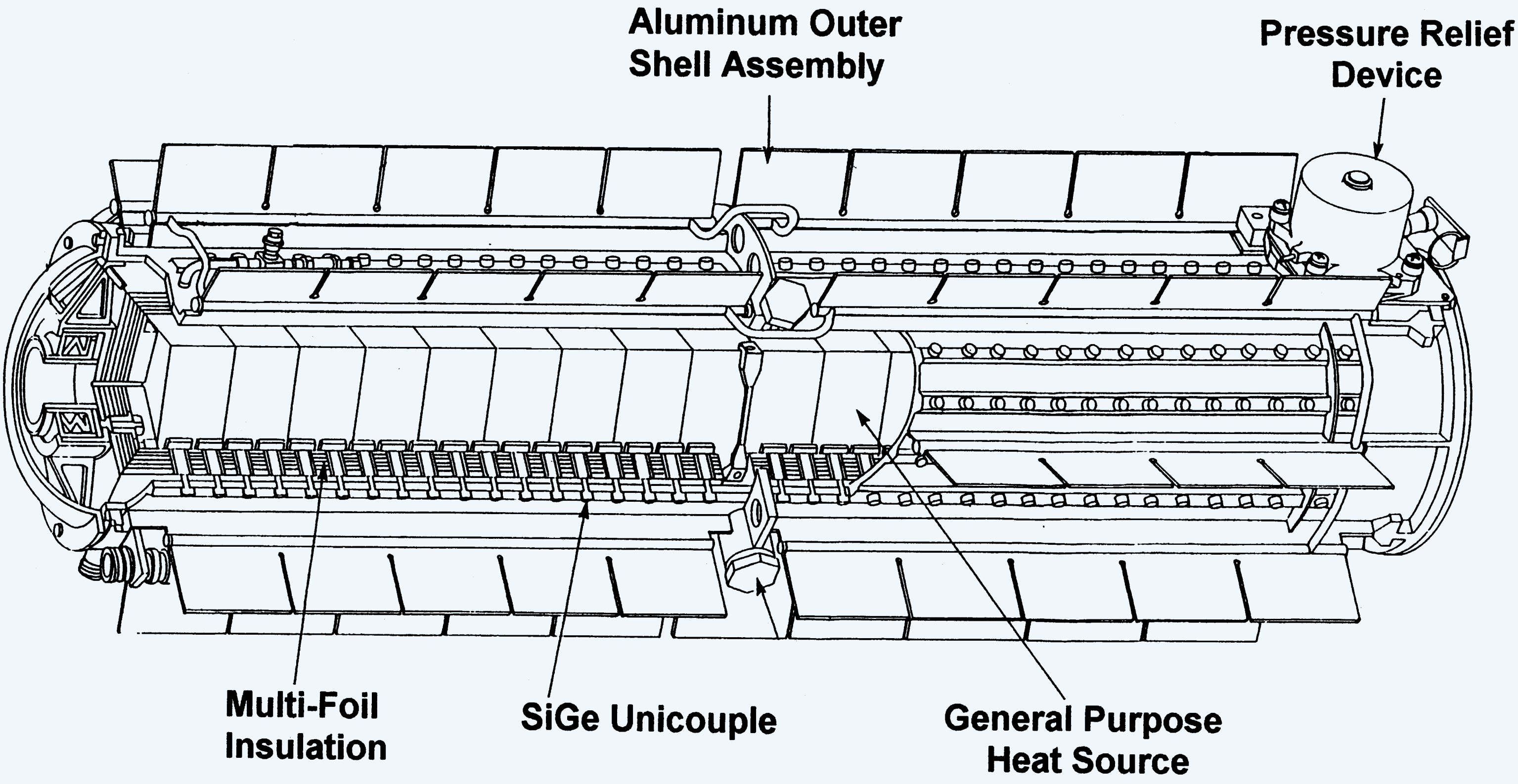

Radioisotope thermoelectric generator (RTG). The length is 44.5 in (113 cm), the diameter is 16.8 in (42.7 cm), and the weight is 124 lb (56.2 kg). (Source: DOE)

U.S. space missions using radioisotope power systems

BY RICHARD R. FURLONG
AND EARL J. WAHLQUIST

Twenty-six U.S. space missions have used nuclear power systems to take spacecraft to places scientists otherwise would not be able to study.

The U.S. Department of Energy and its predecessors have provided nuclear power systems for use in space for about 38 years. These systems have proven to be safe, reliable, maintenance-free, and capable of providing both thermal and electrical power for decades under the harsh environment experienced in deep space.

The unique characteristics of these systems make them especially suited for environments where large solar arrays are not practical, and at long distances from the Sun. To date, the DOE has provided radioisotope power systems and heater units for use on a total of 26 missions to provide some or all of the spacecraft on-board power and heating of critical spacecraft components.

Early program history

Radioisotope power systems have been providing primary spacecraft power for many unique space missions since 1961. In the mid-1950s, research was started on ways to use nuclear energy to generate electrical power for spacecraft. This research resulted in the development of radioisotope thermoelectric generators (RTGs), which are nuclear power generators that convert heat generated by the natural decay of a radioisotope fuel (plutonium-238) into electricity through the use of thermoelectric couples.

The first two space flights with RTGs were the Navy's Transit 4A and 4B navigational satellites, launched in June and November 1961. A 3-watt RTG, which was called Systems for Nuclear Auxiliary Power (SNAP-3), was flown on each spacecraft to prove the operational capability of the RTGs in a space environment. On subsequent flights beginning in 1963, RTGs provided total electrical power for the spacecraft. The DOE and its predecessor agencies have provided radioisotope power systems for missions orbiting Earth, on the Moon, and other solar system bodies. Five *Apollo* missions used RTGs to power the *Apollo* Lunar Surface Experiment Packages. RTGs provided primary electrical power on the *Viking* landers and the *Pioneer, Voyager, Galileo, Ulysses,* and *Cassini* spacecraft. These missions have given

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scientists throughout the world the opportunity to study and investigate the mysteries of the formation of our solar system.

In 1968, a *NIMBUS B-1* weather satellite was destroyed after its launch vehicle malfunctioned a few minutes into its flight from Vandenberg AFB, Calif. The satellite had two SNAP-19B2 RTGs on-board. The plutonium heat sources from the RTGs were recovered intact after five months in 300 feet of seawater, from the bottom of the Santa Barbara Channel near the California coast. No radioactive fuel was released. The heat sources were disassembled and repackaged, and the plutonium was used on the next mission. The photo shows the intact heat sources during the underwater recovery operation. (Source: JPL)

Why use RTGs?

Nuclear power sources are very important for use in space applications for many reasons:

- *Long life*—Nuclear power is the only power source currently available for spacecraft operating in deep space for long missions. Radioisotope power systems provide predictable power levels for mission planners to depend on (RTG power levels reduce about 0.8 percent per year based on the decay rate of Pu-238 fuel).
- *Environment*—Nuclear power sources can operate in extreme environmental conditions, such as the high-radiation belts surrounding Jupiter, extreme temperatures experienced on the moon, and severe dust storms seen on Mars.
- *Operational independence*—RTGs provide power to spacecraft without concern for where the spacecraft is in its orbit or how it is oriented in relation to the sun. An RTG begins to generate electrical power when the radioisotope fuel source is loaded in the converter. Therefore, it can be used for spacecraft system checkouts prior to launch and be available to provide power to the spacecraft when installed on the launch pad.
- *Reliability*—RTGs have proven to be the most reliable power systems ever flown on U.S. spacecraft. For example, the two *Pioneer* spacecraft operated for more than two decades before being shut down, and NASA is planning on an extended *Voyager* mission that could last up to 40 years.

How RTGs work

RTGs operate on the principle of thermoelectric generation that converts heat directly into electricity. The principle was discovered in 1821 by a German scientist, Thomas Johann Seebeck. He observed that an electric current is produced in a closed circuit when the junctions of two dissimilar metals are maintained at different temperatures. Such pairs of junctions are called thermoelectric couples, or thermocouples.

In the design of the RTGs flown on the *Galileo, Ulysses,* and *Cassini* missions, heat generated by the natural decay of the Pu-238 dioxide fuel is converted to electric power by silicon germanium (SiGe) thermoelectric couples or unicouples. A heat source module contains four Pu-238 fuel pellets, each weighing 151 g and encapsulated within a vented iridium clad. Eighteen heat source modules provide the total thermal inventory for an RTG with a heat output of about 4400 watts. The thermoelectric converter portion of the RTG consists of 572 thermoelectric unicouples wired in a two-string, series-parallel electric circuit. This configuration generates about 300 watts of electrical power at initial fuel loading.

Making RTGs

A number of DOE facilities, laboratories, and contractors were used in the development, fabrication, assembly, and testing of the RTGs for the *Cassini* program. The DOE facilities are located at Savannah River Plant (SRP), in Aiken, S.C.; Oak Ridge National Laboratory (ORNL), in Oak Ridge, Tenn.; Los Alamos National Laboratory (LANL), in Los Alamos, N.M.; the Mound Plant, in Miamisburg, Ohio; and Sandia National Laboratories, in Albuquerque, N.M.

The Pu-238 processing facilities at Savannah River were used to process the Pu-238 oxide fuel and package it for shipment to LANL. ORNL was responsible for fabricating iridium cladding that was used to encapsulate Pu-238 fuel pellets. ORNL also fabricated graphite components used in assembling the encapsulated fuel pellets into heat sources. At LANL, the Pu-238 was processed and pressed into fuel pellets. The pellets for the RTG heat sources were encapsulated in iridium cladding provided by ORNL. The encapsulated fuel pellets were shipped from LANL to the Mound Plant where they were assembled into heat sources. Mound completed the RTG assembly by installing a stack of heat sources into the thermoelectric converter built by Lockheed Martin Astronautics, of Valley Forge, Pa. After completion of the RTG assemblies, Mound personnel conducted final acceptance tests of the units, and then packaged and shipped them to the launch site where they were installed on the *Cassini* spacecraft.

RTG safety

Many design improvements have been made over the four decades that RTGs have flown on space missions. In addition to improving the efficiency of RTGs, the DOE conducted extensive safety testing—at Sandia National Laboratories and LANL—to assure that the systems would be safe under all accident conditions, including accidents occurring on or near the launch pad and orbital reentry accidents. The Pu-238 fuel form was changed from a metal to a more stable pressed oxide. During the three mission aborts that did occur, the RTGs performed as designed.

On April 21, 1964, the *Transit 5-BN-3* mission was aborted because of a launch vehicle failure resulting in burnup of the RTG during reentry, in keeping with the RTG design at the time. This resulted in dispersal of the plutonium fuel in the upper atmosphere. Subsequently, the RTG design was changed to provide for survival of the fuel modules during orbital reentry.

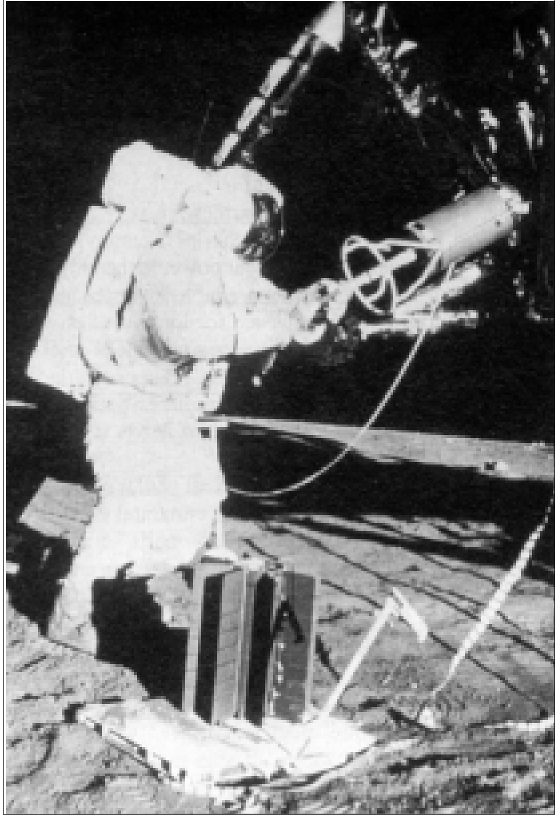
A second accident occurred when the *Nimbus B-1* launch on May 18, 1968, at Vandenberg AFB, Calif., was aborted shortly after launch by a range safety destruct of the vehicle. The heat sources were recovered intact in about 300 feet of water off the California coast with no release of plutonium. The fuel capsules were reworked and the fuel was used in a later mission.

The third incident occurred in April 1970, when the *Apollo 13* mission to the moon was aborted following an oxygen tank explosion in the spacecraft service module. Upon return to Earth, the *Apollo 13* lunar excursion module with a SNAP-27 RTG on board reentered the atmosphere and broke up above the south Pacific Ocean. The graphite reentry cask containing the heat source plunged into the ocean in the vicinity of the Tonga Trench, where the ocean depth is five to six miles. Atmospheric and oceanic monitoring showed no evidence of release of nuclear fuel.

Continued

Power Source	# of RTGs	Spacecraft	Mission Type	Launch Date	Status
SNAP-3	1	Transit 4A	Navigational	6/29/61	Currently in orbit.
SNAP-3	1	Transit 4B	Navigational	11/15/61	Currently in orbit.
SNAP-9A	1	Transit 5BN-1	Navigational	9/28/63	Currently in orbit.
SNAP-9A	1	Transit 5BN-2	Navigational	12/5/63	Currently in orbit.
SNAP-9A	1	Transit 5BN-3	Navigational	4/12/64	Mission aborted. Heat source burned up on reentry as designed.
SNAP-19	2	Nimbus B-1	Meteorological	5/18/68	Mission aborted and heat source retrieved.
SNAP-19	2	Nimbus III	Meteorological	4/14/69	Currently in orbit.
ALRHU	Heater	Apollo 11	Lunar	7/16/69	On lunar surface.
SNAP-27	1	Apollo 12	Lunar/ALSEP	11/14/69	On lunar surface. Station shut down.
SNAP-27	1	Apollo 13	Lunar/ALSEP	4/11/70	Mission aborted. Heat source jettisoned into the Pacific Ocean.
SNAP-27	1	Apollo 14	Lunar/ALSEP	1/31/71	On lunar surface. Station shut down.
SNAP-27	1	Apollo 15	Lunar/ALSEP	7/26/71	On lunar surface. Station shut down.
SNAP-19	4	Pioneer 10	Planetary	3/2/72	Successfully operated to Jupiter and beyond the solar system.
SNAP-27	1	Apollo 16	Lunar/ALSEP	4/16/72	On lunar surface. Station shut down.
Transit-RTG	1	Triad-01-1X	Navigational	9/2/72	Currently in orbit.
SNAP-27	1	Apollo 17	Lunar/ALSEP	12/7/72	On lunar surface. Station shut down.
SNAP-19	4	Pioneer 11	Planetary	4/5/73	Successfully operated to Jupiter, Saturn and beyond the solar system.
SNAP-19	2	Viking 1	Mars Lander	8/20/75	On Martian surface. Lander shut down.
SNAP-19	2	Viking 2	Mars Lander	9/9/75	On Martian surface. Lander shut down.
MHW-RTG	2, 2	LES 8, LES 9	Communication	3/14/76	Currently in orbit.
MHW-RTG	3	Voyager 2	Planetary	8/20/77	Successfully operated to Neptune and beyond the solar system.
MHW-RTG	3	Voyager 1	Planetary	9/5/77	Successfully operated to Saturn and beyond the solar system.
GPHS-RTG	2	Galileo	Planetary	10/18/89	Successfully operating, orbiting Jupiter.
GPHS-RTG	1	Ulysses	Planetary	10/6/90	Successfully operated to the Sun's polar regions, mission continuing.
LWRHU	Heater	Mars Pathfinder	Mars Lander	12/4/96	Successfully operated on Mars.
GPHS-RTG	3	Cassini	Planetary	10/15/97	Successfully operating, on route to Saturn.

U.S. spacecraft launches involving radioisotope systems (Source: DOE)



Deployment of the SNAP-27 RTG during the *Apollo 12* moon mission, on November 19, 1969 (Source: NASA)

The missions

Apollo

Radioisotope power was used on six successful *Apollo* landings on the moon. Beginning with the *Apollo 11* mission in July 1969 and ending with the *Apollo 17* mission in December 1972, radioisotope power systems were an integral and important part of the lunar exploration program. On the first lunar landing, *Apollo 11,* radioisotope heater units (RHUs) were used to provide heating of critical components in a seismic experiment package.

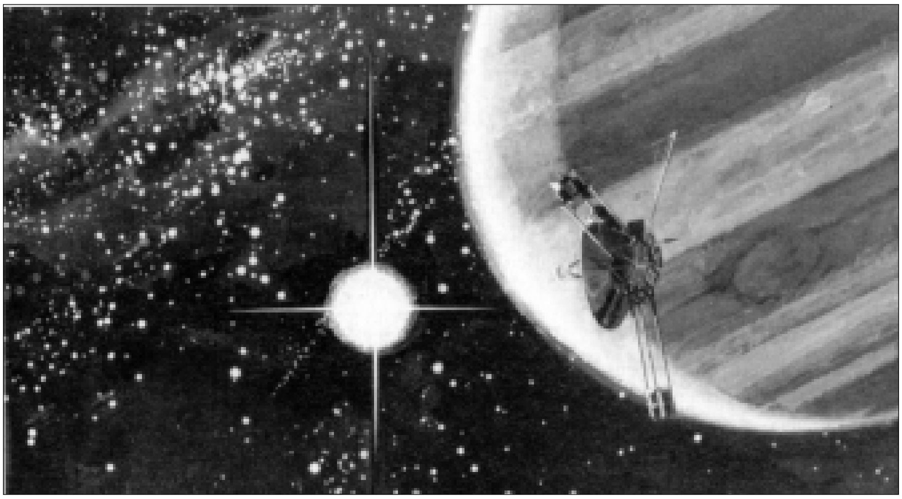
RTGs were employed on the *Apollo 12, 14, 15, 16* and *17* missions to power the *Apollo* Lunar Surface Experiment Packages (ALSEPs). The SNAP-27 RTG, used in the ALSEPS, was designed to supply about 63 watts of power at 16 VDC one year after placement on the lunar surface. Use of RTGs was a natural choice because of their light weight, reliability, and ability to produce full power during the long lunar night-day cycles. Because the ALSEPs were to be positioned on the moon by astronauts, the RTGs were designed to be assembled after landing. The converter and sealed fuel capsule were kept separate in the Lunar Module and assembled on the moon.

The SNAP-27 RTGs powering ALSEPs exceeded their mission requirements in both power output and lifetime. All five ALSEPs were operating when NASA shut down the stations on September 30, 1977.

Pioneer

The *Pioneer 10* and *11* missions, launched in 1972 and 1973, respectively, were spectacular successes in the long-range strategy to explore the outer planets. Each spacecraft was powered by four SNAP-19 RTGs that delivered approximately 165 watts of total electrical power at launch.

Pioneer 10 was the first spacecraft to survive passage through the asteroid belt and the intense radiation environment at Jupiter. After its investigation of Jupiter, *Pioneer 10* began an escape trajectory from the solar system. On February 1, 1999, *Pioneer 10* was about 72 astronomical units (AUs) from the Sun (1 AU equals 93 million miles, the distance from Earth to Sun), heading away from the Sun at 2.6 AU/year. Routine tracking and data processing operations were terminated on March 31, 1997 for budgetary reasons. *Pioneer 10,* however, is still occasionally tracked for training purposes. *Pioneer 10* and its RTGs continue to operate 27 years after launch!



Artist's conception of the *Pioneer 10* Jupiter flyby (Source: NASA)

Pioneer 11 was the second mission to investigate Jupiter and the first to explore the planet Saturn and its rings. During its closest approach on December 4, 1974, *Pioneer 11* passed to within 34 000 km (about 21 000 miles) of Jupiter and passed by Saturn on September 11, 1979, at a distance of 21 000 km (about 13 000 miles). Science operations and daily telemetry ceased on September 30, 1995, when the RTG power level was insufficient to operate any experiments. These spacecraft were the first manmade objects to pass the orbit of Pluto and enter interstellar space.

Viking

NASA's two *Viking* missions to Mars, *Viking 1* and *Viking 2,* each had an orbiter and a lander. *Viking 1* was launched on August 20, 1975, and *Viking 2* on September 9, 1975. Although the orbiters were solar-powered, each lander was powered by two SNAP-19 RTGs, delivering a total of approximately 85 watts of electrical power. The primary objectives of the mission were to obtain high-resolution images of the Martian surface, characterize the structure and composition of the atmosphere and surface, and search for evidence of life.

After each *Viking* spacecraft orbited Mars and returned images to Earth, NASA selected a landing site for each lander. The orbiters and landers were separated, and the landers entered the Martian atmosphere and soft landed at the chosen sites. The orbiters imaged the entire surface of Mars. The landers transmitted higher resolution images of the landing area, took surface samples and analyzed them for composition and signs of life, studied atmospheric composition and meteorology, and deployed seismometers.

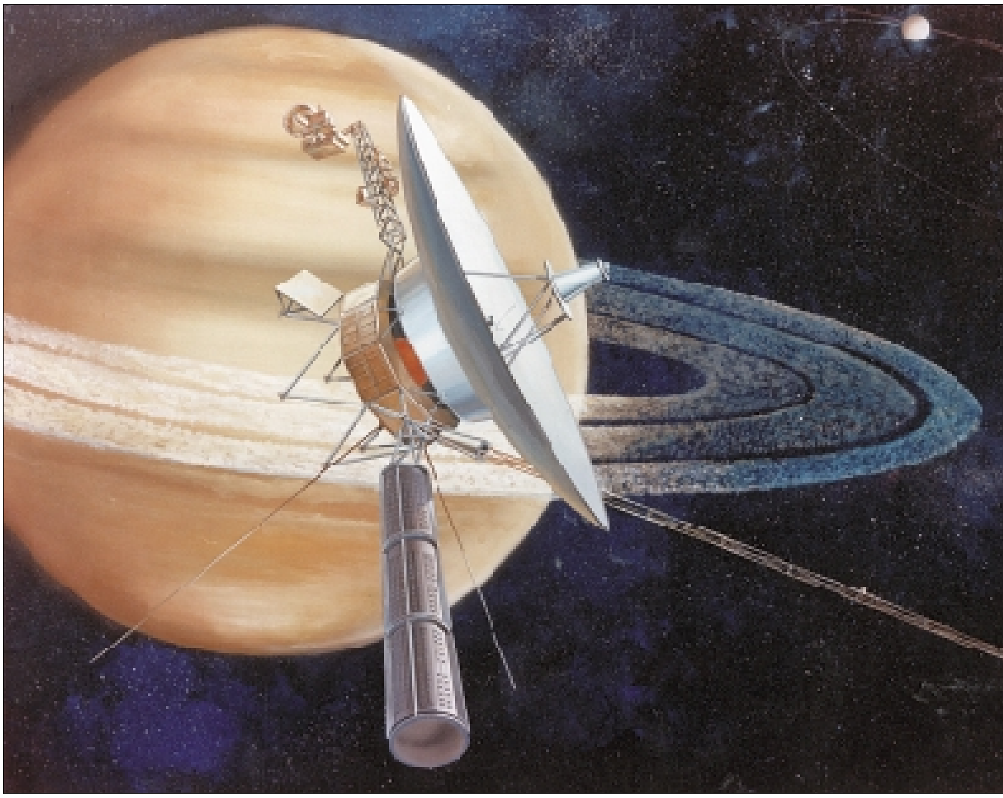
The *Viking 2* orbiter was powered down on July 25, 1978, after 706 orbits, and the *Viking 1* orbiter on August 17, 1980, after more than 1400 orbits. The *Viking 2* lander shut down operations on April 11, 1980, and *Viking 1* on November 13, 1982, after transmitting more than 1400 images of the two landing sites. The results from the two *Viking* missions gave scientists an extensive view of Mars.

Voyager

Voyager 1 and *Voyager 2* were launched in August and September 1977. These spacecraft required a significant increase in power over previous RTG missions and an operational life of at least four years after launch to achieve mission objectives of exploration of Jupiter, Saturn, Uranus, and Neptune. Mission requirements led to the development of the multihundred-watt (MHW) RTG.

The MHW-RTG contained a new heat source of 24 pressed plutonium oxide fuel spheres. Conversion of the decay heat of the plutonium to electrical power was accomplished through 312 silicon-germanium (SiGe) thermoelectric couples. The design thermoelectric couple hot junction temperature was 1273 K (1832 °F) with a cold junction temperature of 573 K (572 °F). Each MHW-RTG provided approximately 157 watts of power at beginning of mission.

The *Voyager* missions successfully completed all of their objectives by the end of 1989 with the close flyby of Neptune by the *Voyager 2* spacecraft. With the continuing healthy operation of the RTG power system and spacecraft scientific instruments, NASA designed a significantly extended mission for the *Voyager* spacecraft called the *Voyager* Interstellar Mission (VIM). VIM has the potential for obtaining useful science data on interplanetary and interstellar magnetic fields, charged particles, and plasma waves until about the year 2020, when the RTGs' ability to generate adequate electrical power for spacecraft operation will come to an end, more than 40 years after launch! To date, the *Voyager* spacecraft have traveled through space more than 15 billion miles.



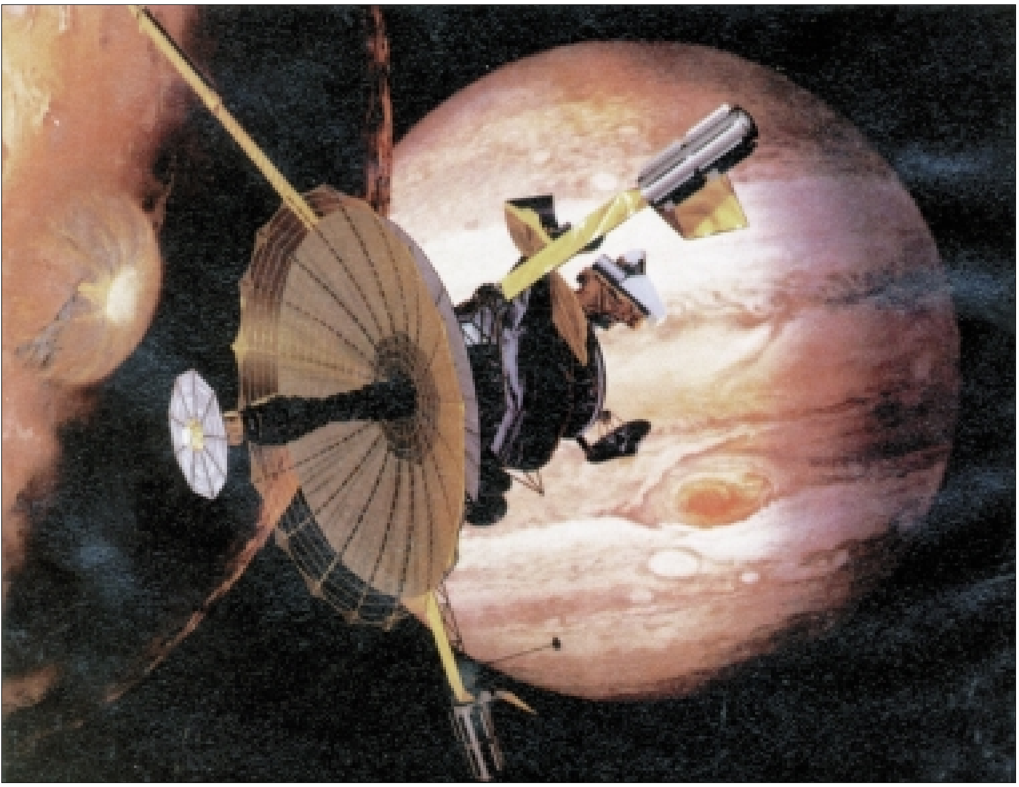
Artist's conception of a *Voyager* spacecraft during Saturn flyby (Image courtesy of DOE)

Galileo

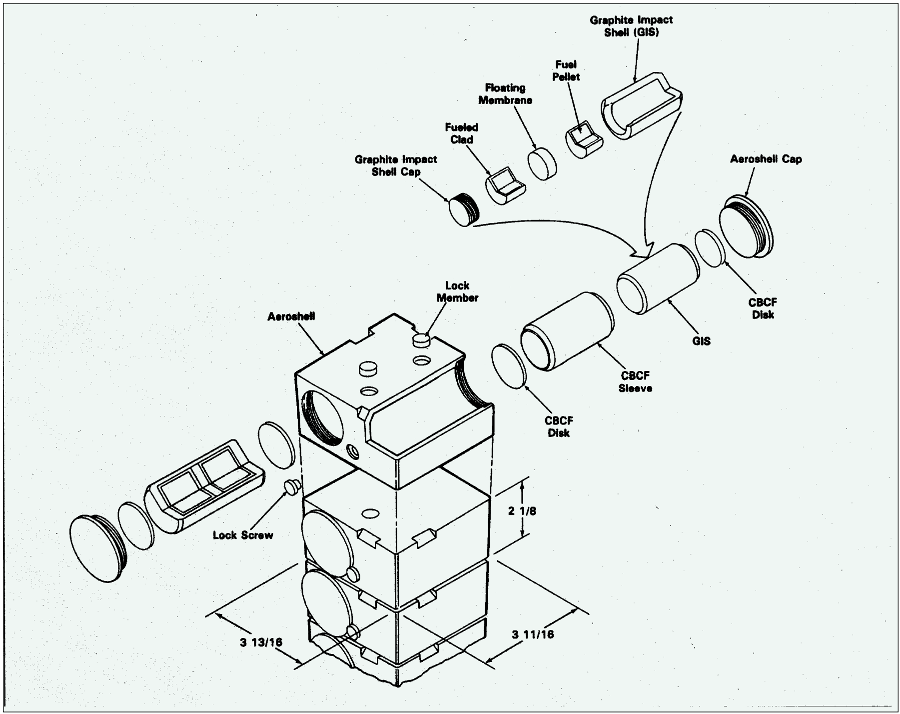
The *Galileo* spacecraft was launched aboard the Space Shuttle *Atlantis* (STS-34) on October 18, 1989. The *Galileo* mission was designed to investigate the Jovian system—the largest planet in our solar system, Jupiter, and four of its major moons: Io, Europa, Ganymede, and Calisto. The spacecraft consisted of a Jupiter Orbiter and an Atmospheric Entry Probe.

To meet the larger power requirements of space missions such as *Galileo* and *Ulysses,* the DOE developed the general purpose heat source (GPHS) RTG. The GPHS-RTG was designed using similar heat-to-electrical conversion technology successfully demonstrated by the MHW-RTGs flown on the Voyager missions. Using SiGe unicouples and the Pu-238–fueled GPHS, the GPHS-RTGs were built to deliver approximately 300 watts of electrical power with a nominal fuel loading yielding about 4400 watts of thermal energy.

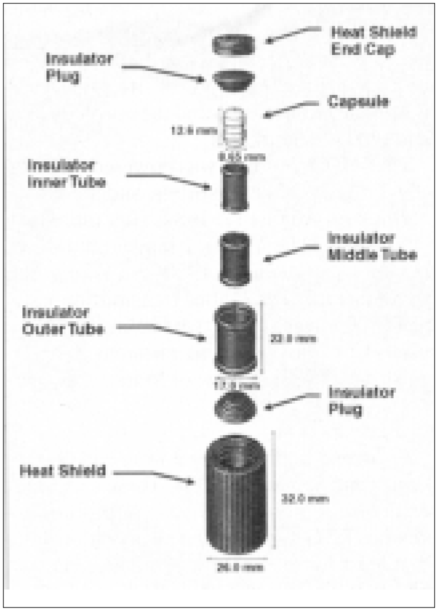
In addition to providing the total electrical power to operate the spacecraft's instruments, communications, and other power demands, 120 lightweight radioisotope heater units (LWRHUs) were used to provide temperature control of sensitive electronic components. LWRHUs consist of a 2.68-g Pu-238 dioxide fuel pellet that produces 1 watt of heat output. Each fuel pellet is encapsulated in a platinum-rhodium cladding and encased in a multilay-



Artist's conception of *Galileo,* near Jupiter and a Jovian moon (Image courtesy of DOE)



General purpose heat source (GPHS) module assembly (Source: DOE)



Lightweight radioisotope heater unit (LWRHU) (Source: DOE)

er graphite containment to protect the pellet in the event of an accident.

On its six-year journey from Earth to Jupiter, the *Galileo* spacecraft followed a trajectory that used the gravity of planets to accelerate the spacecraft onto its final flight path to Jupiter. Inertial Upper Stage (IUS) rocket motors that were approved for shuttle flights were incapable of providing the necessary thrust to inject *Galileo* on a direct Earth-Jupiter transfer trajectory. Therefore, the trajectory designed for the *Galileo* mission included a Venus flyby in February 1990 and Earth flybys in December 1990 and December 1992 to attain the necessary velocity to reach Jupiter.

During the Earth flyby in December 1990, Galileo provided spectacular photographs of the Earth and Moon, the first photographs of the Earth and Moon together ever taken by an unmanned spacecraft. *Galileo* also provided the first closeup photographs of an asteroid, Gaspra, in 1993. On its approach to Jupiter in 1994, *Galileo* was in position to witness and record the only direct photographs ever taken of a comet colliding with a planet, the Shoemaker-Levy 9 comet collision with Jupiter in July 1994.

Galileo arrived at Jupiter on December 7, 1995. Five months before arriving at the giant planet, the atmospheric probe was released for its plunge into the Jovian atmosphere. When the *Galileo* spacecraft began its maneuvers to achieve orbit around Jupiter, it swung by the moon Io and fired its main engine.

Galileo has collected a vast array of scientific data about Jupiter and its four major moons. Examination of some of these data has indicated that Ganymede is the first moon found in the solar system to have its own magnetic field, and Europa may have an ocean beneath a relatively young surface of ice that may be only about 1-km (0.62-mile) thick in places.

Originally, *Galileo's* exploration of the Jovian system was to end on December 7, 1997, but since significant discoveries were found, especially those about Europa, the mission was extended for two years through the end of 1999, and has been named the *Galileo* Europa Mission (GEM). The GEM will complete its studies of Europa, fly by Calisto four times, and lower its orbit in preparation for two flybys of Io.

Ulysses

The *Ulysses* mission was a joint project of the European Space Agency, NASA, and the Jet Propulsion Laboratory. Launched by the Space Shuttle *Discovery* on October 6, 1990, *Ulysses* flew by Jupiter in February 1992, where a gravity assist maneuver lifted the spacecraft out of the ecliptic plane and into a polar orbit about the Sun. *Ulysses* flew over the south pole of the Sun in 1994, and over the North Pole in 1995. The primary studies of the mission resulted in a greater understanding of the behavior of sunspots, solar flares, solar X rays, solar radio noise, and the region known as the heliosphere, which is dominated by the solar wind.

Since existing launch vehicles were not capable of boosting the *Ulysses* spacecraft out of the ecliptic plane, it had to rely on the large gravity assist provided by Jupiter. Because *Ulysses* had to travel to Jupiter and attain a large solar orbit, where the sunlight is about 4 percent of that near Earth, solar arrays were not feasible. A GPHS-RTG of the same design as those flown on the *Galileo* spacecraft provided the required power for *Ulysses.*

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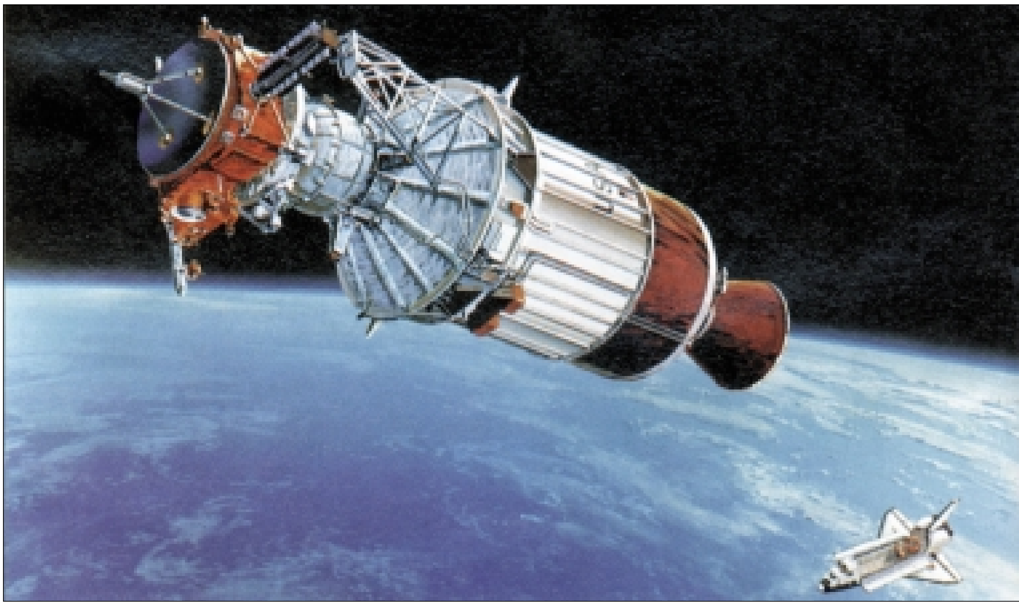


Artist's conception of the *Ulysses* spacecraft after release by the Space Shuttle *Discovery* (Image courtesy of DOE)

With the primary objectives of the *Ulysses* mission successfully accomplished, a second orbit of the Sun was initiated. This investigation will examine for the first time the high-latitude properties of the solar wind during the Sun's maximum solar activity cycle.

Mars Pathfinder

The *Mars Pathfinder* project was one of the first missions in the NASA Discovery Program. Launched on December 4, 1996, the *Mars Pathfinder* arrived at Mars and successfully landed on the Martian surface on July 4, 1997.

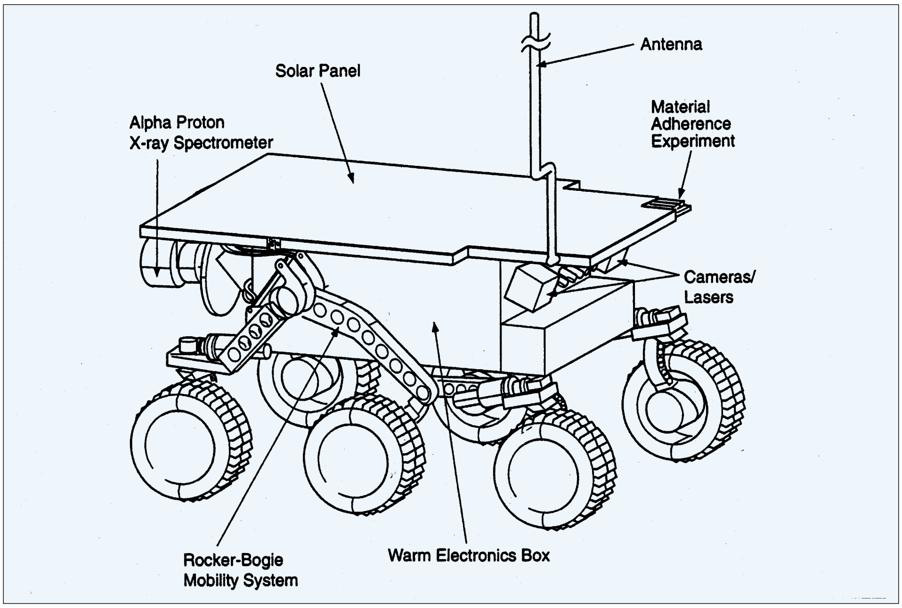
The first robotic rover sent to Mars, the *Sojourner,* was aboard the *Pathfinder* spacecraft. The rover was deployed from the lander to perform a number of experiments on the Martian soil and to demonstrate the ability of a rover to traverse the terrain in the vicinity of the lander.

Three LWRHUs were employed in the *Sojourner* Warm Electronics Box to maintain critical electronic component temperatures within their operating limits during the Martian nights. The LWRHUs, providing essential heat to the *Sojourner* electronics, were key components of the thermal design that enabled the rover to operate for 84 days, 12 times its design lifetime.

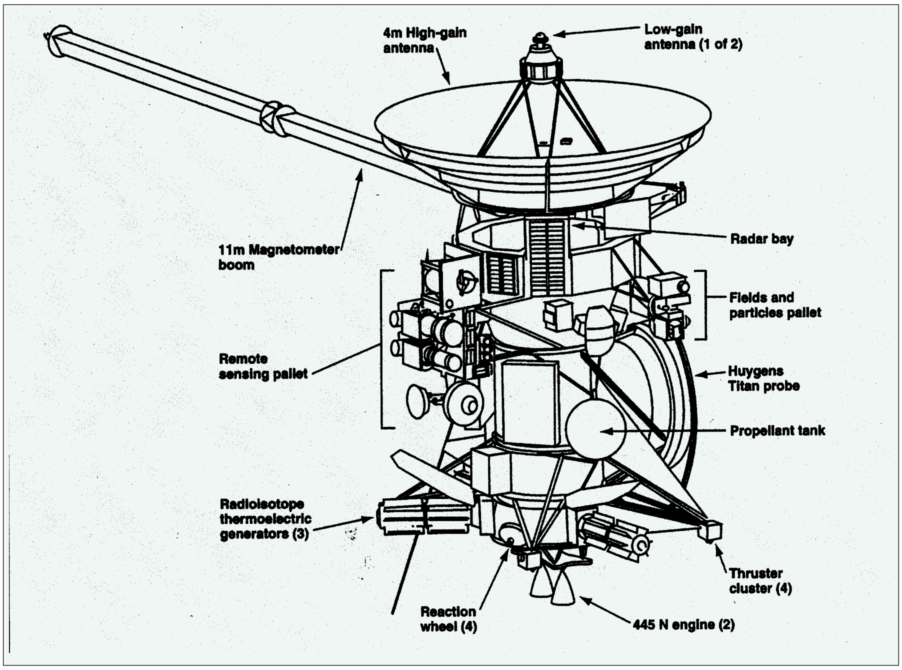
Cassini

The *Cassini* mission is an international cooperative project of NASA, the European Space Agency, the Italian Space Agency, and other academic and industrial partners throughout the world. The mission is managed for NASA by the Jet Propulsion Laboratory.

The goal of the *Cassini* mission is to conduct extensive studies of Saturn and its rings, moons, and magnetosphere, including a deployment of the Huygens probe to the giant moon Titan.



The *Sojourner* rover, part of the *Mars Pathfinder* mission (Source: NASA)



The *Cassini* spacecraft's major components (Source: JPL/NASA)

The *Cassini* spacecraft lifted off at Cape Canaveral Air Station on October 15, 1997, aboard a Titan IV/*Centaur* launch vehicle. *Cassini,* the largest NASA interplanetary spacecraft ever launched, will travel on an interplanetary voyage lasting nearly seven years, arriving at Saturn on July 1, 2004. The *Cassini* spacecraft and probe weighed about 5700 kg (6.3 tons) at liftoff, more than 50 percent of which was liquid fuel. The spacecraft measured more than 6.7 m (22 ft) high and more than 4 m (13.1 ft) wide.

Traveling to distant Saturn, the large spacecraft and probe required 3 GPHS-RTGs and 117 LWRHUs to provide the necessary electrical power to operate *Cassini's* instruments and systems and to maintain temperatures of critical equipment at acceptable levels in the severe cold of deep space. The 3 GPHS-RTGs delivered approximately 888 watts of total electrical power to the spacecraft at time of launch.

Cassini is another spacecraft that uses planetary gravity assists to attain the velocity and final trajectory necessary to complete its journey to Saturn. The spacecraft successfully completed a gravity assist from Venus on April 26, 1998, and will obtain another gravity assist from Venus on June 24, 1999, and from Earth on August 18, 1999, before getting its final gravity assist from Jupiter on December 30, 2000.

After arrival at Saturn, the *Cassini* mission will begin its four-year, closeup study of the Saturnian system. Studying the Saturnian system will help scientists find out how the planet and its rings and moons formed and evolved, and may provide many clues as to the origin of our solar system.

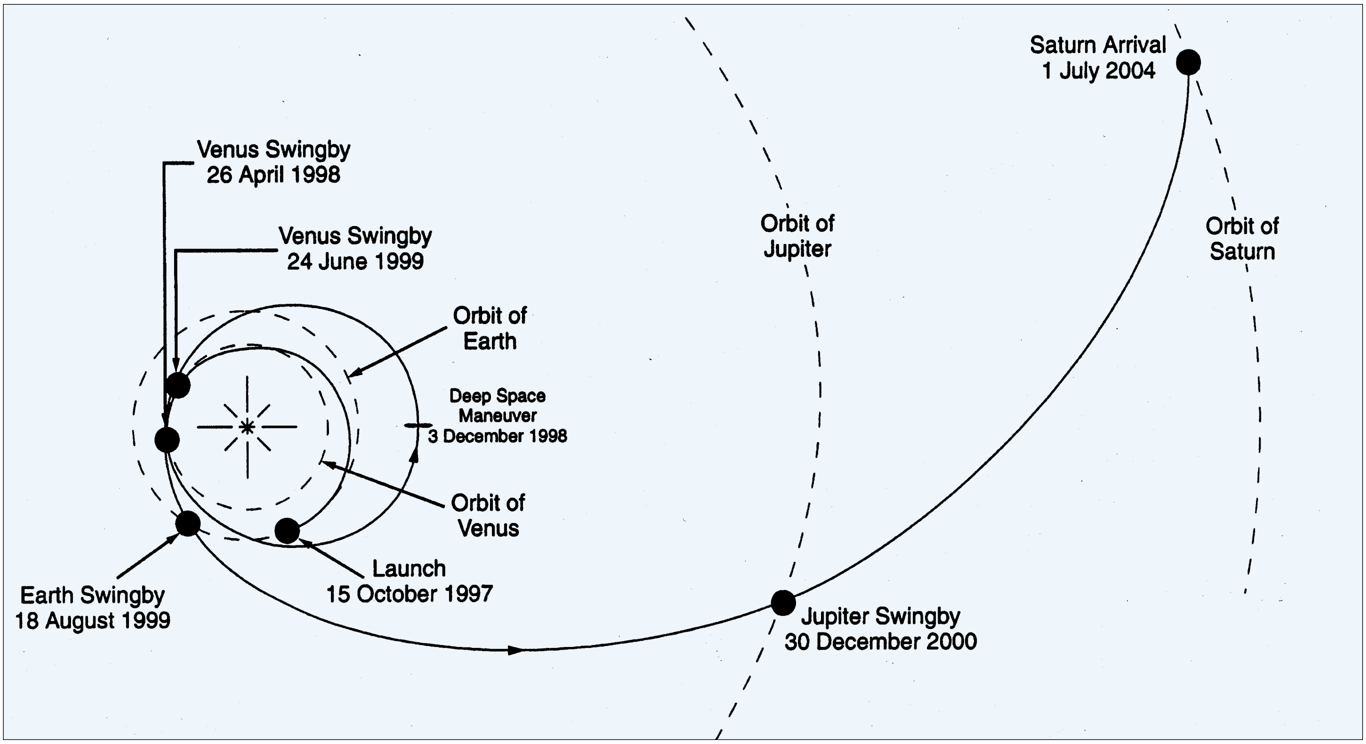
On November 4, 2004, the orbiter spacecraft will release the Huygens probe for its three-week trip to Titan. Upon entering Titan's atmosphere, the probe will deploy its parachute and slowly descend to the surface. The *Cassini* orbiter will receive data from the probe, where it will be stored and eventually relayed to Earth.

During the four-year mission, the *Cassini* spacecraft will conduct some four dozen close flybys of bodies of interest, including about three dozen encounters with Titan and several icy satellites. The orbiter will also make many distant flybys of other Saturnian moons. Changes in orbit inclinations will allow *Cassini* to study Saturn's polar regions and equatorial zone.

The 21st Century

A new program

The DOE Office of Space and Defense Power Systems has embarked on a new program to develop an advanced radioisotope power system (ARPS) that improves the efficiency of heat-to-electric-power conversion in a smaller, lighter-weight system. The system under development uses a technology known as alkali-metal-thermal-to-electric conversion (AMTEC). An ARPS generator will consist of a heat source (GPHS modules), AMTEC cells, and a housing designed for space operation.



Cassini trajectory from Earth to Saturn (Source: JPL/NASA)

The AMTEC cell (see figure, page 34) converts to electricity the heat delivered by the Pu-238 heat source by the following process. Each cell is made up of eight beta alumina solid electrolyte (BASE) tubes connected in series. The end of the cell at which the BASE tubes are located is mounted adjacent to the thermally hot end of the heat source. At this end, liquid sodium (Na) alkali metal is heated and takes the form of a vapor. As the sodium atoms in the vapor are driven through the walls of the BASE tubes, they are stripped of an electron, thus creating positively charged sodium ions (Na+). The vapor is cooled down and collected by a condenser at the cold end of the cell, and the cycle is repeated as the sodium fluid flows through the artery toward the hot surface at the other end of the cell. The cell is designed to use thermal shields located in the upper portion of the cell to reduce radiative bypass heat losses from the hot-side components to the cold-side condenser.

Leads are taken from the first and eighth tubes in series as the positive and negative leads for the cell. The electricity generated is then used to power the spacecraft systems and instruments.

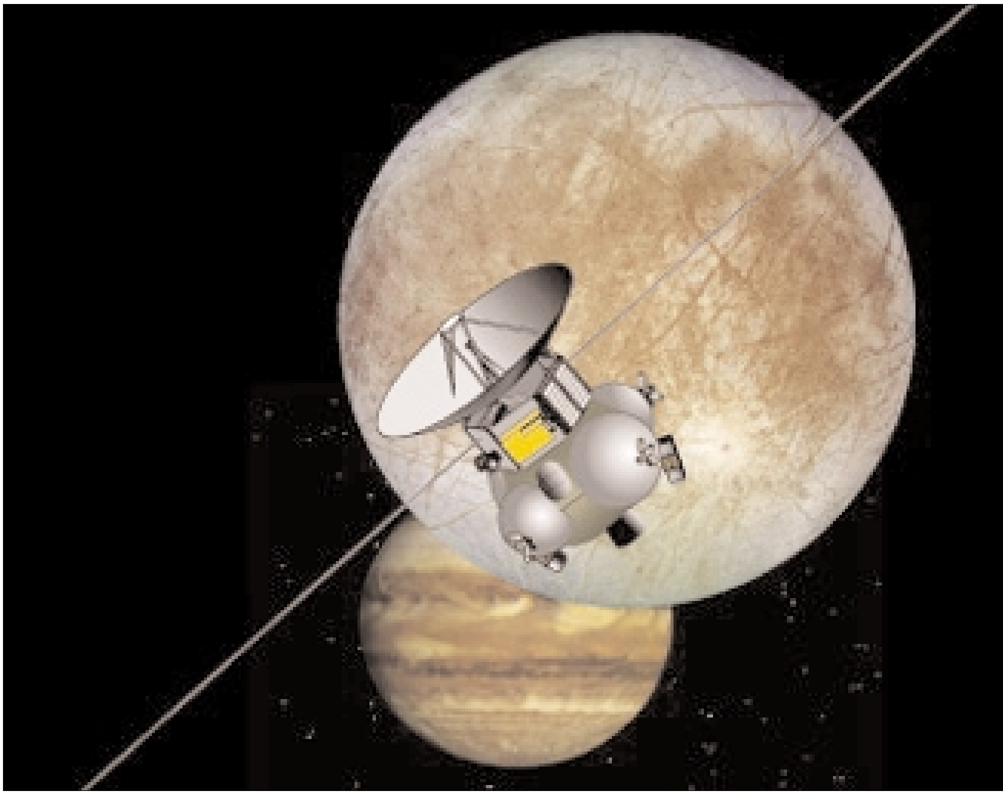
Although specific missions for an ARPS have not yet been selected, potential missions to use these generators include the Outer Planets/*Solar Probe* Project: *Europa Orbiter, Pluto-Kuiper Express,* and *Solar Probe* missions.

Europa

The *Europa Orbiter* is envisioned to circle Jupiter's ice-covered moon searching for subsurface oceans that might support life. The primary objectives of the mission are: (1) to determine if there is a liquid ocean beneath the ice, and, if so, how thick the ice is; (2) characterize the three dimensional distribution of any subsurface liquid water and its overlying ice layers; (3) determine the energy source for the ocean; and (4) identify potential landing sites for future probes.

Recent images have been relayed back to Earth by the *Galileo* spacecraft showing details of a surface of water ice on Europa. Many scientists believe the pictures reveal a relatively young surface of ice, possibly only about 1-km (0.62-mile) thick in places. Internal heating from Europa's inner core and tidal action caused by Jupiter could melt the underside of the ice surface, forming an ocean of liquid water beneath the surface. An instrument called a radar sounder would be used to bounce radio waves through the ice to determine the thickness, and other instruments would reveal details of the surface and interior processes.

Continued



Artist's conception of the *Europa Orbiter* near Europa, the fourth largest moon of Jupiter (in the background) (Source: JPL/NASA)

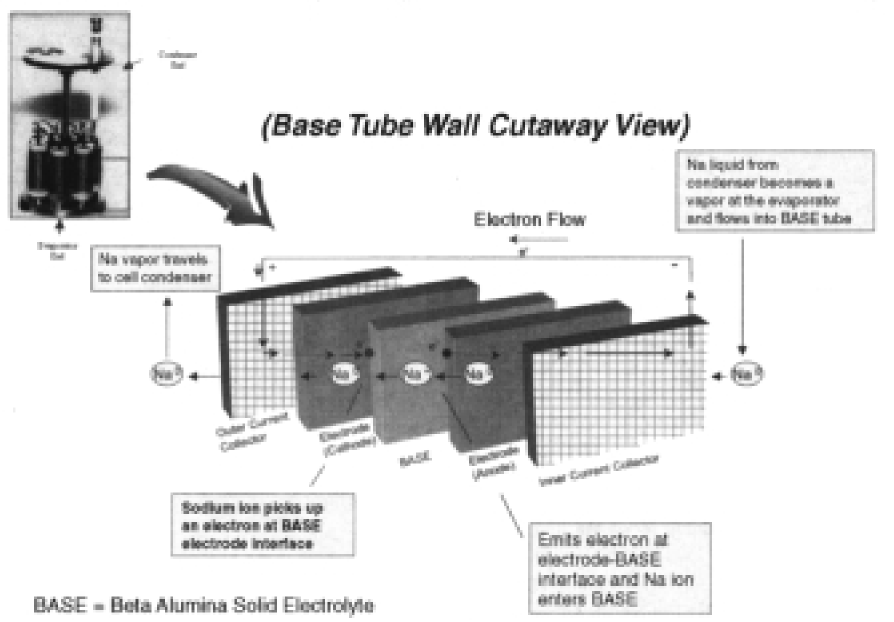
An ARPS has the potential for providing power for the spacecraft systems and instruments. It would be designed to deliver approximately 210 watts of electrical power six years after launch. The *Europa* mission has a potential launch date of November 2003, with an arrival at Europa in 2007.

Pluto/Kuiper Express

The *Pluto/Kuiper Express* mission is envisioned to fly by the only planet in our solar system not yet visited by spacecraft—Pluto and its moon Charon. Pluto's elongated and tilted orbit (inclined 17 degrees relative to the Earth's orbit) is 248 years long. Its thin atmosphere is expected to freeze and collapse in the next 35 years as it moves out to the outer reaches of its orbit, making it impossible to study for 200 years or more. Beyond Pluto lies the recently discovered Edgeworth-Kuiper Disk of "ice dwarfs," or minor planets.

Pluto's tiny size and great distance from Earth make its study a continuing challenge to planetary astronomers. Most of what is known about Pluto was learned since the late 1970s. Many of the key questions about Pluto and its satellite Charon await a closeup observation by a space flight mission. Pluto's history may be connected with the Earth's atmosphere and biosphere.

To gain insight into these connections, NASA is now studying a reconnaissance mission to Pluto-Charon using newly available miniaturized technologies and advanced software systems. The current version of the *Pluto/Kuiper Express* spacecraft would weigh about 225 kilograms (495 pounds) and has a potential launch date of December 2004. A potential radioisotope power system would be designed to provide about 185 watts of electrical power 14 years after launch, with a projected arrival at Pluto in 2012.



How AMTEC works (Source: DOE)

Solar Probe

Another potential mission that might take advantage of using radioisotope power is *Solar Probe.* The current mission design concept would involve the spacecraft's going out to Jupiter first, akin to the Ulysses mission, for a gravity-assisted swingby in order to get into the proper orbit about the Sun. The current version of the *Solar Probe* spacecraft has a mass of about 250 kg (550 lb), making it another member of the new generation of smaller, smarter, and more efficient spacecraft.

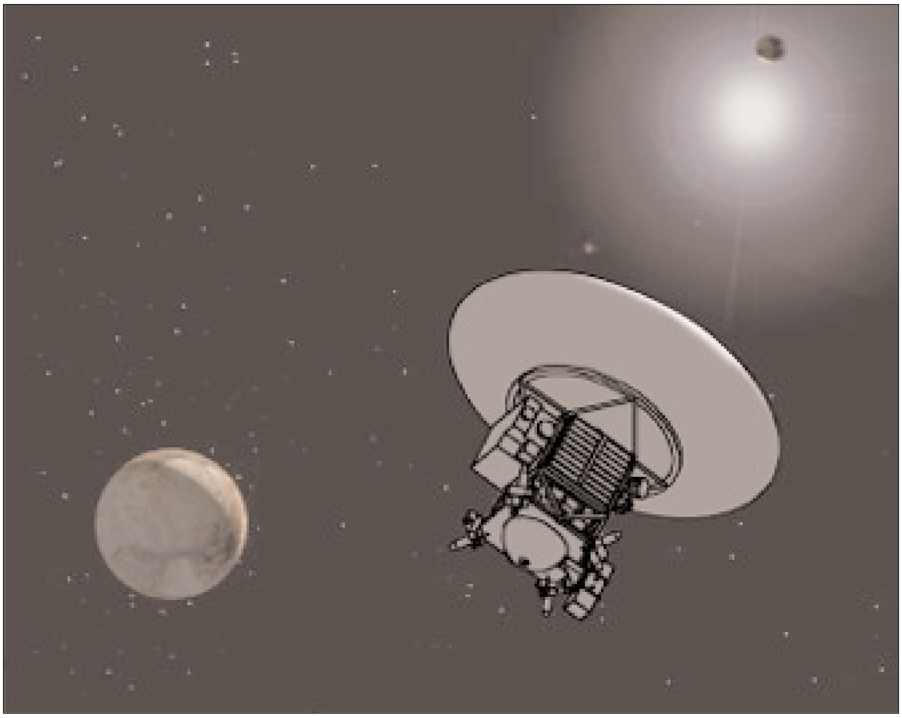
The primary mission objectives are to: (1) measure the birth and acceleration of the solar wind; (2) measure the heating of the solar corona; (3) detect waves and turbulence inside the solar corona; (4) view the poles of the Sun up close for the first time; and (5) view the Sun with the highest spatial resolution ever—20 km (12 miles).

The *Solar Probe* will approach as close as 3 solar radii (about 2 million km or 1.23 million miles) from the surface of the Sun, with a thermal shield designed to withstand temperatures of about 2400 K (3800 °F) to enable science instruments to perform their studies. An anticipated launch date for the *Solar Probe* mission is 2007, with an arrival at the Sun in 2010.

Other potential missions

NASA has identified a number of missions that address numerous objectives for solar system exploration for the years 2000–2015. In the early decades of solar system exploration, missions were dominated by simple flybys and planetary orbiters. Some of the potential future missions may require extensive encounters within the atmospheres or on the surfaces of planetary bodies, moving around within these environments, acquiring and analyzing samples, and potentially returning them to Earth. Some of these missions may also require survival and operation of equipment within harsh thermal and radiation environments.

Some examples of potential missions that could make use of radioisotope power systems are the *Interstellar Probe, Europa Lander, Io Volcanic Observer, Titan Organic Explorer,* and *Neptune Orbiter.* In order to achieve mission objectives, development of small, efficient radioisotope systems may be required to power miniaturized sensors for in-situ measurements, penetrators to carry miniature geophysics/chemistry laboratories, and an efficient thermal-to-electric conversion system with active cooling. These missions are just some of the examples of applications of radioisotope power systems that will enable a broader, more detailed investigation of the mysteries of our solar system. **NN**



Artist's conception of the *Pluto-Kuiper Express.* Pluto is at left and its moon Charon at top right. (Source: JPL/NASA)