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Cosmic Explorers: Radioisotope Thermoelectric Generators

Powering Deep Space Missions

Aira Astralis

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Introduction

A radioisotope thermoelectric generator (RTG, RITEG), or radioisotope power system (RPS), is a type of nuclear battery that uses an array of thermocouples to convert the heat released by the decay of a suitable radioactive material into electricity by the Seebeck effect. This type of generator has no moving parts and is ideal for deployment in remote and harsh environments for extended periods with no risk of parts wearing out or malfunctioning.

RTGs are usually the most desirable power source for unmaintained situations that need a few hundred watts (or less) of power for durations too long for fuel cells, batteries, or generators to provide economically, and in places where solar cells are not practical. RTGs have been used as power sources in satellites, space probes, and uncrewed remote facilities such as a series of lighthouses built by the Soviet Union inside the Arctic Circle.

Safe use of RTGs requires containment of the radioisotopes long after the productive life of the unit. The expense of RTGs tends to limit their use to niche applications in rare or special situations. The RTG was invented in 1954 by Mound Laboratories scientists Kenneth (Ken) C. Jordan (1921-2008) and John Birden (1918-2011). They were inducted into the National Inventors Hall of Fame in 2013.

Jordan and Birden worked on an Army Signal Corps contract (R-65-8- 998 11-SC-03-91) beginning on 1 January 1957, to conduct research on radioactive materials and thermocouples suitable for the direct conversion of heat to electrical energy using polonium-210 as the heat source. RTGs were developed in the US during the late 1950s by Mound Laboratories in Miamisburg, Ohio, under contract with the United States Atomic Energy Commission. The project was led by Dr. Bertram C. Blanke.

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Chapter 01: The Discovery of Radioisotope Thermoelectric Generators

As such, they have flown on the Pioneer pair, both Voyagers, Galileo, Ulysses, Cassini and New Horizons, with Dragonfly's Titan flight next in line. RTGs were also used instead of solar panels to power the two Viking landers, and for the scientific experiments left on the Moon by the crews of Apollo 12 through 17 (SNAP 27s).

Because the Apollo 13 Moon landing was aborted, its RTG rests in the South Pacific Ocean, in the vicinity of the Tonga Trench. The Curiosity and Perseverance Mars rover designs selected RTGs to allow greater flexibility in landing sites and longer lifespan than the solar-powered option, as used in prior generations of rovers. RTGs were also used for the Nimbus, Transit and LES satellites.

By comparison, only a few space vehicles have been launched using full-fledged nuclear reactors: the Soviet RORSAT series and the American SNAP-10A. In addition to spacecraft, the Soviet Union built 1,007 RTGs to power uncrewed lighthouses and navigation beacons on the Soviet Arctic coast by the late 1980s. Many different types of RTGs (including Beta-M type) were built in the Soviet Union for a wide variety of purposes. The lighthouses were not maintained for many years after the dissolution of the Soviet Union in 1991.

Some of the RTG units disappeared during this time - either by looting or by the natural forces of ice/storm/sea. In 1996, a project was begun by Russian and international supporters to decommission the RTGs in the lighthouses, and by 2021, all RTGs had been removed. As of 1992, the United States Air Force also used RTGs to power remotely-located Arctic equipment, and the US government has used hundreds of such units to power remote stations globally.

Sensing stations for Top-ROCC and SEEK IGLOO radar systems, predominantly located in Alaska, use RTGs. The units use strontium-90, and a larger number of such units have been deployed both on the ground and on the ocean floor than have been used on spacecraft, with public regulatory documents suggesting that the US had deployed at least 100-150 during the 1970s and 1980s. In the past, small "plutonium cells" (very small 238Pu-powered RTGs) were used in implanted heart pacemakers to ensure a very long "battery life".

As of 2004, about ninety were still in use. By the end of 2007, the number was reported to be down to just nine. The Mound Laboratory Cardiac Pacemaker

program began on 1 June 1966, in conjunction with NUMEC. The program was cancelled in 1972, when it was recognized that the heat source would not remain intact during cremation and there was no way to completely ensure that the units would not be cremated with their users' bodies.

The design of an RTG is simple by the standards of nuclear technology: the main component is a sturdy container of a radioactive material (the fuel). Thermocouples are placed in the walls of the container, with the outer end of each thermocouple connected to a heat sink. Radioactive decay of the fuel produces heat. It is the temperature difference between the fuel and the heat sink that allows the thermocouples to generate electricity.

A thermocouple is a thermoelectric device that can convert thermal energy directly into electrical energy using the Seebeck effect. It is made of two kinds of metal or semiconductor material. If they are connected to each other in a closed loop and the two junctions are at different temperatures, an electric current will flow in the loop. Typically a large number of thermocouples are connected in series to generate a higher voltage. RTGs and fission reactors use very different nuclear reactions.

Nuclear power reactors (including the miniaturized ones used in space) perform controlled nuclear fission in a chain reaction. The rate of the reaction can be controlled with neutron absorbing control rods, so power can be varied with demand or shut off (almost) entirely for maintenance. However, care is needed to avoid uncontrolled operation at dangerously high power levels, or even nuclear accident. Chain reactions do not occur in RTGs.

Heat is produced through spontaneous radioactive decay at a non-adjustable and steadily decreasing rate that depends only on the amount of fuel isotope and its half-life. In an RTG, heat generation cannot be varied with demand or shut off when not needed and it is not possible to save more energy for later by reducing the power consumption.

Therefore, auxiliary power supplies (such as rechargeable batteries) may be needed to meet peak demand, and adequate cooling must be provided at all times including the pre-launch and early flight phases of a space mission. While spectacular failures like a nuclear meltdown or explosion are impossible with an RTG, there is still a risk of radioactive contamination if the rocket explodes, the device reenters the atmosphere and disintegrates, terrestrial RTGs are damaged by storms or seasonal ice, or are vandalized.

Due to the shortage of plutonium-238, a new kind of RTG assisted by subcritical reactions has been proposed. In this kind of RTG, the alpha decay from the radioisotope is also used in alpha-neutron reactions with a suitable

element such as beryllium. This way a long-lived neutron source is produced. Because the system has a criticality close to but less than 1, i.e. Keff < 1, a subcritical multiplication is achieved which increases the neutron background and produces energy from fission reactions.

The first RTG launched into space by the United States was SNAP 3B in 1961 powered by 96 grams of plutonium-238 metal, aboard the Navy Transit 4A spacecraft. One of the first terrestrial uses of RTGs was in 1966 by the US Navy at uninhabited Fairway Rock in Alaska. RTGs were used at that site until 1995. A common RTG application is spacecraft power supply. Several generations of RTG design have been used for probes that traveled far from the Sun, rendering solar panels impractical.

As such, they have powered the two Pioneers, both Voyagers, Galileo, Ulysses, Cassini and New Horizons, and Dragonfly's planned flight to Titan will carry one too.

Though the number of fissions produced in the RTG is very small (making their gamma radiation negligible), because each fission releases over 30 times more energy than each alpha decay (200 MeV compared to 6 MeV), up to a 10% energy gain is attainable, which translates into a reduction of the 238Pu needed per mission.

The idea was proposed to NASA in 2012 for the yearly NASA NSPIRE competition, which translated to Idaho National Laboratory at the Center for Space Nuclear Research (CSNR) in 2013 for studies of feasibility. However the essentials are unmodified.

RTG have been proposed for use on realistic interstellar precursor missions and interstellar probes.An example of this is the Innovative Interstellar Explorer (2003-current) proposal from NASA.An RTG using 241Am was proposed for this type of mission in 2002.This could support mission extensions up to 1000 years on the interstellar probe, because 241Am decays more slowly than 238Pu.Other isotopes for RTG were also examined in the study, looking at traits such as watt/gram, half-life, and decay products.

An interstellar probe proposal from 1999 suggested using three advanced radioisotope power sources (ARPS). The RTG electricity can be used for powering scientific instruments and communication to Earth on the probes. One mission proposed using the electricity to power ion engines, calling this method radioisotope electric propulsion (REP). A power enhancement for radioisotope heat sources based on a self-induced electrostatic field has been proposed. According to the authors, enhancements of 5-10% could be attainable using beta sources.

A typical RTG is powered by radioactive decay and features electricity from thermoelectric conversion, but for the sake of knowledge, some systems with some variations on that concept are included here. Known spacecraft/nuclear power systems and their fate. Systems face a variety of fates, for example, Apollo's SNAP-27 were left on the Moon. Some other spacecraft also have small radioisotope heaters, for example each of the Mars Exploration Rovers have a 1 watt radioisotope heater.

Spacecraft use different amounts of material, for example MSL Curiosity has 4.8 kg of plutonium-238 dioxide. not really an RTG, the BES-5 Buk (BES-5) reactor was a fast reactor which used thermocouples based on semiconductors to convert heat directly into electricity not really an RTG, the SNAP-10A used enriched uranium fuel, zirconium hydride as a moderator, liquid sodium potassium alloy coolant, and was activated or deactivated with beryllium reflectors Reactor heat fed a thermoelectric conversion system for electrical production.

The amount of energy released per time (power) of a given quantity is inversely proportional to half-life.

An isotope with twice the half-life and the same energy per decay will release power at half the rate per mole. Typical half-lives for radioisotopes used in RTGs are therefore several decades, although isotopes with shorter half-lives could be used for specialized applications. For spaceflight use, the fuel must produce a large amount of power per mass and volume (density). Density and weight are not as important for terrestrial use, unless there are size restrictions.

The decay energy can be calculated if the energy of radioactive radiation or the mass loss before and after radioactive decay is known. Energy release per decay is proportional to power production per mole. Radiation must be of a type easily absorbed and transformed into thermal radiation, preferably alpha radiation. Beta radiation can emit considerable gamma/X-ray radiation through bremsstrahlung secondary radiation production and therefore requires heavy shielding.

Isotopes must not produce significant amounts of gamma, neutron radiation or penetrating radiation in general through other decay modes or decay chain products. The first two criteria limit the number of possible fuels to fewer than thirty nuclides within the entire table of nuclides. Plutonium-238, curium-244, strontium-90, and most recently americium-241 are the most often cited candidate isotopes, but 43 more isotopes out of approximately 1,300 were considered at the beginning in the 1950s.

The table below does not necessarily give power densities for the pure material but for a chemically inert form. For actinides this is of little concern as their oxides are usually inert enough (and can be transformed into ceramics further increasing their stability), but for alkali metals and alkaline earth metals like caesium or strontium respectively, relatively complex (and heavy) chemical compounds have to be used.

For example, strontium is commonly used as strontium titanate in RTGs, which increases molar mass by about a factor of 2. Furthermore, depending on the source, isotopic purity may not be obtainable. Plutonium extracted from spent nuclear fuel has a low share of Pu-238, so plutonium-238 for use in RTGs is usually purpose-made by neutron irradiation of neptunium-237, further raising costs.

If isotope separation, a costly and time-consuming process, is to be avoided, this has to be factored in, too. While historically RTGs have been rather small, there is in theory nothing preventing RTGs from reaching into the megawattthermal range of power.

However, for such applications actinides are less suitable than lighter radioisotopes as the critical mass is orders of magnitude below the mass needed to produce such amounts of power. As Sr-90, Cs-137 and other lighter radionuclides cannot maintain a nuclear chain reaction under any circumstances, RTGs of arbitrary size and power could be assembled from them if enough material can be produced. In general, however, potential applications for such large-scale RTGs are more the domain of small modular reactors, microreactors or non-nuclear power sources.

Plutonium-238 has a half-life of 87.7 years, reasonable power density of 0.57 watts per gram, and exceptionally low gamma and neutron radiation levels. 238Pu has the lowest shielding requirements. Only three candidate isotopes meet the last criterion (not all are listed above) and need less than 25 mm of lead shielding to block the radiation. 238Pu (the best of these three) needs less than 2.5 mm, and in many cases, no shielding is needed in a 238Pu RTG, as the casing itself is adequate.

238Pu has become the most widely used fuel for RTGs, in the form of plutonium(IV) oxide (PuO_2). However, plutonium(IV) oxide containing a natural abundance of oxygen emits neutrons at the rate of roughly 2.3×10^4 n/sec/g of 238Pu. This emission rate is relatively high compared to the neutron emission rate of plutonium-238 metal. The metal containing no light element impurities emits roughly 2.8×10^3 n/sec/g of 238Pu. These neutrons are produced by the spontaneous fission of 238Pu.

The difference in the emission rates of the metal and the oxide is due mainly to the alpha, neutron reaction with the oxygen-18 and oxygen-17 in the oxide. The normal amount of oxygen-18 present in the natural form is 0.204% while that of oxygen-17 is 0.037%. The reduction of the oxygen-17 and oxygen-18 present in the plutonium dioxide will result in a much lower neutron emission rate for the oxide; this can be accomplished by a gas phase 16O2 exchange method.

The radioactive material used in RTGs must meet several demands at once. Its half-life must be long enough that energy flows at a nearly steady rate across a whole mission, yet not so long that power per gram suffers. Its decay should emit little penetrating radiation, so the unit needs no heavy shielding. And it should pack high power into low mass, because every kilogram launched costs propellant. Isotopes with half-lives of a few decades, plutonium-238 among them, hit that balance best.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.