U.S. Space Radioisotope Power Systems and Applications: Past, Present and Future

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1. Introduction

Radioisotope power systems (RPS) have been essential to the U.S. exploration of outer space. RPS have two primary uses: electrical power and thermal power. To provide electrical power, the RPS uses the heat produced by the natural decay of a radioisotope (e.g., plutonium-238 in U.S. RPS) to drive a converter (e.g., thermoelectric elements or Stirling linear alternator). As a thermal power source the heat is conducted to whatever component on the spacecraft needs to be kept warm; this heat can be produced by a radioisotope heater unit (RHU) or by using the excess heat of a radioisotope thermoelectric generator (RTG).

As of 2010, the U.S. has launched 45 RTGs on 26 space systems. These space systems have ranged from navigational satellites to challenging outer planet missions such as Pioneers 10/11, Voyagers 1/2, Galileo, Ulysses, Cassini and the New Horizons mission to Pluto. In the fall of 2011, NASA plans to launch the Mars Science Laboratory (MSL) that will employ the new Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) as the principal power source.

Hundreds of radioisotope heater units (RHUs) have been launched, providing warmth to critical components on such missions as the Apollo 11 experiments package and on the outer planet probes Pioneers 10/11, Voyagers 1/2, Galileo and Cassini.

A radioisotope (electrical) power source or system (RPS) consists of three basic elements: (1) the radioisotope heat source that provides the thermal power, (2) the converter that transforms the thermal power into electrical power and (3) the heat rejection radiator. Figure 1 illustrates the basic features of an RPS.

The idea of a radioisotope power source follows closely after the early investigations of radioactivity by researchers such as Henri Becquerel (1852-1908), Marie Curie (1867-1935), Pierre Curie (1859-1906) and R. J. Strutt (1875-1947), the fourth Lord Rayleigh. Almost 100 years ago, in 1913, English physicist H. G. J. Moseley (1887-1915) constructed the first nuclear battery using a vacuum flask and 20 mCi of radium (Corliss and Harvey, 1964, Moseley and Harling, 1913).

After World War II, serious interest in radioisotope power systems in the U.S. was sparked by studies of space satellites such as North American Aviation's 1947 report on nuclear space power and the RAND Corporation's 1949 report on radioisotope power. (Greenfield, 1947, Gendler and Kock, 1949). Radioisotopes were also considered in early studies of nuclear-powered aircraft (Corliss and Harvey, 1964).

In 1951, the U.S. Atomic Energy Commission (AEC) signed several contracts to study a 1-kWe space power plant using reactors or radioisotopes. Several of these studies, which

were completed in 1952, recommended the use of RPS (Corliss and Harvey, 1964). In 1954, the RAND Corporation issued the summary report of the Project Feedback military satellite study in which radioisotope power was considered (Lipp and Salter, 1954).
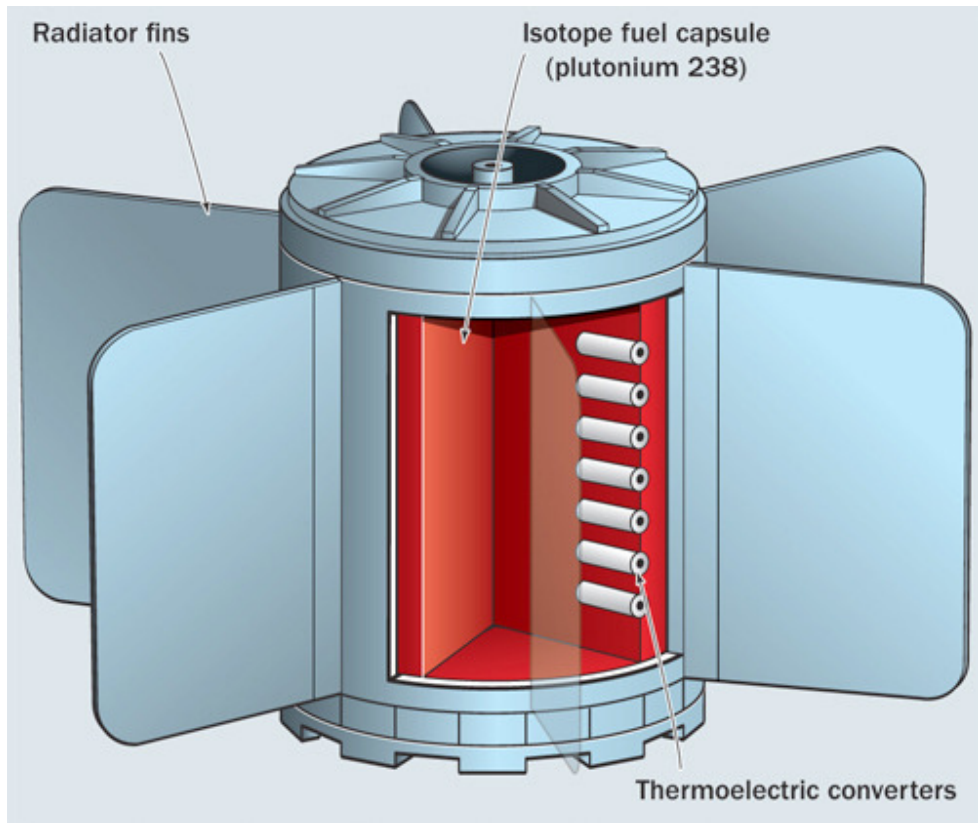

Fig. 1. Cutaway view of a radioisotope power source (RPS) (Image credit: DOE).

Paralleling these studies, in 1954, K. C. Jordan and J. H. Birden of the AEC's Mound Laboratory conceived and built the first RTG using chromel-constantan thermocouples and a polonium-210 (^{210}Po or Po-210) radioisotope heat source (see Figure 2). While the power produced (1.8 mWe) was low by today's standards, this first RTG showed the feasibility of RPS. A second "thermal battery" was built with more Po-210, producing 9.4 mWe. Jordan and Birden concluded that the Po-210 "thermal battery" would have about ten times the energy of ordinary dry cells of the same mass (Jordan and Birden, 1954).

Fig. 2. The first radioisotope thermoelectric generator (RTG).
Figure from the Jordan and Birden 1954 report via (Corliss and Harvey, 1964).The heat source consisted of a 1-cm-diameter sphere of 57 Ci (1.8 Wt) of ^{210}Po inside a capsule of nickel-coated cold-rolled steel all inside a container of Lucite. The thermocouples were silver-soldered chromel-constantan. The "thermal battery" produced 1.8 mWe.

2. Early SNAP program

The AEC began the Systems for Nuclear Auxiliary Power (SNAP) program in 1955 with contracts let to the Martin Company (now Teledyne) to design SNAP-1 and to the Atomics International Division of North American Aviation, Inc. to design SNAP-2. (Under the AEC nomenclature system, the odd-numbered SNAPs had radioisotope heat sources and the even-numbered SNAPs had nuclear fission reactor heat sources.) SNAP-1 was to provide 500 We using the then readily available fission product radioisotope cerium-144 (^{144}Ce) (Corliss and Harvey, 1964).

The Martin Company began with a 133-We RPS design using ^{144}Ce as the radioisotope fuel and a Rankine thermal-to-electric conversion system. From this came the 500-We SNAP-1 RPS design based on ^{144}Ce fuel and a Rankine conversion system (see Figure 3) (Corliss and Harvey, 1964). The use of a dynamic conversion system in the first RPS is a key historical fact in understanding the current focus on developing an Advanced Stirling Radioisotope

Generator (ASRG) (see Section 10). Depending on the design, dynamic conversion systems can provide double, triple and even quadruple the efficiency of state-of-practice thermoelectric conversion systems which means much less radioisotope fuel would be used to achieve the same electrical power (or, conversely, much more electrical power can be produced for the same quantity of radioisotope fuel used in an RTG).
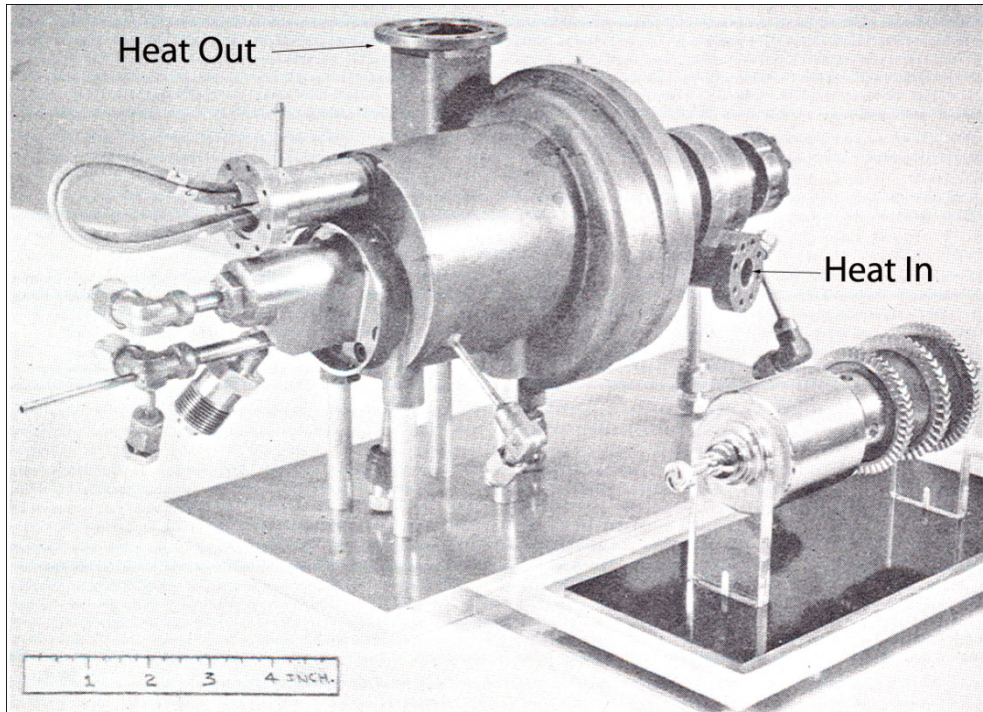

Fig. 3. SNAP-1 turbomachinery package with the shaft assembly shown separately, ruler dimensions are in inches (TRW via Corliss and Harvey, 1964).

In parallel with the SNAP-1 program a series of radioisotope power sources were studied under the umbrella of the SNAP-3 program that was based largely on using thermoelectric elements in the converter. The early SNAP-3 generators were to use ^{210}Po as the fuel but by the late 1950s it was clear that sufficient quantities of ^{238}Pu would be available to provide the fuel for small RTGs. Plutonium-238 provided a number of features that made it more attractive than ^{144}Ce or ^{210}Po, including a longer half-life (87.7 years) and a more benign radiation emission (alpha particles, which can be stopped by material as thin as a sheet of paper) (Corliss and Harvey, 1964).

Safety is the principal design requirement in the use of RPS, so the heat source is designed to contain or immobilize the fuel throughout a range of postulated accidents such as explosions and atmospheric reentries. Over the years this safety design work has led to the development of the general-purpose heat source (GPHS) module, which is the basic building block of U.S. RPS (Bennett, 1995).

All of the U.S. RPS that have flown have been either RTGs or RHUs, (see Fig. 4).

Fig. 4. Light-Weight Radioisotope Heater Unit (LWRU) (DOE)

As of 2010, as shown in Table 1, the U.S. has launched 45 RTGs, hundreds of RHUs and one space nuclear fission reactor. Of the RTGs flown, two different types of thermoelectric materials have been employed: telluride-alloy based or silicon-germanium-alloy based. The following sections will discuss these RTGS to be followed by sections discussing current efforts in radioisotope power sources.

3. The early telluride-based RTGs

The initial and current thermoelectric material of choice is based on telluride technology alloyed with lead (Pb-Te) that, to a first approximation, can be used from room temperature to about 900 K before materials properties become an issue. Above 900 K, the U.S. has had great success with a silicon-germanium alloy (Si-Ge) that has operated exceedingly well at temperatures of about 1300 K.

For the upcoming Mars Science Laboratory (MSL) mission, the U.S. will use a telluride-based thermoelectric material because it meets the requirements of being able to operate both in space on the way to Mars and on the surface of Mars with its dusty, cold, carbon dioxide atmosphere (see Section 8). The successes of the earlier (1976 era) Viking Mars Landers 1 and 2 using SNAP-19 telluride-based technology support this decision.

3.1 SNAP-3B RTGs

The SNAP-3B RTG evolved out of the overall SNAP-3 program with the goal of providing 2.7 We to the U.S. Navy's Transit 4A and Transit 4 B navigational satellites. In particular, the SNAP-3B RTGs were to provide power to the crystal oscillator that was the heart of the electronic system used for Doppler-shift tracking, a precursor of today's global positioning system (Dick and Davis, 1962, JHU/APL, 1980). Both RTGs provided power to their respective spacecraft for over 10 years (Bennett, et al., 1983). Figure 5 shows models of the SNAP-3B RTG and the successor SNAP-9A RTG.

Transit Navy Navigational Satellites

- Transits 4A and 4B (1961) SNAP-3B (2.7 We)
- Transits 5BN-1, 5BN-2 (1963) and *5BN-3 (1964)* SNAP-9A (>25 We)
- Transit TRIAD (1972) Transit-RTG (35 We)

SNAPSHOT Space Reactor Experiment

- SNAP-10A nuclear reactor (1965) (≥500 We)

Nimbus-B-1 Meteorological Satellite

- *SNAP-19B RTGs* (1968) (2 @ 28We each)

Nimbus-3 Meteorological Satellite

- SNAP-19B RTGs (1969) (2 @ 28 We each)

Apollo Lunar Surface Experiments Packages

- Apollo 12 (1969)**,** *13 (1970)*, 14 (1971), 15 (1971), 16 (1972), 17 (1972) SNAP-27 (>70 We each)

Lincoln Experimental Satellites (Communications)

- LES 8 and LES 9 (1976) MHW-RTG (2/spacecraft @ ~154 We each)

Interplanetary Missions

- Pioneer 10 (1972) and Pioneer 11 (1973) SNAP-19 (4/spacecraft @ ~40 We each)
- Viking Mars Landers 1 and 2 (1975) SNAP-19 (2/Lander @ ~42 We each)
- Voyager 1 and Voyager 2 (1977) MHW-RTG (3/spacecraft @ >156 We each)
- Galileo (1989) GPHS-RTG (2 @ 287 We each)
- Ulysses (1990) GPHS-RTG (282 We)
- Cassini (1997) GPHS-RTG (3 @ >290 We each)
- New Horizons (2006) GPHS-RTG (1 @ 245.7 We)

(Spacecraft/Year Launched/Type of Nuclear Power Source/Beginning-of-Mission Power)
Note: SNAP is an acronym for Systems for Nuclear Auxiliary Power
MHW-RTG = Multi-Hundred Watt Radioisotope Thermoelectric Generator
GPHS-RTG = General-Purpose Heat Source Radioisotope Thermoelectric Generator
* Denotes system launched but mission unsuccessful

Table 1. Uses of Space Nuclear Power By The United States

Fig. 5. Nobel Laureate Glenn T. Seaborg, Chairman of the U.S. Atomic Energy Commission, with his hands over a model of the SNAP-9A RTG and program manager Major Robert T. Carpenter holding a model of the SNAP-3B RTG (circa 1963), (AEC). The SNAP-3B RTG produced 2.7 We in a package 12.1-cm in diameter and 14-cm high with a mass of 2.1 kg. The SNAP-9A RTG produced over 25 We at beginning of mission (BOM) within a mass of 12.3 kg and a main body that was 22.9 cm in diameter and 21.3 cm high. (Image credit: AEC)

3.2 SNAP-9A RTGs

The success of the SNAP-3B RTGs on Transits 4A and 4B gave the Johns Hopkins University Applied Physics Laboratory (JHU/APL) confidence to select the next-generation RTG, known as SNAP-9A, to provide all the power for its Transit 5BN-1 and 5BN-2 navigational satellites. The objective for each SNAP-9A was to provide 25 We at beginning of mission (BOM) at a nominal 6 V for five years in space after one year of storage on Earth. The two SNAP-9As showed that RTGs could be easily integrated into a spacecraft to provide all of the electrical power (Bennett, et al., 1984, JHU/APL, 1980). Figure 5 provides a size comparison between the SNAP-9A and its predecessor the SNAP-3B.

4. SNAP-19 RTGs

The development work on the SNAP-9A RTG provided the technology that led to the SNAP-19 RTGs which were the first use of nuclear power in space by NASA.

4.1 Nimbus III

In 1969, NASA successfully launched the Nimbus III meteorological satellite powered by two SNAP-19 RTGs and solar arrays. The two SNAP-19 RTGs, which produced 56.4 We at launch, provided about 20% of the total power of the spacecraft. Had the SNAP-19 RTGs not been onboard Nimbus III, the power would have fallen below the load line about two weeks into the mission because of solar array degradation (Bennett, et al., 1984).

4.2 Pioneers 10 and 11

In 1972, NASA began its exploration of the outer Solar System with the launch to Jupiter of Pioneer 10 powered by four SNAP-19 RTGs which produced a total of 161.2 We at BOM. The next year Pioneer 10 was followed by the Pioneer 11 spacecraft which was also powered by four SNAP-19 RTGs. In the cold, dark, radiation-rich environment of the Jovian system, nuclear power was the only viable option at that time. Because the SNAP-19 RTGs performed so well, NASA was able to retarget Pioneer 11 to go to Saturn after its flyby of Jupiter. Again, the RTGs performed very well, providing steady power to the spacecraft and its scientific instruments, thus allowing scientists their first close-up measurements of the second largest planet in the Solar System (Bennett, et al., 1984).

4.3 Viking Landers 1 and 2

In anticipation of the 200th anniversary in 1976 of the signing of the U.S. Declaration of Independence, NASA launched the two Viking missions in 1975, each launch carrying an Orbiter and a Lander. Each Lander was powered by two SNAP-19 RTGs specially modified to work on the surface of Mars (see Fig. 6). The 35-We Viking SNAP-19 RTGs contained a special dome allowing an interchange of internal gases (initial fill 90:10 helium-argon; reservoir fill 95:5 argon-helium) during operation on the surface of Mars. This allowed for reduced pre-launch temperatures and maximum power output on Mars. All four SNAP-19 RTGs easily met the 90-day operating requirement of the Landers and went on to power the Landers for up to six years giving scientists their first extraordinary in-situ views of the surface of Mars (Bennett, et al., 1984).
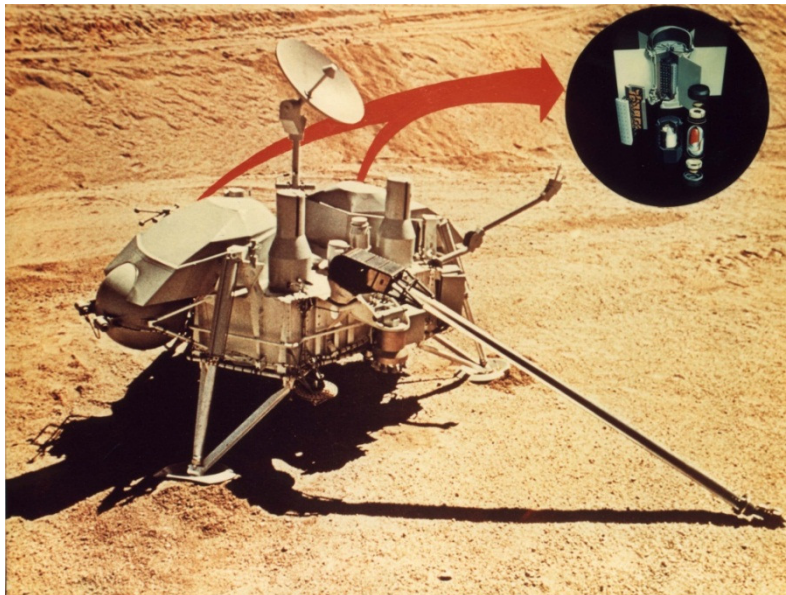

Fig. 6. Viking Lander model showing the location of the two SNAP-19 RTGs. The average power per RTG was 42.7 We at BOM. The overall RTG diameter (across fins) was 58.7 cm and the overall length was 40.4 cm. The mass was 15.2 kg. (Image credit: NASA/JPL/Caltech/ERDA/Teledyne)

The success of the Viking SNAP-19 RTGs was a key factor in the selection of the telluride-thermoelectric-based Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for the upcoming MSL mission (see Section 8).

5. Transit RTG

The successful use of the SNAP-9A RTGs on the Transit 5BN series of Navy navigational satellites led JHU/APL to use a new telluride-based RTG called the "Transit RTG" on its TRIAD navigational satellite. The Transit RTG was based on the SNAP-19 radioisotope heat source design although in this case radiatively coupled to a telluride-based thermoelectric converter instead of being conductively coupled as in the SNAP-19 and SNAP-9A RTGs.

The Transit RTG, which was designed to be modular, produced over 35 We at BOM within a mass of about 13.6 kg. The use of a lower hot-junction temperature (~674 K for the Transit RTG versus ~790+ K for the SNAP-19 RTGs) in a vacuum environment eliminated the SNAP-19 practice of using hermetic sealing and a cover gas to inhibit the sublimation degradation that could cause a reduction in cross section and subsequent increase in electrical resistance of the thermoelectric material. (Lowering the hot junction temperature is also one of the strategies adopted for the MMRTG.) While the TRIAD spacecraft had various problems, the Transit RTG operated well beyond its five-year requirement (Bennett, et al., 1984).

6. SNAP-27 on Apollo

For the Apollo missions to the Moon, RTGs were a natural choice to power scientific instruments during the long (14-Earth-day) lunar night. To provide this power, the U.S. Atomic Energy Commission (AEC) provided NASA with SNAP-27 RTGs built by General Electric (GE, now part of Lockheed-Martin). The SNAP-27 RTGs were designed to provide at least 63.5 We at 16 V one year after lunar emplacement. (In the case of Apollo 17, the requirement was 69 We two years after emplacement). Figure 7 shows Apollo 12 astronaut Alan L. Bean removing the SNAP-27 fuel-cask assembly from the Lunar Module on 19 November 1969. This was the first use of electricity-producing nuclear power on the Moon.

All five SNAP-27 RTGs (Apollo 12, 14, 15, 16, 17) exceeded their mission requirements in both power and lifetime thereby enabling the Apollo Lunar Surface Experiment Packages (ALSEPs) to gather long-term scientific data on the internal structure and composition of the Moon, the composition of the lunar atmosphere, the state of the lunar interior, and the genesis of lunar surface features (Pitrolo, et al., 1969, Bates, et al., 1979). On Apollo 11 the experiment package deployed on the lunar surface was named Early Apollo Scientific Experiments Package (EASAP) and consisted of the laser ranging retro-reflector (LRRR, also deployed on each following Apollo mission, and are still in use today) and the passive seismic experiments package (PSEP). The PSEP utilized 2 RHUs called the Apollo Lunar Radioisotopic Heater (ALRH) for thermal control (Apollo 11 Lunar Landing Mission Press Kit, 1969) and also had a solar array power system that lasted three weeks. The ALRHs contained ~34 gm of ^{238}Pu producing 15 W_{th} each. The subsequent PSEP stations utilized power from the SNAP-27 RTGs.
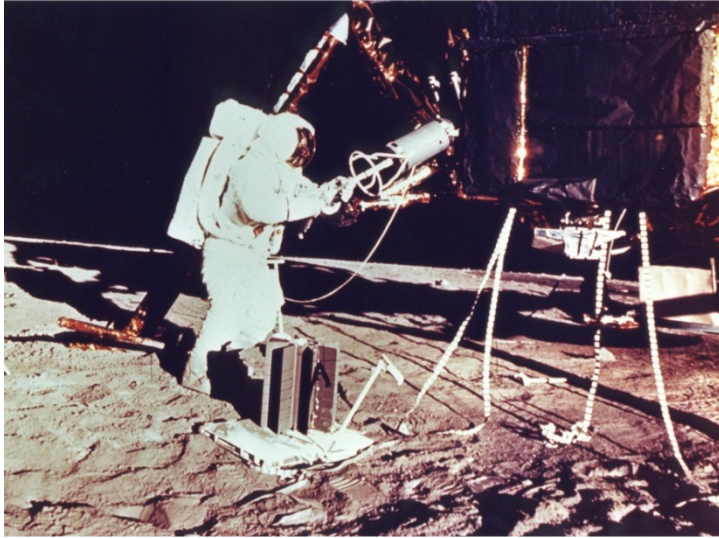
Fig. 7. Apollo 12 astronaut Alan L. Bean removing the SNAP-27 fuel-cask assembly from the Lunar Module. The SNAP-27 converter is shown in front of Bean ready to receive the fuel-cask assembly. (NASA)
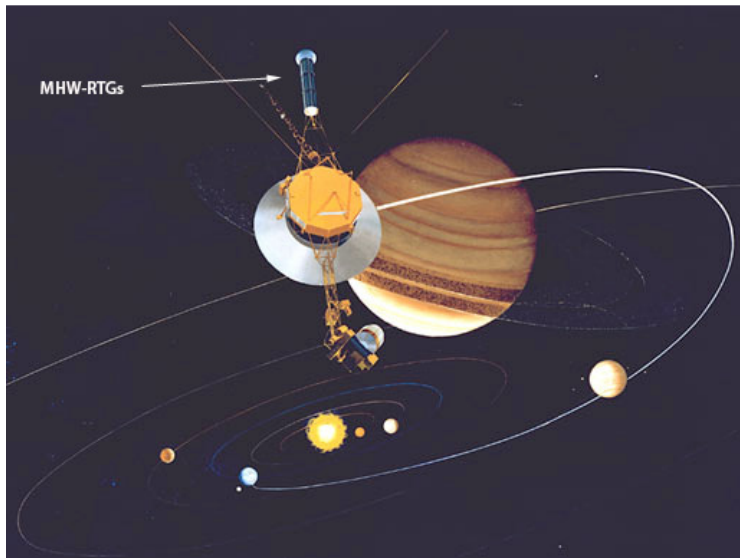

Fig. 8. Artist's concept of a Voyager spacecraft flying by Jupiter and Saturn. The three MHW-RTGs are shown on the boom above the spacecraft. The average power of each MHW-RTG was 158 We. The overall diameter was 39.73 cm and the length was 58.31 cm. The average flight mass for a Voyager MHW-RTG was 37.69 kg.
(Image credit: NASA/JPL/Caltech)

7. Silicon-germanium RTGs

With NASA developing the higher-powered Voyager 1 and Voyager 2 spacecraft (see Figure 8) as the next generation of outer planet explorers the bar was raised for RTG performance. To meet this demand, the AEC funded GE (now part of Lockheed-Martin) to develop the Multi-Hundred Watt Radioisotope Thermoelectric Generator (MHW-RTG), which was based on the use of a silicon-germanium alloy. Silicon-germanium, as noted earlier, can be operated at higher temperatures (~1300 K) than the telluride-based thermoelectrics (~800-900 K). Higher temperatures mean higher heat rejection temperatures, which mean smaller radiators hence lower unit masses. Combining the higher temperature with multifoil insulation (instead of bulk insulation) and vacuum operation (instead of using a cover gas) can yield a specific power that is 40% to over 70% higher than that of a telluride-based RTG (Bennett, et al., 1984). The basic layout of a silicon-germanium RTG is shown in Figure 9.
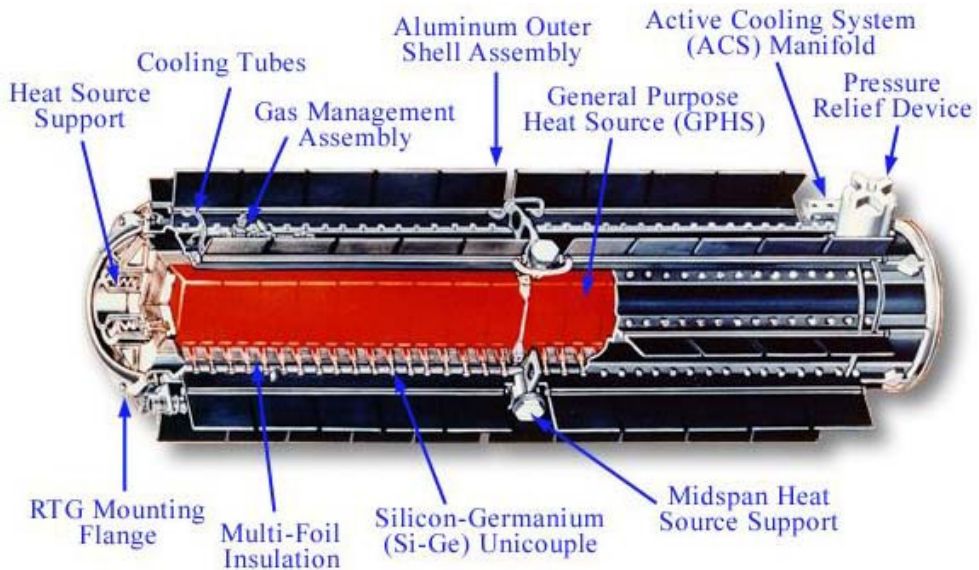

Fig. 9. Cutaway of the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG).

The GPHS-RTG can produce over 300 We at initial fueling. The overall diameter is 42.2 cm and the length is 114 cm. The mass is 55.9 kg (Image credit: DOE).

7.1 MHW-RTG

The MHW-RTG objective was to provide at least 125 We after five years in space. It was designed to produce at least 150 We at BOM, making it the highest-powered RTG at the time (1970s). Once the program was under way, the U.S. Air Force requested four MHW-RTGs for its communications satellites Lincoln Experimental Satellites 8 and 9 (LES-8/9) (Bennett, et al., 1984). As it turned out, LES-8/9 were launched prior to the Voyager launches (1976 versus 1977). Each LES carried two MHW-RTGs. The MHW-RTGs performed so well that the two communications satellites were used for years, including in the first Gulf War and to relay e-mail messages from stations in Antarctica.

Each Voyager spacecraft carried three MHW-RTGs (see Figure 8). The MHW-RTGs performed so well that Voyager 2 was retargeted after its flyby of Saturn (1981) to fly by Uranus and Neptune giving the human race its first close-up views of those distant worlds. Both Voyagers are still operating, almost 34 years after launch.

7.2 General-purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG)

For the Galileo and Ulysses missions the U.S. Department of Energy funded GE (now Lockheed Martin) to develop the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG), a power source essentially equivalent to two MHW-RTGs (see Figure 9). Where the MHW-RTG produced at least 150 We at BOM, the GPHS-RTG was capable of producing 300 We at BOM. Where each MHW-RTG had 312 silicon-germanium thermoelectric elements (called "unicouples"), each GPHS-RTG had 572 unicouples (Bennett, et al., 1984, Bennett, et al., 2006).

NASA's Galileo Orbiter carried two GPHS-RTGs to power its successful exploration of the Jovian system. The Ulysses spacecraft, which was built by the European Space Agency (ESA), carried one GPHS-RTG for its exploration of the polar regions of the Sun (Bennett, et al., 2006).

In 1997, NASA again used the GPHS-RTG, this time three of them to power the Cassini spacecraft that is still in orbit around Saturn. The GPHS-RTGs have performed so well that the mission has been extended several times (Bennett, et al., 2006). Figure 10 illustrates the progress that has been made in RTG performance – *in the span of a little over 30 years the power produced by a space RTG has increased over one-hundredfold!*

The most recent launch of the GPHS-RTG was in 2006 on the New Horizons spacecraft, which is traveling to Pluto. Because of the unavailability of a full complement of fresh Pu-238 fuel, the GPHS-RTG for New Horizons utilized some existing fuel that had decayed for 21 years since its production, yielding 245.7 We of power at BOM instead of the possible 300 We. Still, it is expected that the GPHS-RTG will provide sufficient power (~200 We) at the time of Pluto encounter to meet all of the mission's scientific and operational requirements. Once Pluto and its principal satellite Charon have been visited, New Horizons is designed to continue beyond to explore Kuiper Belt Objects (KBOs) (Bennett, et al., 2006).

Changes have been made in the general-purpose heat source (GPHS) that is the heart of the GPHS-RTG. For New Horizons, additional aeroshell material was added which increased the mass of the RTG. Additional material increases are planned for the GPHS modules to be used to power the MMRTG for MSL. While these changes have the effect of increasing the mass of the GPHS-RTG over the Galileo/Ulysses GPHS-RTGs there are design improvements, which could recreate the high specific power of the GPHS-RTG (Vining and Bennett, 2010).
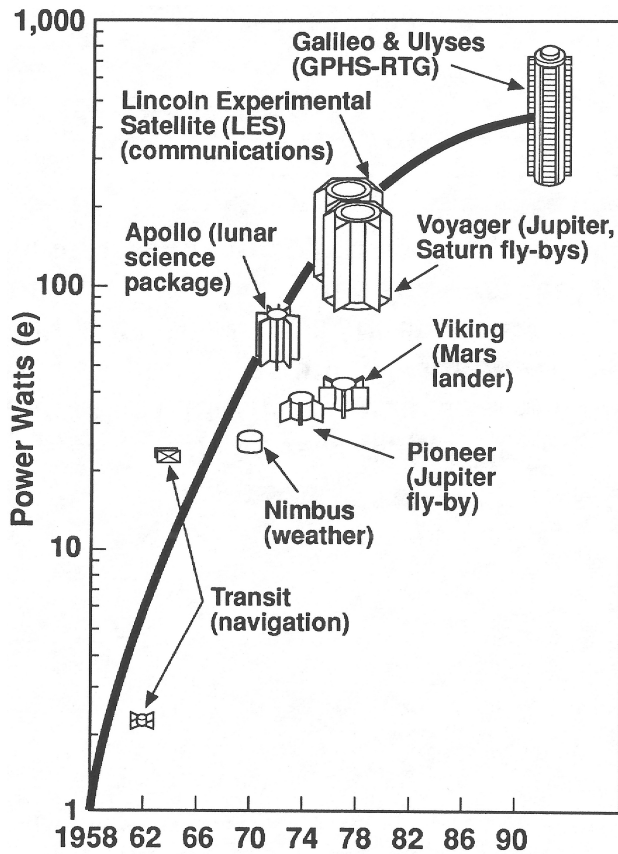
Fig. 10. Progress in RTG development. (Rockwell, 1992)

8. Multi-mission Radioisotope Thermoelectric Generator (MMRTG)

Following the successes of such flagship missions as Galileo and Cassini, NASA turned its attention to providing smaller "faster, better, cheaper" science spacecraft. In looking for an RPS which would satisfy that mandate along with being able to operate both in space and on the surface of a planetary body (e.g., Mars), a joint NASA/DOE team recommended development of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) along with the development of the higher efficiency Advanced Stirling Radioisotope Generator (ASRG) (see Section 10) (unpublished Report of the RPS Provisioning Strategy Team, 2001).

The MMRTG, built by Rocketdyne and Teledyne, is based on the telluride thermoelectric technology used in the SNAP-19 RTG program which had shown that it could work in space (Nimbus III, Pioneers 10/11) and on a planetary surface (Viking Landers 1 and 2). The first mission to employ the MMRTG will be the Mars Science Laboratory (MSL), whose rover has been named "Curiosity" (see Figure 11). The 900-kg MSL is scheduled to be launched in the late fall of 2011 to arrive at Mars in August 2012.

Fig. 11. Artist's concept of the Mars Science Laboratory (MSL) Curiosity rover with the MMRTG shown attached to the back end (right side in the picture). MSL is ~3 m long (not including the arm), 2.7 m wide, 2.1 m tall with a mass of 900 kg. The arm can reach about 2.1 m. (Image credit: NASA/JPL/Caltech).

The overarching science goals of the MSL mission are to search for clues about whether environmental conditions (such as the existence of water for significant periods) could support microbial life today or in the past, and to assess whether the environment has favored the preservation of this evidence. MSL will be the first interplanetary mission to use a sky crane to land and the first to use guided entry to land in a precise location. MSL is designed to last for one Mars year (~687 Earth days) and to travel 20 km during its prime mission.

The MMRTG is designed to provide about 110 We on the surface of Mars at 28 to 32 V. The conversion is achieved using 16 thermoelectric modules of 48 telluride-based thermoelectric elements (Hammel, et al., 2009). The MMRTG is designed to have a minimum lifetime of 14 years. The MMRTG employs a flexible modular design approach that would allow the MMRTG concept to meet the power requirements of a wide range of missions.

Figure 12 shows a cutaway of the MMRTG. The MMRTG gets its ~2-kWt of thermal power from eight GPHS modules, the same heat source technology that was successfully used in the GPHS-RTGs and is planned for use in the ASRG. Like the GPHS-RTG, the converter housing and the eight heat rejection (radiator) fins are made of aluminum. The core assembly with 16 thermoelectric modules, each containing 48 couples (see Figure 13), are located under the eight fins with eight pairs of two modules aligned axially (Hammel, et al., 2009).

The thermoelectric modules are spring loaded to enhance conduction of heat from the GPHS modules and to enhance conduction of heat from the cold junction of the thermoelectric elements into the module bar and then into the converter housing. A bulk insulation system composed of the material Min-K reduces heat losses, in effect forcing the heat to travel through the thermoelectric elements. To enhance reliability the thermoelectric couples are electrically arranged in series and parallel. This redundant arrangement prevents loss of power should one or even several thermoelectric elements fail (Hammel et al., 2009).
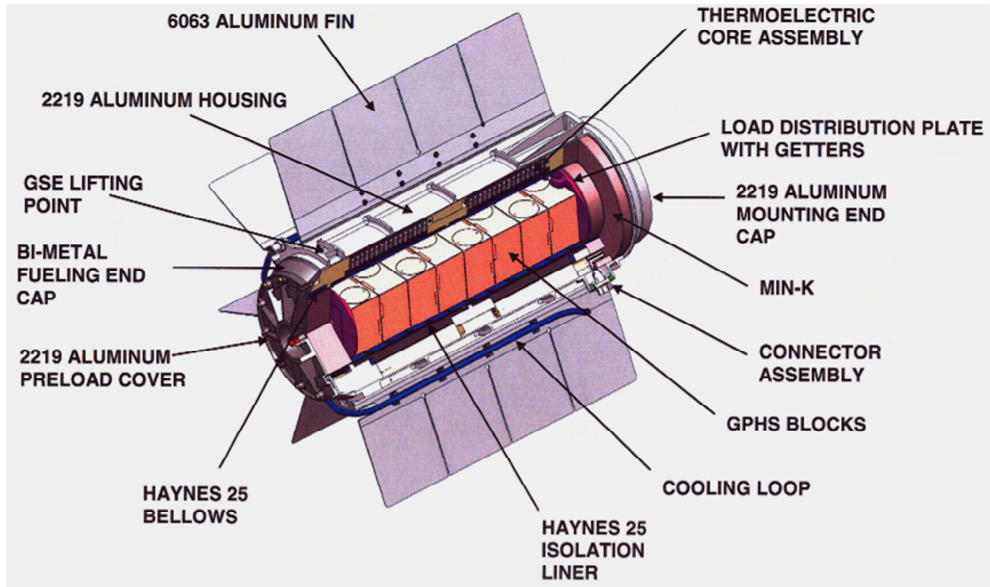
Fig. 12. Cutaway of the Multi-Mission Radioisotope Thermoelectric Generator (Hammel, et al., 2009) The MMRTG is designed to produce ~110 We at BOM with a mass of ~45 kg. The MMRTG is about 64 cm in diameter (fin-tip to fin-tip) by 66 cm long. (Image credit: DOE).
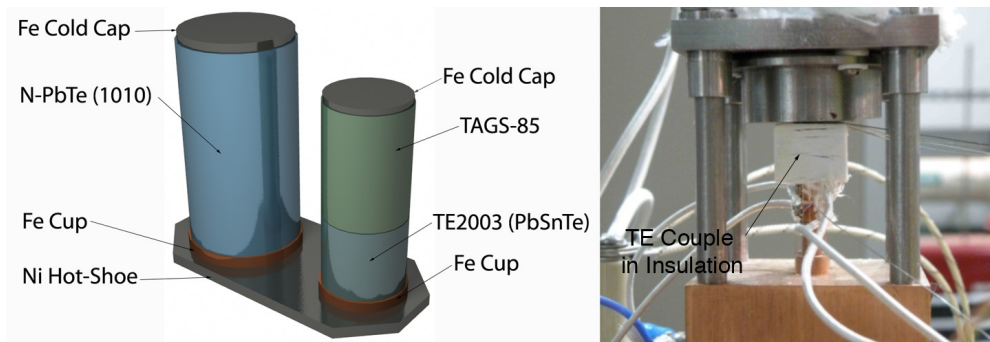

Fig. 13. The MMRTG Thermoelectric (TE) Couple in illustration and in a Test Fixture (Image credit: NASA/JPL/Caltech)

Like the SNAP-19 RTGs, the MMRTG is a sealed RTG with a cover gas. (The MHW-RTGs, GPHS-RTGs and Transit RTG were operated in a vacuum.) The heat source is sealed from the converter by a thin metal liner. Helium buildup from the natural decay of the Pu-238 fuel is prevented by venting it directly to the exterior of the MMRTG. The hermetically sealed converter contains an argon cover gas that reduces parasitic heat losses and protects the thermoelectric elements. With this venting and cover gas arrangement the MMRTG can operate in space or in an atmosphere (e.g., the surface of Mars or Titan) (Hammel, et al., 2009).

Modeling of the MMRTG performance indicates that the MMRTG will be able to provide the necessary power to enable MSL to achieve its objectives (Hammel, et al., 2009).

9. Dynamic Isotope Power System (DIPS)

The Dynamic Isotope Power System (DIPS) program was initiated in 1975 to provide increased power from radioisotope heat sources by using more efficient dynamic conversion systems (Brayton and Rankine). The precedent had been established in the 1950s with the SNAP-1 program (see Section 2) with its mercury Rankine conversion system and the SNAP-2 (3 kWe) and SNAP-8 (30 to 60 kWe) mercury Rankine space reactor programs. In terms of mass and specific power DIPS fills the gap between RTGs and nuclear reactors; in short, it could be the next logical step for increased RPS power after RTGs. Figure 14 illustrates the basic features of a representative DIPS (either Brayton or Rankine) (Bennett and Lombardo, 1989).
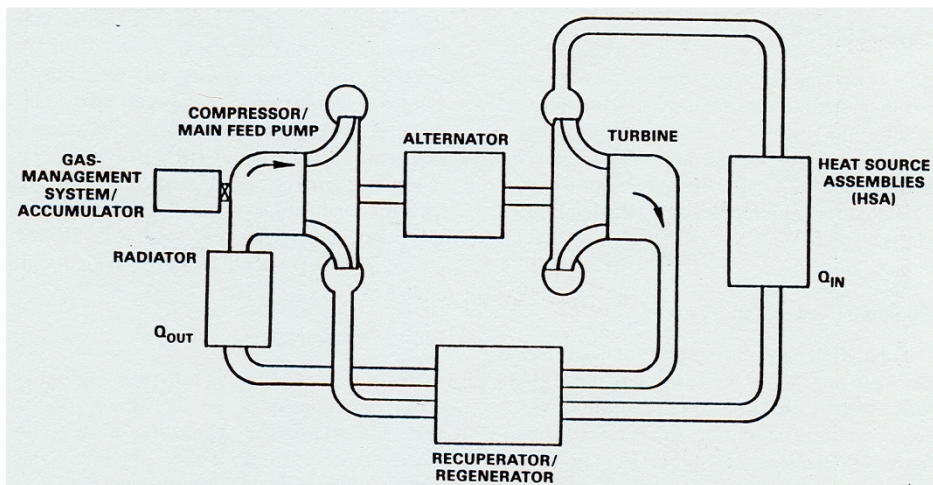

Fig. 14. Functional diagram of a generic Dynamic Isotope Power System (DIPS) (Bennett and Lombardo, 1989).

The original DIPS program was focused on producing a 1.3 kWe radioisotope power source with a mass of ≤204 kg using either a Brayton conversion system or an organic Rankine conversion system. The Brayton conversion system built upon the experience of NASA and its contractors (e.g., Garrett Corporation) dating from 1965 in developing a 2 to 10 kWe closed Brayton cycle (CBC) power system. In parallel, work on ground-based Rankine cycle systems led what was then Sundstrand Corporation to propose using Dowtherm A or toluene as a working fluid in order to avoid the corrosion issues with liquid-metal Rankine systems (Bennett and Lombardo, 1989).

Based on actual hardware tests, both the CBC and the organic Rankine cycle (ORC) were shown to be capable of meeting the DIPS goals. The organic Rankine cycle was chosen for further testing. The lack of a mission led to the termination of the program in 1980 but in 1986 the U.S. Air Force expressed interest in having a DIPS for its Boost Surveillance and Tracking System (Bennett & Lombardo, 1989). The DIPS program was restarted with Rocketdyne as the systems contractor and Sundstrand and Garrett as subcontractors.

This time the CBC was chosen and Rocketdyne developed a basic 2.5-kWe DIPS module that could be used in space or on planetary surfaces. Figure 15 illustrates the basic components of a 2.5-kWe modular DIPS power conversion unit (PCU). While again changing national priorities did not allow DIPS to be developed into a flight system, the basic technology exists to provide an RPS with powers spanning the range from 2 to ≥10 kWe (Rockwell, 1992). Section 10 describes a lower power successor to DIPS, the Advanced Stirling Radioisotope Generator (ASRG) that will provide increased efficiency and use less Pu-238 fuel than existing RTGs
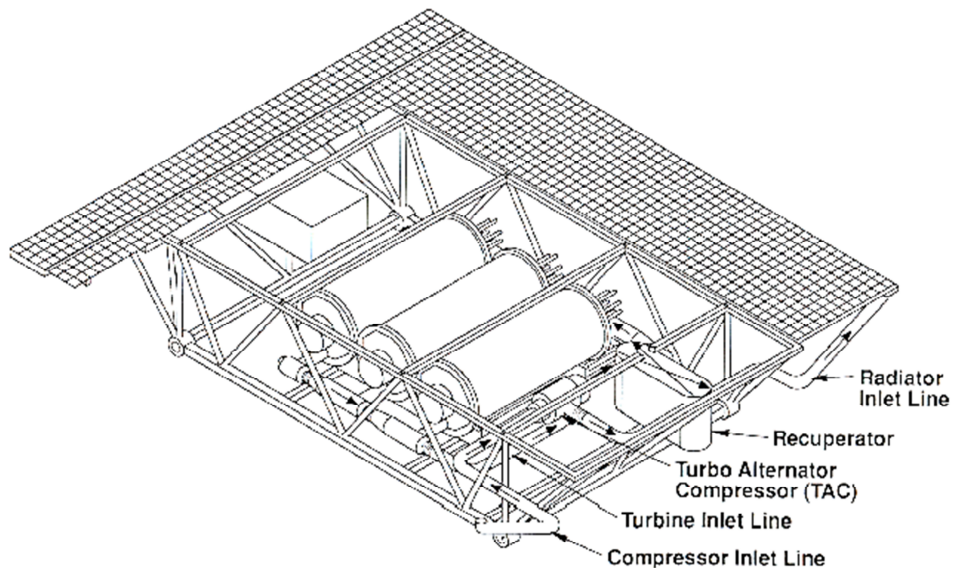

Fig. 15. Components of the proposed 2.5-kWe modular DIPS Power Conversion Unit (PCU).

Overall dimensions for the 2.5-kWe module are 2.44 m x 3.55 m x 0.5 m. (Image credit: Rocketdyne).

10. Advanced Stirling Radioisotope Generator (ASRG)

The ASRG employs an advanced, high efficiency, dynamic Stirling engine for heat-to-electric power conversion. This process is roughly four times more efficient than presently utilized thermoelectric devices. As a result, the ASRG produces comparable power to the MMRTG with only one quarter of the Pu-238, extending the supply of radioisotope fuel available for future space science missions. The higher efficiency provided by dynamic systems, such as the ASRG, could become an enabling power system option for higher power kilowatt class power systems envisioned for flagship class science spacecraft, large planetary rovers, and systems in support of human exploration activities.

The ASRG utilizes an advanced Stirling free-piston heat engine consisting of two major assemblies, the displacer and piston, that reciprocate to convert heat to electrical power as shown in Figure 16. Heat from the GPHS module is conductively coupled to the heater head (not shown). Helium is used as the working fluid and is hermetically contained within the convertor enclosure. The displacer shuttles helium between the expansion

space where heat is received and compression space, where waste heat is removed. The changes in pressures and volumes of the convertor working spaces drive the power piston that reciprocates to produce AC electrical power via a permanent magnet linear alternator (Hoye, et al. 2011).
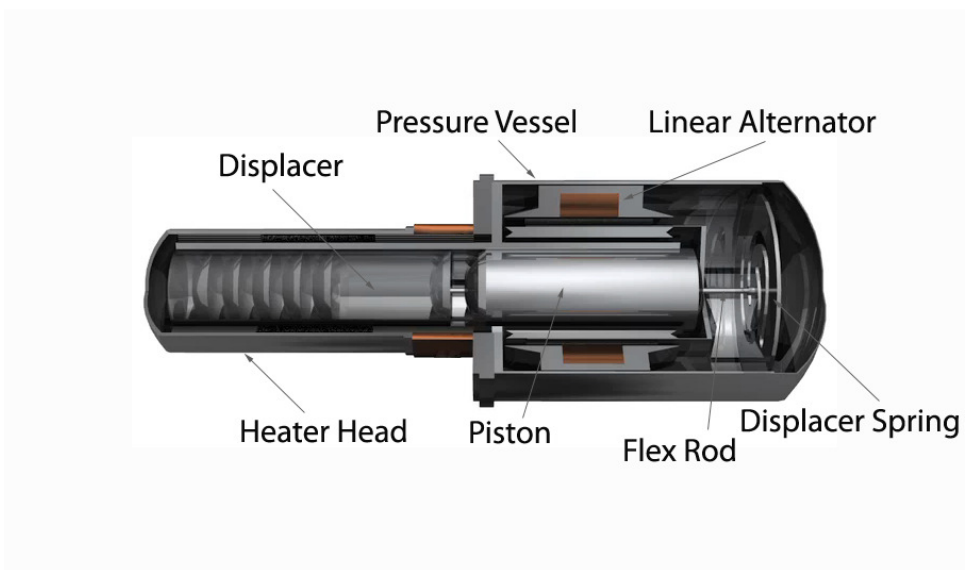

Fig. 16. Advanced Stirling Convertor (Image credit: Kristin Jansen, NASA Glenn).
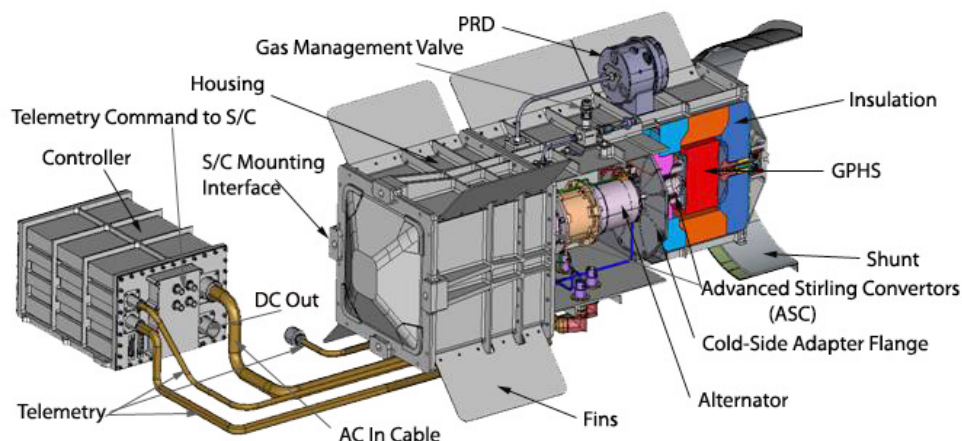
Fig. 17. Cutaway view of the ASRG (Image credit: Lockheed Martin).

Figure 17 shows one of the two GPHS heat sources, one for each advanced Stirling convertor (ASC). Each GPHS module is surrounded by insulation to minimize heat leakage thus maximizing heat input to the convertors. The displacer side of the ASC is toward the GPHS module and cold-side is attached to the housing via the cold-side adapter flange (CSAF). The housing and attached fins provide a view to the environment to maintain sufficient heat rejection. During ground storage and launch pad operations a slightly positive pressure of inert gas is maintained via the Gas Management Valve. The gas within the housing helps dissipate heat not rejected by the ASC via the CSAF. This gas is permanently vented to vacuum by the Pressure Relief Device (PRD) to achieve full operating power in space vacuum.

Operating frequency of the Stirling convertors is 102.2 Hz AC. The controller converts AC current to DC current for a typical 28-34 V spacecraft electrical bus. The shunt maintains a required load on the ASRG when it is not connected to a spacecraft, such as during storage or spacecraft integration. The controller also maintains synchronized displacer/piston movement of the two directionally opposed Stirling convertors to minimize induced disturbance to the spacecraft and its precision instrumentation. The ASRG is capable of producing 45% of total power should one ASC fail to operate. Health monitoring of the ASRG is provided by telemetry signals to the spacecraft and then transmitted back to Earth. The ASRG has an autonomous control system since space distances do not allow for direct operator control. The controller has electronics for each ASC plus a third redundant circuit to replace a failed card thus increasing overall system reliability.

The ASRG is being developed under joint sponsorship by NASA and DOE for potential flight on a future NASA mission opportunity. Projected mass of the flight unit is 32 kg or less. The flight units are anticipated to produce over 130 We in the vacuum of space and at an effective sink temperature of 4 K (deep space). Other applications on planetary bodies would either increase or decrease the power output depending on the temperature and atmosphere of the environment.

ASRG efforts leading up to its flight readiness began in 2000. An engineering unit (EU) was built in 2008 by Lockheed Martin Space Systems incorporating the advanced Stirling

convertor manufactured by Sunpower. Characterization testing was performed for typical launch and space environments.
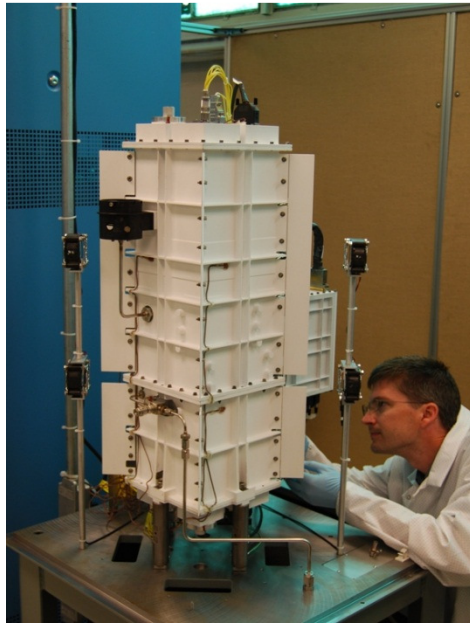

Fig. 18. ASRG engineering unit readied for extended testing at NASA Glenn Research Center (Photo Credit, NASA Glenn).

After successful characterization tests the EU was put on extended operation with electrically heated GPHS simulators as shown in figure 18. A cold gas is passed over the EU to maintain proper thermal operating conditions. The EU is planned to demonstrate 14,000 hours of operation in validating the design's viability for flight on a NASA science mission (Lewandowski and Schreiber, 2010). The EU has achieved over 11,000 hours (April, 2011) with a prototypical flight controller.

11. Future radioisotope technologies

In addition to the MMRTG and ASRG efforts are underway to develop other technologies such as advanced thermoelectric couples (ATEC), thermophotovoltaic (TPV) systems and the Stirling duplex system.

The ATEC effort is developing and demonstrating thermoelectric couples with efficiencies greater than 10% with degradation losses less than 1% per year. Part of this effort is developing high temperature complex advanced materials with twice the state of practice efficiency.

TPV uses photovoltaic cells tuned to certain spectra emitted by a radioisotope heat source. Development efforts include studies of the optical properties and optimization of the emitter, filters and collectors to achieve efficiencies of greater than 15% with low degradation rates.

The Stirling duplex concept combines a power convertor as in the ASRG with a thermodynamic Stirling cycle cooler. This concept provides both power in the range of 100-300 We and 1100 Wth cooling, allowing its potential use for missions in harsh high-temperature environments.

12. Human exploration missions

To this point, discussions have focused on lower-power science mission objectives. However, the concept of high efficiency energy conversion could find application in human exploration, particularly relating to the Moon and Mars. Multi-kilowatt power level radioisotope systems have application for the Moon due to its long 356-hour night period and on Mars due to its distance from the Sun, atmospheric dust attenuation and short winter day periods at higher latitudes.
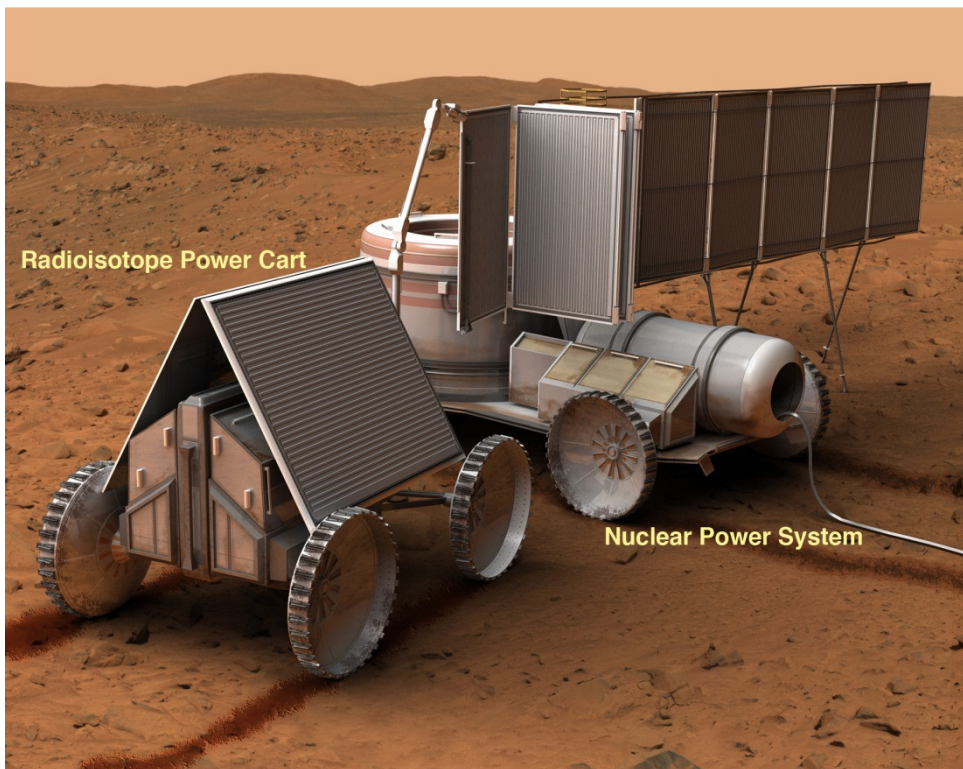

Fig. 19. A concept for a multi-Kilowatt radioisotope power system deploying a fission reactor on the surface of Mars, (Artist concept credit: Bob Souls, John Frassanito and Associates, Courtesy of NASA).

Radioisotope power systems provide continuous power avoiding necessity of solar arrays and battery or fuel cell storage (for night time energy) and the wait to recharge them. Relative mission risk could also be reduced since solar array size for many of these

applications are too large and therefore require stowage during mobility and subsequent deployment for recharging multiple times. For Mars, radioisotope systems could be used in several applications (Cataldo, 2009). Opportunities to travel to Mars occur every 26 months. Many human mission scenarios call for pre-deployment of equipment on the opportunity preceding the piloted flight to simplify launch and mission logistics. One concept for a radioisotope system is a power cart capable of several applications with mobility as a key feature. For example, supplying power to deploy a shielded fission reactor several kilometers from a habitat could be accomplished in several days without the use of large solar arrays. The power cart would have communications capability to Earth via orbiting assets to control its movements and its re-location to future sites.

Once the crew arrives on a subsequent opportunity, the power cart could be used with a pressurized rover. This scenario would allow the crew to perform long-range roving (over ~100's km) to significantly extend the scope of exploration from a single landing site. The power cart could also provide back-up power to the habitat should that become required. Should the base power system be solar instead of fission power a radioisotope-powered habitat back-up system could save significant mass during decreased array output during due to a global dust storm. A radioisotope power system could offer significant flexibility in mission planning for human missions as well as robotic science missions. In addition, since a crew would be available for repairs, maintenance or upgrades, the radioisotope fuel could be placed in a redundant cart with new conversion hardware extending the use of the fuel for many follow-on missions (Cataldo, 2009).

13.Conclusions

The U.S. has had a very successful 50 years of using RPS to power some of the most challenging and scientifically rewarding space missions in human history. These RPS have provided power at or above that required levels, and generally for longer than the original mission specification. RPS can truly be an enabling technology for both robotic probes and human exploration of the Solar System and beyond.

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