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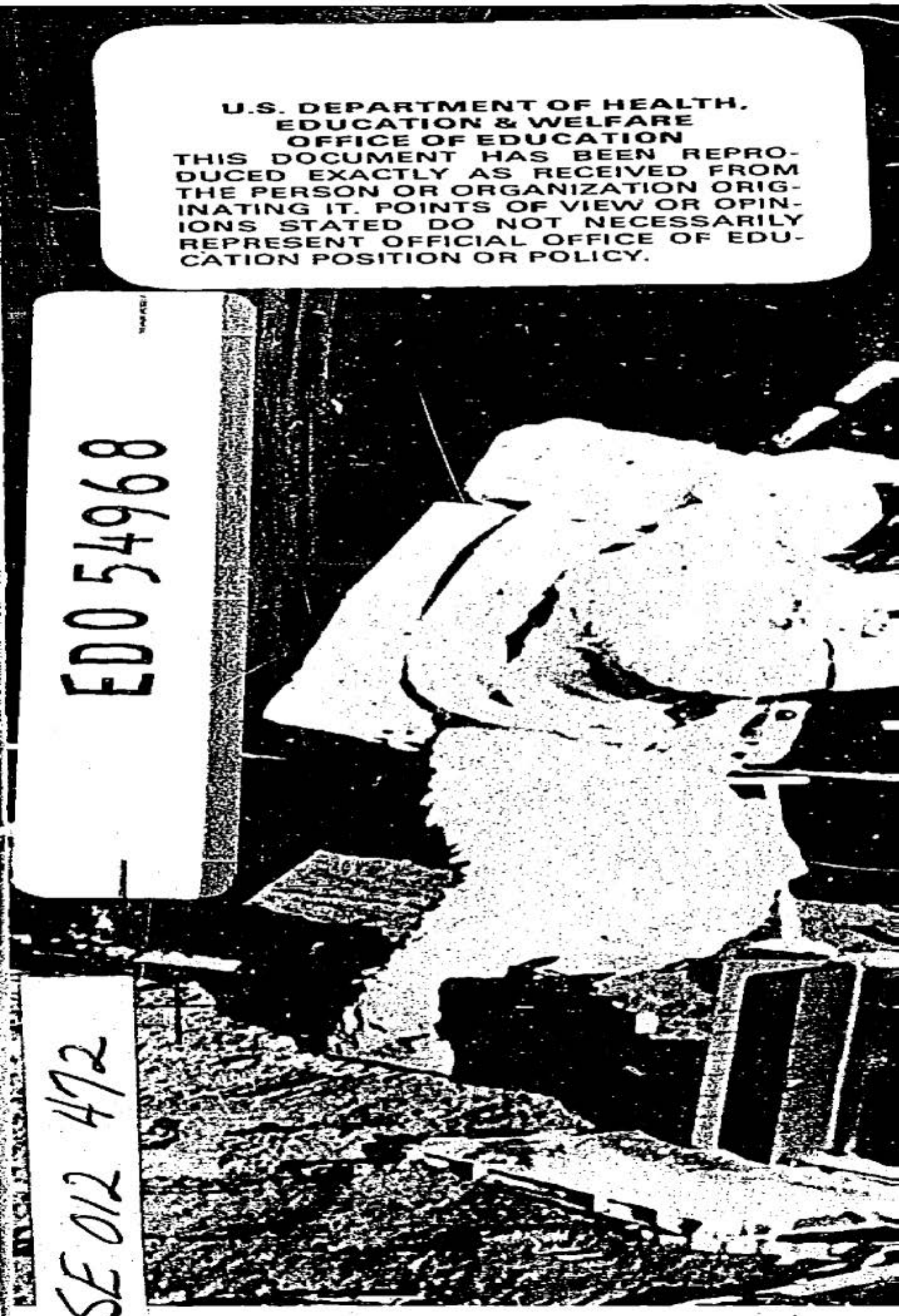
ABSTRACT

This 1971 revision deals with radioisotopes and their use in power generators. Early developments and applications for the Systems for Nuclear Auxiliary Power (SNAP) and Radioisotope Thermoelectric Generators (RTGs) are reviewed. Present uses in space and on earth are included. Uses in space are as power sources in various satellites and space probes. Some projections as to future space objectives are made. The safety factors involved with nuclear materials in space flight are considered, particularly with regard to flight failures. The uses of radioisotope generators on earth are largely in the area of remote weather or communication stations, as in the polar regions, at sea, or under the sea. The choice of radioisotope fuels and the construction of a typical generator are illustrated along with some theoretical considerations of heat transfer and energy converters. Lists of relevant reading topics and of motion pictures are included. (TS)

Power from

by William R. Co



An Understanding

WILLIAM R. CORLISS is an atomic energy consultant and writer with 12 years of industrial experience including service as Director of Advanced Programs for the Martin Company's Nuclear Division. Prior industrial connections were with the Flight Propulsion Laboratory of the General Electric Company and with Pratt & Whitney Aircraft Company. Mr. Corliss has B.S. and M.S. degrees in Physics from Rensselaer Polytechnic Institute and the University of Colorado, respectively. He has taught at those two institutions and at the University of Wisconsin. He is the author of *Propulsion Systems for Space Flight* (McGraw-Hill, 1960), *Space Probes and Planetary Exploration* (Van Nostrand, 1965), *Scientific Satellites* (Government Printing Office, 1967), *Mysteries of the Universe* (Crowell, 1967), *Mysteries Beneath the Sea* (Crowell, 1970), and coauthor of *Radioisotopic Power Generation* (Prentice-Hall, 1964), *Human Factors Applications in Teleoperator Design and Operation* (Wiley, 1971), and *Man and Atom* (Dutton, 1971), as well as numerous articles and papers for technical journals and conferences. In this series he has written *Neutron Activation Analysis, Power Reactors in Small Packages, Direct Conversion of Energy, Computers, Nuclear Propulsion for Space, Space Radiation,* and was coauthor of *Power from Radioisotopes.*

ROBERT L. MEAD is a writer specializing in technical subjects. Now vice president of Ray Thompson and Associates, Inc., he was previously public relations director for the Nuclear Division of the Martin Company, the U. S. Atomic Energy Commission's principal contractor in the development of isotope power generators. He has written booklets, newspaper and magazine articles, and school charts on a number of scientific subjects, and he has produced several award-winning motion pictures on the application of nuclear energy. He is active in Science Fairs and other science education projects in the Baltimore area. Mr. Mead received his B.S. degree from Loyola College, Baltimore, and has also studied at the Johns Hopkins University, Mount St. Mary's College, and the University of Baltimore.

The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

ABOUT THE COVER

Apollo 12 Astronaut Gordon Bean removes the plutonium-238 heat source from its container. The SNAP-27 thermoelectric generator (arrow) is near his feet. The generator produces 73 watts of electrical power for the ALSEP (Apollo Lunar Scientific Experiment Package), which consists of (1) a magnetometer to help reconstruct the geological evolution of the moon; (2) a solar wind spectrometer to determine the composition of the solar wind, (3) a lunar atmosphere detector to learn more about the early history of the moon; and (4) a lunar ionosphere detector to measure positive ions immediately above the lunar surface.

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The moon.

Power from Radioisotopes

by William R. Corliss and Robert L. Mead

THE SNAP PROGRAM

On January 16, 1959, a new device that turned heat from radioactivity into electricity was demonstrated publicly for the first time on the desk of the President of the United States. The device was the size of a grapefruit. It weighed 4 pounds (1.8 kg) and was capable of delivering 11,600 watt-hours of electricity over a period of about 280 days. This is equivalent to the energy produced by nickel-cadmium batteries weighing nearly 700 pounds (318 kg). It was called SNAP-3.

The U. S. Atomic Energy Commission had begun developing a series of these compact devices in 1956 to supply power for several space and terrestrial uses. The devices were all described by the general title: Systems for Nuclear Auxiliary Power. The initials form the word SNAP.

Two entirely different types of SNAP systems are being developed. Both convert heat into electricity. In one system, the heat is obtained from small nuclear reactors; in the other, from the decay of certain radioisotopes. This booklet discusses only the latter type, which are called radioisotope, or, more simply, isotope power generators. (See summary table on pages 50 and 51.) The other system is described in *Nuclear Reactors for Space Power*, a companion booklet in this series.

To understand how radioisotope generators work, it may be helpful to review some basic principles.

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Glenn T. Seaborg, Chairman of the Atomic Energy Commission, compares one of the first radioisotope generators, SNAP-9A (bottom center), with a life-size model of SNAP-3, held by Major R. T. Carpenter, project manager.

Radioisotopes—Characteristics and Uses

The existence of isotopes was discovered about 1913 after nearly a decade of experimenting with naturally radioactive materials. Isotopes of a given element are atoms with the same number of protons and electrons but different numbers of neutrons in the nucleus. Because they have the same number of electrons, they are identical in chemical behavior. Because they have different numbers of neutrons, they differ in weight. Certain isotopes are unstable and undergo a process of decay during which they emit radiation. Such isotopes are called radioisotopes.

By the early 1930s scientists had learned that, by bombarding normally stable chemical elements with subatomic particles, using particle accelerators ("atom smashers"), radioactivity could be induced in the elements. That is, radioisotopes could be made artificially. Quantity production became feasible after the development of nuclear reactors during World War II.* Neutrons, released in

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*See *The First Reactor*, a companion booklet in this series.

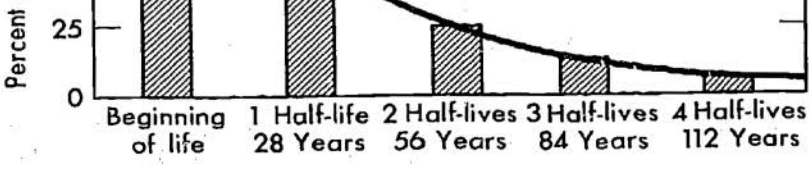
prodigious quantities in reactors, were well suited for bombarding target elements to produce radioisotopes.

Radioisotopes differ in the types of radiation they emit and in the rates at which they decay, or lose their radioactivity. These characteristics help determine their usefulness as well as their dangers to man.

The radiations emitted by radioisotopes are mainly of three types: alpha, beta, and gamma. An alpha particle is identical with the nucleus of a helium atom. It has very little penetrating power. Beta particles, usually negative electrons, are much more penetrating but less damaging than alpha particles. Gamma rays are highly penetrating electromagnetic waves similar to X rays.

Because radioisotopes vary in the rates at which they decay, it has become customary to measure this characteristic in terms of the time required for half the unstable nuclei in a pure sample to decay. This time is called the radioisotope's "half-life". Half-lives of different radioisotopes vary enormously. For example, nitrogen-12 has a half-life of $^{12}/_{1000}$ second, while the half-life of iodine-129 is 16 million years.

Radioisotopes are used in four basically different ways. First, they are used as fixed sources of radiation to make



Radioactive decay pattern of strontium-90.

some change in a target material. For example, cancerous tissue may be destroyed by radiation therapy.

Second, radioisotopes are used, again as fixed sources of radiation, in measuring systems that provide information about a target material by sensing the radiation which penetrates it or is reflected from it. For example, they are used to measure the thickness of a moving sheet of metal.

The third way of using radioisotopes is perhaps the most common and is an important technique in medical and agricultural research. Here, small amounts of radioisotopes (tracers) are mixed directly into the material of interest. Then, by detecting their radiations with instruments such as Geiger counters, it is possible to follow, or trace, the material's course as it undergoes some physical, chemical, or biological process. A typical use is in tracing the uptake of fertilizers by plants.*

A fourth way of using radioisotopes is the basis for the power generators discussed in this booklet. The kinetic energy possessed by radioisotope decay particles is transformed into thermal or radiant energy that may be used to produce electrical power through a number of energy-conversion techniques.

How Radioisotope Power Generators Work†

There are several methods of converting heat energy into electrical energy. The heat created by decaying radioisotopes can be converted into electricity in two ways: (1) By dynamic conversion, using a turbogenerator, or (2) By static conversion, which uses thermoelectric elements, thermionic converters, or other non-moving energy conversion devices.

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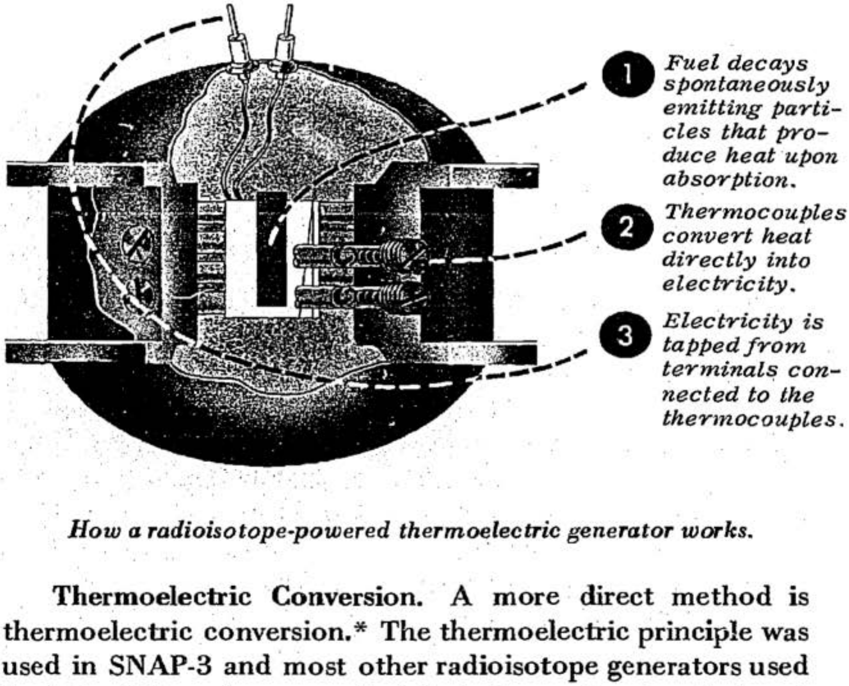
*See *Atoms in Agriculture*, a companion booklet in this series.

†For more details, see the scientific background section at the end of this booklet.

Dynamic Conversion. Perhaps the most familiar method is the use of the heat to boil water. The steam produced can then drive a steam turbine that, in turn, drives an electric generator. Alternate working fluids may be mercury, potassium, sodium, and lithium liquid metals or organic liquids. Dynamic systems have been the most extensively studied. Closed-loop, gaseous-fluid systems employing gases, such as helium and argon, also have been investigated.



How a radioisotope-powered thermoelectric generator works.

Thermoelectric Conversion. A more direct method is thermoelectric conversion.* The thermoelectric principle was used in SNAP-3 and most other radioisotope generators used to date. It is not a new principle but was discovered almost 150 years ago by a German scientist named Thomas Johann Seebeck. He observed that an electric voltage is produced when two dissimilar metals are joined in a closed circuit and the two junctions are kept at different temperatures. Such

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*See *Direct Conversion of Energy,* a companion booklet in this series.

pairs of junctions are called thermoelectric couples or thermocouples.

In a typical temperature-sensing thermocouple, two ordinary metals or alloys are used. For power production, it has been found that some semiconductor materials, "doped" by the addition of impurities to produce a deficiency or an excess of electrons, offer far greater efficiency. A very large number of semiconductor compounds exhibit the "thermoelectric effect". The power output of a thermoelectric material is a function of its operating temperature; some materials are better than others at certain temperatures.

A thermoelectric couple used in a radioisotope generator is composed of one so-called *positive* type element and one *negative* type element. In positive elements the flow of electrons is toward the hot junction. In negative ones it is away from the hot junction. Isotopic power generators using thermoelectric elements are commonly called RTGs (Radioisotope Thermoelectric Generators).

Thermionic Conversion. Radioisotope generators may also use another means of direct energy conversion called thermionic emission. Here an electric current is obtained by collecting the electrons emitted by a hot surface. For example, one can produce electricity by heating the emitter, or cathode, of a vacuum tube and attracting the emitted electrons to the collector, or anode. Instead of a vacuum, present-day thermionic conversion devices use conductive vapors that permit larger current flows.

The First SNAP Units

An early objective of the efforts to develop SNAP isotope power generators was a 500-watt, 60-day generator (SNAP-1) to power instruments in space satellites. Cerium-144, a beta emitter with a 290-day half-life, was selected as the heat source. A small turboelectric generator with high-speed rotating components was developed to convert the heat into electricity. This project was subsequently abandoned in favor of a thermoelectric conversion system called SNAP-1A. Thermoelectric devices, with no moving parts, promised to extend greatly the useful life of the generator. However, SNAP-1A was also too ambitious for its time, and it was cancelled in 1959.

Work followed on projects to develop new and more efficient thermoelectric and thermionic conversion units (SNAP-3)* for use with radioisotope heat sources. The first SNAP-3 generator using thermoelectric conversion was assembled and tested in January 1959. The test was successful, and the unit produced 2.5 watts of electricity with a half charge of polonium-210 fuel. This radioisotope was selected for the test device because it is a concentrated heat source, it was readily available, and, as will be discussed later, it could be handled safely.

With the success of SNAP-3, work began on other generators to power satellites, moon probes, automatic weather stations, and navigational aids. These efforts have stimulated a new technology of far-reaching significance.

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*SNAP projects employing nuclear reactors were assigned even numbers; those using power from radioisotope decay were given odd numbers. SNAP number designations are no longer given to new generators.

Why RTGs Are Useful in Outer Space

Solar cells have been so successful in supplying electric power to many hundreds of satellites that it is logical to ask why RTGs are needed at all. RTGs are superior to solar cells in the following situations:

1. Where sunlight is absent, weak, or undependable, as during the 2-week lunar nights, under the opaque atmospheres of planets such as Venus, and in the outer reaches of our solar system where the sun is only a bright star.
2. In regions where spacecraft temperatures are high—close to the sun, for example. (Solar-cell capabilities drop quickly as temperatures rise.)
3. In high radiation fields, such as those of the Van Allen Belt. (Space radiation degrades solar cells.)
4. On missions close to the outer fringes of the earth's atmosphere (and those of other planets) where large arrays of solar cells would cause too much atmospheric drag.
5. In missions through the asteroid belt or other regions where the density of micrometeoroids is high.
6. Where spacecraft payloads require substantial quantities of heat.

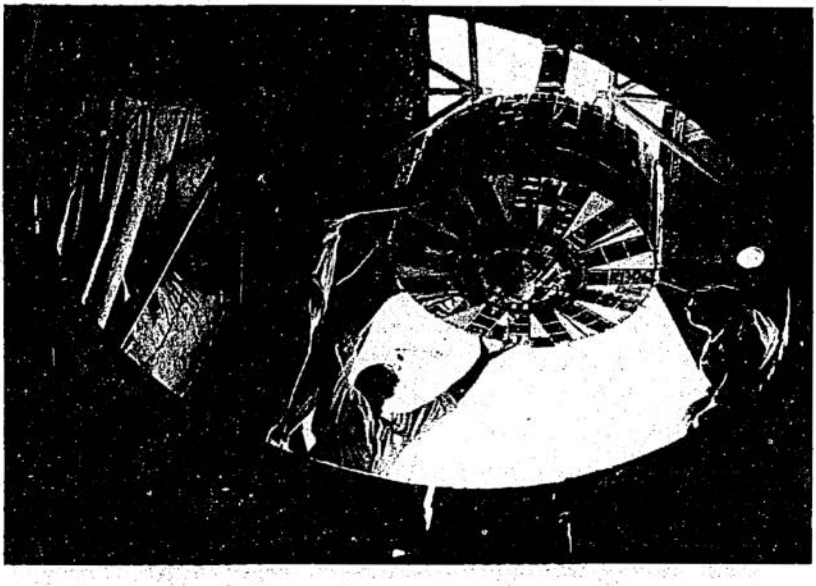
Early Satellite Applications

A milestone was reached in the U. S. space program with the orbiting of a Department of Defense Transit navigation satellite in June 1961. The satellite carried a radioisotope generator as a supplementary source of electricity for its radio transmitters. This marked the first use of atomic power in space.

To do a job effectively over a long period of time, a satellite needs a dependable, long-lived electrical supply. And because pounds are precious in payloads rocketing into space, the electricity source must be light in weight. It must also be rugged to withstand the rigors of a rocket ride, and it must be so safe that in the event of accident there will be no serious consequences from radioactive contamination.

The first space generator was roughly spherical in shape, about 4¾ inches (12.1 cm) in diameter by 5½ inches (14 cm) high. It was housed in a white-coated copper shell that cut down the amount of heat energy absorbed from the sun's rays. The radioisotope fuel, plutonium-238, was contained in a rugged capsule in the center of the sphere.

Like SNAP-3, this generator used thermocouples to convert heat energy into electricity. Its output was 2.7 watts. Plutonium-238 was used as the heat source because of its



Engineers at Cape Kennedy preparing to launch the first atomic power unit to operate in space, June 29, 1961. The small white ball on the bottom of the satellite is the SNAP-3A radioisotope generator, which is still producing its intended power (2.7 watts) on the Department of Defense mission.

relatively long half-life (90 years), the large amount of heat it produces, and safety considerations.

A larger, improved radioisotope generator was developed to supply the power needed by advanced satellites. This model, designated SNAP-9A, produces about 10 times more electricity than the earlier SNAP-3A satellite generators that only supplemented other power from solar cells.

By the end of 1963, two satellites wholly powered by SNAP-9A generators were in orbit. These generators supply 25 watts of electricity. The design lifetime is 5 years. In addition, some waste heat from the generators is used to keep the instruments inside the satellites at a temperature near 20°C. The generators are about 20 inches (50.8 cm) in diameter (including fins) and 10 inches (25.4 cm) high. (See photograph on page 2.) They are mounted on the outer surface of satellites. A third SNAP-9A was launched in 1964, but the Transit satellite failed to reach orbit. The Transit RTGs have proven so successful that new generators have been built for future Navy navigation satellites; these are discussed later in this section.

Atoms to the Moon—SNAP-27

The first unmanned lunar probes, the Rangers, did not need RTGs because they traveled in full sunlight until just before they crashed into the lunar surface. The Surveyor soft-landers, however, had to face the long 2-week lunar nights. Here was a mission where RTGs appeared attractive. Ultimately, however, NASA decided to rely on solar cells and let the Surveyor spacecraft "hibernate" during the lunar night.

When it was decided that the Apollo astronauts would set up and leave behind scientific experiments on the moon, the lunar night problem arose again. This time, RTGs made the passenger list. In July 1969 the Apollo 11 astronauts set up the Early Apollo Scientific Experiment Package (EASEP) on the Sea of Tranquillity. EASEP was kept warm and viable during the lunar night by two 15-thermal-watt, plutonium-238 heaters. (No SNAP numbers were assigned.) These radioisotope heaters generated no electricity and were not RTGs. All subsequent Apollo flights, however, did carry RTGs—SNAP-27s.

SNAP-27 was designed to generate not less than 63.5 watts of electrical power for ALSEP (Apollo Lunar Scientific Experiment Package) throughout its first year of operation. Using plutonium-238 fuel, the SNAP-27s have kept ALSEP's lunar seismometers, magnetometers, and other instruments operating as lunar shadows dropped temperatures hundreds of degrees at the Apollo landing sites. The Apollo 12 ALSEP RTG has greatly extended the Apollo scientific payoff by operating well beyond its 1-year design life, and it continues to produce in excess of 70 watts. (See cover.) A SNAP-27 was also placed on the moon in the Apollo 14 flight in 1970; Apollos 15, 16, and 17 will carry SNAP-27s as well.

The Nimbus Weather Satellite—SNAP-19

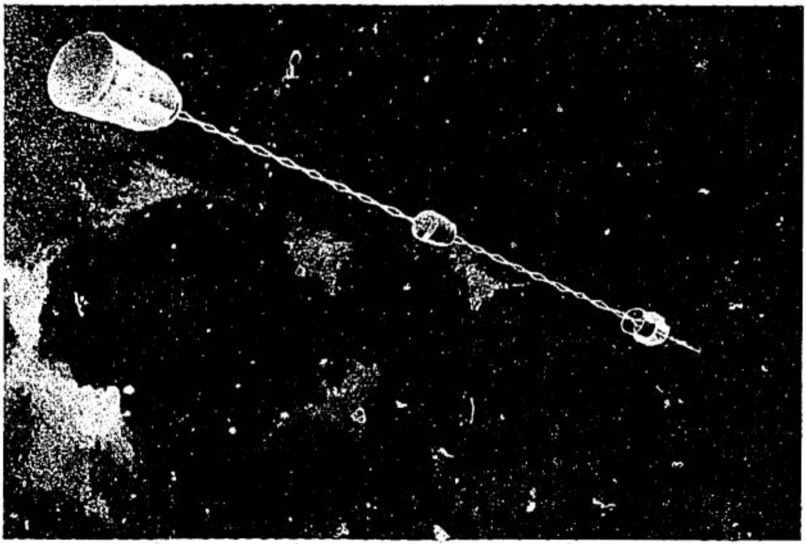
Nimbus weather satellites orbit the earth, snapping pictures of cloud systems and studying the atmosphere and terrain below with instruments sensitive to infrared, ultraviolet, and other portions of the electromagnetic spectrum. The early Nimbus spacecraft were powered exclusively by solar cells, but Nimbus 3, launched in May 1969, carried two SNAP-19 RTGs. The pair of SNAP-19s generated 56 watts at the beginning of the mission and helped supplement the normal solar cells.

The New Transit RTGs

The U. S. Navy's Transit navigation satellites orbit through regions of space where the radiation trapped by the earth's magnetic field is high enough to degrade solar cells stabilize the attitude of the spacecraft. The first flight of the new Transit RTGs will be in the early 1970s.

The Giant of the Solar System

Oblate Jupiter, with its colored bands and magnificent Red Spot, has always intrigued earthbound scientists. In 1972 and 1973 these scientists will launch the first man-made instrument-carrying probe past Mars, through the asteroid belt to Jupiter. It would be a hazardous journey for solar cells considering the debris in the asteroid belt and the anticipated high-radiation fields trapped by Jupiter's magnetic field. Furthermore, the sun's energy flux will have dropped by a factor of approximately 25 at Jupiter's distance. Consequently, these spacecraft, called Pioneers, will



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.

each carry four 30-watt RTGs fueled with plutonium-238 to provide the instrument with electrical power under the adverse conditions forecast for the trip. A great deal of the RTG-generated power will be required to transmit radio signals across the hundreds of millions of miles that separate Jupiter from the earth.

Sampling the Martian Surface

Mariner space probes have already flown past Mars and photographed small portions of its meteor-pocked terrain. More Mariners will orbit Mars in the early 1970s. By the mid-1970s scientists hope to soft-land spacecraft directly on the Martian surface, just as they did with the Surveyor lunar landers during early exploration of the moon. Sunlight has diminished by roughly a factor of 4 at Mars' distance from the Sun, and Martian surface conditions may include blowing dust and other phenomena that would degrade solar-cell performance. RTGs, therefore, have been selected for the Viking Martian landings. Each of the two planned craft will be powered by two 35-watt RTGs fueled with plutonium-238. The electrical power will be used for measuring surface conditions on this planet, for taking samples for automated chemical and biological analysis, and for transmitting the data back to earth.

Bigger RTGs for More Ambitious Missions

The space applications described above—several of which are very ambitious indeed—can be consummated with less than 100 watts of electricity. Anticipating the need for even more power, the AEC has been developing the Multi-Hundred-Watt RTG. Using plutonium-238 fuels, this RTG would be capable of generating 100 to 200 watts for 5 to 10 years.

There is no contest between solar cells and RTGs for missions plumbing the outer regions of the solar system. Sunlight is a negligible power source at Neptune's distance, and only RTGs could be expected to survive almost a decade of meteoroid bombardment and exposure to space radiation.

Gas-Turbine Generator—An Advanced Concept

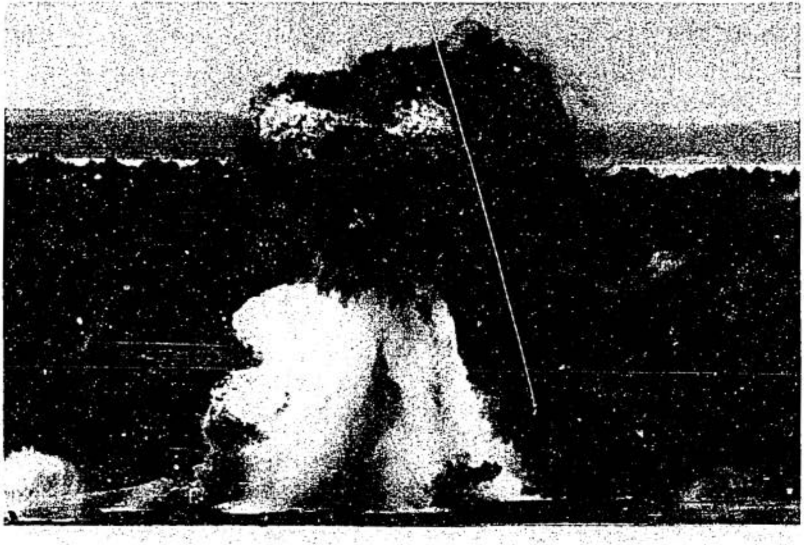
At electrical power levels beyond a kilowatt, thermoelectric elements are heavier and less efficient than turbogenerators—the same kinds of generators that produce electric power for homes. An interesting possibility for large space power plants involves the heating of a gas, such as neon or argon, by radioisotopes. This hot gas would expand through a turbine, which, in turn, drives an electrical generator. Several kilowatts of electricity could be generated efficiently in a dynamic conversion system such as this. Gas-turbine power generators utilize what is termed the Brayton cycle, which is much like the cycle that provides power in a jet engine. A Brayton-cycle radioisotope generator might be used on a manned space station or, perhaps, a large TV broadcast satellite.

Safety in Space

Safety considerations play an important part in the choice of fuel for satellite power generators. Plutonium-238, the only radioisotope used thus far in space, emits alpha radiation, plus very low levels of gamma and neutron radiation. We have noted that alpha radiation is the least penetrating of all. Even without shielding, plutonium-238 radiation presents no hazard to man unless the plutonium source is inhaled or ingested.

All forms of plutonium, however, are poisonous to living organisms, and rigid safety requirements for plutonium generators have been established. For example, fuel capsules are designed to survive accidents on a rocket vehicle launch pad, including fire and explosion. They must withstand impact against the earth if the rocket fails in flight. The generators must be designed so that when they reenter from orbit, they remain intact during flight through the atmosphere and impact on the ground. Realistic tests are conducted to prove that these requirements are met.

The regimen of safety tests is rigorous for all space generators. The fires of a potential launch-pad accident are duplicated on a small scale using the rocket fuel and oxidizer of the planned launch vehicle. The high temperatures of reentry from space are simulated by plasma jets—electric arcs that bombard the test generator with air at white-hot temperatures. To reproduce the shock forces encountered when a generator hits the earth following reentry, high-velocity rocket sleds hurl the test generator into blocks of solid granite. The test generators must survive these traumatic conditions as well as years of exposure to the elements,



A safety test. Fuel capsules of all five isotope generators in this explosion were undamaged.

including long-term immersion in seawater. Under all these conditions, which are made as close to actual conditions as possible during the tests, the generator must contain its radioisotope fuel.

Three "aborts", or flight failures, involving RTGs have occurred: A SNAP-9A on a Transit in 1964; a SNAP-19 on a Nimbus in 1968; and a SNAP-27 on Apollo 13 in 1970. SNAP-9A was designed according to the early safety philosophy which stated that all plutonium fuel in an RTG on an aborted reentering spacecraft should be dispersed at high altitudes by atmospheric burnup. Round-the-world tests made after the 1964 Transit abort indicated that this burnup and wide dispersal of plutonium-238 had indeed occurred, and that no portion of the world's populace had been exposed to dangerous quantities of the radioisotope. SNAP-19 and 27 were designed according to current safety philosophy. Both RTGs reentered the earth's atmosphere intact and no fuel was released anywhere. The two Nimbus SNAP-19s were recovered intact from the Santa Barbara channel. The Apollo 13 SNAP-27 fell into the Pacific and now rests intact under over 2 miles of water.

RADIOISOTOPE GENERATORS ON EARTH

There are many out-of-the-way places on earth where electrical power is needed for weather stations, navigation beacons, and other special installations. In some isolated spots, men are needed primarily to operate the machinery that provides the electricity. Others, which are unmanned, have relatively short-lived batteries to supply power. It is costly to provide men with fuel and the necessities of life in remote locations and to replace batteries at distant unmanned stations. We must forego the benefits of more stations because of the high expense of maintaining them.

The development of cheap, reliable, long-lived radioisotope generators may help solve this problem. Generators with no moving parts have an inherent reliability and freedom from maintenance. The slow decay of isotopes, such as strontium-90 and cesium-137, can provide years of operating life.

An Arctic Weather Station

The world's first atomic-powered weather station was placed on bleak, uninhabited Axel Heiberg Island in Canada, only 700 miles from the North Pole, on August 21, 1961, for a 2-year test. Even with a powerful icebreaker, the scientists and technicians who installed the automatic recording and transmitting equipment could reach the island only at the peak of the summer thaw.

The unmanned station, designed to collect and relay data on temperature, wind, and barometric pressure, was located to fill a gap in the weather network between two manned outposts at Resolute Bay and Eureka. It was part of a joint project of the U. S. and Canadian weather bureaus, and its data were made available to all nations. In a completely successful 2-year test, the station proved one important advantage of atomic power by remaining in operation longer than has any unattended battery-operated station.

The weather station's RTG (code named "Sentry") thermoelectric conversion assembly had 60 pairs of lead telluride elements arranged around a cylindrical strontium-90 source. It produced a continuous power output of 5 watts. Electrical energy was stored in rechargeable chemical batteries between scheduled transmission times, which occurred every 3 hours. Excess heat from the generator was used to keep electronic components in the data processing and transmitting equipment within a narrow temperature range. Strontium-90 was selected because of its 28-year half-life and because it is readily available as a fission product of nuclear reactors.

The weather station was removed from Axel Heiberg Island in July 1965 after successful completion of the Weather Bureau's tests and evaluation.

Navigation Buoy—SNAP-7A

The success of the Axel Heiberg Sentry experiment led to the development of a series of more powerful strontium-90 generators to test in a variety of uses. SNAP-7A, first of the series, was designed to provide power for a 36-watt flashing-light buoy. Installed in December 1961, the buoy light flashed every 5 seconds and could be seen for miles in clear weather. It was tested by the U. S. Coast Guard, which maintains thousands of buoys and other aids to navigation, many of which are difficult and expensive to service.

The buoy generator weighed only 1870 pounds (850 kg), but its fuel lasted many years. Batteries used in similar buoys can weigh as much as 2500 pounds (1130 kg) and must be recharged and replaced frequently.

This was the first radioisotope generator designed to operate underwater. The complete system included the generator, a voltage converter, and a small nickel–cadmium storage battery. The buoy's flashing light drew an average of 5 watts from the storage battery. The generator kept the battery charged. Four fuel capsules containing about 3 pounds of strontium-90 titanate provided heat, which was converted to electricity by a thermoelectric assembly of 60 pairs of lead telluride elements connected in series. The cold junction temperature was 50°C, and the hot junction, 480°C.

SNAP-7A was removed from the buoy in 1967 for dismantling and inspection after almost 6 years of successful operation.

Power for a Lighthouse—SNAP-7B

SNAP-7B was designed to produce 60 watts of electric power, a large increase over previous radioisotope generators. After preliminary testing, the Coast Guard installed this unit in a lighthouse near the entrance to Baltimore harbor in May 1964. It eliminated the need for a lighthouse crew of three men.

SNAP-7B was similar to SNAP-7A. It was 34½ inches (87.6 cm) high, 22 inches (55.8 cm) in diameter, and weighed about 4600 pounds (2090 kg). Its fuel was 225,000 curies* of strontium-90 titanate. It used 120 pairs of lead telluride elements to produce 60 watts of electrical power. A voltage converter provided an output of 32 volts.

SNAP-7B was relocated in August 1966 from Baltimore Harbor to an off-shore oil-well platform in the Gulf of Mexico. There, it successfully operated navigation aids until it was returned to the AEC in 1969.

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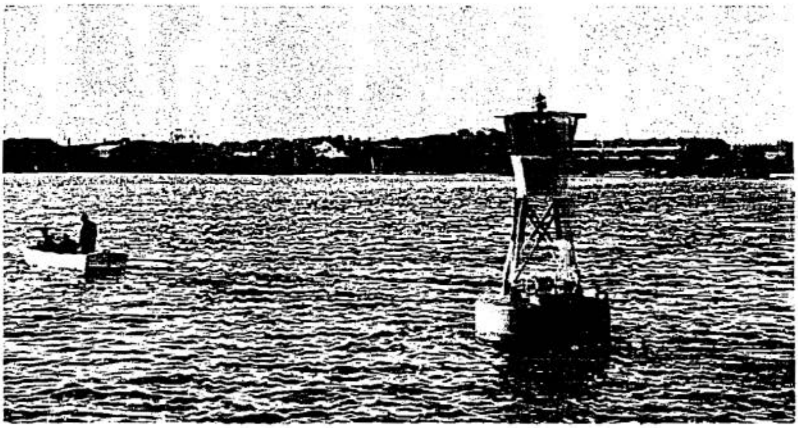
*One curie of strontium-90 is the quantity that has as much radioactivity as one gram of radium. A curie is the basic unit used to describe the intensity of radioactivity in a sample of material.

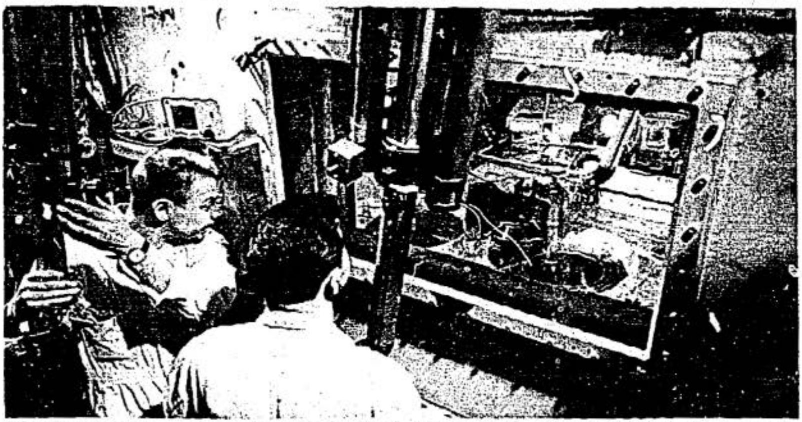


This flashing-light buoy near Baltimore is powered by a SNAP-7A radioisotope generator.

Antarctic Weather Station—SNAP-7C

The Navy tested a radioisotope power generator in an unattended weather station in Antarctica. This unit, SNAP-7C, was installed on Minna Bluff, 700 miles from the South Pole, on February 8, 1962.

SNAP-7C was identical with SNAP-7A. The generator, converter, storage battery, and the station's electronic equip-



Working with manipulators behind three feet of leaded glass, technicians load a strontium-90 fuel capsule into a SNAP-7B generator.

Installing a SNAP-7C radioisotope generator in the ice 700 miles from the South Pole. It provided power for an unattended weather station.

ment were enclosed in a steel cylinder 8 feet (2.44 m) high and 3 feet (0.91 m) in diameter. This cylinder was buried in snow, with steel and wooden outriggers spreading the weight and preventing sinking. Only a whip antenna and the weather-sensing instruments were exposed above the surface. As in the Axel Heiberg station, waste heat from the generator kept the temperature of the buried equipment nearly constant. This prevented freezing, a common failing of battery-operated stations in polar regions.

The station broadcast temperature, wind velocity, wind direction, and barometric pressure every 6 hours to the McMurdo Sound Naval Air Facility. It was triggered to transmit at other times by radio impulses from transmitters on land or in aircraft. Operation was intermittent due to problems with the weather equipment. The RTG was returned to the AEC in 1969.

Floating Weather Station—SNAP-7D

Frequent and accurate weather information is vital to naval operations. For some time the Navy has been using automatic weather stations mounted in small barges moored at sea to supplement other weather data sources. The stations are powered by batteries that must be periodically recharged. In 1964 the Navy began using SNAP-7D in this application.

Such a weather station transmits data for 2 minutes and 20 seconds every 3 hours. The generator operates continuously and charges storage batteries between transmissions. Some power is used to light a navigation beacon to alert passing ships.

Such stations, part of the Navy's NOMAD (Navy Oceanographic and Meteorological Automatic Device) system, measure and transmit air temperature, barometric pressure, and wind velocity and direction. Storm detectors trigger special hourly transmissions during severe weather conditions.

The SNAP-7D generator, installed in a NOMAD weather boat, was placed in operation in January 1964 and continuously supplied power to the weather station for several years. The installation provided significant data before and during two hurricanes that caused heavy damage along the Gulf of Mexico coast. The NOMAD with SNAP-7D installed is now awaiting redeployment after a period in port for buoy maintenance.

Undersea Navigation Beacon—SNAP-7E

SNAP-7E was designed to power an experimental Navy underwater navigation beacon. The thermoelectric generator and other equipment, housed in a vessel made to withstand tremendous pressure, was moored 15,000 feet (4570 m) below the surface of the Atlantic Ocean off Bermuda in July 1964 in a 2-year testing program.

The generator portion of SNAP-7E is nearly identical with that in SNAP-7A and SNAP-7C. It uses four capsules, containing 31,000 curies of strontium-90 titanate fuel and 60 pairs of lead telluride thermoelectric elements. The generator's electrical output is 7.5 watts. A converter steps up the voltage from 4.5 to 28 volts to power electronic equipment.

A submarine navigator may use such a beacon just as he uses a radio beacon or lighthouse. Knowing the position of the beacon on his chart, he can determine the position of his ship with an underwater listening device.

SNAP-7E was recovered from the ocean floor in November 1969 and returned to the AEC.

First Commercial Use—SNAP-7F

SNAP-7F, the first radioisotope generator to provide power for navigation aids on an offshore oil platform, went into unattended operation in June 1965. The Phillips Petroleum Company installed the generator on one of its platforms in the Gulf of Mexico. The generator was a 60-watt unit, almost identical to SNAP-7B and SNAP-7D. Under a 2-year contract, the company tested and evaluated the radioisotope generator and determined its practicality and economic competitiveness with existing power sources.

After 4 months of operation on the oil platform, SNAP-7F experienced a sharp drop in power production. It was subsequently replaced by the SNAP-7B unit from Baltimore Harbor.

Milliwatt RTGs—The SNAP-15 Series

The SNAP-15A and SNAP-15C programs were initiated by the AEC to provide electrical power in the milliwatt range for specialized military and communications applications. Both types of devices used plutonium-238 fuel and both employed thermoelectric conversion techniques. These development programs were initiated in 1963 and have yielded valuable data and engineering experience in this power range. Although both SNAP-15 programs have been completed, a

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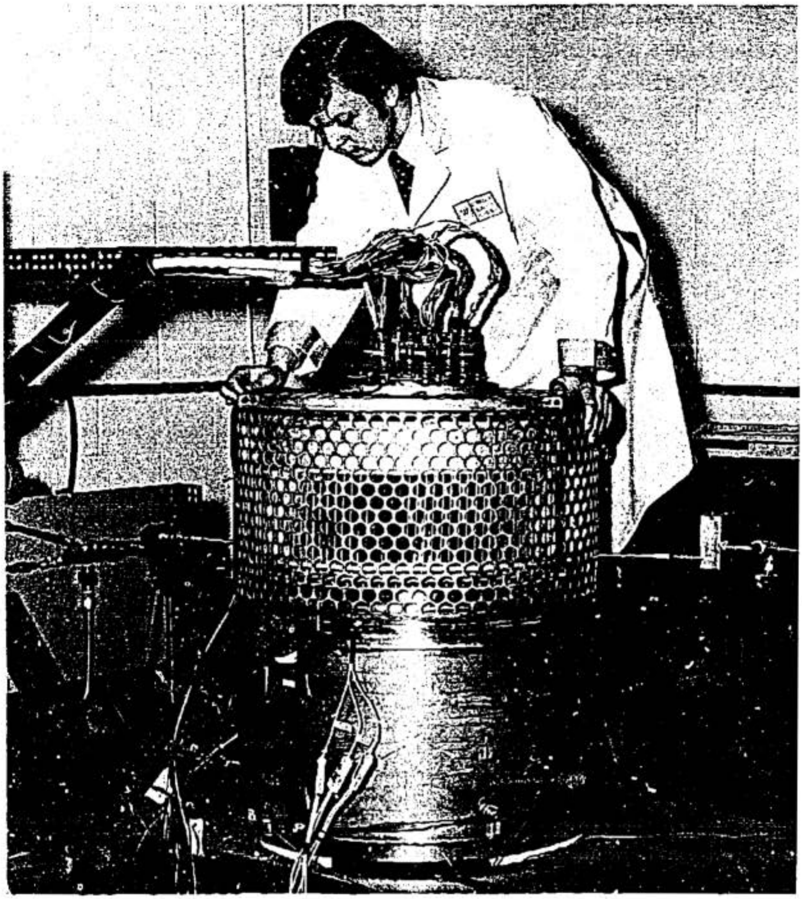


SNAP-23A being tested.

number of the SNAP-15A units have now been on test for over 5 years.

More Deep-Sea RTGs—SNAP-21

The success of the SNAP-7 series in surface and subsurface marine applications led to requests for advanced

RTGs incorporating recent technical developments. In particular, lower RTG weights were desired. The SNAP-21 series of RTGs was the result. Producing 10 watts from the heat released from strontium-90 fuel, the SNAP-21s weigh only about 650 pounds (295 kg), compared to the 1870 pounds (850 kg) of the 10-watt SNAP-7A. Obviously, the SNAP-21s will be far easier to handle and implant on the ocean floor than the SNAP-7s.

Four SNAP-21 units have been built and fueled. Two have already been delivered to the Navy (in June 1970) for deep sea use in the Atlantic Ocean. The applications contemplated for RTGs in the SNAP-21 class include the powering of reliable underwater navigation aids, undersea cable repeaters, and deep ocean experiments.

Advanced Terrestrial RTGs—The SNAP-23 Series

The SNAP-23 program, like that of SNAP-21, was stimulated by the successes of the SNAP-7 RTGs. The SNAP-23s, however, are terrestrial (rather than undersea) power units intended for remote, unattended weather stations and similar duties. The technical objective of the program was the construction of a 60-watt, strontium-90 RTG weighing about 1000 pounds. [The 60-watt SNAP-7B weighed 4600 pounds (2090 kg).] The first SNAP-23 was fueled in February 1970 and is now being tested.

Rankine Cycle for Higher Power

As mentioned in connection with space RTGs, thermoelectric conversion becomes unwieldy at the higher power levels because the thermoelectric elements are too inefficient and too heavy. Whereas the larger space radioisotope power generators will probably employ rotary electrical generators driven by gas turbines (the Brayton cycle), the terrestrial and undersea generators in the 5 kilowatt range and above will more likely use the so-called Rankine cycle. In the Rankine cycle, a fluid is boiled and the hot vapor produced drives a turbine attached to the generator. The vapor is then condensed and pumped back to the heat source. The water-steam Rankine cycle is the mainstay of our huge commercial electrical power plants. The AEC is studying the possibility of using small steam turbines or perhaps a turbine driven by organic vapor, such as Dowtherm A. The liquid phase (water or liquid Dowtherm A) would be heated to the boiling point and turned into vapor by a strontium-90 or cobalt-60 radioisotope heat source.

Commercially Built RTGs

As an outgrowth of the early technology developed under the AEC programs, several companies have undertaken the commercial manufacture and marketing of radioisotope power sources for marine and terrestrial applications.

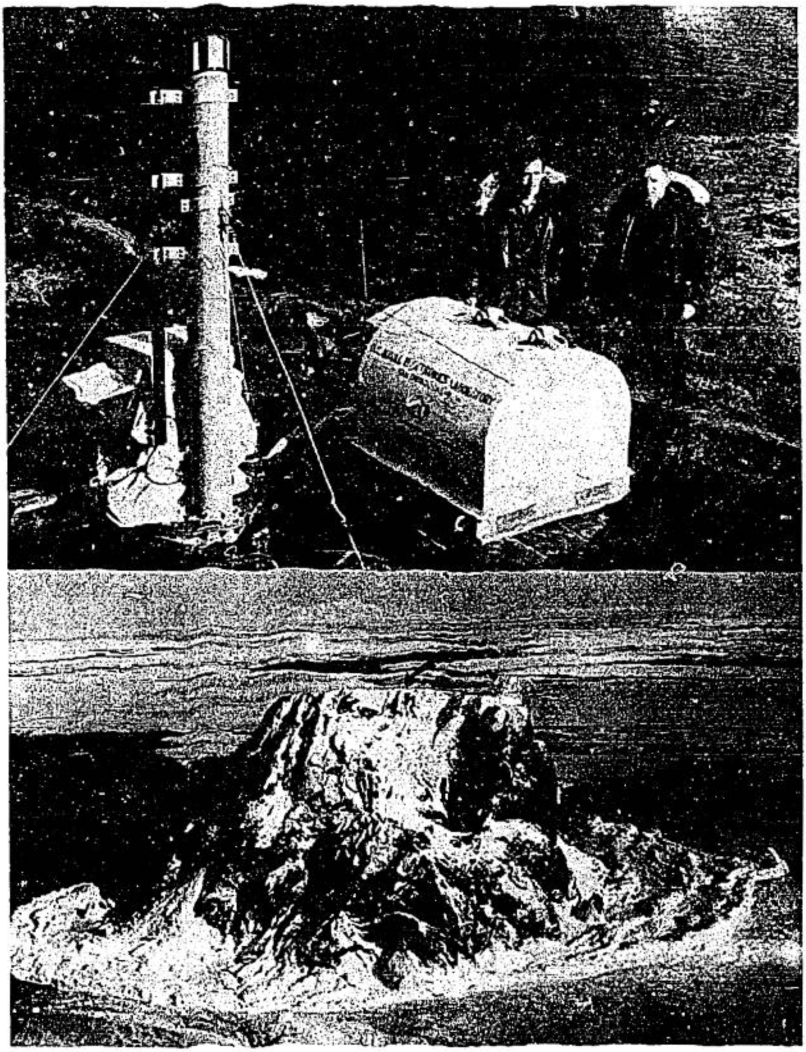
By the end of 1970, roughly two dozen commercial RTGs had been fueled and installed in terrestrial and undersea locations. In addition, many more have been tested and await deployment. So many commercial RTGs now exist that it is impractical to list them all in this booklet. Some broad generalizations will be presented instead.

The great bulk of the commercial RTGs now in service employ strontium-90 fuel and technology derived directly from the SNAP-7 program. These generators produce between 1 and 100 watts of power. The applications of these strontium-90 RTGs are essentially the same as those explored during the SNAP program.

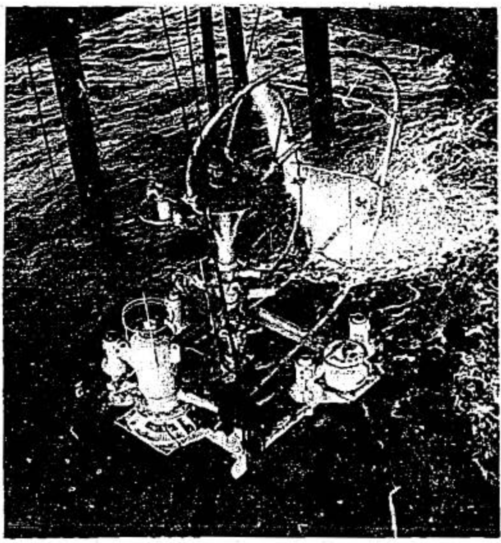
A second class of radioisotope power generators is emerging and is being applied to medical purposes, such as cardiac pacemakers and biotelemetry units. These units make use of plutonium-238 and promethium-147 fuels, which are safer than strontium-90 in these applications. Some consideration is being given to the use of tritium compound fuels for pacemakers in foreign countries. The medical generators are very small: 0.00005 to 0.1 watt. In the context of medical applications of radioisotope power, it should be mentioned that the AEC cooperates with the National Institutes of Health in the development of nuclear-powered cardiac pacemakers. Some of these have been tested successfully in dogs, and in 1970 French and British doctors implanted radioisotope-powered pacemakers in humans. Pacemakers need only tiny fractions of a watt to generate the electrical signals that keep the heart muscles synchronized properly. However, the AEC is already exploring the possibility of radioisotope-powered artificial hearts; that is, implanted mechanical pumps that can replace the natural heart when it cannot be saved. An artificial heart would

An RTG powers a Navy IRLS (Interrogation, Recording, Location System). This buoy operates below the surface to reduce the effects of turbulence and avoid collisions with surface craft.

require about 30 watts of thermal power. The AEC is developing plutonium-238 heat sources for such applications.



In 1966 the Navy installed an unmanned station on the top of Fairway Rock in the Bering Strait. An RTG provided the power for instruments and telemetry.



Wellhead control equipment operating from a platform in the Gulf of Mexico. Two RTGs provide long-lived power.

Safety on Earth

Strontium-90, the fuel for most generators used on earth, presents a special biological problem. It is a *bone-seeking* radioisotope that can be harmful if absorbed in quantity by a man or animal. It tends to enter and remain in bone structure. Nevertheless, it is an excellent heat source. What is done to make this radioisotope safe?

To begin with, the possibility of absorption is eliminated by using the insoluble compound strontium titanate. Strontium-90 is locked chemically in this compound, which remains stable even beyond its melting point of 1910° C. The compound's solubility in seawater is extremely low, and its solubility in fresh water is so low that it has never been measured.

In addition, fuel pellets for generators using strontium-90 are often encased in high-strength nickel alloys. These alloys form strong, rupture-proof fuel capsules, which have a very low corrosion rate even if immersed in the ocean. Further protection for generators is provided by additional layers of the alloy. Generators are designed so sturdily that they can survive a direct hit from a crashing airplane without releasing their fuel.

Beta particles from strontium-90 are stopped in the material surrounding the fuel and do not constitute a radiation hazard. As the beta particles are stopped, however, secondary radiations similar to X rays are produced. These radiations, called bremsstrahlung, are dangerous to man and may require protective shielding. This is provided by casings of lead more than 4 inches (10 cm) thick, depleted uranium* nearly 3 inches thick, or cast iron 8 inches thick.

Such shielding adds weight to generating systems, but this disadvantage is less important in an earth-based generator than in one rocketed into space. Moreover, the bulk provided by the shielding material is often useful. For example, it may serve to protect deep-sea generators from tremendous water pressures on the ocean bottom.

As we have seen, the safety aspects of radioisotope power generators have received most careful consideration.

Looking Ahead

The applications for radioisotope generators described in this booklet are by no means the only ones for which these devices may be suitable. As Dr. Glenn T. Seaborg, Chairman of the U. S. Atomic Energy Commission, has said: "Radioisotope power units appear feasible in almost any situation where there is need for a remote, unattended, long-lived small power source that is relatively impervious to conditions and hazards of its environment. Such uses might include navigation aids in remote areas, communications relay stations, forest fire warning equipment, ocean cable boosters, and so forth."

One may confidently expect that radioisotope power generators will play increasingly important roles, both on earth and in space.

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*Depleted uranium contains a considerably smaller amount of the fissionable isotope uranium-235 than the 0.7% found in natural uranium.

Dissecting a Radioisotope Generator

If the outer shell is peeled off a radioisotope generator, four major components are revealed. First, there is the outer shell itself: A metal case that protects internal components from exposure to the atmosphere or seawater and often serves as a heat radiator. Next, there is usually a massive radiation shield, although this may not be needed if alpha-emitting fuels are used. The third major component is the energy converter section. Here, an array of thermoelectric elements or thermionic converters transforms part of the isotope decay heat into electricity. Finally, at the heart of the generator, there is the energy source, the fuel capsule.

Most radioisotope generators are cylindrical in shape as shown, although the outer shell may be spherical. Anyone who has tried to stitch a baseball cover together knows that cylinders are easier to build than spheres. The four major generator components fit together like the layers of an onion.

During assembly, the energy converters are placed around an empty space reserved for the fuel capsule. The shield, if one is needed, is then wrapped around the converters. The outer shell, except for an end left open for fuel insertion, is soldered or welded around the shield. After the fuel capsule has been inserted by a technician, who is safely located behind the protective walls of a hot cell (see photo on page 23), the last piece of the outer shell is sealed in place. The generator is now ready for testing.

Almost all the nuclear particles emitted by the decaying radioisotopic fuel are absorbed inside the fuel capsule. During the absorption process, the fast nuclear particles collide with the atoms in the fuel capsule, causing them to move more violently and thus raise the capsule temperature. The kinetic energy of the particles is thus turned into heat. The sketch shows how heat flows outward from the fuel capsule toward the energy converter section. Clever placement of thermal insulation will channel most of the heat to the converters. Heat leakage around the converters and through the top and bottom of the generator represents unrecoverable energy losses. Only 5 to 10% of the total heat is converted into electricity; the remaining heat energy produced by the fuel flows into the outer shell. There it is radiated or conducted from the shell to the surrounding air, water, soil, or space.

The simple anatomy of a radioisotope generator is deceptive. Even the grapefruit-sized SNAP-3 requires an enormous amount of analysis by design engineers. Extensive engineering and testing may be needed to produce a safe, high-performance generator for rocket or satellite use.

What Makes a Generator Good or Bad?

First of all, a radioisotope generator must be safe. Under no circumstances should it subject any people on earth to undue radiation. Another important measure of generator performance is its reliability. Unless a generator can operate over long periods of time without failure, no one will wish to use it. Two other criteria, generator weight and cost, seesaw back and forth in importance. For space generators, weight is more crucial. On earth, weight might be sacrificed to reduce cost. Mindful of the priority placed on characteristics, generator designers make every effort to produce a safe, lightweight, cheap, and reliable plant. As nature will have it, however, reducing the weight usually increases the cost. Generator design thus becomes the typical engineering task of balancing conflicting measures of performance.

Fuels

To meet the four performance criteria just discussed, the fuel capsule must be a rupture-proof container filled with a radioisotope that produces a large amount of heat per unit

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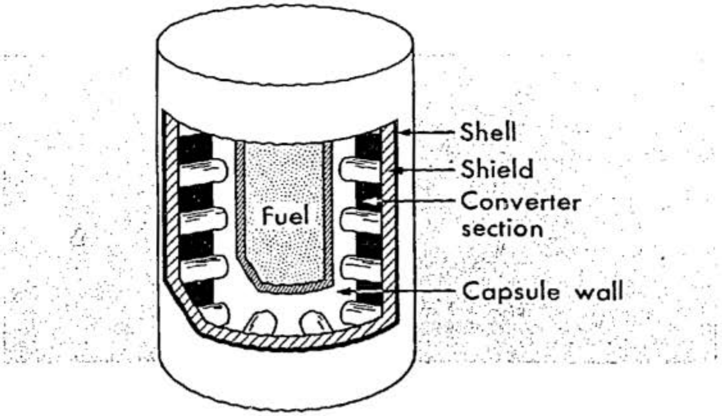
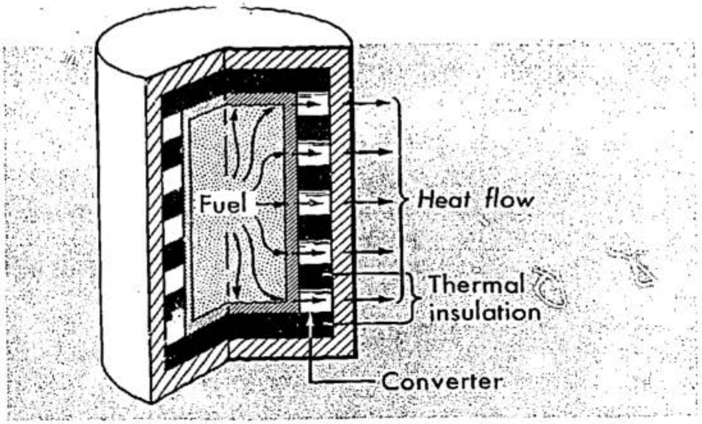


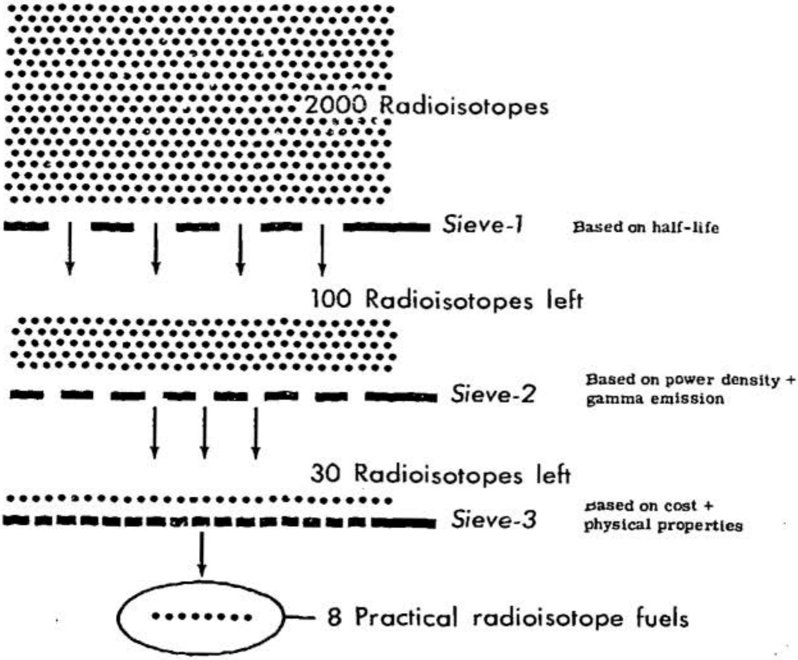
Cutaway view of a radioisotope generator.

volume. The fuel should be inexpensive and easily shielded. Unfortunately all goals are not compatible. For example, the fuel capsule must be rugged enough to withstand impact against rock at high velocity and withstand the searing temperatures of reentry into the earth's atmosphere.

A good choice of fuel contributes much to high generator performance. There are more than 2000 radioisotopes to choose from. The selection process may be likened to using a



How a SNAP generator functions.



Choosing a proper fuel by elimination.

series of sieves. If isotopes with half-lives of less than 100 days or more than 100 years are rejected by the first "sieve", only about 100 will remain. If, using a finer sieve, those radioisotopes with power densities of less than 0.1 watt/gram or with dangerous gamma-ray emissions are discarded, only 30 potential fuels are left. From this group the Atomic Energy Commission has focused its production efforts on eight radioisotopes. These fuels, listed in the table, have the best properties and are relatively cheap to make.

The first four radioisotopes in this list are beta emitters. All except cobalt-60 are fission products that are recovered in abundance from nuclear fuel reprocessing plants. The last four, which emit alpha particles, plus cobalt-60, must be made artificially in nuclear reactors. The alpha emitters are not as cheap as the fission products, but they are much easier to shield and have good power densities. The higher cost of alpha-emitting fuel is more than offset by the weight reduction achieved in space generators, such as SNAP-9A, because heavy radiation shields are not needed.

All RTGs that have been orbited or launched to the moon and the planets have depended on plutonium-238 for heat. On the first few space RTGs, plutonium metal was the *fuel form;* that is, the physical and chemical character of the basic source of heat. On some of the later SNAPs, the plutonium was prepared in microspheres about 125 millionths of an inch in diameter. Both the metallic and microsphere fuel forms were designed to aid wide dispersion of the fuel during an abort leading to reentry into the earth's atmosphere at high speed. When the safety philosophy changed from complete dispersion to complete containment, the fuel form also changed. The change was first in the direction of *cermets* (ceramic-metallic solids), such as a mixture of plutonium oxide and molybdenum. Now plutonium-238 in the form of ceramic plutonium-oxide is being considered. The cermet and ceramic fuel forms improve the probability of containment of the plutonium in the event the mission is aborted and the generator crashes to earth.

Despite the attractiveness of alpha emitters, the real fuel success story is that of strontium-90: A cheap and plentiful radioisotope, but a bone-seeker that first had to be controlled before it could be used safely in a generator.

The story begins with the generator for the weather station on Axel Heiberg Island described on pages 20 and 21. For this terrestrial application, a cheap, long-lived radioisotope was needed. Since strontium-90 has a half-life of 28 years and was available by the megacurie (a million curies) in the AEC's waste storage tanks near Richland, Washington, it easily met these requirements. Next, a strontium chemical compound had to be found that would safely retain the strontium-90 in the event of fire, collision, or other mishap. Extended chemical research at the Martin Company labora-

THE PRACTICAL RADIOISOTOPE FUELS

Radioisotope fuel	Half-life (years)	Initial power density (watts/gram)	Compound form	Compound melting point(°C)	Major radiations
Cobalt-60	5.24	15.8	Metal	1480	Beta, strong gammas
Strontium-90	28	1.0	$SrTiO_3$	1910	Beta, bremsstrahlung
Cesium-137	30	0.22	CsCl	646	Beta, a few gammas
Promethium-147	2.6	1.8	Pm_2O_3	2130	Beta, a few gammas
Thulium-170	0.35	9.6	Tm_2O_3	2375	Alpha
Polonium-210	0.38	45	RePo	1400–2200	Alpha
Plutonium-238	87.6	2.6–4.0	PuO_2 or PuPo	2250	Alpha
Curium-244	18.1	13	Cm_2O_3	2000–2200	Alpha

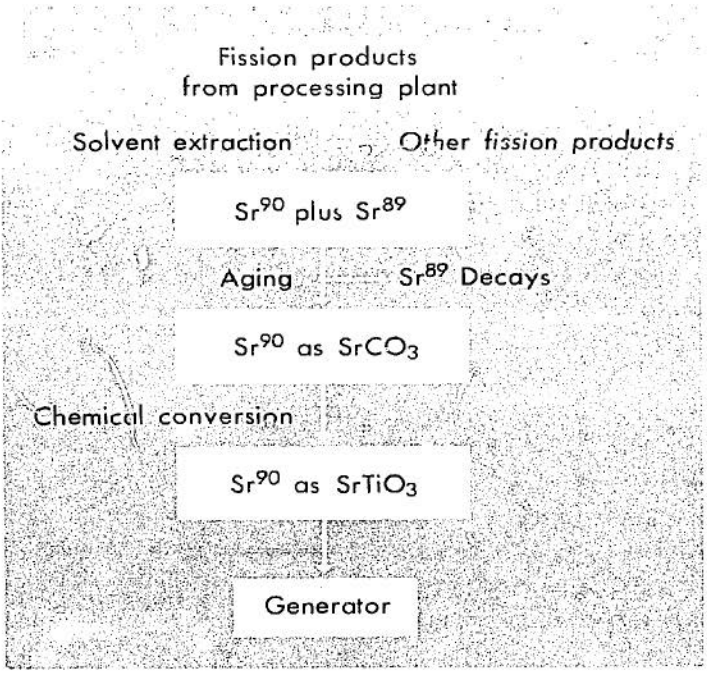
tories identified strontium titanate ($SrTiO_3$) as a good fuel form. Its melting point is 1910°C, high enough to keep the fuel solid in most fires. Further, it is barely soluble in either fresh or salt water, a property that helps keep it out of living organisms. Strontium titanate fuel is also physically strong and resistant to shock.

Once the titanate fuel form was selected, chemical engineers began work on the large-scale separation of strontium-90 from the processing chemicals and the many other fission products in the Richland waste tanks. The situation was complicated not only by the presence of many elements with similar chemical properties, but also by the existence of strontium-89, a short-lived and therefore undesirable isotope, which is chemically indistinguishable from strontium-90.

The strontium isotopes eventually were separated by a chemical process called "solvent extraction" in which similar chemical species are sorted by their slight differences in solubility. The strontium-89 problem was met by aging the separated strontium mixture. Since strontium-89 has a half-life of only 51 days compared to 28 years for strontium 90, it soon decays to an acceptably low level.

The strontium carbonate ($SrCO_3$) resulting from the solvent-extraction process was placed in huge, heavily shielded casks and shipped either to the Oak Ridge National Laboratory in Tennessee or the Martin Company's radioisotope facilities at Quehanna, Pennsylvania. At both places chemical engineers converted the strontium carbonate into strontium titanate ($SrTiO_3$). The strontium titanate was then made into small, tough, cylindrical pellets, which were loaded into fuel capsules.

Strontium-90 fuel has been used not only in the Axel Heiberg Island weather station generator, but also in several SNAP-7 generators and most commercial RTGs. At present this fuel produces more electricity than any other radioisotope.



Steps in the processing of strontium-90 fuel.

Alpha-emitting fuels also involve considerable chemical processing. Fuels like polonium-210, plutonium-238, and the curium isotopes are produced in reactors by neutron irradiation. Although they are not fission products themselves, these fuels must be separated from the many chemical species present in irradiated reactor fuel elements. The complex chemistry and high radiation levels make the production of alpha-emitting fuels a challenging one.

Converting Heat Into Electricity

As the heat from the absorbed nuclear particles flows outward from the fuel capsule, it meets an array of thermoelectric couples or thermionic converters buried in thermal insulation, as shown in the sketch on page 37. The insulation is designed to channel as much heat as possible through the energy converters. The unconverted heat emerging from the cold ends of the converters, 90 to 95% of the total produced, flows to the generator shell where it is radiated or conducted away. The function of the energy converters is to transform as much of this heat as possible into electricity without compromising the weight, cost and reliability.

Thermoelectric and thermionic converters, the two important conversion devices in radioisotopic power generation, are both "heat engines". Both depend on heat flow and temperature differences for their operation. For high efficiency the designer makes the fuel capsule as hot as possible and keeps the generator's shell "cooler" (or near environmental temperature). Sadi Carnot, a young French engineer, helped explain why these actions lead to high efficiency. He postulated that no heat engine could be more efficient than an ideal engine whose efficiency depends only on the temperatures of its hot and cold ends. This relation may be expressed:

$$e = \frac{T_h - T_c}{T_c}$$

where e = the Carnot or ideal efficiency,

T_h = the temperature of the hot end of the converter (measured in degrees Kelvin, °K*), and

T_c = the temperature of the cold end (°K).

Although radioisotope generators never approach this ideal efficiency, their efficiency can be improved by increasing T_h or by reducing T_c.

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*The Kelvin scale measures temperatures relative to absolute zero, which is −273° centigrade.

Generator conversion efficiency was not mentioned in the discussion of weight, cost, and reliability factors. Efficiency is important only as it affects cost and weight. However, fuel cost is the primary cost of a radioisotope generator, and doubling the efficiency cuts total generator cost almost in half. Thus the designer goes to considerable trouble to increase efficiency.

Thermoelectric Converters

Energy losses can occur in thermoelectric elements if their thermal conductivity is too high. Heat entering the hot ends slips through the elements without much of it being converted into electricity. Another loss is caused by high electrical resistance in the elements. Some of the electric current generated within the element is turned back into heat by the so-called Joule or I^2R losses (I = electrical current, R = resistance). Scientists have combined these two factors, together with a third, into a thermoelectric rating, or *figure of merit*, termed Z, defined as

$$Z = S^2/\rho k$$

where S = the Seebeck coefficient, a thermoelectric property of the material equal to the voltage produced by each degree of temperature difference,

ρ (rho) = the electrical resistivity of the thermoelectric material, and

k = the thermal conductivity of the thermoelectric material.

The higher the Z figure, the better the thermoelectric material. Consequently S should be high, and ρ and k low.

The work to improve thermoelectric elements has been primarily a search for better materials. Ordinary metals, like copper, conduct heat too well. Insulators, like glass, do not conduct electricity well enough. The discovery of materials

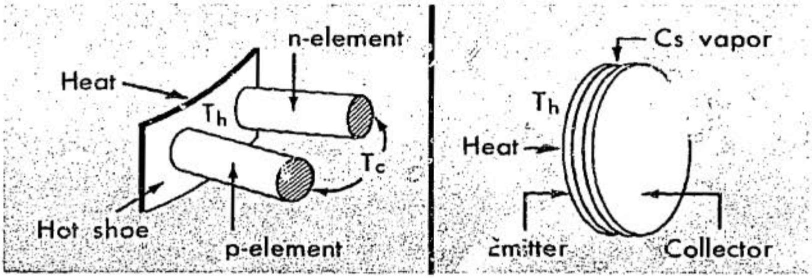


Diagram of thermoelectric elements (left) and thermionic converters.

with properties half way between good conductors and good insulators made *good* thermoelectric generators possible. Such materials are called semiconductors. Typical semiconductor materials that make good thermoelectric elements are lead telluride and silicon germanium.

Thermionic Converters

The field of thermionic energy conversion is still in its infancy. The principle of operation is quite different from that of thermoelectricity. While thermoelectric elements are cigarette-like cylinders, the thermionic converters used in isotope generators are usually flat, coin-like plates separated by a tiny gap, perhaps 0.02 cm across, filled with a metallic vapor such as cesium. Since the hot-end temperature, T_h, has to be high to boil electrons from the emitter, the Carnot efficiency is usually quite high. This gain tends to be neutralized, however, since the same high temperature increases heat loss around the converters.

Energy losses in the thermionic converter are many. Heat is lost across the narrow gap by thermal radiation. If the electrons boiled from the emitter strike the collector with high velocities, their kinetic energy is uselessly turned back into heat. The engineer has some control over these losses but finds his time better spent in trying to reduce heat leakage around the energy converters.

Dynamic Conversion of Energy

Thermoelectric and thermionic energy converters are static; that is, they possess no moving parts. Despite the high reliability of static energy conversion systems, they are inefficient relative to the so-called *dynamic* systems that employ rotating electric generators like those in commercial power plants. If the energy conversion system is inefficient, inordinate quantities of expensive radioisotope fuel will have to be used—ten times as much fuel for a thermoelectric conversion system with 4% efficiency compared to a 30%-efficient system with a turbogenerator. This extra cost is not critical when the quantities of power generated are small but, over an electrical kilowatt or two, dynamic systems are usually cheaper than static systems. This is the fundamental reason why the Rankine and Brayton dynamic power systems are being investigated for large radioisotope-fueled space and undersea power systems.

In a dynamic power conversion system, the generator is driven by a prime mover, usually a turbine that converts some of the energy of a hot gas into energy of rotation. This conversion of heat into mechanical energy takes place as the hot gas or vapor expands against the turbine blades. As energy is extracted from the hot gas, the gas cools. What happens next depends upon whether a gas (Brayton cycle) or a condensable vapor (Rankine cycle) is employed. In the Brayton cycle the gas is cooled further in a radiator where the waste heat is rejected, as required by the Laws of Thermodynamics. Finally, the gas is compressed (with power taken from the turbine) and returned to the heat source. In the Rankine cycle the vapor is cooled, causing it to condense into a liquid. The waste heat is rejected during this process. The liquid is then pumped back to the heat source and vaporized once more (there is no compression required). The basic difference between the two cycles is the type of working fluid used: A single-phase gas in the Brayton cycle and a two-phase fluid in the Rankine cycle. Both cycles convert a portion of the heat received into mechanical energy and reject the unconverted portion as heat to the environment via a radiator.

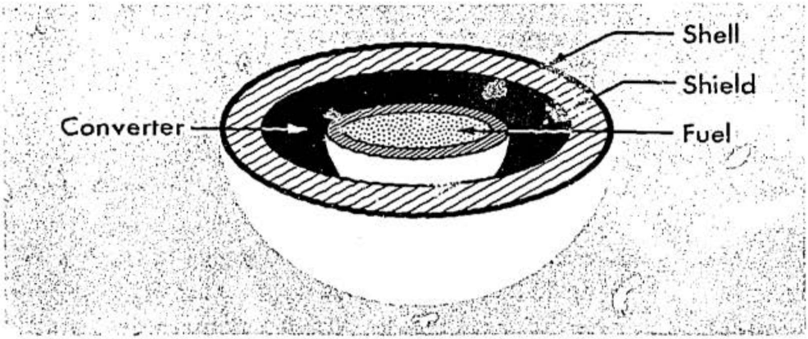
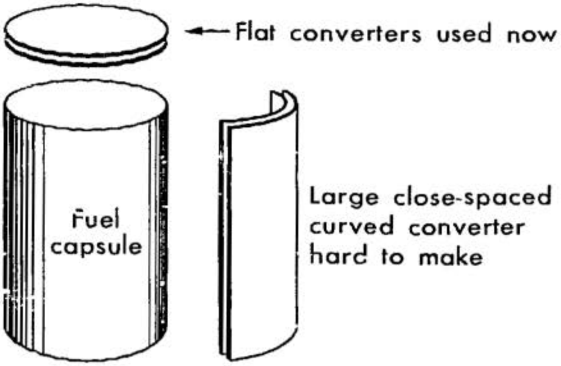


Diagram of an "ideal" generator.

Generator Geometry

The perfect generator would have a spherical fuel capsule surrounded by a solid concentric shell of converter elements, with no insulation-filled interstices. All heat would then *have* to flow through the converters. The more practical cylindrical shapes have open ends, which must be barricaded with insulation to prevent excessive heat leakage. If T_h is low, as it is in thermoelectric generators, insulating the generator is easy, and heat losses can be kept down to 20%. In thermionic generators, however, where T_h is very high, half the heat produced may escape the converter section. The thermionic generator heat losses are higher because (1) the spatial, or geometrical, arrangement of components is more of a problem and (2) thermal insulation is less effective at high temperatures.

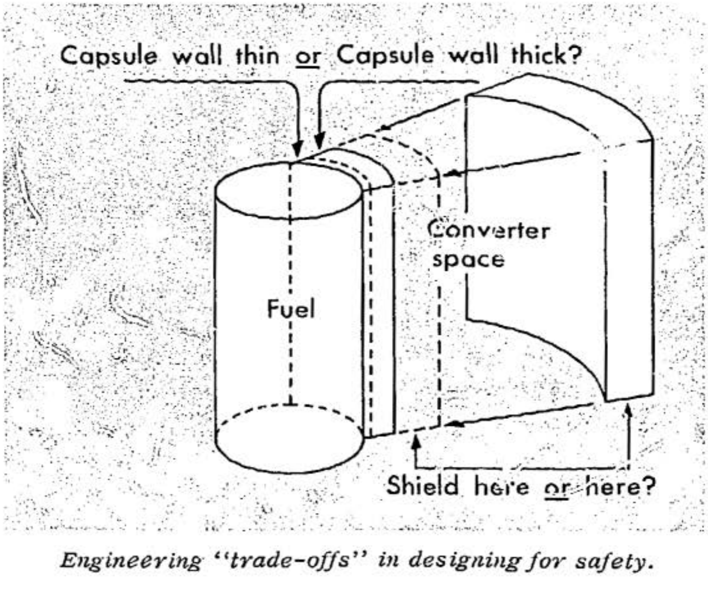


Design problems of thermionic converters.

Generator Safety

Under no circumstances can the radioisotope fuel be released where it might endanger people. The fuel capsule must be able to withstand high-velocity impact in the event of missile failures and withstand the aerodynamic heating of reentry from outer space. The gravity of the problem dictates thorough tests of fuel capsules. Only when it has been proven experimentally that the capsule design is safe can the generator be launched.

Reducing the weight of a generator means more than just using lighter materials and slimming down dimensions. Consider a heavily shielded terrestrial generator like the Axel Heiberg unit. The shield makes up 90% of the generator's 763-kilogram mass. The shield weight could be drastically reduced by placing it between the fuel capsule and the converter section instead of between the outer shell and converter section. Even though the shield thickness must stay fixed, its *volume* can be reduced by moving it closer to the axis of the fuel capsule. But, if the heat traveling outward from the fuel capsule must flow through a thick shield before it enters the converters, the hot-junction temperature, T_h, will drop. The designer is therefore confronted with another compromise. Is the sacrifice in thermal efficiency, leading to a cost increase, worth the reduction in overall weight? The application must be examined and a decision made. Sometimes the shield should be inside; sometimes outside. Such decisions, made in the face of conflicting requirements, are characteristic of radioisotope generator engineering.



Engineering "trade-offs" in designing for safety.

PROBLEMS

1. A radioisotope thermoelectric generator is operating with $T_h = 500°K$. T_c is fixed by the surrounding air at $300°K$. What must T_h be in order to double the Carnot efficiency?

2. A radioisotope fuel, say curium-244, produces an average of 2 watts/gram over a period of 10 years. Gasoline burned with air generates 10,000 joules/gram of combustion products. How much gasoline and air would it take to equal the 10-year heat output of 1 gram of curium-244? Hint: 1 watt = 1 joule/sec.

3. The inner radius of a spherical tungsten radiation shield is 10 centimeters, and the outer radius is 15 centimeters. By what percentage will the shield weight be reduced if the inner radius is moved to 4 centimeters while the thickness stays fixed?

Answers to Problems

1. $T_h = 1500°K$
2. 63,000 grams
3. 72%, 28% of the original

FACTS ABOUT RADIOISOTOPE POWER GENERATORS*

Designation	Use(s)	Electrical power (watts)	Weight (pounds) (kg)	Isotope	Isotope's half-life	Generator life
SNAP-1A	Air Force satellite	125	200 (91)	Cerium-144	285 days	1 year
SNAP-3	Demonstration device	2.5	4 (1.8)	Polonium-210	138 days	90 days
SNAP-3A	Satellite power	2.7	4.6 (2.1)	Plutonium-238	87.6 years	>1 year
Sentry	Axel Heiberg weather station	5	1680 (763)	Strontium-90	28 years	2 years minimum
SNAP-7A	Navigation buoy	10	1870 (850)	Strontium-90	28 years	2 years minimum
SNAP-7B	Fixed navigation light, offshore platform	60	4600 (2090)	Strontium-90	28 years	2 years minimum
SNAP-7C	Weather station	10	1870 (850)	Strontium-90	28 years	2 years minimum
SNAP-7D	Floating weather station	60	4600 (2090)	Strontium-90	28 years	2 years minimum
SNAP-7E	Ocean-bottom beacon	6.5	6000 (2700)	Strontium-90	28 years	2 years minimum
SNAP-7F	Offshore platform	60	4600 (2090)	Strontium-90	23 years	2 years minimum
SNAP-9A	Navigation satellite	25	27 (12.3)	Plutonium-238	87.6 years	>1 year
SNAP-11	Surveyor moon probe (proposed)	21–25	30 (13.6)	Curium-242	162 days	90 days

SNAP-13	Thermionic demonstration device	12.5	4 (1.8)	Curium-242	162 days	90 days
SNAP-15A	Military uses	0.001	1 (0.45)	Plutonium-238	87.6 years	5 years
SNAP-17	Communications satellite	30	30 (13.6)	Strontium-90	28 years	>1 year
SNAP-19B	Nimbus-3 weather satellite	30	30 (13.6)	Plutonium-238	87.6 years	>1 year
SNAP-19C	Remote telemetry station	30	40 (18.2)	Plutonium-238	87.6 years	5 years
SNAP-21A	Deep-sea uses	10	700 (318)	Strontium-90	28 years	5 years
SNAP-23	Terrestrial uses	60	1100 (500)	Strontium-90	28 years	10 years
SNAP-27	Apollo lunar instruments	63.5	68 (30.9)	Plutonium-238	87.6 years	1 year
Pioneer RTG	Unmanned Jupiter probes	30	29 (13.2)	Plutonium-238	87.6 years	3 years
Transit RTG	Navigation satellite	30	28 (12.7)	Plutonium-238	87.6 years	5 years
Viking RTG	Unmanned Mars landers	35	35 (15.9)	Plutonium-238	87.6 years	2 years
Multi-hundred watt RTG	Communication satellites and space probes	145	75 (34.1)	Plutonium-238	87.6 years	5–10 years

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*Only generators that were actually built under the SNAP program are listed.

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Integrating Isotopic Power Systems, R. T. Carpenter and D. G. Harvey, *Astronautics*, **7:** 30 (May 1962).

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SNAP-27 on the Moon, D. L. Prosser, *Isotopes and Radiation Technology*, **7:** 443 (Summer 1970).

MOTION PICTURES

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C. 20545 and from other AEC film libraries.

Atomic Weatherman: Strontium-90 Isotopic Power Applications, 18 minutes, color, 1961. Produced by the Martin-Marietta Corporation. Describes the world's first radioisotope-powered weather station set up at a remote site in the Canadian Arctic.

Nuclear Power for Space—SNAP-9A, 12 minutes, color, 1963. Produced by the Martin Company. Shows the launching of a new satellite wholly powered by a radioisotope generator and explains principles, design, and use of SNAP-9A.

Pax Atomis: SNAP-7 Terrestrial Isotopic Power Systems, 25 minutes, color, 1965. Produced for the AEC by the Martin Company. Describes the development of the strontium-90 fueled, thermoelectric SNAP-7 generators and shows installation of those in operation.

The Weather Eye, 14 minutes, color, 1969. Produced by the AEC. This is the story of the plutonium-238 nuclear power source, SNAP-19, used in the Nimbus "weather eye" satellite that monitors changing weather patterns in the atmosphere. The film describes the design, fabrication, and testing of SNAP-19, which enables the satellite to operate in darkness or sunlight. Heat from plutonium-238 fission is converted directly to electricity by means of lead telluride thermocouples. SNAP-19 is capable of producing 50 watts of electrical power to operate transmitters and electronic equipment aboard the Nimbus.

The Atom and the Man on the Moon, 13 minutes, color, 1969. Produced by the General Electric Company for the AEC. This film describes SNAP-27, its mission, and its role in the Apollo space program. When astronauts landed on the moon, they installed a small scientific laboratory to conduct lunar surface experiments. After they departed for earth, the laboratory—known as ALSEP (Apollo-Lunar Surface Packages)—remained to transmit data to stations on earth for several years. ALSEP is powered by electricity from a SNAP nuclear generator containing plutonium-238 as its fuel. The film describes the information the laboratory is transmitting to earth, how the generator is made, and the tests SNAP-27 has undergone to ensure its operation in the lunar environment.

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