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ABSTRACT

Research has shown that nuclear radioisotope power generators can supply compact, reliable, and efficient sources of energy for a broad range of space missions. These missions range from televising views of planetary surfaces to communicating scientific data to Earth. This publication presents many applications of the advancing technology and commemorates three important milestones in space technology research: (1) the emplacement of the Apollo Lunar Surface Experiments Package on the Moon in November 1969; (2) the first demonstration of nuclear power for space in January 1959; and (3) The Atomic Energy Act of 1954, as amended, that encouraged applications for nuclear energy in a broad range of scientific endeavors, including exploration of space. Spacecraft propulsion had contributions originating from a number of countries. The log of space flights began in November 1957 with the first artificial satellite, Sputnik-1. Presently the total number of satellites has grown to more than 1,693 and a primary vehicle for launching a variety of spacecraft and satellites for research and communications purposes is being provided by the United States Space Shuttle Program. Topics of information include: space power systems and types; key events; space exploration milestones; future planetary missions and generating systems; isotope power systems; and aerospace safety. (RT)

Nuclear
Energy

NUCLEAR POWER IN SPACE

Nuclear Power In Space

Nuclear radioisotope power generators are being designed for a broad range of space missions, where it is necessary to have compact, reliable, and efficient sources of energy. Research has shown that nuclear radioisotope power generators can satisfy these needs, which range from televising views of planetary surfaces to communicating scientific data to Earth. This publication will present the many applications of this advancing technology.

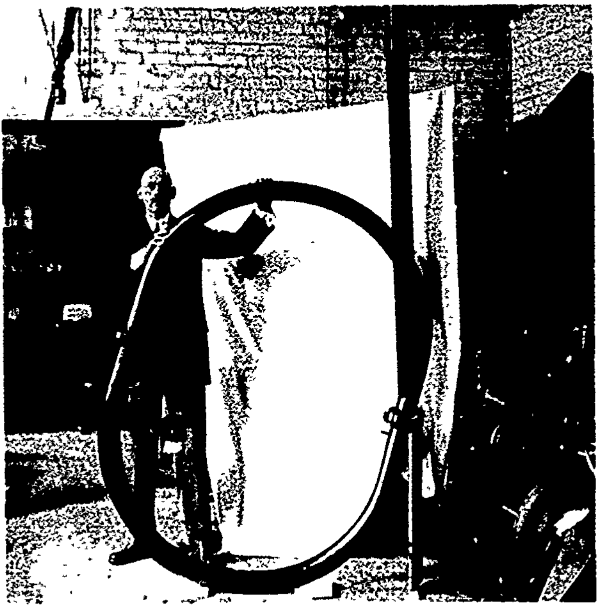
This edition commemorates three important milestones in space technology research:

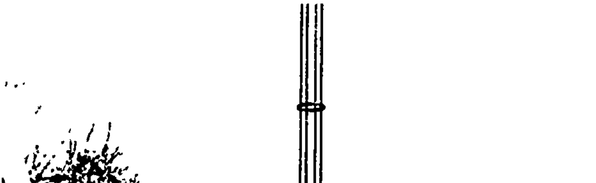
- The emplacement of the Apollo Lunar Surface Experiments Package on the Moon in November 1969
- The first demonstration of nuclear power for space in January 1959
- The Atomic Energy Act of 1954, as amended, that encouraged applications for nuclear energy in a broad range of scientific endeavors, including exploration of space

Space Flight

During this century, dreams about space flight progressed toward reality as aircraft of all types became commonplace. Spacecraft propulsion as we know it today had its origins in contributions from a number of countries. In 1916, R.H. Goddard (U.S.A.) studied solid and liquid propellants and launched a test rocket a distance of 184 feet (56.1 meters). Seven years later, a Rumanian, H. Oberth, wrote of the future of space exploration in his book *The Road to Space Travel*. In 1934, the Germans tested a rocket with 600 pounds (272.2 kg) of thrust that was developed by Dr. Wernher von Braun and his team of scientists. Finally in 1954, U.S. agencies organized Project Orbiter, the first major step in developing satellite technology. Substantial research and development efforts were later pursued in the United States, in which the National Aeronautics and Space Administration (NASA) took a leading role.

The log of space flights began in November 1957 with the successful operation of the first artificial satellite, Sputnik-1, by the Soviet Union. Space exploration was further stimulated by the International Geophysical Year Program, July 1957 to December 1958. By the end of 1969, 1,052 spacecraft had been orbited by ten countries, with the United States in the lead. Within the next 5 years, the total number of satellites would grow to 1,693. Today, the U.S. Space Shuttle Program is providing a primary vehicle for launching a variety of spacecraft and satellites for research and communications purposes.





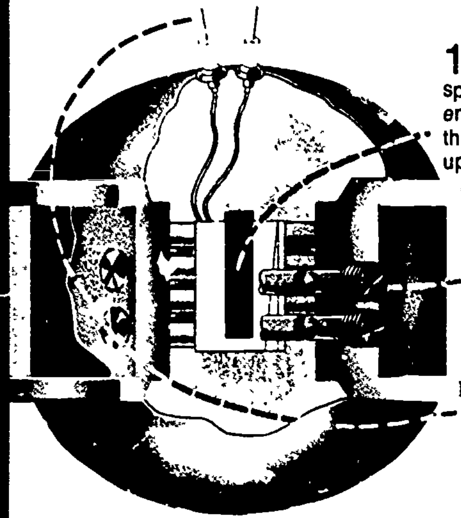
Dr. Robert H. Goddard is acknowledged as the father of American rocketry. He is shown above with a circular vacuum tube, which was used to prove that rocket efficiency was greater in a vacuum than in air. In the bottom photograph, taken 10 years later, Dr. Goddard stands beside the launching frame used to fire a test rocket at Auburn, Massachusetts. His achievements in the science of rocket propulsion gained him more than 200 patents, many of which were issued [illegible]eath.

Space Power Systems

In earlier years, space missions with flight paths relatively close to the Earth and Sun got their electrical energy from lightweight batteries, fuel cells, and/or solar cells. However, as distances increased and missions became more complex, auxiliary energy sources became necessary. At this point, nuclear power was considered as a possible energy source. Two years after the passage of the Atomic Energy Act, research and development began in earnest on the applications of nuclear power to space systems. Several different early types of power units were developed carrying the designation *systems for nuclear auxiliary power* (SNAP). This designation was later dropped in favor of *radioisotope thermoelectric generator* (RTG) when RTGs supplied the entire amount of electrical energy needed for space missions.

Types of Systems

Two types of nuclear systems can generate electricity for spacecraft. One is a nuclear reactor; the other, which has been more widely used, employs radioisotopes. Radioisotopes are unstable elements that give off heat as they undergo a process known as *decay*. This heat energy can be converted to electrical energy in a number of ways. The one used thus far employs the thermoelectric principle discovered in the early 19th century by the German scientist, Thomas Seebeck. He observed that an electric voltage is produced when two metal plates are joined in a closed circuit and the two junctions are kept at different temperatures. Known as *thermocouples*, these were the first devices to produce electricity from heat without moving



How a basic radioisotope-powered thermoelectric generator works.

For applications on Earth, strontium-90 (Sr-90) and cesium-137 (Cs-137) have been considered for heat sources. Their decay rate and ready availability as fission products from nuclear reactors are obvious practical advantages.

A series of generators using Sr-90 as fuel has powered polar weather stations, navigation aids and buoys, lighthouses and underwater beacons, remote seismic sensing stations, and deep ocean devices. However, these generators require heavy radiation shielding. Because weight is an important factor in rocket launches, the generators are not suited for use in space.

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Key Events in the Development of Radioisotope Systems for Space Power

1959

A SNAP-3 RTG the size of a grapefruit was placed on the desk of President Eisenhower to signify the achievement of a milestone in the U.S. schedule of nuclear power for space. This proof-of-principle demonstration unit was fueled by polonium-210, with a half-life of 138.4 days.

The search for a longer-lived heat source eventually led to plutonium-238 (Pu-238), with a half-life of 87.7 years.

This first "atomic generator" received substantial attention from the media, the Joint Committee on Atomic Energy, and the Joint Chiefs of Staff.

The selection criteria for a heat source included lifetime, availability, ease of handling, and safety. In the decay process, Pu-238 emits mainly alpha radiation, which has very low penetrating power. For this reason, only lightweight shielding is required to protect the spacecraft from radiation. This is important

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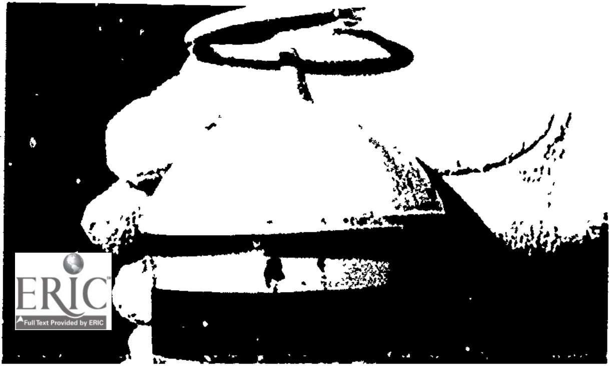
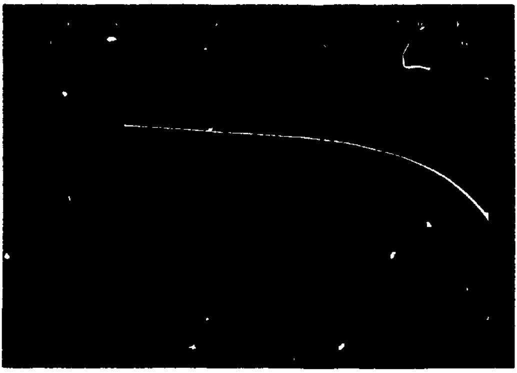


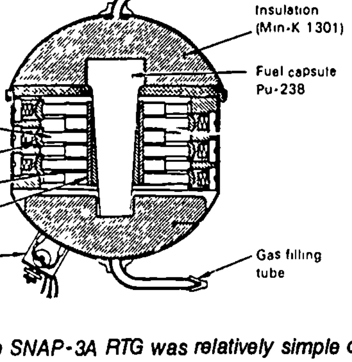
because any extra weight is a liability. Pu-238 can be recovered from the byproducts of conventional nuclear reactors, but for all space missions to date, this isotope has been produced by special irradiation in Government reactors.



Approximately 96 percent of the original heat output of plutonium-238 is available for use after 5 years.

1961

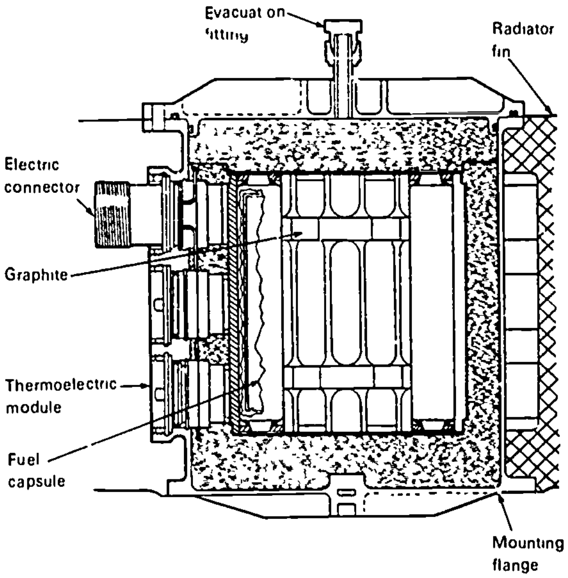
In June and November, respectively, the Navy's Transit 4A and 4B satellites each carried SNAP-3A generators fueled with Pu-238. These units demonstrated the feasibility of operating nuclear power sources in space. The SNAP-3A generators allowed communication with the Transit 4A satellite 15 years after it was launched.



The design of the SNAP-3A RTG was relatively simple compared to later models.

1963

The SNAP family of RTGs continued to grow. Experience gained during operation of the Transit 4B navigational satellite indicated that its solar cell system had been damaged by radiation from a 1962 high-altitude nuclear explosion. The SNAP-9A generators were therefore designed to supply all primary power for 5 years in space after a 1-year storage period on Earth. These units produced 26.8 watts at 6 volts, ten times the power output of their SNAP-3 ancestor that generated 2.7 watts at 2.5 volts. Three SNAP-9A units, fueled by Pu-238, were delivered for the Navy's Transit 4/5BN navigational satellites. Two successful launches were accomplished, but electronics problems limited their use after 1965.



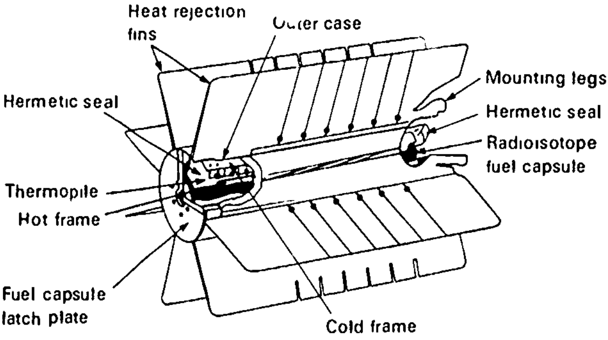
The SNAP-9A RTG had a much greater power output than the SNAP-3A RTG and provided that power for a longer duration.

1969

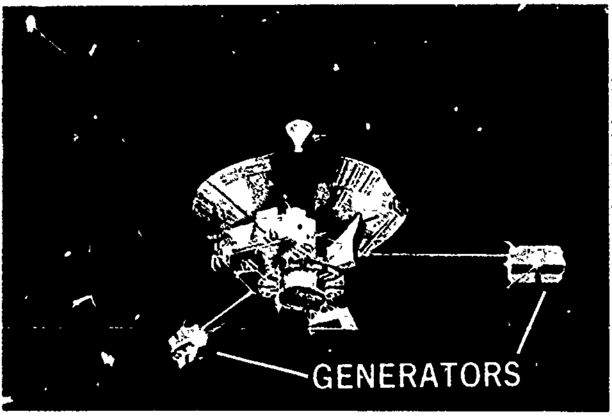
A new type of RTG, the SNAP-19 unit, fueled by Pu-238, provided 28 watts of supplementary power to the Nimbus III meteorological satellite. This was NASA's first application of nuclear power. Long after the solar-cell output had fallen to very low levels, the spacecraft was able to rely on the RTG to provide the power necessary to operate many of the systems on the spacecraft.

The Apollo Moon landing missions left instruments for scientific experiments on the Moon's surface. In July 1969, Apollo-11 astronauts set up the Early Scientific Experiments Pac .age in the Sea of Tranquility. There, during the cold lunar night, radioisotope heater units provided the sole source of heat to keep the instruments warm.

All subsequent Apollo missions during the next 3 years were supplied with SNAP-27 RTGs fueled by Pu-238 dioxide microspheres. They were used on missions to recover data on the lunar atmosphere and the Moon's internal structure and composition. All units exceeded design requirements by delivering at least 63.5 watts of electrical power for a year or more.



The SNAP-27 RTG, with its new heat source, proved to be a highly successful generator.

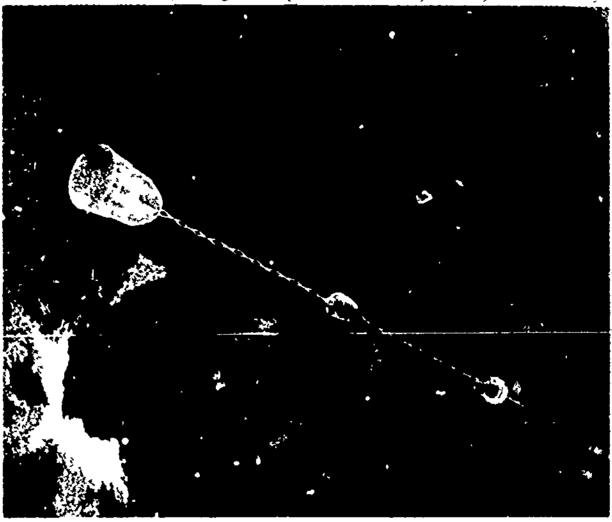


Four nuclear generators provided the electrical power for each of the two NASA Pioneer Jupiter fly-by missions (Pioneer-10 and -11). The Pioneer-10 spacecraft, launched in March 1972, encountered Jupiter in December 1973. The Pioneer-11 spacecraft, launched in April 1973, encountered Jupiter in December 1974. Because of the success of the Pioneer-10 flight, the Pioneer-11 mission was expanded to include a study of Saturn in 1979.

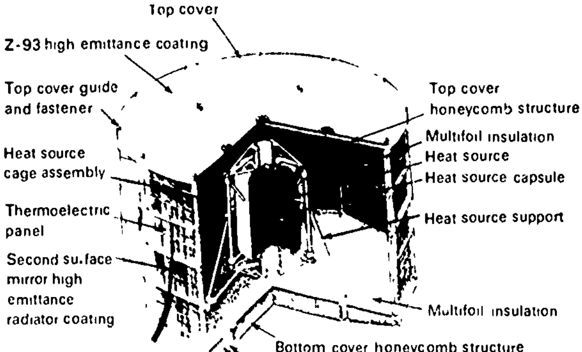
1972

Modifications were made to the basic SNAP-19 RTG converter, heat source, and structure to satisfy the power needs and environments of NASA's Pioneer Jupiter fly-by missions. Plutonium dioxide fuel in the form of molybdenum cermet disks was used in place of the microspheres that had powered previous RTGs. These modifications helped make possible the first close-up color photographs and scientific measurements of Jupiter and Saturn. Both Pioneer units are still operating and are on their way out of the solar system.

During 1972, the U.S. Navy also launched the Triad navigation satellite carrying a new Transit RTG. This unit provided 36 watts of nuclear power, augmenting an on-board battery and solar cell array. While in orbit, the short-term objectives of the satellite were demonstrated, even though the failure of a telemetry converter limited the amount of data it could transmit.



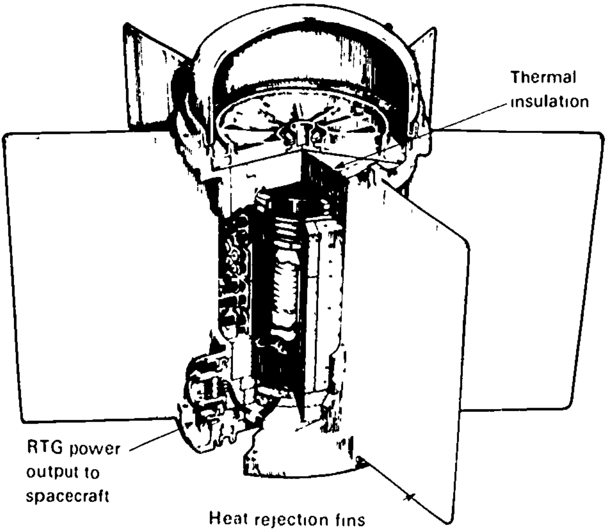
Artist's concept of the new series of Transit navigation satellites. The instruments are in the left-hand module; the central module has equipment to help stabilize the orientation of the satellites; and the RTG is at the far right.



The Transit RTG was used with other power sources to provide all the energy needs of the Triad navigation satellite.

1975

The basic SNAP-19 RTG, powered by Pu-238 cermet disks, again was modified to meet NASA's Viking mission requirements. The generators had to undergo high-temperature sterilization to prevent contamination of the martian environment and be able to retain their charge during the long space voyage. A minimum power output of 35 watts was required to carry out scientific studies and to recharge the nickel-cadmium batteries on the lander units. The unit also had to be modified to withstand the extreme temperatures encountered during the Mars day/night cycle.



The unique design of the Viking/SNAP-19 RTG was necessary for the unit to withstand the harsh environment of Mars.

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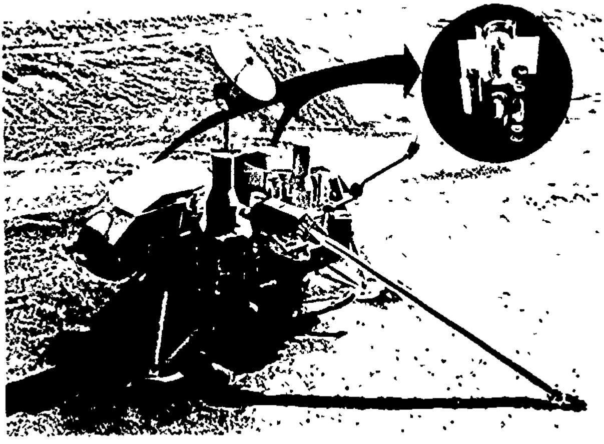
The record of missions accomplished thus far confirmed the inherent advantages of using nuclear power generators. These advantages included:

- continuous and predictable output of heat,
- very reliable power output in useful wattage ranges,
- long service lifetime,
- low weight-per-power output,
- compact structure adaptable to any spacecraft,
- resistance to radiation and meteorite damage, and
- complete independence from the Sun as a source of power.

To capitalize further on these advantages, the U.S. Department of Energy (DOE) pursued a program to develop higher-powered, less expensive, and more versatile RTG units, the first of which was designated the Multihundred-Watt system.



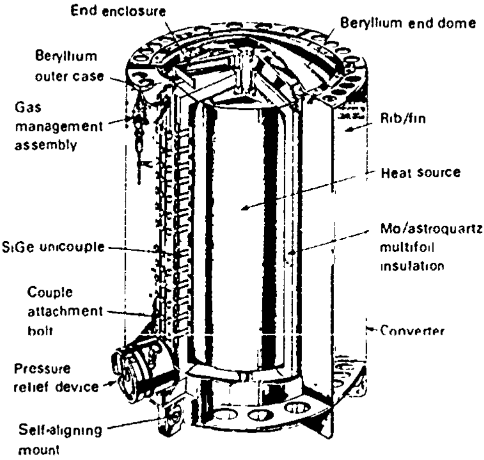
Two nuclear generators provided the electrical power for each of two instrumented vehicles that landed on Mars in 1976 as part of Project Viking.

1976

The Department of Defense (DOD) launched a pair of communications satellites powered by nuclear generators. The launch mission was to evaluate techniques to help satellites survive and continue dependable operation under the difficult conditions found in space. Built for the Air Force by Lincoln Laboratory at the Massachusetts Institute of Technology, they were designated the Lincoln Experimental Satellites (LES-8/9). They were designed to communicate with each other, as well as with aircraft and ships at sea.

These generators are still operational after over 9 years in Earth orbit, thereby confirming the advancement in technology represented by this system.

One of the two Lincoln Experimental Satellites (LES-8/9) launched in March 1976. Two Multihundred-Watt nuclear generators, each providing approximately 150 watts of electrical power, are on board each satellite to support Department of Defense communications systems.



Each of the Multihundred-Watt RTGs used 312 silicon-germanium thermocouples to produce power for the NASA Voyager mission.

1977

The basic Multihundred-Watt RTG unit was also selected for the spectacular NASA Voyager mission. The heat source was composed of 24 pressed Pu-238 oxide spheres, each producing about 100 watts of heat. Electrical conversion was achieved through an advanced system using silicon-germanium thermocouples. This significantly improved the power output efficiency over other elements previously used for electrical conversion in SNAP systems.

Three 150-watt generators are still providing power for each of the Voyager-1 and -2 spacecrafts, which were launched to Jupiter and Saturn in the summer of 1977. These NASA spacecraft provided thousands of spectacular photographs of the surface features and physical aspects of these planets and their moons, as well as a wealth of data on their atmospheres and the interplanetary environment. For the first time, the complex structure of Saturn's rings was revealed.

An artist's conception of the Voyager spacecraft as it passed near Saturn. Three Multihundred-Watt RTGs, shown below the satellite, provided power for the spacecraft.

Milestones in Space Exploration

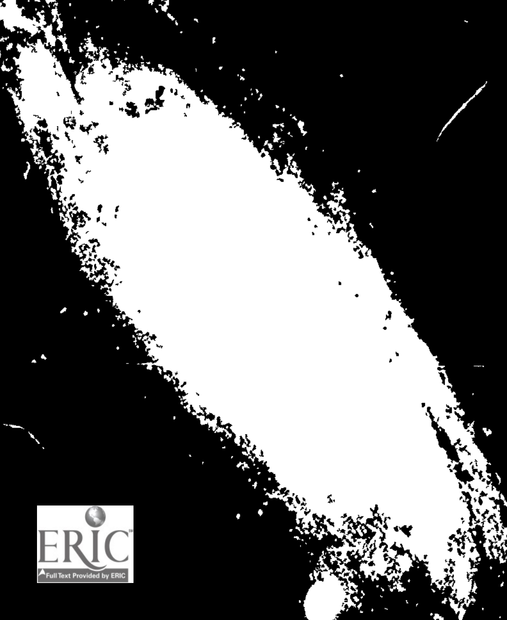
- In 1969, the Apollo mission to our Moon left a scientific laboratory on its surface and retrieved Moon rocks for analysis and study.
- The Viking landers in 1975 sampled the Mars atmosphere and its soil but found no conclusive evidence of life on that planet.
- In the late 1970s, the Pioneer spacecraft investigated Jupiter's magnetic field, its radiation belts, and its turbulent atmosphere. It also recorded data on the nature of the asteroid belt and the dynamics of the solar wind in the region beyond the orbit of Mars.

- In June 1983, after an 11-year journey that provided a great deal of data via the Deep Space Net, Pioneer-10 passed beyond Neptune and Pluto, becoming the first man-made object to leave the solar system.
- En route to Saturn and Uranus in late 1980, Voyager units discovered Saturn's hitherto unknown ring and three additional moons. Volcanic activity was also found on its moon, Io, as well as evidence of tectonic plates on its moon, Ganymede.

These outer planetary missions could not have been accomplished without the reliable power provided by nuclear generators.

On the Moon, Apollo-12 Astronaut Gordon Bean removes the plutonium-238 heat source for the isotope generator from its container. The SNAP-27 thermoelectric generator (arrow) produced 73 watts of electrical power for the Apollo Lunar Surface Experiment package from November 1969 to September 1977 when data processing was concluded.

On the Moon, Apollo-12 Astronaut Gordon Bean removes the plutonium-238 heat source for the isotope generator from its container. The SNAP-27 thermoelectric generator (arrow) produced 73 watts of electrical power for the Apollo Lunar Surface Experiment package from November 1969 to September 1977 when data processing was concluded.

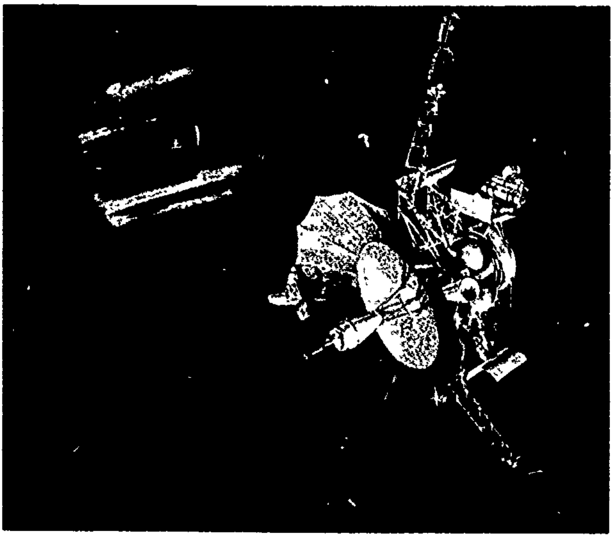


Future Planetary Missions

Planetary explorations persist as a fascinating venture, helping in a major way to answer basic questions about our solar system and its history. Until the dawn of the Space Age, students and scientists alike were restricted in the amount of data about our solar system that was available to them. This was due in part to the limited information astronomers could provide with their optical and radar telescopes.

When Voyager-2 encountered Uranus in January 1986, our knowledge of this remote planet increased dramatically. Equally dramatic findings are expected when Voyager-2 passes Neptune in August 1989.

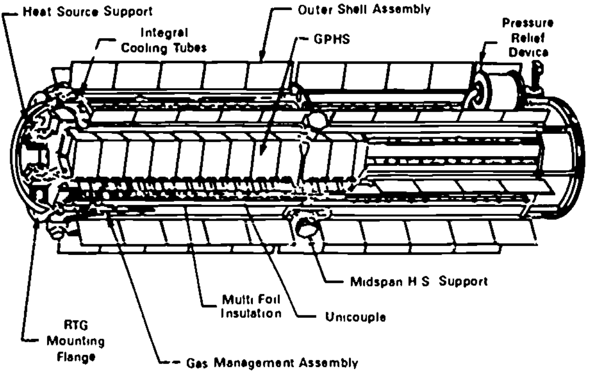
Encouraged by the successes of the Voyager-2 and other space missions, intensive efforts have been initiated on other projects, such as NASA's Galileo mission to Jupiter and the Ulysses mission around the Sun.



The Jupiter Orbiter satellite with its RTG energy sources will transmit valuable data on Jupiter back to Earth.

Galileo Mission

The preliminary reconnaissance of Jupiter's moons by the Pioneer and Voyager spacecraft aided in refining the questions to be answered by the Galileo mission. The objectives will be to study the chemical composition and physical state of the atmosphere of Jupiter and its moons, and the dynamics of its magnetic field. This information is essential to understanding the formation of the entire solar system. Jupiter will also be an ideal laboratory for the study of the conditions that were thought to have been present when life evolved on Earth.



The General Purpose Heat Source (GPHS) used in the Galileo mission was designed to be used in several different types of satellite systems.

In the late 1980s, the Shuttle Transportation System is scheduled to launch a Jupiter Orbiter/Probe spacecraft using a Centaur rocket. Approximately two years later, the spacecraft is expected to target its probe for an entry into Jupiter's clouds and operate at Jupiter for approximately 20 months. Instruments powered by RTGs on board the Probe will transmit the data it gathers upward to the Orbiter, where other RTGs will then supply the power to relay the information to Earth.

The General Purpose Heat Source (GPHS), an advanced Pu-238-fueled modular unit, will provide 4,410 watts of power to an improved silicon-germanium thermoelectric converter.

Each heat source is composed of 18 modules, with four 62.5-watt Pu-238 oxide fuel pellets per module. The modules are designed to survive under a range of accident conditions, including launch vehicle explosion or fire, atmospheric reentry and impact, or post-impact situations. As shown in the sketch below, strong graphitic fibrous blocks and impact shells protect against reentry conditions, while special iridium fuel cladding prevents the release of radioactive material.

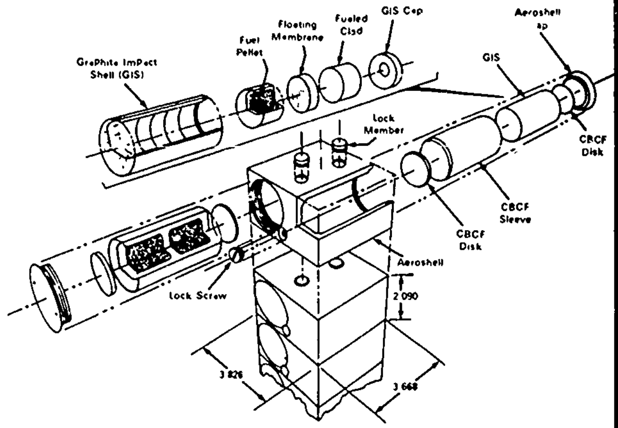


Diagram of the modular units in a general purpose heat source.

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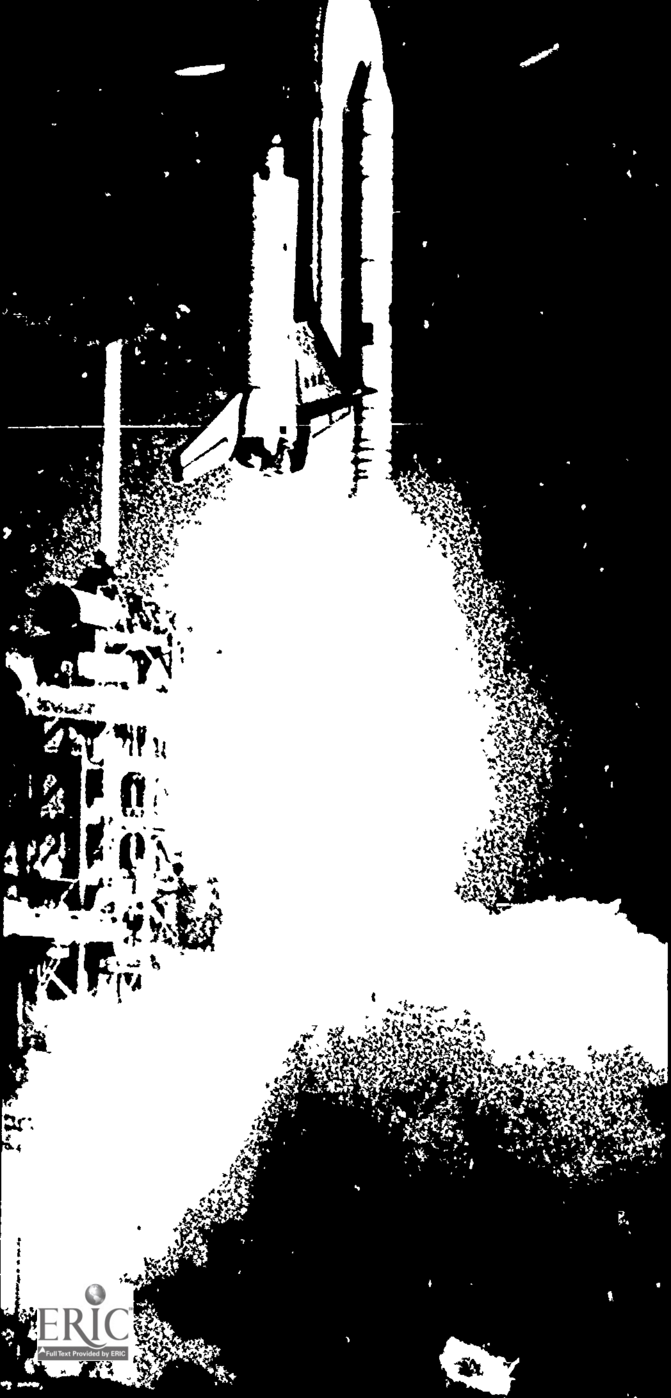
Ulysses Mission

The Ulysses mission, initially called the International Solar Polar Mission (ISPM), is also scheduled for launch in the late 1980s. The spacecraft, developed by the European Space Agency (ESA), will be launched from a NASA Shuttle. A boost into a long, elliptical orbit toward Jupiter will take advantage of Jupiter's gravitational pull to propel the spacecraft toward the Sun. Its flight path is expected to take it over the poles of the Sun about 4 years after launch. This ESA solo flight will also carry out observations of the Sun and the solar wind at high solar latitudes.

The Ulysses spacecraft will carry one GPHS-RTG to provide electrical power for mission requirements. At the mission's end in 1991, the GPHS-RTG is expected to be generating 260 watts.

Since the mid-1980s, the Space Shuttle has been used successfully to launch, repair, and retrieve satellites in space. In the near future, the Shuttle will be used in the Galileo and Ulysses space missions to launch spacecraft to nearby planets.

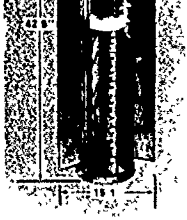


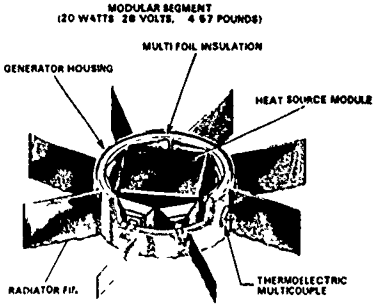
Future Generating Systems

Modular Isotopic Thermoelectric Generator

During the past 20 years, RTGs have shown a steady improvement in performance. Generating systems of today are safer, more reliable, and produce more power without an increase in size. The newest models have a new heat source and thermal insulation, both of which can be installed easily because of their modular design.

The Modular Isotopic Thermoelectric Generator (MITG), which will be used in most future space systems, should produce a power output of 7.7 watts/kg. This is nearly 50 percent greater than that of the Galileo or Ulysses GPHS-RTGs. These features are very appealing to spacecraft designers because of the need for increased power and dependability in future missions.





The Modular Isotopic Thermoelectric Generator (MITG) incorporates the newest technology in generator design.

Dynamic Isotope Power Systems

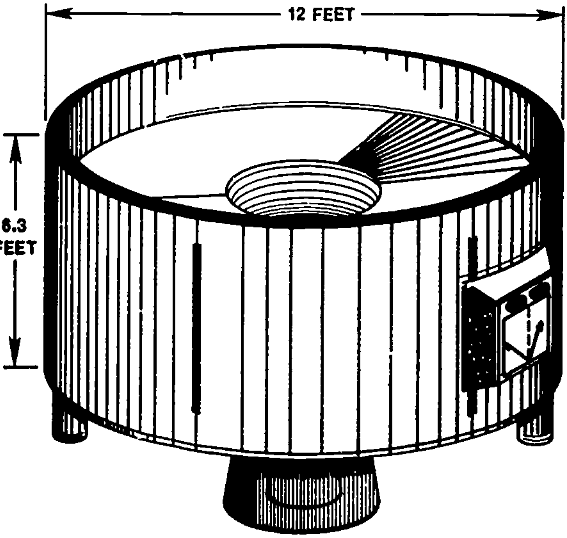
In contrast to the static type of radioisotope generator with no moving parts, dynamic systems employ a rotating turbine/alternator to produce electrical power. These systems offer higher power output, conversion efficiencies in the 18 to 25 percent range, and lower costs per watt of delivered power.

In the early years of space nuclear power development, a Dynamic Isotope Power System (DIPS) generator fueled with cerium-144 was designed for a 500-watt, 60-day service to power instruments in space satellites. However, technical problems at that time forced cancellation in 1959.

Technology programs pursued by DOE in the late 1970s and early 1980s involved demonstrations of two generator systems: the Brayton Isotope Power System, using a gas as the working fluid, and the Kilowatt Isotope Power System, using a condensible vapor. Power levels of 500 to 2,000 watts are readily attainable by varying the fuel loading.

Other studies have shown that a Nuclear Integrated Multimission Spacecraft (NIMS) could accommodate a DIPS generator capable of supporting communications, surveillance, navigation, or meteorology objectives.

The Strategic Defense Initiative, an important new defense program, is anticipated to have space power requirements matching the capabilities of the DIPS power system. In addition, the Air Force and spacecraft contractors have expressed an interest in using the system for a space-based surveillance network. During 1985, DOD studies will be undertaken to consider the application of nuclear power to important defense space missions. A joint DOD/DOE DIPS development program is anticipated to meet the space power requirements of several specific missions.



Sketch of a Nuclear Integrated Multimission Spacecraft (NIMS) satellite powered by nuclear energy.

Aerospace Safety

From the beginning, the U.S. Space Nuclear Power Program has placed great emphasis on the safety of people and protection of the environment. The safety review functions of the Atomic Energy Commission, begun in 1959, are an integral part of this program.

The safety objectives of RTGs have always stressed containment of the radioisotope fuel to the maximum extent possible in the event of an accident. Special flight safety measures are also followed so that exposure levels are within the limits established by international [illegible]ds.

For many years, the United States has been an active member of the United Nation's Working Group on the Use of Nuclear Power Sources in Outer Space. Recently, the group issued an evaluation of the role of nuclear power in space by stating that it "... reaffirms its previous conclusion that nuclear power sources can be used safely in outer space, provided that all necessary safety requirements are met." The United States is committed to these safety requirements so that we may continue the exploration of our solar system and the universe beyond.

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Cover:

View of the unmanned Pioneer-10 spacecraft, which left our solar system in mid-summer 1983. Powered by radioisotope thermoelectric generators (RTGs), it has sent back a tremendous amount of information about our nearby planets. Experts at NASA expect to be able to track Pioneer beyond 5 billion miles.