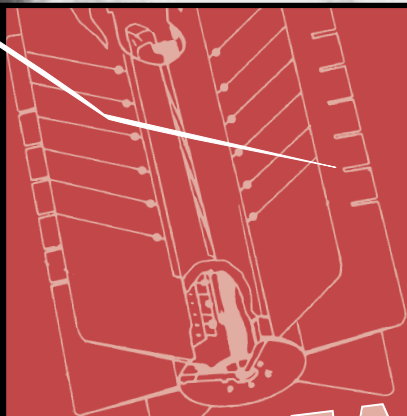


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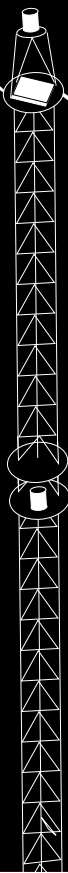
# NUCLEAR

## Power in Space



# NUCLEAR ENERGY

U.S. Department of Energy  
Office of Nuclear Energy,  
Science and Technology



On the cover:

Launch of the Atlantis Space Shuttle  
carrying Galileo into space (October 1989).

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# Nuclear Power in Space

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U.S. Department of Energy  
Office of Nuclear Energy, Science, and Technology  
Washington, D.C. 20585



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# Introduction

In the early years of the United States space program, lightweight batteries, fuel cells, and solar modules provided electric power for space missions. As missions became more ambitious and complex, power needs increased and scientists investigated various options to meet these challenging power requirements. One of the options was nuclear energy.

By the mid-1950s, research had begun in earnest on ways to use nuclear power in space. These efforts resulted in the first radioisotope thermoelectric generators (RTGs), which are nuclear power generators built specifically for space and special terrestrial uses. These RTGs convert the heat generated from the natural decay of their radioactive fuel into electricity. The low-power devices were designed to supplement a craft's primary non-nuclear power source, but as the technology progressed, they soon began shouldering many missions' entire power needs.

Today, RTG-powered spacecraft are exploring the outer planets of the solar system and orbiting the sun and Earth. They have also landed on Mars and the moon. They provide the power that enables us to see and learn about even the farthestmost objects in our solar system.



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## Contemplating the Heavens

Many ancient peoples, including the Aztecs, Egyptians, and the builders of Stonehenge, were intensely interested in astronomy. Their writings and architecture indicate they studied the moon's phases and movement. They related the position and the perceived movement of the sun to Earth and its seasons. Some charted the stars, identifying the constellations.

Through the ages, scholars suggested various explanations for the makeup, movement, and relationship to Earth of these heavenly bodies. Like us today, they wanted to know more about those distant objects, but a lack of technology limited their ability to learn.

Over the centuries, scientists like Galileo and Newton described the structure of the solar system and the movement of the planets. Inventions such as the telescope permitted them to see the moon's craters, the "canals" on Mars, Saturn's rings, and other intriguing details. This knowledge increased their curiosity about the moon, sun, and planets, and they longed for more information. They even dreamed of expeditions across space to encounter them firsthand.

## The Century of Flight

During the 20th century, fantasies about space flight progressed toward reality on the wings of the many types of aircraft that became commonplace. People from various countries contributed to the beginnings of spacecraft propulsion. One of the most important was an American, Robert Goddard, who studied both solid and liquid propellants. In 1916 he launched a test rocket that traveled 184 feet. Two decades later, Werner von Braun and his team of German scientists were developing powerful new rockets that could fly hundreds of miles.

In 1954 the U.S. began Project Orbiter, the nation's first major step in developing satellite systems. The U.S. soon became a world leader in this emerging technology, with the National Aeronautics and Space Administration (NASA) playing a leading role.

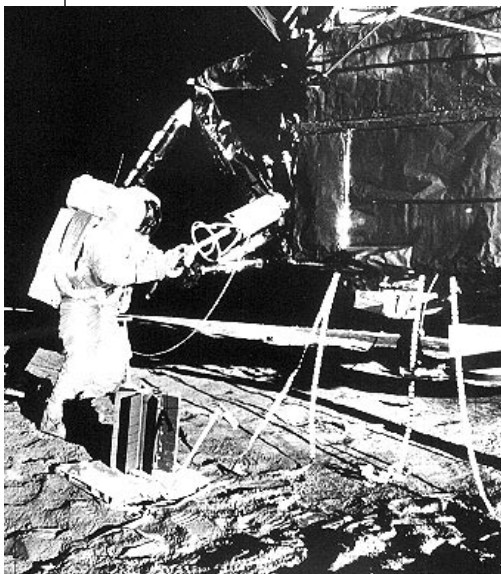


### *The Quest for Reliable Power*

On January 16, 1959, a dramatic photograph appeared in a Washington, D.C., newspaper. The headline proclaimed "President Shows Atom Generator." The photograph, above, pictured President Eisenhower and a group of U.S. Atomic Energy Commission (AEC) officials in the Oval Office at the White House. They were gathered around the president's desk, staring at a strange grapefruit-shaped object. Dubbed the world's first atomic battery, it was actually one of the earliest models of a radioisotope thermoelectric generator (RTG), a nuclear generator specifically developed by the AEC to provide electric power during space missions.

The first unmanned vehicle in space was Sputnik, launched by the Soviet Union in 1957. The U.S. followed three months later with its first unmanned flight, Explorer 1. The number of U.S. and Soviet space missions increased dramatically in the next few years. And by the end of 1969, more than 1,000 spacecraft were orbiting Earth. Five years later the number of these satellites had climbed to nearly 1,700.

Today, the U.S. Space Shuttle Program is the nation's primary space transportation system. It has launched numerous spacecraft and satellites on research and communications missions.



*On the moon, Apollo-12 astronaut Gordon Bean prepares to load the plutonium-238 heat source into the SNAP-2 thermoelectric generator (arrow). The generator produced 73 watts of power for the Apollo lunar surface experiment package for nearly eight years.*



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In 1961, the first RTG used in a space mission was launched aboard a U.S. Navy transit navigation satellite. The electrical power output of this RTG, which was called Space Nuclear Auxiliary Power (SNAP-3), was a mere 2.7 watts. But the important story was that it continued to perform for 15 years after launch.

Since that initial SNAP-3 mission, RTGs have been an indispensable part of America's space program. They have been involved in more than 25 missions, orbiting Earth and traveling to planets and their moons both nearby and in deep space. (Astronauts on five Apollo missions left RTG units on the lunar surface to power the Apollo Lunar Surface Experiment Packages.)

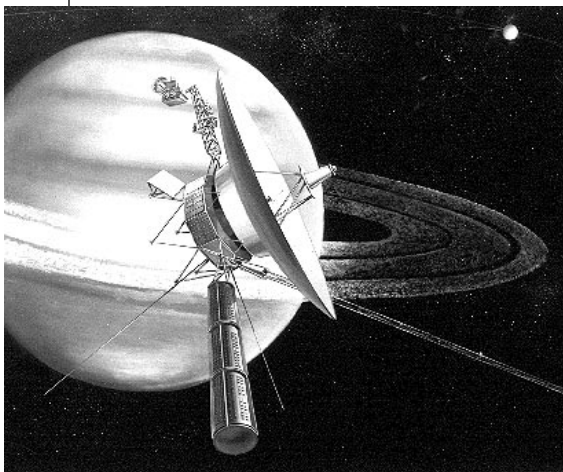
In addition to contributing to numerous navigational, meteorological, and communications flights, RTG power sources have provided all the electrical power required on the Pioneer, Voyager, Galileo, and Ulysses missions. This series of unmanned flights has helped us study the sun and outer planets of the solar system. RTGs should continue to play a pivotal role in major space missions in the next century.

## The Pioneer Missions

The Pioneer 10 and Pioneer 11 missions launched in 1972 and 1973 were spectacular successes in the long-range strategy to explore the outer planets. Pioneer 10 and its RTG survived the asteroid belt and the intense radiation field around Jupiter and continued to perform experiments perfectly. Pioneer 10 continued its journey and finally left the solar system—the first manmade object ever to do so. Pioneer 11 flew by Jupiter, going through the peak radiation zone in even better shape than the earlier Pioneer 10. It also visited Saturn—our first close encounter with the ringed planet. Both Pioneer spacecraft continued to send back data to Earth after 17 years, even as they passed beyond the solar system, because the RTGs provide continuous power.

## The Voyager Missions

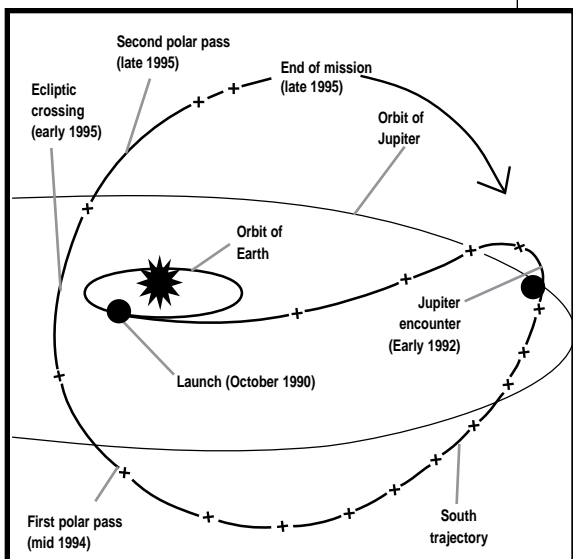
Voyager 1 and Voyager 2 were launched within a few weeks of each other in 1977. Though they used different routes and trajectories (curved paths of flight), both spacecraft visited Jupiter and Saturn. They took spectacular photographs of Saturn's rings and observed 11 of its moons close up. Voyager 2 then continued to Uranus and Neptune. The RTGs powered versatile and complex instruments, including computers and communications equipment that made it possible for the Voyagers to transmit 115,200 bits of data per second from Jupiter.



*Artist's conception of the Voyager spacecraft as it passed near Saturn. Three multihundred-watt RTGs, shown in the foreground, provided power for the spacecraft.*

## The Ulysses Mission

The Ulysses mission is a joint enterprise of the European Space Agency and NASA, with the Jet Propulsion Laboratory in California providing major support. The craft was launched in October 1990 aboard the space shuttle Discovery. Its mission is to study the sun, the magnetic fields and streams of particles the sun generates, and the interstellar space below and above it.



*Ulysses Mission Trajectory. The mission, which was extended beyond the original five-year period, has provided original data on the sun's poles.*

Previous craft launched to study the sun always orbited the sun's equator—the plane in which Earth orbits the sun. Ulysses is the first craft to orbit the sun's poles, giving scientists an entirely new perspective and important new data.

They achieved this new positioning by heading the craft toward Jupiter after launch. The mission called for Jupiter's immense gravity to push the spacecraft out of its ecliptic plane into a polar orbit of the sun. This novel orbit produced original data from areas of the sun not previously studied. It also created a more complete understanding of the sun and its effects on Earth.

In June 1994, mission scientists received the first scientific data on the south pole of the sun. In June 1995, they received data on the north pole as well. Because the RTGs have a long life, mission planners extended the mission to a second orbit cycle, vastly increasing mission data.

A single RTG provides all the power for instruments and other equipment aboard Ulysses. It is the only available power source capable of meeting the mission's power requirements. Furthermore, the RTG will provide power for many years, enabling mission scientists and program managers to extend the life of the spacecraft by several years and reap more scientific benefits. But since Ulysses orbits the sun, why not use solar energy instead of an RTG to power it?

## Why Ulysses Doesn't Use Solar Energy

The closest approach to the sun by the spacecraft occurred when it was launched from Earth. As Ulysses traveled to Jupiter, the sun grew more distant. Near Jupiter, the sun's rays are 25 times weaker than near Earth. A solar panel system large enough to catch this

weak energy would add 1,200 pounds, nearly doubling the weight of the spacecraft. In comparison, the RTG weighs 124 pounds. No rocket booster existed that could have sent Ulysses on its mission with the added weight of solar panels. Chemical power systems and batteries are useful for short missions, but on longer missions, such as the one Ulysses is on, they would also add too much weight.



*The spacecraft Ulysses was named for the Greek warrior king who went on a strange, exotic 10-year journey returning from the Trojan War.*

# The Galileo Mission

Galileo lifted into space in October 1989 aboard the space shuttle Atlantis. Its mission involves a scheduled eight-year, deep-space voyage to the solar system's largest planet, Jupiter, and its four major moons. The spacecraft will go into orbit around Jupiter and conduct detailed investigation of this system. Scientists are intensely interested in Jupiter. Unlike Earth and other planets, Jupiter has kept much of its original composition and can enhance our understanding of the solar system's origins.

Throughout the mission, Galileo's instruments have examined the celestial bodies it has passed, and cameras have relayed photos back to an international team of scientists on Earth. Infrared systems will map Jupiter and its largest moon, and specialized instruments will study the planetary atmosphere.

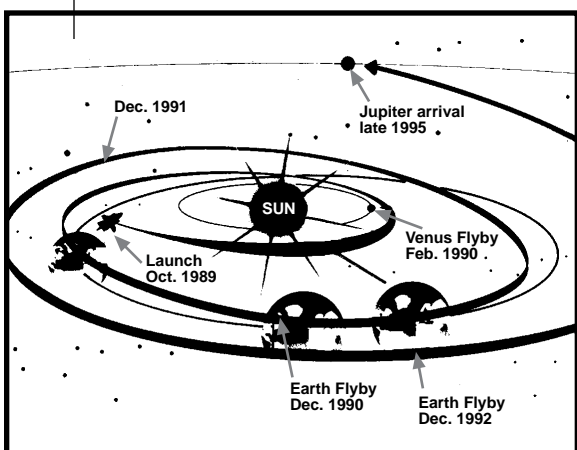
Galileo provided the first close-up photographs of an asteroid, Gaspra, in 1993. It also provided the only direct photos of the impacts on Jupiter of the comet Shoemaker-Levy 9 in July 1994.

Galileo used a technique called gravity-assist to make the journey to Jupiter, which is nearly 500 million miles from Earth.



*The Galileo spacecraft was named after the 17th-century scientist who discovered Jupiter's moons.*

Available launch vehicles were not powerful enough to place Galileo on a direct path to Jupiter. Instead, Galileo used the gravity of other planets to arrive at its destination. The craft flew by Venus first, and then made two passes by Earth. As Galileo flew toward Earth and Venus, the planets exerted gravitational pull on it, finally increasing its velocity enough for it to complete the journey to Jupiter. However, these maneuvers added significantly to the mission's mileage and duration. By the time Galileo made the two passes by Earth, the mission was three years old.



*Galileo's Trajectory to Jupiter*

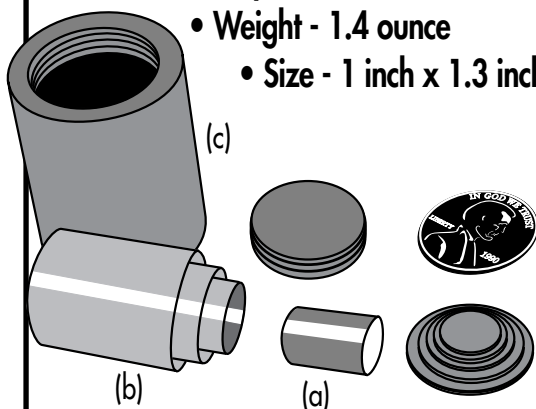
The Galileo mission is built around two distinct pieces of spacecraft, an orbiter and the separate atmospheric probe named Huygens. About 150 days before arriving at Jupiter, the probe separated from the orbiter and entered the planet's atmosphere. For a short 60 to 75 minutes, its instruments took atmospheric measurements and relayed the data to the orbiter for transmission to Earth. The probe descended farther and farther until the increasing temperature and pressure of Jupiter's atmosphere crushed and eventually vaporized it.

The orbiter is scheduled to make 10 orbits of Jupiter over a 22-month period. It will study the planet, its magnetic atmosphere, and the four major Jovian satellites, or moons — Io, Europa, Ganymede, and Callisto.

The Galileo mission involves many challenges, not least of which is meeting the craft's instrument, communications, and other power requirements. Without a reliable source of power, the mission's very reason for existing—to provide valuable new information about our solar system—would be jeopardized.

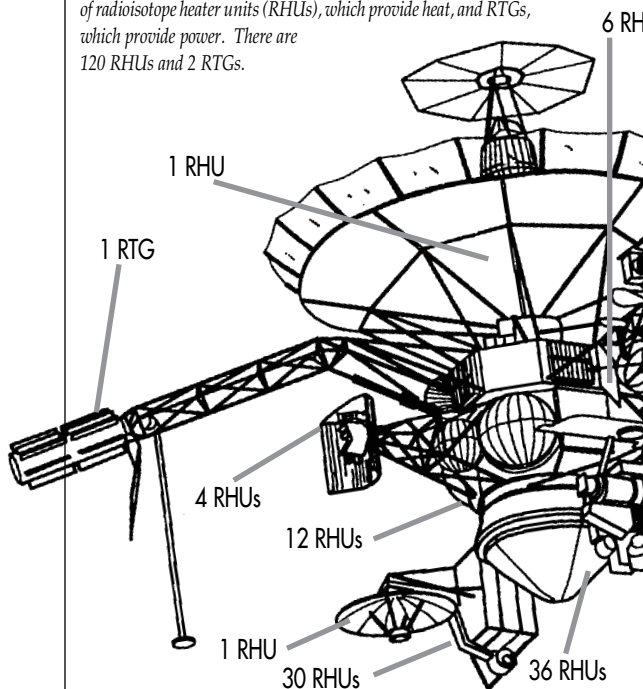
## Radioisotope Heater Unit

- Heat Output - 1 watt
- Weight - 1.4 ounce
- Size - 1 inch x 1.3 inch



*The brick-like ceramic form of the fuel pellets (a) is designed to break into large pieces, instead of dust, on impact. This makes it difficult to inhale and minimizes its exposure to the environment. The cladding (b) and insulator (c) protect the fuel pellet from the extreme heat of re-entry and from the environment in case of accident.*

*This drawing of the Galileo spacecraft shows locations and quantities of radioisotope heater units (RHUs), which provide heat, and RTGs, which provide power. There are 120 RHUs and 2 RTGs.*

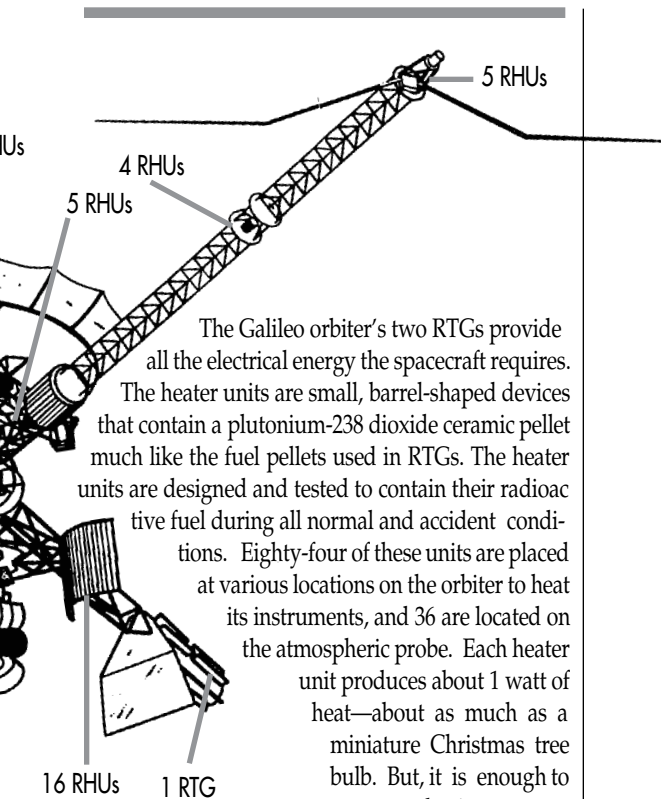


## Electricity and Heat

The effectiveness of Galileo's instruments depends not only on RTG power, but also on heat from radioisotope heater units (RHU). Because the journey is far from the sun, these compact, light, and long-lasting RTG and RHU units are the only effective power and heat sources for the Galileo mission.

Two RTGs provide electrical power to drive the Galileo spacecraft and its instruments. Each RTG produces about 285 watts of electricity at the beginning of the mission. One hundred and twenty small RHUs protect the craft's sensitive instruments from damage in the cold vacuum of outer space, which can reach -400 degrees Fahrenheit.





The Galileo orbiter's two RTGs provide all the electrical energy the spacecraft requires. The heater units are small, barrel-shaped devices that contain a plutonium-238 dioxide ceramic pellet much like the fuel pellets used in RTGs. The heater units are designed and tested to contain their radioactive fuel during all normal and accident conditions. Eighty-four of these units are placed at various locations on the orbiter to heat its instruments, and 36 are located on the atmospheric probe. Each heater unit produces about 1 watt of heat—about as much as a miniature Christmas tree bulb. But, it is enough to protect the instruments from the cold.

The Pioneer, Voyager, Ulysses, and Galileo missions have produced a huge amount of information about the history and makeup of the solar system. None could have been accomplished without RTGs, which have played a key role in helping the U.S. establish its position as the world leader in outer planetary and space science exploration.

RTG technology has evolved steadily and dramatically since the groundbreaking, low-power units of the 1950s. The first RTGs, which produced only a few watts, have evolved into today's generation of RTGs, which produce power in the hundreds of watts.

# The Missions

<u>Power Source</u>	<u>Spacecraft</u>	<u>Mission Type</u>	<u>Launch Date</u>
SNAP-3B7	Transit 4A	Navigational	June 29, 1961
SNAP-3B8	Transit 4B	Navigational	Nov. 15, 1961
SNAP-9A	Transit 5-BN-1	Navigational	Sept. 28, 1963
SNAP-9A	Transit 5-BN-2	Navigational	Dec. 5, 1963
SNAP-9A	Transit 5-BN-3	Navigational	April 21, 1964
SNAP 19B2	Nimbus-B-1	Meteorological	May 18, 1968
SNAP 19B3	Nimbus III	Meteorological	April 14, 1969
ALRH	Apollo 11	Lunar surface	July 14, 1969
SNAP-27	Apollo 12	Lunar surface	Nov. 14, 1969
SNAP-27	Apollo 13	Lunar surface	April 11, 1970
SNAP-27	Apollo 14	Lunar surface	Jan. 31, 1971
SNAP-27	Apollo 15	Lunar surface	July 26, 1971
SNAP-19	Pioneer 10	Planetary	March 2, 1972
SNAP-27	Apollo 16	Lunar surface	April 16, 1972
Transit-RTG	"Transit" (Triad-01-1X)	Navigational	Sept. 2, 1972
SNAP-27	Apollo 17	Lunar surface	Dec. 7, 1972
SNAP-19	Pioneer 11	Planetary	April 5, 1973
SNAP-19	Viking 1	Mars surface	Aug. 20, 1975
SNAP-19	Viking 2	Mars surface	Sept. 9, 1975
MHW-RTG	LES 8*	Communications	March 14, 1976
MHW-RTG	LES 9*	Communications	March 14, 1976
MHW-RTG	Voyager 2	Planetary	Aug. 20, 1977
MHW-RTG	Voyager 1	Planetary	Sept. 5, 1977
GPHS-RTG	Galileo	Planetary	Oct. 18, 1989
GPHS-RTG	Ulysses	Planetary/Solar	Oct. 6, 1990

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# - An Overview

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## Status

RTG operated for 15 years. Satellite now shut down but operational.

RTG operated for 9 years. Satellite operated periodically after 1962 high altitude test. Last reported signal in 1971.

RTG operated as planned. Non-RTG electrical problems on satellite caused satellite to fall after 9 months.

RTG operated for over 6 years. Satellite lost ability to navigate after 1.5 years.

Mission was aborted because of launch vehicle failure. RTG burned up on re-entry as designed.

Mission was aborted because of range safety destruct. RTG heat sources recovered and recycled.

RTGs operated for over 2.5 years.

Radioisotope heater units for seismic experimental package. Station was shut down August 3, 1969.

RTG operated for about 8 years until station was shut down.

Mission aborted on the way to the moon. RTG re-entered earth's atmosphere and landed in South Pacific Ocean. No radiation was released.

RTG operated for over 6.5 years until station was shut down.

RTG operated for over 6 years until station was shut down.

RTGs still operating. Spacecraft successfully operated to Jupiter and is now beyond orbit of Pluto.

RTG operated for about 5.5 years until station was shut down.

RTG still operating.

RTG operated for almost 5 years until station was shut down.

RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.

RTGs operated for over 6 years until lander was shut down.

RTGs operated for over 4 years until relay link was lost.

RTGs still operating.

RTGs still operating.

RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, Neptune, and beyond.

RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.

RTGs still operating. Spacecraft en route to Jupiter.

RTG still operating. Spacecraft en route to solar polar flyby.

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## Power in Space—The Special Requirements

Scientific instruments and electronic, photographic, and communication equipment are the heart of exploratory missions because they collect the data and transmit it back to Earth. Without the technology to reliably power these instruments in space, our knowledge of the solar system would be only a fraction of what it is today. RTG technology was developed to provide that electric power.

Requirements for power in space are highly specialized. The weight and volume of hardware launched into space are carefully considered, including power sources. The generator must meet mission power requirements, as well as weight and space limitations. Safety is also a prime consideration because of hazards associated with launch, re-entry, and other mission activities.

### How Does an RTG Work?

An RTG has no moving parts. It produces electric energy through the interaction of its two main components: the radioactive heat source (fuel and containment) and the thermoelectric generator.

Radioactive material can be used for fuel because it is unstable and decays, or spontaneously disintegrates into a different atomic form. As the material naturally decays, it produces heat. The other main component of the RTG, the thermoelectric generator, converts this heat into electricity.

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This heat-to-electricity conversion occurs through the thermoelectric principle discovered early in the last century. This principle is a way of producing electric current without using a device that has moving parts. It involves two plates, each made of a different metal that conducts electricity. Joining these two plates to form a closed electrical circuit and keeping the two junctions at different temperatures produces an electric current. These pairs of junctions are called thermocouples. In an RTG, the radioisotopic fuel heats one of these junctions while the other junction remains unheated and is cooled by space.

RTGs are reliable because they produce electricity without moving parts that can fail or wear out. This high degree of reliability is especially important in space applications, where the investment is great, and repair or replacement of equipment is not feasible.

## Pu-238—The Radioisotope of Choice for RTGs

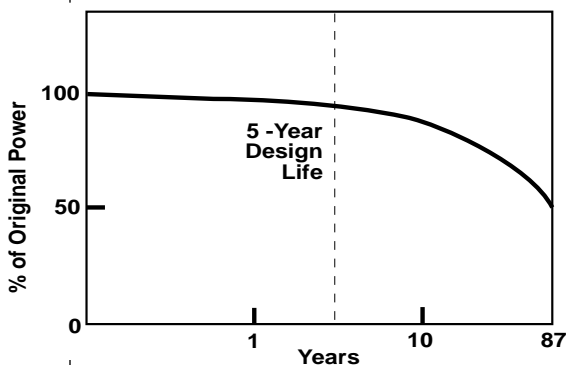
Although other radioactive fuels have been considered for RTGs, plutonium-238 (Pu-238) has been used most widely. Pu-238 is a radioactive isotope—a form of plutonium that gives off energy as rays and particles. It continues to be the radioactive fuel of choice today and in planned future missions.

What qualities make Pu-238 a good choice for fuel in an RTG? Its half-life is one of the most important. Half-life is the time it takes for half of the radioactive material to decay.

Polonium-210, which was used in the early SNAP-3 RTG, has a half-life of 138.4 days. At the end of that time, the amount of radioactive material remaining is half of the original amount. This means there is only half the heat available for conversion into electric energy.

Longer space missions require a radioisotope with a longer half-life. Pu-238, with its half-life of 87.7 years, fills the need. For example, after five years, approximately 96 percent of the original heat output of Pu-238 is still available.

The 87-year half-life of Pu-238 results in 96% of the original heat output even after five years



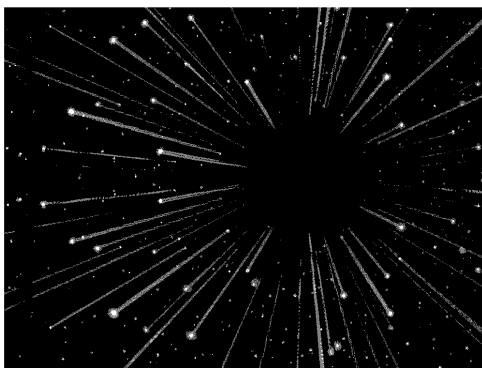
## Safety Issues

Because the nuclear fuel in RTGs is radioactive, safety is a critical issue. As it decays, Pu-238 emits radiation mainly in the form of alpha particles, which have a very low penetrating power. Only lightweight shielding is necessary because alpha particles cannot penetrate a sheet of paper. Radioisotopes producing more penetrating radiation, such as beta or gamma particles, would be more difficult to handle safely and would require heavier shielding, a distinct drawback on space missions.

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## Smaller and Lighter Power

The weight and volume of solar panels can cause problems on some space missions. With RTGs, weight and volume are far less of a concern. Pu-238 has a relatively high power density, and a given volume or weight of Pu-238 can produce a relatively high number of watts of power for long periods of time. These qualities lead to smaller and lighter heat sources than comparable power levels from other sources. This makes Pu-238 fuel an efficient power producer for the space it occupies and the weight it adds to a mission.



## RTGs— The Safety Factor

Any penetrating radiation that escapes a radioisotope heat source is of potential concern. RTG safety efforts revolve around containing the radioactive fuel in case of accident during a critical time in the mission, such as launch or re-entry. Multiple layers of special material enclose the plutonium-238 fuel to contain it under both normal and accident conditions. Extensive testing and analysis are used to demonstrate that safety design criteria are met. Today we design to have the fuel capsule remain intact even after Earth re-entry and impact. The Apollo 13 accident and subsequent re-entry of the RTG, without any material release, provided further proof of this safety principle.

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## General Purpose Heat Source

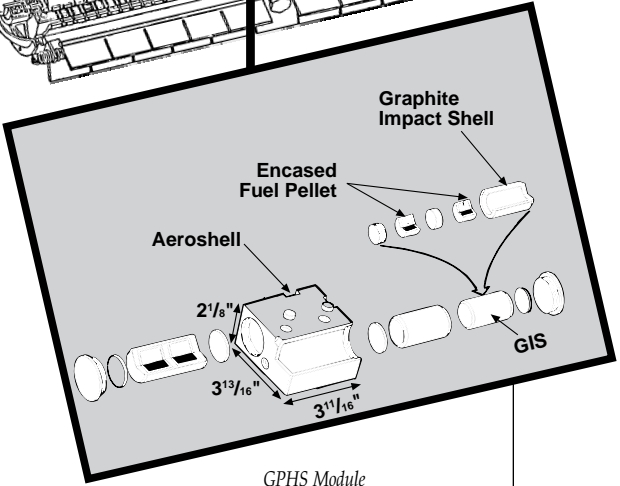
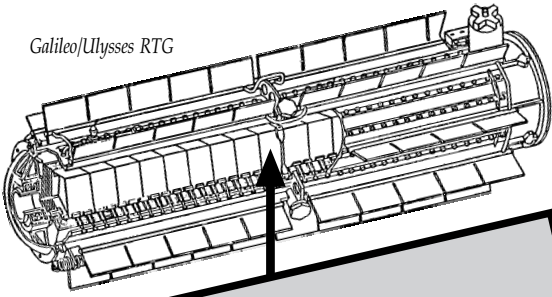
The general purpose heat source (GPHS) is the radioactive fuel package being used in RTGs of current and planned space missions. GPHSs use Pu-238 fuel just as earlier-model RTGs did, but the unique fuel containment is designed to maximize safety in an accident. The basic heat source unit is the GPHS module. Each GPHS/RTG contains 18 modules.

Design features include:

- Fuel pellets made of hard, ceramic plutonium-238 oxide that do not dissolve in water. The pellets are also highly resistant to vaporizing or fracturing into breakable particles following impact on hard surfaces. Each of the GPHS's 18 modules contains four fuel pellets, for a total of 72 pellets per GPHS RTG.
- Iridium, a very stable metal with elastic properties that encapsulates each fuel pellet. These capsules (about the size and shape of a marshmallow) would tend to stretch or flatten instead of ripping open if the GPHS module struck the ground at high speed. This would help keep the capsules intact and contain the fuel.
- A high-strength graphite cylinder called a graphite impact shell that holds a pair of fuel pellets. The graphite impact shell is designed to limit damage to the iridium fuel capsules from free-fall or explosion fragments.
- An "aeroshell," which encloses a pair of graphite impact shells. It serves as a shield designed to withstand the heat of re-entering Earth's atmosphere in case of an accident.



Galileo/Ulysses RTG



GPHS Module

Each of the RTG's 18 modules contains four Pu-238 fuel pellets enclosed in three layers of protection -- the metal encasing the pellets, the graphite shell, and the aeroshell.

## Testing the Possibilities

The nuclear fuel in the GPHS faces a variety of possible accidents during a space mission. Launch and re-entry pose many types of risks to the spacecraft and its components.

As a result, rigorous testing is conducted to ensure the RTG's nuclear fuel will survive a launch accident or other mishap, remain intact, and contain the fuel. The battery of tests that the GPHS's fuel modules have undergone included the effects of:

**Fire** - Direct exposure to solid propellant fires, such as the GPHS might encounter in a launch accident, produced minimal damage and no nuclear fuel release.

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**Blast** - Blast waves greater than those predicted from a shuttle fuel explosion were simulated with explosives; no fuel was released during the tests.

**Re-entry** - The modules survived the high temperatures of simulated atmospheric orbital decay entry, as tested in an arc-jet furnace; no fuel was released.

**Earth Impact** - Impact at 120 miles per hour (approximate top speed for an aeroshell falling to Earth) on sand, water, or soil produced no release of heat source module fuel. Impact on rock and concrete sometimes produced releases, but much of the fuel was retained by the surrounding graphite module, leaving only small amounts of low-level radioactive material to enter the localized environment.

**Immersion in Water** - Long-term exposure to the corrosive effects of seawater showed the iridium capsule is corrosion-resistant and the fuel itself is highly insoluble.

**Shrapnel** - Researchers used aluminum and titanium bullets to simulate the small fragments that might be present in a launch vehicle explosion. Speeds of test fragments exceeded those predicted for an actual explosion. Results indicated that shrapnel would not cause a release of nuclear fuel.

**Large Fragments** - In tests representing solid rocket booster failures, steel plates were fired at simulated RTGs. Some unlikely events, such as impact with the edges of steel plates, caused some release in a few fuel capsules. More likely events, such as impacts with the faces of steel plates, did not produce a release.

The safety tests demonstrated that the RTGs are extremely rugged and capable of meeting the design objective *to prevent or minimize any fuel release.*

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# The Future of RTGs in Space

## The Technology

Other nuclear generator technologies for space applications have been under investigation. These technologies involve more efficient conversion of heat into electricity. Safety and reliability are key factors in determining the possible value of each technology in space missions.

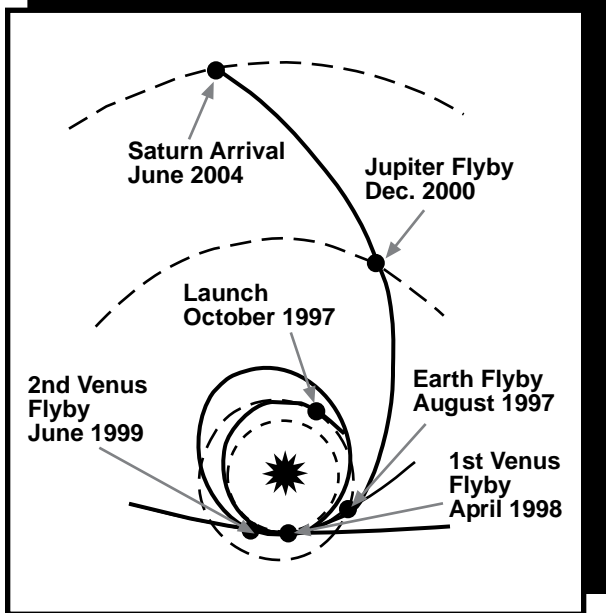
One option is the dynamic isotope power systems (DIPS), which are much more efficient in converting heat into electricity than the RTGs used on recent missions. The dynamic systems have moving parts that transform heat into mechanical energy, which is used to generate electricity. One such engine, the Stirling engine, contains helium that expands by absorbing heat on the hot side of the engine and rejecting it on the cold side. The rapidly changing pressure cycles cause a piston to move back and forth, driving an alternator and producing electricity.

The range of technologies under investigation is wide. For instance, a process called Alkaline Metal Thermal to Electric Conversion (AMTEC) converts infrared radiation into electricity using liquid metal ions, which are charged atoms. By contrast, the thermo-photovoltaic (TPV) converter changes infrared radiation emitted by a hot surface into electricity. Design goals for AMTEC and TPV technology call for even more efficient conversion of heat into electricity of about 20-30%, or a three-fold increase over RTGs.

The higher efficiencies of these new technologies mean that future spacecraft may require less Pu-238 than RTGs typically use. This makes these new space power technologies highly attractive due to lower weight and less radioactive material for the same power output.

## The Cassini Mission to Saturn

The Cassini mission is scheduled to begin in October 1997 when a Titan IV launch vehicle lifts its payload into orbit. The mission is a joint U.S.-European venture to explore Saturn in detail, a journey that will take nearly seven years. Like Galileo, Cassini will use gravity-assists from other planets to achieve the necessary speed to reach Saturn. Cassini will employ four flybys: two by Venus, one by Earth, and one by Jupiter, to reach its destination in deep space.



*Cassini Mission. Four flybys will enable the Cassini spacecraft to reach Saturn, its destination in deep space.*

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Scientists have an intense interest in the Saturnian system—an interest beyond the planet’s vast and beautiful system of rings. Saturn’s largest and most intriguing moon, Titan, has a dense atmosphere that resembles the Earth’s early atmosphere, and some scientists suggest there may be oceans on Titan.

Cassini consists of an orbiter and a probe. The probe, named Huygens after the Dutch scientist who discovered Titan in 1659, will descend by parachute to the surface of Titan late in 2004. It will beam data to the orbiter during descent and after landing. Once there, it will examine the surface of Titan with three dozen sensors.

After releasing the Huygens probe for descent to Titan, the Cassini orbiter will explore the Saturnian system for nearly four years, flying some 60 orbits of the giant planet during that time. The electrical energy to power Cassini’s mission equipment, including all its communications and scientific sensors, will come from three RTG units that provide a total of 850 watts of power.

One way the craft uses this energy is to control its data-gathering systems. For example, it can point sensors to accuracies of a 10th of a degree, maintain stability levels over 10 times slower than the motion of a clock’s hour hand, navigate to accuracies of 30 kilometers (about 20 miles), and broadcast data to Earth at rates as high as 140,000 bits per second.

## Future Requirements

NASA has identified a number of potential missions that can best or only be undertaken using radioisotope power and/or heat sources. These future missions depend upon two important conditions.

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First, there must be a reliable and continuing supply of Pu-238 fuel from the U.S. Department of Energy. U.S. facilities that could supply Pu-238 are being considered, as are foreign sources such as Russia, England, and France.

Second, smaller and more efficient power systems will have to be developed consistent with NASA's needs.

## Conclusion

RTGs have made vital contributions to the U.S. space program from its earliest days to the present. And they are slated for service on future projects such as the 1997 Cassini mission to Saturn, Mars Pathfinder, and Pluto Express.

For many missions on which RTGs were used, there was no other viable option for providing power. These missions include Apollo, Viking, Pioneer, Voyager, Galileo, and Ulysses, which have provided scientists with critical information about the origins of the solar system.

Nuclear fuel has proven to be an ideal source of energy in space because of its high power, acceptable weight and volume, and excellent reliability and safety when used in RTGs.

Because of its many advantages, it seems likely that nuclear energy will continue to provide power on space missions into the next century, whether in RTGs, other advanced generators, or nuclear reactors.



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