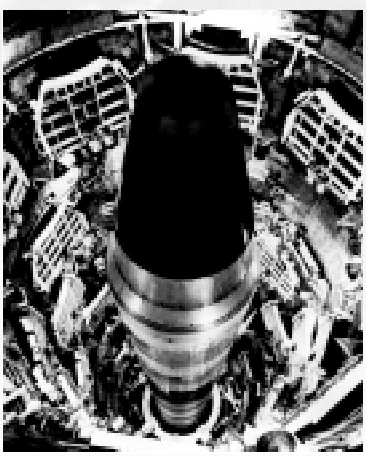
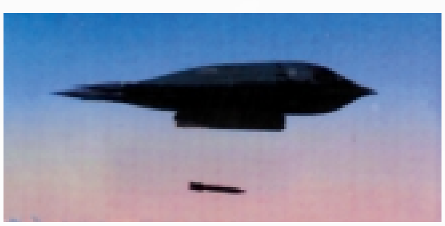
Plutonium in Use
From single atoms to multiton amounts

Plutonium is highly toxic and radioactive, virtually nonexistent in nature, and very expensive to produce. Clearly, one must have good reason to justify its use. The only significant applications for plutonium to date, therefore, are those capitalizing on the "factor of millions" gained by using the energy of the nucleus: nuclear explosives and nuclear power. Moreover, the persistent radioactive decay of plutonium has also made this metal useful as a compact heat source to produce electricity for deep-space missions.

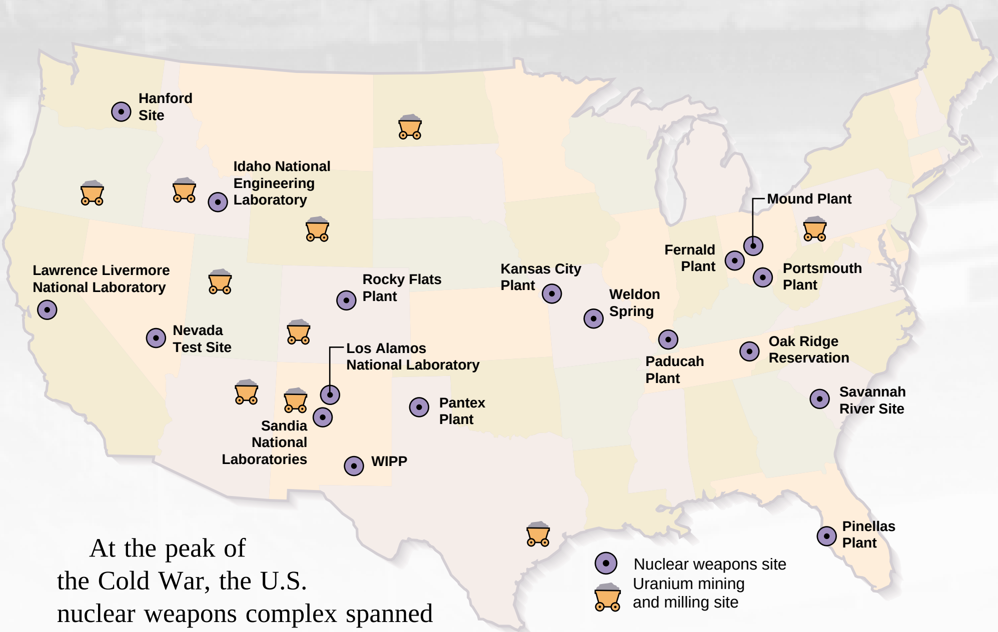




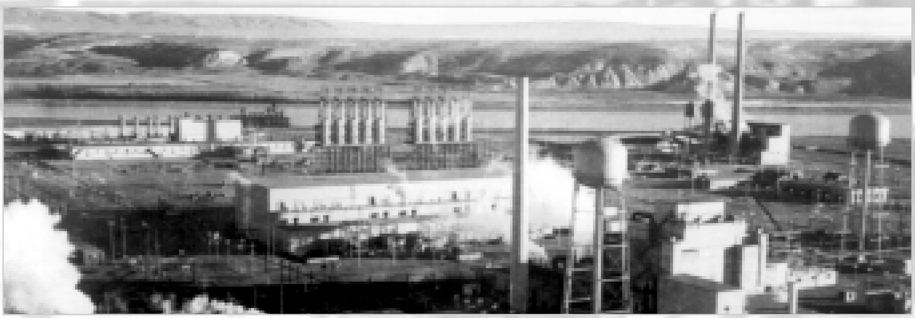
The U.S. nuclear triad: submarine launched missiles, land-based missiles, and air-dropped bombs.

Nuclear Weapons

During the Manhattan Project, the plutonium challenge was to produce sufficient material for a few bombs and to fabricate it into the desired shape. But in the years that followed, the effort shifted to the mass production of plutonium, and the designing, building, and testing of large numbers of nuclear weapons.



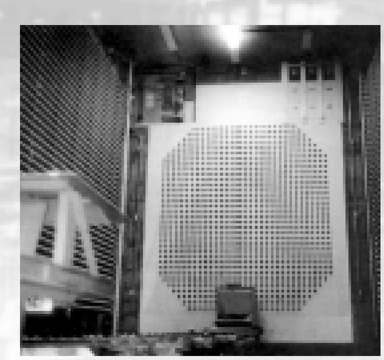
At the peak of the Cold War, the U.S. nuclear weapons complex spanned the country with 18 facilities. Nine plutonium production reactors were in operation at the Hanford Site in Washington, and five more at the Savannah River site (top of opposite page) that was established in 1950 near Aiken, SC. Those two sites also hosted seven reprocessing facilities to extract the plutonium from the irradiated uranium fuel rods. Weapon parts were manufactured in Colorado, Florida, Missouri, Ohio, Tennessee, and Washington, and the final warhead assembly took place at the Pantex Plant near Amarillo, TX. The national laboratories in New Mexico and California designed the warheads, which were subsequently tested at the site in Nevada. In more than 50 years of operation, the nuclear weapons complex created over 100 tonnes of plutonium, produced tens of thousands of nuclear warheads, and oversaw more than 1000 detonations.

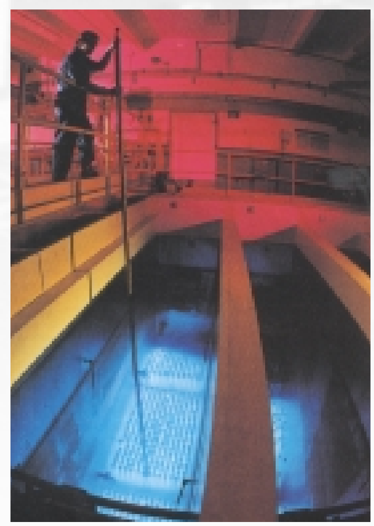


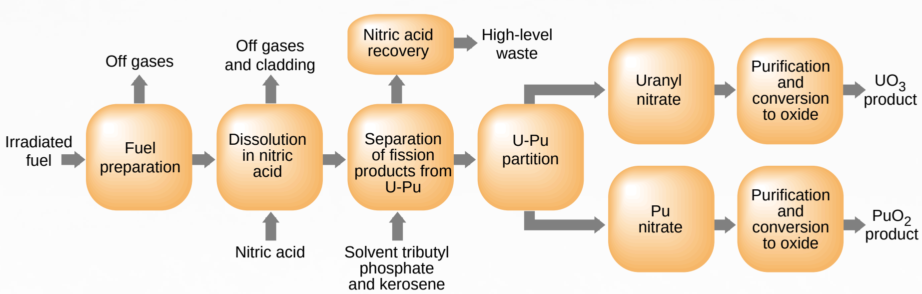
All plutonium production reactors in the United States are now shut down. The U.S. government declared nearly half of the 99.5 tonnes still in the inventory (in forms ranging from plutonium pits in stockpiled weapons systems to oxides, scrap, residues, and waste) as excess to the nation's defense needs. The United States has, however, more than an adequate supply of plutonium for the triad of land-based missiles, submarine-launched missiles, and air-delivered bombs that constitute the U.S. nuclear deterrent.

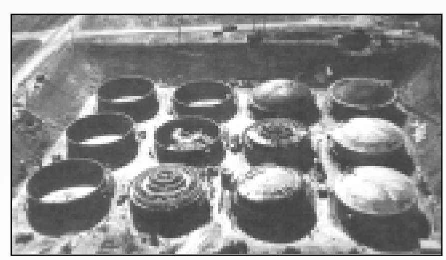
The Soviet nuclear weapons program began in earnest right after Hiroshima. The nuclear bomb first tested by the Soviets was a copy (obtained through espionage) of the U.S. plutonium design tested at Trinity Site on July 16, 1945. During the Cold War, the Soviets built an enormous plutonium production infrastructure at three major sites: Chelyabinsk-65 (in the South Urals), Tomsk-7 (in Siberia), and Krasnoyarsk-26 (in Siberia). The Soviet Union matched the United States step by step in developing its nuclear arsenal. The Soviets also created the ultimate doomsday weapon, a 100-megaton device (tested at half yield in 1961).

We do not know how much plutonium was produced in the Soviet Union and how much remains in Russia today because Russia still considers its plutonium inventories to be state secrets. Our best estimate is that today Russia has between 125 and 200 tonnes of plutonium in its military program in many different forms. The stockpiles of military plutonium in the rest of the world, including the United Kingdom, France, China, India, Pakistan, Israel and North Korea, are small and total about 18 tonnes.









Plutonium is created in nuclear reactors, such as the N reactor (upper right) at the Hanford Site (top left). Once the fuel is removed from the reactor core, it is placed in a cooling tank (middle right) to allow shortest-lived fission products to decay. The PUREX process (lower left) is used to separate plutonium and uranium from the remaining fission products in the irradiated nuclear fuel. The highly radioactive waste from PUREX is stored in enormous tanks (lower right) located on-site.

Nuclear Reactors

Mark I, a prototype reactor that could be used in a submarine, became the first U.S. reactor to produce substantial amounts of power on May 31, 1953. Two years later, under the able leadership of Admiral Hyman G. Rickover, the United States launched its naval reactor program with the first sea trials of the U.S.S. Nautilus, a nuclear-power submarine.

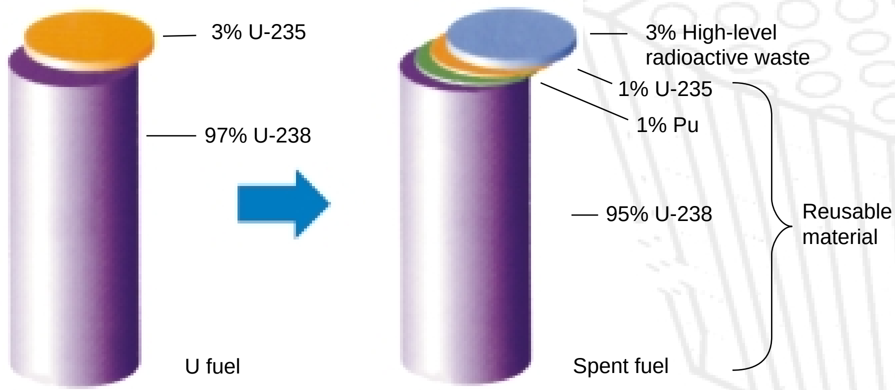
Shortly after the discovery of radioactivity, people started dreaming about the peaceful use of atomic energy for virtually inexhaustible power production. In his book *The Interpretation of Radium*, published in 1909, Frederick Soddy referred to nuclear energy as being "the real wealth of the world. It is a legitimate aspiration to believe that one day [man] will attain the power to regulate for his own purposes the primary fountains of energy which Nature now so jealously conserves for the future." Enrico Fermi also dreamed about the potential of limitless nuclear energy shortly after his reactor, CP-1, sustained the first controlled-fission reaction on December 2, 1942. (See the article "From Alchemy to Atoms" on page 62.)

Commercial nuclear power received a significant boost when President Eisenhower launched the Atoms for Peace Program with a speech at the United Nations on December 8, 1953. Although nuclear power has not expanded at the rate it was projected during Eisenhower's years, it nevertheless has become an indispensable part of the world's energy supply. Some 430 nuclear power reactors around the world supply nearly 20 percent of the world's electricity today, providing electric power for nearly one billion people. One hundred and four reactors are in service today in the United States. However, no new nuclear power plants have been ordered in the United States for over 20 years.

Nuclear reactors were also developed to power the Navy's submarines under the able leadership of Admiral Hyman G. Rickover. The United States launched its naval reactor program in January 1955 with the sea trials of the first nuclear-power submarine, the U.S.S. Nautilus. The Soviets not only followed suit with a nuclear submarine program of their own, but they built many other seafaring vessels, including the first nuclear-powered ice breaker, the Lenin, in 1959.

Nuclear reactors are designed to foster a fission chain reaction and to extract the nuclear energy in a controlled manner. Commercial reactors typically use fuel that is 95 to 98 percent uranium-238, with the fissile isotope uranium-235 making

The Soviet Union claimed it demonstrated the world's first nuclear power plant at Obninsk (a) commissioned on June 27, 1954. It was a graphite-moderated, water-cooled reactor designed to produce 5 MW of electric power. The United Kingdom was first to operate a truly commercial nuclear power plant at Sellafield (b) in 1956. The first U.S. commercial power plant was commissioned at Shippingport, Pennsylvania (c), in December 1957.



Fuel that has been through one reactor burn cycle is called spent fuel even though it contains 2% fissile material and 95% fertile material. **(This illustration was adapted with permission from *PowerLine*, Japan.)**

up the rest. To be fissile means that the nucleus fissions when it absorbs a neutron of any energy, including low-energy neutrons that are in thermal equilibrium with the environment (known as thermal neutrons). Fertile isotopes, which can be transmuted into fissile isotopes, will fission only with high-energy neutrons. Uranium-238 and thorium-232 are fertile isotopes.

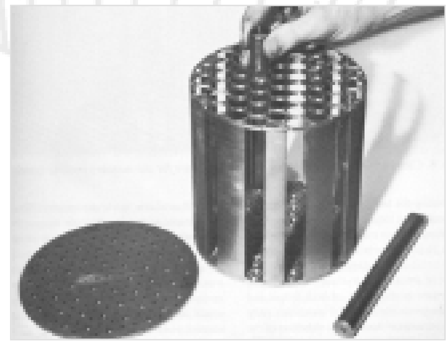
Thermal reactors use thermal neutrons to “burn” the fissile component of the uranium fuel. Atoms of uranium-235 that absorb the low-energy neutrons fission into two nuclei of nearly equal mass. These fission products fly away from each other with tremendous energy, most of which is converted to heat as the product nuclei come to rest in the fuel rod. The heat is extracted by a coolant (typically water) that is run through a heat-exchanger. Water on the other side of the heat exchanger is converted to steam, which drives a turbine coupled to an electric generator. Today’s large commercial reactors have an electrical generating capacity of more than a billion watts.

On average, about 2.5 neutrons are released when uranium-235 fissions. Only one of those neutrons needs to be absorbed by another uranium-235 atom to maintain the chain reaction. The other neutrons are absorbed by the many uranium-238 atoms, which subsequently decay to plutonium-239. Since plutonium-239 is fissile, it too can fission and release energy. In modern reactors, the “in-grown” plutonium accounts for approximately 30 percent of the generated power.

Within the civilian sector, worldwide plutonium inventories are currently estimated at over 1000 tonnes—an amount that dwarfs military inventories. This commercial, or reactor-grade, plutonium contains nearly 40 percent nonfissile isotopes. In contrast, the weapons-grade plutonium produced in military reactors consists of over 93 percent fissile plutonium-239 and less than 7 percent other plutonium isotopes.

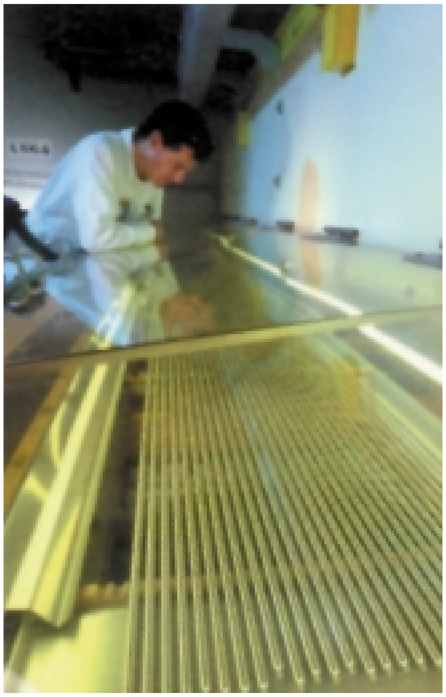
In the generic thermal reactor described above, only a small fraction of the uranium-235 and the in-grown plutonium is actually consumed during one cycle of power generation. The fertile uranium-238 that makes up most of the fuel rod is essentially inert—its energy potential is tapped only after it absorbs a neutron and is transmuted to fissile plutonium-239. Thus, most of the energy potential of the fuel is unused. Shortly after World War II, Fermi and other scientists recognized the possibility of enhancing plutonium production and creating more fissile fuel than was consumed. After fuel has burnt for one cycle, the excess plutonium could be extracted, separated from uranium-238, and reprocessed into fuel rods. By “breeding” plutonium within a closed fuel cycle, we can tap most of the nuclear energy.

A breeder reactor uses high-energy (fast) neutrons, rather than thermal neutrons, to sustain the chain reaction. The fission cross section decreases with neutron energy, so the chain reaction is maintained by increased amounts of fissile material (either uranium-235 or plutonium-239). Because each fission event produces an excess of neutrons, the net effect is that, within the reactor, many neutrons are available to transmute uranium-238 and breed plutonium.



Several research reactors were developed at Los Alamos. They were designed to produce a high-neutron flux that could be used to obtain neutron cross-section data relevant for nuclear weapons. Of note was the Clementine reactor that was built toward the end of 1946. It used plutonium metal as fuel and fast neutrons to achieve the chain reaction. The plutonium fuel led to severe corrosion problems, and Clementine ceased operations in 1952.

The first fast reactor to fully explore the breeder concept and to produce usable power was the Experimental Breeder Reactor I (EBR-I), located at Arco, Idaho. On December 20, 1951, the reactor powered up and initially produced enough electricity to light four 150-W light bulbs. Its output later reached 100 kW of electric power.



For 35 years, plutonium has been recycled by burning of mixed-oxide (MOX) fuel in nuclear reactors. Today, European conventional water-cooled nuclear reactors are licensed to load around one-third of the core with MOX fuel. In the photo above, a technician is checking MOX fuel rods. **(This photo was reproduced courtesy of *Nuclear Recycling*.)**

Breeder reactors are much more difficult to control and far more expensive to build than thermal reactors. For several decades, the breeder reactor program was pursued aggressively in the United States, the Soviet Union, and France. But the Carter Administration strongly opposed the U.S. breeder program, which finally came to a halt in 1983 with the cancellation of the Clinch River Breeder Reactor program. France, Russia, and Japan are still pursuing breeder technology today with the hope of reviving commercial interest early in this century.

Another way to fully utilize the power potential of the uranium is to recycle or reprocess the spent fuel. Unburned uranium and plutonium grown in during reactor operation are chemically separated from each other and from the radioactive fission products. (The fission products poison the chain reaction by absorbing neutrons and must therefore be removed.) However, the efficiency gained by recycling nuclear fuel is offset by the fact that the separated plutonium can be used to make nuclear weapons.

In 1977, President Carter judged the proliferation risk too great, and he decided not to allow U.S. commercial nuclear power plants to recycle plutonium from spent fuel. He hoped to set an example, which the other nuclear power nations would follow. However, they did not. Instead, they followed the economic incentive to reprocess plutonium from spent fuel.

Reprocessed plutonium can be mixed with uranium to form a mixed-oxide (MOX) fuel. One gram of MOX fuel will produce as much electricity as burning one ton of oil, and oil is a commodity that countries such as France and Japan have to import. Today, 32 reactors in Belgium, France, Germany, and Switzerland use MOX fuel. Japan has also begun to burn MOX fuel.

Peaceful Nuclear Explosives

The Atoms for Peace program also led to the exploration of nuclear explosions for peaceful purposes known as peaceful nuclear explosions (PNEs). The U.S. Plowshare Project began in 1957 and initially explored using PNEs for large-scale earth moving, including excavating a second Atlantic-to-Pacific canal through Central America. Additional peaceful applications, such as oil and gas stimulation, were also considered.

The United States detonated 27 PNEs. However, a PNE with a yield of about 10 kilotons injects several kilograms of fission products and actinides into the local environment. Radioactive contamination is therefore part of the risk associated with the detonations. The program was abandoned in the mid-1970s because the risks were considered to outweigh the benefits.

The Soviet Union responded to the U.S. Plowshare Project with its own "industrial nuclear explosion" carried out in 1965 at the Semipalatinsk Test Site in Kazakhstan. The purpose of the test was to build a dam across a small river. The lip of the test crater was to form the dam during spring runoff. The test created a major lake of some 10 million cubic meters of water. It released substantial radioactivity into the atmosphere. Today, the lake is known as Lake Balapan, is used for water control, and supplies water to cattle in the area. Modern PNE nuclear devices, such as those shown here from the Atomic Museum in Snezhinsk, were designed to minimize the fission yields in order to reduce radiological contamination.

The Soviet Union carried out 124 underground PNEs. They were used as giant excavation tools for creating dams and lakes or diverting rivers. With PNEs, geologic mapping was completed throughout vast regions of the Soviet Union, and huge underground cavities were created for the storage of gas condensates. Russian nuclear scientists have continued to advocate using PNEs for the destruction of chemical weapons, chemical wastes, or even nuclear devices. However, following the recommendation of the United States, all nuclear explosions, including PNEs, were banned by the 1996 Comprehensive Test Ban Treaty.

Nuclear Batteries

Plutonium is the power source for nuclear batteries that provide heat and electricity. When plutonium decays by α-particle emission, the α-particles lose most of their 5 million electron volts of energy to electrons in the plutonium lattice. As a result, heat is generated. Each gram of plutonium-239 produces a modest 0.002 watt as a result of its intrinsic α-particle decay. But plutonium-238, which is also produced in nuclear reactors, has a half-life of 89 years and an α-activity roughly 280 times greater than that of plutonium-239. Its intrinsic heat output is approximately 0.5 watt per gram. A thermoelectric device can convert the heat to electricity, and a few hundred grams of plutonium-238 is sufficient to generate usable amounts of electric power.

Several applications were initially considered for nuclear batteries, including powering heart pacemakers and remote terrestrial power stations. However, the difficulties of dealing with plutonium in commercial applications are such that today nuclear batteries are used only for deep-space missions. The spectacular photographs and scientific data sent back from the Pioneer and Voyager satellites were made possible by the extremely dependable performance of plutonium-238 power sources.

A modern battery, known as a general purpose heat source (GPHS) consists of a 150-gram pellet of plutonium-238 dioxide encased in many layers of protective materials. Seventy-two GPHS are stacked together with a set of thermocouples to make a radioisotope thermoelectric generator (RTG), which has an output of 285 watts of electricity. The RTG unit is compact and extremely reliable. Smaller capsules (known as radioisotope heater units, RHU) contain 2.7 grams of plutonium-238 dioxide. These are used as heat sources to keep equipment warm and functioning. Three RHUs, for example, were on the small Mars robot lander. ■

For several decades, both the Soviet Union and the United States operated compact, uranium-fueled nuclear reactors in space for applications requiring much greater power than those delivered by the thermoelectric generators. These reactors have had a checkered safety history. Today, interest in them is maintained only at a research level.

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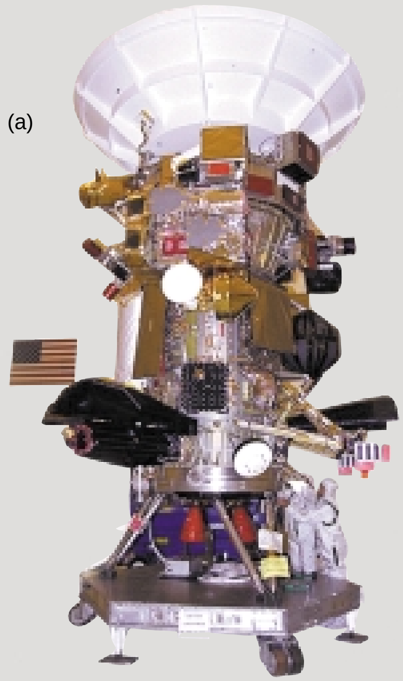

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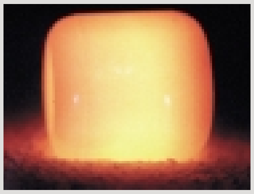

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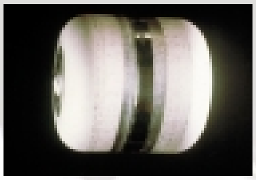

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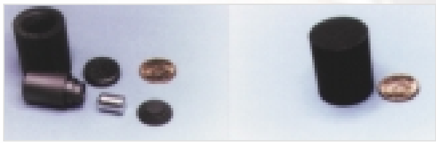

(a) By 2004, the Cassini spacecraft, shown here during assembly, should reach Saturn, where it will collect scientific data for four years. Aboard Cassini, almost 1 kW of electricity is supplied by three thermoelectric generators, each powered by a general-purpose heat source containing 72 plutonium-238 dioxide pellets. Each pellet produces 62 W of heat from the natural radioactive decay of plutonium-238. When thermally isolated, each pellet glows a brilliant orange, as shown in (b). The pellets are clad with iridium and welded as shown in (c) before they are further protected with several graphite shells for heat and impact resistance. (d) Lightweight, 1-W plutonium-238 heater units are used to warm sensitive electrical and mechanical systems aboard the spacecraft.