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ADVANCED RADIOISOTOPE POWER SYSTEMS (RPSs)

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***Abstract*—This paper provides a review on advances of radioisotope power systems. Radioisotope power systems have shown many advantages over other types of power supplies especially for space applications, and for remote marine and industrial locations. Development and advancement can be achieved by proper selection of radioisotope heat source and coherent design of new power conversion technologies. The most practical and optimum radioisotope fuel that have been used is Pu-238 in the form of 238PuO2 fuel pellets. The range of power output for most RPSs is between 2.7 to 2000 W. Moreover, the range of thermal conversion efficiency is about (6 %) for RTGs and (29 %) for ASRGs.**

Keywords—Radioisotope power systems, Thermal conversion efficiency, Power density, Radioisotope fuel

Introduction

Radioisotope power systems are classified, based on conversion technologies, into static and dynamic power systems. Static radioisotope power systems have no moving parts, silent in operation, and more reliable over long periods in remote and tough environments. Static radioisotope power systems include radioisotope thermoelectric generators (RTGs) and radioisotope thermionic generators. RTGs use thermocouples connected in series and parallel (modules) to produce electricity from heat of radioisotope decay. An example is an MMRTG (multi-mission radioisotope thermoelectric generator. However, radioisotope thermionic generators use electrodes (anodes and cathodes) and plasma gas to produce electricity from heat of radioisotope decay. Dynamic radioisotope power systems utilize moving parts such as rotating or reciprocating heat engines. They include radioisotope Sterling, Brayton, and Rankine power systems. Radioisotope Sterling system uses a moving piston and a cylinder with helium gas as a working fluid in the thermodynamic cycle to produce electricity. An example is ASRG (advanced Stirling radioisotope generator). Radioisotope Brayton system uses a turbine engine and a mixture of helium-xenon as a working fluid through the thermodynamic cycle. However, Radioisotope Rankine system uses a turbine engine with two-phase organic fluid to generate electricity.

In 1956, the US Atomic Energy Commission began developing direct-conversion devices to convert the energy of decaying isotopes into electricity. The goal of this program was the potential use of the generators in space and in isolated locations such as Antarctica, and in their use as navigational buoys. The first isotopic power generator was produced in 1959. It employed a thermoelectric generator, produced 2.5 W of power, and used Po-210 as fuel. The whole generator weighed only 4 lb. Contrast this with a conventional nickel-cadmium battery (weighing about 700 lb) producing equivalent energy. The first commercial isotopic power generator became available in 1966. It was produced through the joint efforts of the Martin Company and the Atomic Energy Commission. The unit is a thermoelectric device powered by Sr-90. It guaranteed to produce 25 W of electricity for five years (Foster and Wright, 1983).

O'Brien et al. (2008) examined several isotopes as alternatives to Pu-238 that is traditionally used in radioisotope thermoelectric generators (RTGs) and heating units (RHUs). The radioisotopes discussed

include Am-241, Po-208, Po-210, and Sr-90. Yang and Caillat (2006) reviewed thermoelectric energy-conversion technology for radioisotope space power systems and waste-heat recovery in the automotive industry. Lal et al. (2005) developed a radioisotope micro-power generator for self-powered sensor microsystems to make pervasive computing systems more reliable. Whalen et al. (2008) built and tested a prototype miniaturized thermoelectric power source that generates 450 µW of electrical power in a system volume of 4.3 cm^3. The measured power density of 104 $\mu W/cm^3$ exceeds that of any previously reported thermoelectric power system of equivalent size. Wong et al. (2006) developed advanced radioisotope power systems that have high efficiency and high specific power (W/Kg) in order to meet mission requirements with less radioisotope fuel and lower mass. This research and development include a variety of power conversion technologies consisting of Brayton, Stirling, thermoelectrics, and thermophotovoltaics. Romer et al. (2008) found that the radioisotope cells (RCs) are projected to have superior specific energy but inferior specific power, while the borohydride/peroxide fuel cells (FC) shows an impressive range for both parameters. Langley et al. (2017) developed alphavoltaics to increase the energy output by a factor of 100 in comparison to beta-voltaic power source. They converted the 5-MeV alpha decays into electrical current by using the diamond and gallium nitride (GaN) system. Light weight radioisotopes (LWR) Sr-89 and Sr-90 are obtained from used rods in fission atomic plants (Bennun, 2013). Sr-89 after separation from Sr-90 is used in the treatment of bone cancer, and as fuel in radioisotope light generator (RLG). Rosch (2013) described the development and the current status of Ge-68/Ga-68 radionuclide generators. He realized the great potential of the Ge-68/Ga-68 generator for modern nuclear medicine in general. Free-piston Stirling convertors have been tested for potential use in radioisotope power systems (Shreiber, 2006). These convertors tend to be in the 35 to 80 W electric power output range. Free-piston Stirling convertors for radioisotope power systems make use of non-contacting operation that eliminates wear and is suited for long-term operation. Gusev et al. (2011) developed a milliwatt-power radioisotope thermoelectric generator (RTG) based on plutonium-238. Rowe (1987) reviewed the silicon-germanium technology of building modules to be used in a multi-hundred watt radioisotope thermoelectric generator. Liu et al. (2018) prepared and optimized a miniaturized rmadioisotope thermoelectric generator with a maximum output power of 150.95 µW. The optimal result is obtained when the ratio of N- to P- type circle radius and the thermoelectric filament's length are 0.1 and 20 mm, respectively. This RTG is able to provide power support for space microelectronic devices. Khajepour and Rahmani (2017) designed a Sr-90 radioisotope thermoelectric generator (RTG) with power output of milli-watt. This designed RTG contains Sr-90 as a radioisotope heat source (RHS) and 127 coupled thermoelectric modules (TEMs) based on bismuth telluride. The NASA Glenn Research Center has developed an advanced Stirling radioisotope generator (ASRG) by Shaltens and Wong (2007). This was done to meet future mission requirements to use less plutonium-fueled general purpose heat source modules and reduce system mass. Liu et al. (2018) designed a concentric thermoelectric filament structure for RTG (radioisotope thermoelectric generator). This device exports an open-circuit voltage (Voc) of 84.5 mV and a maximum power output (Pmax) of 42.5 µW at the hot surface temp. of 398.15 K°. *S*mith et al. (2016) investigated the values of ZT (the figure of merit), thermal and electrical conductance, Seebeck coefficient and power factor as the bismuth telluride (Bi_2Te_3) thermoelectric generator decreases in size. Yang and Peng (2008) analyzed the effects of conductivity, resistivity, Seebeck factor and the calculation of changing physical character of the materials on working characteristics of thermoelectric generator. Pei et al. (2011) investigated the thermoelectric transport properties of P-type PbTe : Na with high hole concentration of about $10^{20}/cm^3$. The thermoelectric figure of merit (ZT) reaches 1.4 at 750 K°. Zink oxide (ZnO, n-type) and copper oxide (CuO, p-type) nanowires have been synthesized and investigated as innovative materials for the fabrication of a thermoelectric generator (Zappa et al., 2014).

1. Radioisotope thermoelectric generators (RTGs)

Thermoelectric converters are highly reliable over extended operating lifetimes, compact, rugged, 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. Thermoelectric conversion efficiency is low, typically less than 10%. Thermoelectric materials, when operating over a temperature gradient, produce a voltage called the Seebeck voltage. Power is produced in a thermoelectric element (thermocouple) placed between a heat source and a heat sink. Normally, thermocouples are low voltage devices so a number of them must be connected in series to produce useful load voltages. The most widely used thermoelectric materials, in order of increasing temperature capability, are BiTe, PbTe, TAGS, PbSnTe, and SiGe. The telluride materials are limited to a maximum hot junction temperature of 550 Cº. However, SiGe materials can be operated at hot junction temperature up to 1000 Cº. The figure of merit (ZT) for most thermocouples used in practical thermoelectric generators does not exceed 1.

1.1 Multi-mission radioisotope thermoelectric generator (MMRTG)

The recent model of space RTGs is MMRTG, shown in Fig. (1). This lower-powered RTG is being developed for use in missions on the surface of Mars as well as for in deep space.

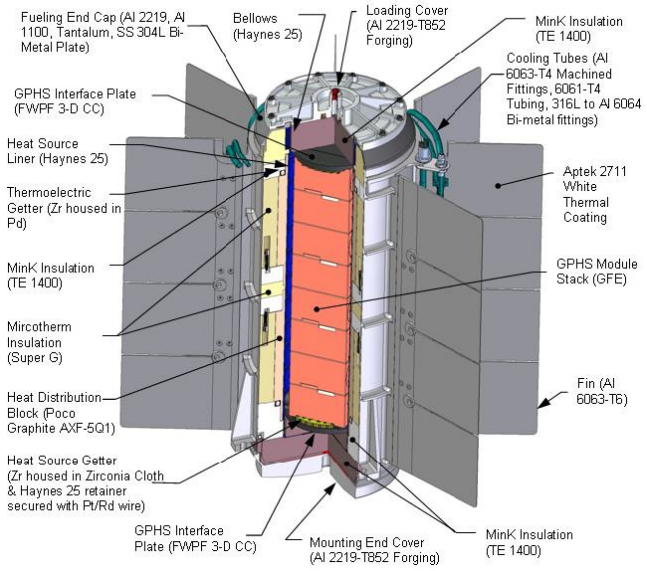

Fig. 1 Multi-mission radioisotope thermoelectric generator (MMRTG), (Lange and Caroll, 2008)

The MMRTG produces about 120 We 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. It weighs 44 Kg with a specific power of 2.73 We/Kg. The thermoelectric converter is composed of 16 modules of 48 thermocouples each, for a total of 768 thermocouples. The thermoelectric materials employed are PbTe/TAGS. The thermocouples are connected in series-parallel electrical circuit to enhance reliability. The PbTe/TAGS thermocouples operate between a hot junction temp. of 811 Kº and a cold junction temp. of about 483 Kº 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.

1.2 Advanced Stirling radioisotope generator (ASRG)

The DOE and NASA have developed the ASRG to enable more efficient use of Pu-238 and to be used in potential missions on the Martian surface or in deep space. The ASRG, shown in Fig. (2), is designed to produce at least 147 We. It includes two Stirling generators, each with its own GPHS module, for a nominal total heat input of 500 Wt. The ASRG flight design mass is expected to be 21 Kg for a specific power of 7 We/Kg.

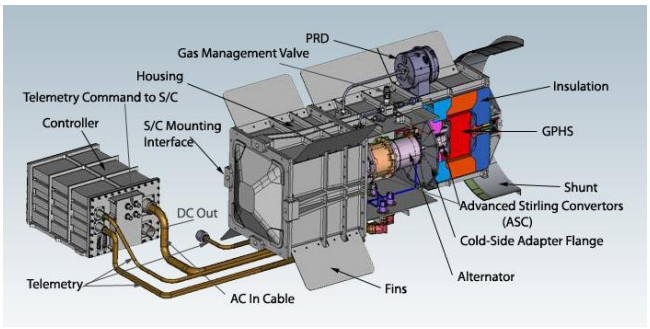

Fig. 2 Advanced Stirling radioisotope generator (ASRG), (National Aeronautics Space Administration, 2013)

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 temp. of 640 Cº. The closed-cycle system, with a single phase helium gas as a working fluid, converts the heat from a GPHS module into a reciprocating motion. This mechanical motion is converted, through a linear alternator, into an ac electrical power output and then to dc electrical power. Table 1 shows important specifications of the MMRT and ASRG

Table 1 Comparison between the MMRTG and ASRG

	MMRTG	ASRG
Power output, We	125	150
Heat input, Wt	2000	500
Thermal conversion efficiency, %	6.3	30
Total system weight, Kg	44.2	21
Specific power, We/Kg	2.8	8
Number of GPHS modules	8	2
GPHS module weight, Kg	3.5	0.88
Pu-238 weight, Kg	12.9	3.2

2. Radioactive decay processes

Radioactive decay takes place in several ways including alpha decay, beta decay, electron capture, proton decay, and neutron emission. In each of these processes the mass of the resultant particles is less than that of the parent nucleus. The difference may show up as gamma radiation or as kinetic energy shared by the daughter nucleus and an emergent particle. An example of alpha decay: when an unstable nucleus ejects an alpha particle, the atomic number is reduced by 2 and the mass number decreases by 4. An example is U-234, which may decay by the ejection of an alpha accompanied by the emission of a gamma, which in this case has an energy of 0.053 MeV. This same isotope can also decay without gamma emission, and the alpha will have a correspondingly higher energy.

$U_{92}^{234} \rightarrow Th_{90}^{230} + \alpha_2^4 + \gamma + KE$

kinetic energy of the resultant nucleus and the emergent particle (in this case the Th-230 and the α) is designated as KE. The The combined sum of the kinetic energy and the gamma energy is equal to the difference in mass between the original nucleus and the final particles. This total mass-energy conversion is called Q.

$Q = KE + \gamma = (m_u - m_{Th} - m_{He}) \times 931$

Substituting yields

$Q = (234.0409 - 230.0331 - 4.00260) \times 931 = 4.84$ MeV

This represents the total mass-energy conversion for the process. The kinetic energy shared by the particles is

$KE = Q - \gamma = 4.84 - 0.053 = 4.79$ MeV

3. Selection of a Radioisotope Fuel

A radioisotope, to be used as a fuel, must have the characteristics of long half-life, low gamma emissions, high power density and specific power, stable fuel form with a high melting point. It must be produced safely, easily, and at a reasonable cost. These restrictions narrow the selection to nine practical radioisotopes. Four of these are beta-emitting fission products which can be recovered in fuel reprocessing. Four are alpha emitters which must be produced in reactors and, consequently, are more expensive. The ninth, Co-60, is available in plentiful supply but is a gamma emitter. Table 2 lists the nuclear and physical properties of practical radioisotope fuels.

Table 2 Properties of practical radioisotope fuels, (Foster and Wright, 1983)

	Ce-144	Sr-90	Cs-137	Pm-147	C0-60	Cm-242	Cm-244	Po-210	Pu-238
Compound	Ce_2O_3	$SrTiO_3$		Pm_2O_3		Cm_2O_3	Cm_2O_3	GdPo	PuO_2
Half-life	284.5 d	27.7 yr	30 yr	2.67 yr	5.26 yr	162.5 d	18.1 yr	138 d	86 yr
Activity (Ci/gm)	440	33	16	742	360	3044	72.6	4486	17
Specific power (W/gm)	2.84	0.223	0.0774	0.41	5.32	44.1	2.53	140	0.4
Emission type	β	β	β, γ	β	β, γ	α	α	α	α
Melting point (℃)	2680	1910	28.4	2350	1480	1950	1950	590	2744

Safety is an important factor when choosing a radioisotope as a power source in the power generator. γ-rays has the highest ability to penetrate through materials so it needs a lot of shielding medium. α-rays has the lowest ability to penetrate. The higher specific power and half-life of a radioisotope the longer power source that will stay last, so the better radioactive to be chosen as a decay heat source in the power generator.

4. Production of Pu-238 and $^{238}PuO_2$

Pu-238 is the most suitable radioisotope as an RPS fuel for long duration missions because of its long half-life (88 yr), α-emissions, high power density, high specific power, stable fuel form ($^{238}PuO_2$), availability, and reasonable cost. Pu-238 does not occur in nature, it is created by irradiating Np-237 in a nuclear reactor or accelerator

β

$^{237}Np + {}^{1}n \rightarrow {}^{238}Np \rightarrow {}^{238}Pu$

α

$^{238}Pu \rightarrow {}^{234}U + 5.6$ MeV

Pu-238 is spontaneously oxidized by oxygen to produce a solid ceramic

$^{238}Pu + O_2 \rightarrow {}^{238}PuO_2$

$^{238}PuO_2$ is a ceramic oxide that has a high melting point and very low solubility in water. Each $^{238}PuO_2$ fuel pellet is encapsulated in a ductile, high-temp. iridium-base alloy. Two encapsulated $^{238}PuO_2$ fuel pellets are packaged within a cylindrical graphite impact shell constructed of a carbon-carbon composite. This assembly is called a general purpose heat source (GPHS) module.

Conclusions

The following facts can be derived from this review study: For RTGs, even with good design and insulation only about 5 to 10 percent of the heat produced by the decaying elements can be converted into electricity. Pu-238 and Cm-244 are the best among practical radioisotopes to be used as heat sources in the power generators. Continuous production and processing capability of Pu-238 is of crucially importance in order to supply the RPSs with heat sources. Moreover, continuous research and development of higher-efficiency systems is very necessary to use radioisotope fuels more effectively.

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