

**RADIOISOTOPE POWER: A KEY TECHNOLOGY FOR DEEP SPACE
EXPLORATION**

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ABSTRACT

A Radioisotope Power System (RPS) generates power by converting the heat released from the nuclear decay of radioactive isotopes, such as Plutonium-238 (Pu-238), into electricity. First used in space by the U.S. in 1961, these devices have enabled some of the most challenging and exciting space missions in history, including the Pioneer and Voyager probes to the outer solar system; the Apollo lunar surface experiments; the Viking landers; the Ulysses polar orbital mission about the Sun; the Galileo mission to Jupiter; the Cassini mission orbiting Saturn; and the recently launched New Horizons mission to Pluto. Radioisotopes have also served as a versatile heat source for moderating equipment thermal environments on these and many other missions, including the Mars exploration rovers, Spirit and Opportunity. The key advantage of RPS is its ability to operate continuously, independent of orientation and distance relative to the Sun. Radioisotope systems are long-lived, rugged, compact, highly reliable, and relatively insensitive to radiation and other environmental effects. As such, they are ideally suited for missions involving long-lived, autonomous operations in the extreme conditions of space and other planetary bodies. This paper reviews the history of RPS for the U.S. space program. It also describes current development of a new Stirling cycle-based generator that will greatly expand the application of nuclear-powered missions in the future.

INTRODUCTION

A radioisotope Power System (RPS) generates electrical power by converting heat released from the nuclear decay of radioactive isotopes into electricity. Because all the units that have flown in space have employed thermoelectrics, a static process for heat-to-electrical energy conversion that employs no moving parts, the term, Radioisotope Thermoelectric Generator (RTG), has been more popularly associated with these devices. However, the advent of new

generators based on dynamic energy conversion and alternative static conversion processes favors use of "RPS" as a more accurate term for this power technology.

RPSs were first used in space by the U.S. in 1961. Since that time, the U.S. has successfully flown 41 RTGs, as a power source for 23 space systems. These applications have included Earth-orbital weather and communication satellites, scientific stations on the Moon, robotic explorer spacecraft on Mars, and highly

sophisticated deep space interplanetary missions to Jupiter, Saturn and beyond. The New Horizons mission to Pluto, which was launched in January 2006, represents the most recent use of an RTG. The former U.S.S.R. also employed RTGs on several of its early space missions. In addition to electrical power generation, the U.S. and former U.S.S.R. have used radioisotopes extensively for heating components and instrumentation.

RPSs have consistently demonstrated unique capabilities over other types of space power systems. A comparison between RPS and other forms of space power is shown in Fig. 1, which maps the most suitable power technologies for different ranges of power level and mission duration. In general, RPS is best suited for applications involving long-duration use beyond several months and power levels up to one to 10 kilowatts.

It is important to recognize that solar power competes very well within this power level range, and offers much higher specific powers (power per unit system mass) for applications up to several Astronomical Units (AU) from the Sun. However, RPS offers the unique advantage of being able to operate continuously, regardless of its distance and orientation with respect to the Sun. The flight history of RTGs has demonstrated that these systems are long-lived, rugged, compact, highly reliable, and relatively insensitive to radiation and other environmental effects. Thus, RTGs and the more capable RPS options of the future are ideally suited for missions at distances and extreme conditions where solar-based power generation becomes impractical. These include travel beyond the asteroid belt, operation within the radiation-intensive environments around Jupiter and close to the Sun, extended operation within permanently shadowed and occulted areas on planetary surfaces, and general applications requiring robust, unattended operations.

Table 1 presents a chronological summary of the U.S. missions that have utilized radioisotopes for power and heat generation. Although three missions were aborted by launch vehicle or spacecraft failures, all of the RTGs that flew met

or exceeded design expectations, and demonstrated the principles of safe and reliable operation, long life, high reliability, and versatility of operating in hostile environments. All of the RTGs flown by the U.S. comprise seven basic designs: SNAP-3/3B, SNAP-9A, SNAP-19/19B, SNAP-27, TRANSIT-RTG, MHW-RTG and GPHS-RTG. The first four types were developed by the Atomic Energy Commission (AEC) under the auspices of its Systems for Nuclear Auxilliary Power (SNAP) program. Although the original objective was to provide systems for space, the SNAP program also developed generators for non-space, terrestrial applications.

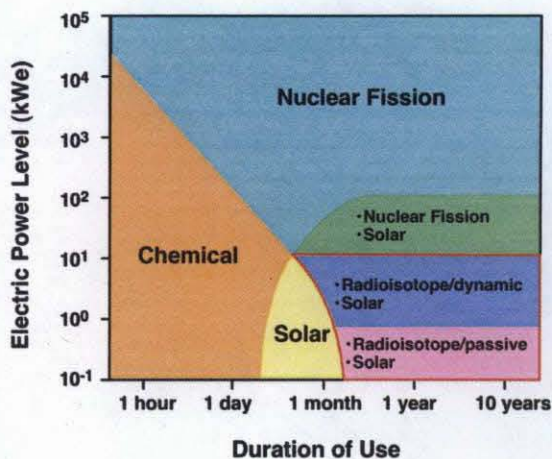


Figure 1: Suitability of space power system technologies.

The GPHS-RTG is the most recently developed unit, and has been the workhorse on all RPS missions since 1989. NASA and the Department of Energy (DOE) are looking beyond this capability, and are currently developing two new units: the Multi-Mission RTG (MMRTG), which draws on the design heritage of the SNAP-19, and the new Advanced Stirling Radioisotope Generator (ASRG) with its dramatically more efficient dynamic conversion cycle.

Table 1. U.S. Missions Using Radioisotopes for Power and Heat

	Spacecraft/ System	Principal Energy Source (#)	Destination/ Application	Launch Date	Status
1	Transit 4A	SNAP-3B7 RTG (1)	Earth Orbit/ Navigation Sat	29 June 1961	RTG operated for 15 yrs. Satellite now shutdown.
2	Transit 4B	SNAP-3B8 RTG (1)	Earth Orbit/ Navigation Sat	15 Nov 1961	RTG operated for 9 yrs. Operation intermittent after 1962 high alt test. Last signal in 1971.
3	Transit 5BN-1	SNAP-9A RTG (1)	Earth Orbit/ Navigation Sat	28 Sep 1963	RTG operated as planned. Non-RTG electrical problems on satellite caused failure after 9 months.
4	Transit 5BN-2	SNAP-9A RTG (1)	Earth Orbit/ Navigation Sat	5 Dec 1963	RTG operated for over 6 yrs. Satellite lost navigational capability after 1.5 yrs.
5	Transit 5BN-3	SNAP-9A RTG (1)	Earth Orbit/ Navigation Sat	21 Apr 1964	Mission aborted because of launch vehicle failure. RTG burned up on reentry as designed.
6	Nimbus B-1	SNAP-19B2 RTG (2)	Earth Orbit/ Meteorology Sat	18 May 1968	Mission aborted because of range safety destruct. RTG heat sources recovered and recycled.
7	Nimbus III	SNAP-19B3 RTG (2)	Earth Orbit/ Meteorology Sat	14 Apr 1969	RTGs operated for over 2.5 yrs. No data taken after that.
8	Apollo 11	ALRH Heater	Lunar Surface/ Science Payload	14 July 1969	Heater units for seismic experimental package. Station shut down Aug 3, 1969.
9	Apollo 12	SNAP-27 RTG (1)	Lunar Surface/ Science Station	14 Nov 1969	RTG operated for about 8 years until station was shutdown.
10	Apollo 13	SNAP-27 RTG (1)	Lunar Surface/ Science Station	11 Apr 1970	Mission aborted. RTG reentered intact with no release of Pu-238. Currently located at bottom of Tonga Trench in South Pacific Ocean.
11	Apollo 14	SNAP-27 RTG (1)	Lunar Surface/ Science Station	31 Jan 1971	RTG operated for over 6.5 years until station was shutdown.
12	Apollo 15	SNAP-27 RTG (1)	Lunar Surface/ Science Station	26 July 1971	RTG operated for over 6 years until station was shutdown.
13	Pioneer 10	SNAP-19 RTG (4)	Planetary/Payload & Spacecraft	2 Mar 1972	Last signal in 2003. Spacecraft now well beyond orbit of Pluto.
14	Apollo 16	SNAP-27 RTG (1)	Lunar Surface/ Science Station	16 Apr 1972	RTG operated for about 5.5 years until station was shutdown.
15	Triad-01-1X	Transit-RTG (1)	Earth Orbit/ Navigation Sat	2 Sep 1972	RTG still operating as of mid-1990s.
16	Apollo 17	SNAP-27 RTG (1)	Lunar Surface/ Science Station	7 Dec 1972	RTG operated for almost 5 years until station was shutdown.
17	Pioneer 11	SNAP-19 RTG (4)	Planetary/Payload & Spacecraft	5 Apr 1973	Last signal in 1995. Spacecraft now well beyond orbit of Pluto.
18	Viking 1	SNAP-19 RTG (2)	Mars Surf/Payload & Spacecraft	20 Aug 1975	RTGs operated for over 6 years until lander was shutdown.
19	Viking 2	SNAP-19 RTG (2)	Mars Surf/Payload & Spacecraft	9 Sep 1975	RTGs operated for over 4 years until relay link was lost.
20	LES 8, LES 9	MHW-RTG (4)	Earth Orbit/ Com Sats	14 Mar 1976	Single launch with double payload. LES 8 shutdown in 2004. LES 9 RTG still operating.
21	Voyager 2	MHW-RTG (3)	Planetary/ Payload & Spacecraft	20 Aug 1977	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, Neptune, and beyond.
22	Voyager 1	MHW-RTG (3)	Planetary/ Payload & Spacecraft	5 Sep 1977	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.
23	Galileo	GPHS-RTG (2)	Planetary/Payload & Spacecraft	18 Oct 1989	RTGs continued to operate until 2003, when spacecraft was intentionally deorbited into Jupiter atmosphere.
24	Ulysses	GPHS-RTG (1)	Planetary/Payload & Spacecraft	6 Oct 1990	RTG continued to operate until 2008, when spacecraft was deactivated.
25	Mars Pathfinder	RHU Heater	Mars Surf/Rover Electronics	4 Dec 1996	Heater units and used to maintain payload temperature. Units still presumed active.
26	Cassini	GPHS-RTG (3)	Planetary/Payload & Spacecraft	15 Oct 1997	RTGs continue to operate successfully. Scientific mission and operations still continue.
27	Mars MER Spirit	RHU Heater	Mars Surf/Rover Electronics	June 10 2003	Heater units still operational and used to maintain payload temperature.
28	Mars MER Opportunity	RHU Heater	Mars Surf/Rover Electronics	July 7 2003	Heater units still operational and used to maintain payload temperature.
29	New Horizons	GPHS-RTG (1)	Planetary/Payload & Spacecraft	Jan 19 2006	RTG continues to operate successfully. Spacecraft in transit to Pluto.

THE EARLY YEARS

The history of RPS began in the early years of the Cold War, when surveillance satellites were a major impetus for the early space race. The Manhattan project and the years leading up to it had yielded a wealth of knowledge on nuclear physics, particularly the radio-decay properties of actinides and other alpha particle-producing materials. The energy released from the radioactive decay of different elements had become well characterized, and it was recognized early on that radioisotopes could provide power for military satellites and other remote applications. An early study by the North American Aviation Corporation had considered radioisotopes for space power. Then a RAND Corporation report in 1949 evaluated options for space power, and concluded that a radioactive cell-mercury vapor system could feasibly supply 500 We (watts-electric) for up to one year. In 1952, RAND issued a report with an extensive discussion on radioisotope power for space applications, which spurred interest in applying the technology on satellites.

Recognizing the viability of nuclear power for reconnaissance satellites, the Department of Defense (DOD) requested in August 1955 that the Atomic Energy Commission (AEC) perform studies and limited experimental work toward developing a nuclear reactor auxiliary power unit for an Air Force satellite system concept. AEC agreed, but wanted to broaden its examination to both radioisotope and reactor heat sources. This marked the beginning of the SNAP program, which was structured into parallel power plant efforts with two corporations. Odd-numbered SNAP projects focused on RPS and were spearheaded by the Martin Company, while even-numbered SNAP projects using reactors were performed by the Atomic International Division of North American Aviation, Inc.

In these early days, efforts focused on dynamic energy conversion. The work of the Martin Company progressed through an early SNAP-1 effort that used the decay heat of Cerium-144 to boil Mercury and drive a small turbine. In early 1954, a new simpler static energy conversion

method was conceived by Kenneth Jordan and John Birden of the AEC's Mound Laboratory in Miamisburg, Ohio. Having been frustrated in their efforts to use radioisotope heat sources to generate electricity via steam turbines, these two researchers considered using two metals with markedly different electrical conductivities to generate electricity directly from an applied heat load. This thermoelectric method was patented by Jordan and Birden, and has remained the basis for all RTGs to the present day. In 1958, work began on two thermoelectric demonstration devices at Westinghouse Electric and 3M, while AEC contracts with other companies explored the development of demonstration thermionic units.

The project to develop a generator based on thermoelectric energy conversion was given the designation, SNAP-3. The 3M Company delivered a workable converter to the Martin Company in December 1958. Shortly thereafter, a complete radioisotope-powered generator was delivered to the AEC as a proof-of-principle device, producing 2.5 We with a half charge of Polonium-210 (Po-210) fuel.

That SNAP-3 actually never flew in space, but it became an invaluable showpiece for RPS and the SNAP program. President Eisenhower, who had been keenly interested in developing nuclear power for U.S. surveillance satellites, was shown this breakthrough device in January 1959, when the SNAP-3 was displayed on his desk in the Oval Office (Fig. 2). Eisenhower used the opportunity to emphasize his view of "peaceful uses" of nuclear technology, and it afforded him an opportunity to issue a challenge to NASA to develop missions that could exploit the device's potential. The SNAP-3 continued its marketing role, and was shown at several foreign capitals as part of the U.S.'s "Atoms for Peace" exhibits.

SYSTEM INTEGRATION

The first successful use of RTGs in space took place with the U.S. Navy's Transit satellite program. Also known as the NNS (Navy Navigation Satellite), the Transit system was used by the Navy to provide accurate location information to ballistic missile submarines. It



Figure 2: SNAP-3 presentation to President Eisenhower.

was also used for general navigation by the Navy, as well as hydrographic and geodetic surveying, and was the first such system to be used operationally. The Johns Hopkins Applied Physics Laboratory (APL) developed the system, starting in 1957. Many of the technologies developed under the Transit program are now in use on the Global Positioning System (GPS).

Several of the Transit developers had been considering the use of RPS since the beginning of the program. Although solar cells and batteries had powered the first six Transit satellites, there was concern that the battery hermetic seals would not meet the five-year mission requirement. Thus, APL accepted an offer from the AEC to include an auxiliary nuclear power source on the satellite. At that time, however, the radioisotope fuel of choice, Plutonium-238 (Pu-238), was unavailable due to AEC restrictions, and APL refused to use beta-decaying Strontium-90 because of the excessive weight associated with its necessary shielding. The AEC eventually acquiesced and agreed to provide the Pu-238 fuel. The SNAP-3 was converted from use of Po-210 to Pu-238, and acquired the new designation, SNAP-3B. The SNAP-3B RTGs on board these spacecraft supplemented solar cell arrays and demonstrated operation of nuclear systems for space power applications.

A schematic of the SNAP-3B generator is shown in Fig. 3. Each unit had a mass of 2.1 kg and an initial power output of 2.7 We, and was

designed to last five years. Although this power level was quite low, the RTG performed the critical function of powering the crystal oscillator that was the heart of the electronic system used for Doppler-shift tracking. It also powered the buffer-divider-multiplier, phase modulators and power amplifiers. The heat source produced approximately 52.5 Wt from 92.7 grams of encapsulated plutonium metal, which had an isotopic mass composition of 80% Pu-238, 16% Pu-239, 3% Pu-240, and 1% Pu-241. The power conversion assembly consisted of 27 spring-loaded, series-connected pairs of Lead-Telluride (Pb-Te) thermoelectric elements operating at a hot-juncture temperature of about 783 K and a cold-juncture temperature of about 366 K. The power system had a power-conversion efficiency of 5 to 6 percent and a specific power of 1.3 We/kg.

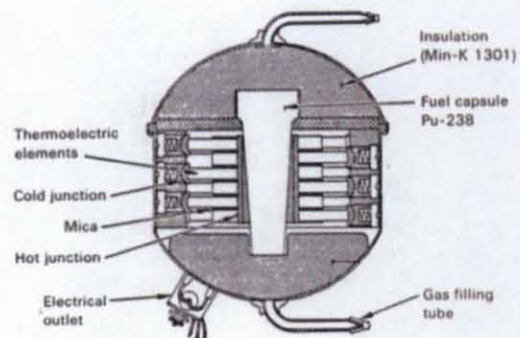


Figure 3. SNAP-3B Schematic.

Transit 4A was launched, along with two other satellites (Fig. 4), on June 29, 1961 aboard a Thor-Able rocket. Transit 4B was launched soon afterward on November 15, 1961. Even for this first use of nuclear power in space, there was controversy stemming from concerns over launch safety. The State Department, in particular, expressed concern with its trajectory over Cuba and South America. As part of the aerospace nuclear safety philosophy at that time, the generators were designed for burnup and high altitude fuel dispersal to concentrations below the background radiation attributed to atmospheric nuclear weapons testing. In addition, the spacecraft were placed into 1,100-

km orbits, which provided orbital lifetimes (>1,000 years) sufficient for the fuel to decay to these background levels. The Transit 4A generator operated for 15 years, and was shutdown in 1976. The last reported signal from Transit 4B was in April 1971.

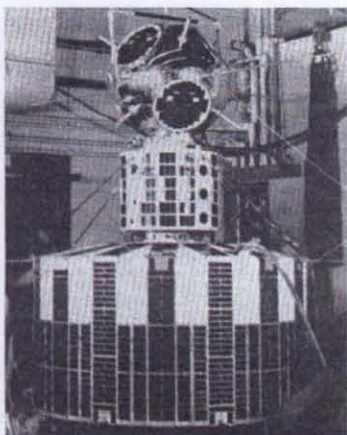


Figure 4. Integrated Transit payload. *Transit satellite is positioned at bottom of stack.*

SNAP-9A

After the success of SNAP-3B, the team consisting of the AEC, Martin, 3M, Mound Laboratory and APL proceeded to develop the SNAP-9A for the next series of Transit satellites. There was also a growing demand for isotope power for terrestrial applications. For instance, the SNAP-7 series of devices was under development for the Navy, Coast Guard, and Weather Bureau for navigation lights and weather stations on Earth.

DOD decided to continue using RTGs for its navigational satellites because of their resistance to radiation. A high-altitude nuclear explosive test in 1962 had adversely impacted the solar cells of earlier Transit satellites, and DOD was concerned with their susceptibility to radiation and other space effects in the future. The SNAP-9A was essentially an expanded version of the SNAP-3B, and was the first RTG employed as the primary spacecraft power source. Its power capability of 26.8 We at beginning of mission (BOM) was nearly an order of magnitude greater than the SNAP-3B.

Each 12.3-kg SNAP-9A was designed to provide continuous power for five years in space after one year of storage on Earth. The thermal inventory of 525 Wt (watts-thermal) was supplied by Pu-238 metal encapsulated in a heat source of six fuel capsules maintained in a segmented graphite heat-accumulator block. As shown in Fig. 5, the main body was a sealed cylindrical magnesium-thorium shell containing six heat-dissipating magnesium fins. The unit was 26.7 cm tall and had a fin-to-fin diameter (fin span) of 50.8 cm. The 70 pairs of series-connected Pb-Te thermoelectric couples were assembled in 35 modules of two couples each. Hot junction temperature was calculated at about 790 K at beginning of life. Some waste heat from the RTG was used to maintain electronic instruments in the satellite at a temperature near 293 K.

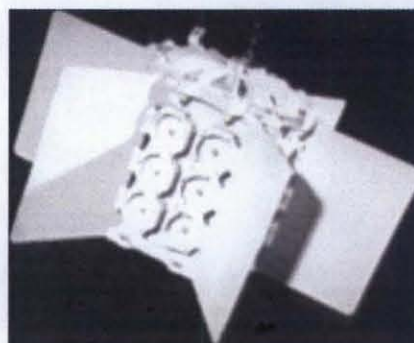


Figure 5. SNAP-9A RTG.

The SNAP-9A missions in 1963 also marked the beginning of a formal launch safety review process. Although the launches were for DOD systems, NASA was invited to participate in the reviews, which were made a responsibility of the joint AEC/NASA Space Nuclear Power Office. It was during these early launches that efficient and comprehensive review and approval procedures were developed. As early as January 1963, a model charter had been developed for an ad-hoc interagency review committee. Eventually this became known as the INSRP (Interagency Nuclear Safety Review Panel).

After a period of program delays, Transit 5BN-1 (Fig. 6) was launched successfully on September 28, 1963, followed by Transit 5BN-2 on

December 5, 1963. The third and last launch of the Transit 5BN-3 on April 21, 1964 was not as successful. A mission abort occurred after the payload had reached an altitude of 1,000 miles over the South Pole. Preliminary data indicated that the payload reentered the atmosphere over the Mozambique Channel at a steep angle. The Pu-238 fuel was designed to burn up into particles of about one millionth of an inch in diameter and disperse widely so as not to constitute a health hazard. Balloon samples taken over the next few years confirmed that the generator's fuel had indeed burned up as expected after the spacecraft failed to achieve orbit.



Figure 6. Transit 5BN-1.

Although there was a commitment to fly higher power NASA missions, the loss of Transit 5BN-3 led to concerns that the dispersion approach would be unsafe with larger inventories of fuel. Thus, the basic safety concept changed from designing for burn-up and dispersion to designing for intact reentry. By the time that new approach was integrated into an RTG-powered space mission, however, the mechanisms for interagency review and meticulous safety analysis were well established. Another change was the mobilization and decentralization of technical and administrative support so as to directly involve more of the laboratories and facilities of both AEC and NASA.

SNAP-19 – NIMBUS

Noting the success of the SNAP-3A, NASA requested the AEC to evaluate the feasibility of a 50-We RTG for an upcoming Nimbus weather satellite. Nimbus was the first U.S. weather satellite system to make day and night global temperature measurements at varying levels in the atmosphere, and all earlier satellites had been powered exclusively by solar cells. The request led to design and integration studies by the AEC and establishment of the SNAP-19 technology improvement program. With Nimbus, the SNAP program received its first opportunity to test and demonstrate an RTG on a NASA spacecraft.



Figure 7. Nimbus III. First NASA application of Radioisotope power.

The unit that eventually flew on Nimbus, SNAP-19B, was used as an auxiliary system. As shown in Fig. 7, each Nimbus satellite carried two SNAP-19B RTGs, which provided about 20% of the total power delivered to the spacecraft bus. This extra continuous power enabled full-time operation of a number of extremely important atmospheric-sounder experiments. Without the RTGs, the total delivered power would have fallen below the load line about two weeks into the mission. SNAP-19B was very similar to the SNAP-9A in terms of configuration and performance. It had a height of 26.7 cm and a fin span of 53.8 cm.

Its mass of 13.4-kg and BOM power level of 23.5 We yielded a specific power of 2.1 We/kg, the same as SNAP-9A.

The SNAP-19B was unique in its use of a new 645 Wt heat source, called the Intact Impact Heat Source (IIHS), in conjunction with an array of 90 Pb-Te thermocouples. The IIHS was designed to contain the fuel under normal operating conditions and to limit probability of contaminating the environment in the event of a launch abort or accident. In contrast to the SNAP-9A fuel design, the fuel form for SNAP-19B was changed from Plutonium metal to small Plutonium oxide (PuO₂) microspheres carried in capsules. Even in a worst-case scenario involving release and dispersal of the microspheres, the particles would be too big for inhalation. Additional safety design requirements included survival upon reentry and containment/immobilization of the fuel upon impact.

Launch of the Nimbus-B-1 took place on May 18, 1968. Unfortunately an error in setting a guidance gyro caused Nimbus-B-1 to veer off course. The Range Safety Officer sent the destruct signal 120 seconds into flight, thus blowing up the Agena stage at an altitude of 100,000 feet. The upper portion of the stage, including the satellite, fell into water depths of 300 to 600 feet about two to four miles to the north of San Miguel Island in the Santa Barbara Channel. The unit was found in September 1968, and was sent back to the Mound Laboratory for reuse. A second Nimbus satellite (Nimbus III or Nimbus-B-2) was launched and successfully placed into orbit on April 14, 1969. The SNAP-19B RTGs used here had slightly more fuel than their predecessors due to the use of less efficient but more stable thermoelectrics. The units operated fine for approximately 20,000 hours (2.5 years) until they experienced a sharp degradation in performance. This decline was attributed to the sublimation of thermoelectric material and loss of the hot junction bond due to internal cover gas depletion.

Nimbus was the first and last time RTGs were used in Earth orbit by NASA. At that time, solar

photovoltaics were still relatively new. With advancement in this area, NASA did not feel that RTGs were warranted for applications where solar cells could work. In addition with the more structured launch safety review process, it was much more cost effective to use solar cells whenever possible.

SNAP-19 – PIONEER AND VIKING

The successful demonstration of Nimbus III encouraged NASA to commit to use of SNAP-19 on the Pioneer and Viking missions, arguably NASA's most exciting science missions of the 1970's. The SNAP-19 design for these applications (Fig. 8), however, had to be modified. For Pioneer, this was driven by the need for a mission life of up to six years. Other modifications were required to deliver a higher power, and to withstand the unique environments of Mars and deep space. For Pioneer, the most significant modification was incorporation of TAGS/Sn-Te thermoelectric elements (thermocouple legs consisting of Tellurium, Antimony, Germanium, Silver and Tin), which increased efficiency, lifetime and power performance. The generator height was also increased to 28.2 cm, and the fin span was reduced to 50.8 cm. This yielded a power output of 40.3 We. The resultant specific power of 3.0 We/kg was nearly 50% higher than the Nimbus design.

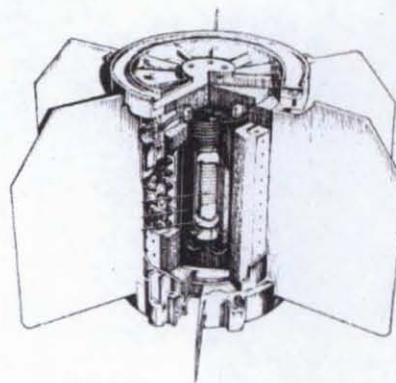


Figure 8. Pioneer SNAP-19.

Pioneers 10 and 11 were launched on 2 March 1972 and 6 April 1973, respectively. Pioneer 10

was the first spacecraft to travel through the asteroid belt and to make direct observations of Jupiter, which it encountered on 3 December 1973. According to some definitions, Pioneer 10 became the first artificial object to leave the solar system, on 13 June 1983. Pioneer 11 also encountered Jupiter, and in addition to conducting measurements, the spacecraft used a Jupiter gravity assist maneuver to alter its trajectory toward Saturn. After nearly five years, Pioneer 11 encountered Saturn in September 1979, and provided the first local measurements of this planet and its rings before it followed an escape trajectory out of the solar system.

The most noteworthy aspect of the SNAP-19s used for these missions (Fig. 9) was the extremely long time the units continued to operate past their primary tasks and baseline mission lifetimes. Both of these spacecraft continued to transmit data far beyond the orbit of Pluto, and more than fulfilled the original expectations for their operation.

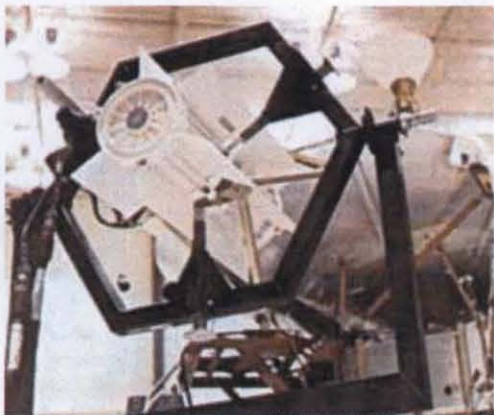


Figure 9. SNAP-19s installed on Pioneer.

The modifications for Viking went further to ensure the RTG, which is shown in Fig. 10, could withstand high temperature sterilization procedures in support of the planetary quarantine protocol, storage during the flight to Mars, and the severe temperature extremes of the Martian surface. The landers were sterilized before launch to prevent contamination of Mars by terrestrial microorganisms. Among the modifications to the Pioneer SNAP-19 design

was the addition of a dome reservoir to allow a controlled interchange of gases. This minimized heat source operating temperatures prior to launch, while maximizing electrical power output at the end of mission. This resulted in the Viking SNAP-19 being slightly larger and more massive than the version used on Pioneer (40.4 cm tall, 58.7 cm fin span, 15.2 kg mass, and 2.8 We/kg specific power).



Figure 10. Viking SNAP-19.

Vikings 1 and 2 were identical spacecraft (Fig. 11), each of which consisted of a Lander, with a robot laboratory to study the nature of the surface, and an Orbiter, designed to serve as a communications relay to Earth. Each Lander carried two SNAP-19s. Viking 1 was launched on 20 August 1975 from Cape Canaveral. It reached Mars orbit on 19 June 1976, and reached the surface on 20 July 1976 on the western slope of Chryse Planitia. Viking 2 was launched on 9 September 1975, and it touched down on the surface on 3 September 1976 at Utopia Planitia.

The Viking missions were a complete success. In addition to characterization of the Mars environment, the Landers provided over 4,500 high quality images of the Martian landscape. All four SNAP-19 RTGs easily met their

original 90-day requirement, thus allowing the Viking Landers to operate for years until other system failures led to a loss of data. When the last data were received from Viking 1 in November 1982, it had been estimated that the RTGs were capable of providing sufficient power for operation until 1994, 18 years beyond the original mission requirement.



Figure 11. Viking Lander.

TRANSIT-RTG (TRIAD)

Interest in RTGs for Navy navigation satellites continued after the earlier Transit missions. The next DOD application of RTGs took place with TRIAD, the first in a series of three experimental spacecraft designed to test and demonstrate improvements to the NNS. These were all developed under the Transit Improvement Program (TIP), which was established in 1969 to provide a radiation-hardened satellite that could maintain its correct position for over five days without an update from the ground.

The Transit-RTG was designed to serve as the primary power source for the satellite, with auxiliary power provided by four solar-cell panels and a 6 Amp-hr Nickel Cadmium battery. The 13.6-kg Transit RTG was modular in design, and was 36.3 cm tall and approximately 61 cm across its lower attachment (Fig. 12). The RTG delivered 35.6 We at BOM, and used a SNAP-19 heat source. The Transit RTG was the first to employ radiative heat coupling between its heat source and thermocouples, although this was accomplished at some loss in efficiency.

The 12-sided converter used Pb-Te thermoelectric "Isotec" panels operated at a low hot-side temperature of 673 K in a vacuum, thus eliminating the need for hermetic sealing and a cover gas to inhibit thermoelectric material sublimation. Each of the 12 Isotec panels contained 36 Pb-Te thermocouples arranged in a series-parallel matrix with four couples in a row in webbed, magnesium-thorium corner posts with Teflon insulators.

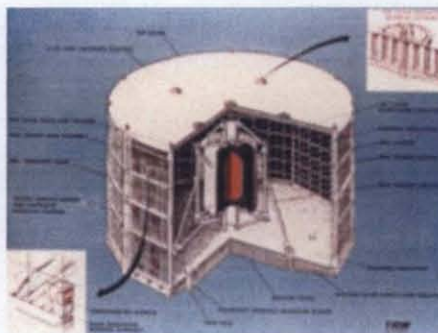


Figure 12. Cutaway of TRANSIT RTG.

The TRIAD satellite (Fig. 13) was launched on September 2, 1972 from Vandenberg Air Force Base into a 700 to 800 km orbit. The short-term objectives of the TRIAD satellite were successfully demonstrated, including a checkout of RTG performance. However, a telemetry-converter failure onboard the spacecraft caused a loss of telemetry data about a month into the mission. This, in turn, precluded measuring the Transit-RTG power level versus time. However, the TRIAD satellite continued to operate normally for some time and provided magnetometer data using power from the RTG.

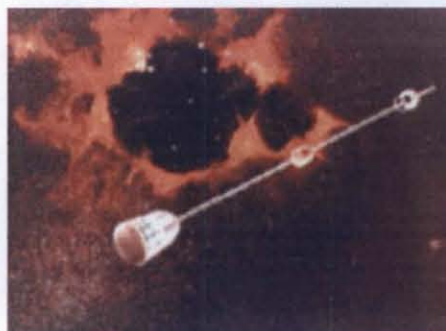


Figure 13. Transit TRIAD Satellite.

SNAP-27

During the 1960's, scientists involved with the Apollo program envisioned placing scientific stations on the lunar surface that could transmit data long after the astronauts returned to Earth. They were interested in many measurements, including fluctuations in solar and terrestrial magnetic fields, changes in the low concentrations of gas in the lunar atmosphere, and internal structure and composition of the Moon. These ideas culminated in the Apollo Lunar Surface Experiment Package (ALSEP), led by Bendix Aerospace Systems Division. The requirement for multi-year operation and survival over many 14-day lunar day/night cycles favored use of RPS as the primary power source for ALSEP. Although NASA looked at using the new SNAP-19 for this application, ALSEP power requirements would have necessitated multiple SNAP-19s per mission and considerable effort in deployment by the Apollo crew. Instead, the AEC was requested to develop a new RTG, called the SNAP-27 (Fig. 14).

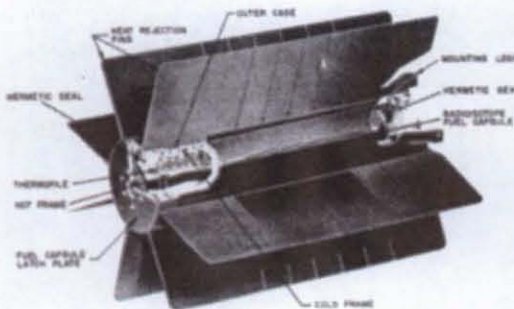


Figure 14. SNAP-27.

Special features were added to the SNAP-27 to ensure safety and facilitate its deployment by the astronauts on the lunar surface (Fig. 15). Chief of these was the separate storage of the heat source in a graphite lunar module fuel cask (GLFC) carried on the Lunar Excursion Module (LEM). The GLFC enclosed the fuel module during the trip to the Moon, and provided thermal and blast protection in the event of a launch pad explosion, launch abort, or reentry into the Earth's atmosphere and ground impact.



Figure 15. Use of SNAP-27 on the Moon. Alan Bean deploying SNAP-27 on Apollo 12.

Thermal energy from the fuel capsule was transferred to the generator hot frame by radiative coupling. When deployed on the lunar surface, the fuel capsule operated at 1005 K, while the Inconel 102 alloy hot frame was 880 K. The hot junction temperature ranged between 855 K and 865 K, reflecting an overall temperature drop of 15 to 25 K. On the Moon's surface, where temperatures can vary from 350 K during the lunar day to a frigid 100 K during the lunar night, the generator's cold side temperature operated at 545 K. Pb-Te served as the TE material and the couples were assembled in a series-parallel electrical arrangement to prevent string loss. The power capability for the 19.6 kg RTG was at least 63.5 We at 16 Vdc for one year after lunar emplacement. The converter was 46 cm tall and 40 cm wide across the fins. The specific power was greater than 3.2 We/kg, which represented a 10% increase over the Pioneer SNAP-19.

The five units deployed on the lunar surface from 1969 to 1972 operated flawlessly. Telemetry data from their operation stopped in 1977 when the ALSEPs were intentionally shutdown. Until then, their degradation in performance matched all predictions.

The only potential problem with SNAP-27 occurred with the Apollo-13 mission, when there was concern over the SNAP-27 onboard the LEM reentering the Earth's atmosphere. Normal reentry trajectory and velocity were achieved as had been assumed in the pre-launch

review accounting for this type of event. The detached LEM broke up on reentry, as anticipated, while the graphite-encased Pu-238 fuel cask survived the breakup and went down intact in the 20,000 foot deep Tonga Trench, as had been projected for an aborted mission in a lifeboat mode situation.

MULTIHUNDRED WATT (MHW) RTG

In anticipation that NASA would require higher power RTGs for increasingly ambitious robotic science missions in the future, the AEC contracted with GE to conduct a technology readiness effort for an RTG with a power capability in the range of several hundred We. Development of this unit, which later became known as the MHW-RTG, was initiated in anticipation that NASA would conduct a Grand Tour mission of the planets. This was realized with the Voyager missions launched in 1977. At the same time, the DOD also had a requirement for a hundred watt-class RTG, and requested the AEC to develop such a unit for two communication satellite technology demonstrators built by MIT's Lincoln Laboratory. These Lincoln Experimental Satellites (LES) 8 and 9 were launched together in 1976.

The MHW-RTG represented a dramatic advancement in RTG technology with its use of Silicon-Germanium (Si-Ge) thermoelectric materials and a much higher temperature heat source. The higher hot-side temperature translated to greater power conversion efficiency, and, most importantly, enabled radiation of waste heat at higher temperatures. This allowed a substantial reduction in radiator size and a significant increase in specific power over its Pb-Te/TAGS predecessors. Thermocouples made of Si-Ge can operate over a broad temperature range, up to 1,000 C, much higher than telluride-based thermocouples. Plus with a Silicon Nitride coating, Si-Ge does not sublimate significantly, and allows operation without a cover gas in the vacuum of space.

The MHW-RTG had a length of 58.3 cm and fin span of 39.7 cm (Fig. 16). The converter housing consisted of a beryllium outer shell and

pressure domes, with unicouples attached directly to the outer shell. Like SNAP-19, the heat source was designed to immobilize and contain the fuel in the event of a launch abort. It was shaped as a right circular cylinder, and contained twenty-four 3.7-cm diameter fuel containers of PuO₂ (Fig. 17). Each fuel container produced 100 Wt, and had a metallic iridium shell containing the PuO₂ fuel and a graphite impact shell, which provided the primary resistance to mechanical impact loads.



Figure 16. MHW-RTG. Cutaway view on left. Installation in test fixture on right.

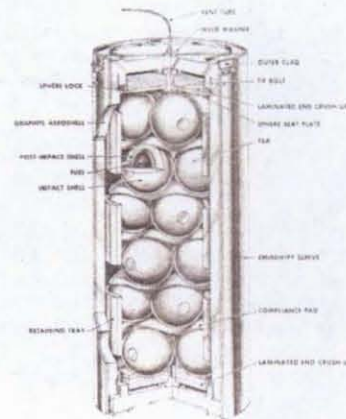


Figure 17. MWH-RTG heat source.

The power converter contained 312 Si-Ge unicouples arranged in 24 circumferential rows with each row containing 13 couples. The MHW-RTGs flown on LES 8 and 9 had an average mass of 39.7 kg, BOM power of 154 We, and specific power of 3.9 We/kg. The six RTGs for Voyager were modified to yield a higher specific power of 4.2 We/kg, based on an

average mass of 37.7 kg and BOM power of 158 We.

LES 8 and 9 were launched together aboard a Titan IIIC launch vehicle on 15 March 1976, and were deployed to a geosynchronous orbit altitude of approximately 36,000 km (Fig. 18). Each LES used two MHW generators (Fig. 16), which provided primary power for all spacecraft systems. The MHW-RTGs more than met the mission goals for lifetime. They also enabled the demonstration of improved methods for maintaining voice or digital data circuits among widely separated mobile communications terminals. Although its RTGs were still providing usable electric power, LES-8 was turned off on 2 June 2004 due to control difficulties. LES-9, however, continues to operate over 30 years after launch.



Figure 18. LES-8 and 9 in orbit.

The Voyager 2 spacecraft launched on 20 August 1977 aboard a Titan-Centaur launch vehicle (Fig. 19). Each Voyager probe carried three MHW generators. Voyager 1 followed on 5 September 5, also aboard a Titan-Centaur rocket. The Voyager spacecraft explored the most territory of any mission in history, including all the giant planets of the outer solar system, 48 of their moons, and the unique system of rings and magnetic fields those planets possess. The final planetary encounter was conducted by Voyager 2, which had its closest approach with Neptune on 25 August 1989. Although Pioneers 10 and 11 were the first spacecraft to fly beyond all the planets, Voyager



Figure 19. Voyager spacecraft.

1 passed Pioneer 10 to become the most distant human-made object in space. As of 11 August 2007, the power generated by the spacecraft had dropped to about 60% of the power at launch. This is better than the pre-launch predictions based on a conservative thermocouple degradation model. As the electrical power decreases, spacecraft loads must be turned off, eliminating some spacecraft capabilities.

GENERAL PURPOSE HEAT SOURCE (GPHS) RTG

Following the successful launches of the Voyager spacecraft, DOE turned its focus on developing a new selenide-based RTG for NASA's planned International Solar Polar Mission (ISPM) and the Jupiter Orbiter Probe, which later became the Ulysses and Galileo missions, respectively. Nuclear power was required for these missions, since they would both operate in the vicinity of Jupiter with its low solar energy flux, cold temperatures and intense radiation environment. Both missions were to be launched in the mid-1980s aboard the then under development U.S. Space Shuttle.

Upon determining that selenide thermoelectrics would not be suitable for long-duration missions, DOE went back to Si-Ge technology and considered modifying flight spares of the MHW-RTG for use on Galileo. However, the joint NASA-ESA ISPM team requested a new, larger, more powerful RTG for their spacecraft. When the Galileo project saw the benefits of the planned ISPM RTG they requested two for the

Galileo spacecraft. As a result the ISPM RTG was renamed the GPHS-RTG.

The GPHS-RTG used the same Si-Ge alloy unicouples used in the MHW-RTG. Because production of the unicouples had been stopped after the Voyager program there was a need to restart production. However, the rest of the design was very different. For one, the converter housing was made of a less expensive and more manufacturable Aluminum 2219-T6 alloy, instead of the beryllium used in the MHW-RTG. Another big difference was the heat source, which employed an assembly of newly developed General Purpose Heat Source (GPHS) modules. This modular approach to heat source design opened the door for developing RTGs of different sizes and powers in the future, but it required an extensive development and qualification program to replace the fuel sphere assemblies used in the MHW-RTG. Finally, DOE had decided to move the RTG assembly and testing work from its RTG contractors to DOE's Mound Laboratory, which necessitated a rapid buildup of the infrastructure at a new location.

The GPHS-RTG, shown in Fig. 20, was composed of two main elements: a linear stack of 18 GPHS modules and the converter. As shown in Fig. 21, each GPHS module contains four fuel clads that produce up to 250 Wt per module, with fresh PuO₂ fuel. Each fuel clad consists of a PuO₂ fuel pellet encased in an iridium shell that contains the fuel. Two of these fueled clads are combined in a Graphite Impact Shell (GIS) and are separated by a floating graphite membrane that provides resistance to mechanical impact loads. The GPHS assembly is completed by insertion of two GISs into the aeroshell, which serves as an ablator and the main structural element. All of these elements contribute to making each GPHS module completely autonomous in providing for safe containment and immobilization of fuel in the event of launch abort or reentry into the atmosphere.

The converter surrounds the heat source stack, and consists of 572 radiatively-coupled Si-Ge unicouples, which operate at a hot side

temperature of 1,275 K and a cold side/heat rejection temperature of 575 K. The outer case of the RTG provides the main support for the converter and heat source assembly, which is axially preloaded to withstand the mechanical stress environments of launch and to avoid separation of GPHS modules. The converter also provides axial and mid-span heat source supports, a multifoil insulation packet and a gas management system. The latter provides an inert gas environment for partial power operation on the launch pad, and also protects the multifoil and refractory materials during storage and ground operations.

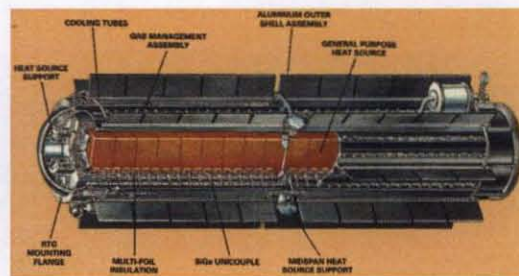


Figure 20. GPHS-RTG.

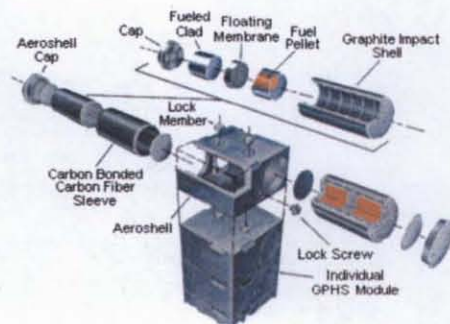


Figure 21. GPHS module assembly.

The complete GPHS-RTG has an overall length of 114 cm and a fin span of 42.2 cm. Its mass of 55.9 kg and BOM power level of up to 300 We provides a specific power of 5.1 to 5.3 We/kg, far greater than any of its predecessors.

The Galileo spacecraft (Fig. 22) was launched on 18 October 1989 on the Space Shuttle, after a 3.5-year delay caused by the Challenger accident. Forced to take a long, circuitous trajectory involving Earth and Venus gravity



Figure 22. Galileo spacecraft. *Pre-launch assembly on left. Artist concept of spacecraft in orbit around Jupiter on right.*

assists, Galileo arrived at Jupiter in December 1995. The Orbiter spacecraft investigated the Jupiter and its Galilean satellites from space, while the Galileo Probe, which was battery-powered but kept warm via a number of small radioisotope heater units, entered Jupiter's atmosphere on 7 December 1995. Both GPHS-RTGs met their end of mission (EOM) power requirements, thus allowing NASA to extend the Galileo mission three times. However on 21 September 2003, after eight years of service in orbit about Jupiter, the mission was terminated by intentionally forcing the orbiter to burn up in Jupiter's atmosphere. This was done to avoid any chance of contaminating local moons, especially Europa, with micro-organisms from Earth.

The Ulysses (Fig. 23) was launched nearly a year later by the Space Shuttle on 6 October 1990. The mission included a Jupiter gravity assist performed on 8 February 1992 in order to place the spacecraft in a trajectory over the polar regions of the Sun. The single GPHS-RTG performed flawlessly and exceeded its design requirement. As a result, the Ulysses mission was extended beyond its original planned lifetime goal, thus allowing it to take measurements over the Sun's poles for the third time in 2007 and 2008. However after it became clear that the power output from the RTG would be insufficient to operate science instruments and keep onboard hydrazine propellant from freezing, the decision was made to end the mission on 1 July 2008.

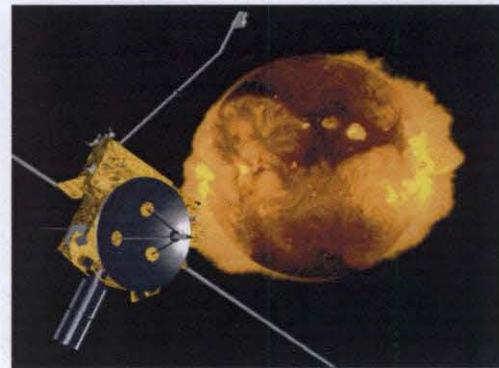


Figure 23. Ulysses spacecraft. *Installation and checkout of RTG on left. Artist concept of vehicle on right.*

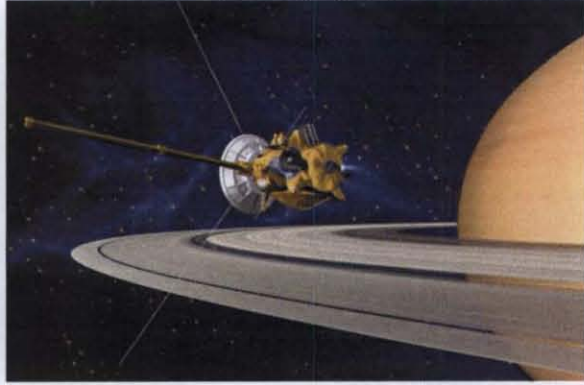


Figure 24. Cassini spacecraft. *Pre-launch checkout of RTG on left. Artist concept of vehicle on right.*

The third mission to use the GPHS-RTG was Cassini (Fig. 24), which was launched, along with the ESA-built Huygens Titan Probe, on 15 October 1997 aboard a Titan IV/Centaur launch vehicle. Cassini achieved Saturn orbit insertion on 1 July 2004 after a 6.7-year transit involving gravity assists about Venus and Earth. The Huygens probe, which carried the same radioisotope heater units as Galileo, successfully landed on Titan and provided the first close-up views of that enigmatic world. Because of mission complexity, Cassini needed more power than used on previous flagship-class missions. The three GPHS-RTGs that were used have so far operated flawlessly and have exceeded their expected power output. The mission has been approved for an extended mission in 2008, and could operate well into next decade.

The most recent mission to use a GPHS-RTG is

the New Horizons mission to Pluto (Fig. 25), which was launched on 19 January 2006 aboard an Atlas V 551. The spacecraft is currently on a 9.5-year transit to Pluto and Charon. At encounter, which is expected in July 2015, New Horizons will characterize and map the surfaces of Pluto and Charon and their atmospheres. From 2016 to 2020, the spacecraft will continue to conduct encounters with one or two Kuiper Belt Objects. So far, it is anticipated that the RTG will exceed its power and lifetime requirements.

MULTI-MISSION RTG (MMRTG)

Although the GPHS-RTG served well on Ulysses and Galileo and continues to meet requirements for Cassini and New Horizons, it is not suitable for future missions on Mars and other planetary bodies with atmospheres. The



Figure 25. New Horizons spacecraft. *Pre-launch integration with spacecraft on left. Artist concept of New Horizons flyby of Pluto and Charon on right.*

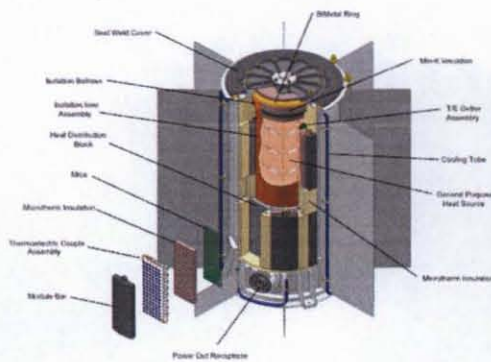


Figure 26. Multi-Mission RTG (MMRTG). *Cutaway schematic of power unit on left. MMRTG Qualification Unit undergoing tests on right.*

GPHS-RTG was only designed to function effectively in a vacuum environment. Furthermore, its relatively large size and power level limit its modularity and ease of integration on future small to mid-size spacecraft.

DOE and NASA are currently developing a new generation of RPS generators that could be used for a variety of space missions. One is the Multi-Mission RTG (MMRTG), which is being designed to operate on planetary bodies with atmospheres, such as Mars, as well as in the vacuum of space. The MMRTG's smaller size of about 120 We is more modular in design and flexible in meeting the needs of a broader range of different missions as it generates electrical power in smaller increments. The design goals for the MMRTG include ensuring a high degree of safety and reliability, optimizing power levels over a minimum lifetime of 14 years, and minimizing mass.

The MMRTG (Fig. 26) is designed to use a heat source consisting of eight Step 2 GPHS modules. These Step 2 modules have additional material in the GPHS aeroshell that improves structural integrity and performance. Although the Pb-Te/TAGS thermoelectric materials are the same as those used on SNAP-19, and represent a thoroughly flight proven technology, the physical dimensions and material changes to improve performance have resulted in different degradation compared to the SNAP-19. The MMRTG generator has a fin span of 64 cm, a length of 66 cm, and a mass of about 43 kg. Its

BOM power level of approximately 120 We yields a specific power of ~ 3 We/kg, which is comparable to the SNAP-19. However, the purpose in pursuing this unit is really to minimize development risk, while providing an RPS capable of operating in different mission environments.

The MMRTG is being developed to serve as the primary power source on the Mars Science Laboratory (MSL), a concept of which is shown in Fig. 27. This mission is currently planned for launch in 2011, and is anticipated to land on Mars in 2012.



Figure 27. Mars Science Laboratory.

MSL is considerably larger than the Mars Exploration Rovers that landed on the planet in 2004. It will carry more advanced scientific instruments than any other Mars mission to date, including analysis of samples scooped up from the soil and drilled powders from rocks. It will also investigate the past and present ability of

Mars to support life. The MSL rover will use power from an MMRTG to supply heat and electricity for its components and science instruments. A coolant loop and heat exchanger coupled with the MMRTG radiators will transport waste heat to the electronics, thus extending operation of the rover into the Martian night and winter season. The goal is to operate for at least one Martian year (i.e., two Earth years) over a wide range of possible landing sites.

The MMRTG could be used on a number of other potential missions in the future. One exciting prospect is to use the MMRTG as the principal electrical power and heat source for a Titan aerobot/balloon mission (Fig. 28). In this scenario, the considerable waste heat produced by the MMRTG would be used to heat a gas and generate buoyancy for a balloon carrying a long-lived payload, in addition to providing electrical power to onboard instruments.

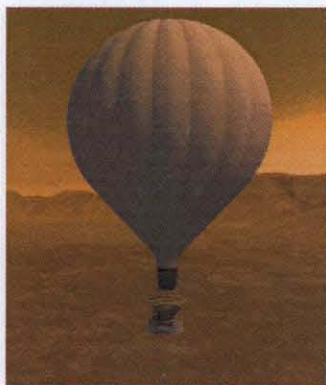


Figure 28. Titan Aerobot.

ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG)

When the potential of radioisotope power became apparent in the 1950s, the original focus was on development of dynamic power conversion systems. Most of these activities concentrated on applying the high efficiencies achievable with Brayton and Rankine cycles, in expectation that systems would evolve to larger power levels in the future.

Although thermoelectric technology supplanted this approach and became the dominant power conversion option for every RPS flown in space, work on Dynamic Isotope Power Systems (DIPS) continued at various times throughout the intervening decades. The principal focus of these efforts was on eventual development of power systems capable of producing up to tens of kilowatts of power. These higher power technologies would be used in conjunction with the ambitious crewed missions anticipated in the future. The studies of DIPS pointed to its excellent suitability for lunar and planetary surface exploration, particularly surface rovers, remote science stations and backup power supplies to central base power.

Interest in DIPS was particularly high during the Space Exploration Initiative (SEI) of the early-1990s. However with the demise of that effort in 1992, the focus shifted to determine how dynamic power conversion could benefit radioisotope power systems in the multi-hundred watt range. During the 1990s, several advanced dynamic and static conversion technologies were researched and evaluated. Several technologies that had appeared promising initially proved to be ill-suited for the unique demands of deep space missions. In the end, it became apparent that the free-piston Stirling engine offered the best hope of advancing the efficiency of future generators, while offering lifetimes up to a decade or two. Unlike previous DIPS designs, which were based on turbomachinery-based conversion technologies (e.g. Brayton), small Stirling DIPS could be advantageously scaled down to multihundred-watt unit size while preserving size and mass competitiveness with RTGs.

In 2002, NASA and DOE began a Stirling Radioisotope Generator (SRG) project focused on evaluating and demonstrating a unit for flight development. The work was initiated ostensibly to provide a back-up RPS for the MSL mission. The unit used Stirling converters built and tested under a technology development effort funded by DOE. Although the SRG could achieve a four-fold reduction in fuel requirements for the same power, the final system specific power of

the unit was only slightly better than the MMRTG.

In less than two years, it became apparent that the MMRTG would be selected by NASA's Mars program, so that the rover could make use of the significant waste heat produced by that unit. Finally, a small business technology project initiated in the early 2000s with Sunpower Technologies in Athens, Ohio, indicated that converters with much better mass performance could be developed and substituted into an SRG-based design. Such a unit could potentially achieve specific powers of about 7 We/kg. With the advancement in Stirling generator heater head materials and with improved temperature margin and higher temperature operation, the unit could be optimized to achieve specific powers greater than 8 We/kg, more than three times greater than the MMRTG.

In 2005, the decision was made to redirect efforts toward development of an Advanced SRG (ASRG) technology demonstration Engineering Unit (EU). The effort drew upon the work that had gone on previously with the controller, housing and insulation systems for the SRG, but incorporated use of the higher specific power Sunpower generators. In addition to high specific power, the ASRG would likely achieve an efficiency over 30%. This is four to five times higher than that from a GPHS-RTG, and is particularly important for conserving the very limited worldwide supply of Pu-238 fuel.

If the decision is made to proceed to flight, the ASRG will likely exceed 8 We/kg with incorporation of more advanced materials to improve performance capability of the Stirling convertor with a higher temperature heater head. In addition to providing significant mass improvements for RPS-based missions, the ASRG is being designed for multi-mission use in environments with and without atmospheres for both deep space and the Mars atmosphere.

The ASRG, which is shown in Fig. 29, is being developed under the joint sponsorship of the U.S. Department of Energy (DOE) and NASA.

The prime contractor is Lockheed-Martin Corporation of Valley Forge, PA, with Sunpower, Inc. of Athens, Ohio as the main subcontractor. NASA Glenn Research Center (GRC) is supporting the technology development, along with evaluation and testing of the Stirling convertors used in the device.

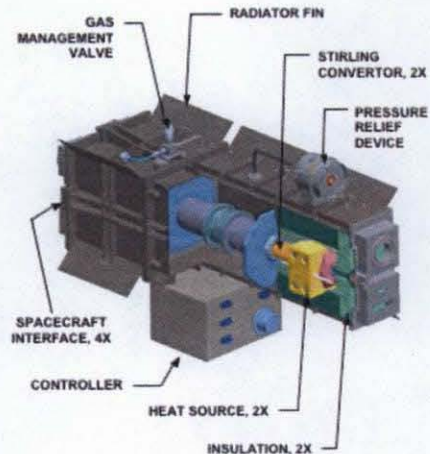


Figure 29. Advanced Stirling Radioisotope Generator (ASRG).

Activities were focused on developing and testing the ASRG-EU in thermal and vibrational environments that closely approximate qualification-level tests (Fig. 30).

The ASRG-EU uses two axially-opposed Advanced Stirling Convertors (ASCs), operating at a hot-end temperature of 650 deg C, producing about 140 We. Sunpower is developing the ASC under a 2002 NASA Research Announcement (NRA) with GRC. The low mass of the ASC is key to the ASRG's high overall system specific power. With a specific power of 90 We/kg, the ASC represents a six-fold improvement over state of the art. These convertors will be provided to Lockheed-Martin as government-furnished equipment.

Sunpower and GRC are developing a higher-temperature ASC with a MarM-247 alloy heater head and capability of operating up to an 850 C hot-end temperature. This has the potential to increase the ASRG specific power to ~8.4 We/kg and provides increased margin with the



Figure 30. ASRG Engineering Unit.

MarM-247 material at 850 C, compared to the current Inconel 718 material which is limited to 650 C. Continuous around-the-clock testing of the ASCs was initiated in January 2007, and these units have operated without any performance degradation since that time. The Inconel-based EU ASCs were shipped to Lockheed-Martin in October 2007, where they were integrated into the ASRG-EU.

The ASRG has achieved a TRL 6 (system demonstration in a relevant environment) with operation at qualification level thermal and dynamic environments. Tests on the ASRG-EU were completed in June 2008 at the Lockheed-Martin Space System Company in King of Prussia, PA. These evaluations included thermal balance, thermal performance, mechanical disturbance, sine transient, random vibration, simulated pyrotechnic shock and electromagnetic interference and magnetic field emission tests. Over 1000 hours of successful

EU operating time with numerous startup and shutdown cycles were accumulated during the testing at Lockheed-Martin. The ASRG-EU is now undergoing extended/multi-year duration testing at NASA GRC, and has achieved over 5,000 hours of successful operation. The next step of the ASRG Project is for the flight qualification of a fueled generator.

Ongoing ASRG-EU tests use electrical resistance heaters that simulate the heating characteristics of the actual GPHS module. Avoiding use of nuclear materials during early phases of development greatly facilitates testing and evaluation of the ASRG subsystems.

OTHER POTENTIAL APPLICATIONS

MMRTG and ASRG should satisfy most RPS mission requirements well beyond 2010, particularly for those applications involving several hundred watts of power. However, there will likely be a demand for additional types of units in the future. One potential need identified by the space science community is for small RPS units ranging in power from ~10 milliwatts (mW_e) to ~20 W_e . These so-called 'milliwatt' and 'multiwatt-class' power supplies could extend the capability of small, low cost missions supported through NASA's small to mid-size programs, and augment human missions involving deployment of monitoring stations and autonomous devices. Although flight-qualified systems in this size range do not presently exist, their promise has led NASA and DOE to consider developing at least one type of unit for missions that would fly by the early part of the next decade. Smaller multiwatt units will benefit from use of the GPHS fuel module.

Nuclear Electric Propulsion (NEP) has been studied since the early 1960's because of its potential for future high-energy space missions. Almost all NEP assessments to date have assumed fission as the nuclear energy source. Unlike solar-powered electric propulsion (SEP) systems, NEP operation is generally independent of distance and orientation with respect to the Sun. Over the last decade, several studies have pointed to Radioisotope Power Systems (RPS), instead of reactor power sources, as the best way

of implementing NEP. Radioisotope-based NEP, also known as Radioisotope Electric Propulsion (REP), has been evaluated before, but has not been seriously considered for flight due to the low specific power range of traditional RPS (e.g., 3 to 5 We/kg). However, the prospects for REP have improved substantially with the advent of the ASRG and its likely improvement in specific power.

In this capacity, REP would principally be used as an interplanetary stage for long-duration deceleration and acceleration in deep space. At remote destinations, REP would perform deceleration, orbit insertion and maneuvers around outer planets and other planetary bodies. REP-based spacecraft could also provide ample power at destination for sophisticated science instruments and communications, but it would fit better within the relatively modest kilowatt-scale power requirements of the space science community.

CONCLUSION

Radioisotope power systems will continue to play an important role in NASA's exploration efforts. These systems also have the potential for use in a variety of new applications, which would benefit from the technology's versatility in a broad range of space and planetary environments. In the near-term, the MMRTG will expand the capability for conducting science on the surface of Mars. The ASRG will enable even higher performance missions. These units would also enable more ambitious exploration of other planetary surfaces and provide a reliable means of powering spacecraft in deep space. Current activities would also allow the potential development of new systems that could expand application of RPS to smaller science missions. The key to successful implementation of the RPS program is maintaining close ties with potential users and the science community at large. With these advancements, radioisotope power systems and technology will offer tremendous benefits for future exploration endeavors.

ACKNOWLEDGEMENTS

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Radioisotope Power: A Key Technology for Deep Space Exploration

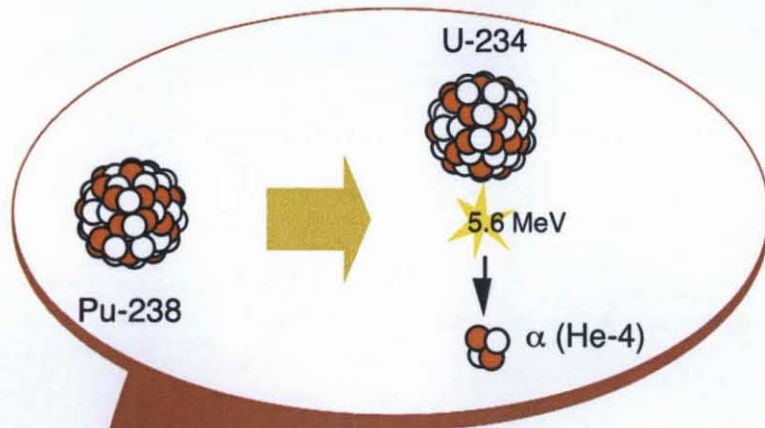
*IAC 2009
12 Oct - 16 Oct 2009*

*George Schmidt and Tom Sutliff
NASA Glenn Research Center*

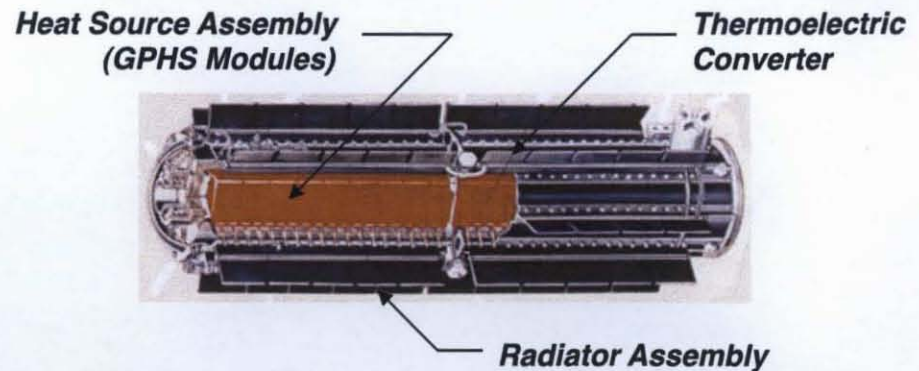
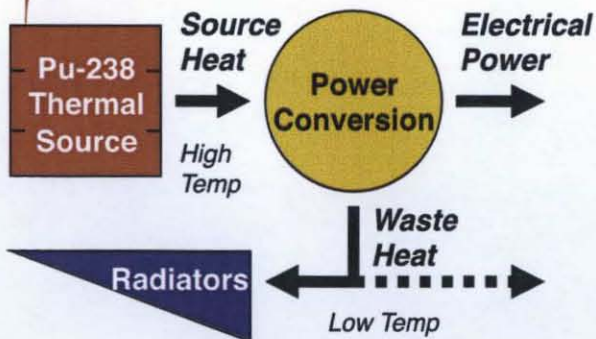
*Leonard Dudzinski
NASA Headquarters*



Radioisotope Power Systems (RPS)



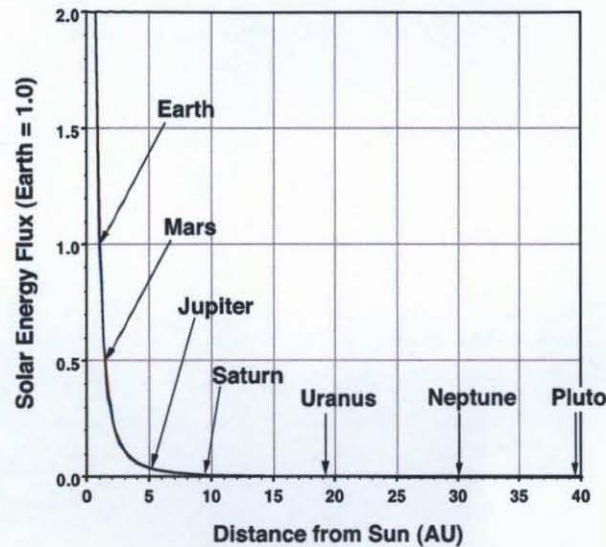
- **Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
 - 87.7-year half-life
- **Small portion of heat energy (6%-35%) converted to electricity via passive or dynamic processes**
 - Thermoelectric (existing & under development)
 - Stirling (under development)
 - Brayton, TPV, etc. (future candidates)
- **Waste heat rejected through radiators – portion can be used for thermal control of spacecraft subsystems**



GPHS-Radioisotope Thermoelectric Generator (RTG)



Benefits of RPS

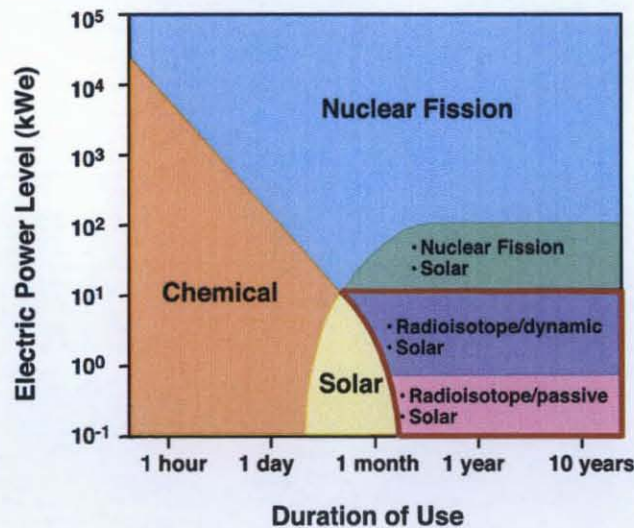


Unique features of nuclear power

- Steady power independent of distance and orientation w/respect to Sun;
- Operation in thick atmospheres and shadowed areas;
- Operation in extreme and high-radiation environments (e.g., Venus, Titan, Jovian space);
- Long duration operation (≥ 10 years);

Added advantages of:

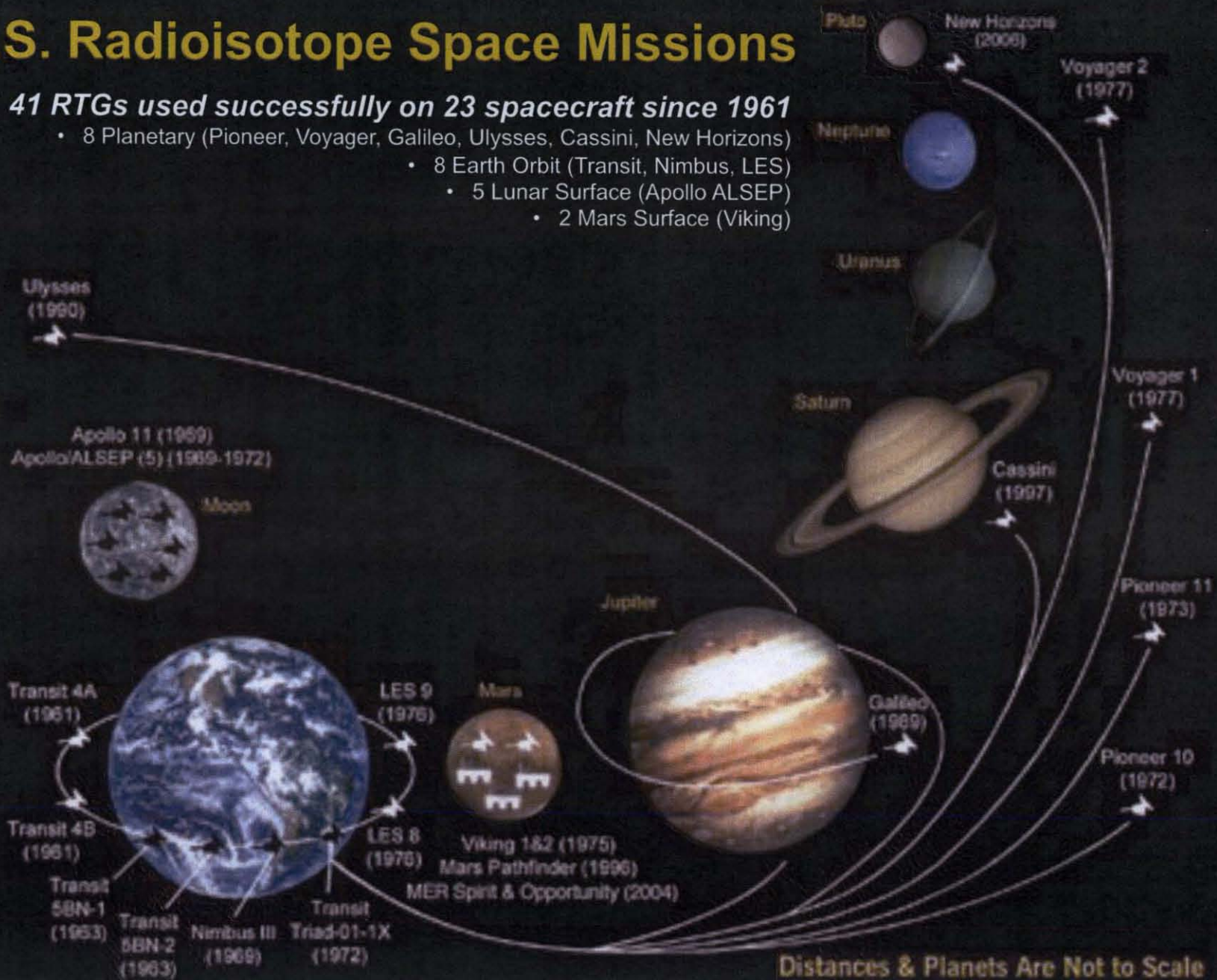
- Scalability to very low power levels ($\leq 1-10$ kWe);
- Use in close proximity to crew (low penetrating radiation);
- Readily available excess heat;
- Compactness and ease of transport;
- Enables Radioisotope Electric Propulsion (REP) – benefits of NEP with low power spacecraft (1-5 kWe)
 - High-performance electric propulsion in deep space
 - Specific powers comparable to near-term reactor-based NEP
 - Much smaller spacecraft



U.S. Radioisotope Space Missions

41 RTGs used successfully on 23 spacecraft since 1961

- 8 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
- 8 Earth Orbit (Transit, Nimbus, LES)
- 5 Lunar Surface (Apollo ALSEP)
- 2 Mars Surface (Viking)



Distances & Planets Are Not to Scale



Early Days

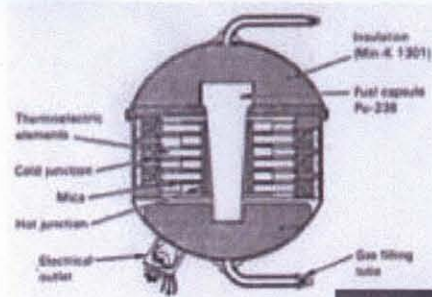
- Original impetus was national security surveillance satellites. Potential for RPS identified by North American Aviation and RAND in late-1940's.
- In early-1950's, DOD requested AEC to conduct studies and technology work on space nuclear power. AEC broadened consideration to radioisotopes. Origin of Systems for Nuclear Auxilliary Power (SNAP).
- Early SNAP efforts focused on dynamic energy conversion. SNAP-1 was Ce-144 powered Mercury Rankine generator.
- Thermoelectric energy conversion invented at AEC's Mound Laboratory by Kenneth Jordan and John Birden in 1954.
- SNAP-3 project developed thermoelectric-based device using Polonium-210 fuel.
- President Eisenhower used SNAP-3 to advocate expanded use of space nuclear power, particularly for NASA. Becomes marketing centerpiece of "Atoms for Peace."



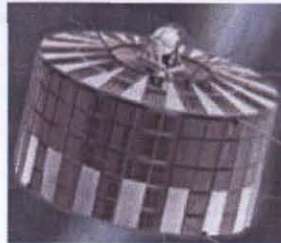
Oval Office Presentation of SNAP-3 in January 1959



Early Flight Units



SNAP-3B RTG



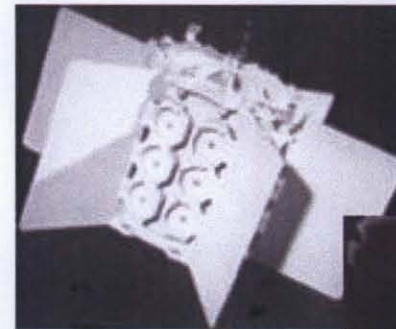
Transit-4A Satellite

SNAP-3B

- Supplemental power source for Transit 4A and 4B navigational satellites
 - Launched in June and Nov 1961 to 1,100 km altitude
 - RTG powered crystal oscillator and other sensitive electronic components
- Features:
 - Pu-238 metal fuel and Pb-Te thermoelectrics
 - 2.7 We BOM, 2.1 kg, **1.3 We/kg specific power**
 - 5-year design lifetime: 4A and 4B RTGs operated for 9 and >15 years, respectively

SNAP-9A

- Primary power source on Transit 5BN-1 and 5BN-2 navigational satellites
 - Launched in Sept and Dec 1963
- Features:
 - SNAP-3B fuel form and thermoelectrics
 - 25 We BOM, 12.3 kg, **2.0 We/kg specific power**
 - 6-year design lifetime: 5BN-1 failed in 9 months due to electrical problems, 5BN-2 RTG operated >6 years



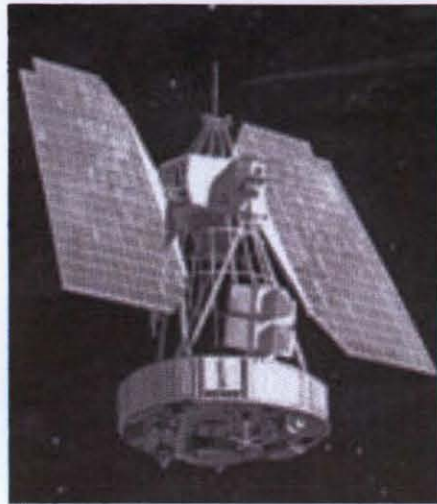
SNAP-9A



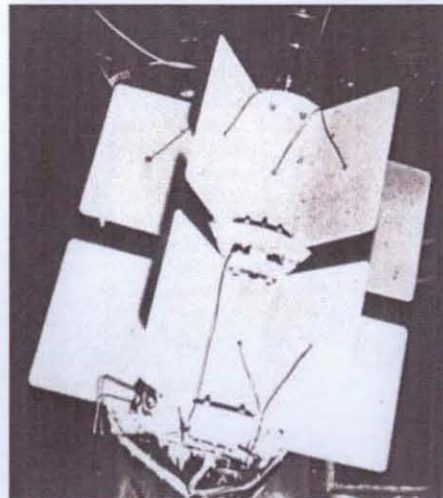
Transit-5BN-1 Satellite



SNAP-19B



Nimbus III Satellite



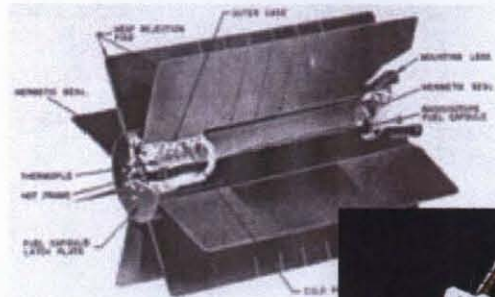
Assembly of 2 SNAP-19B RTGs

Nimbus Meteorological Satellite

- First NASA application of RPS
- 2 RTGs served as primary power source
- Nimbus B-1 launch on 18 May 1968
 - Launch vehicle failure forced destruction by Range Safety Officer
 - Agena Upper Stage in Santa Barbara Channel
 - RTGs recovered and fuel reused
- Nimbus III (B-2) launch on 14 April 1969
 - Operated for ~2.5 years
 - Sharp degradation in performance due to sublimation of thermoelectric materials and loss of hot junction bond due to internal cover gas depletion
- Features:
 - Intact Impact Heat Source (IHS)
 - PuO₂ microspheres in capsules for fuel - microspheres too big for inhalation
 - Pb-Te thermoelectrics (6.2% efficiency)
 - 23.5 We BOM, 13.4 kg, **2.1 We/kg specific power**
 - 2-year design lifetime



Early Flight Units



SNAP-27



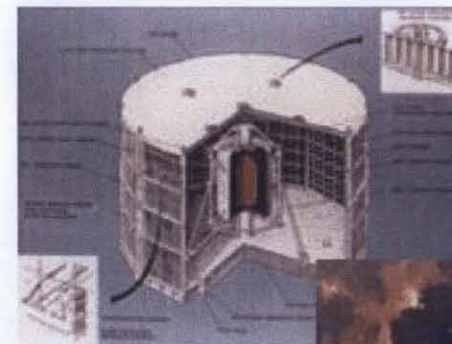
Alan Bean removing SNAP-27 fuel container from LEM

SNAP-27

- Power source for Apollo Lunar Surface Experiment Package (ALSEP)
 - Deployed on Apollo missions 12, 14, 15, 16 and 17
- Features:
 - $^{238}\text{PuO}_2$ fuel metal fuel and Pb-Te thermoelectrics
 - 63.5 We BOM, 19.6 kg, **3.2 We/kg specific power**
 - 2-year design lifetime: All deployed units operated 5-8 years until ALSEP station shutdown

Transit RTG

- Used on Transit Triad satellite
 - Launched in Sept 1972
 - Served as primary source with PV/battery auxiliary power
- Features:
 - $^{238}\text{PuO}_2/\text{Mo}$ Cermet fuel
 - Radiatively-coupled Pb-Te thermoelectrics
 - 35.6 We BOM, 13.6 kg, **2.6 We/kg specific power**
 - 5-year design lifetime: RTG still operating as of Feb 2008



Transit RTG



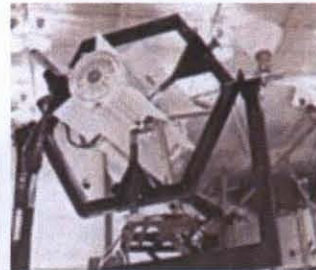
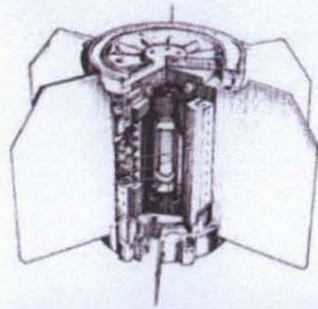
Transit Triad Satellite



SNAP-19

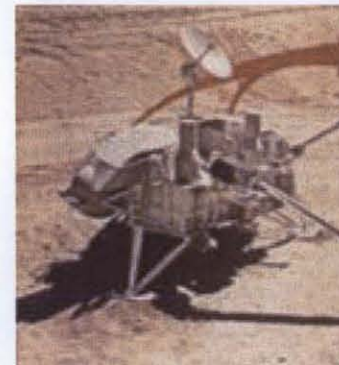
Pioneer Deep Space Probes

- Pioneer 10 and 11 each had 4 SNAP-19 RTGs for primary power source
- Modified version of SNAP-19B
 - Incorporation of TAGS/Sn-Te material for thermoelectrics – increased efficiency (6.2%) and lifetime
 - Longer, narrower generator size
 - 40.3 We BOM, 13.6 kg, **3.0 We/kg specific power**
 - 5-year design lifetime
- Launch on 2 March 1972 and 6 April 1973
 - Last signal from Pioneer 10 in 2003
 - Last signal from Pioneer 11 in 1995



Viking Landers

- Vikings 1 and 2 each had 2 RTGs for primary power
- Modified for Mars environment
 - Larger and more massive than Pioneer
 - 42.6 We BOM, 15.2 kg, **2.8 We/kg specific power**
 - 90-day operational requirement
- Launch on 20 Aug 1975 and 9 Sept 1975
 - Last data from Viking 1 in 1982
 - Relay link from Viking 2 lost in 1979





High-Performance RTGs



LES 8



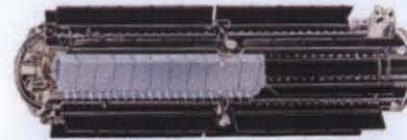
Voyager

Multi-Hundred Watt (MHW) RTG

- Primary Power on 4 Spacecraft
 - Lincoln Experimental Satellites (LES) 8 and 9 (Launched in 1976)
 - Voyager 1 and 2 Space Probes (Launched in 1975)
- Features:
 - $^{238}\text{PuO}_2$ Fuel and Si-Ge Thermoelectrics (6.6% efficiency)
 - 37.6 kg, 158 We BOM, **4.2 We/kg specific power**
 - RTGs still operating as of Feb 2008

General Purpose Heat Source (GPHS) RTG

- Primary Power on 4 Most Recent Deep Space Spacecraft
 - Galileo (May 1989)
 - Ulysses (1990)
 - Cassini (1997)
 - Pluto New Horizons (2006)
- Features:
 - $^{238}\text{PuO}_2$ Fuel and Si-Ge Thermoelectrics (6.8% efficiency)
 - 56.1 kg, 292 We BOM, **5.2 We/kg specific power**
 - All RTGs, except Galileo's, operating as of Feb 2008



Ulysses



Cassini



Galileo

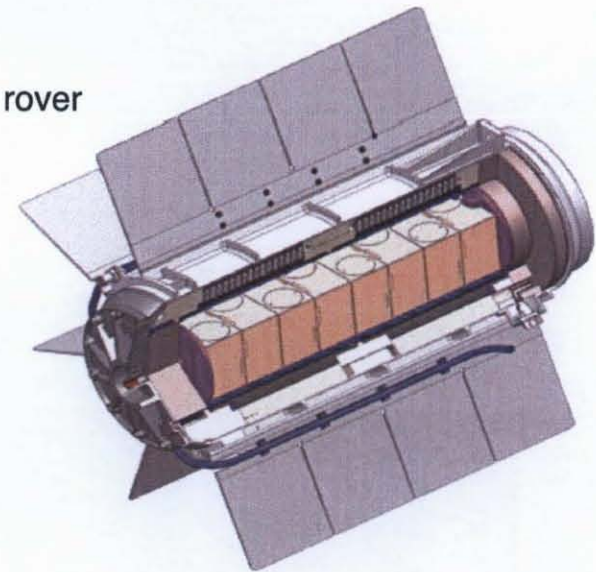


New Horizons



Multi-Mission RTG (MMRTG)

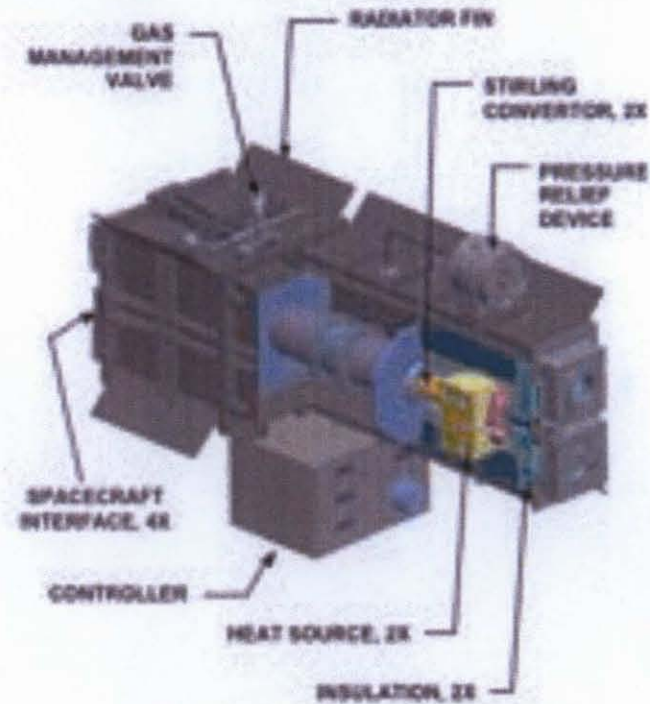
- Development funded by Mars Program for use on Mars Science Laboratory – launch in 2009
- 1 MMRTG serves as primary power source on large Mars surface rover
- Available for use on other surface and deep space missions
- Design Features:
 - 123 We @ BOM; 99 We @ 14 yrs
 - 8 GPHS heat sources per MMRTG
 - Pb-Te/TAGS thermoelectrics (6.3% efficiency)
 - 44 kg, **2.8 We/kg specific power**
 - 14-year design lifetime
 - Approx Dimensions: 66 cm (length) x 60 cm (dia)
- Milestones:
 - Authority to Proceed – July 2003
 - Completed Qualification Unit tests in 2007
 - Flight unit being assembled and readied for shipment to the Cape





Advanced Stirling Radioisotope Generator (ASRG)

- Dramatic advancement in RPS capability
 - High efficiency Stirling power conversion ($\geq 30\%$)
 - Substantial increase in specific power (2-3 times greater than MMRTG)
- Technology demonstration of flight-design generator with Stirling power conversion
 - Qual-level thermal and vibrational tests
 - Flight unit design processes
- Would be compatible for use on planetary surface and deep space missions – 14-year design lifetime
- Engineering Unit Features:
 - 140 We
 - 2 simulated GPHS heat sources per ASRG
 - 20 kg, **7.0 We/kg specific power**
- Flight Unit Features:
 - ≥ 160 We
 - 2 GPHS heat sources per MMRTG
 - ≤ 20 kg, **8.0 We/kg specific power**
- Potential Missions:
 - Discovery/Scout – 2012/13 timeframe
 - Titan or Europa Flagship – ≥ 2016



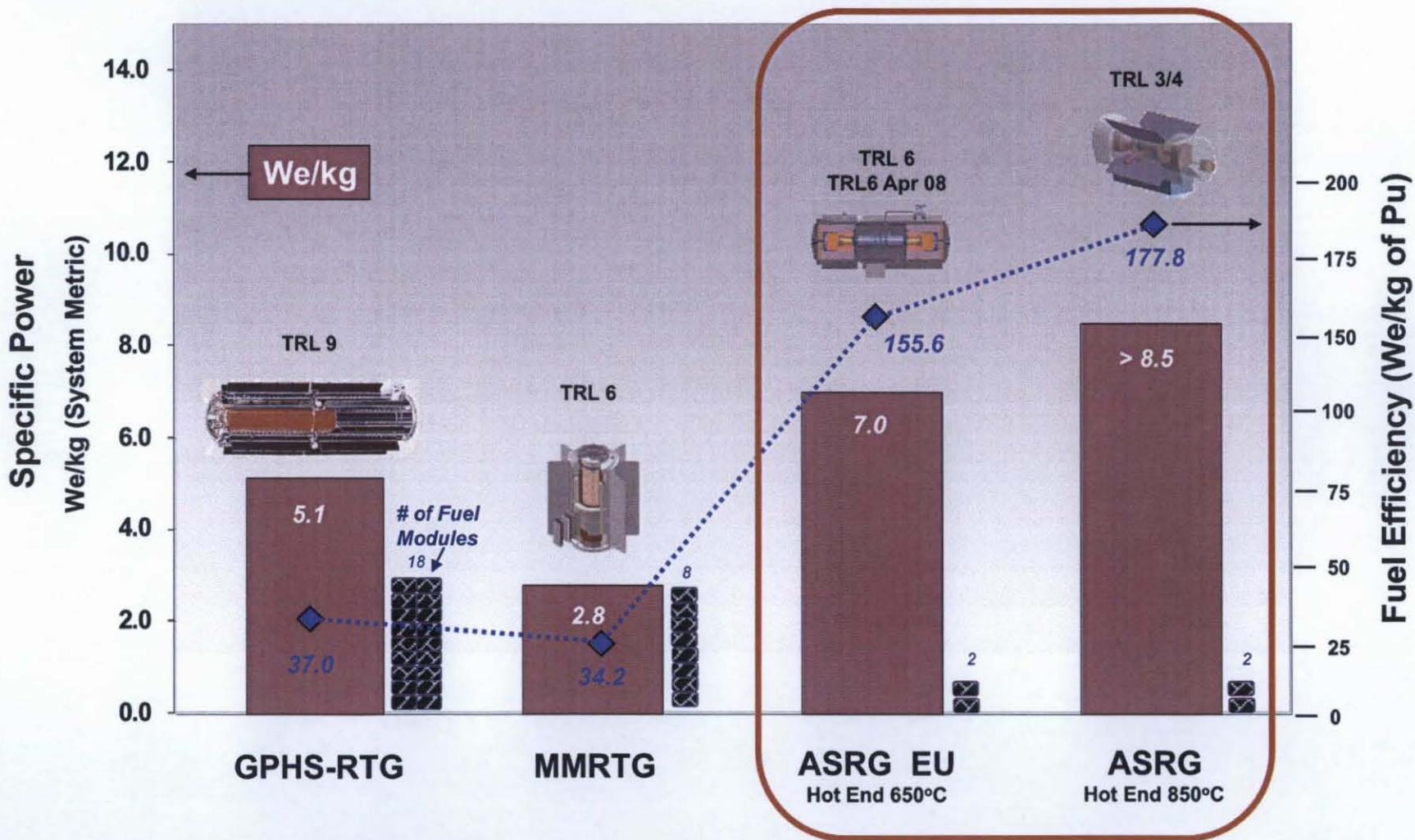
Sunpower-built Stirling Converter



Sunpower-built Stirling Converter



ASRG is large improvement in RPS capability



ASRG Provides High Specific Power RPS Generator

Images not to scale

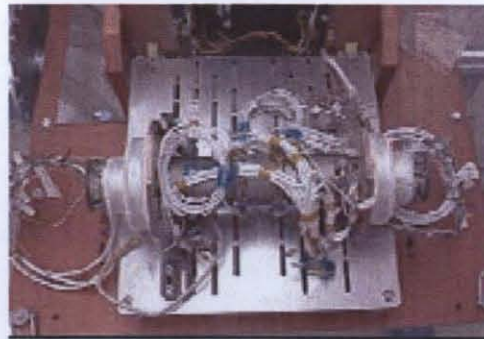


ASRG Technology Project Strategy

- **ASC Convertor Life and Reliability - Test, Test, Test**
 - Early hermetic developmental convertors for GRC extended operation
 - Three pairs of ASCs now testing 24/7, > 50,000 hrs as of 9/09
- **ASRG Generator Life and Reliability**
 - ASRG EU reassembly @ GRC for life testing ~ Aug/Sept 08
 - Performance testing 24/7 operations
- **Component and materials Life and Reliability - Testing & Analysis**
 - Plan for 10 Pre-EU convertors to validate processes and product quality, and build ASC data base for ASRGs



ASC-E Convertor



Pair of ASC-E Convertors during Integration



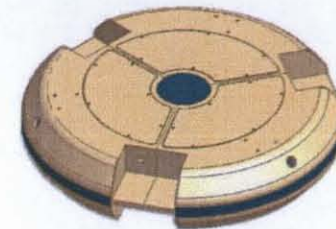
Completed ASRG Engineering Unit



Additional Applications for Small and Large RPS

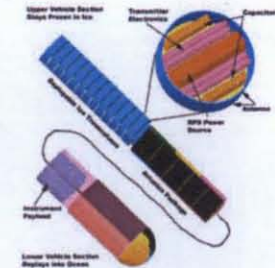
Small RPS (mWe to several We)

- Numerous potential planetary surface and space applications (e.g., networked science stations, deployable mini-payloads)
- 3 general size ranges using existing Pu-238 thermal sources
 - 40-80 mW (based on 1-few RHUs)
 - 0.1-few W (based on multiple RHUs or fractional GPHS)
 - 10-20 W (based on single GPHS module)



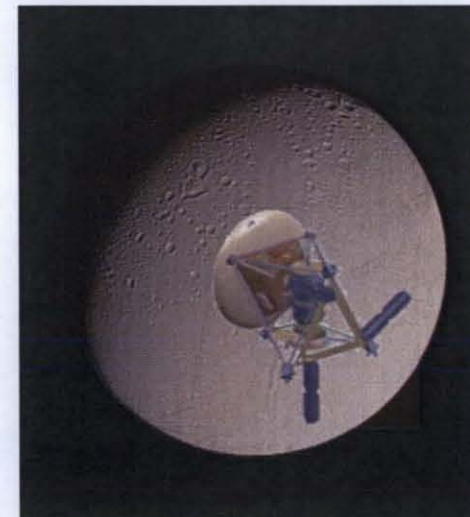
Transponder/Sensor Unit

Cryobot Probe with Deployable Transceivers (JPL)



Radioisotope Electric Propulsion (REP)

- Low-power NEP based on RPS as principal power source
- Enables use of high-performance electric propulsion independent of distance from Sun (i.e., deep space)
- Science application for large power reqmts (≥ 1 kWe)
- Compatibility on small spacecraft permits launch system injection into C3 > 0 and offsets performance disadvantage of low specific power



REP-based Spacecraft Concept (NASA GRC)



Summary

- **RPS is one of the great success stories of the Space Age.**
 - Enabled some of the most exciting and ambitious space missions over the last 40 years
- **Even with no new technologies, RPS will continue to be a mainstay for deep space exploration.**
- **New Stirling technology promises to greatly expand mission capabilities in future.**
 - Improved spacecraft mass performance
 - Better Pu-238 utilization
 - REP missions
- **Main challenge for RPS is the limited availability of Pu-238 fuel. Even with exclusive use of ASRG after MSL, only <4 kW available for future missions.**
 - Resume national Pu-238 production?
 - Alternative production techniques?
 - Alternative isotopes?

