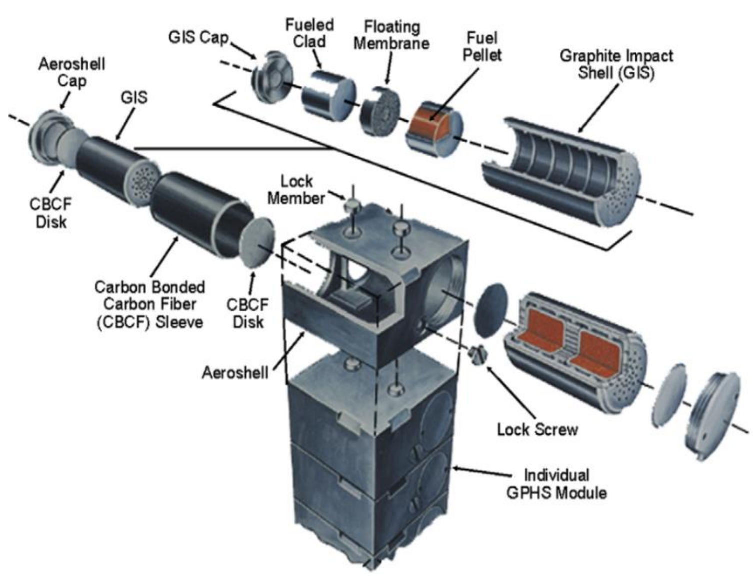


Fig. 6 General purpose heat source (GPHS).

Two fueled clads are encased in a graphite impact shell (GIS) made of FWPF, a carbon-carbon composite material. The cylindrical GIS is designed to provide protection to the fueled clads for postulated impact accidents. In turn, two graphite impact shell assemblies, each containing two fueled clads, are located in each FWPF aero shell. A carbon-bonded carbon fiber (CBCF) insulator surrounds each GIS within the aero shell to limit the peak temperature of the fueled clad during inadvertent reentry and to maintain a sufficiently high temperature to ensure its ductility upon the subsequently postulated impact. The aero shell serves as the primary structural member of the GPHS module as it is stacked inside the GPHS-RTG. The aero shell is designed to contain the two graphite impact shell assemblies under a wide range of postulated reentry conditions and to provide additional protection against postulated impacts on hard surfaces at terminal velocity. FWPF was selected because its composite structure gave it a high margin of safety against the thermal stresses associated with postulated atmospheric reentries. The aero shell also provides protection for the fueled clads from postulated launch vehicle explosion overpressures and fragment impacts and it can provide protection in the event of a propellant fire. For the New Horizons GPHS-RTG, a modification of the aero shell was made to include a web around the graphite impact shells. This has been termed the “Step 1” modification to the basic GPHS design and, while it was done to enhance safety, it also increased the mass of the module to about 1.51 kg.

6. GPHS-RTGs 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 unicouples, shown in Figure.7 are individually fastened to the outer shell. The two silicon-germanium (SiGe) alloy legs of the couple and their corresponding sections of the silicon-molybdenum alloy (SiMo) hot shoe are doped to provide thermoelectric polarity: phosphorous is the dopant for the N-leg and boron is the dopant for the P-leg. The N and P legs are equal in size, 2.74 mm x 6.50 mm in cross section, with a total length of 20.3 mm. Couple height is 31.1 mm and the hot shoe measures 22.9 mm x 22.9 mm and is 1.9 mm thick. The SiGe alloy thermocouple is bonded to a cold stack assembly of tungsten, copper, molybdenum, stainless steel, and alumina parts which separate the electrical and thermal currents. Copper connectors form the electrical circuit in the space between the inside of the outer shell (“converter housing”) and the outside of the insulation system. The electrical circuit uses a two-string, series-parallel wiring design for reliability (power is still provided in the event of a single unicouple open circuit or short-circuit failure). The circuit loops are arranged to minimize the net magnetic field of the generator. Each unicouple is electrically insulated from the multifoil insulation by several layers of Astroquartz (SiO_2) yarn (nominal diameter 0.76 mm) wound tightly around the couple legs and by an alumina wafer beneath the hot shoe.

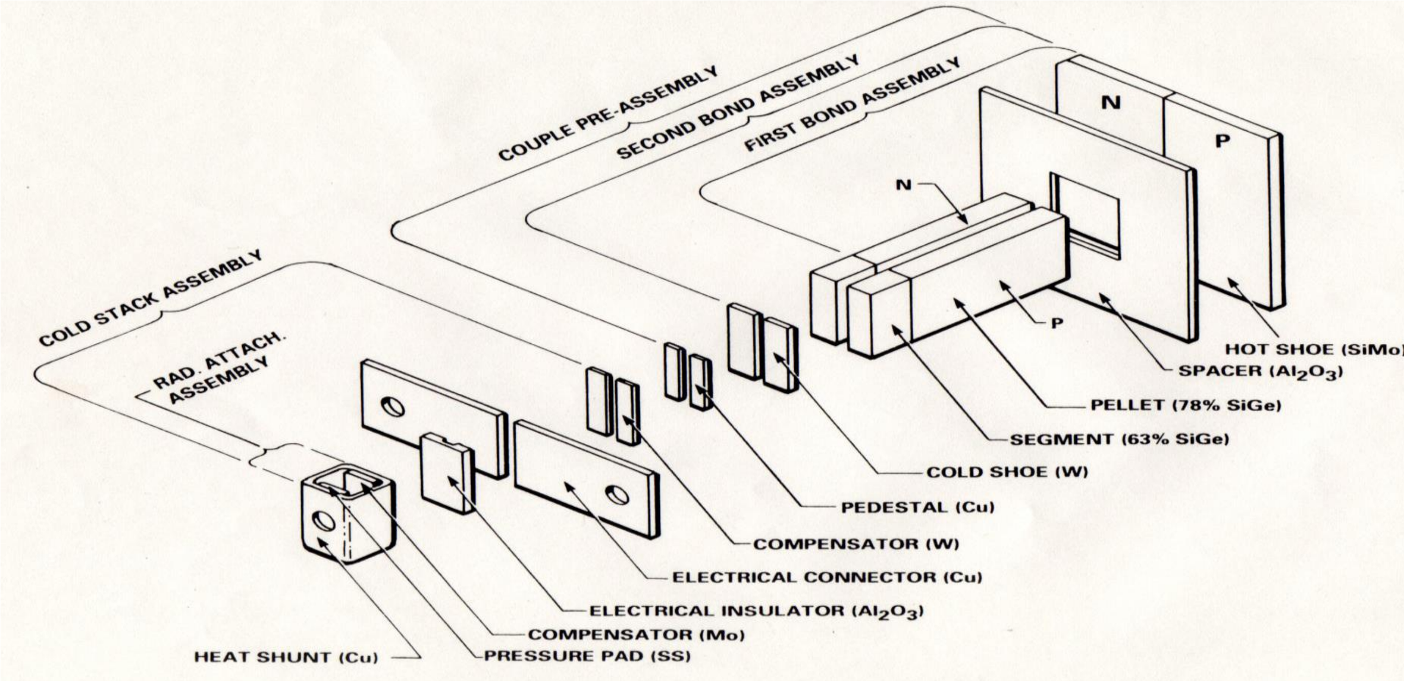


Fig.7 Exploded view of a silicon-germanium alloy thermoelectric element ("unicouple") as used in the GPHS-RTG.

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.

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, an active cooling system (ACS) consisting of tubular passages near the base of each fin permits water circulation to remove approximately 3,500 Watt.

There are two principal modes of operation for the GPHS-RTG: air and vacuum. During air (ground) operation, the RTG is filled with an inert gas (normally argon for testing and storage and xenon at launch) to protect the molybdenum and graphitic components from oxidation. Full power operation in space is achieved after venting the inert gas through the PRD.

7. THE GENERAL PURPOSE HEAT SOURCE RADIOISOTOPE THERMO ELECTRIC GENERATORS (GPHS-RTGs)

The current state-of-the-art in space RTGs is represented by the GPHS–RTG, so named because it was the first to employ the GPHS modules. The GPHS–RTG, shown in Fig.8, is the largest Pu-238 fueled, long-lived RTG built for use in space missions. Utilizing recently precipitated Pu-238, it produces at least 285 We at launch from a Pu-238 heat source assembly containing a stack of 18 GPHS modules. The GPHS–RTG operates at a normal voltage output of 28 -30 V-dc. The overall dimensions of the GPHS–RTG are 42.2 cm (16.6 in.) diameter by 114 cm (44.9 in.) long. The GPHS–RTG weighs 55.9 kg (123.3 lb.) for a specific power at launch of 5.1 Weight/kg (2.3 Weight/lb.).

The unicouples are connected in two series-parallel electric wiring circuits in parallel to enhance reliability and provide the full output voltage. The electrical wiring is also arranged to minimize the magnetic field of the RTG. Since 1989, a total of seven GPHS–RTGs have been launched on four missions. The most recent use of a GPHS–RTG was on the New Horizons mission, launched in January 2006 to encounter Pluto and Charon in 2015. All of these GPHS–RTGs performed, and continue to perform, as predicted.

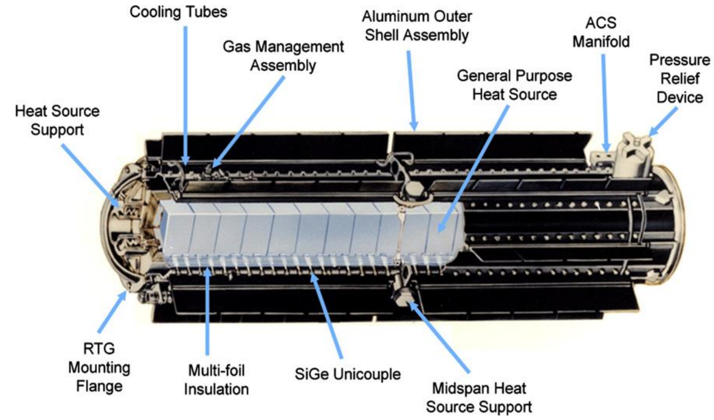
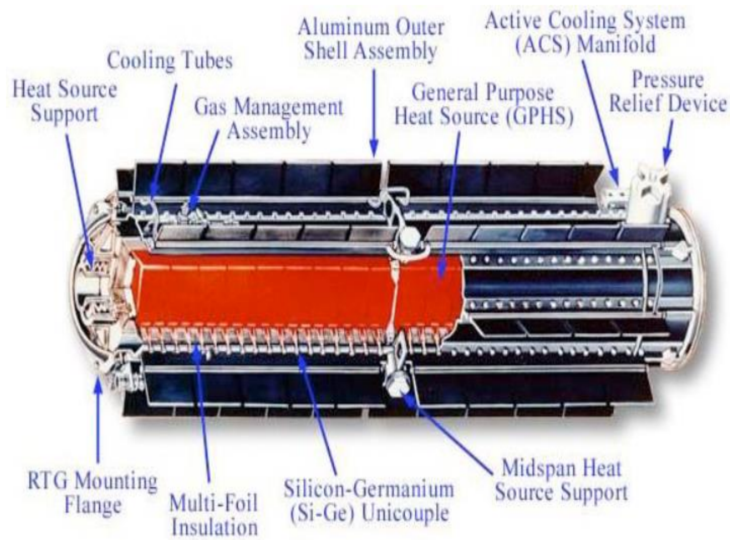
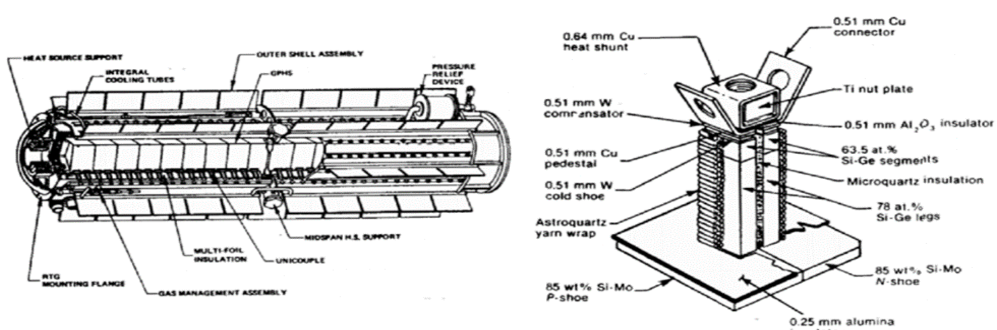


Fig.8 Cutaway of the General-Purpose Heat Source Radioisotope Thermoelectric Generator.





(a) (b)

8. MULTI-MISSION RADIOISOTOPE THERMOELECTRIC GENERATORS (MMRTGs).

The next generation of space RTGs is represented by the MMRTG. This lower-powered RTG is being developed by DOE for use in missions on the Martian surface as well as for potential missions in deep space. This mission flexibility is the primary reason for development of the MMRTG, as the GPHS–RTG was only designed for mission use in the vacuum of space. The first planned use of the MMRTG is to provide power for the Mars Science Laboratory (MSL) rover scheduled for launch in September 2009.

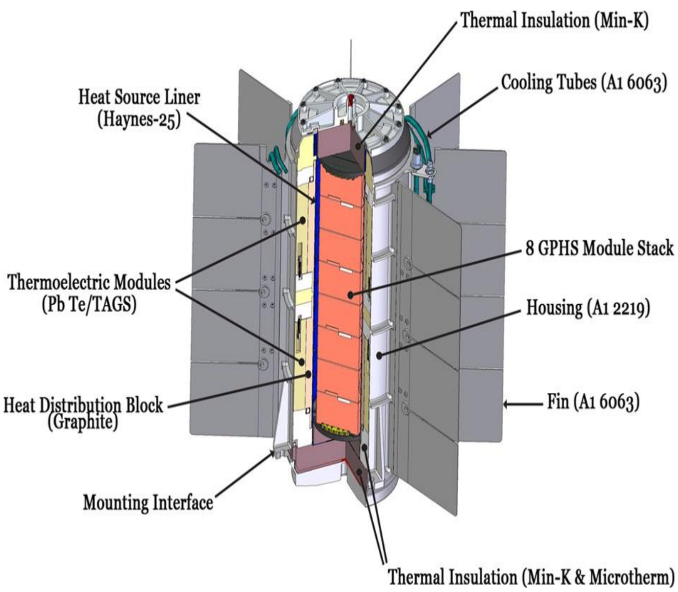


Fig.9 MM-RTGs

The MMRTG will produce 110 We minimum at launch from a Pu-238 heat source assembly containing a stack of 8 GPHS modules. The MMRTG operates at a normal output voltage of 28 V-dc. The overall dimensions of the MMRTG are 64 cm (25 in.) diameter by 66 cm (26 in.) long. The MMRTG weighs 44 kg (97 lb.) for a specific power at launch of 2.73 Weight/kg (1.24 Weight/lb.).

The central heat source cavity is separated from the thermoelectric converter cavity by a helium isolation liner. The helium generated within the heat source by alpha decay of the Pu-238 is dumped to the environment by diffusion through an elastomeric gasket seal. The thermoelectric converter cavity is hermetically sealed so that it can operate in an atmospheric environment or in the hard vacuum of space.

The thermoelectric converter is composed of 16 modules of 48 thermocouples each, for a total of 768 thermocouples. The thermoelectric materials employed are the same PbTe/ TAGS materials used in the SNAP-19 RTGs for the Pioneer 10/11 and Viking 1/2 missions. The thermoelectric elements are smaller in diameter to increase the voltage output of the RTGs. The individual thermocouples are spring-loaded between the cold-end module bars and the hot-side graphite heat accumulator block. The thermocouples are connected in a series-parallel electrical circuit to enhance reliability. Fibrous bulk thermal insulation is used to minimize bypass heat losses. The thermoelectric converter operates in an inert cover gas to reduce sublimation/ vaporization of the thermoelectric materials and power degradation during the operating life of the MM-RTGs. The PbTe/TAGS thermocouples operate between a hot junction temperature of 811 K and a cold junction temperature of about 483 K to produce a thermoelectric efficiency of about 6.8%.

Waste heat is radiated from the eight radial fins on the housing. Both the housing and fins are made of aluminum alloys that will readily disintegrate and release the GPHS modules in the case of an inadvertent reentry into the Earth's atmosphere. The housing and fins are coated with a high-emissivity coating. For the MSL rover mission, the MM-RTGs is equipped with coolant tubes attached to the fin roots for use in providing waste heat for thermal control of the rover's equipment. The size of the radiator fins can be tailored to various mission heat sink conditions.

9. CONCLUSION

It was observed that the safety criteria, long-life, high specific power and power density and high melting of Pu-238 were the main reasons behind choosing it for the past, present and future thermal radioisotope power generators. The efficiency of radioisotope thermoelectric generators (GPHS-RTG and MM-RTG) depends on the thermal and electrical conductivity of thermocouples, and the temperature difference between the hot and cold sides, but it may limit improvements to very high efficiencies. Because the melting point of the generator components would not be able to withstand this high temperature. Therefore an idea emerged to include a thermodynamic cycle in such generators such as Stirling engine cycle. Significant success, in terms of efficiency and the amount of used Pu-238 have been achieved with these new systems.

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