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First Flights: Nuclear Power to Advance Space Exploration

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FIRST FLIGHTS:
NUCLEAR POWER TO ADVANCE SPACE EXPLORATION

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Abstract

One of the 20th century's breakthroughs that enabled and/or enhanced challenging space flights was the development of nuclear power sources for space applications. Nuclear power sources have allowed spacecraft to fly into regions where sunlight is dim or virtually nonexistent. Nuclear power sources have enabled spacecraft to perform extended missions that would have been impossible with more conventional power sources (e.g., photovoltaics and batteries). It is fitting in the year of the 100th anniversary of the first powered flight to consider the advancements made in space nuclear power as a natural extension of those first flights at Kitty Hawk to extending human presence into the Solar System and beyond. Programs were initiated in the mid 1950s to develop both radioisotope and nuclear reactor power sources for space applications. The success of this technology development allowed the U.S. Navy to choose with confidence for the first flights a small (2.7-We) radioisotope power source (SNAP-3B) to provide auxiliary power for the Transit 4A and 4B navigational satellites in 1961. These early SNAP (Systems for Nuclear Auxiliary Power) radioisotope power sources used the heat from the natural decay of plutonium-238 to produce electricity by means of thermoelectric elements. Such radioisotope power sources are commonly referred to as RTGs (radioisotope thermoelectric generators). Altogether, the U.S. has successfully flown 41 nuclear power sources (40 RTGs, one nuclear reactor) on 23 space systems, including such scientifically rewarding missions as the Apollo Lunar Surface Experiments Packages, Pioneers 10/11, Viking Landers 1/2, Voyagers 1/2, Galileo, Ulysses, and Cassini.

INTRODUCTION

On 17 December 1903, Orville and Wilbur Wright made the first powered flight of a human-carrying aircraft. As the world celebrates that momentous event it is fitting to consider other "firsts" in powered flight.

Once airspace was open to human exploration it was only natural that humans should focus more strongly on how to extend human flight into outer space. On 29 June 1961, the world's first powered flight of a nuclear-powered spacecraft (Transit 4A) was achieved. From this breakthrough came a number of firsts in the use of nuclear power in outer space, such as the flights of the Pioneer 10 and 11 spacecraft to Jupiter, Saturn and beyond; the first successful long-term landers on Mars (Viking Landers 1/2); the first human-installed scientific stations on the Moon; the Voyager 1 and 2 flights to Jupiter, Saturn, Uranus, Neptune and beyond; the first orbital reconnaissance of Jupiter (Galileo); the first polar exploration of the Sun (Ulysses); and the upcoming first orbital reconnaissance of Saturn (Cassini). Table 1 summarizes these missions (including beginning-of-mission, BOM, powers). The interested reader is referred to References 1 and 2 for more details.

The reader will note that just as aircraft moved from that first 12-s, ~37-m flight, space nuclear power sources (NPSs) have also made major strides in performance.

Table 1

Uses of Space Nuclear Power By the United States

(Spacecraft/Year Launched/NPS/BOM Power)

Transit Navy Navigational Satellites

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

SNAPSHOT Space Reactor Experiment

SNAP-10A reactor (1965) (>500 We)

Nimbus III Meteorological Satellite

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

Apollo Lunar Surface Experiments Packages

Apollos 12 (1969), 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)

Launching the U.S. SNAP program

Three technologies, whose development was accelerated by World War II, were critical in shaping the world of the late 20th and early 21st centuries: electronics, rocketry, and nuclear power. It was only natural that scientists and engineers should consider how to harness these technologies to further human exploration. A number of studies, some conducted under the title Project Feedback, were conducted in the U.S. after World War II. These studies highlighted the advantages of using nuclear power (either radioisotope or reactor) to power military satellites. As a result of these studies, the U.S. Atomic Energy Commission (USAEC), beginning in 1951, requested several studies on using radioisotopes and nuclear reactors to power spacecraft.[3]

As currently used, both radioisotope power sources and nuclear reactor power sources are essentially heat engines, i.e., they each produce thermal power which is converted into useable electrical power by means of a conversion system (e.g., thermoelectrics, turbine-alternators, linear alternators, etc.). The radioisotope power source produces its thermal power through the natural decay of its radioisotope "fuel" (^{238}Pu-based in all U.S. radioisotope power sources that have been flown). The nuclear reactor power source produces its thermal power through the fissioning of its "fuel" (^{235}U-based in all U.S. and Russian reactors that have been flown).

The USAEC-sponsored studies were completed in 1952. While efforts proceeded on the follow-up activities, K. C. Jordan and J. H. Birden, two researchers working at what was then the USAEC's Mound Laboratory (then operated by Monsanto Research Corporation), built the first radioisotope thermoelectric generator (RTG) in 1954. This first RTG produced only 1.8 mWe of power but it did show the feasibility of coupling radioisotopes with thermocouple-type conversion systems.[3]

In 1955, the USAEC initiated the SNAP (Systems for Nuclear Auxiliary Power) program to develop radioisotope power sources and nuclear reactor power sources for space and terrestrial applications. The first contracts were let to the Nuclear Division of Martin Company to develop radioisotope power sources and to the Atomics International Division of North American Aviation, Inc. to develop space nuclear reactors. The radioisotope power sources were given odd numbers (e.g., SNAP-1, SNAP-3, etc.) and the nuclear reactor power sources were given even numbers (e.g., SNAP-2).[3]

The "Odd" SNAPs

In rapid succession came a number of RTG developments under the SNAP program. For example, SNAP-1 was a ground test of a radioisotope-powered, mercury-based Rankine conversion system that produced 500 We. SNAP-1A was a thermoelectric power source designed to produce 125 We. Both of these radioisotope power sources were to use ^{144}Ce as the "fuel".[3]

In parallel with the SNAP-1 program a series of radioisotope power sources were studied under the umbrella of the SNAP-3 program. 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. Moreover, ^{238}Pu provided a number of features which 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 almost anything).[3]

Under the SNAP-3 program, twelve radioisotope power sources reached various stages of development. Both thermoelectric and thermionic conversion systems were considered.[3]

In addition to using radioisotopes to produce electrical power, NASA has used radioisotopes to supply thermal power to instruments and spacecraft subsystems that require temperature control. These devices, known as radioisotope heater units (RHUs) were used in various sizes in the Apollo 11 Early Apollo Scientific Experiment Package (EASEP) and on the Pioneer 10/11, Voyager 1/2, Galileo and Cassini spacecraft. Three small RHUs were also used on Sojourner, the Mars Pathfinder rover which was launched on 4 December 1996.

The "Even" SNAPs

In parallel with the SNAP radioisotope power source program, Atomics International, under contract to the USAEC, began the design and development of the SNAP-2 reactor, which was to produce 3 kWe using a mercury-based Rankine conversion system. Other SNAP reactors included SNAP-4 and SNAP-6 for undersea applications; SNAP-8, a 35-kWe mercury-based Rankine system for space applications and SNAP-10, a 300-We conductively cooled thermoelectric system. This technology base gave decision-makers the confidence to conduct the first flight of a nuclear reactor using SNAP-10A, a reactor that combined aspects of SNAP-2 technology and SNAP-10 technology.

SNAP-3B: FIRST FLIGHT

In 1958, the Applied Physics Laboratory (operated for the U.S. Navy by Johns Hopkins University) conceived the idea of a satellite Doppler navigation system which was soon named "Transit". Originally these Transit navigational satellites were to be powered with an array of solar cells and a storage battery. In those early days of the space program it was not clear how long either solar cells or batteries would last in the space environment so APL was receptive to an offer from the USAEC to provide radioisotope power sources for the Transit satellites.[4]

Transit 4A, which is shown in an artist's illustration in Figure 1, was designed to incorporate a small, 2.7-We RTG (or "RIPS", radioisotope power source, as APL termed it) for supplemental power. This RTG, which evolved from the SNAP-3 program, was designated SNAP-3B7 (see Figure 2). Everything was set for the launch with the Transit 4A spacecraft sitting on top of a fueled Thor-Able-Star launch vehicle at Cape Canaveral ready to go, when at the last minute, despite all the launch approval work, the U.S. Department of State nixed the launch on the grounds that it did not want to risk having a launch failure with an RTG on board.[4]

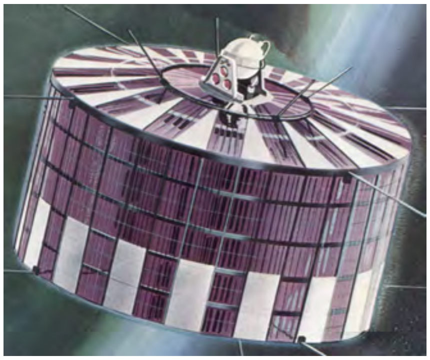

Figure. 1. Artist's conception of the Transit 4A navigational satellite in orbit. The SNAP-3B7 RTG is shown mounted on top of the spacecraft. (Martin Co.) Transit 4A was the first spacecraft to carry a nuclear power source. Transit 4A was 109-cm in diameter by 78.7-cm high with a mass of 78.75 kg.

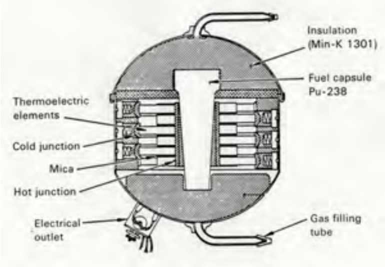

Figure. 2. Cutaway of the SNAP-3B RTG showing the two basic features of an RTG: the radioisotope heat source surrounded by the thermoelectric converter. SNAP-3B was 12.1 cm OD by 14 cm L with a mass of ~2.1 kg. SNAP-3B produced 2.7 We at beginning of mission (BOM). (Martin/DOE)

State was no doubt motivated by an earlier launch abort which had resulted in a Transit satellite falling on Cuba. Fidel Castro had been duly outraged. With the launch scheduled for the following Monday, USAEC Chairman Glenn Seaborg successfully appealed the decision directly to President John F. Kennedy late on Friday evening.[4] (Some involved in the program have speculated that State deliberately waited until the last minute to veto the launch so that there would not be enough time to transport the SNAP-3B7 to the Cape if their decision was overturned.)

The only way to transport the SNAP-3B7 to the Cape over the weekend was for Theodore Wyatt, one of the APL Transit participants and a Marine Corps reserve officer, to "borrow" a Marine Corps attack plane. With U.S. Air Force Captain Robert T. Carpenter (who was part of the USAEC Isotope Power Branch) carrying the small RTG between his legs, Wyatt flew the plane to the Cape in time for the launching on 29 June 1961. Figure 3 shows Carpenter carrying the SNAP-3B7 in its shipping container down from the Marine Corps aircraft. Figure 4 shows Paul J. Dick of the Nuclear Division of the Martin Company preparing to install SNAP-3B7 on Transit 4A. Wyatt would later write, "Thus, as the result of rather extreme measures, we were first to use any form of nuclear power in space".[4]

Figure 3. Captain Robert T. Carpenter carrying the SNAP-3B7 in its shipping container, June 1961.

Figure 4. Paul J. Dick preparing to install the SNAP-3B7 RTG on the Transit 4A satellite, June 1961.

On 15 November 1961, Transit 4B was launched with the 2.7-We SNAP-3B8 providing auxiliary power. The Transit 4A and 4B RTGs supplied power to the crystal oscillator that was the heart of the electronic system used for Doppler-shift tracking. Despite various failures in the spacecraft, the data from Transit 4A showed that SNAP-3B7 was still providing power in 1976, well beyond the design life of five years. Similarly, analyses by APL indicated that the SNAP-3B8 was still providing power in 1971, also well beyond its design life of five years.[5,6]

SNAP-9A: MOVING TO TOTAL POWER

The success of the SNAP-3Bs on Transits 4A and 4B gave APL the confidence to select the next-generation RTG, known as SNAP-9A, to provide all the power for its Transit 5BN-1 and 5BN-2 satellites. Transit 5BN-1 made history in the realm of "first flights" by becoming the first satellite to rely on an RTG for all primary power. Figure 5 is an artist's conception of the Transit 5BN-1 satellite showing it in the gravity gradient stabilization mode with the SNAP-9A RTG mounted at the aft end. Each SNAP-9A was designed to provide 25 We at a nominal 6 V for five years in space after one year of storage on Earth.

Figure 5. Artist's conception of the Transit 5BN-1 navigational satellite in orbit. The SNAP-9A RTG is mounted at the lower left in this drawing. Transit 5BN-1 was the first spacecraft to be totally powered by a nuclear power source. Transit 5BN-1 was an octagonal prism 45.7-cm across by 30.5-cm high. (JHU/APL)

APL summarized this first flight as follows: "Satellite 5BN-1 was the first artificial earth satellite to employ nuclear energy as its primary power source. The satellite was stabilized by means of a gravity gradient system. In her role as a pioneer nuclear satellite, 5BN-1 demonstrated the extreme simplicity with which thermoelectric generators may be integrated into the design, not only to provide the electrical power but also to aid in thermal control".[5]

Following the Transit 5BN series, APL used an RTG on the TRIAD navigational satellite which was launched on 2 September 1972. The "Transit RTG", which was built by TRW and General Atomics using SNAP-19 heat source technology (see next section), allowed TRIAD to provide data related to magnetospheric and auroral physics well beyond the five-year lifetime requirement.[5]

SNAP-19: IMPROVING THE TECHNOLOGY

The SNAP-19 technology improvement program built on the SNAP-9A development program to become the starting point for NASA's subsequent use of RTGs on outerplanetary spacecraft. All of the SNAP-19 RTGs were built by what is now Teledyne Energy Systems, Inc. (formerly the Nuclear Division of the Martin Company). The SNAP-19B RTG, which was used on NASA's Nimbus III meteorological satellite, was designed to provide 25 We after one year in orbit. The two SNAP-19B RTGs on Nimbus III provided about 20% of the total power with the rest being provided by solar arrays. Had the 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.[1]

Pioneers 10/11: Moving into the Outer Solar System

In 1972, as part of the first exploration of the outer Solar System, NASA launched Pioneer 10, the first of two totally nuclear-powered NASA Pioneer spacecraft (see Figure 6). The mission requirement was that the four SNAP-19 RTGs on each Pioneer spacecraft had to produce 120 We total at the Jupiter flyby. At Jupiter encounter, the four RTGs on Pioneer 10 produced 144.0 We while the four RTGs on Pioneer 11 produced 142.6 We. This excellent performance allowed NASA to target Pioneer 11 for the first flyby of Saturn. The Pioneer 11 RTGs exceeded the 90 We required at Saturn by producing 119.3 We.[1]

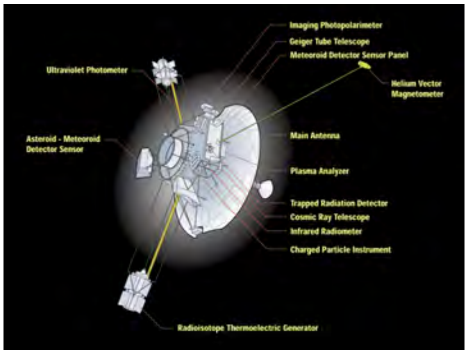

Figure 6. Diagram of the Pioneer 10 spacecraft showing the four SNAP-19 RTGs mounted two apiece on two booms. The high-gain antenna was 2.74-m in diameter. (NASA)

When Pioneer 10 was launched it was the fastest human-made object to leave Earth and it became the first human-made object to pass the orbit of Pluto. Pioneers 10 and 11 were the first to cross the asteroid belt and the first to flyby Jupiter and Pioneer 11 was the first to flyby Saturn. The last signal from Pioneer 10 was received on 22 January 2003, more than 30 years after launch! (The last signal from Pioneer 11 was received on 30 September 1995.) Considering that both Pioneers 10 and 11 were to operate for 21 months, the RTGs clearly made these spacecraft quite productive as they made extensive measurements into the outer Solar System and beyond.

Viking 1/2: Landing on Mars

The next first for RTGs was the Viking program with its goal of landing the first long-duration scientific platforms on the surface of Mars in 1976. Each of the two Viking Landers carried two modified SNAP-19 RTGs. Each Viking SNAP-19 RTG, which had been modified to undergo high-temperature (400 K) sterilization and to operate on the surface of Mars, was designed to produce a minimum of 35 We during the 90-day primary mission. Figure 7 is a cutaway drawing of a Viking/SNAP-19 RTG. All four RTGs easily met their 90-day requirement thereby allowing both Landers to operate in an extended mission mode for up to six years. In addition to providing power for the scientific instruments and for recharging four nickel-cadmium batteries, the RTGs supplied the Landers with thermal power to maintain the electronics at specified operational temperatures.[7]

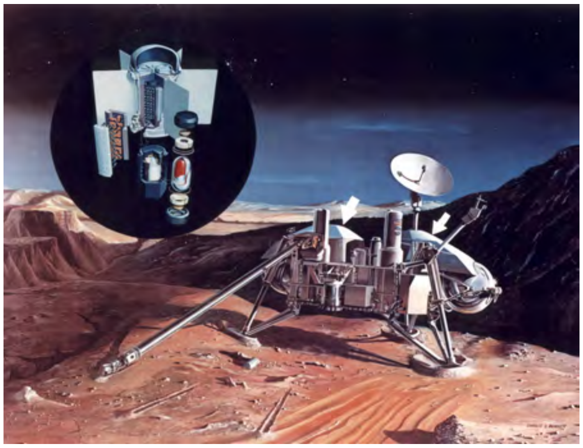

Figure 7. Artist's conception of a Viking Lander on the surface of Mars. A cutaway of the Viking/SNAP-19 RTG is shown as an insert with arrows indicating where the two SNAP-19 RTGs were placed on the Lander. The overall RTG diameter (across fins) was 58.7 cm and the overall length was 40.4 cm. The mass was 15.2 kg. (NASA/ERDA/Teledyne)

APOLLO: NUCLEAR POWERED SCIENCE ON THE MOON

Given the long (14-Earth-day) lunar night, nuclear power was a natural choice for NASA's scientific platforms emplaced on the Moon by the Apollo astronauts. Two 15-thermal-watt (Wt) radioisotope heater units (RHUs) were part of the Early Apollo Scientific Experiment Package (EASEP) that astronauts Neal A. Armstrong and Edwin E. "Buzz" Aldrin, Jr. set up on the Moon during the Apollo 11 first human mission to the Moon. All of the subsequent Apollo missions carried SNAP-27 RTGs designed and built by General Electric Company (now part of Lockheed-Martin) to power the Apollo Lunar Scientific Experiment Packages (ALSEPs). The first RTG-powered ALSEP was assembled on 19 November 1969 by Apollo 12 astronauts Charles Conrad Jr. and Alan L. Bean (see Figure 8).

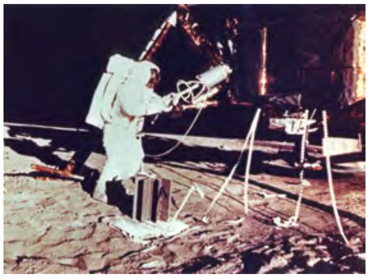

Figure 8. Apollo 12 astronaut Alan L. Bean removing the SNAP-27 fuel-cask assembly from the Lunar Module on 19 November 1969. The SNAP-27 converter is shown in front of Bean ready to receive the fuel-cask assembly. (NASA)

The SNAP-27 RTG power requirement was to provide at least 63.5 We at 16 V DC one year after lunar emplacement. (In the case of Apollo 17, the requirement was 69 We two years after emplacement.) All five SNAP-27 RTGs (Apollo 12, 14, 15, 16, 17) exceeded their mission requirements in both power and lifetime thereby enabling the ALSEP stations 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.[8,9]

MULTIHUNDRED-WATT RTG: THE GRAND TOUR

In response to NASA and U.S. Department of Defense (DoD) requirements the USAEC launched the Multi-hundred Watt (MHW) RTG program to provide at least 125 We after five years. The MHW-RTG represented a quantum leap over previous RTGs in that it had to produce over 150 We at beginning of mission (BOM) with a higher efficiency (6.6%) and a higher specific power (4.2 We/kg on Voyager) than any previous RTG. To do this required the use of the higher temperature capabilities of silicon-germanium alloys instead of the telluride-based alloys used in all the previous RTG thermoelectric elements. In the MHW-RTG design the hot junction temperature was

1273 K versus ~890 K on SNAP-27 and 819 K on the Viking/SNAP-19 RTGs.[1] An artist's conception of the MHW-RTG is shown in Figure 9.

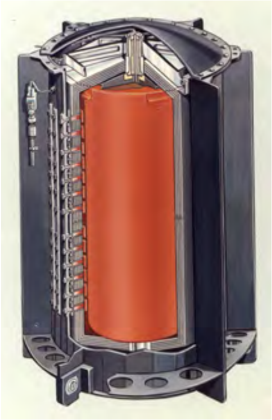

Figure 9. Cutaway of the MHW-RTG which was used on LES 8/9 and Voyager 1/2. The overall diameter was 39.73 cm and the length was 58.31 cm. The average flight mass for Voyager 1/2 was 37.69 kg. (ERDA/GE)

LES 8/9: First Air Force Use of RTGs

To meet the various requirements for the U.S. Air Force (USAF) Lincoln Experimental Satellites 8 and 9 (LES 8/9), Lincoln Laboratory (operated for USAF by the Massachusetts Institute of Technology) selected two MHW-RTGs per spacecraft. Each MHW-RTG was to produce 125 We at 30 V at the end of mission -- an operational life of at least five years after launch (which occurred on 14 March 1976). 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 from stations in Antarctica.

Voyager: The Grand Tour

NASA employed three MHW-RTGs for each of the two Voyager spacecraft in their epoch-making tour of the outer Solar System (see Figure 10). While Pioneer 10 was the first to reach Jupiter and Pioneer 11 was the first to reach Saturn, the improvements in technology for Voyager allowed NASA to greatly improve the science measurements at Jupiter and Saturn. Voyager 2 became the first spacecraft to visit Uranus and Neptune. The Voyager spacecraft benefited greatly from increased power of the MHW-RTGs (~158 We per RTG for Voyager versus ~40 We per RTG for Pioneer). In short, each of the three MHW-RTGs on each Voyager spacecraft produced almost as much power as all four of the Pioneer RTGs. Thanks to nuclear power, humans have been able to explore all four of the gas giants and beyond. Both Voyagers are now in an extended interstellar mission searching for the heliopause among other scientific objectives.

Figure 10. Artist's conception of the Voyager 1 spacecraft in its interstellar cruise mode. The three MHW-RTGs are shown mounted on a boom below the spacecraft bus. The high-gain antenna is 3.7-m in diameter. (NASA)

GPHS-RTG: ORBITING SOLAR SYSTEM BODIES

The next leap forward in RTG technology has been the general-purpose heat source (GPHS) RTG which was designed and built by GE (now Lockheed-Martin) and U.S. Department of Energy (DOE) laboratories for use on the original International Solar Polar Mission (now the Ulysses mission launched in 1990). The GPHS-RTG was then chosen for the Galileo mission (launched in 1989). Building on the MHW-RTG technology, the GPHS-RTG extended the power from ~150 We/RTG to ~300 We/RTG. Figure 11 shows a cutaway of the GPHS-RTG.

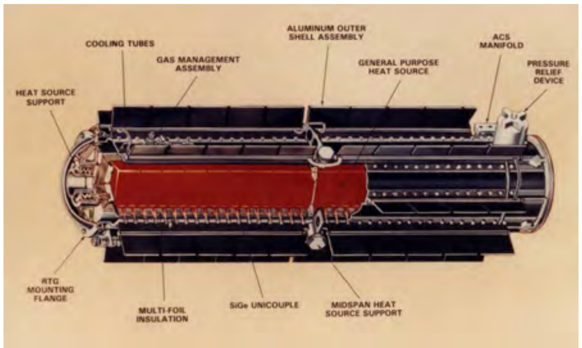

Figure 11. Diagram of the GPHS-RTG. The overall diameter is 42.2 cm and the length is 114 cm. The mass is 55.9 kg. The RTG can produce over 300 We at initial fueling. (GE/DOE)

Galileo, with two GPHS-RTGs, has had a highly successful orbital mission around Jupiter, in the process becoming the first spacecraft to orbit an outer planet (see Figure 12). Meanwhile, Ulysses continues its highly successful first-ever polar orbit of the Sun (see Figure 13).

Figure 12. Artist's concept of Galileo arriving at Jupiter. One of the GPHS-RTGs is shown at the top mounted on a boom. (NASA)

Figure 13. Artist's conception of Ulysses flying over the Sun (the spacecraft does not come this close). The GPHS-RTG is shown mounted on the lower right hand side of the spacecraft. The high-gain antenna is 1.65-m in diameter. (ESA/NASA)

The Cassini spacecraft, which was launched in 1997, is on course to become in 2004 the first spacecraft to orbit Saturn (see Figure 14).

Figure 14. Artist's conception of the Huygens probe being released from the Cassini spacecraft over Titan, the largest satellite of Saturn. Two of the three GPHS-RTGs can be seen mounted to Cassini in the upper left in the figure. The high-gain antenna is 4-m in diameter. (NASA)

Under NASA's new Nuclear Systems Initiative planning is under way to develop improved radioisotope power sources using higher efficiency conversion systems such as dynamic conversion (e.g., Stirling and Brayton).[10] Reference 11 summarizes some of these technologies.

SPACE REACTORS: THE NEXT QUANTUM LEAP

For the higher power levels (typically above 1-2 kWe), the lowest mass nuclear option is the space nuclear reactor. As noted earlier, the U.S. began a space nuclear reactor program in the 1950s concurrently with its radioisotope power program.

SNAPSHOT: First into Space

On 3 April 1965, the U.S. launched the first space nuclear reactor into space. Known as SNAP-10A, this reactor was an outgrowth of the SNAP-2 and SNAP-10 reactor programs. SNAP-10A was to produce not less than 500 We for one year. The code name for this experiment was SNAPSHOT.[12]

The reactor was placed into a 1288-km by 1307-km nuclear safe orbit (see artist's concept in Figure 15). The automatic startup and operation of SNAP-10A was flawless.[12]

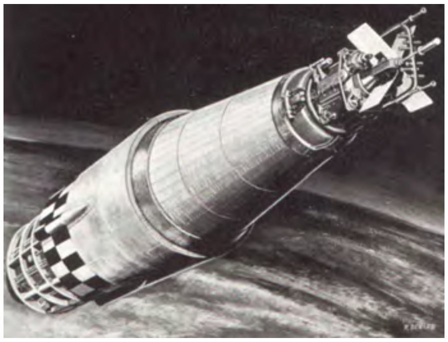

Figure 15. Artist's conception of the SNAP-10A reactor mounted on the Agena launch vehicle. The SNAP-10A system, which looks like a truncated cone, had an overall length of 3.48 m and a mounting base diameter of 1.27 m. The total reactor system mass was 435 kg (including shield). This was the first nuclear reactor ever flown in space. (AI/AEC)

Even though a failure of a voltage regulator in the Agena "spacecraft" caused a termination of the power operation after 43 days, SNAP-10 achieved a number of important milestones showing that it was feasible to remotely operate a liquid-metal-cooled nuclear reactor in space.[12] A ground test twin to the flight reactor successfully operated at full power for 10,000 hours thereby demonstrating the capability of SNAP-10A to operate unattended for a year.[12]

While the U.S. focused on ground testing of advanced space reactor concepts through the 1960s, the former Soviet Union followed up by operating at least 33 space reactors.[2]

Beyond SNAP-10A

The U.S. continued to study space reactors with the most recent major program being the SP-100 space nuclear reactor power system. The generic flight system configuration shown in Figure 16 was established in the early 1980s to support operational missions requiring relatively high power (100-kWe-class) for 10-year mission durations, but scalable from about 10 to 1000 kWe.

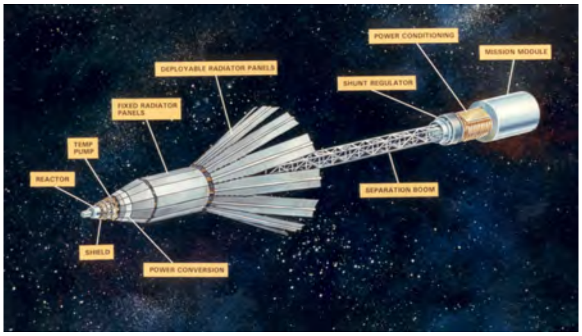

Figure 16. Main features of the generic SP-100 space nuclear reactor power system module. The diameter and length of the main body (less the radiator panels) was to be 3.5 and 6 m, respectively. The design mass was 4575 kg for the 100-kWe generic flight system. (GE/DOE)

Currently, under its Nuclear Systems Initiative, NASA is planning "Project Prometheus", a nuclear-reactor-powered spacecraft to orbit Jupiter and its major satellites. (Figure 17 is an earlier artist's concept of SP-100 powering a "Jovian Grand Tour" mission, somewhat similar to Project Prometheus.) The nuclear reactor would be used to provide both power and propulsion (via electric propulsion).

Figure 17. Artist's conception of an SP-100-powered Jovian grand tour mission using ion thrusters. (NASA)

CONCLUDING REMARKS

The use of nuclear power in space has enabled some of the most important U.S. space missions, including the first long-term study of the surfaces of the Moon and Mars; the first exploratory visits to Jupiter, Saturn, Uranus, and Neptune; the first orbital reconnaissance of Jupiter; and the first polar orbital study of the Sun. In general, the nuclear power sources, from the first SNAP-3B to the GPHS-RTG, met or exceeded their design requirements by providing power at or above that required and beyond the planned lifetime. All of the power sources met their safety requirements. This successful performance has laid a secure foundation for future U.S. missions that will use nuclear power.

Acknowledgments

The authors acknowledge with thanks the contributions made by the hundreds upon hundreds of highly dedicated and skilled people at contractor sites and DOE laboratories who have, over more than half a century, made space nuclear power possible. They have literally given us the keys to the future.

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