Nuclear Technology

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Nuclear Technology

A residential smoke detector is the most familiar piece of nuclear technology for some people

Nuclear technology is technology that involves the reactions of atomic nuclei. It has found applications from smoke detectors to nuclear reactors, and from gun sights to nuclear weapons.

History and scientific background

Discovery

The vast majority of common, natural phenomena on Earth only involve gravity and electromagnetism, and not nuclear reactions. This is because atomic nuclei are generally kept apart because they contain positive electrical charges and therefore repel each other.

In 1896, Henri Becquerel was investigating phosphorescence in uranium salts when he discovered a new phenomenon which came to be called radioactivity. He, Pierre Curie and Marie Curie began investigating the phenomenon. In the process, they isolated the element radium, which is highly radioactive. They discovered that radioactive materials produce intense, penetrating rays of three distinct sorts, which they labeled alpha, beta,

and gamma after the Greek letters. Some of these kinds of radiation could pass through ordinary matter, and all of them could be harmful in large amounts. All the early researchers received various radiation burns, much like sunburn, and thought little of it.

The new phenomenon of radioactivity was seized upon by the manufacturers of quack medicine (as had the discoveries of electricity and magnetism, earlier), and a number of patent medicines and treatments involving radioactivity were put forward. Gradually it was realized that the radiation produced by radioactive decay was ionizing radiation, and that even quantities too small to burn posed a severe long-term hazard. Many of the scientists working on radioactivity died of cancer as a result of their exposure. Radioactive patent medicines mostly disappeared, but other applications of radioactive materials persisted, such as the use of radium salts to produce glowing dials on meters.

As the atom came to be better understood, the nature of radioactivity became clearer. Some larger atomic nuclei are unstable, and so decay (release matter or energy) after a random interval. The three forms of radiation that Becquerel and the Curies discovered are also more fully understood. Alpha decay is when a nucleus releases an alpha particle, which is two protons and two neutrons, equivalent to a helium nucleus. Beta decay is the release of a beta particle, a high-energy electron. Gamma decay releases gamma rays, which unlike alpha and beta radiation are not matter but electromagnetic radiation of very high frequency, and therefore energy. This type of radiation is the most dangerous, and most difficult to block. All three types of radiation occur naturally in certain elements.

It has also become clear that the ultimate source of most terrestrial energy is nuclear, either through radiation from the Sun caused by stellar thermonuclear reactions or by radioactive decay of uranium within the Earth, the principal source of geothermal energy.

Fission

In natural nuclear radiation, the byproducts are very small compared to the nuclei from which they originate. Nuclear fission is the process of splitting a nucleus into roughly equal parts, and releasing energy and neutrons in the process. If these neutrons are captured by another unstable nucleus, they can fission as well, leading to a chain reaction. The average number of neutrons released per nucleus that go on to fission another nucleus is referred to as k. Values of k larger than 1 mean that the fission reaction is releasing more neutrons than it absorbs, and therefore is referred to as a self-sustaining chain reaction. A mass of fissile material large enough (and in a suitable configuration) to induce a self-sustaining chain reaction is called a critical mass.....

When a neutron is captured by a suitable nucleus, fission may occur immediately, or the nucleus may persist in an unstable state for a short time. If there are enough immediate decays to carry on the chain reaction, the mass is said to be prompt critical, and the energy release will grow rapidly and uncontrollably, usually leading to an explosion.

When discovered on the eve of World War II, this insight led multiple countries to begin programs investigating the possibility of constructing an atomic bomb — a weapon

which utilized fission reactions to generate far more energy than could be created with chemical explosives. The Manhattan Project, run by the United States with the help of the United Kingdom and Canada, developed multiple fission weapons which were used against Japan in 1945. During the project, the first fission reactors were developed as well, though they were primarily for weapons manufacture and did not generate electricity.

However, if the mass is critical only when the delayed neutrons are included, then the reaction can be controlled, for example by the introduction or removal of neutron absorbers. This is what allows nuclear reactors to be built. Fast neutrons are not easily captured by nuclei; they must be slowed (slow neutrons), generally by collision with the nuclei of a neutron moderator, before they can be easily captured. Today, this type of fission is commonly used to generate electricity.

Fusion

If nuclei are forced to collide, they can undergo nuclear fusion. This process may release or absorb energy. When the resulting nucleus is lighter than that of iron, energy is normally released; when the nucleus is heavier than that of iron, energy is generally absorbed. This process of fusion occurs in stars, which derive their energy from hydrogen and helium. They form, through stellar nucleosynthesis, the light elements (lithium to calcium) as well as some of the heavy elements (beyond iron and nickel, via the S-process). The remaining abundance of heavy elements, from nickel to uranium and beyond, is due to supernova nucleosynthesis, the R-process.

Of course, these natural processes of astrophysics are not examples of nuclear "technology". Because of the very strong repulsion of nuclei, fusion is difficult to achieve in a controlled fashion. Hydrogen bombs obtain their enormous destructive power from fusion, but their energy cannot be controlled. Controlled fusion is achieved in particle accelerators; this is how many synthetic elements are produced. A fusor can also produce controlled fusion and is a useful neutron source. However, both of these devices operate at a net energy loss. Controlled, viable fusion power has proven elusive, despite the occasional hoax. Technical and theoretical difficulties have hindered the development of working civilian fusion technology, though research continues to this day around the world.

Nuclear fusion was initially pursued only in theoretical stages during World War II, when scientists on the Manhattan Project (led by Edward Teller) investigated it as a method to build a bomb. The project abandoned fusion after concluding that it would require a fission reaction to detonate. It took until 1952 for the first full hydrogen bomb to be detonated, so-called because it used reactions between deuterium and tritium. Fusion reactions are much more energetic per unit mass of fuel than fission reactions, but starting the fusion chain reaction is much more difficult.

Nuclear Weapons

A nuclear weapon is an explosive device that derives its destructive force from nuclear reactions, either fission or a combination of fission and fusion. Both reactions release vast quantities of energy from relatively small amounts of matter. Even small nuclear devices can devastate a city by blast, fire and radiation. Nuclear weapons are considered weapons of mass destruction, and their use and control has been a major aspect of international policy since their debut.

The design of a nuclear weapon is more complicated than it might seem. Such a weapon must hold one or more subcritical fissile masses stable for deployment, then induce criticality (create a critical mass) for detonation. It also is quite difficult to ensure that such a chain reaction consumes a significant fraction of the fuel before the device flies apart. The procurement of a nuclear fuel is also more difficult than it might seem, as no naturally occurring substance is sufficiently unstable for this process to occur.

One isotope of uranium, namely uranium-235, is naturally occurring and sufficiently unstable, but it is always found mixed with the more stable isotope uranium-238. The latter accounts for more than 99% of the weight of natural uranium. Therefore some method of isotope separation based on the weight of three neutrons must be performed to enrich (isolate) uranium-235.

Alternatively, the element plutonium possesses an isotope that is sufficiently unstable for this process to be usable. Plutonium does not occur naturally, so it must be manufactured in a nuclear reactor.

Ultimately, the Manhattan Project manufactured nuclear weapons based on each of these elements. They detonated the first nuclear weapon in a test code-named "Trinity", near Alamogordo, New Mexico, on July 16, 1945. The test was conducted to ensure that the implosion method of detonation would work, which it did. A uranium bomb, Little Boy, was dropped on the Japanese city Hiroshima on August 6, 1945, followed three days later by the plutonium-based Fat Man on Nagasaki. In the wake of unprecedented devastation and casualties from a single weapon, the Japanese government soon surrendered, ending World War II.

Since these bombings, no nuclear weapons have been deployed offensively. Nevertheless, they prompted an arms race to develop increasingly destructive bombs to provide a nuclear deterrent. Just over four years later, on August 29, 1949, the Soviet Union detonated its first fission weapon. The United Kingdom followed on October 2, 1952; France, on February 13, 1960; and China on October 16, 1964. These five powers are permitted to possess nuclear weapons under the Nuclear Non-Proliferation Treaty. Only four recognized sovereign states are not parties to the treaty: India, Israel, Pakistan and North Korea. India, Pakistan and North Korea have openly tested and declared that they possess nuclear weapons. Israel has had a policy of opacity regarding its own nuclear weapons program. North Korea acceded to the treaty, violated it, and withdrew it in 2003.

Unlike convention weapons, the intense light, heat, and explosive force is not the only deadly component to a nuclear weapon. Approximately half of the deaths from Hiroshima and Nagasaki died two to five years afterward from radiation exposure. A radiological weapons is a type of nuclear weapon designed to distribute hazardous nuclear material in enemy areas. Such a weapon would not have the explosive capability of a fission or fusion bomb, but would kill many people and contaminate a large area. A radiological weapon has never been deployed. While considered useless by a conventional military, such a weapon raises concerns over nuclear terrorism.

There have been over 2,000 nuclear tests conducted since 1945. In 1963, all nuclear and many non-nuclear states signed the Limited Test Ban Treaty, pledging to refrain from testing nuclear weapons in the atmosphere, underwater, or in outer space. The treaty permitted underground nuclear testing. France continued atmospheric testing until 1974, while China continued up until 1980. The last underground test by the United States was in 1992, the Soviet Union in 1990, the United Kingdom in 1991, and both France and China continued testing until 1996. After signing the Comprehensive Test Ban Treaty in 1996 (which had as of 2011 not entered into force), all of these states have pledged to discontinue all nuclear testing. Non-signatories India and Pakistan last tested nuclear weapons in 1998.

Nuclear weapons are the most destructive weapons known - the archetypal weapons of mass destruction. Throughout the Cold War, the opposing powers had huge nuclear arsenals, sufficient to kill hundreds of millions of people. Generations of people grew up under the shadow of nuclear devastation, portrayed in films such as *Dr. Strangelove* and *The Atomic Cafe*.

However, the tremendous energy release in the detonation of a nuclear weapon also suggested the possibility of a new energy source.

Civilian uses

Nuclear power

Nuclear power is a type of nuclear technology involving the controlled use of nuclear fission to release energy for work including propulsion, heat, and the generation of electricity. Nuclear energy is produced by a controlled nuclear chain reaction which creates heat—and which is used to boil water, produce steam, and drive a steam turbine. The turbine is used to generate electricity and/or to do mechanical work.

Currently nuclear power provides approximately 15.7% of the world's electricity (in 2004) and is used to propel aircraft carriers, icebreakers and submarines (so far economics and fears in some ports have prevented the use of nuclear power in transport ships). All nuclear power plants use fission. Despite years of effort and the occasional hoax (i.e. cold fusion), no man-made fusion reaction has produced more energy than it consumed and been a viable source of electricity.

Medical applications

The medical applications of nuclear technology are divided into diagnostics and radiation treatment.

Imaging - medical and dental x-ray imagers use of Cobalt-60 or other x-ray sources. Technetium-99m is used, attached to organic molecules, as radioactive tracer in the human body, before being excreted by the kidneys. Positron emitting nucleotides are used for high resolution, short time span imaging in applications known as Positron emission tomography.

Radiation therapy is an effective treatment for cancer.

Industrial applications

Oil and Gas Exploration- Nuclear well logging is used to help predict the commercial viability of new or existing wells. The technology involves the use of a neutron or gamma-ray source and a radiation detector which are lowered into boreholes to determine the properties of the surrounding rock such as porosity and lithography.

Road Construction - Nuclear moisture/density gauges are used to determine the density of soils, asphalt, and concrete. Typically a Cesium-137 source is used.

Commercial applications

An ionization smoke detector includes a tiny mass of radioactive americium-241, which is a source of alpha radiation. Tritium is used with phosphor in rifle sights to increase nighttime firing accuracy. Luminescent exit signs use the same technology.

Food processing and agriculture

The Radura logo, used to show a food has been treated with ionizing radiation.

Food irradiation is the process of exposing food to ionizing radiation in order to destroy microorganisms, bacteria, viruses, or insects that might be present in the food. The radiation sources used include radioisotope gamma ray sources, X-ray generators and

electron accelerators. Further applications include sprout inhibition, delay of ripening, increase of juice yield, and improvement of re-hydration. Irradiation is a more general term of deliberate exposure of materials to radiation to achieve a technical goal (in this context 'ionizing radiation' is implied). As such it is also used on non-food items, such as medical hardware, plastics, tubes for gas-pipelines, hoses for floor-heating, shrink-foils for food packaging, automobile parts, wires and cables (isolation), tires, and even gemstones. Compared to the amount of food irradiated, the volume of those every-day applications is huge but not noticed by the consumer.

The genuine effect of processing food by ionizing radiation relates to damages to the DNA, the basic genetic information for life. Microorganisms can no longer proliferate and continue their malignant or pathogen activities. Spoilage causing micro-organisms cannot continue their activities. Insects do not survive or become incapable of procreation. Plants cannot continue the natural ripening or aging process. All these effects are beneficial to the consumer and the food industry, likewise.

The amount of energy imparted for effective food irradiation is low compared to cooking the same; even at a typical dose of 10 kGy most food, which is (with regard to warming) physically equivalent to water, would warm by only about 2.5 °C (4.5 °F).

The specialty of processing food by ionizing radiation is the fact, that the energy density per atomic transition is very high, it can cleave molecules and induce ionization (hence the name) which cannot be achieved by mere heating. This is the reason for new beneficial effects, however at the same time, for new concerns. The treatment of solid food by ionizing radiation can provide an effect similar to heat pasteurization of liquids, such as milk. However, the use of the term, cold pasteurization, to describe irradiated foods is controversial, because pasteurization and irradiation are fundamentally different processes, although the intended end results can in some cases be similar.

Food irradiation is currently permitted by over 40 countries and volumes are estimated to exceed 500,000 metric tons (490,000 LT; 550,000 ST) annually world wide.

Food irradiation is essentially a non-nuclear technology; it relies on the use of ionizing radiation which may be generated by accelerators for electrons and conversion into bremsstrahlung, but which may use also gamma-rays from nuclear decay. There is a worldwide industry for processing by ionizing radiation, the majority by number and by processing power using accelerators. Food irradiation is only a niche application compared to medical supplies, plastic materials, raw materials, gemstones, cables and wires, etc.

Accidents

Nuclear accidents, because of the powerful forces involved, are often very dangerous. Historically, the first incidents involved fatal radiation exposure. Marie Curie died from aplastic anemia which resulted from her high levels of exposure. Two scientists, an American and Canadian respectively, Harry Daghlian and Louis Slotin, died after

mishandling the same plutonium mass. Unlike convention weapons, the intense light, heat, and explosive force is not the only deadly component to a nuclear weapon. Approximately half of the deaths from Hiroshima and Nagasaki died two to five years afterward from radiation exposure.

Civilian nuclear and radiological accidents primarily involve nuclear power plants. Most common are nuclear leaks that expose workers to hazardous material. A nuclear meltdown refers to the more serious hazard of releasing nuclear material into the surrounding environment. The most significant meltdowns occurred at Three Mile Island in Pennsylvania and Chernobyl in the Soviet Ukraine. The earthquake and tsunami on March 11, 2011 caused serious damage to three nuclear reactors and a spent fuel storage pond at the Fukushima Daiichi nuclear power plant in Japan. Military reactors that experienced similar accidents were Windscale in the United Kingdom and SL-1 in the United States.

Military accidents usually involve the loss or unexpected detonation of nuclear weapons. The Castle Bravo test in 1954 produced a larger yield than expected, which contaminated nearby islands, a Japanese fishing boat (with one fatality), and raised concerns about contaminated fish in Japan. In the 1950s through 1970s, several nuclear bombs were lost from submarines and aircraft, some of which have never been recovered. The last twenty years have seen a marked decline in such accidents.

Chapter-2

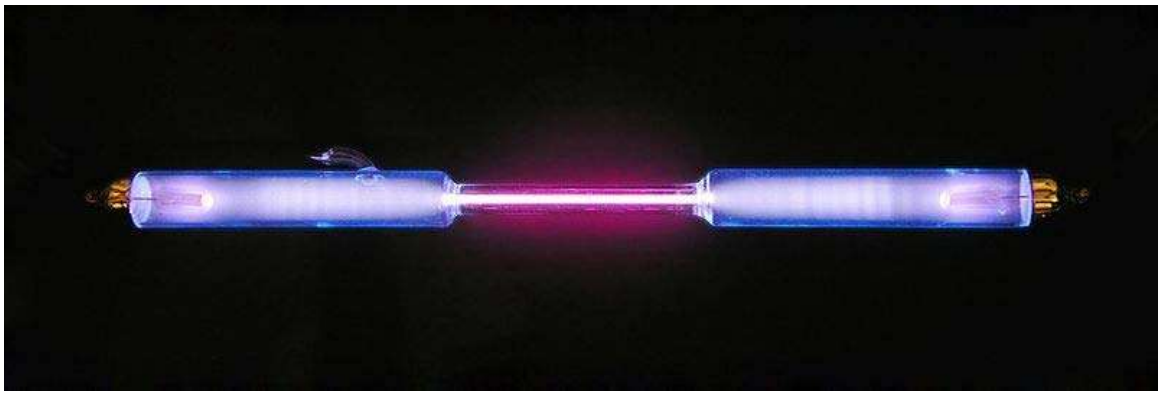
Deuterium

Deuterium, also called **heavy hydrogen**, is a stable isotope of hydrogen with a natural abundance in the oceans of Earth of approximately one atom in 6,400 of hydrogen (~156.25 ppm). Deuterium thus accounts for approximately 0.0156% (alternately, on a mass basis: 0.0312%) of all naturally occurring hydrogen in the oceans on Earth.

The nucleus of deuterium, called a **deuteron**, contains one proton and one neutron, whereas the far more common hydrogen nucleus contains no neutron. The isotope name is formed from the Greek *deuteros* meaning "second", to denote the two particles composing the nucleus.

Differences between deuterium and common hydrogen (protium)

Chemical symbol



Deuterium discharge (spectrum) tube

Electric discharge in pure deuterium shows its characteristic purple colour.

Deuterium is frequently represented by the chemical symbol D. Since it is an isotope of hydrogen with mass number 2, it is also represented by ^{2}H. IUPAC allows both D and ^{2}H, although ^{2}H is preferred. A distinct chemical symbol is used for convenience because of the isotope's common use in various scientific processes. Also, its large mass difference with protium (^{1}H) (deuterium has a mass of 2.014102 u, compared to the mean hydrogen atomic weight of 1.007947 u, and protium's mass of 1.007825 u) confers non-negligible chemical dissimilarities with protium-containing compounds, whereas the isotope weight ratios within other chemical elements are largely insignificant in this regard.

Natural abundance

Deuterium occurs in trace amounts naturally as deuterium gas, written $^{2}H_2$ or D_2, but most natural occurrence in the universe is bonded with a typical ^{1}H atom, a gas called hydrogen deuteride (HD or $^{1}H^{2}H$).

The natural deuterium abundance seems to be a very similar fraction of hydrogen, wherever hydrogen is found. Thus, the existence of deuterium at a low but constant fraction in all hydrogen, is one of the arguments in favor of the Big Bang theory over the steady state theory of the universe. It is estimated that the abundances of deuterium have not evolved significantly since their production about 13.7 bya.

Deuterium abundance on Jupiter is about 2.25×10^{-5}(roughly 22 atoms in a million, or 15% of the terrestrial deuterium-to-hydrogen ratio); these ratios presumably reflect the early solar nebula ratios, and those after the Big Bang. However, other sources suggest a much higher abundance of e.g. 6×10^{-4}(6 atoms in 10,000 or 0.06% atom basis). There is thought to be little deuterium in the interior of the Sun and other stars, as at temperatures there nuclear fusion reactions that consume deuterium happen much faster than the proton-proton reaction that creates deuterium. However, it continues to persist in the outer solar atmosphere at roughly the same concentration as in Jupiter.

The existence of deuterium on Earth, elsewhere in the solar system (as confirmed by planetary probes), and in the spectra of stars, is an important datum in cosmology. Gamma radiation from ordinary nuclear fusion dissociates deuterium into protons and neutrons, and there are no known natural processes other than the Big Bang nucleosynthesis, which might have produced deuterium at anything close to the observed natural abundance of deuterium (deuterium is produced by the rare cluster decay, and occasional absorption of naturally-occurring neutrons by light hydrogen, but these are trivial sources).

Concentrating natural abundance deuterium

Deuterium is concentrated for industrial, scientific and military purposes as heavy water from ordinary water. The world's leading supplier of deuterium was Atomic Energy of Canada Limited, in Canada, until 1997 when the last plant was shut down. Canada uses heavy water as a neutron moderator for the operation of the CANDU reactor design. India is now probably the world's largest concentrator of heavy water, also used in nuclear power reactors.

Properties

Physical properties

The physical properties of deuterium compounds can exhibit significant kinetic isotope effects and other physical and chemical property differences from the hydrogen analogs; for example, D_2O is more viscous than H_2O. Chemically, deuterium behaves similarly to ordinary hydrogen, but there are differences in bond energy and length for compounds of heavy hydrogen isotopes which are larger than the isotopic differences in any other element. Bonds involving deuterium and tritium are somewhat stronger than the corresponding bonds in hydrogen, and these differences are enough to make significant changes in biological reactions.

Deuterium can replace the normal hydrogen in water molecules to form heavy water (D_2O), which is about 10.6% denser than normal water (enough that ice made from it sinks in ordinary water). Heavy water is slightly toxic in eukaryotic animals, with 25% substitution of the body water causing cell division problems and sterility, and 50% substitution causing death by cytotoxic syndrome (bone marrow failure and gastrointestinal lining failure). Prokaryotic organisms, however, can survive and grow in

pure heavy water (though they grow more slowly). Consumption of heavy water does not pose a health threat to humans, it is estimated that a 70 kg person might drink 4.8 liters of heavy water without serious consequences. Small doses of heavy water (a few grams in humans, containing an amount of deuterium comparable to that normally present in the body) are routinely used as harmless metabolic tracers in humans and animals.

Quantum properties

The deuteron has spin +1 ("triplet") and is thus a boson. The NMR frequency of deuterium is significantly different from common light hydrogen. Infrared spectroscopy also easily differentiates many deuterated compounds, due to the large difference in IR absorption frequency seen in the vibration of a chemical bond containing deuterium, versus light hydrogen. The two stable isotopes of hydrogen can also be distinguished by using mass spectrometry.

The triplet deuteron nucleon barely is bound at E_B = 2.23 MeV, so all the higher energy states are not bound. The singlet deuteron is a virtual state, with a negative binding energy of ~60 keV. There is no such stable particle, but this virtual particle transiently exists during neutron-proton inelastic scattering, accounting for the unusually large neutron scattering cross-section of the proton.

Nuclear properties (the deuteron)

Deuteron mass and radius

The nucleus of deuterium is called a **deuteron**. It has a mass of 2.013553212724(78) u
The charge radius of the deuteron is 2.1402(28) fm

Spin and energy

Deuterium is one of only four stable nuclides with an odd number of protons and odd number of neutrons. (^{2}H, ^{6}Li, ^{10}B, ^{14}N; also, the long-lived radioactive nuclides ^{40}K, ^{50}V, ^{138}La, ^{180m}Ta occur naturally.) Most odd-odd nuclei are unstable with respect to beta decay, because the decay products are even-even, and are therefore more strongly bound, due to nuclear pairing effects. Deuterium, however, benefits from having its proton and neutron coupled to a spin-1 state, which gives a stronger nuclear attraction; the corresponding spin-1 state does not exist in the two-neutron or two-proton system, due to the Pauli exclusion principle which would require one or the other identical particle with the same spin to have some other different quantum number, such as orbital angular momentum. But orbital angular momentum of either particle gives a lower binding energy for the system, primarily due to increasing distance of the particles in the steep gradient of the nuclear force. In both cases, this causes the diproton and dineutron nucleus to be unstable.

The proton and neutron making up deuterium can be dissociated through neutral current interactions with neutrinos. The cross section for this interaction is comparatively large,

and deuterium was successfully used as a neutrino target in the Sudbury Neutrino Observatory experiment.

Isospin singlet state of the deuteron

Due to the similarity in mass and nuclear properties between the proton and neutron, they are sometimes considered as two symmetric types of the same object, a nucleon. While only the proton has an electric charge, this is often negligible due of the weakness of the electromagnetic interaction relative to the strong nuclear interaction. The symmetry relating the proton and neutron is known as isospin and denoted I (or sometimes T).

Isospin is an SU(2) symmetry, like ordinary spin, so is completely analogous to it. The proton and neutron form an isospin doublet, with a "down" state (↓) being a neutron, and an "up" state (↑) being a proton.

A pair of nucleons can either be in an antisymmetric state of isospin called singlet, or in a symmetric state called triplet. In terms of the "down" state and "up" state, the singlet is

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right).$$

This is a nucleus with one proton and one neutron, i.e. a deuterium nucleus. The triplet is

$$\begin{pmatrix} \uparrow\uparrow \\ \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow) \\ \downarrow\downarrow \end{pmatrix}$$

and thus consists of three types of nuclei, which are supposed to be symmetric: a deuterium nucleus (actually a highly excited state of it), a nucleus with two protons, and a nucleus with two neutrons. The latter two nuclei are not stable or nearly stable, and therefore so is this type of deuterium (meaning that it is indeed a highly excited state of deuterium).

Approximated wavefunction of the deuteron

The deuteron wavefunction must be antisymmetric if the isospin representation is used (since a proton and a neutron are not identical particles, the wavefunction need not be antisymmetric in general). Apart from their isospin, the two nucleons also have spin and spatial distributions of their wavefunction. The latter is symmetric if the deuteron is symmetric under parity (i.e. have an "even" or "positive" parity), and antisymmetric if the deuteron is antisymmetric under parity (i.e. have an "odd" or "negative" parity). The parity is fully determined by the total orbital angular momentum of the two nucleons: if it is even then the parity is even (positive), and if it is odd then the parity is odd (negative).

The deuteron, being an isospin singlet, is antisymmetric under nucleons exchange due to isospin, and therefore must be symmetric under the double exchange of their spin and location. Therefore it can be in either of the following two different states:

- Symmetric spin and symmetric under parity. In this case, the exchange of the two nucleons will multiply the deuterium wavefunction by (-1) from isospin exchange, (+1) from spin exchange and (+1) from parity (location exchange), for a total of (-1) as needed for antisymmetry.
- Antisymmetric spin and antisymmetric under parity. In this case, the exchange of the two nucleons will multiply the deuterium wavefunction by (-1) from isospin exchange, (-1) from spin exchange and (-1) from parity (location exchange), again for a total of (-1) as needed for antisymmetry.

In the first case the deuteron is a spin triplet, so that its total spin s is 1. It also has an even parity and therefore even orbital angular momentum l ; The lower its orbital angular momentum, the lower its energy. Therefore the lowest possible energy state has $s = 1$, $l = 0$.

In the second case the deuteron is a spin singlet, so that its total spin s is 0. It also has an odd parity and therefore odd orbital angular momentum l. Therefore the lowest possible energy state has $s = 0$, $l = 1$.

Since $s = 1$ gives a stronger nuclear attraction, the deuterium ground state is in the $s = 1$, $l = 0$ state.

The same considerations lead to the possible states of an isospin triplet having $s = 0$, $l =$ even or $s = 1$, $l =$ odd. Thus the state of lowest energy has $s = 1$, $l = 1$, higher than that of the isospin singlet.

The analysis just given is in fact only approximate, both because isospin is not an exact symmetry, and more importantly because the strong nuclear interaction between the two nucleons is related to angular momentum in spin-orbit interaction that mixes different s and l states. That is, s and l are not constant in time (they do not commute with the Hamiltonian), and over time a state such as $s = 1$, $l = 0$ may become a state of $s = 1$, $l = 2$. Parity is still constant in time so these do not mix with odd l states (such as $s = 0$, $l = 1$). Therefore the quantum state of the deuterium is a superposition (a linear combination) of the $s = 1$, $l = 0$ state and the $s = 1$, $l = 2$ state, even though the first component is much bigger. Since the total angular momentum j is also a good quantum number (it is a constant in time), both components must have the same j, and therefore $j = 1$. This is the total spin of the deuterium nucleus.

To summarize, the deuterium nucleus is antisymmetric in terms of isospin, and has spin 1 and even (+1) parity. The relative angular momentum of its nucleons l is not well defined, and the deuteron is a superposition of mostly $l = 0$ with some $l = 2$.

Magnetic and electric multipoles

In order to find theoretically the deuterium magnetic dipole moment μ, one uses the formula for a nuclear magnetic moment

$$\mu = \frac{1}{(j+1)}\langle (l,s), j, m_j = j | \overrightarrow{\mu} \cdot \overrightarrow{j} | (l,s), j, m_j = j \rangle$$

with

$$\overrightarrow{\mu} = g^{(l)} \overrightarrow{l} + g^{(s)} \overrightarrow{s}$$

$g^{(l)}$ and $g^{(s)}$ are g-factors of the nucleons.

Since the proton and neutron have different values for $g^{(l)}$ and $g^{(s)}$, one must separate their contributions. Each gets half of the deuterium orbital angular momentum $\overrightarrow{l}$ and spin $\overrightarrow{s}$. One arrives at

$$\mu = \frac{1}{(j+1)}\langle (l,s), j, m_j = j | \left(\frac{1}{2}\overrightarrow{l} g^{(l)}{}_p + \frac{1}{2}\overrightarrow{s}(g^{(s)}{}_p + g^{(s)}{}_n) \right) \cdot \overrightarrow{j} | (l,s), j, m_j = j \rangle$$

where subscripts p and n stand for the proton and neutron, and $g^{(l)}{}_n = 0$.

By using the same identities as here and using the value $g^{(l)}{}_p = 1$ μN, we arrive at the following result, in nuclear magneton units

$$\mu = \frac{1}{4(j+1)}\left[(g^{(s)}{}_p + g^{(s)}{}_n)(j(j+1) - l(l+1) + s(s+1)) + (j(j+1) + l(l+1) - s(s+1)) \right]$$

For the $s = 1$, $l = 0$ state ($j = 1$), we obtain

$$\mu = \frac{1}{2}(g^{(s)}{}_p + g^{(s)}{}_n) = 0.879$$

For the $s = 1$, $l = 2$ state ($j = 1$), we obtain

$$\mu = -\frac{1}{4}(g^{(s)}{}_p + g^{(s)}{}_n) + \frac{3}{4} = 0.310$$

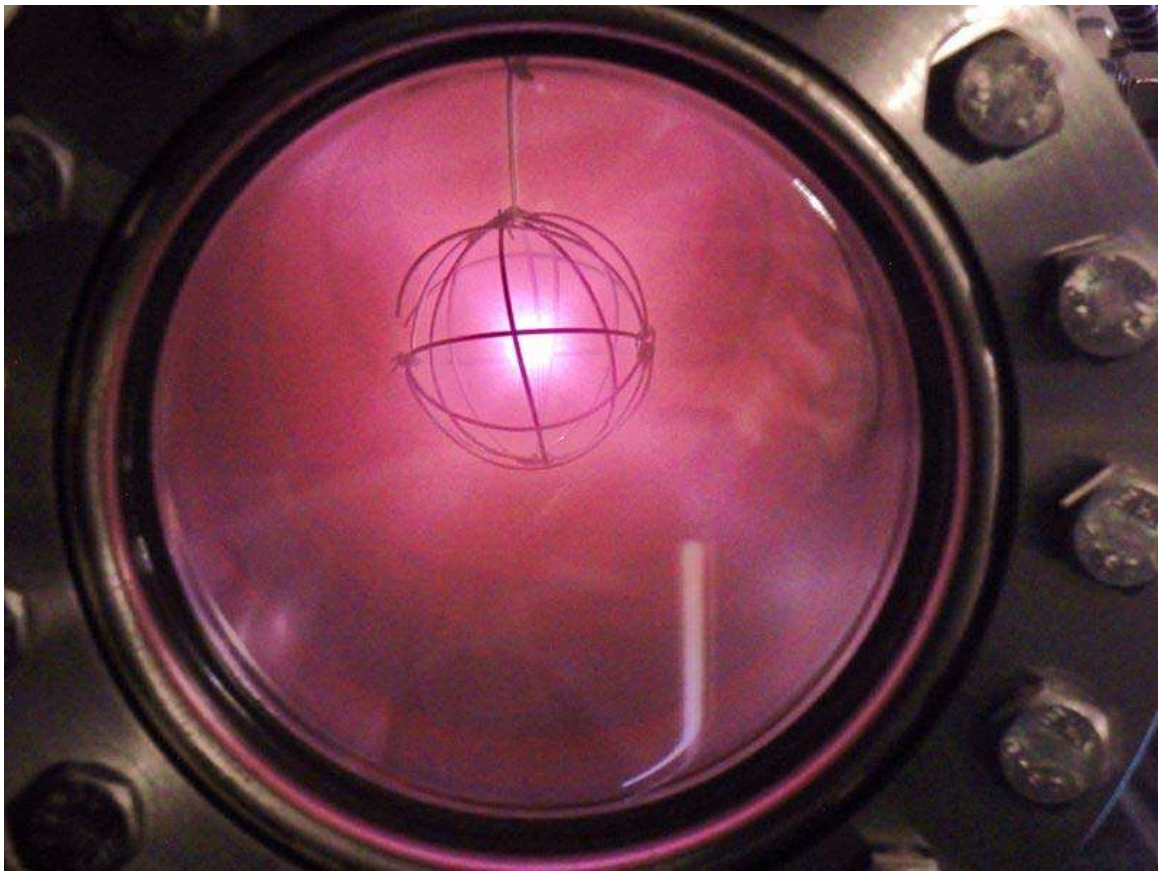
The measured value of the deuterium magnetic dipole moment, is 0.857 μN. This suggests that the state of the deuterium is indeed only approximately $s = 1$, $l = 0$ state, and is actually a linear combination of (mostly) this state with $s = 1$, $l = 2$ state.

The electric dipole is zero as usual.

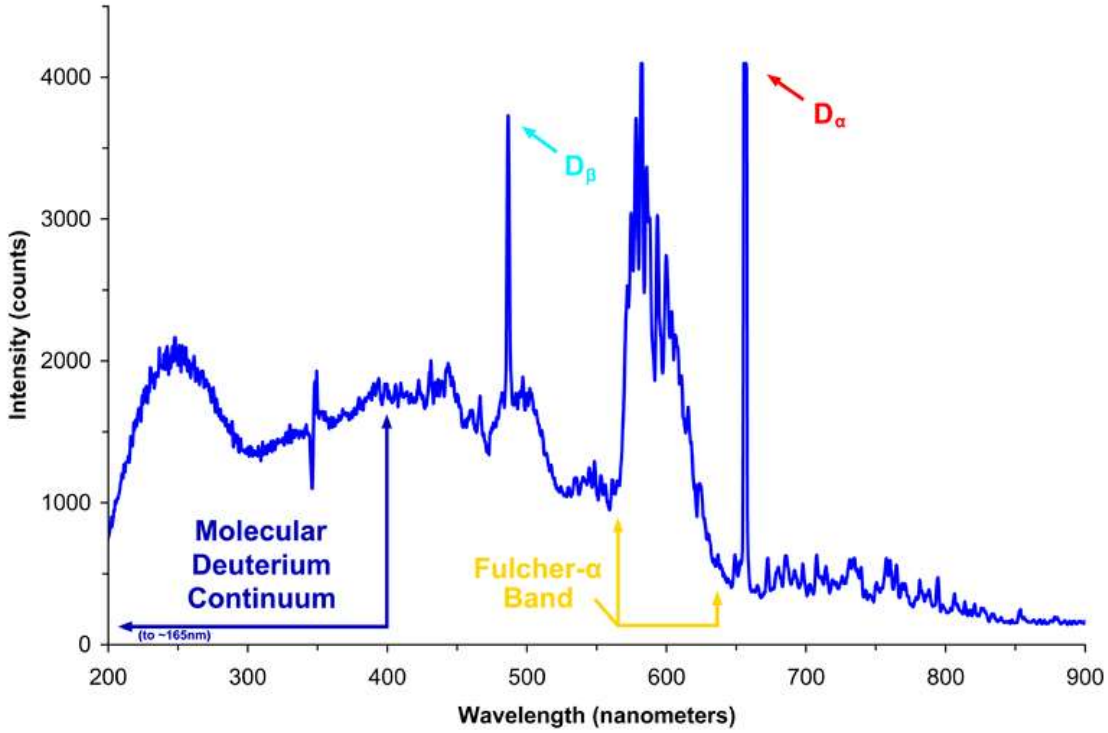
The measured electric quadrupole of the deuterium is 0.2859 e·fm^2. While the order of magnitude is reasonable, since the deuterium radius is of order of 1 femtometer and its electric charge is e, the above model does not suffice for its computation. More specifically, the electric quadrupole does not get a contribution from the l =0 state (which is the dominant one) and does get a contribution from a term mixing the l =0 and the l =2 states, because the electric quadrupole operator does not commute with angular momentum. The latter contribution is dominant in the absence of a pure l = 0 contribution, but cannot be calculated without knowing the exact spatial form of the nucleons wavefunction inside the deuterium.

Higher magnetic and electric multipole moments cannot be calculated by the above model, for similar reasons.

Applications



Ionized deuterium in an IEC fusion reactor giving off its characteristic pinkish-red glow.



Emission spectrum of an ultraviolet deuterium arc lamp.

Deuterium has a number of commercial and scientific uses. These include:

Nuclear reactors

Deuterium is useful in nuclear fusion reactions, especially in combination with tritium, because of the large reaction rate (or nuclear cross section) and high energy yield of the D–T reaction. There is an even higher-yield D–^{3}He fusion reaction, though the breakeven point of D–^{3}He is higher than that of most other fusion reactions; together with the scarcity of ^{3}He, this makes it implausible as a practical power source until at least D–T and D–D fusion reactions have been performed on a commercial scale.

Deuterium is used in heavy water moderated fission reactors, usually as liquid D_2O, to slow neutrons without high neutron absorption of ordinary hydrogen.

NMR spectroscopy

Deuterium NMR spectra are especially informative in the solid state because of its relatively small quadrupole moment in comparison with those of bigger quadrupolar nuclei such as chlorine-35, for example.

Tracing

In chemistry, biochemistry and environmental sciences, deuterium is used as a non-radioactive, stable isotopic tracer, for example, in the doubly-labeled water test. In chemical reactions and metabolic pathways, deuterium behaves somewhat similarly to ordinary hydrogen (with a few chemical differences, as noted). It can be distinguished from ordinary hydrogen most easily by its mass, using mass spectrometry or infrared spectrometry. Deuterium can be detected by femtosecond infrared spectroscopy, since the mass difference drastically affects the frequency of molecular vibrations; deuterium-carbon bond vibrations are found in locations free of other signals.

Measurements of small variations in the natural abundances of deuterium, along with those of the stable heavy oxygen isotopes ^{17}O and ^{18}O, are of importance in hydrology, to trace the geographic origin of Earth's waters. The heavy isotopes of hydrogen and oxygen in rainwater (so-called meteoric water) are enriched as a function of the environmental temperature of the region in which the precipitation falls (and thus enrichment is related to mean latitude). The relative enrichment of the heavy isotopes in rainwater (as referenced to mean ocean water), when plotted against temperature falls predictably along a line called the global meteoric water line (GMWL). This plot allows samples of precipitation-originated water to be identified along with general information about the climate in which it originated. Evaporative and other processes in bodies of water, and also ground water processes, also differentially alter the ratios of heavy hydrogen and oxygen isotopes in fresh and salt waters, in characteristic and often regionally-distinctive ways.

Contrast properties

Neutron scattering techniques particularly profit from availability of deuterated samples: The H and D cross sections are very distinct and different in sign, which allows contrast variation in such experiments. Further, a nuisance problem of ordinary hydrogen is its large incoherent neutron cross section, which is nil for D. The substitution of hydrogen atoms for deuterium atoms thus reduces scattering noise.

Hydrogen is an important and major component in all materials of organic chemistry and life science, but is barely interacts with X-rays. As hydrogen (and deuterium) interact strongly with neutrons, neutron scattering techniques, together with a modern deuteration facility, fills a niche in many studies of macromolecules in biology and many other areas.

Nuclear resonance spectroscopy

Deuterium is useful in hydrogen nuclear magnetic resonance spectroscopy (proton NMR). NMR ordinarily requires compounds of interest to be analyzed as dissolved in solution. Because of deuterium's nuclear spin properties which differ from the light hydrogen usually present in organic molecules, NMR spectra of hydrogen/protium are highly differentiable from that of deuterium, and in practice deuterium is not "seen" by an NMR instrument tuned to light-hydrogen. Deuterated solvents (including heavy water,

but also compounds like deuterated chloroform, $CDCl_3$) are therefore routinely used in NMR spectroscopy, in order to allow only the light-hydrogen spectra of the compound of interest to be measured, without solvent-signal interference.

History

Suspicion of lighter element isotopes

The existence of nonradioactive isotopes of lighter elements had been suspected in studies of neon as early as 1913, and proven by mass spectroscopy of light elements in 1920. The prevailing theory at the time, however, was that the isotopes were due to the existence of differing numbers of "nuclear electrons" in different atoms of an element. It was expected that hydrogen, with a measured average atomic mass very close to 1 u, the known mass of the proton, always had a nucleus composed of a single proton (a known particle), and therefore could not contain any nuclear electrons without losing its charge entirely. Thus, hydrogen could have no heavy isotopes.

Deuterium predicted and finally detected

It was first detected spectroscopically in late 1931 by Harold Urey, a chemist at Columbia University. Urey's collaborator, Ferdinand Brickwedde, distilled five liters of cryogenically-produced liquid hydrogen to 1 mL of liquid, using the low-temperature physics laboratory that had recently been established at the National Bureau of Standards in Washington, D.C. (now the National Institute of Standards and Technology). This concentrated the fraction of the mass-2 isotope of hydrogen to a degree that made its spectroscopic identification unambiguous.

Name

Urey called the new isotope "deuterium", from the Greek deuteros (second), and the nucleus to be called "deuteron" or "deuton". Isotopes and new elements were traditionally given the name that their discoverer decided, but some British chemists, like Ernest Rutherford, wanted the isotope to be called "diplogen", from the Greek diploos (double), and the nucleus to be called diplon. The British magazine Nature also published a letter where only the denomination "diplogen" was used, perhaps annunciating that British could prefer that name over the name given by its discoverer. Urey and his two co-discoverers sent a letter to Nature saying that they had already considered that name and they had rejected it because "The compound NH1H2/2 would be called di-diplogen mono-hydrogen nitride", which would repeat the syllable "di." They also said that the British seemed to object on the basis that "neutron" and "deuton" could be confused with each other, and Urey pointed out that American workers were using the terms and they didn't seem to be having any such confusion.

Abundance, purification, and impact

The amount inferred for normal abundance of this heavy isotope of hydrogen was so small (only about 1 atom in 6400 hydrogen atoms in ocean water) that it had not noticeably affected previous measurements of (average) hydrogen atomic mass. This explained why it hadn't been experimentally suspected before. Urey was able to concentrate water to show partial enrichment of deuterium. Gilbert Newton Lewis prepared the first samples of pure heavy water in 1933.

The discovery of deuterium, coming before the discovery of the neutron in 1932, was an experimental shock to theory, but when the neutron was reported, making deuterium's existence more explainable, deuterium won Urey the Nobel Prize in chemistry in 1934.

"Heavy water" experiments in World War II

Shortly before the war, Hans von Halban and Lew Kowarski moved their research on neutron moderation from France to England, smuggling the entire global supply of heavy water (which had been made in Norway) across in twenty-six steel drums.

During World War II, Nazi Germany was known to be conducting experiments using heavy water as moderator for a nuclear reactor design. Such experiments were a source of concern because they might allow them to produce plutonium for an atomic bomb. Ultimately it led to the Allied operation called the "Norwegian heavy water sabotage", the purpose of which was to destroy the Vemork deuterium production/enrichment facility in Norway. At the time this was considered important to the potential progress of the war.

After World War II ended, the Allies discovered that Germany was not putting as much serious effort into the program as had been previously thought. The Germans had completed only a small, partly-built experimental reactor (which had been hidden away). By the end of the war, the Germans did not even have a fifth of the amount of heavy water needed to run the reactor, partially due to the Norwegian heavy water sabotage operation. However, even had the Germans succeeded in getting a reactor operational (as the U.S. did with a graphite reactor in late 1942), they would still have been at least several years away from development of an atomic bomb with maximal effort. The engineering process, even with maximal effort and funding, required about two and a half years (from first critical reactor to bomb) in both the U.S. and U.S.S.R, for example.

Data

- Density: 0.180 kg/m^3 at STP (0 °C, 101.325 kPa).
- Atomic weight: 2.0141017926 u.
- Mean abundance in ocean water about 0.0156% of H atoms = 1/6400 H atoms.

Data at approximately 18 K for D_2 (triple point):

- Density:
  - Liquid: 162.4 kg/m^3
  - Gas: 0.452 kg/m^3
- Viscosity: 12.6 μPa·s at 300 K (gas phase)
- Specific heat capacity at constant pressure c_p:
  - Solid: 2,950 J/(kg·K)
  - Gas: 5,200 J/(kg·K)

Anti-deuterium

An **antideuteron** is the antiparticle of the nucleus of deuterium, consisting of an antiproton and an antineutron. The antideuteron was first produced in 1965 at the Proton Synchrotron at CERN and the Alternating Gradient Synchrotron at Brookhaven National Laboratory. A complete atom, with a positron orbiting the nucleus, would be called *antideuterium*, but as of 2005 antideuterium has not yet been created. The proposed symbol for antideuterium is D, that is, D with an overbar.

Pycnodeuterium

Deuterium atoms can be absorbed into a palladium (Pd) lattice. They are effectively solidified as an ultrahigh density deuterium lump (*Pycnodeuterium*) inside each octahedral space within the unit cell of the palladium host lattice. It was once reported that deuterium absorbed into palladium enabled nuclear cold fusion. However, cold fusion by this mechanism has not been generally accepted by the scientific community.

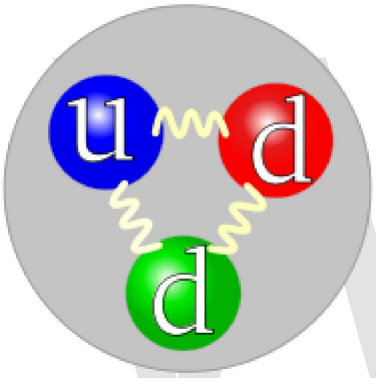
Ultra-dense deuterium

The existence of **ultra-dense deuterium** is suggested by experiment. This material, at a density of 140 kg/cm^3, would be a million times more dense than regular deuterium, denser than the core of the Sun. This ultra-dense form of deuterium may facilitate achieving laser-induced fusion. Only minute amounts of ultra-dense deuterium have been produced thus far.

Chapter-3

Neutron

Neutron



The quark structure of the neutron. (The color assignment of individual quarks is not important, only that all three colors are present.)

Classification:	Baryon
Composition:	1 up quark, 2 down quarks
Particle statistics:	Fermionic
Group:	Hadron
Interaction:	Gravity, Weak, Strong
Symbol(s):	n, n^0 , N^0
Antiparticle:	Antineutron
Theorized:	Ernest Rutherford (1920)
Discovered:	James Chadwick (1932)
Mass:	$1.67492729(28)\times10^{-27}$ kg 939.565560(81) MeV/c^2 1.0086649156(6) u

Mean lifetime:	885.7(8) s (free)
Electric charge:	0 e 0 C
Electric dipole moment:	$<2.9\times10^{-26}$ e·cm
Electric polarizability:	$1.16(15)\times10^{-3}$ fm^3
Magnetic moment:	$-1.9130427(5)\ \mu_N$
Magnetic polarizability:	$3.7(20)\times10^{-4}$ fm^3
Spin:	$\frac{1}{2}$
Isospin:	$\frac{1}{2}$
Parity:	+1
Condensed:	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

The **neutron** is a subatomic particle with no net electric charge and a mass slightly larger than that of a proton. With the exception of hydrogen, nuclei of atoms consist of protons and neutrons, which are therefore collectively referred to as nucleons. The number of protons in a nucleus is the atomic number and defines the type of element the atom forms. The number of neutrons is the neutron number and determines the isotope of an element. For example, the abundant carbon-12 isotope has 6 protons and 6 neutrons, while the very rare radioactive carbon-14 isotope has 6 protons and 8 neutrons.

While bound neutrons in stable nuclei are stable, free neutrons are unstable; they undergo beta decay with a mean lifetime of just under 15 minutes (885.7±0.8 s). Free neutrons are produced in nuclear fission and fusion. Dedicated neutron sources like research reactors and spallation sources produce free neutrons for use in irradiation and in neutron scattering experiments. Even though it is not a chemical element, the free neutron is sometimes included in tables of nuclides. It is then considered to have an atomic number of zero and a mass number of one, and is sometimes referred to as neutronium.

The neutron has been the key to nuclear power production. After the neutron was discovered in 1932, it was realized in 1933 that it might mediate a nuclear chain reaction. In the 1930s, neutrons were used to produce many different types of nuclear transmutations. When nuclear fission was discovered in 1938, it was soon realized that this might be the mechanism to produce the neutrons for the chain reaction, if the process also produced neutrons, and this was proven in 1939, making the path to nuclear power production evident. These events and findings led directly to the first man-made nuclear chain reaction which was self-sustaining (Chicago Pile-1, 1942) and to the first nuclear weapons (1945).

Discovery

In 1920, Ernest Rutherford conceptualised the possible existence of the neutron. In particular, Rutherford considered that the disparity found between the atomic number of

an atom and its atomic mass could be explained by the existence of a neutrally charged particle within the atomic nucleus.

In 1930 Viktor Ambartsumian and Dmitri Ivanenko in USSR found that, contrary to the prevailing opinion of the time, the nucleus cannot consist of protons and electrons. They proved that some neutral particles must be present besides the protons.

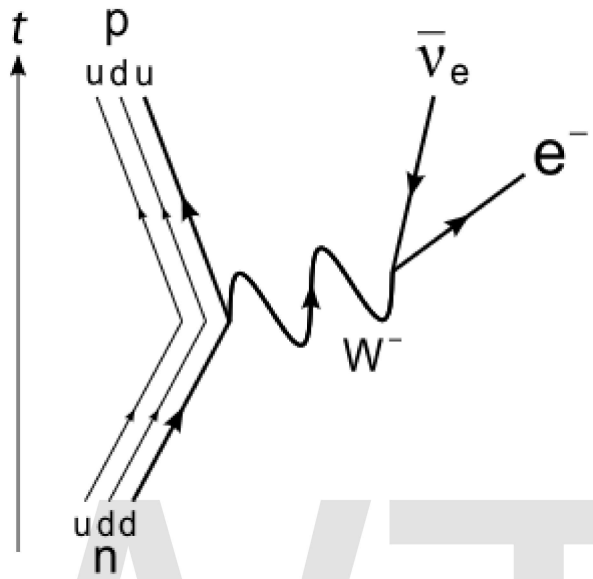
In 1931, Walther Bothe and Herbert Becker in Germany found that if the very energetic alpha particles emitted from polonium fell on certain light elements, specifically beryllium, boron, or lithium, an unusually penetrating radiation was produced. At first this radiation was thought to be gamma radiation, although it was more penetrating than any gamma rays known, and the details of experimental results were very difficult to interpret on this basis. The next important contribution was reported in 1932 by Irène Joliot-Curie and Frédéric Joliot in Paris. They showed that if this unknown radiation fell on paraffin, or any other hydrogen-containing compound, it ejected protons of very high energy. This was not in itself inconsistent with the assumed gamma ray nature of the new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such a hypothesis.

In 1932, James Chadwick performed a series of experiments at the University of Cambridge, showing that the gamma ray hypothesis was untenable. He suggested that the new radiation consisted of uncharged particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. These uncharged particles were called *neutrons*, apparently from the Latin root for *neutral* and the Greek ending *-on* (by imitation of *electron* and *proton*).

The discovery of the neutron explained a puzzle involving the spin of the nitrogen-14 nucleus, which had been experimentally measured to be 1 ħ. It was known that atomic nuclei usually had about half as many positive charges as if they were composed completely of protons, and in existing models this was often explained by proposing that nuclei also contained some "nuclear electrons" to neutralize the excess charge. Thus, nitrogen-14 would be composed of 14 protons and 7 electrons to give it a charge of +7 but a mass of 14 atomic mass units. However, it was also known that both protons and electrons carried an intrinsic spin of $\frac{1}{2}$ ħ, and there was no way to arrange an odd number (21) of spins $\pm\frac{1}{2}$ ħ to give a spin of 1 ħ. Instead, when nitrogen-14 was proposed to consist of 3 pairs of protons and neutrons, with an additional unpaired neutron and proton each contributing a spin of $\frac{1}{2}$ ħ in the same direction for a total spin of 1 ħ, the model became viable. Soon, nuclear neutrons were used to naturally explain spin differences in many different nuclides in the same way, and the neutron as a basic structural unit of atomic nuclei was accepted.

Intrinsic properties

Stability and beta decay



The Feynman diagram for beta decay of a neutron into a proton, electron, and electron antineutrino via an intermediate heavy W boson

Under the Standard Model of particle physics, because the neutron consists of three quarks, the only possible decay mode without a change of baryon number is for one of the quarks to change flavour via the weak interaction. The neutron consists of two down quarks with charge $-\frac{1}{3}$ e and one up quark with charge $+\frac{2}{3}$ e, and the decay of one of the down quarks into a lighter up quark can be achieved by the emission of a W boson. By this means the neutron decays into a proton (which contains one down and two up quarks), an electron, and an electron antineutrino.

Outside the nucleus, free neutrons are unstable and have a mean lifetime of 885.7±0.8 s (about 14 minutes, 46 seconds); therefore the half-life for this process (which differs from the mean lifetime by a factor of ln(2) = 0.693) is 613.9±0.8 s (about 10 minutes, 14 seconds). Free neutrons decay by emission of an electron and an electron antineutrino to become a proton, a process known as beta decay:

$$n^0 \rightarrow p^+ + e^- + \nu_e$$

Neutrons in unstable nuclei can also decay in this manner. However, inside a nucleus, protons can also transform into a neutron via inverse beta decay. This transformation occurs by emission of a antielectron (also called positron) and a neutrino:

$$p^+ \rightarrow n^0 + e^+ + \nu_e$$

The transformation of a proton to a neutron inside of a nucleus is also possible through electron capture:

$$p^+ + e^- \longrightarrow n^0 + \nu_e$$

Positron capture by neutrons in nuclei that contain an excess of neutrons is also possible, but is hindered because positrons are repelled by the nucleus, and quickly annihilate when they encounter electrons.

When bound inside of a nucleus, the instability of a single neutron to beta decay is balanced against the instability that would be acquired by the nucleus as a whole if an additional proton were to participate in repulsive interactions with the other protons that are already present in the nucleus. As such, although free neutrons are unstable, bound neutrons are not necessarily so. The same reasoning explains why protons, which are stable in empty space, may transform into neutrons when bound inside of a nucleus.

Electric dipole moment

The Standard Model of particle physics predicts a tiny separation of positive and negative charge within the neutron leading to a permanent electric dipole moment. The predicted value is, however, well below the current sensitivity of experiments. From several unsolved puzzles in particle physics, it is clear that the Standard Model is not the final and full description of all particles and their interactions. New theories going beyond the Standard Model generally lead to much larger predictions for the electric dipole moment of the neutron. Currently, there are at least four experiments trying to measure for the first time a finite neutron electric dipole moment, including:

- Cryogenic neutron EDM experiment being set up at the Institut Laue-Langevin
- nEDM experiment under construction at the new UCN source at the Paul Scherrer Institute
- nEDM experiment being envisaged at the Spallation Neutron Source
- nEDM experiment being built at the Institut Laue-Langevin

Magnetic moment

The magnetic moment of a neutron is nonzero, unexpected from an electrically neutral particle. This indicates that the neutron is a composite particle.

Anti-neutron

The antineutron is the antiparticle of the neutron. It was discovered by Bruce Cork in the year 1956, a year after the antiproton was discovered. CPT-symmetry puts strong constraints on the relative properties of particles and antiparticles, so studying antineutrons yields provide stringent tests on CPT-symmetry. The fractional difference in the masses of the neutron and antineutron is $9 \pm 5 \times 10^{-5}$

. Since the difference is only about two standard deviations away from zero, this does not give any convincing evidence of CPT-violation.

Structure and geometry of charge distribution within the neutron

An article published in 2007 featuring a model-independent analysis concluded that the neutron has a negatively charged exterior, a positively charged middle, and a negative core. In a simplified classical view, the negative "skin" of the neutron assists it to be attracted to the protons with which it interacts in the nucleus. However, the main attraction between neutrons and protons is via the nuclear force, which does not involve charge.

Neutron compounds

Dineutrons and tetraneutrons

The existence of stable clusters of 4 neutrons, or tetraneutrons, has been hypothesised by a team led by Francisco-Miguel Marqués at the CNRS Laboratory for Nuclear Physics based on observations of the disintegration of beryllium-14 nuclei. This is particularly interesting because current theory suggests that these clusters should not be stable.

The dineutron is another hypothetical particle.

Neutronium and neutron stars

At extremely high pressures and temperatures, nucleons and electrons are believed to collapse into bulk neutronic matter, called neutronium. This is presumed to happen in neutron stars.

Detection

The common means of detecting a charged particle by looking for a track of ionization (such as in a cloud chamber) does not work for neutrons directly. Neutrons that elastically scatter off atoms can create an ionization track that is detectable, but the experiments are not as simple to carry out; other means for detecting neutrons, consisting of allowing them to interact with atomic nuclei, are more commonly used. The commonly used methods to detect neutrons can therefore be categorized according to the nuclear processes relied upon, mainly neutron capture or elastic scattering. A good discussion on neutron detection is found in chapter 14 of the book *Radiation Detection and Measurement* by Glenn F. Knoll (John Wiley & Sons, 1979).

Neutron detection by neutron capture

A common method for detecting neutrons involves converting the energy released from neutron capture reactions into electrical signals. Certain nuclides have a high probability to absorb a neutron. Upon neutron capture, the compound nucleus emits more easily

detectable radiation, for example an alpha particle, which is then detected. The nuclides ^{3}He, ^{6}Li, ^{10}B, ^{233}U, ^{235}U, ^{237}Np and ^{239}Pu are useful for this purpose.

Neutron detection by elastic scattering

Neutrons can elastically scatter off nuclei, causing the struck nucleus to recoil. Kinematically, a neutron can transfer more energy to light nuclei such as hydrogen or helium than to heavier nuclei. Detectors relying on elastic scattering are called fast neutron detectors. Recoiling nuclei can ionize and excite further atoms through collisions. Charge and/or scintillation light produced in this way can be collected to produce a detected signal. A major challenge in fast neutron detection is discerning such signals from erroneous signals produced by gamma radiation in the same detector.

Fast neutron detectors have the advantage of not requiring a moderator, and therefore being capable of measuring the neutron's energy, time of arrival, and in certain cases direction of incidence.

Uses

The neutron plays an important role in many nuclear reactions. For example, neutron capture often results in neutron activation, inducing radioactivity. In particular, knowledge of neutrons and their behavior has been important in the development of nuclear reactors and nuclear weapons. The fissioning of elements like uranium-235 and plutonium-239 is caused by their absorption of neutrons.

Cold, *thermal* and *hot* neutron radiation is commonly employed in neutron scattering facilities, where the radiation is used in a similar way one uses X-rays for the analysis of condensed matter. Neutrons are complementary to the latter in terms of atomic contrasts by different scattering cross sections; sensitivity to magnetism; energy range for inelastic neutron spectroscopy; and deep penetration into matter.

The development of "neutron lenses" based on total internal reflection within hollow glass capillary tubes or by reflection from dimpled aluminum plates has driven ongoing research into neutron microscopy and neutron/gamma ray tomography.

A major use of neutrons is to excite delayed and prompt gamma rays from elements in materials. This forms the basis of neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA). NAA is most often used to analyze small samples of materials in a nuclear reactor whilst PGNAA is most often used to analyze subterranean rocks around bore holes and industrial bulk materials on conveyor belts.

Another use of neutron emitters is the detection of light nuclei, particularly the hydrogen found in water molecules. When a fast neutron collides with a light nucleus, it loses a large fraction of its energy. By measuring the rate at which slow neutrons return to the probe after reflecting off of hydrogen nuclei, a neutron probe may determine the water content in soil.

Sources

Because free neutrons are unstable, they can be obtained only from nuclear disintegrations, nuclear reactions, and high-energy reactions (such as in cosmic radiation showers or accelerator collisions). Free neutron beams are obtained from neutron sources by neutron transport. For access to intense neutron sources, researchers must go to specialist facilities, such as the ISIS facility in the United Kingdom, which is currently the world's most intense pulsed neutron and muon source.

The neutron's lack of total electric charge makes it difficult to steer or accelerate them. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields. These methods have little effect on neutrons beyond a small effect of an inhomogeneous magnetic field because of the neutron's magnetic moment. Neutrons can be controlled by methods that include moderation, reflection and velocity selection.

Protection

Exposure to free neutrons can be hazardous, since the interaction of neutrons with molecules in the body can cause disruption to molecules and atoms, and can also cause reactions which give rise to other forms of radiation (such as protons). The normal precautions of radiation protection apply: avoid exposure, stay as far from the source as possible, and keep exposure time to a minimum. Some particular thought must be given to how to protect from neutron exposure, however. For other types of radiation, e.g. alpha particles, beta particles, or gamma rays, material of a high atomic number and with high density make for good shielding; frequently lead is used. However, this approach will not work with neutrons, since the absorption of neutrons does not increase straightforwardly with atomic number, as it does with alpha, beta, and gamma radiation. Instead one needs to look at the particular interactions neutrons have with matter. For example, hydrogen rich materials are often used to shield against neutrons, since ordinary hydrogen both scatters and slows neutrons. This often means that simple concrete blocks or even paraffin-loaded plastic blocks afford better protection from neutrons than do far more dense materials. After slowing, neutrons may then be absorbed with an isotope which has high affinity for slow neutrons without causing secondary capture-radiation, such as lithium-6.

Hydrogen-rich ordinary water affects neutron absorption in nuclear fission reactors: usually neutrons are so strongly absorbed by normal water that fuel-enrichment with fissionable isotope is required. The deuterium in heavy water has a very much lower absorption affinity for neutrons than does protium (normal light hydrogen). Deuterium is therefore used in CANDU-type reactors, in order to slow (moderate) neutron velocity, to increase the probability of nuclear fission compared to neutron capture.

Production

Institut Laue–Langevin (ILL) in Grenoble, France – one of the most important neutron research facilities worldwide

Various nuclides become more stable by expelling neutrons as a decay mode; this is known as neutron emission, and happens commonly during spontaneous fission.

Cosmic radiation interacting with the Earth's atmosphere continuously generates neutrons that can be detected at the surface. Even stronger neutron radiation is produced at the surface of Mars where the atmosphere is thick enough to generate neutrons from cosmic ray spallation, but not thick enough to provide significant protection from the neutrons produced. These neutrons not only produce a Martian surface neutron radiation hazard from direct downward-going neutron radiation, but also a significant hazard from reflection of neutrons from the Martian surface, which will produce reflected neutron radiation penetrating upward into a Martian craft or habitat from the floor.

Nuclear fission reactors naturally produce free neutrons; their role is to sustain the energy-producing chain reaction. The intense neutron radiation can also be used to produce various radioisotopes through the process of neutron activation, which is a type of neutron capture.

Experimental nuclear fusion reactors produce free neutrons as a waste product. However, it is these neutrons that possess most of the energy, and converting that energy to a useful form has proved a difficult engineering challenge. Fusion reactors which generate

neutrons are likely to create around twice the amount of radioactive waste of a fission reactor, but the waste is composed of neutron-activated lighter isotopes, which have relatively short (50–100 years) decay periods as compared to typical half lives of 10,000 years for fission waste, which is long primarily due to the long half life of alpha-emitting transuranic actinides. Nuclear power#Solid waste

Neutron temperature

Thermal neutrons

A **thermal neutron** is a free neutron that is Boltzmann distributed with kT = 0.0253 eV (4.0×10^{-21} J) at room temperature. This gives characteristic (not average, or median) speed of 2.2 km/s. The name 'thermal' comes from their energy being that of the room temperature gas or material they are permeating. After a number of collisions (often in the range of 10–20) with nuclei, neutrons arrive at this energy level, provided that they are not absorbed.

In many substances, thermal neutrons have a much larger effective cross-section than faster neutrons, and can therefore be absorbed more easily by any atomic nuclei that they collide with, creating a heavier — and often unstable — isotope of the chemical element as a result.

Most fission reactors use a neutron moderator to slow down, or *thermalize* the neutrons that are emitted by nuclear fission so that they are more easily captured, causing further fission. Others, called fast breeder reactors, use fission energy neutrons directly.

Cold neutrons

These neutrons are thermal neutrons that have been equilibrated in a very cold substance such as liquid deuterium. These are produced in neutron scattering research facilities.

Ultracold neutrons

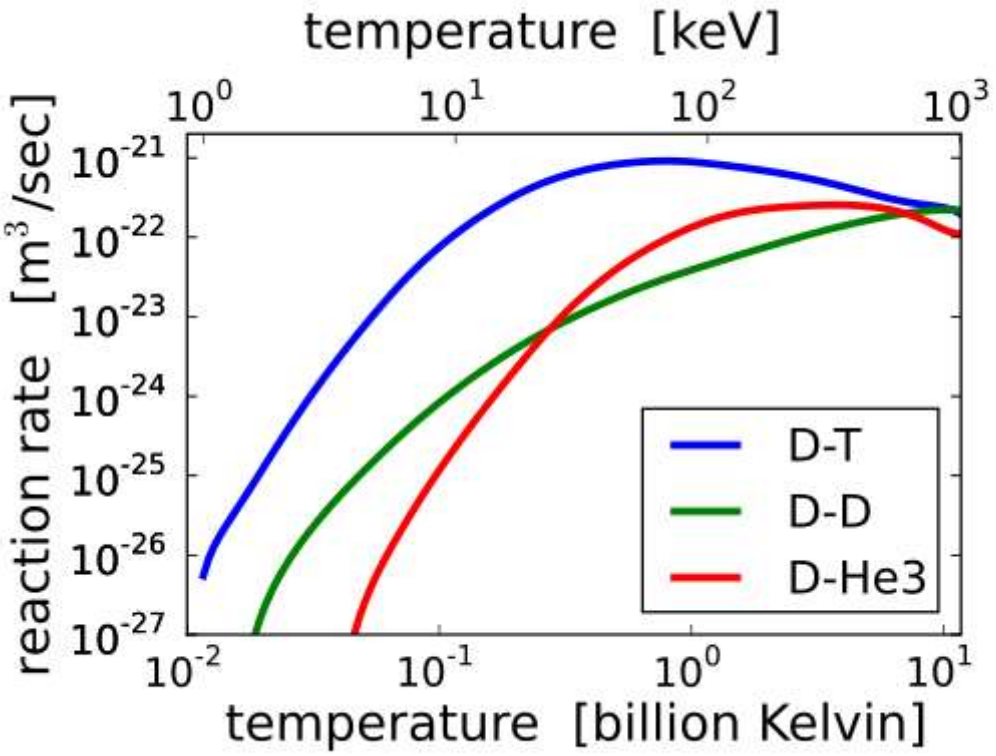
Ultracold neutrons are produced by inelastically scattering cold neutrons in substances with a temperature of a few kelvins, such as solid deuterium or superfluid helium. An alternative production method is the mechanical deceleration of cold neutrons.

Fission energy neutrons

A **fast neutron** is a free neutron with a kinetic energy level close to 2 MeV (20 TJ/kg), hence a speed of ~20,000 km/s (~ 6% of the speed of light). They are named *fission energy* or *fast* neutrons to distinguish them from lower-energy thermal neutrons, and high-energy neutrons produced in cosmic showers or accelerators. Fast neutrons are produced by nuclear processes such as nuclear fission.

Fast neutrons can be made into thermal neutrons via a process called moderation. This is done with a neutron moderator. In reactors, typically heavy water, light water, or graphite are used to moderate neutrons.

Fusion neutrons



The fusion reaction rate increases rapidly with temperature until it maximizes and then gradually drops off. The DT rate peaks at a lower temperature (about 70 keV, or 800 million kelvins) and at a higher value than other reactions commonly considered for fusion energy.

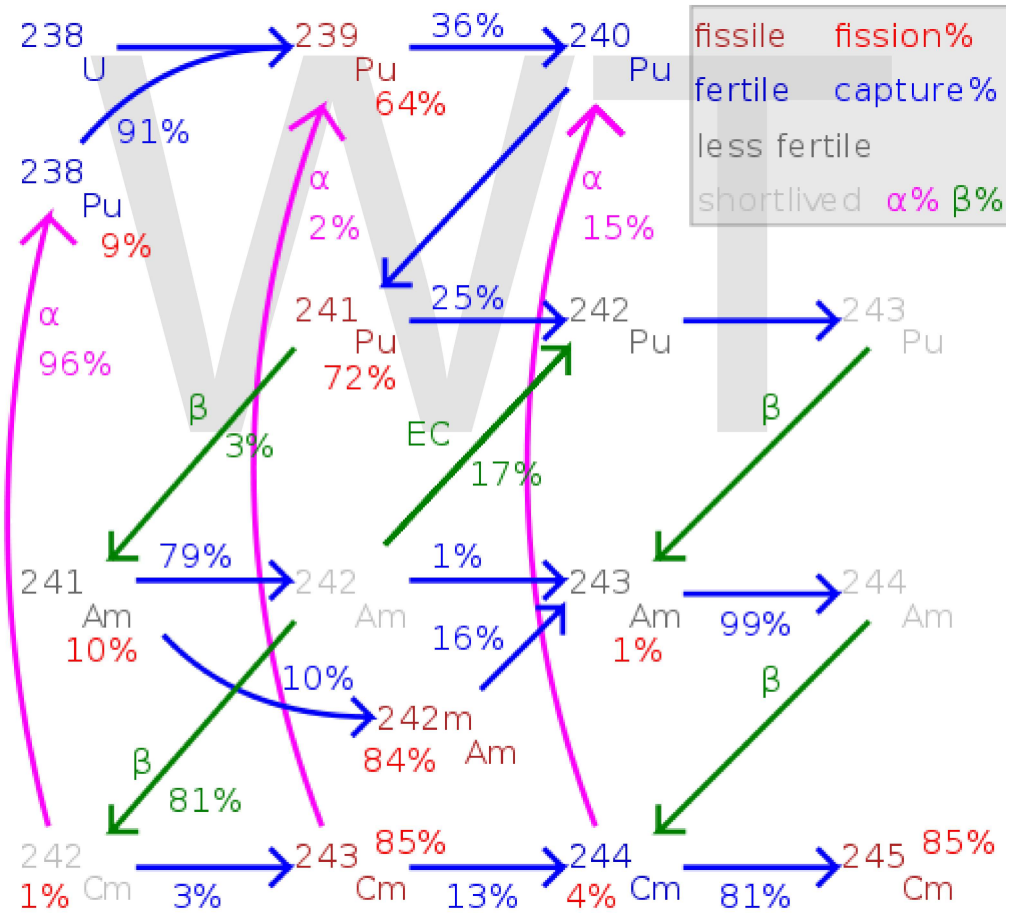
D-T (deuterium-tritium) fusion is the fusion reaction that produces the most energetic neutrons, with 14.1 MeV of kinetic energy and traveling at 17% of the speed of light. D-T fusion is also the easiest fusion reaction to ignite, reaching near-peak rates even when the deuterium and tritium nuclei have only a thousandth as much kinetic energy as the 14.1 MeV that will be produced.

14.1 MeV neutrons have about 10 times as much energy as fission neutrons, and are very effective at fissioning even non-fissile heavy nuclei, and these high-energy fissions produce more neutrons on average than fissions by lower-energy neutrons. This makes D-T fusion neutron sources such as proposed tokamak power reactors useful for transmutation of transuranic waste. 14.1 MeV neutrons can also produce neutrons by knocking them loose from nuclei.

On the other hand, these very high energy neutrons are less likely to simply be captured without causing fission or spallation. For these reasons, nuclear weapon design extensively utilizes D-T fusion 14.1 MeV neutrons to cause more fission. Fusion neutrons are able to cause fission in ordinarily non-fissile materials, such as depleted uranium (uranium-238), and these materials have been used in the jackets of thermonuclear weapons. Fusion neutrons also can cause fission in substances that are unsuitable or difficult to make into primary fission bombs, such as reactor grade plutonium. This physical fact thus causes ordinary non-weapons grade materials to become of concern in certain nuclear proliferation discussions and treaties.

Other fusion reactions produce much less energetic neutrons. D-D fusion produces a 2.45 MeV neutron and helium-3 half of the time, and produces tritium and a proton but no neutron the other half of the time. D-^{3}He fusion produces no neutron.

Intermediate-energy neutrons



Transmutation flow in LWR which is a thermal-spectrum reactor

A fission energy neutron that has slowed down but not yet reached thermal energies is called an epithermal neutron.

Cross sections for both capture and fission reactions often have multiple resonance peaks at specific energies in the epithermal energy range. These are of less significance in a fast neutron reactor where most neutrons are absorbed before slowing down to this range, or in a well-moderated thermal reactor where epithermal neutrons mostly interact with moderator nuclei, not with either fissile or fertile actinide nuclides. However, in a partially moderated reactor with more interactions of epithermal neutrons with heavy metal nuclei, there are greater possibilities for transient changes in reactivity which might make reactor control more difficult.

Ratios of capture reactions to fission reactions are also worse (more captures without fission) in most nuclear fuels such as plutonium-239, making epithermal-spectrum reactors using these fuels less desirable, as captures not only waste the one neutron captured but also usually result in a nuclide which is not fissile with thermal or epithermal neutrons, though still fissionable with fast neutrons. The exception is uranium-233 of the thorium cycle which has good capture-fission ratios at all neutron energies.

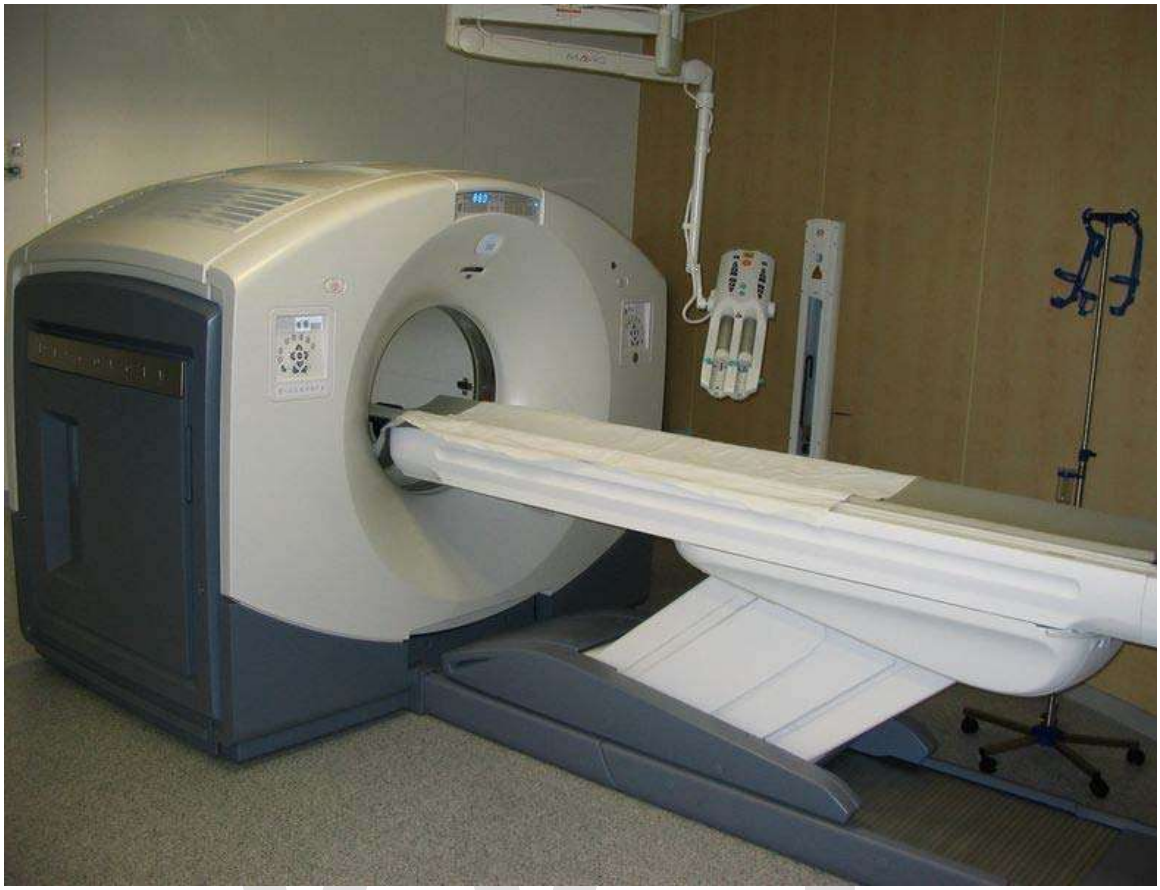
High-energy neutrons

These neutrons have more energy than fission energy neutrons and are generated as secondary particles by particle accelerators or in the atmosphere from cosmic rays. They can have energies as high as tens of joules per neutron. These neutrons are extremely efficient at ionization and far more likely to cause cell death than X-rays or protons.

Chapter-4

Positron Emission Tomography

Image of a typical positron emission tomography (PET) facility



PET/CT-System with 16-slice CT; the ceiling mounted device is an injection pump for CT contrast agent

Positron emission tomography (**PET**) is a nuclear medicine imaging technique which produces a three-dimensional image or picture of functional processes in the body. The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule. Three-dimensional images of tracer concentration within the body are then constructed by computer analysis. In modern scanners, three dimensional imaging is often accomplished with the aid of a CT X-ray scan performed on the patient during the same session, in the same machine.

If the biologically active molecule chosen for PET is FDG, an analogue of glucose, the concentrations of tracer imaged then give tissue metabolic activity, in terms of regional glucose uptake. Although use of this tracer results in the most common type of PET scan, other tracer molecules are used in PET to image the tissue concentration of many other types of molecules of interest.

History

The concept of emission and transmission tomography was introduced by David E. Kuhl and Roy Edwards in the late 1950s. Their work later led to the design and construction of several tomographic instruments at the University of Pennsylvania. Tomographic imaging techniques were further developed by Michel Ter-Pogossian, Michael E. Phelps and others at the Washington University School of Medicine.

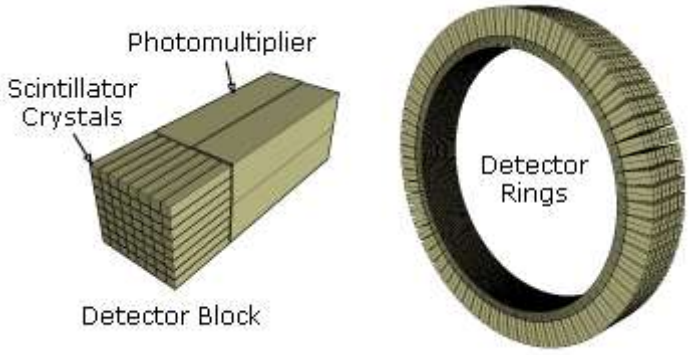
Work by Gordon Brownell, Charles Burnham and their associates at the Massachusetts General Hospital beginning in the 1950s contributed significantly to the development of PET technology and included the first demonstration of annihilation radiation for medical imaging. Their innovations, including the use of light pipes, and volumetric analysis have been important in the deployment of PET imaging. In 1961, James Robertson and his associates at Brookhaven National Laboratory built the first single-plane PET scan, nicknamed the "head-shrinker."

It is interesting that one of the factors most responsible for the acceptance of positron imaging was the development of radiopharmaceuticals. In particular, the development of labeled 2-fluorodeoxy-D-glucose (2FDG) by the Brookhaven group under the direction of Al Wolf and Joanna Fowler was a major factor in expanding the scope of PET imaging. The compound was first administered to two normal human volunteers by Abass Alavi in August 1976 at the University of Pennsylvania. Brain images obtained with an ordinary (non-PET) nuclear scanner demonstrated the concentration of FDG in that organ. Later, the substance was used in dedicated positron tomographic scanners, to yield the modern procedure.

The logical extension of positron instrumentation was a design using two 2-dimensional arrays. PC-I was the first instrument using this concept and was designed in 1968, completed in 1969 and reported in 1972. The first applications of PC-I in tomographic mode as distinguished from the computed tomographic mode were reported in 1970. It soon became clear to many of those involved in PET development that a circular or cylindrical array of detectors was the logical next step in PET instrumentation. Although many investigators took this approach, James Robertson and Z.H. Cho were the first to propose a ring system which has become the prototype of the current shape of PET.

The PET/CT scanner, attributed to Dr David Townsend and Dr Nutt was named by TIME Magazine as the medical invention of the year in 2000.

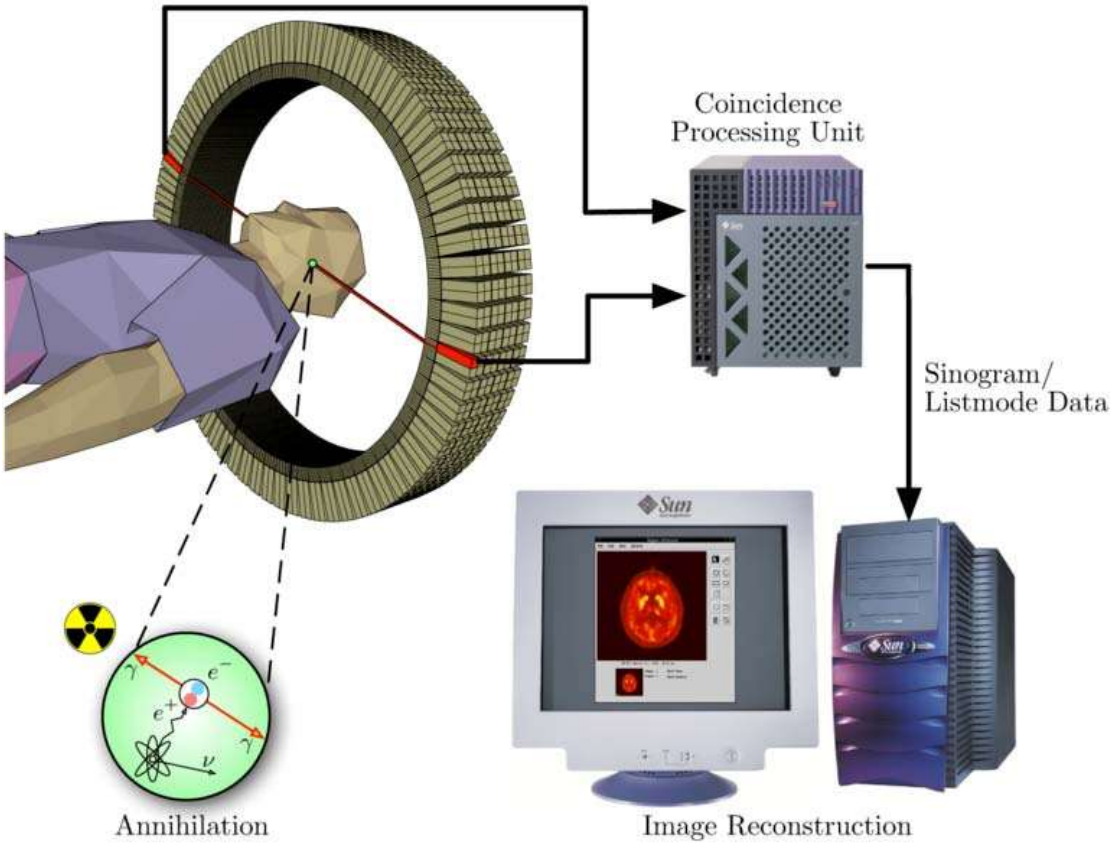
Description



Schematic view of a detector block and ring of a PET scanner

Operation

To conduct the scan, a short-lived radioactive tracer isotope is injected into the living subject (usually into blood circulation). The tracer is chemically incorporated into a biologically active molecule. There is a waiting period while the active molecule becomes concentrated in tissues of interest; then the subject is placed in the imaging scanner. The molecule most commonly used for this purpose is fluorodeoxyglucose (FDG), a sugar, for which the waiting period is typically an hour. During the scan a record of tissue concentration is made as the tracer decays.



Schema of a PET acquisition process

As the radioisotope undergoes positron emission decay (also known as positive beta decay), it emits a positron, an antiparticle of the electron with opposite charge. The emitted positron travels in tissue for a short distance (typically less than 1 mm, but dependent on the isotope), during which time it loses kinetic energy, until it decelerates to a point where it can interact with an electron. The encounter annihilates both electron and positron, producing a pair of annihilation (gamma) photons moving in approximately opposite directions. These are detected when they reach a scintillator in the scanning device, creating a burst of light which is detected by photomultiplier tubes or silicon avalanche photodiodes (Si APD). The technique depends on simultaneous or coincident detection of the pair of photons moving in approximately opposite direction (it would be exactly opposite in their center of mass frame, but the scanner has no way to know this, and so has a built-in slight direction-error tolerance). Photons that do not arrive in temporal "pairs" (i.e. within a timing-window of a few nanoseconds) are ignored.

Localization of the positron annihilation event

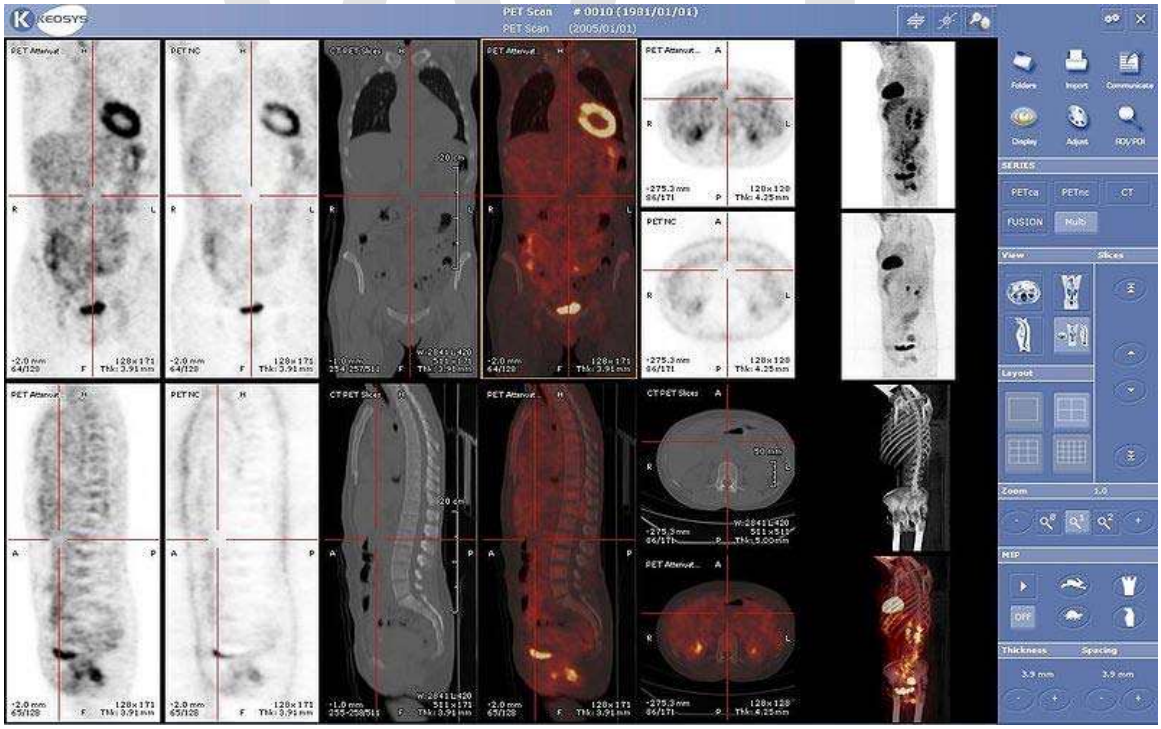
The most significant fraction of electron-positron decays result in two 511 keV gamma photons being emitted at almost 180 degrees to each other; hence it is possible to localize their source along a straight line of coincidence (also called the **line of response**, or **LOR**). In practice the LOR has a finite width as the emitted photons are not exactly 180

degrees apart. If the resolving time of the detectors is less than 500 picoseconds rather than about 10 nanoseconds, it is possible to localize the event to a segment of a chord, whose length is determined by the detector timing resolution. As the timing resolution improves, the signal-to-noise ratio (SNR) of the image will improve, requiring fewer events to achieve the same image quality. This technology is not yet common, but it is available on some new systems.

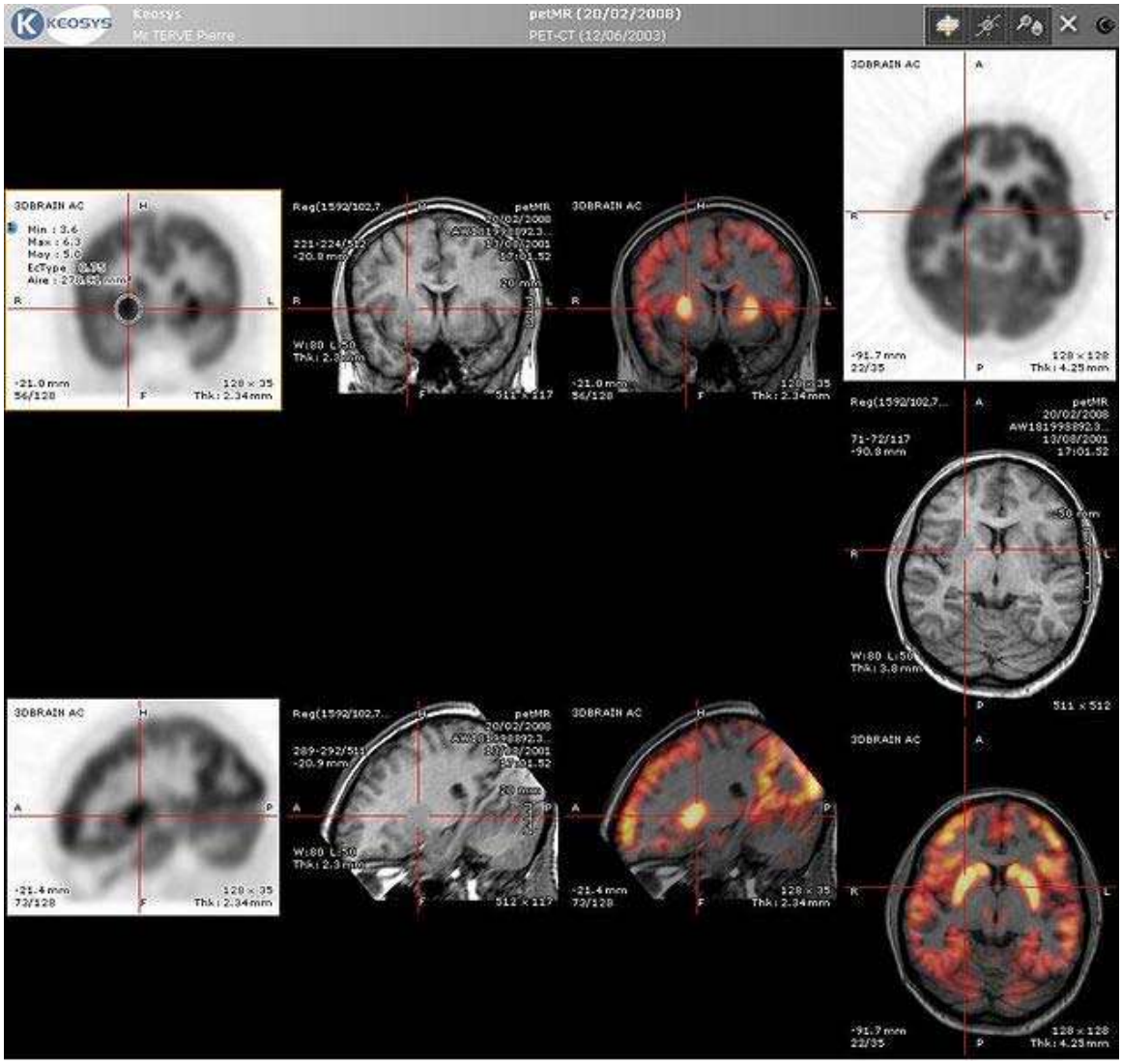
Image reconstruction using coincidence statistics

More commonly, a technique much like the reconstruction of computed tomography (CT) and single photon emission computed tomography (SPECT) data is used, although the data set collected in PET is much poorer than CT, so reconstruction techniques are more difficult.

Using statistics collected from tens-of-thousands of coincidence events, a set of simultaneous equations for the total activity of each parcel of tissue along many LORs can be solved by a number of techniques, and thus a map of radioactivities as a function of location for parcels or bits of tissue (also called voxels), may be constructed and plotted. The resulting map shows the tissues in which the molecular tracer has become concentrated, and can be interpreted by a nuclear medicine physician or radiologist in the context of the patient's diagnosis and treatment plan.



A complete body PET / CT Fusion image



A Brain PET / MRI Fusion image

Combination of PET with CT or MRI

PET scans are increasingly read alongside CT or magnetic resonance imaging (MRI) scans, the combination ("co-registration") giving both anatomic and metabolic information (i.e., what the structure is, and what it is doing biochemically). Because PET imaging is most useful in combination with anatomical imaging, such as CT, modern PET scanners are now available with integrated high-end multi-detector-row CT scanners. Because the two scans can be performed in immediate sequence during the same session, with the patient not changing position between the two types of scans, the two sets of images are more-precisely registered, so that areas of abnormality on the PET imaging can be more perfectly correlated with anatomy on the CT images. This is very useful in showing detailed views of moving organs or structures with higher anatomical variation, which is more common outside the brain.

At the Jülich Institute of Neurosciences and Biophysics, the world's largest PET/MRI device began operation in April 2009: a 9.4-tesla magnetic resonance tomograph (MRT) combined with a positron emission tomograph (PET). Presently, only the head and brain can be imaged at these high magnetic field strengths.

Radionuclides

Radionuclides used in PET scanning are typically isotopes with short half lives such as carbon-11 (~20 min), nitrogen-13 (~10 min), oxygen-15 (~2 min), and fluorine-18 (~110 min). These radionuclides are incorporated either into compounds normally used by the body such as glucose (or glucose analogues), water or ammonia, or into molecules that bind to receptors or other sites of drug action. Such labelled compounds are known as radiotracers. It is important to recognize that PET technology can be used to trace the biologic pathway of any compound in living humans (and many other species as well), provided it can be radiolabeled with a PET isotope. Thus the specific processes that can be probed with PET are virtually limitless, and radiotracers for new target molecules and processes are being synthesized all the time; as of this writing there are already dozens in clinical use and hundreds applied in research. Presently, however, by far the most commonly used radiotracer in clinical PET scanning is Fludeoxyglucose, an analogue of glucose that is labeled with fluorine-18.

Due to the short half lives of most radioisotopes, the radiotracers must be produced using a cyclotron in close proximity to the PET imaging facility. The half life of fluorine-18 is long enough that radiotracers labeled with fluorine-18 can be manufactured commercially at offsite locations and shipped to imaging centers.

11C-Metomidate is used to detect tumors of adrenocortical origin.

Limitations

The minimization of radiation dose to the subject is an attractive feature of the use of short-lived radionuclides. Besides its established role as a diagnostic technique, PET has an expanding role as a method to assess the response to therapy, in particular, cancer therapy, where the risk to the patient from lack of knowledge about disease progress is much greater than the risk from the test radiation.

Limitations to the widespread use of PET arise from the high costs of cyclotrons needed to produce the short-lived radionuclides for PET scanning and the need for specially adapted on-site chemical synthesis apparatus to produce the radiopharmaceuticals. Few hospitals and universities are capable of maintaining such systems, and most clinical PET is supported by third-party suppliers of radiotracers which can supply many sites simultaneously. This limitation restricts clinical PET primarily to the use of tracers labelled with fluorine-18, which has a half life of 110 minutes and can be transported a reasonable distance before use, or to rubidium-82, which can be created in a portable generator and is used for myocardial perfusion studies. Nevertheless, in recent years a few on-site cyclotrons with integrated shielding and hot labs have begun to accompany

PET units to remote hospitals. The presence of the small on-site cyclotron promises to expand in the future as the cyclotrons shrink in response to the high cost of isotope transportation to remote PET machines

Because the half-life of fluorine-18 is about two hours, the prepared dose of a radiopharmaceutical bearing this radionuclide will undergo multiple half-lives of decay during the working day. This necessitates frequent recalibration of the remaining dose (determination of activity per unit volume) and careful planning with respect to patient scheduling.

Image reconstruction

The raw data collected by a PET scanner are a list of 'coincidence events' representing near-simultaneous detection (typically, within a window of 6 to 12 nanoseconds of each other) of annihilation photons by a pair of detectors. Each coincidence event represents a line in space connecting the two detectors along which the positron emission occurred. Modern systems with a higher time resolution (roughly 3 nanoseconds) also use a technique (called "Time-of-flight") where they more precisely decide the difference in time between the detection of the two photons and can thus localize the point of origin of the annihilation event between the two detectors to within 10 cm.

Coincidence events can be grouped into projection images, called sinograms. The sinograms are sorted by the angle of each view and tilt (for 3D images). The sinogram images are analogous to the projections captured by computed tomography (CT) scanners, and can be reconstructed in a similar way. However, the statistics of the data are much worse than those obtained through transmission tomography. A normal PET data set has millions of counts for the whole acquisition, while the CT can reach a few billion counts. As such, PET data suffer from scatter and random events much more dramatically than CT data does.

In practice, considerable pre-processing of the data is required - correction for random coincidences, estimation and subtraction of scattered photons, detector dead-time correction (after the detection of a photon, the detector must "cool down" again) and detector-sensitivity correction (for both inherent detector sensitivity and changes in sensitivity due to angle of incidence).

Filtered back projection (FBP) has been frequently used to reconstruct images from the projections. This algorithm has the advantage of being simple while having a low requirement for computing resources. However, shot noise in the raw data is prominent in the reconstructed images and areas of high tracer uptake tend to form streaks across the image. Also, FBP treats the data deterministically - it does not account for the inherent randomness associated with PET data, thus requiring all the pre-reconstruction corrections described above.

Iterative expectation-maximization algorithms are now the preferred method of reconstruction. These algorithms compute an estimate of the likely distribution of

annihilation events that led to the measured data, based on statistical principles. The advantage is a better noise profile and resistance to the streak artifacts common with FBP, but the disadvantage is higher computer resource requirements.

Attenuation correction: As different LORs must traverse different thicknesses of tissue, the photons are attenuated differentially. The result is that structures deep in the body are reconstructed as having falsely low tracer uptake. Contemporary scanners can estimate attenuation using integrated x-ray CT equipment, however earlier equipment offered a crude form of CT using a gamma ray (positron emitting) source and the PET detectors.

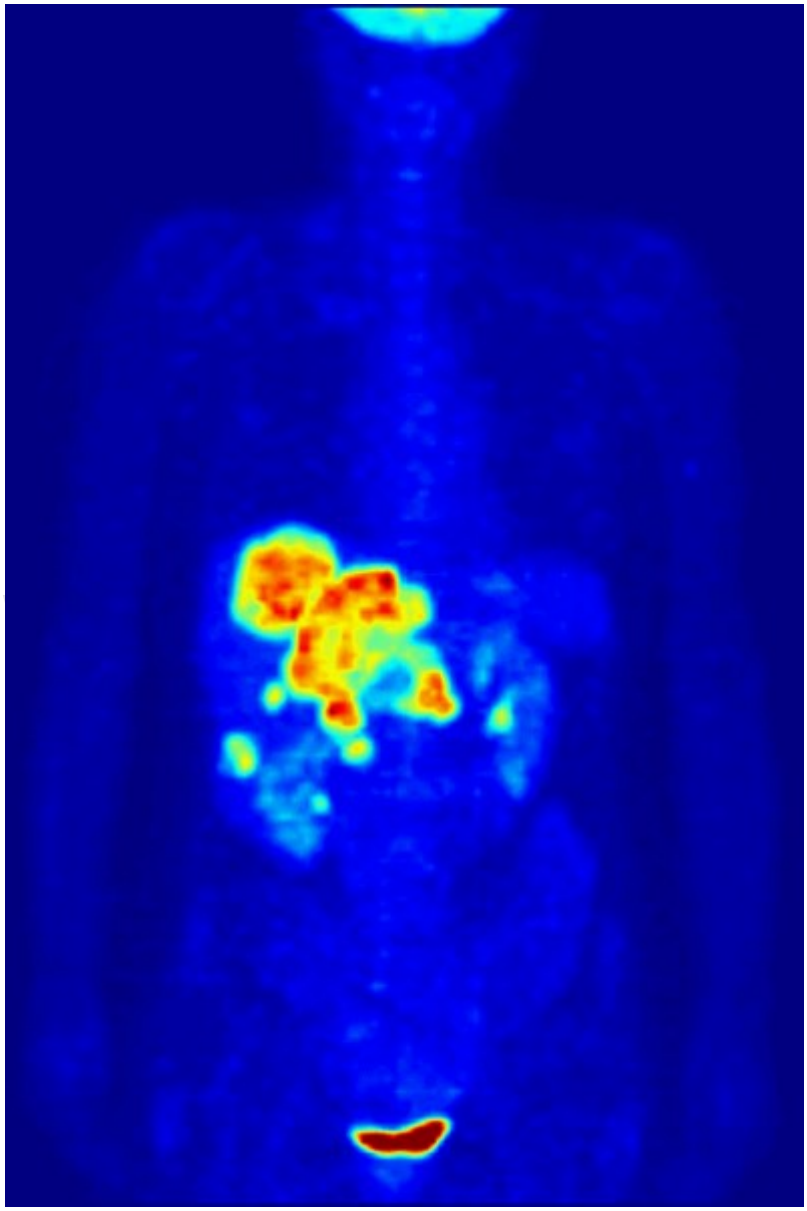
While attenuation-corrected images are generally more faithful representations, the correction process is itself susceptible to significant artifacts. As a result, both corrected and uncorrected images are always reconstructed and read together.

2D/3D reconstruction: Early PET scanners had only a single ring of detectors, hence the acquisition of data and subsequent reconstruction was restricted to a single transverse plane. More modern scanners now include multiple rings, essentially forming a cylinder of detectors.

There are two approaches to reconstructing data from such a scanner: 1) treat each ring as a separate entity, so that only coincidences within a ring are detected, the image from each ring can then be reconstructed individually (2D reconstruction), or 2) allow coincidences to be detected between rings as well as within rings, then reconstruct the entire volume together (3D).

3D techniques have better sensitivity (because more coincidences are detected and used) and therefore less noise, but are more sensitive to the effects of scatter and random coincidences, as well as requiring correspondingly greater computer resources. The advent of sub-nanosecond timing resolution detectors affords better random coincidence rejection, thus favoring 3D image reconstruction.

Applications



Maximum intensity projection (MIP) of a F-18 FDG wholebody PET acquisition; liver metastases of a colorectal tumor are clearly visible within the abdominal region of the image. Normal physiological isotope uptake is seen in the brain, renal collection systems and bladder.

PET is both a medical and research tool. It is used heavily in clinical oncology (medical imaging of tumors and the search for metastases), and for clinical diagnosis of certain diffuse brain diseases such as those causing various types of dementias. PET is also an important research tool to map normal human brain and heart function.

PET is also used in pre-clinical studies using animals, where it allows repeated investigations into the same subjects. This is particularly valuable in cancer research, as it results in an increase in the statistical quality of the data (subjects can act as their own control) and substantially reduces the numbers of animals required for a given study.

Alternative methods of scanning include x-ray computed tomography (CT), magnetic resonance imaging (MRI) and functional magnetic resonance imaging (fMRI), ultrasound and single photon emission computed tomography (SPECT).

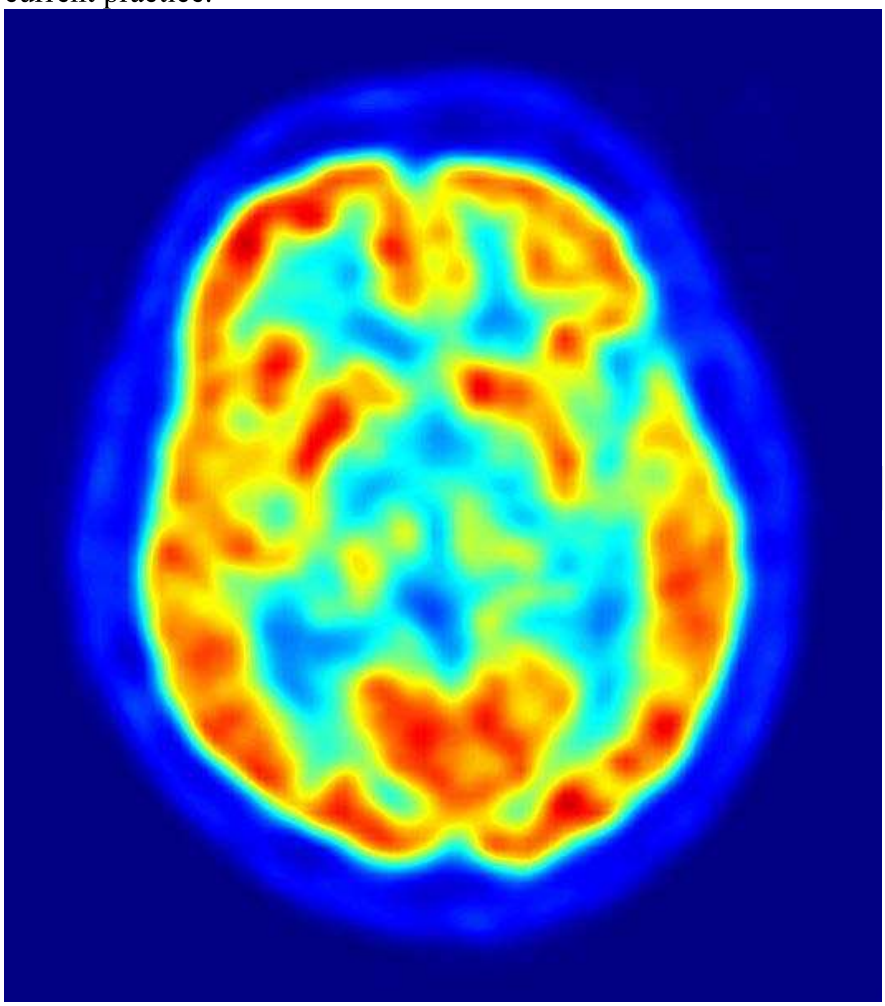
While some imaging scans such as CT and MRI isolate organic anatomic changes in the body, PET and SPECT are capable of detecting areas of molecular biology detail (even prior to anatomic change). PET scanning does this using radiolabelled molecular probes that have different rates of uptake depending on the type and function of tissue involved. Changing of regional blood flow in various anatomic structures (as a measure of the injected positron emitter) can be visualized and relatively quantified with a PET scan.

PET imaging is best performed using a dedicated PET scanner. However, it is possible to acquire PET images using a conventional dual-head gamma camera fitted with a coincidence detector. The quality of gamma-camera PET is considerably lower, and acquisition is slower. However, for institutions with low demand for PET, this may allow on-site imaging, instead of referring patients to another center, or relying on a visit by a mobile scanner.

PET is a valuable technique for some diseases and disorders, because it is possible to target the radio-chemicals used for particular bodily functions.

1. Oncology: PET scanning with the tracer fluorine-18 (F-18) fluorodeoxyglucose (FDG), called FDG-PET, is widely used in clinical oncology. This tracer is a glucose analog that is taken up by glucose-using cells and phosphorylated by hexokinase (whose mitochondrial form is greatly elevated in rapidly growing malignant tumours). A typical dose of FDG used in an oncological scan is 200-400 MBq for an adult human. Because the oxygen atom which is replaced by F-18 to generate FDG is required for the next step in glucose metabolism in all cells, no further reactions occur in FDG. Furthermore, most tissues (with the notable exception of liver and kidneys) cannot remove the phosphate added by hexokinase. This means that FDG is trapped in any cell which takes it up, until it decays, since phosphorylated sugars, due to their ionic charge, cannot exit from the cell. This results in intense radiolabeling of tissues with high glucose uptake, such as the brain, the liver, and most cancers. As a result, FDG-PET can be used for diagnosis, staging, and monitoring treatment of cancers, particularly in Hodgkin's lymphoma, non-Hodgkin lymphoma, and lung cancer. Many other types of solid tumors will be found to be very highly labeled on a case-by-case basis—a fact which becomes especially useful in searching for tumor metastasis, or for recurrence after a known highly active primary tumor is removed. Because individual PET scans are more expensive than "conventional" imaging with computed tomography (CT) and magnetic resonance imaging (MRI), expansion

of FDG-PET in cost-constrained health services will depend on proper health technology assessment; this problem is a difficult one because structural and functional imaging often cannot be directly compared, as they provide different information. Oncology scans using FDG make up over 90% of all PET scans in current practice.

2. 

PET scan of the human brain.

Neurology: PET neuroimaging is based on an assumption that areas of high radioactivity are associated with brain activity. What is actually measured indirectly is the flow of blood to different parts of the brain, which is generally believed to be correlated, and has been measured using the tracer oxygen-15. However, because of its 2-minute half-life O-15 must be piped directly from a medical cyclotron for such uses, and this is difficult. In practice, since the brain is normally a rapid user of glucose, and since brain pathologies such as Alzheimer's disease greatly decrease brain metabolism of both glucose and oxygen in tandem, standard FDG-PET of the brain, which measures regional glucose use, may also be successfully used to differentiate Alzheimer's disease from other dementing processes, and also to make early diagnosis of Alzheimer's disease. The advantage

of FDG-PET for these uses is its much wider availability. PET imaging with FDG can also be used for localization of seizure focus: A seizure focus will appear as hypometabolic during an interictal scan. Several radiotracers (i.e. radioligands) have been developed for PET that are ligands for specific neuroreceptor subtypes such as [^{11}C] raclopride and [^{18}F] fallypride for dopamine D2/D3 receptors, [^{11}C]McN 5652 and [^{11}C]DASB for serotonin transporters, or enzyme substrates (e.g. 6-FDOPA for the AADC enzyme). These agents permit the visualization of neuroreceptor pools in the context of a plurality of neuropsychiatric and neurologic illnesses. A novel probe developed at the University of Pittsburgh termed PIB (Pittsburgh compound B) permits the visualization of amyloid plaques in the brains of Alzheimer's patients. This technology could assist clinicians in making a positive clinical diagnosis of AD pre-mortem and aid in the development of novel anti-amyloid therapies. [^{11}C]PMP (N-[^{11}C]methylpiperidin-4-yl propionate) is a novel radiopharmaceutical used in PET imaging to determine the activity of the acetylcholinergic neurotransmitter system by acting as a substrate for acetylcholinesterase. Post-mortem examination of AD patients have shown decreased levels of acetylcholinesterase. [^{11}C]PMP is used to map the acetylcholinesterase activity in the brain which could allow for pre-mortem diagnosis of AD and help to monitor AD treatments. Avid Radiopharmaceuticals of Philadelphia has developed a compound called 18F-AV-45 that uses the longer-lasting radionuclide fluorine-18 to detect amyloid plaques using PET scans.

3. Cardiology, atherosclerosis and vascular disease study: In clinical cardiology, FDG-PET can identify so-called "hibernating myocardium", but its cost-effectiveness in this role versus SPECT is unclear. Recently, a role has been suggested for FDG-PET imaging of atherosclerosis to detect patients at risk of stroke .
4. Neuropsychology / Cognitive neuroscience: To examine links between specific psychological processes or disorders and brain activity.
5. Psychiatry: Numerous compounds that bind selectively to neuroreceptors of interest in biological psychiatry have been radiolabeled with C-11 or F-18. Radioligands that bind to dopamine receptors (D1,D2, reuptake transporter), serotonin receptors (5HT1A, 5HT2A, reuptake transporter) opioid receptors (mu) and other sites have been used successfully in studies with human subjects. Studies have been performed examining the state of these receptors in patients compared to healthy controls in schizophrenia, substance abuse, mood disorders and other psychiatric conditions.
6. Pharmacology: In pre-clinical trials, it is possible to radiolabel a new drug and inject it into animals. Such scans are referred to as biodistribution studies. The uptake of the drug, the tissues in which it concentrates, and its eventual elimination, can be monitored far more quickly and cost effectively than the older technique of killing and dissecting the animals to discover the same information. Much more commonly, however, drug occupancy at a purported site of action can be inferred indirectly by competition studies between unlabeled drug and radiolabeled compounds known apriori to bind with specificity to the site. A

single radioligand can be used this way to test many potential drug candidates for the same target. A related technique involves scanning with radioligands that compete with an endogenous (naturally occurring) substance at a given receptor to demonstrate that a drug causes the release of the natural substance.

7. PET technology for small animal imaging: A miniature PET tomograph has been constructed that is small enough for a fully conscious and mobile rat to wear on its head while walking around. This RatCAP (Rat Conscious Animal PET) allows animals to be scanned without the confounding effects of anesthesia. PET scanners designed specifically for imaging rodents or small primates are marketed for academic and pharmaceutical research.
8. Musculo-Skeletal Imaging: PET has been shown to be a feasible technique for studying skeletal muscles during exercises like walking. One of the main advantages of using PET is that it can also provide muscle activation data about deeper lying muscles such as the vastus intermedialis and the gluteus minimus, as compared to other muscle studying techniques like Electromyography, which can only be used on superficial muscles (i.e. directly under the skin). A clear disadvantage, however, is that PET provides no timing information about muscle activation, because it has to be measured after the exercise is completed. This is due to the time it takes for FDG to accumulate in the activated muscles.

Safety

PET scanning is non-invasive, but it does involve exposure to ionizing radiation. The total dose of radiation is significant, usually around 5–7 mSv. However, in modern practice, a combined PET/CT scan is almost always performed, and for PET/CT scanning, the radiation exposure may be substantial - around 23-26 mSv (for a 70 kg person - dose is likely to be higher for higher body weights). When compared to the classification level for radiation workers in the UK, of 6 mSv it can be seen that PET scans need proper justification. This can also be compared to 2.2 mSv average annual background radiation in the UK, 0.02 mSv for a chest x-ray and 6.5 - 8 mSv for a CT scan of the chest, according to the Chest Journal and ICRP. A policy change suggested by the IFALPA member associations in year 1999 mentioned that an aircrew member is likely to receive a radiation dose of 4–9 mSv per year.

Chapter-5

Single Photon Emission Computed Tomography

Single photon emission computed tomography (SPECT, or less commonly, SPET) is a nuclear medicine tomographic imaging technique using gamma rays. It is very similar to conventional nuclear medicine planar imaging using a gamma camera. However, it is able to provide true 3D information. This information is typically presented as cross-sectional slices through the patient, but can be freely reformatted or manipulated as required.

The basic technique requires injection of a gamma-emitting radioisotope (called radionuclide) into the bloodstream of the patient. Occasionally the radioisotope is a simple soluble dissolved ion, such as a radioisotope of gallium(III), which happens to also have chemical properties which allow it to be concentrated in ways of medical interest for disease detection. However, most of the time in SPECT, a marker radioisotope, which is of interest only for its radioactive properties, has been attached to a special radioligand, which is of interest for its chemical binding properties to certain types of tissues. This marriage allows the combination of ligand and radioisotope (the radiopharmaceutical) to be carried and bound to a place of interest in the body, which then (due to the gamma-emission of the isotope) allows the ligand concentration to be seen by a gamma-camera.

Principles

In the same way that a plain X-ray is a 2-dimensional (2-D) view of a 3-dimensional structure, the image obtained by a gamma camera is a 2-D view of 3-D distribution of a radionuclide.

SPECT imaging is performed by using a gamma camera to acquire multiple 2-D images (also called projections), from multiple angles. A computer is then used to apply a tomographic reconstruction algorithm to the multiple projections, yielding a 3-D dataset. This dataset may then be manipulated to show thin slices along any chosen axis of the

body, similar to those obtained from other tomographic techniques, such as MRI, CT, and PET.

SPECT is similar to PET in its use of radioactive tracer material and detection of gamma rays. In contrast with PET, however, the tracer used in SPECT emits gamma radiation that is measured directly, whereas PET tracer emits positrons which annihilate with electrons up to a few millimeters away, causing two gamma photons to be emitted in opposite directions. A PET scanner detects these emissions "coincident" in time, which provides more radiation event localization information and thus higher resolution images than SPECT (which has about 1 cm resolution). SPECT scans, however, are significantly less expensive than PET scans, in part because they are able to use longer-lived more easily-obtained radioisotopes than PET.

Because SPECT acquisition is very similar to planar gamma camera imaging, the same radiopharmaceuticals may be used. If a patient is examined in another type of nuclear medicine scan but the images are non-diagnostic, it may be possible to proceed straight to SPECT by moving the patient to a SPECT instrument, or even by simply reconfiguring the camera for SPECT image acquisition while the patient remains on the table.

To acquire SPECT images, the gamma camera is rotated around the patient. Projections are acquired at defined points during the rotation, typically every 3–6 degrees. In most cases, a full 360 degree rotation is used to obtain an optimal reconstruction. The time taken to obtain each projection is also variable, but 15–20 seconds is typical. This gives a total scan time of 15–20 minutes.

Multi-headed gamma cameras can provide accelerated acquisition. For example, a dual headed camera can be used with heads spaced 180 degrees apart, allowing 2 projections to be acquired simultaneously, with each head requiring 180 degrees of rotation. Triple-head cameras with 120 degree spacing are also used.

Cardiac gated acquisitions are possible with SPECT, just as with planar imaging techniques such as MUGA. Triggered by Electrocardiogram (EKG) to obtain differential information about the heart in various parts of its cycle, gated myocardial SPECT can be used to obtain quantitative information about myocardial perfusion, thickness, and contractility of the myocardium during various parts of the cardiac cycle; and also to allow calculation of left ventricular ejection fraction, stroke volume, and cardiac output.

HMPAO brain 3D SPECT for neuropsychiatric diagnosis

Most SPECT scanner workstations can render the 2D slices in a variety of formats. In a 3D Surface View, the cortical surface of the brain is reconstructed from the 2D slices. Holes or defects in the surface of the brain actually represent decreases in perfusion which may be related to decreases in neuronal activity. In a 3D Active View the interior of the brain is displayed as a lattice gridwork. Daniel Amen, a California-based physician who has utilized 3D SPECT scanning heavily in his medical practice, has standardized 3D Active Views such that average activity is shown in a blue color, higher activity is

shown in red and very high activity is shown in white. Some utility of brain HMAPO 3D SPECT scan in neuropsychiatric diagnosis and management has been found.

Application

SPECT can be used to complement any gamma imaging study, where a true 3D representation can be helpful. E.g. tumor imaging, infection (leukocyte) imaging, thyroid imaging or bone imaging.

Because SPECT permits accurate localisation in 3D space, it can be used to provide information about localised function in internal organs, such as functional cardiac or brain imaging.

Myocardial perfusion imaging

Myocardial perfusion imaging (MPI) is a form of functional cardiac imaging, used for the diagnosis of ischemic heart disease. The underlying principle is that under conditions of stress, diseased myocardium receives less blood flow than normal myocardium. MPI is one of several types of cardiac stress test.

A cardiac specific radiopharmaceutical is administered. E.g. ^{99m}Tc-tetrofosmin (Myoview, GE healthcare), ^{99m}Tc-sestamibi (Cardiolite, Bristol-Myers Squibb). Following this, the heart rate is raised to induce myocardial stress, either by exercise or pharmacologically with adenosine, dobutamine or dipyridamole (aminophylline can be used to reverse the effects of dipyridamole).

SPECT imaging performed after stress reveals the distribution of the radiopharmaceutical, and therefore the relative blood flow to the different regions of the myocardium. Diagnosis is made by comparing stress images to a further set of images obtained at rest. As the radionuclide redistributes slowly, it is not usually possible to perform both sets of images on the same day, hence a second attendance is required 1–7 days later (although, with a Tl-201 myocardial perfusion study with dipyridamole, rest images can be acquired as little as two-hours post stress). However, if stress imaging is normal, it is unnecessary to perform rest imaging, as it too will be normal – thus stress imaging is normally performed first.

MPI has been demonstrated to have an overall accuracy of about 83% (sensitivity: 85%; specificity: 72%), and is comparable with (or better than) other non-invasive tests for ischemic heart disease.

Functional brain imaging

Usually the gamma-emitting tracer used in functional brain imaging is ^{99m}Tc-HMPAO (hexamethylpropylene amine oxime). ^{99m}Tc is a metastable nuclear isomer which emits gamma rays which can be detected by a gamma camera. When it is attached to HMPAO,

this allows ^{99m}Tc to be taken up by brain tissue in a manner proportional to brain blood flow, in turn allowing brain blood flow to be assessed with the nuclear gamma camera.

Because blood flow in the brain is tightly coupled to local brain metabolism and energy use, the ^{99m}Tc-HMPAO tracer (as well as the similar ^{99m}Tc-EC tracer) is used to assess brain metabolism regionally, in an attempt to diagnose and differentiate the different causal pathologies of dementia. Meta analysis of many reported studies suggests that SPECT with this tracer is about 74% sensitive at diagnosing Alzheimer's disease vs. 81% sensitivity for clinical exam (mental testing, etc.). More recent studies have shown the accuracy of SPECT in Alzheimer's diagnosis may be as high as 88%. In meta analysis, SPECT was superior to clinical exam and clinical criteria (91% vs. 70%) in being able to differentiate Alzheimer's disease from vascular dementias. This latter ability relates to SPECT's imaging of local metabolism of the brain, in which the patchy loss of cortical metabolism seen in multiple strokes differs clearly from the more even or "smooth" loss of non-occipital cortical brain function typical of Alzheimer's disease.

^{99m}Tc-HMPAO SPECT scanning competes with fludeoxyglucose (FDG) PET scanning of the brain, which works to assess regional brain glucose metabolism, to provide very similar information about local brain damage from many processes. SPECT is more widely available, however, for the basic reason that the radioisotope generation technology is longer-lasting and far less expensive in SPECT, and the gamma scanning equipment is less expensive as well. The reason for this is that ^{99m}Tc is extracted from relatively simple technetium-99m generators, which are delivered to hospitals and scanning centers weekly to supply fresh radioisotope, whereas FDG PET relies on FDG which must be made in an expensive medical cyclotron and "hot-lab" (automated chemistry lab for radiopharmaceutical manufacture), then must be delivered directly to scanning sites, with delivery-fraction for each trip handicapped by its natural short 110-minute half-life.

Reconstruction

Reconstructed images typically have resolutions of 64×64 or 128×128 pixels, with the pixel sizes ranging from 3–6 mm. The number of projections acquired is chosen to be approximately equal to the width of the resulting images. In general, the resulting reconstructed images will be of lower resolution, have increased noise than planar images, and be susceptible to artifacts.

Scanning is time consuming, and it is essential that there is no patient movement during the scan time. Movement can cause significant degradation of the reconstructed images, although movement compensation reconstruction techniques can help with this. A highly uneven distribution of radiopharmaceutical also has the potential to cause artifacts. A very intense area of activity (e.g. the bladder) can cause extensive streaking of the images and obscure neighboring areas of activity. (This is a limitation of the filtered back projection reconstruction algorithm. Iterative reconstruction is an alternative algorithm which is growing in importance, as it is less sensitive to artifacts and can also correct for attenuation and depth dependent blurring).

Attenuation of the gamma rays within the patient can lead to significant underestimation of activity in deep tissues, compared to superficial tissues. Approximate correction is possible, based on relative position of the activity. However, optimal correction is obtained with measured attenuation values. Modern SPECT equipment is available with an integrated x-ray CT scanner. As X-ray CT images are an attenuation map of the tissues, this data can be incorporated into the SPECT reconstruction to correct for attenuation. It also provides a precisely registered CT image which can provide additional anatomical information.

Chapter-6

Radioisotope Thermoelectric Generator

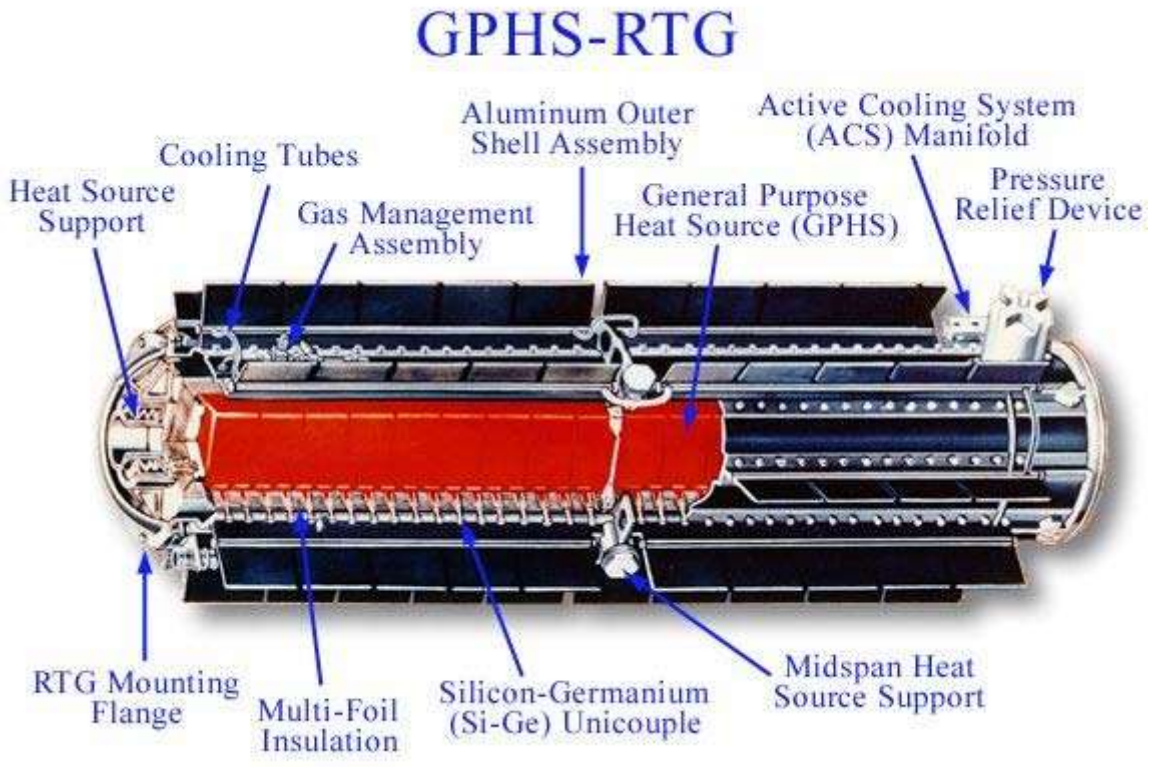


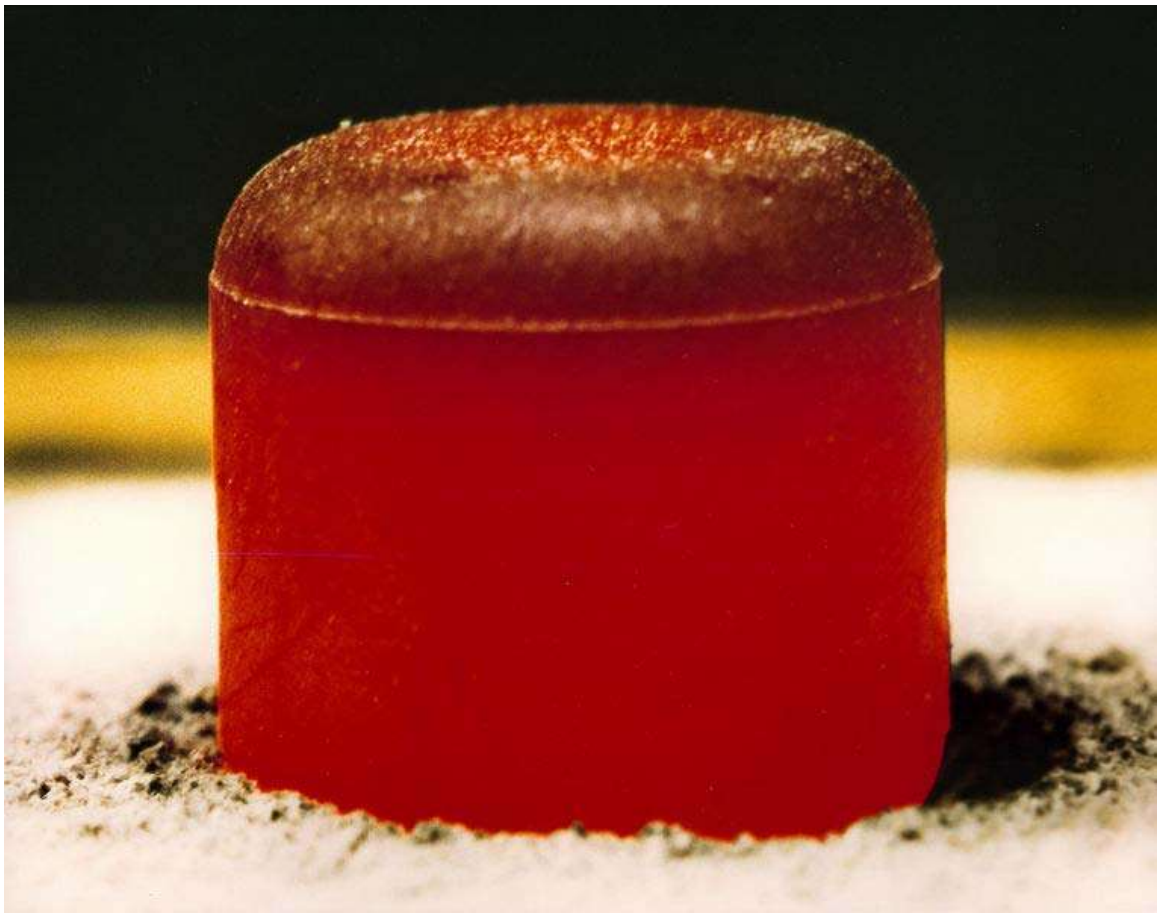
Diagram of an RTG used on the Cassini probe

A **radioisotope thermoelectric generator** (**RTG**, **RITEG**) is a nuclear reactor technology electrical generator that obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples.

RTGs can be considered as a type of battery and have been used as power sources in satellites, space probes and unmanned remote facilities, such as a series of lighthouses built by the former Soviet Union inside the Arctic Circle. RTGs are usually the most

desirable power source for robotic or unmaintained situations needing 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 viable. Safe use of RTGs requires containment of the radioisotopes long after the productive life of the unit.

History



A pellet of $^{238}PuO_2$ to be used in an RTG for either the Cassini or Galileo mission. The initial output is 62 watts and the pellet glows because of the heat generated by the radioactive decay (primarily α). Photo is taken after insulating the pellet under a graphite blanket for minutes and removing the blanket.

The first RTG launched in space by the United States was SNAP 3 in 1961 aboard the Navy Transit 4A spacecraft. One of the first terrestrial uses of RTGs was in 1966 by the US Navy at the uninhabited Fairway Rock Island in Alaska, where it remained in use until its removal in 1995.

A common application of RTGs is as power sources on spacecraft. Systems for Nuclear Auxiliary Power (SNAP) units were used especially for probes that travel far enough from the Sun that solar panels are no longer viable. As such they are used with Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Ulysses, Cassini and New Horizons. In

addition, RTGs were used 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 Apollo 13 was aborted, its RTG now rests in the South Pacific ocean, in the vicinity of the Tonga Trench. 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 constructed many unmanned lighthouses and navigation beacons powered by RTGs. Powered by Strontium 90 (^{90}Sr), they are very reliable and provide a steady source of power. Critics argue that they could cause environmental and security problems, as leakage or theft of the radioactive material could pass unnoticed for years (or possibly forever: some of these lighthouses cannot be found because of poor record keeping). In one instance, the radioactive compartments were opened by a thief. In another case, three woodcutters in Georgia came across one of the units and slept close to it as a heat source during a cold night. Two of the three were later hospitalized with severe radiation burns. The unit was eventually recovered and isolated.

There are approximately 1,000 such RTGs in Russia. All of them have long exhausted their 10-year engineered life spans. They are likely no longer functional, and may be in need of dismantling. Some of them have become the prey of metal hunters, who strip the RTGs' metal casings, regardless of the risk of radioactive contamination.

The United States Air Force uses RTGs to power remote sensing stations for *Top-ROCC* and *Save-Igloo* radar systems predominantly located in Alaska.

In the past, small "plutonium cells" (very small ^{238}Pu-powered RTGs) were used in implanted heart pacemakers to ensure a very long "battery life". As of 2004 about 90 were still in use. When the wearer dies and if the generator is not removed before cremation, the device will be subject to great heat. The plutonium dioxide is a stable solid which is normally sintered in air at a temperature much higher than that used in the cremation of human remains, and so is unlikely to be dispersed.

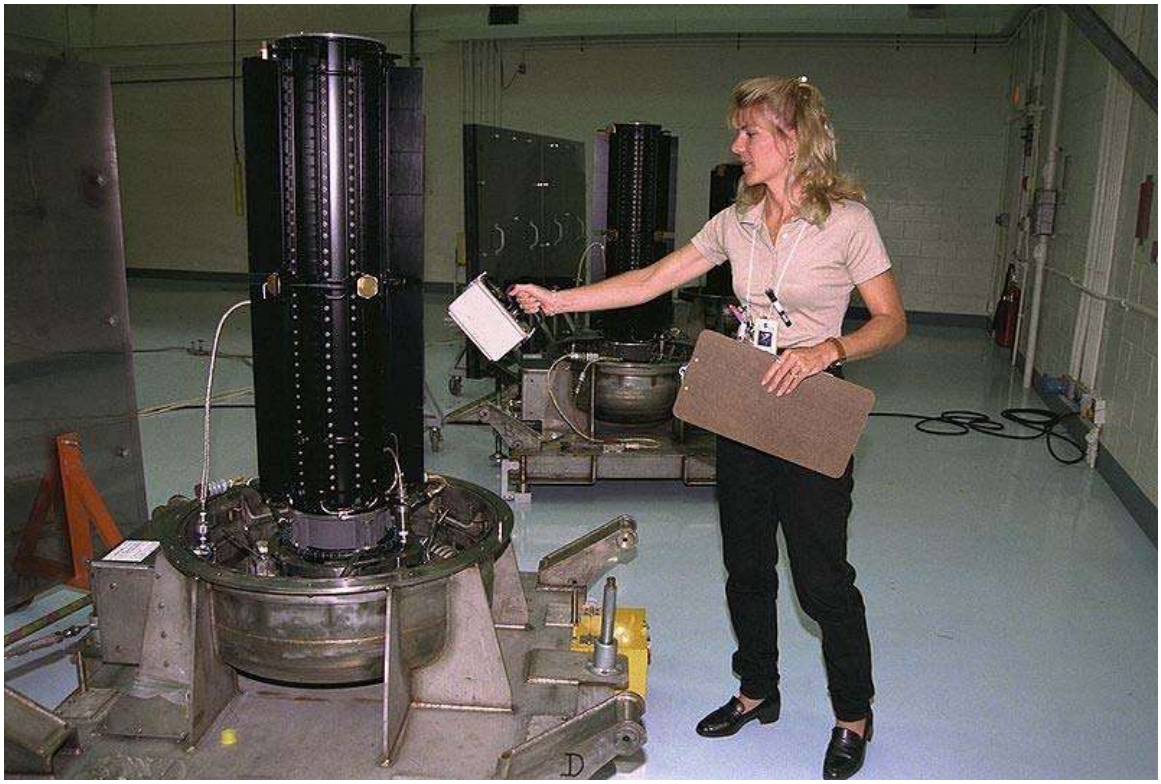
Although not strictly RTGs, similar units called radioisotope heater units are also used by various spacecraft including the Russian Lunokhod moon rover (using a Polonium 210 heat generator), and the Mars Exploration Rovers, Galileo and Cassini. These devices use small samples of radioactive material to produce heat directly, instead of electricity.

Design

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 which flows through the thermocouples to the heat sink, generating electricity in the process.

A thermocouple is a thermoelectric device that converts thermal energy directly into electrical energy using the Seebeck effect. It is made of two kinds of metal (or semiconductors) that can both conduct electricity. They are connected to each other in a closed loop. If the two junctions are at different temperatures, an electric current will flow in the loop.

Fuels



Inspection of Cassini spacecraft RTGs before launch

New Horizons in assembly hall

Criteria

The radioactive material used in RTGs must have several characteristics:

- It should produce high energy radiation. Energy release per decay is proportional to power production per mole. Alpha decays in general release about 10 times as much energy as the beta decay of strontium-90 or caesium-137.
- Radiation must be of a type easily absorbed and transferred into thermal radiation, preferably alpha radiation. Beta radiation can give off considerable amounts of gamma/X-ray radiation through bremsstrahlung secondary radiation production, thus requiring 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 half-life must be long enough that it will release energy at a relatively continuous rate for a reasonable amount of time. The amount of energy released per time (power) of a given quantity is inversely proportional to half-life. Twice the half-life will result in half the power 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.

Selection of isotopes

The first two criteria limit the number of possible fuels to fewer than 30 atomic isotopes within the entire table of nuclides. Plutonium-238, curium-244 and strontium-90 are the most often cited candidate isotopes, but other isotopes such as polonium-210, promethium-147, caesium-137, cerium-144, ruthenium-106, cobalt-60, curium-242 and thulium isotopes have also been studied.

^{238}Pu, ^{90}Sr

Plutonium-238 has the lowest shielding requirements and longest half-life. Only three candidate isotopes meet the last criterion (not all are listed above) and need less than 25 mm of lead shielding to keep radiation. ^{238}Pu (the best of these three) needs less than 2.5 mm, and in many cases no shielding is needed in a ^{238}Pu RTG, as the casing itself is adequate.

^{238}Pu has become the most widely used fuel for RTGs, in the form of plutonium(IV) oxide (PuO_2). ^{238}Pu has a half-life of 87.7 years, reasonable power density and exceptionally low gamma and neutron radiation levels. Some Russian terrestrial RTGs have used strontium-90; this isotope has a shorter half-life, much lower power density and produces gamma radiation, but is cheaper.

^{210}Po

Some prototype RTGs, first built in 1958 by USA Atomic Energy Commission, have used polonium-210. This isotope provides phenomenal power density due to its high radioactive activity, but has limited use because of its very short half-life of 138 days, again due to its high activity. A kilogram of pure ^{210}Po in the form of a cube would be about 48 mm (about 2 inches) on a side and emit about 140kW. The heat of melting is about 60kJ/kg, the heat of evaporation about 10 times larger. If there is no efficient cooling, the self heating power is sufficient for melting then partly vaporizing itself.

^{242}Cm, ^{244}Cm, ^{241}Am

Curium-242 and curium-244 have also been studied as well, but require heavy shielding from gamma and neutron radiation produced from spontaneous fission.

Americium-241 is a potential candidate isotope with a longer half-life than ^{238}Pu: ^{241}Am has a half-life of 432 years and could hypothetically power a device for centuries. However, the power density of ^{241}Am is only 1/4 that of ^{238}Pu, and ^{241}Am produces more

penetrating radiation through decay chain products than ^{238}Pu and needs about 18 mm worth of lead shielding. Even so, its shielding requirements in an RTG are the second lowest of all possible isotopes: only ^{238}Pu requires less. With a current global shortage of ^{238}Pu, a closer look is being given to ^{241}Am.

Life span

Soviet RTGs in dilapidated and vandalized condition, powered by Strontium-90 ^{90}Sr.

Most RTGs use ^{238}Pu which decays with a half-life of 87.7 years. RTGs using this material will therefore diminish in power output by 0.787% of their capacity per year. 23 years after production, such an RTG will have decreased in power by 16.6%, i.e. providing 83.4% of its initial output. Thus, with a starting capacity of 470 W, after 23 years it would have a capacity of 392 W. However, the bi-metallic thermocouples used to convert thermal energy into electrical energy degrade as well; at the beginning of 2001, the power generated by the Voyager RTGs had dropped to 315 W for Voyager 1 and to 319 W for Voyager 2. Therefore in early 2001, the thermocouples were working at about 80% of their original capacity.

This life span was of particular importance during the Galileo mission. Originally intended to launch in 1986, it was delayed by the Space Shuttle Challenger accident. Due to this unforeseen event the probe had to sit in storage for 4 years before launching in 1989. Subsequently, its RTGs had decayed somewhat, necessitating replanning the power budget for the mission.

Efficiency

RTGs use thermoelectric couples or "thermocouples" to convert heat from the radioactive material into electricity. Thermocouples, though very reliable and long-lasting, are very inefficient; efficiencies above 10% have never been achieved and most RTGs have

efficiencies between 3–7%. Thermoelectric materials in space missions to date have included silicon germanium alloys, lead telluride and tellurides of antimony, germanium and silver (TAGS). Studies have been done on improving efficiency by using other technologies to generate electricity from heat. Achieving higher efficiency would mean less radioactive fuel is needed to produce the same amount of power, and therefore a lighter overall weight for the generator. This is a critically important factor in spaceflight launch cost considerations.

A thermionic converter – an energy conversion device which relies on the principle of thermionic emission—can achieve efficiencies between 10–20%, but requires higher temperatures than those at which standard RTGs run. Some prototype ^{210}Po RTGs have used thermionics, and potentially other extremely radioactive isotopes could also provide power by this means, but short half-lives make these infeasible. Several space-bound nuclear reactors have used thermionics, but nuclear reactors are usually too heavy to use on most space probes.

Thermophotovoltaic cells work by the same principles as a photovoltaic cell, except that they convert infrared light emitted by a hot surface rather than visible light into electricity. Thermophotovoltaic cells have an efficiency slightly higher than thermocouples and can be overlaid on top of thermocouples, potentially doubling efficiency. Systems with radioisotope generators simulated by electric heaters have demonstrated efficiencies of 20%, but have not been tested with actual radioisotopes. Some theoretical thermophotovoltaic cell designs have efficiencies up to 30%, but these have yet to be built or confirmed. Thermophotovoltaic cells and silicon thermocouples degrade faster than thermocouples, especially in the presence of ionizing radiation.

Dynamic generators can provide power at more than 4 times the conversion efficiency of RTGs. NASA and DOE have been developing a next-generation radioisotope-fueled power source called the Stirling Radioisotope Generator (SRG) that uses free-piston Stirling engines coupled to linear alternators to convert heat to electricity. SRG prototypes demonstrated an average efficiency of 23%. Greater efficiency can be achieved by increasing the temperature ratio between the hot and cold ends of the generator. The use of non-contacting moving parts, non-degrading flexural bearings, and a lubrication-free and hermetically sealed environment have, in test units, demonstrated no appreciable degradation over years of operation. Experimental results demonstrate that an SRG could continue running for decades without maintenance. Vibration can be eliminated as a concern by implementation of dynamic balancing or use of dual-opposed piston movement. Potential applications of a Stirling radioisotope power system include exploration and science missions to deep-space, Mars, and the Moon.

Safety

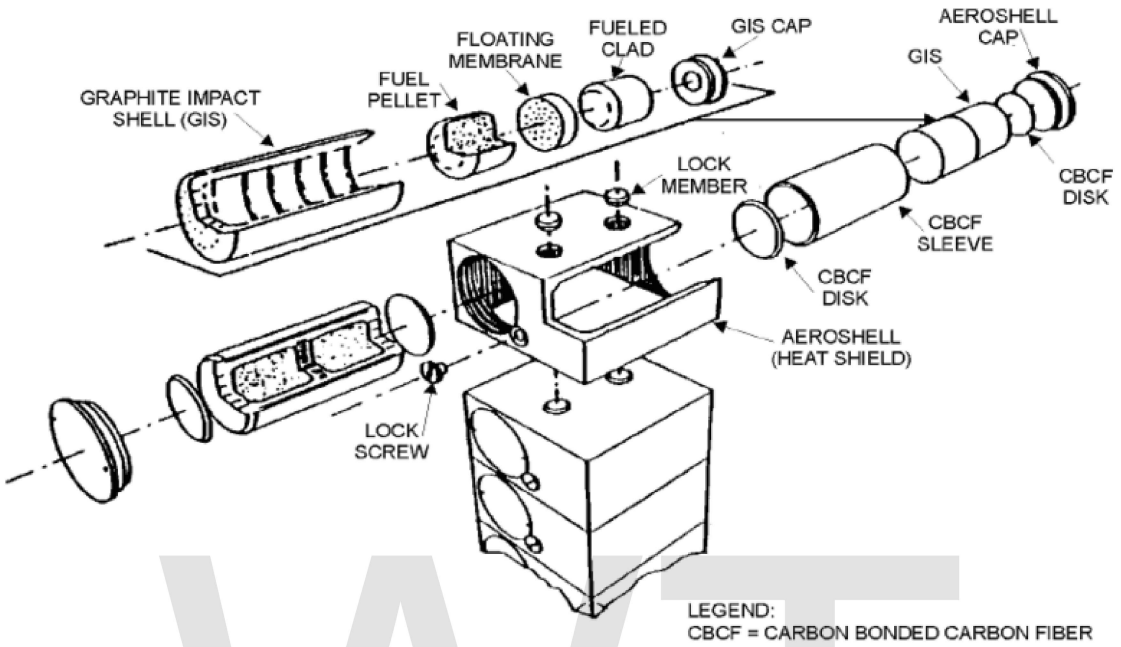


FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE

Diagram of a stack of general purpose heat source modules as used in RTGs

Radioactive contamination

RTGs may pose a risk of radioactive contamination: if the container holding the fuel leaks, the radioactive material may contaminate the environment.

For spacecraft, the main concern is that if an accident were to occur during launch or a subsequent passage of a spacecraft close to Earth, harmful material could be released into the atmosphere; and their use in spacecraft and elsewhere has attracted controversy.

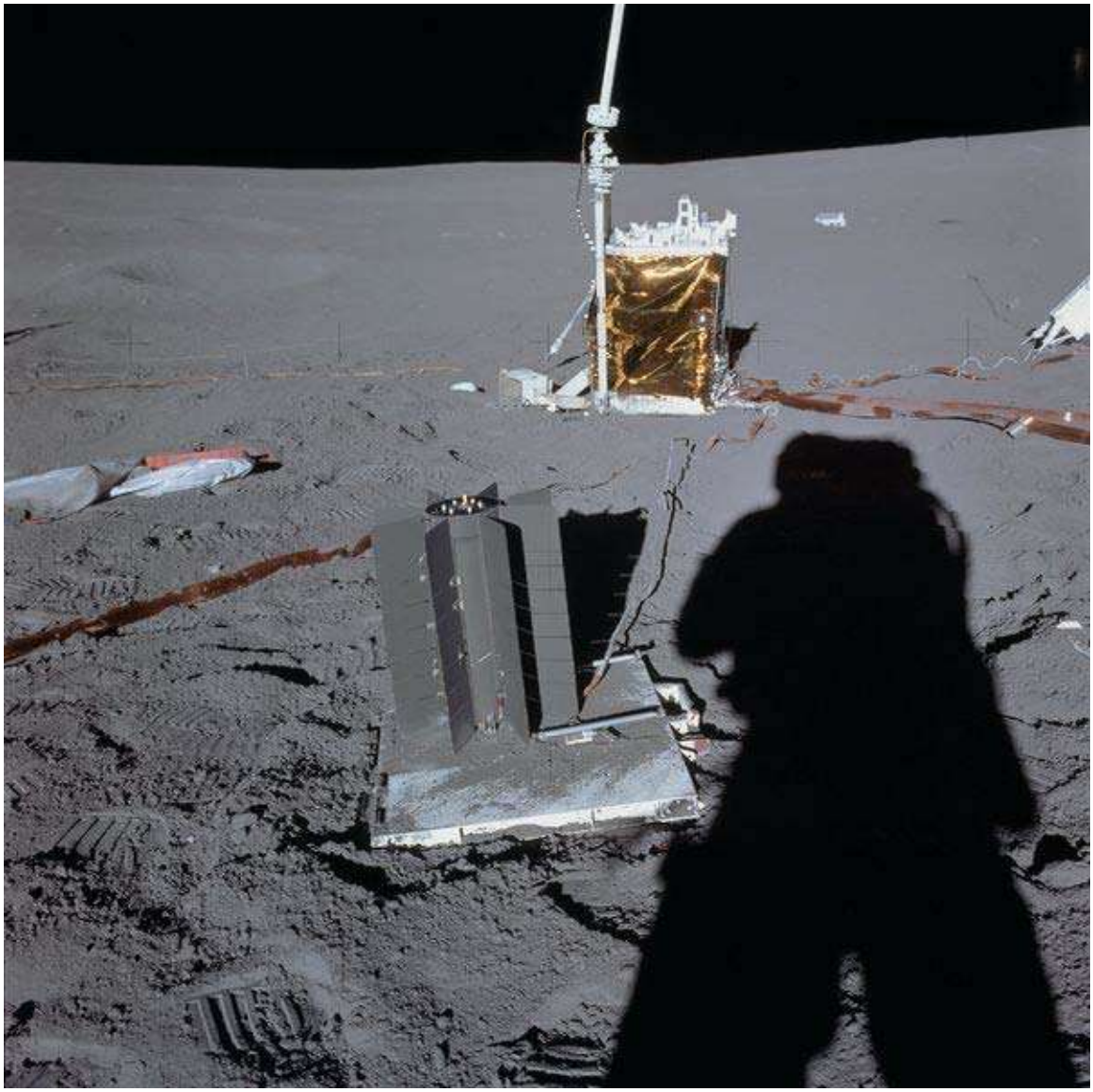
However, this event is not considered likely with current RTG cask designs. For instance, the environmental impact study for the Cassini-Huygens probe launched in 1997 estimated the probability of contamination accidents at various stages in the mission. The probability of an accident occurring which caused radioactive release from one or more of its 3 RTGs (or from its 129 radioisotope heater units) during the first 3.5 minutes following launch was estimated at 1 in 1,400; the chances of a release later in the ascent into orbit were 1 in 476; after that the likelihood of an accidental release fell off sharply to less than 1 in a million. If an accident which had the potential to cause contamination occurred during the launch phases (such as the spacecraft failing to reach orbit), the probability of contamination actually being caused by the RTGs was estimated at about 1 in 10. In any event, the launch was successful and Cassini-Huygens reached Saturn.

The plutonium 238 used in these RTGs has a half-life of 87.74 years, in contrast to the 24,110 year half-life of plutonium 239 used in nuclear weapons and reactors. A consequence of the shorter half life is that plutonium 238 is about 275 times more radioactive than plutonium 239 (i.e. 17.3 Ci/g compared to 0.063 Ci/g). For instance, 3.6 kg of plutonium 238 undergoes the same number of radioactive decays per second as 1 tonne of plutonium 239. Since the morbidity of the two isotopes in terms of absorbed radioactivity is almost exactly the same, plutonium 238 is around 275 times more toxic by weight than plutonium 239.

The alpha radiation emitted by either isotope will not penetrate the skin, but it can irradiate internal organs if plutonium is inhaled or ingested. Particularly at risk is the skeleton, the surface of which is likely to absorb the isotope, and the liver, where the isotope will collect and become concentrated.

There have been at least six known accidents involving RTG-powered spacecraft:

1. the first one was a launch failure on 21 April 1964 in which the U.S. Transit-5BN-3 navigation satellite failed to achieve orbit and burnt up on re-entry north of Madagascar. The 17,000 Ci (630 TBq) plutonium metal fuel in its SNAP-9a RTG was injected into the atmosphere over the Southern Hemisphere where it burnt up, and traces of plutonium 238 were detected in the area a few months later.
2. the second was the Nimbus B-1 weather satellite whose launch vehicle was deliberately destroyed shortly after launch on 21 May 1968 because of erratic trajectory. Launched from the Vandenberg Air Force Base, its SNAP-19 RTG containing relatively inert plutonium dioxide was recovered intact from the seabed in the Santa Barbara Channel five months later and no environmental contamination was detected.
3. two more were failures of Soviet Cosmos missions containing RTG-powered lunar rovers in 1969, both of which released radioactivity as they burnt up.
4. there were also five failures involving Soviet or Russian spacecraft which were carrying nuclear reactors rather than RTGs between 1973 and 1993.



A SNAP-27 RTG deployed by the astronauts of Apollo 14 identical to the one lost in the reentry of Apollo 13

5. the failure of the Apollo 13 mission in April 1970 meant that the Lunar Module reentered the atmosphere carrying an RTG and burnt up over Fiji. It carried a SNAP-27 RTG containing 44,500 curies (1,650 TBq) of plutonium dioxide which survived reentry into the Earth's atmosphere intact, as it was designed to do, the trajectory being arranged so that it would plunge into 6–9 kilometers of water in the Tonga trench in the Pacific Ocean. The absence of plutonium 238 contamination in atmospheric and seawater sampling confirmed the assumption that the cask is intact on the seabed. The cask is expected to contain the fuel for at least 10 half-lives (i.e. 870 years). The US Department of Energy has conducted seawater tests and determined that the graphite casing, which was designed to withstand reentry, is stable and no release of plutonium should occur. Subsequent

investigations have found no increase in the natural background radiation in the area. The Apollo 13 accident represents an extreme scenario due to the high re-entry velocities of the craft returning from cislunar space. This accident has served to validate the design of later-generation RTGs as highly safe.

To minimize the risk of the radioactive material being released, the fuel is stored in individual modular units with their own heat shielding. They are surrounded by a layer of iridium metal and encased in high-strength graphite blocks. These two materials are corrosion- and heat-resistant. Surrounding the graphite blocks is an aeroshell, designed to protect the entire assembly against the heat of reentering the Earth's atmosphere. The plutonium fuel is also stored in a ceramic form that is heat-resistant, minimising the risk of vaporization and aerosolization. The ceramic is also highly insoluble.

The most recent accident involving a spacecraft RTG was the failure of the Russian Mars 96 probe launch on 16 November 1996. The two RTGs onboard carried in total 200 g of plutonium and are assumed to have survived reentry (as they were designed to do). They are thought to now lie somewhere in a northeast-southwest running oval 320 km long by 80 km wide which is centred 32 km east of Iquique, Chile.

Many Beta-M RTGs produced by the Soviet Union to power lighthouses and beacons have become orphaned sources of radiation. Several of these units have been illegally dismantled for scrap metal resulting in the complete exposure of the Sr-90 source, fallen into the ocean, or have defective shielding due to poor design or physical damage. The US Department of Defense cooperative threat reduction program has expressed concern that material from the Beta-M RTGs can be used by terrorists to construct a dirty bomb.

NASA claims 28 U.S. space missions have safely flown radioisotope energy sources since 1961.

Nuclear fission

RTGs and nuclear power reactors use very different nuclear reactions. Nuclear power reactors use controlled nuclear fission. When an atom of U-235 or Pu-239 fuel fissions, neutrons are released that trigger additional fissions in a chain reaction at a rate that can be controlled with neutron absorbers. This is an advantage in that power can be varied with demand or shut off entirely for maintenance. It is also a disadvantage in that care is needed to avoid uncontrolled operation at dangerously high power levels.

Chain reactions do not occur in RTGs, so heat is produced at a fully predictable and steadily decreasing rate that depends only on the amount of fuel isotope and its half-life. An accidental power excursion is impossible. On the other hand, heat generation cannot be varied with demand or shut off when not needed. 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 prelaunch and early flight phases of a space mission.

There are no nuclear proliferation risks associated with plutonium-238. The same properties, primarily its high specific power, that make it a desirable RTG fuel make it useless in nuclear weapons. Pu-238 is fissionable, not fissile. It will occasionally spontaneously fission instead of undergoing alpha decay or it can be induced to fission with an external source of fast neutrons produced by various fusion reactions, but it cannot sustain the chain-reaction needed in a nuclear weapon fission primary. Because of its relatively high spontaneous fission rate compared with that of the fissile bomb fuel isotope Pu-239, its presence even as a contaminant would degrade performance by increasing the likelihood of a fizzle, a low yield caused by premature initiation of the chain reaction before optimum conditions have been reached. Any significant amounts of Pu-238 would also generate heat that would have to be continually dissipated until the bomb was used.

Pu-238 could in principle be used as the tertiary stage to boost the yield of a fission-fusion-fission (thermonuclear) weapon, but there is no reason to use it in this way. Natural or even depleted uranium will also fission with fast fusion neutrons, is far more readily available, and generates essentially no heat in storage.

Pu-238 could conceivably be used in a radiological or dirty bomb to exploit the significant public fear of plutonium.

RTG for interstellar probes

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. A RTG using Am-241 was proposed for this type of mission in 2002. This could support mission extensions up to 1000 years on the interstellar probe, because the power output would be more stable in the long-term than plutonium. 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 source (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).

Models

Space

MHW = Multi-Hundred Watt

Name & Model	Used On (# of RTGs per User)	Maximum output		Radio-isotope	Max fuel used (kg)	Mass (kg)
		Electrical (W)	Heat (W)			

ASRG*	in prototype phase, Discovery Program	~140 (2x70)	~500	^{238}Pu	~1	~34
MMRTG	in prototype phase, MSL	~110	~2000	^{238}Pu	~4	<45
GPHS-RTG	Cassini (3), New Horizons (1), Galileo (2), Ulysses (1)	300	4400	^{238}Pu	7.8	55.9–57.8
MHW-RTG	LES-8/9, Voyager 1 (3), Voyager 2 (3)	160	2400	^{238}Pu	~4.5	37.7
SNAP-3B	Transit-4A (1)	2.7	52.5	^{238}Pu	?	2.1
SNAP-9A	Transit 5BN1/2 (1)	25	525	^{238}Pu	~1	12.3
SNAP-19	Nimbus-3 (2), Pioneer 10 (4), Pioneer 11 (4)	40.3	525	^{238}Pu	~1	13.6
modified SNAP-19	Viking 1 (2), Viking 2 (2)	42.7	525	^{238}Pu	~1	15.2
SNAP-27	Apollo 12–17 ALSEP (1)	73	1480	^{238}Pu	3.8	20

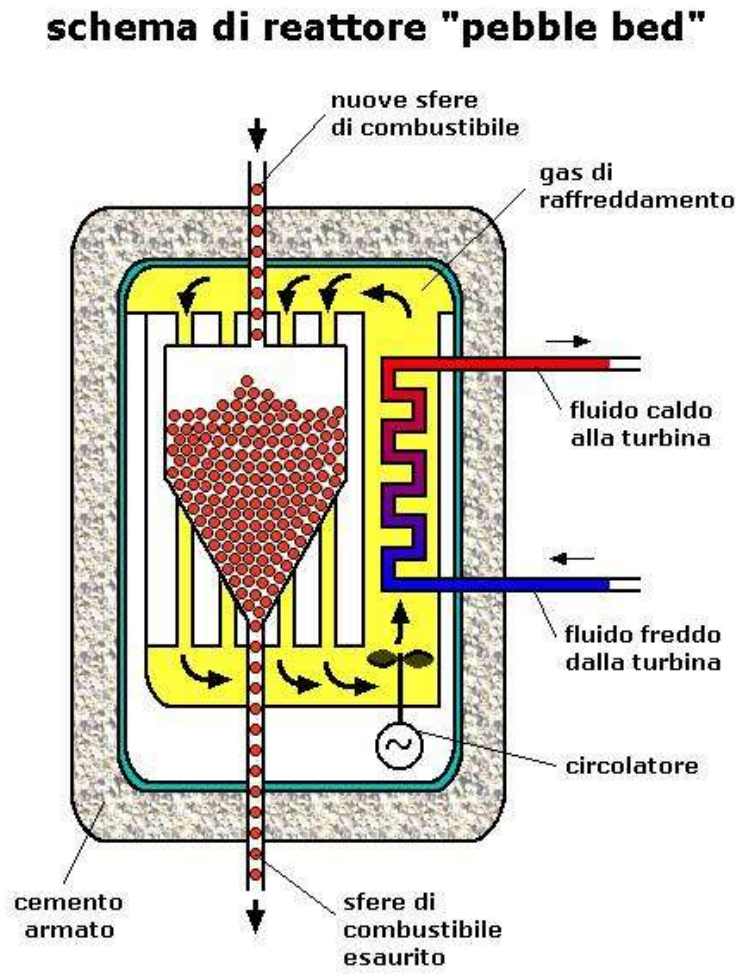
- The ASRG is in fact not an RTG; it is a stirling power device that runs on radioisotope

Terrestrial

Name & Model	Used On (# of RTGs per User)	Maximum output		Radioisotope	Max fuel used (kg)	Mass (kg)
		Electrical (W)	Heat (W)			
Beta-M	Obsolete Soviet unmanned lighthouses & beacons	10	230	^{90}Sr	0.26	560
Efir-MA		30	720	?	?	1250
IEU-1		80	2200	?	?	2500
IEU-2		14	580	?	?	600
Gong		18	315	?	?	600
Gorn		60	1100	^{90}Sr	?	1050
IEU-2M		20	690	?	?	600
IEU-1M		120 (180)	2200 (3300)	?	?	2(3) × 1050
Sentinel 25		9–20		$SrTiO_J$	0.54	907–1814
Sentinel 100F		53		Sr_2Ti0_4	1.77	1234

Chapter-7

Pebble Bed Reactor



Sketch of a pebble bed-reaktor.

Graphite Pebble for Reactor

The **pebble bed reactor** (**PBR**) is a graphite-moderated, gas-cooled, nuclear reactor. It is a type of very high temperature reactor (VHTR), one of the six classes of nuclear reactors in the Generation IV initiative. Like other VHTR designs, the PBR uses TRISO fuel particles, which allows for high outlet temperatures and passive safety.

The base of the PBR's design is the spherical fuel elements called *pebbles*. These tennis ball-sized pebbles are made of pyrolytic graphite (which acts as the moderator), and they contain thousands of micro fuel particles called TRISO particles. These TRISO fuel particles consist of a fissile material (such as ^{235}U) surrounded by a coated ceramic layer of silicon carbide for structural integrity and fission product containment. In the PBR, thousands of pebbles are amassed to create a reactor core, and are cooled by an inert or semi-inert gas such as helium, nitrogen or carbon dioxide.

This type of reactor is claimed to be passively safe; that is, it removes the need for redundant, active safety systems. Because the reactor is designed to handle high temperatures, it can cool by natural circulation and still survive in accident scenarios, which may raise the temperature of the reactor to 1,600 °C. Because of its design, its high temperatures allow higher thermal efficiencies than possible in traditional nuclear power plants (up to 50%) and has the additional feature that the gases do not dissolve contaminants or absorb neutrons as water does, so the core has less in the way of

radioactive fluids. A number of prototypes have been built. Active development continued in South Africa until 2010 as the PBMR design, and in China whose HTR-10 is the only prototype currently operating.

The technology was first developed in Germany but political and economic decisions were made to abandon the technology. In various forms, it is currently under development by MIT, University of California at Berkeley, the South African company PBMR, General Atomics (U.S.), the Dutch company Romawa B.V., Adams Atomic Engines , Idaho National Laboratory, and the Chinese company Huaneng.

One proposed design of a nuclear thermal rocket uses pebble-like fuel containers in a fluidized bed to achieve extremely high temperatures.

Pebble bed design

A pebble bed power plant combines a gas-cooled core and a novel packaging of the fuel that dramatically reduces complexity while improving safety.

The uranium, thorium or plutonium nuclear fuels are in the form of a ceramic (usually oxides or carbides) contained within spherical pebbles a little smaller than the size of a tennis ball and made of pyrolytic graphite, which acts as the primary neutron moderator. The pebble design is relatively simple, with each sphere consisting of the nuclear fuel, fission product barrier, and moderator (which in a traditional water reactor would all be different parts). Simply piling enough pebbles together in a critical geometry will allow for criticality.

The pebbles are held in a vessel, and an inert gas (such as helium, nitrogen or carbon dioxide) circulates through the spaces between the fuel pebbles to carry heat away from the reactor. If helium is used, because it is lighter than air, air can displace the helium if the reactor wall is breached. Pebble bed reactors need fire-prevention features to keep the graphite of the pebbles from burning in the presence of air although the flammability of the pebbles is disputed. Ideally, the heated gas is run directly through a turbine. However, if the gas from the primary coolant can be made radioactive by the neutrons in the reactor, or a fuel defect could still contaminate the power production equipment, it may be brought instead to a heat exchanger where it heats another gas or produces steam. The exhaust of the turbine is quite warm and may be used to warm buildings or chemical plants, or even run another heat engine.

Much of the cost of a conventional, water-cooled nuclear power plant is due to cooling system complexity. These are part of the safety of the overall design, and thus require extensive safety systems and redundant backups. A water-cooled reactor is generally dwarfed by the cooling systems attached to it. Additional issues are that the core irradiates the water with neutrons causing the water and impurities dissolved in it to become radioactive and that the high pressure piping in the primary side becomes embrittled and requires continual inspection and eventual replacement.

In contrast, a pebble bed reactor is gas cooled, sometimes at low pressures. The spaces between the pebbles form the "piping" in the core. Since there is no piping in the core and the coolant contains no hydrogen, embrittlement is not a failure concern. The preferred gas, helium, does not easily absorb neutrons or impurities. Therefore, compared to water, it is both more efficient and less likely to become radioactive.

A large advantage of the pebble bed reactor over a conventional light-water reactor is in operating at higher temperatures. The reactor can directly heat fluids for low pressure gas turbines. The high temperatures allow a turbine to extract more mechanical energy from the same amount of thermal energy; therefore, the power system uses less fuel per kilowatt-hour.

A significant technical advantage is that some designs are throttled by temperature, not by control rods. The reactor can be simpler because it does not need to operate well at the varying neutron profiles caused by partially-withdrawn control rods. For maintenance, many designs include control rods, called "absorbers" that are inserted through tubes in a neutron reflector around the reactor core. A reactor can change power quickly just by changing the coolant flow rate and can also change power more efficiently (say, for utility power) by changing the coolant density or heat capacity.

Pebble bed reactors are also capable of using fuel pebbles made from different fuels in the same basic design of reactor (though perhaps not at the same time). Proponents claim that some kinds of pebble-bed reactors should be able to use thorium, plutonium and natural unenriched uranium, as well as the customary enriched uranium. There is a project in progress to develop pebbles and reactors that use MOX fuel, that mixes uranium with plutonium from either reprocessed fuel rods or decommissioned nuclear weapons.

In most stationary pebble-bed reactor designs, fuel replacement is continuous. Instead of shutting down for weeks to replace fuel rods, pebbles are placed in a bin-shaped reactor. A pebble is recycled from the bottom to the top about ten times over a few years, and tested each time it is removed. When it is expended, it is removed to the nuclear waste area, and a new pebble inserted.

The core generates less power as its temperature rises, and therefore cannot have a criticality excursion when the machinery fails, it is power-limited or inherently self controlling due to Doppler broadening. At such low power densities, the reactor can be designed to lose more heat through its walls than it would generate. In order to generate much power it has to be cooled, and then the energy is extracted from the coolant.

Safety features

When the nuclear fuel increases in temperature, the rapid motion of the atoms in the fuel causes an effect known as Doppler broadening. The fuel then sees a wider range of relative neutron speeds. U^{238}, which forms the bulk of the uranium in the reactor, is much more likely to absorb fast or epithermal neutrons at higher temperatures. This reduces

the number of neutrons available to cause fission, and reduces the power of the reactor. Doppler broadening therefore creates a negative feedback because as fuel temperature increases, reactor power decreases. All reactors have reactivity feedback mechanisms, but the pebble bed reactor is designed so that this effect is very strong and does not depend on any kind of machinery or moving parts. Because of this, its passive cooling, and because the pebble bed reactor is designed for higher temperatures, the pebble bed reactor can passively reduce to a safe power level in an accident scenario. This is the main passive safety feature of the pebble bed reactor, and it makes the pebble bed design (as well as other very high temperature reactors) unique from conventional light water reactors which require active safety controls.

The reactor is cooled by an inert, fireproof gas, so it cannot have a steam explosion as a light-water reactor can. The coolant has no phase transitions—it starts as a gas and remains a gas. Similarly, the moderator is solid carbon; it does not act as a coolant, move, or have phase transitions (i.e., between liquid and gas) as the light water in conventional reactors does.

A pebble-bed reactor thus can have all of its supporting machinery fail, and the reactor will not crack, melt, explode or spew hazardous wastes. It simply goes up to a designed "idle" temperature, and stays there. In that state, the reactor vessel radiates heat, but the vessel and fuel spheres remain intact and undamaged. The machinery can be repaired or the fuel can be removed. These safety features were tested (and filmed) with the German AVR reactor. All the control rods were removed, and the coolant flow was halted. Afterward, the fuel balls were sampled and examined for damage and there was none.

PBRs are intentionally operated above the 250 °C annealing temperature of graphite, so that Wigner energy is not accumulated. This solves a problem discovered in an infamous accident, the Windscale fire. One of the reactors at the Windscale site in England (not a PBR) caught fire because of the release of energy stored as crystalline dislocations (Wigner energy) in the graphite. The dislocations are caused by neutron passage through the graphite. At Windscale, a program of regular annealing was put in place to release accumulated Wigner energy, but since the effect was not anticipated during the construction of the reactor, and since the reactor was cooled by ordinary air in an open cycle, the process could not be reliably controlled, and led to a fire.

The continuous refueling means that there is no excess reactivity in the core. Continuous refueling also permits continuous inspection of the fuel elements.

The design and reliability of the pebbles is crucial to the reactor's simplicity and safety, because they contain the nuclear fuel. The pebbles are the size of tennis balls. Each has a mass of 210 g, 9 g of which is uranium. It takes 380,000 to fuel a reactor of 120 MW_e. The pebbles are mostly high density graphite which keeps its structural stability at the maximum equilibrium temperature of the reactor. The graphite is the moderator for the reactor, and are strong containment vessels. In fact, most waste disposal plans for pebble-bed reactors plan to store the waste within the spent pebbles.

The pebbles contain about fifteen thousand TRISO particles. Each TRISO particle is the size of a grain of sand (0.5 mm), and contain a kernel of fissile material.

Containment

Most pebble-bed reactors contain many reinforcing levels of containment to prevent contact between the radioactive materials and the biosphere.

1. Most reactor systems are enclosed in a containment building designed to resist aircraft crashes and earthquakes.
2. The reactor itself is usually in a two-meter-thick-walled room with doors that can be closed, and cooling plenums that can be filled from any water source.
3. The reactor vessel is usually sealed.
4. Each pebble, within the vessel, is a 60 mm (2.36") hollow sphere of pyrolytic graphite.
5. A wrapping of fireproof silicon carbide
6. Low density porous pyrolytic carbon, high density nonporous pyrolytic carbon
7. The fission fuel is in the form of metal oxides or carbides

Pyrolytic graphite is the main structural material in these pebbles. It sublimates at 4000 °C, more than twice the design temperature of most reactors. It slows neutrons very effectively, is strong, inexpensive, and has a long history of use in reactors. Its strength and hardness come from anisotropic crystals of carbon. Pyrolytic graphite is also used, unreinforced, to construct missile reentry nose-cones and large solid rocket nozzles. It is nothing like the powdered mixture of flakes and waxes in pencil leads or lubricants.

Pyrolytic carbon can burn in air when the reaction is catalyzed by a hydroxyl radical (e.g., from water). Infamous examples include the accidents at Windscale and Chernobyl—both graphite-moderated reactors. Some engineers insist that pyrolytic carbon cannot burn in air, and cite engineering studies of high-density pyrolytic carbon in which water is excluded from the test. However, all pebble-bed reactors are cooled by inert gases to prevent fire. All pebble designs also have at least one layer of silicon carbide that serves as a fire break, as well as a seal.

The fissionables are also stable oxides or carbides of uranium, plutonium or thorium which have higher melting points than the metals. The oxides cannot burn in oxygen, but have some potential to react via diffusion with graphite at sufficiently high temperatures; the carbides might burn in oxygen but cannot react with graphite. The fission materials are about the size of a sand grain, so they are too heavy to be dispersed in the smoke of a fire.

The layer of porous pyrolytic graphite right next to the fissionable ceramic absorbs the radioactive gases (mostly xenon) emitted when the heavy elements split. Most reaction products remain metals, and reoxidize. A secondary benefit is that the gaseous fission products remain in the reactor to contribute their energy. The low density layer of graphite is surrounded by a higher-density nonporous layer of pyrolytic graphite. This is

another mechanical containment. The outer layer of each seed is surrounded by silicon carbide. The silicon carbide is nonporous, mechanically strong, very hard, and also cannot burn. However, at temperatures > 1300°C it starts to become destroyed in air, as experiments indicate. A drawback of SiC is its poor retention capability for certain metallic fission products, e.g. Ag, Cs and Ru, at high operation temperatures. Thus, He-temperatures of at maximum 750°C are recommended for current fuel, which however excludes applications as hydrogen generation by water splitting.

Pebble bed reactors do not have a pressure retaining containment (cost reasons). US-NRC has announced that the presence of a full containment as in all other types of reactors would facilitate PBR licensing.

Many authorities consider that pebbled radioactive waste is stable enough that it can be safely disposed of in geological storage thus used fuel pebbles could just be transported to disposal.

Production of fuel

Most authorities agree (2002) that German fuel-pebbles release about three orders of magnitude (1000 times) less radioactive gas than the U.S. equivalents.

All kernels are precipitated from a sol-gel, then washed, dried and calcined. U.S. kernels use uranium carbide, while German (AVR) kernels use uranium dioxide.

The precipitation of the pyrolytic graphite is by a mixture of argon, propylene and acetylene in a fluidized-bed coater at about 1275 °C. The fluidized bed moves gas up through the bed of particles, "floating" them against gravity. The high-density pyrolytic carbon uses less propylene than the porous gas-absorbing carbon. German particles are produced in a continuous process, from ultra-pure ingredients at higher temperatures and concentrations. U.S. coatings are produced in a batch process. Although the German carbon coatings are more porous, they are also more isotropic (same properties in all directions), and resist cracking better than the denser U.S. coatings.

The silicon carbide coating is precipitated from a mixture of hydrogen and methyltrichlorosilane. Again, the German process is continuous, while the U.S. process is batch-oriented. The more porous German pyrolytic carbon actually causes stronger bonding with the silicon carbide coat. The faster German coating process causes smaller, equiaxial grains in the silicon carbide. Therefore, it may be both less porous and less brittle.

Some experimental fuels plan to replace the silicon carbide with zirconium carbide to run at higher temperatures.

Criticisms of the reactor design

The most common criticism of pebble bed reactors is that encasing the fuel in combustible graphite poses a hazard. When the graphite burns, fuel material could potentially be carried away in smoke from the fire. Since burning graphite requires oxygen, the fuel kernels are coated with a layer of silicon carbide, and the reaction vessel is purged of oxygen. While silicon carbide is strong in abrasion and compression applications, it does not have the same strength against expansion and shear forces. Some fission products such as xenon-133 have a limited absorbance in carbon, and some fuel kernels could accumulate enough gas to rupture the silicon carbide layer. Even a cracked pebble will not burn without oxygen, but the fuel pebble may not be rotated out and inspected for months, leaving a window of vulnerability.

Some designs for pebble bed reactors lack a containment building, potentially making such reactors more vulnerable to outside attack and allowing radioactive material to spread in the case of an explosion. However, the current emphasis on reactor safety means that any new design will likely have a strong reinforced concrete containment structure. Also, any explosion would most likely be caused by an external factor, as the design does not suffer from the steam explosion-vulnerability of some water-cooled reactors.

Since the fuel is contained in graphite pebbles, the volume of radioactive waste is much greater, but contains about the same radioactivity when measured in becquerels per kilowatt-hour. The waste tends to be less hazardous and simpler to handle. Current US legislation requires all waste to be safely contained, therefore pebble bed reactors would increase existing storage problems. Defects in the production of pebbles may also cause problems. The radioactive waste must either be safely stored for many human generations, typically in a deep geological repository, reprocessed, transmuted in a different type of reactor, or disposed of by some other alternative method yet to be devised. The graphite pebbles are more difficult to reprocess due to their construction, which is not true of the fuel from other types of reactors. Proponents point out that this is a plus, as it is difficult to re-use pebble bed reactor waste for nuclear weapons.

Critics also often point out an accident in Germany in 1986, which involved a jammed pebble damaged by the reactor operators when they were attempting to dislodge it from a feeder tube. This accident released radiation into the surrounding area, and probably was one reason for the shutdown of the research program by the West German government.

In 2008, a report about safety aspects of the AVR reactor in Germany and some general features of pebble bed reactors have drawn attention. The claims are under contention. Main points of discussion are

- No possibility to place standard measurement equipment in the pebble bed core, i.e. pebble bed = black box
- Contamination of the cooling circuit with metallic fission products (Sr-90, Cs-137) due to the insufficient retention capabilities of fuel pebbles for metallic

fission products. Even modern fuel elements do not sufficiently retain strontium and cesium.
- improper temperatures in the core (more than 200 °C above calculated values)
- necessity of a pressure retaining containment
- unresolved problems with dust formation by pebble friction (dust acts as a mobile fission product carrier)

Moormann requests for safety reasons a limitation of average hot Helium temperatures to 800°C minus the uncertainty of the core temperatures (which is at present at about 200°C).

The pebble bed reactor has an advantage over traditional reactors in that the gases do not dissolve contaminants or absorb neutrons as water does, so the core has less in the way of radioactive fluids. However, the pebbles generate graphite particulates that can blow through the coolant loop and will absorb fission products if fission products escape the TRISO particles.

There is significantly less experience with production scale Pebble Bed Reactors than Light Water Reactors. As such, claims made by both proponents and detractors are more theory-based than based on practical experience.

History

The first suggestion for this type of reactor came in 1947 from Prof. Dr. Farrington Daniels at Oak Ridge, who also created the name "pebble bed reactor". The concept of a very simple, very safe reactor, with a commoditized nuclear fuel was developed by Professor Dr. Rudolf Schulten in the 1950s. The crucial breakthrough was the idea of combining fuel, structure, containment, and neutron moderator in a small, strong sphere. The concept was enabled by the realization that engineered forms of silicon carbide and pyrolytic carbon were quite strong, even at temperatures as high as 2000 °C (3600 °F). The natural geometry of close-packed spheres then provides the ducting (the spaces between the spheres) and spacing for the reactor core. To make the safety simple, the core has a low power density, about 1/30 the power density of a light water reactor.

Germany

AVR

AVR in Germany.

A 15 MW_e demonstration reactor, Arbeitsgemeinschaft Versuchsreaktor (AVR translates to *experimental reactor consortium*), was built at the Jülich Research Centre in Jülich, West Germany. The goal was to gain operational experience with a high-temperature gas-cooled reactor. The unit's first criticality was on August 26, 1966. The facility ran successfully for 21 years, and was decommissioned on December 1, 1988, in the wake of the Chernobyl disaster and operational problems. During removal of the fuel elements until 1998 it became obvious that the graphitic bottom reflector under the pebble bed core was broken during operation. Some hundred fuel elements remained stuck in the crack. During this examination it became also obvious that the AVR is the most heavily beta-contaminated (Strontium) nuclear installation worldwide and that this contamination is present in the worst form, as dust. In 1978 the AVR suffered from a water/steam ingress accident of 30 metric tons, which led to contamination of soil and groundwater by strontium and by tritium. The leak in the steam generator, leading to this accident, was probably caused by too high core temperatures. A re-examination of this accident, which is supposed to be much more severe than known, was announced by the local government in July, 2010.

The AVR was originally designed to breed Uranium^{233} from Thorium^{232}. Thorium^{232} is about 400 times as abundant in the Earth's crust as Uranium^{235}, and an effective thorium breeder reactor is therefore considered valuable technology. However, the fuel design of the AVR contained the fuel so well that the transmuted fuels were uneconomic to extract—it was cheaper to simply use natural uranium isotopes.

The AVR used helium coolant. Helium has a low neutron cross-section. Since few neutrons are absorbed, the coolant remains less radioactive. In fact, it is practical to route the primary coolant directly to power generation turbines. Even though the power generation used primary coolant, it is reported that the AVR exposed its personnel to less than 1/5 as much radiation as a typical light water reactor.

The fuel temperature instabilities during operation with locally far too high temperatures, mentioned above in the criticism section, resulted in a heavy contamination of the whole vessel by Cs-137 and Sr-90. Some contamination was also found in soil/groundwater under the reactor, as the German government confirmed in January, 2010. Thus the reactor vessel was filled with light concrete in order to fix the radioactive dust and in 2012 the reactor vessel of 2100 metric tons will be airlifted to an intermediate storage. There exists currently no dismantling method for the AVR vessel, but it is planned to develop some procedure during the next 60 years and to start with vessel dismantling at the end of the century. In the meantime, after transport of the AVR vessel into the intermediate storage, the reactor buildings will be dismantled and soil and groundwater will be decontaminated. AVR dismantling costs will exceed its construction costs by far. In August 2010 the German government published a new cost estimate for AVR dismantling, however without consideration of the vessel dismantling: An amount of 600 Mio € ($750 Mio) is now expected (200 Mio € more than in an estimate of 2006), which corresponds to 0.4 € ($0.55) per kWh of electricity generated by the AVR. Consideration of the unresolved problem of vessel dismantling is supposed to increase the total dismantling costs to more than 1 bn €. Construction costs of AVR were 115 Mio Deutschmark (1966), corresponding to a 2010 value of 180 Mio €. A separate containment was erected for dismantling purposes, as seen in the AVR-picture.

Thorium High Temperature Reactor

Following the experience with AVR, a full scale power station (the Thorium High Temperature Reactor or THTR-300 rated at 300 MW) was constructed, dedicated to using thorium as fuel. THTR-300 suffered a number of technical difficulties and owing to these and political events in Germany was closed after only four years of operation. One cause of the closing was an accident on 4 May 1986 with a limited release of the radioactive inventory into the environment. Although the radiological impact of this accident remained small it is of major relevance for PBR history: The release of radioactive dust was caused by a human error during a blockage of pebbles in a pipe. Trying to restart the pebble movement by increased gas flow led to mobilization of dust, always present in PBRs and—due to an erroneously open valve—to an unfiltered dust release into the environment.

In spite of the limited amount of radioactivity released (0.1 GBq Co^{60}, Cs^{137}, Pa^{233}), the THTR management tried to hide the accident, probably because this accident pointed to some specific problems of pebble bed reactors, i.e. pebble flow and radioactive dust. The management probably expected that the emission might not be detected due to the Chernobyl fallout happening just in the same time. However a whistle-blower informed authorities and public. The THTR management continued to charge the Chernobyl fallout for all the contamination in the surrounding, until the presence of Pa-233 in the vicinity of the THTR-300 was detected: Pa^{233} is not formed in Uranium reactors as Chernobyl, but only in thorium reactors. Thus, step by step, the THTR management reported the whole truth. The activity in the vicinity of the THTR-300 was finally found to result to 25 % from Chernobyl and to 75 % from THTR-300. The handling of this minor accident severely damaged the credibility of the German pebble bed community, and pebble bed reactors lost a lot of support in Germany.

The reactor also suffered from the unplanned high destruction rate of pebbles during normal operation and the resulting higher contamination of the containment and problems with compact pebble allocations which caused deformations to the control rods and of the side reflector arrangement. Ammonia, which was added to helium as lubricant for core rods moving in the pebble bed, was found to cause intolerable corrosion on metallic components. Pebble debris and graphite dust blocked some of the coolant channels in the bottom reflector, as was detected during fuel removal some years after final shut-down. A failure of insulation required frequent reactor shut down for inspection, because the insulation could not be repaired. Further metallic components of the hot gas duct failed September 1988, probably due to thermal fatigue induced by unexpected hot gas currents. This failure led to a long term shut-down for inspections. In August, 1989 the THTR company became almost bankrupt but was financially supported by the government. Because there was no longer any interest on THTR operation in industry and utilities and because of the unexpected high costs of THTR operation, the government decided to finish THTR operation end of September, 1989. From 1985 to 1989 the THTR-300 registered 16,410 operation hours and generated 2,891,000 MWh electrical power. This corresponds to 14 months of full power operation only.

At present THTR-300 is in the status of safestore, at least until 2027. Dismantling costs were estimated by the owner to about 430 Mio € (550 Mio $) but are expected to rise.

Current designs

Stationary

China

China has licensed the German technology and is actively developing a pebble bed reactor for power generation. The 10 megawatt prototype is called the **HTR-10**. It is a conventional helium-cooled, helium-turbine design. The program is at Tsinghua University in Beijing. The first 250-MW plant is scheduled to begin construction in 2009 and commissioning in 2013. There are firm plans for thirty such plants by 2020 (6

gigawatts). By 2050, China plans to deploy as much as 300 gigawatts of reactors of which PBMRs will be a major component. If PBMRs are successful, there may be a substantial number of reactors deployed. This may be the largest planned nuclear power deployment in history.

Tsinghua's program for Nuclear and New Energy technology also plans in 2006 to begin developing a system to use the high temperature gas of a pebble bed reactor to crack steam to produce hydrogen. The hydrogen could serve as fuel for hydrogen vehicles, reducing China's dependence on imported oil. Hydrogen can also be stored, and distribution by pipelines may be more efficient than conventional power lines.

South Africa

In June 2004, it was announced that a new PBMR would be built at Koeberg, South Africa by Eskom, the government-owned electrical utility. There is opposition to the PBMR from groups such as Koeberg Alert and Earthlife Africa, the latter of which has sued Eskom to stop development of the project. In September 2009 the demonstration power plant was postponed indefinitely. In February 2010 the South African government stopped funding of the PBMR because of a lack of customers and investors. PBMR Ltd started retrenchment procedures and stated the company intends to reduce staff by 75%.

On the September 17, 2010 the South African Minister of Public Enterprises announced the closure of the PBMR. The PMBR testing facility will likely be decommissioned and placed in a "care and maintenance mode" to protect the IP and the assets.

Mobile power systems

Pebble-bed reactors can theoretically power vehicles. There is no need for a heavy pressure vessel. The pebble bed heats gas that could directly drive a lightweight gas turbine.

Romawa

Romawa B.V., Netherlands, promotes a design called **Nereus**. This is a 24 MW_{th} reactor designed to fit in a container, and provide either a ship's power plant, isolated utilities, backup or peaking power. Romawa has neither produced nor is licensed to produce a nuclear reactor at this time.

It is basically a replacement for large diesel generators and gas turbines, but without fuel transportation expenses or air pollution. Because it requires external air, Romawa's design limits itself only to environments in which diesel engines can already be used.

Romawa's reactor heats helium, which in turn heats air that drives a conventional gas turbine that are well-developed for the aircraft and stationary power industries. The Romawa design reduces the size and expense of heat exchangers by operating at very high temperatures, and should therefore be small, inexpensive and efficient. The design

exhausts the air from the turbine, avoiding the large, inefficient, expensive low-temperature heat exchanger that would otherwise be necessary to cool the turbine's exhaust.

The air passing through the turbine never passes through the reactor, and is therefore never exposed to neutron flux, and therefore particles and gasses cannot become radioactive. The turbine is likewise not part of the primary loop, and uses air as its working fluid. The technology is therefore very standard. Most moving parts do not touch the primary loop, and therefore service should be relatively easy and safe. Romawa proposes two types of throttling. For vehicular power, they advocate a valve between the turbine and reactor while for efficient utility-style throttling, they advocate a system that reduces the pressure of helium in the coolant loop that connects the reactor to the turbine.

Romawa proposes a refueling and maintenance plan, based on "pool service." Users of large gas turbines customarily pool their repair resources to minimize expensive equipment, spares and training. By shipping entire reactors, Romawa plans to eliminate on-site service, and provide all service in one or a few centralized, specialized workshops.

Romawa has a business agreement with Adams Atomic Engines in the US, which promotes a similar reactor system.

Adams Atomic Engines

AAE's engine is completely self-contained, and therefore adapts to dusty, space, polar and underwater environments. The primary coolant loop uses nitrogen, and passes it directly though a conventional low-pressure gas turbine. Nitrogen is a major component of air, so a turbine designed for air should work well with very few changes. The gas turbine can be directly throttled using a technique discovered and patented by AAE, and due to the rapid ability of the turbine to change speeds, it can be used in applications where instead of the turbine's output being converted to electricity, the turbine itself could directly drive a mechanical device, for instance, a propeller aboard a ship.

AAE's engine is inherently safe, as the engine naturally shuts down due to Doppler broadening, stopping heat generation if the fuel in the engine gets too hot. (The engine also naturally shuts down in the event of a loss of coolant or a loss of coolant flow as well.) This phenomenon suggests that some form of heat removal in the engine, somewhat like a radiator in a motor vehicle, to remove residual heat from the closed engine cooling loop and gas circulation system could be beneficial for the design to work optimally. This could be a sea-water-cooled heat exchanger aboard a ship, while a stationary engine might use a small forced-draft or natural-draft cooling tower, and in a very small version of the engine, some form of passive heat rejection system might be optimal for use, for instance, a passive metal heat sink cooled by convection of air, or passive heat pipes. Further, the heat rejected could be used for process heating, district heating and cooling, or desalinization.

AAE held the U.S. patent on direct throttling of a closed-cycle gas turbine system, U.S. Patent 5,309,492, including those turbines driven by atomic energy or other power sources. Prior to this advance in the art, closed cycle gas turbines were throttled indirectly, either by varying the pressure of the working gas (inventory control) or by bypassing the turbine completely (bypass control); direct throttle control will allow a greater degree of responsiveness from the turbine to rapidly changing conditions. As of 2009, Adams Atomic Engines has not yet produced an atomic engine, but developments within the United States indicate that there is increased interest in high-temperature gas reactors due to the near-term construction of the U.S. Next Generation Nuclear Plant by the U.S. Department of Energy, and U.S. collaboration with the South African developers of the Pebble Bed Modular Reactor.

Other issues

Both Romawa and AAE plan to use neutron reflectors (graphite) and radiation shields (heavy metals) that are bins of balls. This means that the shielding need not have complex ducting to cool it.

Chapter-8

Advanced Boiling Water Reactor

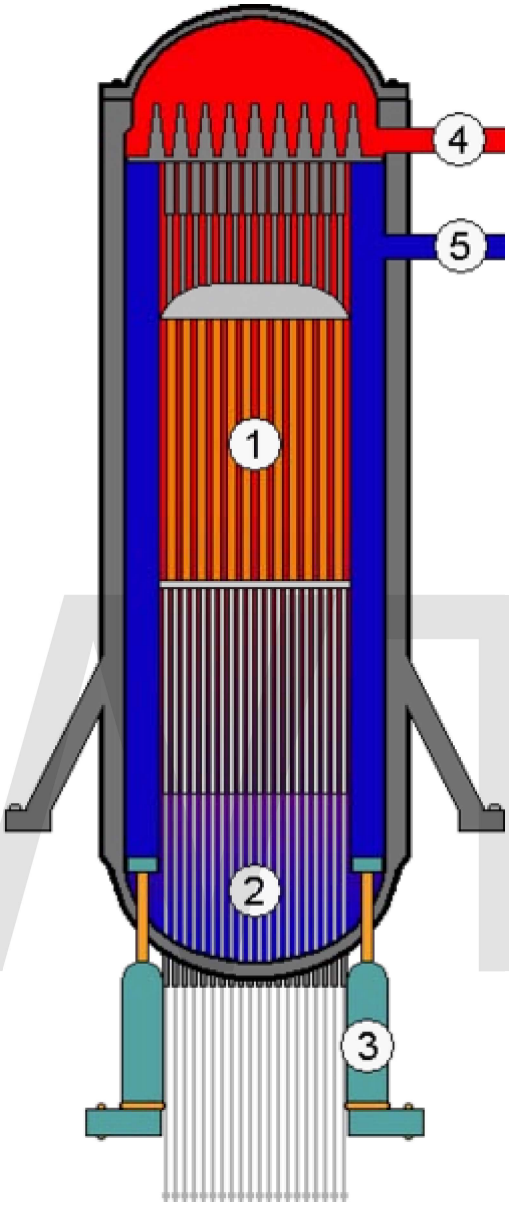
Construction of two ABWRs at Lungmen Nuclear Power Plant in Taiwan

The **advanced boiling water reactor (ABWR)** is a Generation III boiling water reactor. The ABWR is currently offered by GE Hitachi Nuclear Energy. The ABWR generates electrical power by using steam to power a turbine connected to a generator; the steam is boiled from water using heat generated by fission reactions within nuclear fuel.

Boiling water reactors (BWRs) are the second most common form of light water reactor with a design that is simpler and less costly to build, but bigger and slightly less efficient, than the classic pressurized water reactor (PWR). The ABWR is the present state of the art in boiling water reactors, and is the first Generation III reactor design to be fully built, with several reactors complete and operating. The first reactors were built on time and under budget in Japan, with several more nearing completion in that nation and in Taiwan. Several ABWRs are on order in the United States, including two reactors at the South Texas Project site.

The standard ABWR plant design has a net output of about 1350 MWe (3926 MWth); however, GE Hitachi Nuclear Energy also offers a design with greater electrical output. It has also been certified as a final design in final form by the U.S. Nuclear Regulatory Commission, meaning that its performance, efficiency, output, and safety have already been verified, making it bureaucratically easier to build it rather than a non-certified design.

Overview of the design



Pressure vessel from the ABWR. 1: Reactor core 2: Control rods 3: Internal Water Pump 4: Steam pipeline to the Turbine generator 5: Cooling water flow to the core

While GE Hitachi's ESBWR represents a somewhat major departure from the present standard BWR design with an emphasis on full passive nuclear safety and an entirely different approach to power regulation (natural circulation rather than circulation pumps), the ABWR represents a more evolutionary route for the BWR family, with numerous changes and improvements to the standard BWR design.

Major areas of improvement include:

- The addition of reactor internal pumps (RIPs) to the bottom of the RPV (reactor pressure vessel) - 10 in total - which achieve improved performance while eliminating large-diameter and complex piping structures at the bottom of the RPV (e.g. the recirculation loop found in earlier BWR models). Only the RIP motor is located outside of the RPV in the ABWR. According to the Tier 1 Design Control Document (which is the officially certified Nuclear Regulatory Commission document generally describing the design of the plant), each RIP has a capacity of 6912 m^3/h at nominal capacity and several can be turned off with the reactor at capacity.
- The control rod adjustment capabilities have been supplemented with the addition of the electro-hydraulic Fine Motion Control Rod Drive (FMCRD), allowing for fine position adjustment, while not losing the reliability or redundancy of traditional hydraulic systems which are designed to accomplish rapid shutdown in 2.80 seconds from receipt of an initiating signal, or ARI (alternate rod insertion) in a greater but still insignificant time period. The FMCRD also improves defence-in-depth in the event of primary hydraulic and ARI contingencies.
- A fully digital Reactor Protection System (with redundant digital backups as well as redundant manual backups) ensures a high level of reliability and simplification for safety condition detection and response. Standard BWR half plus half (2 out of 4) rapid shutdown logic ensures that nuisance rapid shutdowns are not triggered by single instrument failures. RPS can trigger ARI, FMCRD rod run-in, as well as SLCS (standby liquid control system) actuation in the event these capabilities and systems are necessary.
- Fully digital reactor controls (with redundant digital backup and redundant manual backups) allow the control room to easily and rapidly control plant operations and processes. Separate, redundant critical and non-critical digital multiplexing buses allow for reliability and diversity of instrumentation and control.
    - In particular, the reactor can both "fly on autopilot" and also "take off and land on autopilot" or go critical and ascend to power using automatic systems only and do a standard shutdown using automatic systems only. Of course, human operators remain essential to reactor control, but much of the busy-work of bringing the reactor to power and descending from power can be automated at operator discretion.
- The Reactor Water Cleanup System has been enhanced to ensure prompt and complete removal of soluble neutron absorbers injected by the SLCS in an anticipated transient without scram (ATWS) contingency. This decreases operator reticence to utilize the SLCS prior to using other channels to mitigate an ATWS. Indeed, the SLCS is now able to be automatically actuated by the RPS if necessary in the ABWR, as prompt cleanup of soluble neutron absorbers can be achieved.
- The Emergency Core Cooling System (ECCS) has been improved in many areas, providing a very high level of defence-in-depth against accidents, contingencies, and incidents.

- The overall system has been divided up into 3 divisions; each division is capable - by itself - of reacting to the maximally contingent Limiting Fault/Design Basis Accident (DBA) and terminating the accident prior to core uncovery, even in the event of loss of offsite power and loss of proper feedwater. Previous BWRs had 2 divisions, and uncovery (but no core damage) was predicted to occur for a short time in the event of a severe accident, prior to ECCS response.
- Eighteen SORVs (safety overpressure relief valves), ten of which are part of the ADS (automatic depressurization system), ensure that RPV overpressure events are quickly mitigated, and that if necessary, that the reactor can be depressurized rapidly to a level where low pressure core flooder (LPCF, the high-capacity mode of the residual heat removal system, which replaces the LPCI and LPCS in previous BWR models) can be used.
- Further, LPCF can inject against much higher RPV pressures, providing an increased level of safety in the event of intermediate-sized breaks, which could be small enough to result in slow natural depressurization but could be large enough to result in high pressure corespray/coolant injection systems' capacities for response being overwhelmed by the size of the break.
- Though the Class 1E (life safety critical) power bus is still powered by 3 highly-reliable emergency diesel generators that are safety rated, an additional Plant Investment Protection power bus using a combustion gas turbine is located on-site to generate electricity to provide defence in depth against station blackout contingencies as well as to power important but non-safety critical systems in the event of a loss of offsite power, as well as to start the plant in the event grid black start is needed. Additional diesel firewater pumps may be tied into the plant's service water system too, to enhance cooling capabilities.
- Though one division of the ECCS does not have high pressure flood (HPCF) capacities, there exists a steam-driven, safety-rated reactor core isolation cooling (RCIC) turbopump outside of the 3 primary ECCS divisions, that is high-pressure rated and has extensive battery backup for its instrumentation and control systems, ensuring cooling is maintained even in the event of a full station blackout with failure of all 3 emergency diesel generators, the combustion gas turbine, primary battery backup, and the diesel firewater pumps.
- There exists an extremely thick basalt fiber reinforced concrete (BiMAC) pad under the RPV that will both catch and hold any heated fluids that might fall on that pad in extraordinarily contingent situations. In addition, there are several valves within the weir wall (the wall separating the wetwell from the drywell) that are squib-actuated and can perform an orderly flood of the BiMAC pad using the wetwell's water supply, ensuring cooling of that area even with the failure of standard mitigatory systems (e.g. overhead flood capabilities).

- The containment has been significantly improved over old BWR types. Like the old types, it is of the pressure suppression type, designed to handle evolved steam in the event of a transient, incident, or accident by routing the steam using pipes that go into a pool of water, called the wetwell (or torus), the low temperature of which will condense the steam back into liquid water. This will keep pressure low. Notably, the typical ABWR containment has numerous hardened layers between the interior of the primary containment and the outer shield wall, and is cubical in shape. One major enhancement is that the reactor has a standard safe shutdown earthquake acceleration of .2 G (slightly less than 2 m/s^2); further, it is designed to withstand a tornado of Old Fujita Scale 6, with > 320 mph wind). Seismic hardening is possible in earthquake-prone areas and has been done at the Lungmen facility in Taiwan which has been hardened up .3 G (slightly less than 3 m/s^2) in any direction.
- The ABWR is designed for a lifetime of at least 60 years, though operation beyond that 60 year point will certainly be possible unless safety limits within the expensive to replace reactor pressure vessel is reached. The comparatively simple design of the ABWR also means that no expensive steam generators need to be replaced, either, decreasing total cost of operation.
- According to GE, only after at least 30 million years does the core damage frequency (CDF) of the ABWR reach 50% (e.g. 3E-7), better than both the AP1000 and the European Pressurised Reactor designs.

The RPV and NS^3 have significant improvements, such as the substitution of Internal recirculation pumps improve reliability and performance, eliminating complex Internal recirculation pumps inside of the reactor pressure vessel (RPV) are a major improvement over previous GE reactor plant designs (BWR/6 and prior). These pumps are powered by wet-rotor motors with the housings connected to the bottom of the RPV and eliminating large diameter external recirculation pipes that are possible leakage paths. Construction costs are also reduced. The 10 internal recirculation pumps are located at the bottom of the annulus downcomer region (i.e., between the core shroud and the inside surface of the RPV).

Even though BWRs can operate using only the available natural recirculation thermal pumping head without forced recirculation flow, forced flow is desirable in order to increase the available output from the reactor and as a convenient method to change the reactor output by changing the flow.

Prior to the ABWR, all large commercial nuclear steam supply systems provided by GE from the BWR/3 through the BWR/6 designs used jet pump recirculation systems. These systems have two large recirculation pumps (each up to 9000 Hp) located outside of the reactor pressure vessel (RPV). Each external recirculation pump takes a suction from the bottom of the annulus downcomer region through a large diameter nozzle and discharges through multiple jet pumps inside of the RPV in the annulus downcomer region. There is one nozzle per jet pump for the discharge back into the RPV and the external headers supplying these nozzles. Isolation valves are provided for each of the two external recirculation pumps. In the event of a pipe rupture close to the RPV, those isolation

valves will be ineffective and the top region of the reactor may not be covered with water. With all of the jet pumps intact after this design basis accident (DBA)a minimum of two thirds (2/3) of the core will remain covered in water. Calculations indicate that fuel failure would be averted by "steam cooling" wherein the boiling of water in the lower core region will produce mixed quality steam that will absorb heat from the upper core region.

Consequently, internal recirculation pumps eliminate all of the jet pumps (typically 10), all of the external piping, the isolation valves and the large diameter nozzles that penetrated the RPV and needed to suction water from and return it to the RPV. This design therefore reduces the worst leak below the core region to effectively equivalent to a 2-inch-diameter (51 mm) leak. The conventional BWR3-BWR6 product line has an analogous potential leak of 24 or more inches in diameter. A major benefit of this design is that it greatly reduces the flow capacity required of the emergency core cooling systems (ECCS). In the event of a fuel failure, a specially constructed basaltic floor with passive cooling features will terminate the flow of melted core before it breaches primary containment.

The first reactors to use internal recirculation pumps were designed by ASEA-Atom (now Westinghouse Electric Company by way of mergers and buyouts, which is owned by Toshiba) and built in Sweden. These plants have operated very successfully for many years.

The internal pumps reduce the required pumping power for the same flow to about half that required with the jet pump system with external recirculation loops. Thus, in addition to the safety and cost improvements due to eliminating the piping, the overall plant thermal efficiency is increased. Eliminating the external recirculation piping also reduces occupational radiation exposure to personnel during maintenance.

A nice operational feature in the ABWR design is electric fine motion control rod drives, first used in the BWRs of AEG (later Kraftwerk Union AG, now AREVA). Older BWRs use a hydraulic locking piston system to move the control rods in six-inch increments. Additionally the fine motion control rod design greatly enhances positive actual control rod position and similarly reduces the risk of a control rod drive accident to the point that no velocity limiter is required at the base of the cruciform control rod blades.

The ABWR is fully automated in response to a loss-of-coolant accident (LOCA), and operator action is not required for 3 days. After 3 days the operators must replenish ECCS water supplies. These and other improvements make the plant significantly safer than previous reactors.

As of December 2006, four ABWRs were in operation in Japan: Kashiwazaki-Kariwa units 6 and 7, which opened in 1996 and 1997, Hamaoka unit 5, opened 2004 having started construction in 2000, and Shika 2 commenced commercial operations on March 15, 2006. Another two, identical to the Kashiwazaki-Kariwa reactors, were nearing completion at Lungmen in Taiwan, and one more (Shimane Nuclear Power Plant 3) had

just commenced construction in Japan, with major siteworks to start in 2008 and completion in 2011. Plans for at least six other ABWRs in Japan have been postponed, cancelled, or converted to other reactor types, but three of these (Higashidōri 1 and 2 and Ohma) were still listed as *on order* by the utilities, with completion dates of 2012 or later.

Several ABWRs are proposed for construction in the United States under the Nuclear Power 2010 Program. However these proposals face fierce competition from more recent designs such as the ESBWR (Economic Simplified BWR, a generation III+ reactor also from GE) and the AP1000 (Advanced, Passive, 1000MWe, from Westinghouse). These designs take passive safety features even further than the ABWR does, as do more revolutionary designs such as the pebble bed modular reactor. However, the US market incentive for construction of an ABWR is that the Nuclear Regulatory Commission (NRC) approved the ABWR design in 1997 and construction would have a smaller regulatory burden for approval; hence ABWRs could be constructed faster than other designs pending approval. There are no ESBWR design reactors in service world wide and the ESBWR design is pending approval by the NRC. The ESBWR is a natural circulation plant with features to be resolved such as the power oscillations expected to the local power induced thermal hydraulic instabilities during initial startup.

On June 19, 2006 NRG Energy filed a Letter Of Intent with the Nuclear Regulatory Commission to build two 1358 MWe ABWRs at the South Texas Project site. On September 25, 2007, NRG Energy and CPS Energy submitted a Construction and Operations License (COL) request for these plants with the NRC. NRG Energy is a merchant generator and CPS Energy is the nation's largest municipally owned utility.

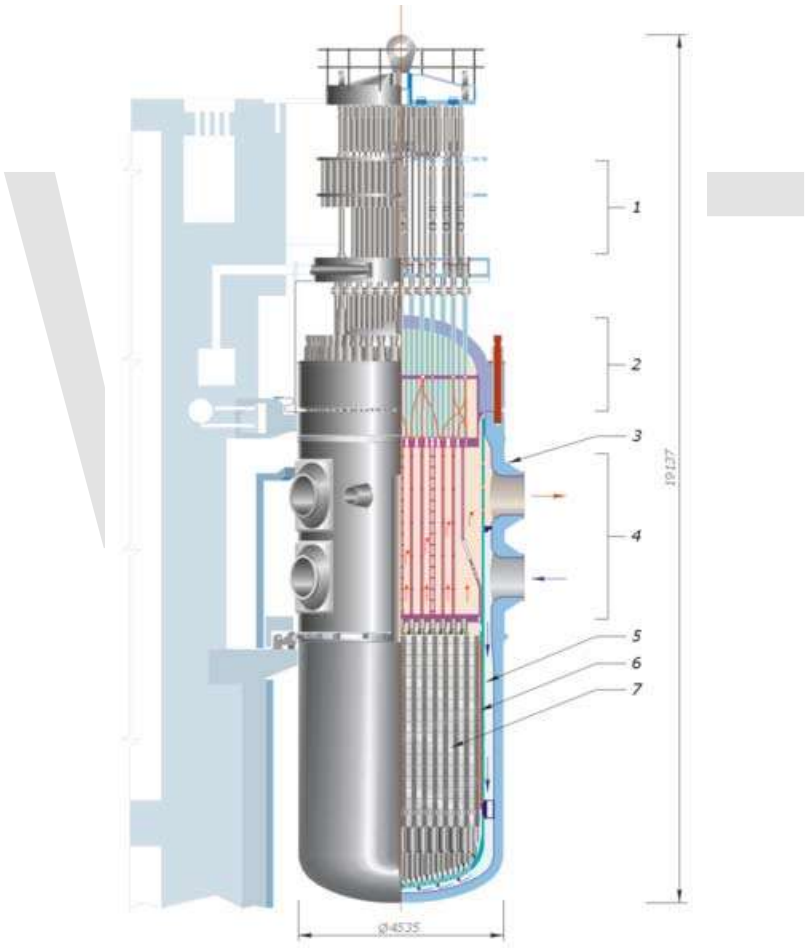
Deployments

Plant Name	Number of Reactors	Rated Capacity	Location	Operator	Construction Started	Year Completed (First criticality)	Cost (USD)	Notes
Kashiwazaki-Kariwa Nuclear Power Plant	2	1356MW	Kashiwazaki, Japan	TEPCO	1993	1997		First Installation
Shika Nuclear Power Plant	1	1358MW	Shika, Japan	Hokuriku Electric Power Company		2006		
Hamaoka Nuclear Power Plant	1	1267MW	Omaezaki, Japan	Chuden	2000	2005		
Shimane Nuclear Power Plant	1	1373MW	Matsue, Japan	Chugoku Electric Power Company		2012		
Lungmen Nuclear Power Plant	2	1350MW	Gongliao Township, Republic of China	Taiwan Power Company	1997	2011	$9.2 Billion	Under Construction, Completion Est.

								December 2011
Higashidōri Nuclear Power Plant	3	1385MW	Higashidōri, Japan	Tohoku Electric Power and TEPCO	2010	Est 2017		All units Under Construction
Ōma Nuclear Power Plant	1	1383MW	Ōma, Japan	J-Power		Est 2014		Under Construction, First nuclear plant for J-Power
South Texas Project	2	1358MW	Bay City, United States	NRG Energy, TEPCO and CPS Energy			$14 Billion	Awaiting NRC Approval; First deployment to United States

Chapter-9

VVER



WWER-1000 (or VVER-1000 as a direct transliteration of Russian ВВЭР-1000) is a 1000 MW Russian nuclear power reactor of PWR type.

The **VVER** (From Russian: Водо-водяной энергетический реактор; transliterates as *Vodo-Vodyanoi Energetichesky Reactor*; *Water-Water Energetic Reactor*) is a series of pressurised water reactors (PWRs) originally developed by the Soviet Union, and now Russia. Power output ranges from 440 MWe to 1200 MWe with the latest Russian

development of the design. VVER power stations are used by Armenia, Bulgaria, China, Czech Republic, Finland, former East Germany, Hungary, India, Iran, Slovakia, Ukraine, and the Russian Federation.

History

The earliest VVERs were built before 1970. The VVER-440 Model V230 is the most common design, delivering 440 MW of electrical power. The V230 employs six primary coolant loops each with a horizontal steam generator. A modified version of VVER-440, Model V213, was a product of the first nuclear safety standards adopted by Soviet designers. This model includes added emergency core cooling and auxiliary feedwater systems as well as upgraded accident localization systems.

The larger VVER-1000 was developed after 1975 and is a four-loop system housed in a containment-type structure with a spray steam suppression system. VVER reactor designs have been elaborated to incorporate automatic control, passive safety and containment systems associated with Western third generation nuclear reactors.

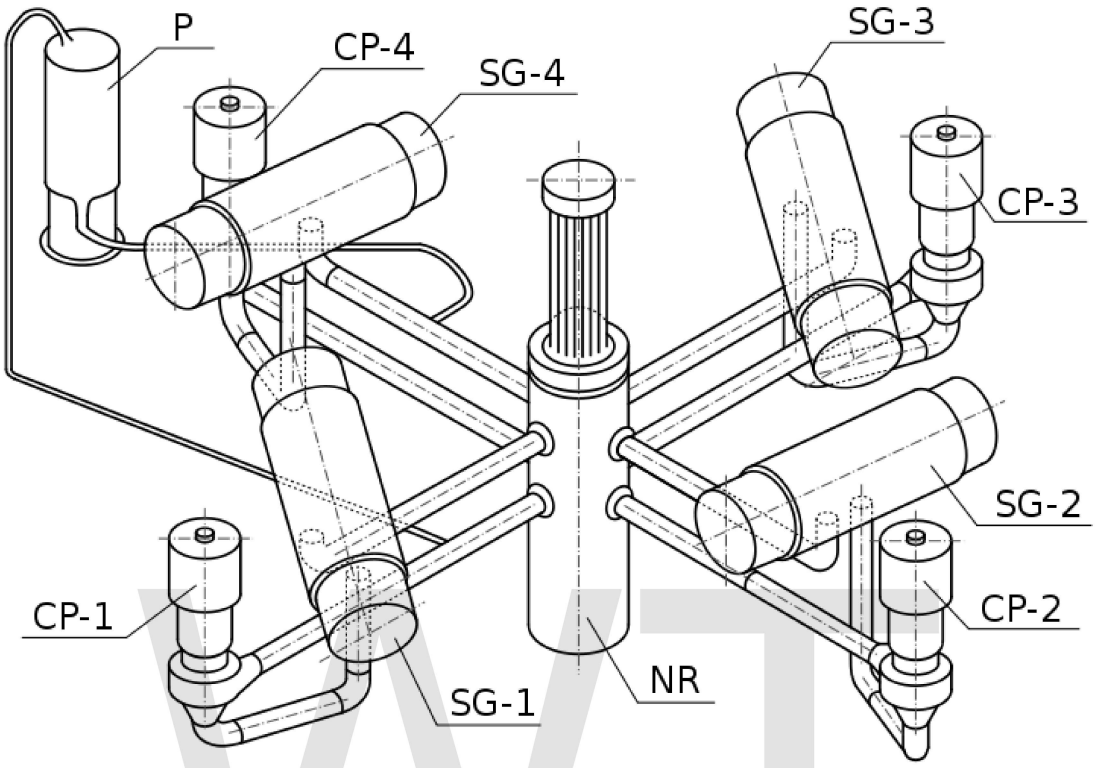
VVER series nuclear reactors were also scaled down in size and used by the Soviet Navy and RFAS nuclear submarine fleet as well as by surface warships.

Design

The Russian abbreviation VVER stands for water-cooled, water-moderated energy reactor. This describes the pressurized water reactor design. Reactor fuel rods are fully immersed in water kept at 15 MPa of pressure so that it does not boil at normal (220 to over 300 °C) operating temperatures. Water in the reactor serves both as a coolant and a moderator which is an important safety feature. Should coolant circulation fail the neutron moderation effect of the water diminishes, reducing reaction intensity and compensating for loss of cooling, a condition known as negative void coefficient. The whole reactor is encased in a massive steel pressure shell. Fuel is low enriched (ca. 2.4–4.4% ^{235}U) uranium dioxide (UO_2) or equivalent pressed into pellets and assembled into fuel rods.

Intensity of the nuclear reaction is controlled by control rods that can be inserted into the reactor from above. These rods are made from a neutron absorbing material and depending on depth of insertion hinder the chain reaction. If there is an emergency, a reactor shutdown can be performed by full insertion of the control rods into the core.

Primary cooling circuit



Stereometric scheme of primary cooling circuit VVER-1000

As stated above, water in the primary circuit is kept under constant pressure to avoid boiling. Since the water transfers all the heat from the core and is irradiated, integrity of this circuit is most crucial. In the circuit four subsystems can be distinguished:

1. Reactor: Water flows through fuel rod assemblies and is heated by the nuclear chain reaction.
2. Volume compensator: To keep the water under constant but controlled pressure, the volume compensator regulates pressure employing self-regulation of saturated steam-water interface and by means of electrical heating and relief valves.
3. Steam Generator: In the steam generator, heat from primary coolant water is used to boil water in the secondary circuit.
4. Pump: The pump ensures proper circulation of the water through the circuit.

To ensure safety primary components are redundant.

Secondary circuit and electrical output

The secondary circuit also consists of different subsystems:

1. Steam Generator: Secondary water is boiled taking heat from the primary circuit. Before entering the turbine remaining water is separated from the steam so that the steam is dry.
2. Turbine: The expanding steam drives a turbine, which connects to an electrical generator. The turbine is split into high and low pressure sections. To prevent condensation (Water droplets at high speed damage the turbine blades) steam is reheated between these sections. Reactors of the VVER-1000 type deliver 1 GW of electrical power.
3. Condenser: The steam is cooled and allowed to condense, shedding waste heat into a cooling circuit.
4. Deaerator: Removes gases from the coolant.
5. Pump: The circulation pumps are each driven by their own small steam turbine.

To increase efficiency of the process, steam from the turbine is taken to reheat coolant before the deaerator and the steam generator. Water in this circuit is not supposed to be radioactive.

Cooling circuit

The cooling circuit is an open circuit diverting water from an outside reservoir such as a lake or river. Evaporative cooling towers, cooling basins or ponds exhaust waste heat from the generation circuit, releasing it into the environment. In addition to generating electricity most VVERs have a capability to supply heat for residential and industrial use. Operational examples of such systems are the plants at Bohunice and Dukovany.

Safety barriers

The two VVER-440 units in Loviisa have containment buildings that fulfil Western safety standards.

A typical design feature of nuclear reactors is layered safety barriers preventing escape of radioactive material. VVER reactors have four layers:

1. Fuel pellets: Radioactive elements are retained within the crystal structure of the fuel pellets.
2. Fuel rods: The zircaloy tubes provide a further barrier resistant to heat and high pressure.
3. Reactor Shell: A massive steel shell encases the whole fuel assembly hermetically.
4. Reactor Building: A concrete containment building that encases the whole first circuit is strong enough to resist the pressure surge a breach in the first circuit would cause.

Currently operating Russian VVERs are inherently safer designs than the RBMK reactors of Chernobyl disaster. The Soviet Union opted to construct graphite-moderated RBMK series nuclear reactors without containment structures on grounds of cost as well as the relative ease of re-fueling RBMK reactors. An RBMK reactor can be re-fueled while still operational compared to the VVER which needs to be shut down. Many levels of protection and containment have both been proposed and constructed for RBMK and VVER type reactors.

Operational life of VVER 1000

When first built the VVER design was intended to be operational for 35 years. A mid-life major overhaul including a complete replacement of critical parts such as fuel and control rod channels was thought necessary after that. Since RBMK reactors specified a major replacement programme at 35 years designers originally decided this needed to happen in the VVER type as well, although they are of more robust design than the RBMK type. Most of Russia's VVER plants are now reaching and passing the 35 year mark. More recent design studies have allowed for an extension of lifetime up to 50 years with replacement of equipment. New VVERs will be nameplated with the extended lifetime.

In 2010 the oldest VVER-1000, at Novovoronezh, was shut down for modernization to extend its operating life for an additional 30 years; the first to undergo such an operating life extension. The works include the modernization of management, protection and emergency systems, and improvement of security and radiation safety systems.

VVER-1200

The VVER-1200 is an evolution of the VVER-1000 being offered for domestic and export use. Specifications include a $1,200 per kW electric capital cost, 54 month planned construction time, and expected 50 year lifetime at 90% capacity factor. The VVER 1200 will produce 1,200 MWe of power. Safety features include a containment building and missile shield. It will have full emergency systems that include an emergency core cooling system, emergency backup diesel power supply, advanced refueling machine, computerized reactor control systems, backup feedwater supply and

reactor SCRAM system. The nuclear reactor and associated systems will be hosted in one single building and there will be another building for the turbogenerators. The main building will comprise the reactor, refueling machine and diesel backup power supply, steam generators and reactor control systems.

If a VVER 1200 experiences a loss of coolant accident or loss of power accident the turbogenerators 'coast down' for 30 seconds, during which time a shutdown can be initiated using residual power in the system. Further emergency power is available from a backup set of diesel generators kept on standby to maintain cooling flow to the reactor. The reactor design has been refined to optimize fuel efficiency.

The first two units are proposed for Leningrad Nuclear Power Plant II and Novovoronezh Nuclear Power Plant II. A standardized design has not been elected. Mainly are more reactors with a VVER-1200/491 like the Leningrad-II-design are firmly planned (Kaliningrad and Nizhny Novgorod NPP) and under construction. The VVER-1200/392M where under construction at the Novovoronezh NPP-II is selected for the Seversk, Zentral and South-Urals NPP. A standarized design elected after commercial operation of the first units.

Power plants

List of operational VVER installations

Power plant	Country	Reactors	Notes
Akkuyu	Turkey	(4 × VVER-1200/491) (AES-2006)	Plan in place.
Balakovo	Russia	4 × VVER-1000/320 (2 × VVER-1000/320)	Unit 5 and 6 construction suspended.
Belene	Bulgaria	(2 × VVER-1000/446)	Planned.
Bohunice	Slovakia	2 × VVER-440/230 2 × VVER-440/213	Split in two plants, V-1 and V-2 with two reactors each. VVER-440/230 units decommissioned in 2007.
Bushehr	Iran	1 × VVER-1000/446 (3 × VVER-1000/446)	A version of the V-320 adapted to the Bushehr site. Unit 2 and 3 planned, unit 4 cancelled.
Dukovany	Czech Republic	4 × VVER 440/213	Now upgraded to 502 MW in 2009-2012.
Greifswald	Germany	4 × VVER-440/230 1 × VVER-	Decomissioned. Unit 6 finished, but never operated. Unit 7 and 8 construction suspended.

		440/213 (3 × VVER-440/213)	
Kalinin	Russia	2 × VVER-1000/338 1 × VVER-1000/320 (1 × VVER-1000/320)	Unit 4 under construction, operational 2011.
Khmelnitskiy	Ukraine	2 × VVER-1000/320 (2 × VVER-1000/392B)	Unit 3 and 4 under construction.
Kola	Russia	2 × VVER-440/230 2 × VVER-440/213	
Koodankulam	India	(2 × VVER-1000/412) (AES-92)	Under construction, operational 2008/2009 with four additional units planned.
Kozloduy	Bulgaria	4 × VVER-440/230 2 × VVER-1000	VVER-440/230 units decommissioned 2003-2006.
Leningrad II	Russia	2 × VVER-1200/491 (2 × VVER-1200/491)	The units are the prototypes of the VVER-1200/491 (AES-2006) and under construction.
Loviisa	Finland	2 × VVER-440/213	Western control systems, Totally different containment structures. Later modified for a 488 MW output.
Metsamor	Armenia	2 × VVER-440/230	One reactor was shut down in 1989.
Mochovce	Slovakia	2 × VVER-440/213 (2 × VVER-440/213)	Units 3 and 4 construction suspended due to lack of funds, planned to be operational in 2012.
Novovoronezh	Russia	1 x VVER-210 (V-1) 1 x VVER-365 (V-3) 2 × VVER-440/179 1 × VVER-1000/187	All units are prototypes. Unit 1 and 2 shutdown. Unit 3 modernised in 2002.

Novovoronezh II	Russia	(2 × VVER-1200/392M) (AES-2006)	The units are the prototypes of the VVER-1200/392M (AES-2006) and under construction.
Paks	Hungary	4 × VVER-440/213	Two VVER-1000/320 plan was cancelled.
Rheinsberg	Germany	1 × VVER-210	Unit decomissioned
Rivne	Ukraine	2 × VVER-440/213 2 × VVER-1000/320 (2 × VVER-1000/320)	Unit 5 and 6 planning suspended.
South Ukraine	Ukraine	1 × VVER-1000/302 1 × VVER-1000/338 1 × VVER-1000/320 (1 × VVER-1000/320)	unit 4 construction suspended.
Stendal	Germany	(4 × VVER-1000/320)	All 4 units construction cancelled after Germany reunification.
Temelin	Czech Republic	2 × VVER-1000/320 (2 × VVER-1000/320)	Unit 3 and 4 construction suspended. Now unit 3 and 4 in planning again (operated in 2025).
Tianwan	China	2 × VVER-1000/428 (AES-91) (6 × VVER-1000/428)	Unit 3 to 8 firmly planned.
Volgodonsk	Russia	2 × VVER-1000/320 (2 × VVER-1000/320)	Unit 3 and 4 is under construction and planned to be operational in 2013 and 2014.
Zaporizhzhia	Ukraine	6 × VVER-1000/320	Largest nuclear power plant in Europe.

Russia recently installed two nuclear reactors in China at the Tianwan Nuclear Power Plant, and an extension consisting of a further two reactors was just approved. This is the first time the two countries have co-operated on a nuclear power project. The reactors are the VVER 1000 type, which Russia has improved incrementally while retaining the basic design. These VVER 1000 reactors are housed in a confinement shell capable of being hit by an aircraft weighing 20 tonnes and suffering no expected damage. Other important

safety features include an emergency core cooling system and core confinement system. Russia delivered initial fuel loads for the reactors, but China plans to begin indigenous fuel fabrication for the Tianwan plant in 2009. The IAEA has referred to the station as the "safest nuclear power plant in the world".

The Tianwan Nuclear Power Plant uses many third party parts. While the reactor and turbogenerators are of Russian design, the control room was designed and built by an international consortium. In this way the plant was brought to meet widely recognised safety standards; safety systems were already mostly in place but the previous monitoring of these systems did not meet international safety standards. The new VVER 1000 plant built in China has 94% of its systems automated, meaning the plant can control itself under most situations. Even refueling procedures require little human intervention. Five people are still needed in the control room.

Chapter-10

Nuclear Weapons Testing

Nuclear weapons tests are experiments carried out to determine the effectiveness, yield and explosive capability of nuclear weapons. Throughout the twentieth century, most nations that have developed nuclear weapons have tested them. Testing nuclear weapons can yield information about how the weapons work, as well as how the weapons behave under various conditions and how structures behave when subjected to nuclear explosions. Additionally, nuclear testing has often been used as an indicator of scientific and military strength, and many tests have been overtly political in their intention; most nuclear weapons states publicly declared their nuclear status by means of a nuclear test.

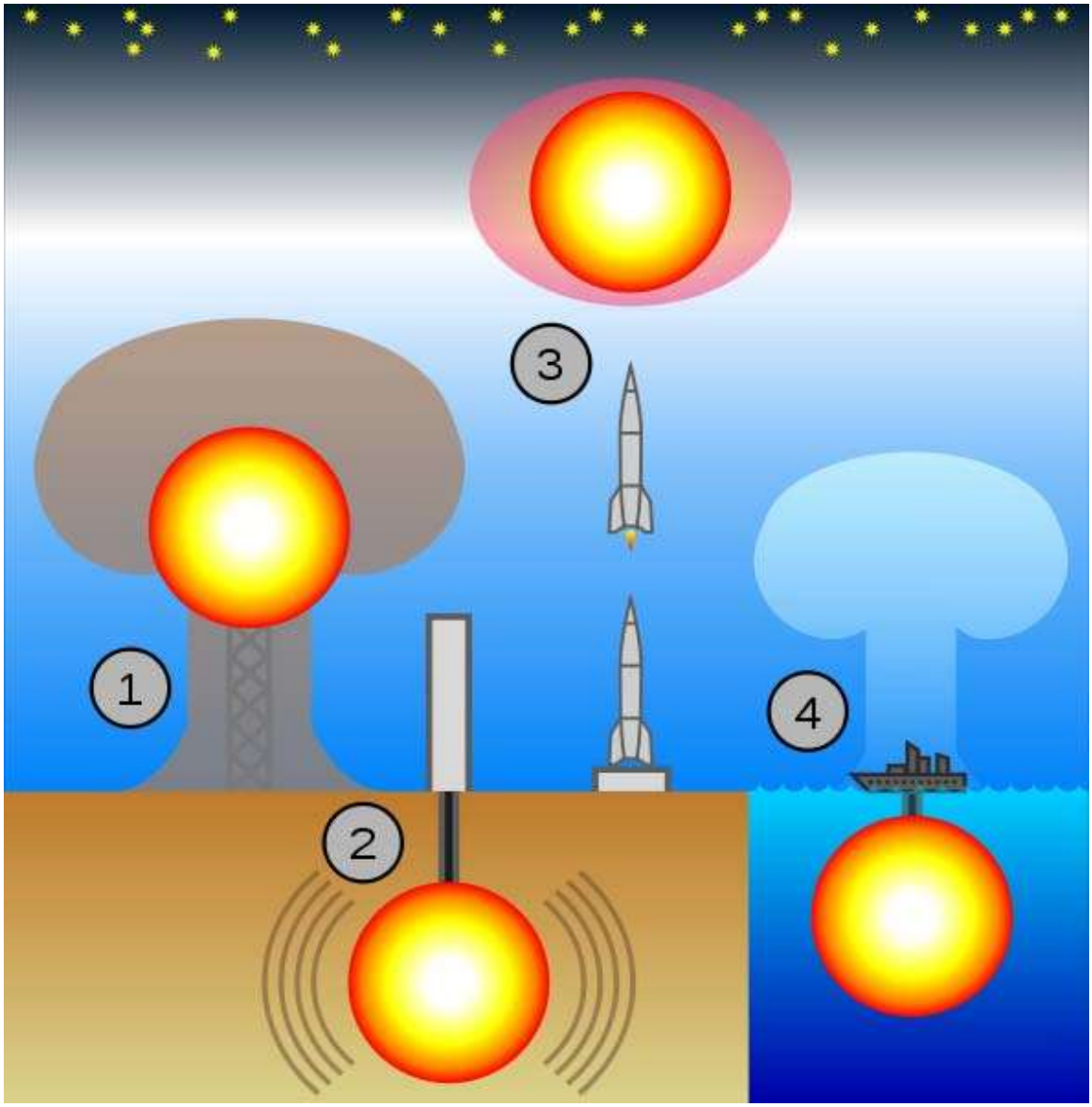
The first nuclear weapon was detonated as a test by the United States at the Trinity site on July 16, 1945, with a yield approximately equivalent to 20 kilotons. The first hydrogen bomb, codenamed "Mike", was tested at the Enewetak atoll in the Marshall Islands on November 1 (local date) in 1952, also by the United States. The largest nuclear weapon ever tested was the "Tsar Bomba" of the Soviet Union at Novaya Zemlya on October 30, 1961, with an estimated yield of around 50 megatons.

In 1963, all nuclear and many non-nuclear states signed the Limited Test Ban Treaty, pledging to refrain from testing nuclear weapons in the atmosphere, underwater, or in outer space. The treaty permitted underground nuclear testing. France continued atmospheric testing until 1974, China continued up until 1980.

Underground Tests in the United States continued until 1992 (its last nuclear testing), the Soviet Union in 1990, the United Kingdom in 1991, and both China and France in 1996. After signing the Comprehensive Test Ban Treaty in 1996 (which had as of 2011 not yet entered into force), all of these states have pledged to discontinue all nuclear testing. Non-signatories India and Pakistan last tested nuclear weapons in 1998.

The most recent nuclear test was announced by North Korea on May 25, 2009.

Types



Four major types of nuclear testing: 1. atmospheric, 2. underground, 3. exoatmospheric, and 4. underwater.

Nuclear weapons tests have historically been broken into categories (by treaties) reflecting the medium or location of the test: atmospheric, underwater, and underground.

- **Atmospheric** testing designates explosions which take place in or above the atmosphere. Generally these have occurred as devices detonated on towers, balloons, barges, islands, or dropped from airplanes. A limited number of high altitude nuclear explosions have also been conducted, generally fired from rockets. Nuclear explosions which are close enough to the ground to draw dirt and debris into their mushroom cloud can generate large amounts of nuclear fallout

due to irradiation of the debris. High altitude nuclear explosions can generate an electromagnetic pulse (EMP), and charged particles resulting from the blast can cross hemispheres to create an auroral display.

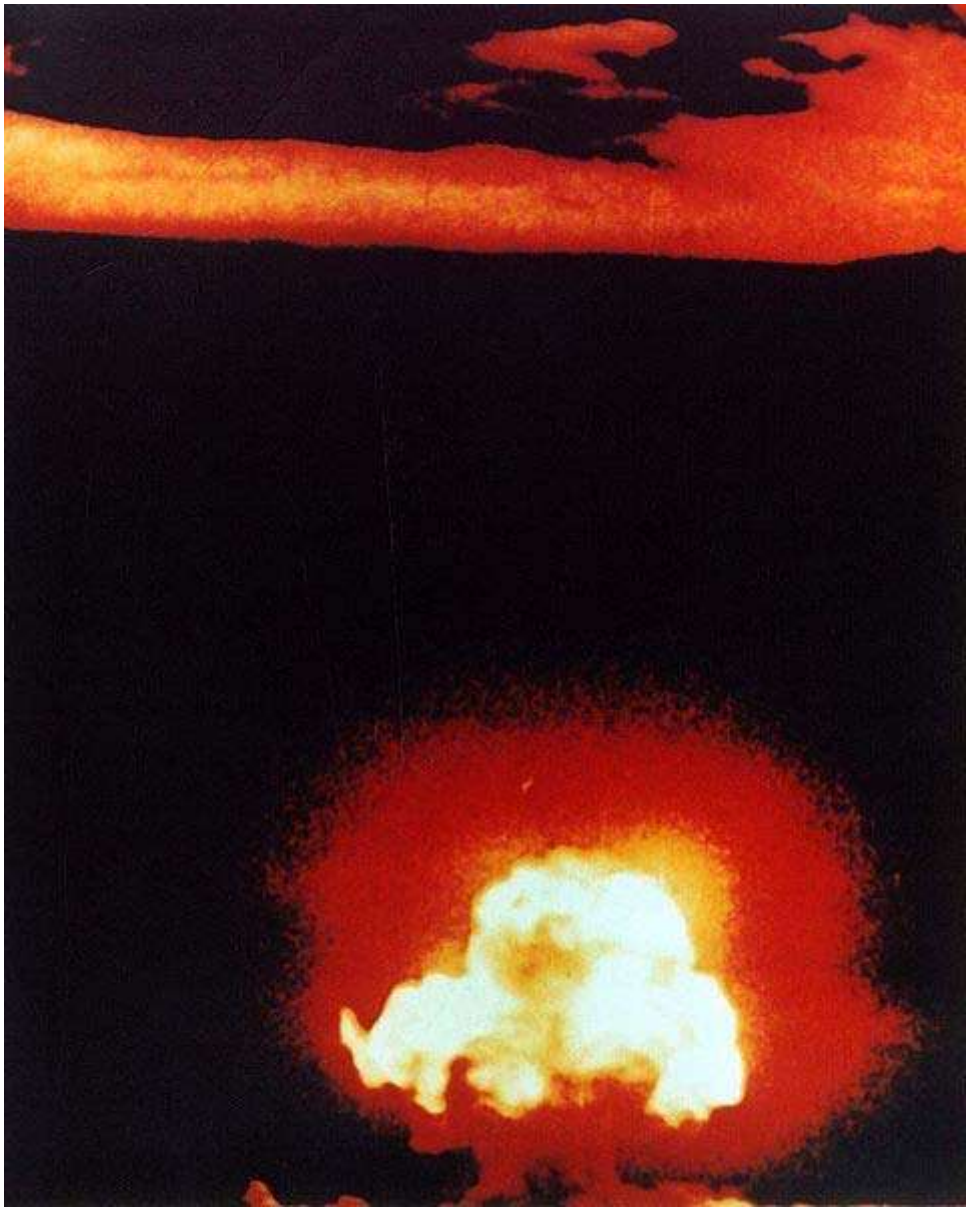
- **Underwater** testing results from nuclear devices being detonated underwater, usually moored to a ship or a barge (which is subsequently destroyed by the explosion). Tests of this nature have usually been conducted to evaluate the effects of nuclear weapons against naval vessels (such as in Operation Crossroads), or to evaluate potential sea-based nuclear weapons (such as nuclear torpedoes or depth-charges). Underwater tests close to the surface can disperse large amounts of radioactive water and steam, contaminating nearby ships or structures.

- **Underground** testing refers to nuclear tests which are conducted under the surface of the earth, at varying depths. Underground nuclear testing made up the majority of nuclear tests by the United States and the Soviet Union during the Cold War; other forms of nuclear testing were banned by the Limited Test Ban Treaty in 1963. When the explosion is fully contained, underground nuclear testing emits a negligible amount of fallout. However, underground nuclear tests can "vent" to the surface, producing considerable amounts of radioactive debris as a consequence. Underground testing can result in seismic activity depending on the yield of the nuclear device and the composition of the medium it is detonated in, and generally result in the creation of subsidence craters. In 1976, the United States and the USSR agreed to limit the maximum yield of underground tests to 150 kt with the Threshold Test Ban Treaty.

Separately from these designations, nuclear tests are also often categorized by the purpose of the test itself. Tests which are designed to garner information about how (and if) the weapons themselves work are *weapons related* tests, while tests designed to gain information about the effects of the weapons themselves on structures or organisms are known as *weapons effects* tests. Additional types of nuclear tests are possible as well (such as nuclear tests which are also part of anti-ballistic missile testing).

Nuclear-weapons-related testing which purposely results in *no* yield is known as **subcritical testing** or **cold testing**, referring to the lack of a creation of a critical mass of fissile material. Additionally, there have been simulations of nuclear tests using conventional explosives (such as the Minor Scale U.S. test in 1985).

History

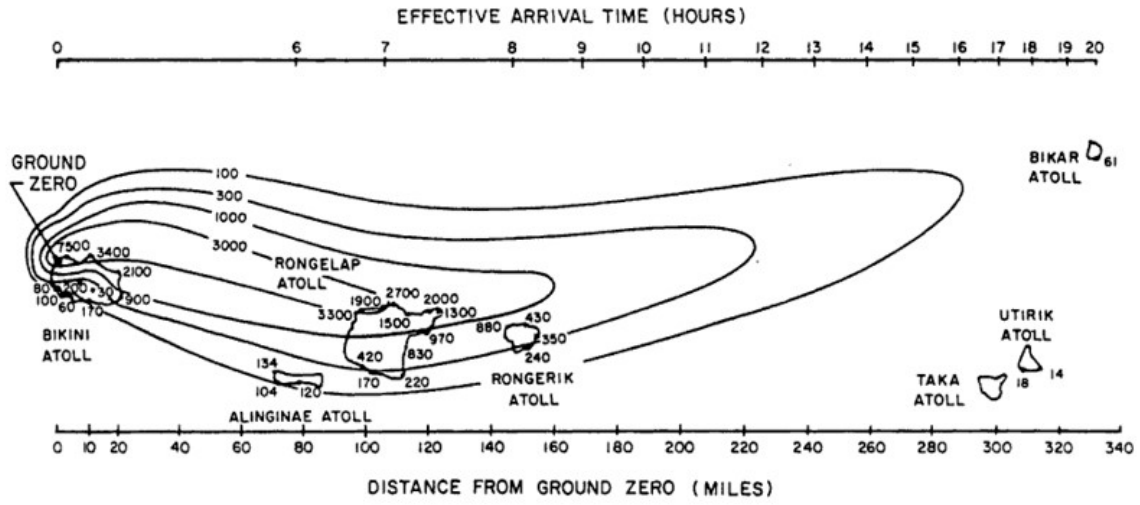


The first nuclear test, "Trinity", took place on July 16, 1945.

The first nuclear weapons test was conducted in Alamogordo, New Mexico, on July 16, 1945, during the Manhattan Project, and given the codename "Trinity". The test was originally to confirm that the implosion-type nuclear weapon design was feasible, and to give an idea of what the actual size and effects of a nuclear explosion would be before they were used in combat against Japan. While the test gave a good approximation of many of the explosion's effects, it did not give an appreciable understanding of nuclear fallout, which was not well understood by the project scientists until well after the atomic bombings of Hiroshima and Nagasaki.

The United States conducted six nuclear tests before the Soviet Union developed their first atomic bomb (RDS-1) and tested it on August 29, 1949. Neither country had very many nuclear weapons to spare at first, and so testing was relatively infrequent (when the U.S. used two weapons for *Operation Crossroads* in 1946, they were detonating over 20% of their current arsenal). However, by the 1950s the United States had established a dedicated test site on its own territory (Nevada Test Site) and was also using a site in the Marshall Islands (Pacific Proving Grounds) for extensive nuclear testing.

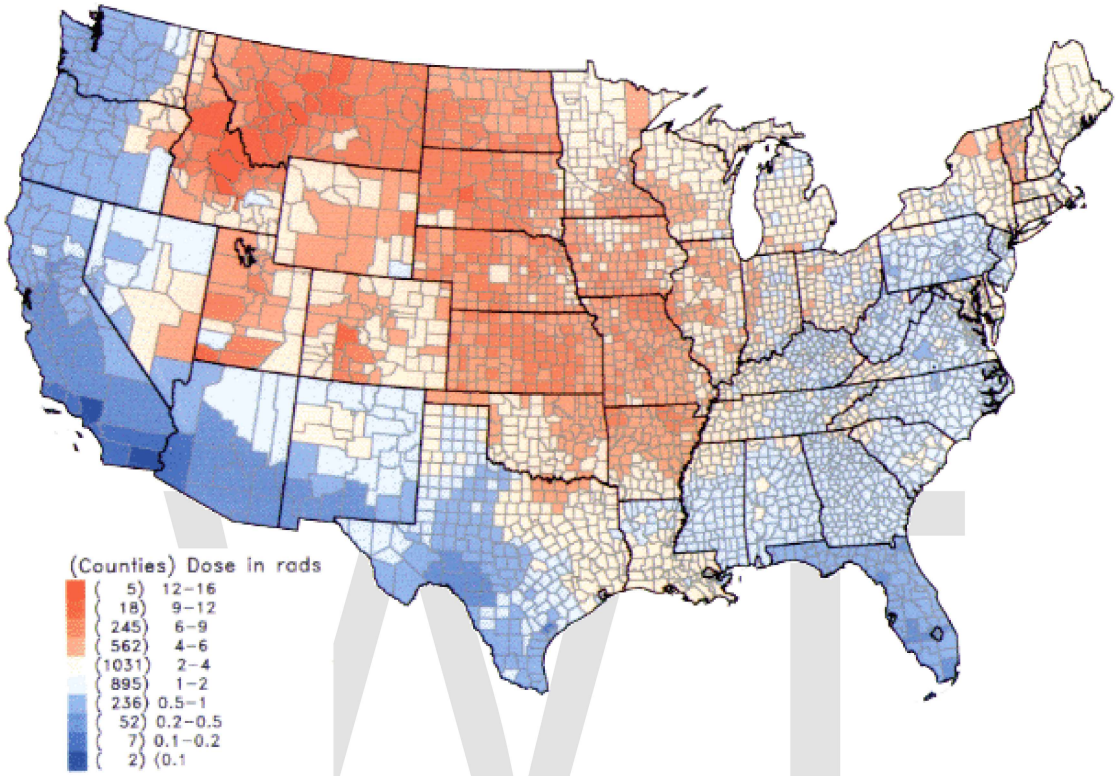
The early tests were used primarily to discern the military effects of nuclear weapons (*Crossroads* had involved the effect of nuclear weapons on a navy, and how they functioned underwater) and to test new weapon designs. During the 1950s these included new hydrogen bomb designs, which were tested in the Pacific, and also new and improved fission weapon designs. The Soviet Union also began testing on a limited scale, primarily in Kazakhstan. During the later phases of the Cold War, though, both countries developed accelerated testing programs, testing many hundreds of bombs over the last half of the twentieth century.



In 1954 the Castle Bravo fallout plume spread dangerous levels of radiation over an area over 100 miles long, including inhabited islands.

Nuclear tests can involve many hazards. A number of these were illustrated in the U.S. Castle Bravo test in 1954. The weapon design tested was a new form of hydrogen bomb, and the scientists underestimated how vigorously some of the weapon materials would react. As a result, the explosion – with a yield of 15 Mt – was over twice what was predicted. Aside from this problem, the weapon also generated a large amount of radioactive nuclear fallout, more than had been anticipated, and a change in the weather pattern caused the fallout to be spread in a direction which had not been cleared in advance. The fallout plume spread high levels of radiation for over a hundred miles, contaminating a number of populated islands in nearby atoll formations (though they were soon evacuated, many of the islands' inhabitants suffered from radiation burns and later from other effects such as increased cancer rate and birth defects), as well as a

Japanese fishing boat (*Daigo Fukuryū Maru*). One member of the boat's crew died from radiation sickness after returning to port, and it was feared that the radioactive fish they had been carrying had made it into the Japanese food supply.



Because of concerns about worldwide fallout levels, the Partial Test Ban Treaty was signed in 1963. Above are the per capita thyroid doses (in rads) in the continental United States resulting from all exposure routes from all atmospheric nuclear tests conducted at the Nevada Test Site from 1951-1962.

Bravo was the worst U.S. nuclear accident, but many of its component problems – unpredictably large yields, changing weather patterns, unexpected fallout contamination of populations and the food supply – occurred during other atmospheric nuclear weapons tests by other countries as well. Concerns over worldwide fallout rates eventually led to the Partial Test Ban Treaty in 1963, which limited signatories to underground testing. Not all countries stopped atmospheric testing, but because the United States and the Soviet Union were responsible for roughly 86% of all nuclear tests their compliance cut the overall level substantially. France continued atmospheric testing until 1974, and People's Republic of China until 1980.

Almost all new nuclear powers have announced their possession of nuclear weapons with a nuclear test. The only acknowledged nuclear power which claims never to have conducted a test was South Africa, which has since dismantled all of its weapons. Israel is widely thought to possess a sizeable nuclear arsenal, though it has never tested, unless they were involved in Vela. Experts disagree on whether states can have reliable nuclear

arsenals – especially ones using advanced warhead designs, such as hydrogen bombs and miniaturized weapons – without testing, though all agree that it is very unlikely to develop significant nuclear innovations without testing. One other approach is to use supercomputers to conduct "virtual" testing, but codes need to be validated against test data.

The Sedan test of 1962 was an experiment by the United States in using nuclear weapons to excavate large amounts of earth.

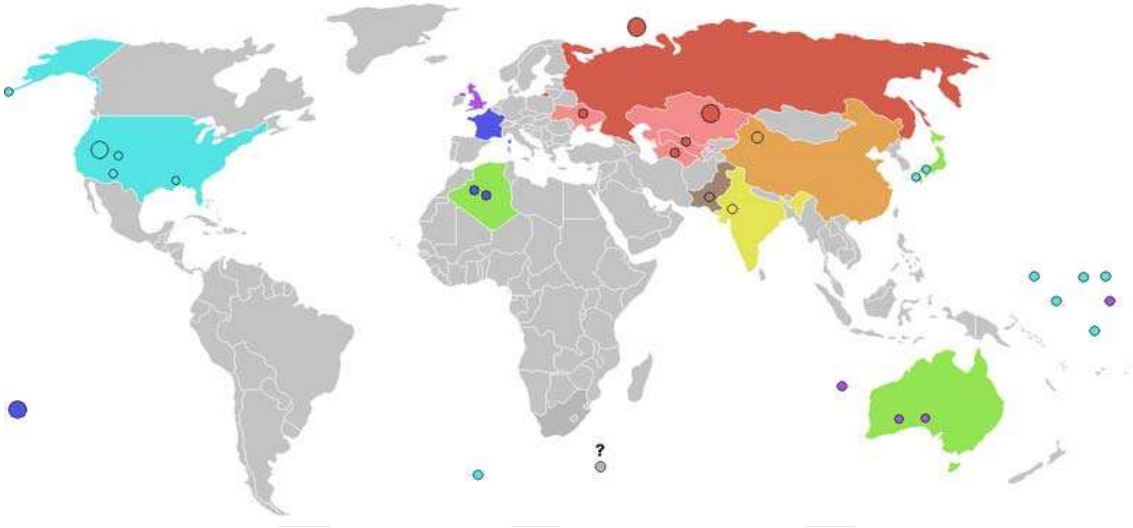
Some nuclear tests have been for peaceful purposes. These peaceful nuclear explosions were used to evaluate whether nuclear explosions could be used for non-military purposes such as digging canals and artificial harbors, or to stimulate oil and gas fields. The tests were eventually abandoned for economic, political, and environmental reasons.

Nuclear testing has also been used for clearly political purposes. The most explicit example of this was the detonation of the largest nuclear bomb ever created, the 50 megaton Tsar Bomba, by the Soviet Union in 1961. This weapon was too large to be practically used against an enemy target, and it is not thought that any were manufactured except the one detonated in the test.

There have been many attempts to limit the number and size of nuclear tests; the most far-reaching was the Comprehensive Test Ban Treaty of 1996, which was not ratified by the United States. Nuclear testing has since become a controversial issue in the United States, with a number of politicians saying that future testing might be necessary to maintain the aging warheads from the Cold War. Because nuclear testing is seen as furthering nuclear arms development, many are also opposed to future testing as an acceleration of the arms race.

Nuclear testing by country

The nuclear powers have conducted more than 2,000 nuclear test explosions (numbers are approximated, as some test results have been disputed):



Over 2,000 nuclear explosions have been conducted, in over a dozen different sites around the world.

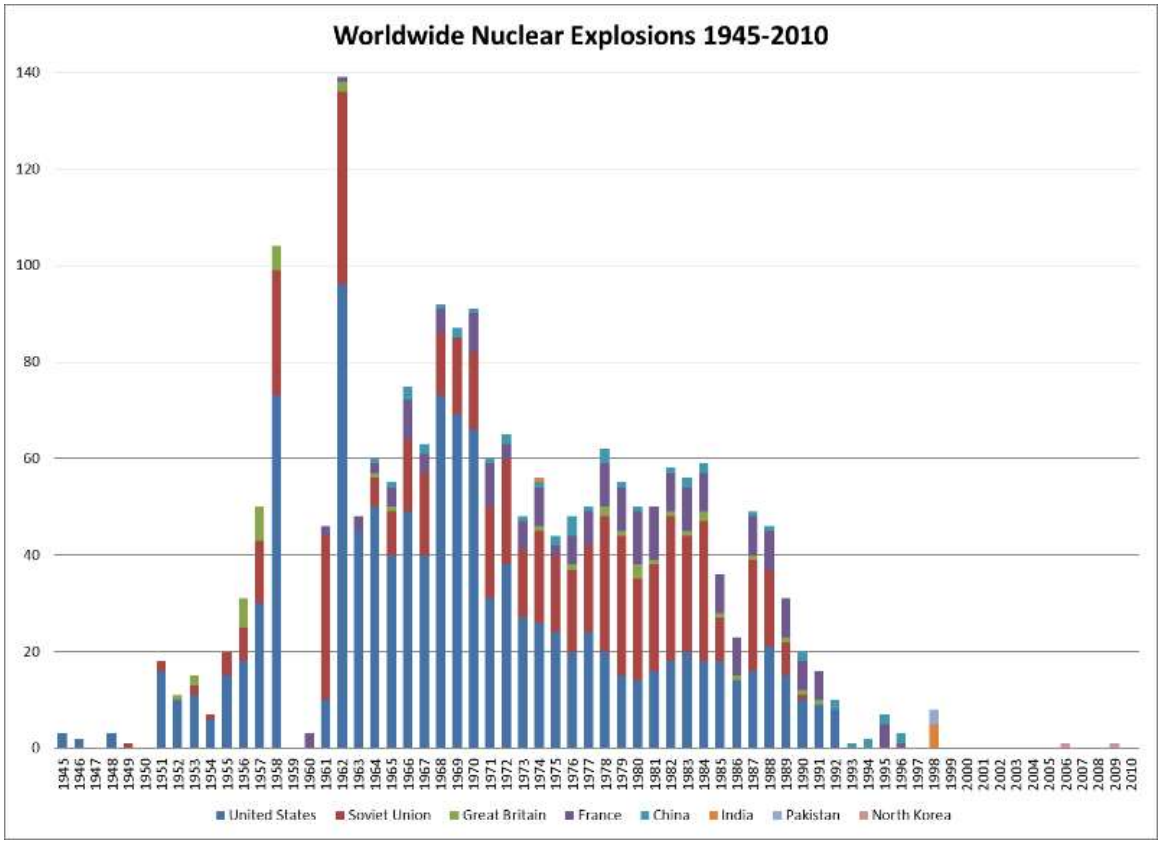
"Baker Shot", part of Operation Crossroads, a nuclear test by the United States at Bikini Atoll in 1946

- **United States**: 1,054 tests by official count (involving at least 1,151 devices, 331 atmospheric tests), most at Nevada Test Site and the Pacific Proving Grounds in the Marshall Islands, with 10 other tests taking place at various locations in the United States, including Amchitka Alaska, Colorado, Mississippi, and New Mexico.
- **Soviet Union**: 715 tests (involving 969 devices) by official count, most at Semipalatinsk Test Site and Novaya Zemlya, and a few more at various sites in Russia, Kazakhstan, Turkmenistan, and Ukraine.
- **France**: 210 tests by official count (50 atmospheric, 160 underground), 4 atomic atmospheric tests at C.E.S.M. near Reggane, 13 atomic underground tests at C.E.M.O. near In Ekker in the then-French Algerian Sahara, and nuclear atmospheric tests at Fangataufa and nuclear undersea tests Moruroa in French Polynesia. Additional atomic and chemical warfare tests took place in the secret base B2-Namous, near Ben Wenif, other tests involving rockets and missiles at C.I.E.E.S, near Hammaguir, both in the Sahara.
- **United Kingdom**: 45 tests (21 in Australian territory, including 9 in mainland South Australia at Maralinga and Emu Field, some at Christmas Island in the Pacific Ocean, plus many others in the United States as part of joint test series)
- **China**: 45 tests (23 atmospheric and 22 underground, at Lop Nur Nuclear Weapons Test Base, in Malan, Xinjiang)
- **India**: 6 underground tests (including the first one in 1974), at Pokhran.
- **Pakistan**: 6 underground tests, at Ras Koh Hills, Chagai District and Kharan Desert, Kharan District in Balochistan Province.

- **North Korea**: two tests at Hwadae-ri.

Additionally, there may have been at least three alleged but unacknowledged nuclear explosions. Of these, the only one taken seriously as a possible nuclear test is the Vela Incident, a possible detection of a nuclear explosion in the Indian Ocean in 1979.

From the first nuclear test in 1945 until tests by Pakistan in 1998, there was never a period of more than 22 months with no nuclear testing. June 1998 to October 2006 was the longest period since 1945 with no acknowledged nuclear tests.



Compensation for victims

Over 500 atmospheric nuclear weapons tests were conducted at various sites around the world from 1945 to 1980. As public awareness and concern mounted over the possible health hazards associated with exposure to the nuclear fallout, various studies were done to assess the extent of the hazard. A Centers for Disease Control and Prevention/ National Cancer Institute study claims that nuclear fallout might have led to approximately 11,000 excess deaths, most caused by thyroid cancer linked to exposure to iodine-131.

- **United States**: As of March 2009, the U.S. is the only nation that compensates nuclear test victims. Since the Radiation Exposure Compensation Act of 1990, more than $1.38 billion in compensation has been approved. The money is going to people who took part in the tests, notably at the Nevada Test Site, and to others exposed to the radiation.

- **France**: In March 2009, the French Government offered to compensate victims for the first time and legislation is being drafted which would allow payments to people who suffered health problems related to the tests. The payouts would be available to victims' descendants and would include Algerians, who were exposed to nuclear testing in the Sahara in 1960. However, victims say the eligibility requirements for compensation are too narrow.

- **Britain**: There is no formal British government compensation program. However, nearly 1,000 veterans of Christmas Island nuclear tests in the 1950s are planning to sue the Ministry of Defense for negligence. They say they suffered health problems and were not warned of potential dangers before the experiments.

- **Russia**: Decades later, Russia offered compensation to veterans who were part of the 1954 Totsk test. However, there was no compensation to civilians sickened by the Totsk test. Anti-nuclear groups say there has been no government compensation for other nuclear tests.

- **China**: China has undertaken highly secretive atomic tests in remote deserts in a Central Asian border province. Anti-nuclear activists say there is no known government program for compensating victims.

Milestone nuclear explosions

The following list is of milestone nuclear explosions. In addition to the atomic bombings of Hiroshima and Nagasaki, the first nuclear test of a given weapon type for a country is included, and tests which were otherwise notable (such as the largest test ever). All yields (explosive power) are given in their estimated energy equivalents in kilotons of TNT. Putative tests (like Vela Incident) have not been included.

Date	Name	Yield (kT)	Country	Significance
1945-07-16	***Trinity***	19	USA	First fission device test, first plutonium implosion detonation
1945-08-06	***Little Boy***	15	USA	Bombing of Hiroshima, Japan, first detonation of an enriched uranium gun-type device, first use of a nuclear device in military combat.
1945-08-09	***Fat Man***	21	USA	Bombing of Nagasaki, Japan, as of this writing the last use of a nuclear device in military combat.
1946-07-01	***Test Able***	23	USA	Bikini Atoll; the *Crossroads tests* were the fourth and fifth nuclear explosions conducted by the United States. Their purpose was to investigate the effect of nuclear weapons on naval ships. They were
1946-07-25	***Test Baker***	23	USA	

				the first of many nuclear tests held in the Marshall Islands, and the first to be publicly announced beforehand and observed by an invited audience, including a large press corps.
1949-08-29	***RDS-1***	22	USSR	First fission weapon test by the USSR
1951-05-09	***Test George***	225	USA	"George" shot was physics experiment relating to the hydrogen bomb.
1952-10-03	***Hurricane***	25	UK	First fission weapon test by the UK
1952-11-01	***Ivy Mike***	10,400	USA	First cryogenic fusion fuel "staged" thermonuclear weapon, primarily a test device and not weaponized
1953-08-12	***Joe 4***	400	USSR	First fusion weapon test by the USSR (not "staged")
1954-03-01	***Castle Bravo***	15,000	USA	First dry fusion fuel "staged" thermonuclear weapon; a serious nuclear fallout accident occurred
1955-11-22	***RDS-37***	1,600	USSR	First "staged" thermonuclear weapon test by the USSR (deployable)
1957-11-08	***Grapple X***	1,800	UK	First (successful) "staged" thermonuclear weapon test by the UK
1960-02-13	***Gerboise Bleue***	70	France	First fission weapon test by France
1961-10-31	***Tsar Bomba***	57,000	USSR	Largest thermonuclear weapon ever tested—scaled down from its initial 100 Mt design by 50%
1964-10-16	***596***	22	PR China	First fission weapon test by the People's Republic of China
1967-06-17	***Test No. 6***	3,300	PR China	First "staged" thermonuclear weapon test by the People's Republic of China
1968-08-24	***Canopus***	2,600	France	First "staged" thermonuclear test by France
1974-05-18	***Smiling Buddha***	12	India	First fission nuclear explosive test by India
1998-05-11	***Pokhran-II***	20	India	First potential fusion/boosted weapon test by India; first deployable fission weapon test by India
1998-05-28	***Chagai-I***	9-12	Pakistan	First fission weapon test by Pakistan
2006-	***2006 North***	~1	North	First fission plutonium-based device tested

10-09	***Korean nuclear test***		Korea	by North Korea; likely resulted as a fizzle
2009-05-25	***2009 North Korean nuclear test***	5–15	North Korea	First successful fission device tested by North Korea

"Staging" refers to whether it was a "true" hydrogen bomb of the so-called Teller-Ulam configuration or simply a form of a boosted fission weapon. Some exact yield estimates, such as that of the Tsar Bomba and the tests by India and Pakistan in 1998, are somewhat contested among specialists.