Review of recent advances of radioisotope power systems

Robert G. Lange*, Wade P. Carroll

US Department of Energy, 19901 Germantown Road, Germantown, MD 20874, United States

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Abstract

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. This paper provides a brief review of the factors influencing selection of radioisotopes and design of power systems, and discusses the current state of practice and future programmatic and technical challenges to continued use of radioisotope power systems in space.

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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 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.

Since before the first Sputnik was launched into space, the Department of Energy (DOE) and its predecessor agencies have been developing the technology to fabricate and deliver radioisotope power systems for use on US military and civilian space missions. Since 1961, the United States has launched 45 radioisotope thermoelectric generators (RTGs) on 26 spacecraft for various NASA and Department of Defense missions in high and low Earth orbit, on the surfaces of the moon and Mars, and fly-bys to and beyond the outer planets (see Table 1).

2. Radioisotope fuels

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

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* Corresponding author. Tel.: +1 301 903 3456; fax: +1 301 903 1510.
  E-mail address: Robert.Lange@nuclear.energy.gov (R.G. Lange).

Table 1
US spacecraft using nuclear power systems

Power source	# RTGs	Spacecraft	Mission type	Launch	Status
SNAP-3	1	Transit 4A	Navigational	1961	Currently in orbit
SNAP-3	1	Transit 4B	Navigational	1961	Currently in orbit
SNAP-9A	1	Transit 5BN-1	Navigational	1963	Currently in orbit
SNAP-9A	1	Transit 5BN-2	Navigational	1963	Currently in orbit
SNAP-9A	1	Transit 5BN-3	Navigational	1964	Mission aborted; heat source burned up as designed
SNAP-10A	Reactor	Snapshot	Experimental	1965	Achieved orbit; was shut down after 43 days
SNAP-19	2	Nimbus B-1	Meteorological	1968	Mission aborted; heat sources retrieved
SNAP-19	2	Nimbus III	Meteorological	1969	Currently in orbit
ALRHU	Heater	Apollo 11	Lunar	1969	On lunar surface
SNAP-27	1	Apollo 12	Lunar/ALSEP	1969	On lunar surface; station shut down
SNAP-27	1	Apollo 13	Lunar/ALSEP	1970	Mission aborted; heat source jettisoned into ocean
SNAP-27	1	Apollo 14	Lunar/ALSEP	1971	On lunar surface; station shut down
SNAP-27	1	Apollo 15	Lunar/ALSEP	1971	On lunar surface; station shut down
SNAP-19	4	Pioneer 10	Planetary	3/2/72	Operated to Jupiter and beyond solar system
SNAP-27	1	Apollo 16	Lunar/ALSEP	1972	On lunar surface; station shut down
Transit-RTG	1	Triad-01-1X	Navigational	1972	Currently in orbit
SNAP-27	1	Apollo 17	Lunar/ALSEP	1972	On lunar surface; station shut down
SNAP-19	4	Pioneer 11	Planetary	1973	Operated to Jupiter, Saturn, beyond solar system
SNAP-19	2 ea.	Viking 1,2	Mars landers	1975	On Martian surface; landers shut down
MHW–RTG	2 ea.	LES 8, LES 9	Communication	1976	Currently in earth orbit
MHW–RTG	3 ea.	Voyager 1,2	Planetary	1977	Still operating; extended interstellar mission
GPHS–RTG	2	Galileo	Planetary	1987	Deliberately crashed into Jupiter at end-of-mission
GPHS–RTG	1	Ulysses	Planetary	1990	Successful ongoing mission to the Sun's polar regions
LWRHU	Heaters	Mars pathfinder	Mars rover	1996	Mission successfully completed
GPHS–RTG	3	Cassini	Planetary	1997	Successful ongoing mission to Saturn and its moons
LWRHU	Heaters	MER	Mars rovers (2)	2003	Extended mission ongoing
GPHS–RTG	1	New horizons	Planetary	2006	Successfully operating en route to Pluto

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.

When it is determined that a proposed fuel form can be produced in adequate quantities and with the desired nuclear characteristics, the production quality fuel form, along with its encapsulation and other heat source components, must be extensively tested to qualify it for space use and to support the necessary launch safety reviews and approvals. Development and qualification of a new heat source for flight use requires a large effort in terms of costs and schedule. In addition, there are only a limited number of radioisotope fuels that meet the requirements of half-life, radiation, power density, fuel form, and availability for use in space power system applications.

3. Historical fuels perspective

Development of radioisotope power systems began in the early 1950s and since then a variety of radioisotopes has been evaluated for space and terrestrial applications.

The isotope initially selected for development was cerium-144 (Ce-144) because it was one of the most plentiful fission products available from reprocessing defense nuclear reactor fuel. Its short half-life (290 days) made Ce-144 compatible with the 6-month military reconnaissance satellite mission envisioned as its primary application at that time. The cerium oxide fuel form and its heavy fuel capsule met all safety tests for intact containment of the fuel during potential launch abort fires, explosions, and terminal impacts. However, the high radiation field associated with the beta/gamma emission of Ce-144 caused handling and payload interaction problems as well as safety problems upon random reentry from orbit. The Ce-144 fueled SNAP-1 (SNAP stands for Systems for Nuclear Auxiliary Power) power system was never used in space.

By the late 1950s, large amounts of polonium-210 (Po-210) became available, also as a byproduct of the nuclear weapons program. Po-210 is an alpha emitter with a very high power density and low radiation emissions. Po-210 metal was used to fuel the small SNAP-3 technology demonstration RTG that was first displayed at the White House in January 1959. Several SNAP-3 RTGs were fueled with Po-210 and used in various exhibits. However, the short half-life of Po-210 (138 days) makes it suitable for only limited duration space power applications and no SNAP-3 RTGs were deployed in space.

In order to provide a longer-lived radioisotope fuel, strontium-90 (Sr-90), an abundant fission product with a 28.6-year half-life, was recovered from defense wastes at Hanford. A very stable and insoluble fuel form, strontium titanate, was developed and widely used in terrestrial power systems. Sr-90 and its daughter Yttrium-90 give off significant radiation that requires heavy shielding, but shield weights are not as critical in most terrestrial power systems as for space power systems.

By 1960, plutonium-238 (Pu-238) had been identified as an attractive radioisotope fuel that could be made by irradiating neptunium-237 (Np-237) targets in the defense production reactors. Its availability was extremely limited due to shortage of Np-237 target material that must be recovered from recycling high burnup, enriched uranium fuel. However, Pu-238 has all of the necessary nuclear characteristics for a space power system fuel: long half-life (87.74 years), low radiation emissions, high power density, and useful fuel forms (metal or oxide). After flight qualification of its heat source, a Pu-238 fueled SNAP-3 RTG was launched on the Transit 4A Navy navigation satellite in June 1961 – the first use of nuclear power in space.

Because of the limited availability of Pu-238, several other radioisotopes have been thoroughly evaluated for space use. Sr-90 and Po-210 fuels were considered for use in higher powered military satellite constellations for which there were insufficient quantities of Pu-238 available, but these projects were all cancelled before launch. Curium-244 (Cm-244) was expected to become available in significant quantities from the US breeder reactor fuel cycle and was investigated as a potential alternative long-lived fuel

to Pu-238. However, this source has failed to materialize. The short-lived isotope curium-242 (Cm-242) was also initially selected to fuel an isotope power system for the 90-day Surveyor mission to the Moon, but the Surveyor program later decided not to use isotope systems. None of these alternative fuels has been used in space by the United States.

In the final analysis, Pu-238 is clearly superior to other radioisotope fuels for use in long-duration space missions especially for deep space exploration. The technology for producing and processing Pu-238 fuel forms has been clearly demonstrated over more than 40 years. Pu-238 fueled heat sources have been through rigorous flight qualification testing and have performed safely and reliably in all of the radioisotope power systems employed in the US space program to date. The availability of Pu-238 fuel for future space missions is a continuing concern. For nearly 30 years the production and processing of Pu-238 fuel was accomplished as a byproduct of the production of materials for nuclear weapons. Changes in the Nation's nuclear weapons program eliminated this traditional capability to produce Pu-238 in 1986. Therefore, for Pu-238 fuel to continue to be available for use in the space program, a reliable source or sources must be established. Since 1996, Pu-238 has been purchased from Russia for use in US space missions. Alternative domestic production capabilities for Pu-238 are currently being investigated by DOE.

4. General purpose heat source (GPHS)

Once the appropriate isotope is selected for a space mission, it must be combined with other components to create a heat source. The heat source must efficiently and reliably transfer the isotope heat to the conversion system while withstanding routine mission environments and postulated accident scenarios. Numerous heat source designs have been used for terrestrial and space applications. However, since the launch of the Galileo spacecraft in 1989, all NASA missions powered by radioisotopes have used some version of the general purpose heat source (GPHS). The GPHS module has undergone an extensive safety analysis and test program and was the only radioisotope heat source to be qualified for and used in a launch on the Space Shuttle. All current-generation radioisotope power systems designed for use on US space missions incorporate the GPHS.

The GPHS module is shown in Fig. 1. Each module is designed to deliver up to 250 thermal watts (W_t) at BOM and has a mass of 1.43 kg (3.16 lb). The module size and shape were selected to survive orbital reentry through the atmosphere and impact the Earth at a modest terminal velocity of 50 m/s (164 ft/s). Each module is a cuboid with the overall dimensions of 9.72 cm × 9.32 cm × 5.31 cm (3.83 in. × 3.67 in. × 2.09 in.).

Each GPHS module contains four pressed and sintered Pu-238 oxide fuel pellets, each with nominal output of 62.5 W_t. The cylindrical fuel pellet is 2.75 cm (1.08 in.) in
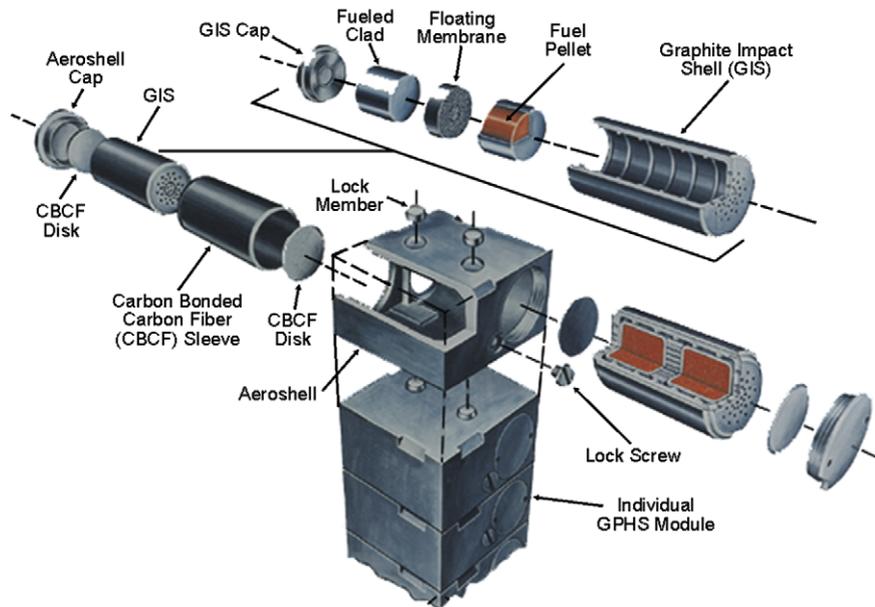
Fig. 1. General purpose heat source (GPHS).

diameter and 2.75 cm (1.08 in.) in length. Each fuel pellet is individually encapsulated in a welded iridium alloy containment shell or cladding with a minimum wall thickness of 0.05 cm (0.02 in.). The iridium alloy is capable of resisting oxidation in the post-impact environment while it also provides chemical compatibility with the fuel and graphite components during high-temperature operation and postulated accident conditions. The iridium fuel cladding is equipped with a frit vent that allows release of helium produced by the decay of the Pu-238 without releasing plutonia particles. The combination of fuel pellet and cladding is called a fueled clad.

Two fueled clads are encased in a Graphite Impact Shell (GIS) made of Fine Weave Pierced Fabric (FWPF) carbon–carbon composite material. The GIS is designed to limit the damage to the iridium clads during free-fall impacts. Two of these GISs are inserted into an aeroshell that is also made of FWPF graphite. A thermal insulation layer of Carbon Bonded Carbon Fiber graphite surrounds each GIS to limit the peak temperature of the iridium cladding during atmospheric reentry heating and to maintain its ductility during the subsequent impact. The aeroshell is designed to contain the two GISs under severe reentry conditions and to provide additional impact protection against hard surfaces at its terminal velocity. It also provides protection for the fueled clads against overpressures and fragment impacts during postulated missile explosion events. The aeroshell serves as the primary structural member to maintain the integrity and position of a stack of GPHS modules within a power system during normal operations including testing, transportation, and launch.

The original GPHS module (shown in Fig. 1) was used on the Galileo, Ulysses, and Cassini missions. It has been improved since then by adding an internal web in the aeroshell between the two GISs. This modification, known as a Step 1 GPHS module, was used on the New Horizons mission to Pluto. Systems currently being designed will incorporate another improvement to the aeroshell, which makes the broad ablation faces thicker. This variation of the GPHS is known as Step 2. The Step 2 GPHS module is 9.96 cm × 9.32 cm × 5.82 cm (3.92 in. × 3.67 in. × 2.29 in.) and weighs 1.60 kg (3.53 lbs.). The more robust GPHS aeroshell provides additional protection for the fueled clads during potential launch pad accidents and higher-velocity reentries into the atmosphere.

5. Energy conversion systems

The radioisotope heat source delivers its heat to some type of energy conversion system that converts part of the heat into useful electrical power. There are two general classes of energy conversion systems, static and dynamic. Static systems include thermoelectric, thermionic, and thermophotovoltaic conversion devices that can convert heat to electricity directly with no moving parts. Dynamic systems involve heat engines with working fluids that transform heat to mechanical energy that in turn is used to generate electricity. Both rotating and reciprocating engines may be used. Potential dynamic systems include Rankine, Brayton, and Stirling engines that operate on various types of working fluids.

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.

6. Radioisotope thermoelectric generators

Of the various static conversion technologies, thermoelectric energy conversion has received the most interest, both in development and use, for radioisotope power systems. Thermoelectric converters are highly reliable over extended operating lifetimes, compact, rugged, radiation resistant, easily adapted to various applications, and produce no noise, vibration, or torque during operation. Thermoelectric converters require no start-up devices to operate. They start producing electrical power as soon as the heat source is installed. Power output is easily regulated at design level by maintaining a matched resistive load on the converter. A limiting feature of thermoelectric conversion is its relatively low conversion efficiency, typically less than 10%.

Thermoelectric materials, when operating over a temperature gradient, produce a voltage called the Seebeck voltage. When connected in series with a load, the internally generated voltage causes an electron current to flow through the load producing useful power. Power is produced in a thermoelectric element (thermocouple) placed between a heat source and a heat sink. Typically, thermocouples are low voltage devices so a number of them must be connected in series to produce normal load voltages. Thermocouples can be connected in a series-parallel arrangement to enhance reliability by minimizing the effect on total power due to failure of a single thermocouple.

The most widely used thermoelectric materials, in order of increasing temperature capability, are bismuth telluride (BiTe); lead telluride (PbTe); tellurides of antimony, germanium, and silver (TAGS); lead tin telluride (PbSnTe); and silicon germanium (SiGe). All of these except BiTe have been used in RTGs that have been flown on space missions. Many more materials have been, and are still being, investigated in hopes of producing higher-efficiency, lower weight power systems with stable performance over long operating lifetimes.

The telluride materials are limited to a maximum hot junction temperature of 550 °C. Due to the deleterious effects of oxygen on these materials and their high vapor pressures, the tellurides must be operated in a sealed generator with an inert cover gas to retard sublimation and vapor phase transport within the converter. Bulk-type, fibrous thermal insulation is used due to the presence of the cover gas. Helium gas buildup within the converter must be controlled by using a separate container around the heat source or permeable seals in the generator design. Gas management considerations in the generator housing design and the use of bulk insulation materials increase the size and weight of the generator. However, this type of RTG is equally useful for space vacuum or for planetary atmospheric applications.

SiGe materials can be operated at hot junction temperatures up to 1000 °C. Their sublimation rates and oxidation effects, even at these higher temperatures, can be controlled by use of sublimation barriers around the elements and an inert cover gas within the generator during ground operation. The advantage of SiGe RTGs is clearest in space vacuum applications. In this case, a pressure release device opens on reaching altitude to vent the cover gas to space. This allows the use of lightweight multifoil thermal insulation and operation of the unicouples without a cover gas, eliminating significant mass when compared to telluride RTGs.

The efficiency of current RTGs using either PbTe/TAGS or SiGe thermoelectric elements can be improved by using more efficient thermoelectric materials capable of operating up to 1273 K. Since the 1990s, investigation of materials with low thermal conductivity has been a key aspect in the research and development of advanced thermoelectric materials at the NASA Jet Propulsion Laboratory (JPL). A comprehensive review of recent development in thermoelectric materials has been provided in a recent volume of the Materials Research Bulletin [1]. Exciting results have been obtained on thin-films, superlattices and quantum dot materials. These materials may, however, be more appropriate for small-scale electronics applications where spot cooling or low levels of power generation may be required. Half-Heuslers intermetallic alloys have also received increasing attention as potential high-temperature thermoelectric materials.

Efforts at NASA JPL have primarily focused on skutterudites, zintl, and zinc antimonide materials. Filled and unfilled skutterudites have been intensively investigated mostly because of the possibility of independently manipulating the thermal and electronic transport properties. While much development work remains before any of these materials could be successfully integrated into a power generator either for space or terrestrial applications, recent results clearly indicate that the figure of merit (ZT) ~ 1 limit observed for most of the thermoelectric materials used to date in practical thermoelectric generators can be broken, offering future prospects for higher efficiency generators.

7. Dynamic conversion systems

While RTGs have a long history of providing reliable power for long-duration space missions, the higher conversion efficiencies of dynamic systems would allow for better use of limited radioisotope fuel and would offer higher system power per unit mass. System efficiencies of 25% or

more are achievable, reducing the radioisotope inventory required to less than one-third of what would be required for a comparable RTG. However, a great deal of testing will be required in order to demonstrate a reliability level comparable to that of an RTG. Dynamic conversion radioisotope power systems have not yet been used in space.

The difference between static and dynamic systems is the thermal-to-electric power conversion mechanism. For dynamic systems, the thermal energy in the working fluid is partially transformed into mechanical work to drive an alternator to produce electricity. The three different dynamic conversion concepts that have received the most attention for use in radioisotope power systems employ Rankine, Brayton or Stirling cycles. The Rankine cycle is based on a two-phase working fluid that requires special vapor–liquid boiler and condenser designs for use in the microgravity of space. Development programs have considered Rankine systems using liquid metal and organic working fluids. Brayton and Stirling cycles use a single gas working fluid such as a helium–xenon mixture for Brayton and pure helium for Stirling.

In a Brayton or Rankine system, the gaseous working fluid from the heat source heat exchanger turns a turbine rotor that is mounted on a common shaft with the alternator rotor and the compressor or liquid pump rotor. The remainder of the power conversion system includes the turbine housing, turbine nozzles, bearings, alternator coils, pump housing, and cooling ducts to form a compact energy conversion unit. To minimize size and weight, the rotor shaft turns at very high speeds and the alternator produces high-frequency alternating current. To start such a system, electrical power from a battery would be used to spin up the rotor until the system's temperature, pressure, and mass flow rates permit it to be self-sustaining. A power control and conditioning system would also be required to regulate operating speed and electrical output.

The two general areas of concern with the use of a turbine-driven electrical power system are reliability and spacecraft interactions. The main reliability issues have to do with bearings, loss of working fluid and failure of electronic parts in the control system. Foil bearings are used in Brayton designs to allow the rotating shaft to ride on a thin film of working fluid gas during operation. Organic Rankine units can use either foil bearings or hydrodynamic thrust and journal bearings lubricated by the organic working fluid. Both have been shown to be highly stable and reliable once operating conditions are achieved and bearing temperatures are controlled. Since a puncture by a micrometeoroid or a crack caused by thermal or mechanical stresses during operation could cause the loss of the working fluid and total loss of power, this single-point failure mechanism must receive particular attention during the design. Conservative wall thicknesses, expansion joints, and meteoroid armor are usually employed to reduce the probability of failures of this kind. Totally redundant power conversion loops can also be used if the additional weight can be tolerated.

Stirling cycle systems differ from Rankine and Brayton systems in that they do not include turbines, pumps or compressors. The Stirling cycle uses a working gas that expands by absorption of heat on the hot-side and contracts by rejection of heat on the cold side causing rapidly changing pressure cycles across a piston, forcing it to move in a reciprocating fashion. The most promising type of Stirling engine for radioisotope generator applications is the free-piston Stirling engine, which requires no lubricating fluids and produces electricity by means of a linear alternator within a hermetically sealed engine housing. The piston moves back and forth at a resonant frequency on a cushion of working gas between it and the surrounding cylinder wall. A permanent magnet is attached to the power piston to produce electrical currents in surrounding alternator coils as it oscillates back and forth. Since the reciprocating motion of the piston would cause unbalanced vibration loads, Stirling engines for space applications are generally designed in pairs with dynamically opposed pistons to minimize the net load transmitted to the spacecraft.

The Stirling cycle provides higher conversion efficiencies than the Rankine and Brayton cycles at the same cycle temperatures. System efficiencies of 30% or more are possible at operating temperatures achievable with isotope heat sources and oxidation-resistant superalloy structural materials. The Stirling cycle also retains its high performance characteristics at lower power levels than the Brayton and Rankine systems, an attractive feature for radioisotope power systems.

8. Current state of technology

In the years since RTGs were first used, the fuel form and heat source technologies have been steadily improved to operate at higher temperatures with increasingly larger fuel inventories to meet the aerospace nuclear safety goals consistent with the As Low As Reasonably Achievable (ALARA) approach. As the power levels of the RTGs have increased, improved thermoelectric materials and thermal insulation approaches have been developed to increase long-term power stability and specific power of the RTGs to meet the needs of more ambitious space exploration missions. Advanced technology programs have also been pursued to take advantage of the greater efficiency offered by dynamic power conversion systems. The remainder of this section describes the three major radioisotope power systems currently being used on active NASA missions or being developed for potential near-term use.

9. General purpose heat source-radioisotope thermoelectric generator (GPHS–RTG)

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. 2, is the largest Pu-238 fueled, long-lived RTG built for use in space missions. Utilizing recently precipitated
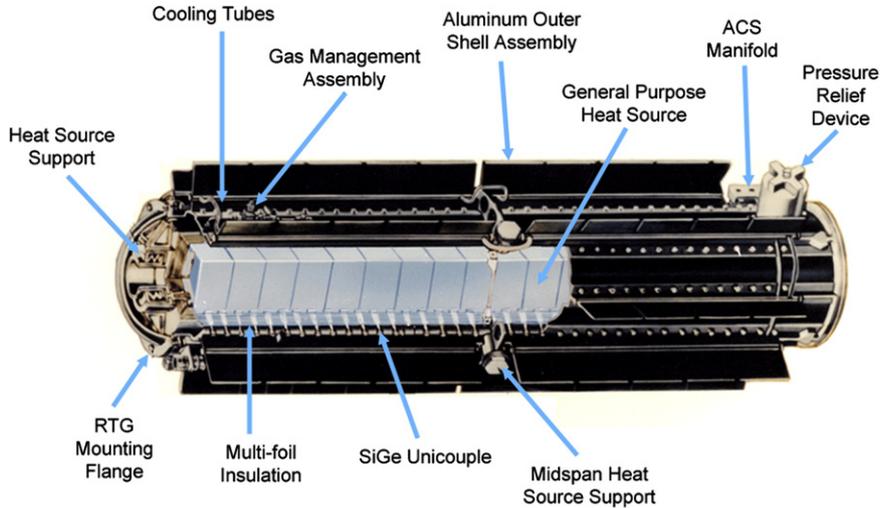
Fig. 2. General purpose heat source radioisotope thermoelectric generator (GPHS-RTG).

Pu-238, it produces at least 285 W_e 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 W_e/kg (2.3 W_e/lb).

The heat source assembly is surrounded by 572 silicon germanium (SiGe) thermocouples, also known as unicouples. The unicouples are individually bolted to and cantilevered from the aluminum alloy generator housing and are surrounded by a thermal insulation package consisting of 60 alternating layers of molybdenum foil and astroquartz fibrous insulation. The silicon molybdenum (SiMo) hot shoes are radiatively coupled to the heat source. 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.

10. Multi-mission radioisotope thermoelectric generator (MMRTG)

The next generation of space RTGs is represented by the MMRTG shown in Fig. 3. 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
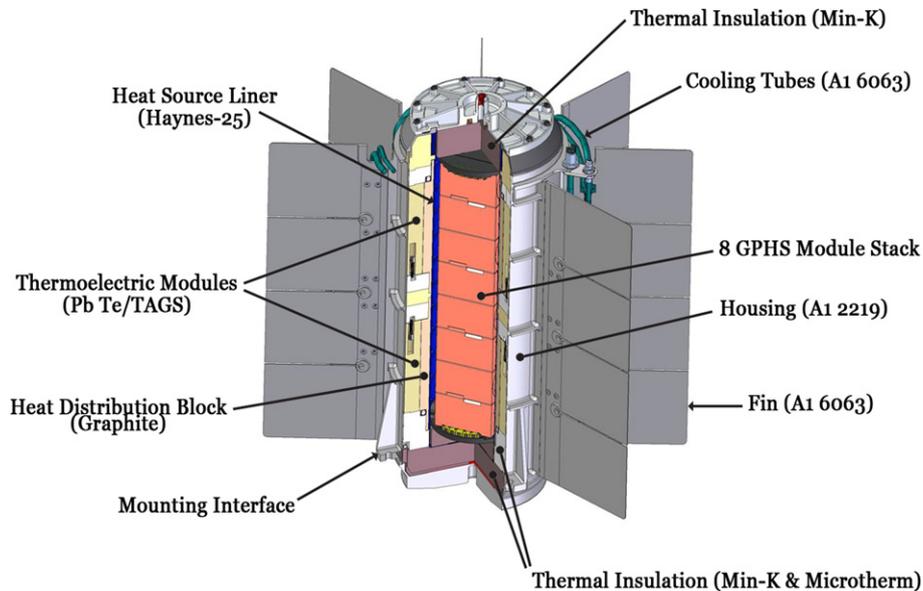

Fig. 3. Multi-mission radioisotope thermoelectric generator (MMRTG).

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.

The MMRTG will produce 110 W_e minimum (120 W_e estimated) at launch from a Pu-238 heat source assembly containing a stack of 8 Step 2 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 W_e/kg (1.24 W_e/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 RTG. 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 MMRTG. 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 MMRTG 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.

11. Advanced stirling radioisotope generator (ASRG)

In addition to continued development of RTGs, the Department of Energy and NASA are also pursuing advanced power conversion technologies that will enable more efficient use of Pu-238. One of these technologies,

the Stirling generator, is being developed for potential flight use in the ASRG, shown in Fig. 4. Like the MMRTG, the ASRG is being developed for use in potential missions on the Martian surface or in deep space.

An ASRG engineering unit is scheduled to be assembled in December 2007 and tested in April 2008. This engineering unit will include all system components and will be used for both reliability and flight environments testing. Once the engineering unit testing is complete, qualification and flight systems could be built based on the current design or system development could continue, incorporating known changes to further increase system specific power. The description that follows is based on the current system design.

The ASRG is designed to produce at least 147 W_e at beginning of mission (defined as space operation just after launch). It includes two Stirling generators, each with its own GPHS module, for a nominal total heat input of 500 W_t. Its overall dimensions are 76 cm (30 in.) by 45 cm (18 in.) by 39 cm (15 in.). The ASRG flight design mass is expected to be 21 kg (46.3 lb) for a specific power (at launch) of 7.0 W_e/kg (3.17 W_e/lb).

The advanced stirling generator is a free-piston heat engine that operates on a Stirling thermodynamic cycle. Heat is supplied to each generator by a single GPHS module at a hot-end operating temperature of 640 °C. Heat is rejected from the cold-end of the generator at roughly 60 °C (this temperature varies with environments and fuel decay). The closed-cycle system converts the heat from a GPHS module into reciprocating motion, which through a linear alternator is then converted into an ac electrical power output.

The ASRG is designed to operate with the Stirling generators in synchronous opposed pairs, which will help
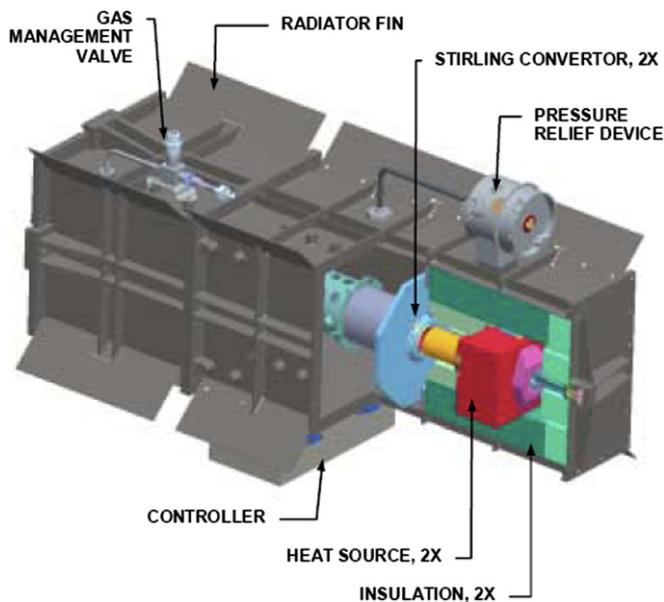

Fig. 4. Advanced stirling radioisotope generator (ASRG) engineering unit.

minimize vibration levels under normal operating conditions. Operation of an earlier generation of generators in this configuration was shown to reduce generator vibration levels by a factor of over 100 when compared to an unbalanced single generator; however, work remains to demonstrate the performance of the ASRG in a flight configuration.

The ASRG uses an active power factor control scheme to convert ac power to dc for the spacecraft bus, while synchronizing the generator motion, maintaining proper hot-end temperature and piston stroke, and providing telemetry signals to the spacecraft. Although the ASRG is designed for autonomous operation, the controller may also accept commands from the spacecraft as needed for specific missions. The controller is being designed for single fault tolerance. Each generator will have its own control board, with a third board included for redundancy.

12. Future developments

Over the next decade, the US Radioisotope Power Systems Program faces several programmatic and technological challenges if it is to continue to provide radioisotope power systems for use in NASA space missions that require them. NASA has identified a number of potential missions that will require radioisotope power and/or heat sources.

In order to meet this need, DOE must have a reliable and continuing supply of Pu-238. Efforts are underway to investigate alternative facilities in the United States to provide a continuing Pu-238 production and processing capability. Until these Pu-238 supply issues are mitigated by the establishment of a new source, the development and qualification of higher-efficiency systems will be an important step toward making effective use of the small remaining inventory.

Reference

[1] Harvesting energy through thermoelectrics: power generation and cooling. Mater Res Soc Bull. 2006;31:3.