Nuclear power

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See also: Nuclear energy and Nuclear binding energy

Nuclear power is the use of sustained nuclear fission to generate heat and do useful work. Nuclear Electric Plants, Nuclear Ships and Submarines use controlled nuclear energy to heat water and produce steam, while in space, nuclear energy decays naturally in a radioisotope thermoelectric generator. Scientists are experimenting with fusion energy for future generation, but these experiments do not currently generate useful energy.

Nuclear power provides about 6% of the world's energy and 13–14% of the world's electricity,[2] with the U.S., France, and Japan together accounting for about 50% of nuclear generated electricity.[3] Also, more than 150 naval vessels using nuclear propulsion have been built.

Cattenom Nuclear Power Plant

Some serious nuclear and radiation accidents have occurred. Nuclear power plant accidents include the Chernobyl disaster (1986), Fukushima I nuclear accidents (2011), and the Three Mile Island accident (1979).[4] Nuclear-powered submarine mishaps include the K-19 reactor accident (1961),[5] the K-27 reactor accident (1968),[6] and the K-431 reactor accident (1985).[4] International research is continuing into safety improvements such as passively safe plants,[7] and the possible future use of nuclear fusion.

The 2011 Fukushima Daiichi nuclear disaster in Japan, the worst nuclear accident in 25 years, displaced 50,000 households after radiation leaked into the air, soil and sea.[1]

Nuclear power is controversial and there is an ongoing debate about the use of nuclear energy.[8][9][10] Proponents, such as the World Nuclear Association and IAEA, contend that nuclear power is a sustainable energy source that reduces carbon emissions.[11] Opponents, such as Greenpeace International and NIRS, believe that nuclear power poses many threats to people and the environment.[12][13][14] Japan's Fukushima disaster has prompted a rethink of nuclear energy policy worldwide, underlined by Germany's decision to close all its reactors by 2022, and Italy's vote to ban nuclear power for decades.[15]

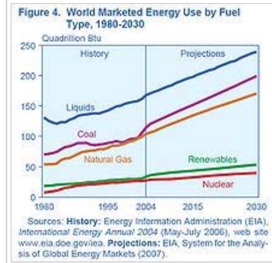
Contents

Use

See also: Nuclear power by country and List of nuclear reactors

As of 2005, nuclear power provided 6.3% of the world's energy and 15% of the world's electricity, with the U.S., France, and Japan together accounting for 56.5% of nuclear generated electricity.[3] In 2007, the IAEA reported there were 439 nuclear power reactors in operation in the world,[16] operating in 31 countries.[17] As of December 2009, the world had 436 reactors.[18] Since commercial nuclear energy began in the mid 1950s, 2008 was the first year that no new nuclear power plant was connected to the grid, although two were connected in 2009.[18][19]

Annual generation of nuclear power has been on a slight downward trend since 2007, decreasing 1.8% in 2009 to 2558 TWh with nuclear power meeting 13–14% of the world's electricity demand.[2] One factor in the nuclear power percentage decrease since 2007 has been the prolonged shutdown of large reactors at the Kashiwazaki-Kariwa Nuclear Power Plant in Japan following the Niigata-Chuetsu-Oki earthquake.[2]

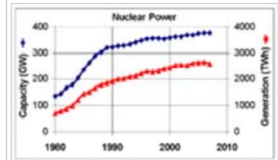


Historical and projected world energy use by energy source, 1980-2030, Source: International Energy Outlook 2007, EIA.

The United States produces the most nuclear energy, with nuclear power providing 19%[20] of the electricity it consumes, while France produces the highest percentage of its electrical energy from nuclear reactors—80% as of 2006.[21] In the European Union as a whole, nuclear energy provides 30% of the electricity.[22] Nuclear energy policy differs among European Union countries, and some, such as Austria, Estonia, Ireland and Italy, have no active nuclear power stations. In comparison, France has a large number of these plants, with 16 multi-unit stations in current use.

In the US, while the coal and gas electricity industry is projected to be worth $85 billion by 2013, nuclear power generators are forecast to be worth $18 billion.[23]

Many military and some civilian (such as some icebreaker) ships use nuclear marine propulsion, a form of nuclear propulsion.[24] A few space vehicles have been launched using full-fledged nuclear reactors: the Soviet RORSAT series and the American SNAP-10A.



Nuclear power installed capacity and generation, 1980 to 2007 (EIA).

International research is continuing into safety improvements such as passively safe plants,[7] the use of nuclear fusion, and additional uses of process heat such as hydrogen production (in support of a hydrogen economy), for desalinating sea water, and for use in district heating systems.

Nuclear fusion

Main articles: Nuclear fusion and Fusion power

Nuclear fusion reactions have the potential to be safer and generate less radioactive waste than fission.[25][26] These reactions appear potentially viable, though technically quite difficult and have yet to be created on a scale that could be used in a functional power plant. Fusion power has been under intense theoretical and experimental investigation since the 1950s.

The status of nuclear power globally (click image for legend)

Use in space

Both fission and fusion appear promising for space propulsion applications, generating higher mission velocities with less reaction mass. This is due to the much higher energy density of nuclear reactions: some 7 orders of magnitude (10,000,000 times) more energetic than the chemical reactions which power the current generation of rockets.

Radioactive decay has been used on a relatively small scale (few kW), mostly to power space missions and experiments by using radioisotope thermoelectric generators such as those developed at Idaho National Laboratory.

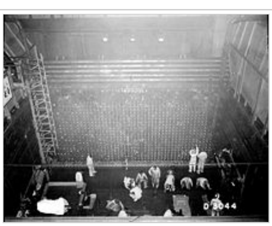
History

Origins

See also: Nuclear fission#History

The pursuit of nuclear energy for electricity generation began soon after the discovery in the early 20th century that radioactive elements, such as radium, released immense amounts of energy, according to the principle of mass–energy equivalence. However, means of harnessing such energy was impractical, because intensely radioactive elements were, by their very nature, short-lived (high energy release is correlated with short half-lives). However, the dream of harnessing "atomic energy" was quite strong, even it was dismissed by such fathers of nuclear physics like Ernest Rutherford as "moonshine." This situation, however, changed in the late 1930s, with the discovery of nuclear fission.

In 1932, James Chadwick discovered the neutron, which was immediately recognized as a potential tool for nuclear experimentation because of its lack of an electric charge. Experimentation with bombardment of materials with neutrons led Frédéric and Irène Joliot-Curie to discover induced radioactivity in 1934, which allowed the creation of radium-like elements at much less the price of natural radium. Further work by Enrico Fermi in the 1930s focused on using slow neutrons to increase the effectiveness of induced radioactivity. Experiments bombarding uranium with neutrons led Fermi to believe he had created a new, transuranic element, which he dubbed hesperium.



Constructing the core of B-Reactor at Hanford Site during the Manhattan Project.

But in 1938, German chemists Otto Hahn[27] and Fritz Strassmann, along with Austrian physicist Lise Meitner[28] and Meitner's nephew, Otto Robert Frisch,[29] conducted experiments with the products of neutron-bombarded uranium, as a means of further investigating Fermi's claims. They determined that the relatively tiny neutron split the nucleus of the massive uranium atoms into two roughly equal pieces, contradicting Fermi. This was an extremely surprising result: all other forms of nuclear decay involved only small changes to the mass of the nucleus, whereas this process—dubbed "fission" as a reference to biology—involved a complete rupture of the nucleus. Numerous scientists, including Leó Szilárd, who was one of the first, recognized that if fission reactions released additional neutrons, a self-sustaining nuclear chain reaction could result. Once this was experimentally confirmed and announced by Frédéric Joliot-Curie in 1939, scientists in many countries (including the United States, the United Kingdom, France, Germany, and the Soviet Union) petitioned their governments for support of nuclear fission research, just on the cusp of World War II.

In the United States, where Fermi and Szilárd had both emigrated, this led to the creation of the first man-made reactor, known as Chicago Pile-1, which achieved criticality on December 2, 1942. This work became part of the Manhattan Project, which made enriched uranium and built large reactors to breed plutonium for use in the first nuclear weapons, which were used on the cities of Hiroshima and Nagasaki.

After World War II, the prospects of using "atomic energy" for good, rather than simply for war, were greatly advocated as a reason not to keep all nuclear research controlled by military organizations. However, most scientists agreed that civilian nuclear power would take at least a decade to master, and the fact that nuclear reactors also produced weapons-usable plutonium created a situation in which most national governments (such as those in the United States, the United Kingdom, Canada, and the USSR) attempted to keep reactor research under strict government control and classification. In the United States, reactor research was conducted by the U.S. Atomic Energy Commission, primarily at Oak Ridge, Tennessee, Hanford Site, and Argonne National Laboratory.

Work in the United States, United Kingdom, Canada, and USSR proceeded over the course of the late 1940s and early 1950s. Electricity was generated for the first time by a nuclear reactor on December 20, 1951, at the EBR-I experimental station near Arco, Idaho, which initially produced about 100 kW. Work was also strongly researched in the US on nuclear marine propulsion, with a test reactor being developed by 1953 (eventually, the USS Nautilus, the first nuclear-powered submarine, would launch in 1955). In 1953, US President Dwight Eisenhower gave his "Atoms for Peace" speech at the United Nations, emphasizing the need to develop "peaceful" uses of nuclear power quickly. This was followed by the 1954 Amendments to the Atomic Energy Act which allowed rapid declassification of U.S. reactor technology and encouraged development by the private sector.

The first light bulbs ever lit by electricity generated by nuclear power at EBR-1 at what is now Idaho National Laboratory.

Early years

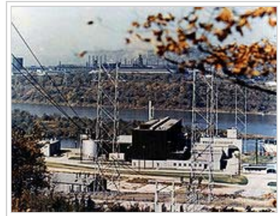
Calder Hall nuclear power station in the United Kingdom was the world's first nuclear power station to produce electricity in commercial quantities.[30]

On June 27, 1954, the USSR's Obninsk Nuclear Power Plant became the world's first nuclear power plant to generate electricity for a power grid, and produced around 5 megawatts of electric power.[31][32]

Later in 1954, Lewis Strauss, then chairman of the United States Atomic Energy Commission (U.S. AEC, forerunner of the U.S. Nuclear Regulatory Commission and the United States Department of Energy) spoke of electricity in the future being "too cheap to meter".[33] Strauss was very likely referring to hydrogen fusion[34][35]—which was secretly being developed as part of Project Sherwood at the time—but Strauss's statement was interpreted as a promise of very cheap energy from nuclear fission. The U.S. AEC itself had issued far more conservative testimony regarding nuclear fission to the U.S. Congress only months before, projecting that "costs can be brought down... [to]... about the same as the cost of electricity from conventional sources..." Significant disappointment would develop later on, when the new nuclear plants did not provide energy "too cheap to meter."

In 1955 the United Nations' "First Geneva Conference", then the world's largest gathering of scientists and engineers, met to explore the technology. In 1957 EURATOM was launched alongside the European Economic Community (the latter is now the European Union). The same year also saw the launch of the International Atomic Energy Agency (IAEA).

The world's first commercial nuclear power station, Calder Hall in Sellafield, England was opened in 1956 with an initial capacity of 50 MW (later 200 MW).[30][36] The first commercial nuclear generator to become operational in the United States was the Shippingport Reactor (Pennsylvania, December 1957).

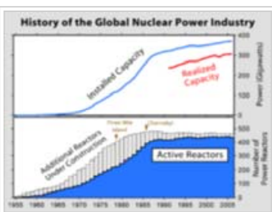


The Shippingport Atomic Power Station in Shippingport, Pennsylvania was the first commercial reactor in the USA and was opened in 1957.

One of the first organizations to develop nuclear power was the U.S. Navy, for the purpose of propelling submarines and aircraft carriers. The first nuclear-powered submarine, USS *Nautilus* (SSN-571), was put to sea in December 1954.[37] Two U.S. nuclear submarines, USS *Scorpion* and USS *Thresher*, have been lost at sea. Several serious nuclear and radiation accidents have involved nuclear submarine mishaps.[4][6] The Soviet submarine K-19 reactor accident in 1961 resulted in 8 deaths and more than 30 other people were over-exposed to radiation.[5] The Soviet submarine K-27 reactor accident in 1968 resulted in 9 fatalities and 83 other injuries.[6]

The U.S. Army also had a nuclear power program, beginning in 1954. The SM-1 Nuclear Power Plant, at Fort Belvoir, Virginia, was the first power reactor in the U.S. to supply electrical energy to a commercial grid (VEPCO), in April 1957, before Shippingport. The SL-1 was a U.S. Army experimental nuclear power reactor at the National Reactor Testing Station in eastern Idaho. It underwent a steam explosion and meltdown in January 1961, which killed its three operators.[38]

Development



History of the use of nuclear power (top) and the number of active nuclear power plants (bottom).

Installed nuclear capacity initially rose relatively quickly, rising from less than 1 gigawatt (GW) in 1960 to 100 GW in the late 1970s, and 300 GW in the late 1980s. Since the late 1980s worldwide capacity has risen much more slowly, reaching 366 GW in 2005. Between around 1970 and 1990, more than 50 GW of capacity was under construction (peaking at over 150 GW in the late 70s and early 80s) — in 2005, around 25 GW of new capacity was planned. More than two-thirds of all nuclear plants ordered after January 1970 were eventually cancelled.[37] A total of 63 nuclear units were canceled in the USA between 1975 and 1980.[39]

During the 1970s and 1980s rising economic costs (related to extended construction times largely due to regulatory changes and pressure-group litigation)[40] and falling fossil fuel prices made nuclear power plants then under construction less attractive. In the 1980s (U.S.) and 1990s (Europe), flat load growth and electricity liberalization also made the addition of large new baseload capacity unattractive.

The 1973 oil crisis had a significant effect on countries, such as France and Japan, which had relied more heavily on oil for electric generation (39%[41] and 73% respectively) to invest in nuclear power.[42] Today, nuclear power supplies about 80% and 30% of the electricity in those countries, respectively.

Some local opposition to nuclear power emerged in the early 1960s,[43] and in the late 1960s some members of the scientific community began to express their concerns.[44] These concerns related to nuclear accidents, nuclear proliferation, high cost of nuclear power plants, nuclear terrorism and radioactive waste disposal.[45] In the early 1970s, there were large protests about a proposed nuclear power plant in Wyhl, Germany. The project was cancelled in 1975 and anti-nuclear success at Wyhl inspired opposition to nuclear power in other parts of Europe and North America.[46][47] By the mid-1970s anti-nuclear activism had moved beyond local protests and politics to gain a wider appeal and influence, and nuclear power became an issue of major public protest.[48] Although it lacked a single co-ordinating organization, and did not have uniform goals, the movement's efforts gained a great deal of attention.[49] In some countries, the nuclear power conflict "reached an intensity unprecedented in the history of technology controversies".[50] In France, between 1975 and 1977, some 175,000 people protested against nuclear power in ten demonstrations.[51] In West Germany, between February 1975 and April 1979, some 280,000 people were involved in seven demonstrations at nuclear sites. Several site occupations were also attempted. In the aftermath of the Three Mile Island accident in 1979, some 120,000 people attended a demonstration against nuclear power in Bonn.[51] In May 1979, an estimated 70,000 people, including then governor of California Jerry Brown, attended a march and rally against nuclear power in Washington, D.C.[52] Anti-nuclear power groups emerged in every country that has had a nuclear power programme. Some of these anti-nuclear power organisations are reported to have developed considerable expertise on nuclear power and energy issues.[53]

Health and safety concerns, the 1979 accident at Three Mile Island, and the 1986 Chernobyl disaster played a part in stopping new plant construction in many countries,[54][55] although the public policy organization Brookings Institution suggests that new nuclear units have not been ordered in the U.S. because of soft demand for electricity, and cost overruns on nuclear plants due to regulatory issues and construction delays.[56]

Unlike the Three Mile Island accident, the much more serious Chernobyl accident did not increase regulations affecting Western reactors since the Chernobyl reactors were of the problematic RBMK design only used in the Soviet Union, for example lacking "robust" containment buildings.[57] Many of these reactors are still in use today. However, changes were made in both the reactors themselves (use of low enriched uranium) and in the control system (prevention of disabling safety systems) to reduce the possibility of a duplicate accident.


Washington Public Power Supply System Nuclear Power Plants 3 and 5 were never completed.

An international organization to promote safety awareness and professional development on operators in nuclear facilities was created: WANO; World Association of Nuclear Operators.

Opposition in Ireland and Poland prevented nuclear programs there, while Austria (1978), Sweden (1980) and Italy (1987) (influenced by Chernobyl) voted in referendums to oppose or phase out nuclear power. In July 2009, the Italian Parliament passed a law that canceled the results of an earlier referendum and allowed the immediate start of the Italian nuclear program.[58] One Italian minister even called the nuclear phase-out a "terrible mistake".[59]

Nuclear power plant

Main article: nuclear power plant

Just as many conventional thermal power stations generate electricity by harnessing the thermal energy released from burning fossil fuels, nuclear power plants convert the energy released from the nucleus of an atom, typically via nuclear fission.

Nuclear reactor technology

Main article: Nuclear reactor technology


Diablo Canyon Power Plant in San Luis Obispo County, California, USA

Three nuclear powered ships, (top to bottom) nuclear cruisers USS Bainbridge and USS Long Beach with *USS Enterprise* the first nuclear powered aircraft carrier in 1964. Crew members are spelling out Einstein's mass-energy equivalence formula $E = mc^2$ on the flight deck.

When a relatively large fissile atomic nucleus (usually uranium-235 or plutonium-239) absorbs a neutron, a fission of the atom often results. Fission splits the atom into two or more smaller nuclei with kinetic energy (known as fission products) and also releases gamma radiation and free neutrons.[60] A portion of these neutrons may later be absorbed by other fissile atoms and create more fissions, which release more neutrons, and so on.[61]

This nuclear chain reaction can be controlled by using neutron poisons and neutron moderators to change the portion of neutrons that will go on to cause more fissions.[61] Nuclear reactors generally have automatic and manual systems to shut the fission reaction down if unsafe conditions are detected.[62]

There are many different reactor designs, utilizing different fuels and coolants and incorporating different control schemes. Some of these designs have been engineered to meet a specific need. Reactors for nuclear submarines and large naval ships, for example, commonly use highly enriched uranium as a fuel. This fuel choice increases the reactor's power density and extends the usable life of the nuclear fuel load, but is more expensive and a greater risk to nuclear proliferation than some of the other nuclear fuels.[63]

A number of new designs for nuclear power generation, collectively known as the Generation IV reactors, are the subject of active research and may be used for practical power generation in the future. Many of these new designs specifically attempt to make fission reactors cleaner, safer and/or less of a risk to the proliferation of nuclear weapons. Passively safe plants (such as the ESBWR) are available to be built[64] and other designs that are believed to be nearly fool-proof are being pursued.[65] Fusion reactors, which may be viable in the future, diminish or eliminate many of the risks associated with nuclear fission.[66]

There are trades to be made between safety, economic and technical properties of different reactor designs for particular applications. Historically these decisions were often made in private by scientists, regulators and engineers, but this may be considered problematic, and since Chernobyl and Three Mile Island, many involved now consider informed consent and morality should be primary considerations.[67]

Cooling system

A cooling system removes heat from the reactor core and transports it to another area of the plant, where the thermal energy can be harnessed to produce electricity or to do other useful work. Typically the hot coolant will be used as a heat source for a boiler, and the pressurized steam from that boiler will power one or more steam turbine driven electrical generators.[68]

Flexibility of nuclear power plants

It is often claimed that nuclear stations are inflexible in their output, implying that other forms of energy would be required to meet peak demand. While that is true for the vast majority of reactors, this is no longer true of at least some modern designs.[69]

Nuclear plants are routinely used in load following mode on a large scale in France.[70] Unit A at the German Biblis Nuclear Power Plant is designed to in- and decrease his output 15 % per minute between 40 and 100 % of its nominal power.[71] Boiling water reactors normally have load-following capability, implemented by varying the recirculation water flow.[citation needed]

Life cycle

Main article: Nuclear fuel cycle

A nuclear reactor is only part of the life-cycle for nuclear power. The process starts with mining (see *Uranium mining*). Uranium mines are underground, open-pit, or in-situ leach mines. In any case, the uranium ore is extracted, usually converted into a stable and compact form such as yellowcake, and then transported to a processing facility. Here, the yellowcake is converted to uranium hexafluoride, which is then enriched using various techniques. At this point, the enriched uranium, containing more than the natural 0.7% U-235, is used to make rods of the proper composition and geometry for the particular reactor that the fuel is destined for. The fuel rods will spend about 3 operational cycles (typically 6 years total now) inside the reactor, generally until about 3% of their uranium has been fissioned, then they will be moved to a spent fuel pool where the short lived isotopes generated by fission can decay away. After about 5 years in a spent fuel pool the spent fuel is radioactively and thermally cool enough to handle, and it can be moved to dry storage casks or reprocessed.

Conventional fuel resources

Main articles: Uranium market and Energy development - Nuclear energy

The nuclear fuel cycle begins when uranium is mined, enriched, and manufactured into nuclear fuel, (1) which is delivered to a nuclear power plant. After usage in the power plant, the spent fuel is delivered to a reprocessing plant (2) or to a final repository (3) for geological disposition. In reprocessing 95% of spent fuel can be recycled to be returned to usage in a power plant (4).

Uranium is a fairly common element in the Earth's crust. Uranium is approximately as common as tin or germanium in Earth's crust, and is about 40 times more common than silver.[72] Uranium is a constituent of most rocks, dirt, and of the oceans. The fact that uranium is so spread out is a problem because mining uranium is only economically feasible where there is a large concentration. Still, the world's present measured resources of uranium, economically recoverable at a price of 130 USD/kg, are enough to last for "at least a century" at current consumption rates.[73][74] This represents a higher level of assured resources than is normal for most minerals. On the basis of analogies with other metallic minerals, a doubling of price from present levels could be expected to create about a tenfold increase in measured resources, over time. However, the cost of nuclear power lies for the most part in the construction of the power station. Therefore the fuel's contribution to the overall cost of the electricity produced is relatively small, so even a large fuel price escalation will have relatively little effect on final price. For instance, typically a doubling of the uranium market price would increase the fuel cost for a light water reactor by 26% and the electricity cost about 7%, whereas doubling the price of natural gas would typically add 70% to the price of electricity from that source. At high enough prices, eventually extraction from sources such as granite and seawater become economically feasible.[75][76]

Current light water reactors make relatively inefficient use of nuclear fuel, fissioning only the very rare uranium-235 isotope. Nuclear reprocessing can make this waste reusable and more efficient reactor designs allow better use of the available resources.[77]

Breeding

Main article: Breeder reactor

As opposed to current light water reactors which use uranium-235 (0.7% of all natural uranium), fast breeder reactors use uranium-238 (99.3% of all natural uranium). It has been estimated that there is up to five billion years' worth of uranium-238 for use in these power plants.[78]

Breeder technology has been used in several reactors, but the high cost of reprocessing fuel safely requires uranium prices of more than 200 USD/kg before becoming justified economically.[79] As of December 2005, the only breeder reactor producing power is BN-600 in Beloyarsk, Russia. The electricity output of BN-600 is 600 MW — Russia has planned to build another unit, BN-800, at Beloyarsk nuclear power plant. Also, Japan's Monju reactor is planned for restart (having been shut down since 1995), and both China and India intend to build breeder reactors.

Another alternative would be to use uranium-233 bred from thorium as fission fuel in the thorium fuel cycle. Thorium is about 3.5 times more common than uranium in the Earth's crust, and has different geographic characteristics. This would extend the total practical fissionable resource base by 450%.[80] Unlike the breeding of U-238 into plutonium, fast breeder reactors are not necessary — it can be performed satisfactorily in more conventional plants. India has looked into this technology, as it has abundant thorium reserves but little uranium.

Fusion

Fusion power advocates commonly propose the use of deuterium, or tritium, both isotopes of hydrogen, as fuel and in many current designs also lithium and boron. Assuming a fusion energy output equal to the current global output and that this does not increase in the future, then the known current lithium reserves would last 3000 years, lithium from sea water would last 60 million years, and a more complicated fusion process using only deuterium from sea water would have fuel for 150 billion years.[81] Although this process has yet to be realized, many experts believe fusion to be a promising future energy source due to the short lived radioactivity of the produced waste, its low carbon emissions, and its prospective power output.

Solid waste

For more details on this topic, see Radioactive waste.

See also: List of nuclear waste treatment technologies

The most important waste stream from nuclear power plants is spent nuclear fuel. It is primarily composed of unconverted uranium as well as significant quantities of transuranic actinides (plutonium and curium, mostly). In addition, about 3% of it is fission products from nuclear reactions. The actinides (uranium, plutonium, and curium) are responsible for the bulk of the long-term radioactivity, whereas the fission products are responsible for the bulk of the short-term radioactivity.[82]

High-level radioactive waste

See also: High-level radioactive waste management and High-level waste


The Susquehanna Steam Electric Station, a boiling water reactor. The reactors are located inside the rectangular containment buildings towards the front of the cooling towers.

After about 5% of a nuclear fuel rod has reacted inside a nuclear reactor that rod is no longer able to be used as fuel (due to the build-up of fission products). Today, scientists are experimenting on how to recycle these rods so as to reduce waste and use the remaining actinides as fuel (large-scale reprocessing is being used in a number of countries).

A typical 1000-MWe nuclear reactor produces approximately 20 cubic meters (about 27 tonnes) of spent nuclear fuel each year (but only 3 cubic meters of vitrified volume if reprocessed).[83][84] All the spent fuel produced to date by all commercial nuclear power plants in the US would cover a football field to the depth of about one meter.[85]

Spent nuclear fuel is initially very highly radioactive and so must be handled with great care and forethought. However, it will decrease with time. After 40 years, the radiation flux is 99.9% lower than it was the moment the spent fuel was removed from operation. Still, this 0,1% is dangerously radioactive.[77] After 10,000 years of radioactive decay, according to United States Environmental Protection Agency standards, the spent nuclear fuel will no longer pose a threat to public health and safety.[*citation needed*]

When first extracted, spent fuel rods are stored in shielded basins of water (spent fuel pools), usually located on-site. The water provides both cooling for the still-decaying fission products, and shielding from the continuing radioactivity. After a period of time (generally five years for US plants), the now cooler, less radioactive fuel is typically moved to a dry-storage facility or dry cask storage, where the fuel is stored in steel and concrete containers. Most U.S. waste is currently stored at the nuclear site where it is generated, while suitable permanent disposal methods are discussed.

As of 2007, the United States had accumulated more than 50,000 metric tons of spent nuclear fuel from nuclear reactors.[86] Permanent storage underground in U.S. had been proposed at the Yucca Mountain nuclear waste repository, but that project has now been effectively cancelled - the permanent disposal of the U.S.'s high-level waste is an as-yet unresolved political problem.[87]

The amount of high-level waste can be reduced in several ways, particularly nuclear reprocessing. Even so, the remaining waste will be substantially radioactive for at least 300 years even if the actinides are removed, and for up to thousands of years if the actinides are left in.[citation needed] Even with separation of all actinides, and using fast breeder reactors to destroy by transmutation some of the longer-lived non-actinides as well, the waste must be segregated from the environment for one to a few hundred years, and therefore this is properly categorized as a long-term problem. Subcritical reactors or fusion reactors could also reduce the time the waste has to be stored.[88] It has been argued that the best solution for the nuclear waste is above ground temporary storage since technology is rapidly changing. Some people believe that current waste might become a valuable resource in the future.[citation needed]

According to a 2007 story broadcast on *60 Minutes*, nuclear power gives France the cleanest air of any industrialized country, and the cheapest electricity in all of Europe.[89] France reprocesses its nuclear waste to reduce its mass and make more energy.[90] However, the article continues, "Today we stock containers of waste because currently scientists don't know how to reduce or eliminate the toxicity, but maybe in 100 years perhaps scientists will... Nuclear waste is an enormously difficult political problem which to date no country has solved. It is, in a sense, the Achilles heel of the nuclear industry... If France is unable to solve this issue, says Mandil, then 'I do not see how we can continue our nuclear program.'"[90] Further, reprocessing itself has its critics, such as the Union of Concerned Scientists.[91]

Low-level radioactive waste

See also: Low-level waste

The Ikata Nuclear Power Plant, a pressurized water reactor that cools by secondary coolant exchange with the ocean

The nuclear industry also produces a large volume of low-level radioactive waste in the form of contaminated items like clothing, hand tools, water purifier resins, and (upon decommissioning) the materials of which the reactor itself is built. In the United States, the Nuclear Regulatory Commission has repeatedly attempted to allow low-level materials to be handled as normal waste: landfilled, recycled into consumer items, etcetera.[citation needed] Most low-level waste releases very low levels of radioactivity and is only considered radioactive waste because of its history.[92]

Comparing radioactive waste to industrial toxic waste

In countries with nuclear power, radioactive wastes comprise less than 1% of total industrial toxic wastes, much of which remains hazardous indefinitely.[77] Overall, nuclear power produces far less waste material by volume than fossil-fuel based power plants. Coal-burning plants are particularly noted for producing large amounts of toxic and mildly radioactive ash due to concentrating naturally occurring metals and mildly radioactive material from the coal. A recent report from Oak Ridge National Laboratory concludes that coal power actually results in more radioactivity being released into the environment than nuclear power operation, and that the population effective dose equivalent from radiation from coal plants is 100 times as much as from ideal operation of nuclear plants.[93] Indeed, coal ash is much less radioactive than nuclear waste, but ash is released directly into the environment, whereas nuclear plants use shielding to protect the environment from the irradiated reactor vessel, fuel rods, and any radioactive waste on site.[94]

Waste disposal

Disposal of nuclear waste is often said to be the Achilles' heel of the industry.[95] Presently, waste is mainly stored at individual reactor sites and there are over 430 locations around the world where radioactive material continues to accumulate. Experts agree that centralized underground repositories which are well-managed, guarded, and monitored, would be a vast improvement.[95] There is an "international consensus on the advisability of storing nuclear waste in deep underground repositories",[96] but no country in the world has yet opened such a site.[96][97][98][99]

Reprocessing

For more details on this topic, see Nuclear reprocessing.

Reprocessing can potentially recover up to 95% of the remaining uranium and plutonium in spent nuclear fuel, putting it into new mixed oxide fuel. This produces a reduction in long term radioactivity within the remaining waste, since this is largely short-lived fission products, and reduces its volume by over 90%. Reprocessing of civilian fuel from power reactors is currently done on large scale in Britain, France and (formerly) Russia, soon will be done in China and perhaps India, and is being done on an expanding scale in Japan. The full potential of reprocessing has not been achieved because it requires breeder reactors, which are not yet commercially available. France is generally cited as the most successful reprocessor, but it presently only recycles 28% (by mass) of the yearly fuel use, 7% within France and another 21% in Russia.[100]

Reprocessing is not allowed in the U.S.[101] The Obama administration has disallowed reprocessing of nuclear waste, citing nuclear proliferation concerns.[102] In the U.S., spent nuclear fuel is currently all treated as waste.[103]

Depleted uranium

Main article: Depleted uranium

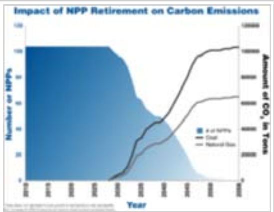
Uranium enrichment produces many tons of depleted uranium (DU) which consists of U-238 with most of the easily fissile U-235 isotope removed. U-238 is a tough metal with several commercial uses—for example, aircraft production, radiation shielding, and armor—as it has a higher density than lead. Depleted uranium is also controversially used in munitions; DU penetrators (bullets or APFSDS tips) "self sharpen", due to uranium's tendency to fracture along shear bands.[104][105]

Economics

Main article: Economics of new nuclear power plants

The economics of new nuclear power plants is a controversial subject, since there are diverging views on this topic, and multi-billion dollar investments ride on the choice of an energy source. Nuclear power plants typically have high capital costs for building the plant, but low fuel costs. Therefore, comparison with other power generation methods is strongly dependent on assumptions about construction timescales and capital financing for nuclear plants. Cost estimates also need to take into account plant decommissioning and nuclear waste storage costs. On the other hand measures to mitigate global warming, such as a carbon tax or carbon emissions trading, may favor the economics of nuclear power.

In recent years there has been a slowdown of electricity demand growth and financing has become more difficult, which has an impact on large projects such as nuclear reactors, with very large upfront costs and long project cycles which carry a large variety of risks.[106] In Eastern Europe, a number of long-established projects are struggling to find finance, notably Belene in Bulgaria and the additional reactors at Cernavoda in Romania, and some potential backers have pulled out.[106] Where cheap gas is available and its future supply relatively secure, this also poses a major problem for nuclear projects.[106]



This graph illustrates the potential rise in CO_2 emissions if base-load electricity currently produced in the U.S. by nuclear power were replaced by coal or natural gas as current reactors go offline after their 60 year licenses expire. Note: graph assumes all 104 American nuclear power plants receive license extensions out to 60 years.

Analysis of the economics of nuclear power must take into account who bears the risks of future uncertainties. To date all operating nuclear power plants were developed by state-owned or regulated utility monopolies[107] where many of the risks associated with construction costs, operating performance, fuel price, accident liability and other factors were borne by consumers rather than suppliers. In addition, because the potential liability from a nuclear accident is so great, the full cost of liability insurance is generally limited/capped by the government, which the U.S. Nuclear Regulatory Commission concluded constituted a significant subsidy.[108] Many countries have now liberalized the electricity market where these risks, and the risk of cheaper competitors emerging before capital costs are recovered, are borne by plant suppliers and operators rather than consumers, which leads to a significantly different evaluation of the economics of new nuclear power plants.[109]

Following the 2011 Fukushima I nuclear accidents, costs are likely to go up for currently operating and new nuclear power plants, due to increased requirements for on-site spent fuel management and elevated design basis threats.[110]

Accidents and safety

Main articles: Nuclear safety and Nuclear and radiation accidents

See also: Lists of nuclear disasters and radioactive incidents

Three of the reactors at Fukushima I overheated, causing meltdowns that eventually led to explosions, which released large amounts of radioactive material into the air.[111]

Following an earthquake, tsunami, and failure of cooling systems at Fukushima I Nuclear Power Plant and issues concerning other nuclear facilities in Japan on March 11, 2011, a nuclear emergency was declared. This was the first time a nuclear emergency had been declared in Japan, and 140,000 residents within 20 km (12 mi) of the plant were evacuated.[112] Explosions and a fire have resulted in dangerous levels of radiation, sparking a stock market collapse and panic-buying in supermarkets.[113] The UK, France and some other countries advised their nationals to consider leaving Tokyo, in response to fears of spreading nuclear contamination. The accidents have drawn attention to ongoing concerns over Japanese nuclear seismic design standards and caused other governments to re-evaluate their nuclear programs. As of April 2011, water is still being poured into the damaged reactors to cool melting fuel rods. John Price, a former member of the Safety Policy Unit at the UK's National Nuclear Corporation, has said that it "might be 100 years before melting fuel rods can be safely removed from Japan's Fukushima nuclear plant".[114]

Nuclear power plant accidents with more than US$300 million in property damage, to 2009[115][116][117]

Date	Location	Description	Cost (in millions 2006 $)[118]
December 7, 1975	Greifswald, East Germany	Electrician's error causes fire in the main trough that destroys control lines and five main coolant pumps	US$443
February 22, 1977	Jaslovské Bohunice, Czechoslovakia	Severe corrosion of reactor and release of radioactivity into the plant area, necessitating total decommission	US$1,700
March 28, 1979	Middletown, Pennsylvania, US	Loss of coolant and partial core meltdown, see Three Mile Island accident and Three Mile Island accident health effects	US$2,400
March 9, 1985	Athens, Alabama, US	Instrumentation systems malfunction during startup, which led to suspension of operations at all three Browns Ferry Units - operations restarted in 1991 for unit 2, in 1995 for unit 3, and (after a $1.8 billion recommissioning operation) in 2007 for unit 1	US$1,830
April 11, 1986	Plymouth, Massachusetts, US	Recurring equipment problems force emergency shutdown of Boston Edison's Pilgrim Nuclear Power Plant	US$1,001
April 26, 1986	Chernobyl, near the town of Pripyat, Ukraine	Steam explosion and meltdown with 4,057 deaths (see Chernobyl disaster) necessitating the evacuation of 300,000 people from the most severely contaminated areas of Belarus, Russia, and Ukraine, and dispersing radioactive material across Europe (see Chernobyl disaster effects)	US$6,700
March 31, 1987	Delta, Pennsylvania, US	Peach Bottom units 2 and 3 shutdown due to cooling malfunctions and unexplained equipment problems	US$400

Nuclear proliferation

Many technologies and materials associated with the creation of a nuclear power program have a dual-use capability, in that they can be used to make nuclear weapons if a country chooses to do so. When this happens a nuclear power program can become a route leading to the atomic bomb or a public annex to a secret bomb program. The crisis over Iran's nuclear activities is a case in point.[119]

A fundamental goal for American and global security is to minimize the nuclear proliferation risks associated with the expansion of nuclear power. If this development is "poorly managed or efforts to contain risks are unsuccessful, the nuclear future will be dangerous".[119]

Environmental effects of nuclear power

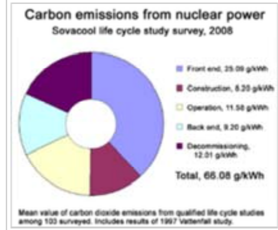
Main articles: Environmental effects of nuclear power and Comparisons of life-cycle greenhouse gas emissions

Life cycle analysis (LCA) of carbon dioxide emissions show nuclear power as comparable to renewable energy sources. Emissions from burning fossil fuels are many times higher.[120][121][122]

Debate on nuclear power

Main article: Nuclear power debate

See also: Nuclear energy policy and Anti-nuclear movement



A 2008 synthesis of 103 studies, published by Benjamin K. Sovacool, estimated that the value of CO_2 emissions for nuclear power over the lifecycle of a plant was 66.08 g/kW·h. Comparative results for various renewable power sources were 9–32 g/kW·h.[120]

The nuclear power debate is about the controversy[9][10][49] which has surrounded the deployment and use of nuclear fission reactors to generate electricity from nuclear fuel for civilian purposes. The debate about nuclear power peaked during the 1970s and 1980s, when it "reached an intensity unprecedented in the history of technology controversies", in some countries.[50][123]

Proponents of nuclear energy contend that nuclear power is a sustainable energy source that reduces carbon emissions and increases energy security by decreasing dependence on imported energy sources.[11] Proponents claim that nuclear power produces virtually no conventional air pollution, such as greenhouse gases and smog, in contrast to the chief viable alternative of fossil fuel. Proponents also believe that nuclear power is the only viable course to achieve energy independence for most Western countries. M. King Hubbert saw oil as a resource which would soon run out, and believed uranium had much more promise as an energy source.[124] Proponents claim that the risks of storing waste are small and can be further reduced by using the latest technology in newer reactors, and the operational safety record in the Western world is excellent when compared to the other major kinds of power plants.[125]

Opponents believe that nuclear power poses many threats to people and the environment.[12][13][14] These threats include the problems of processing, transport and storage of radioactive nuclear waste, the risk of nuclear weapons proliferation and terrorism, as well as health risks and environmental damage from uranium mining.[126][127] They also contend that reactors themselves are enormously complex machines where many things can and do go wrong, and there have been serious nuclear accidents.[116][128] Critics do not believe that the risks of using nuclear fission as a power source can be offset through the development of new technology. They also argue that when all the energy-intensive stages of the nuclear fuel chain are considered, from uranium mining to nuclear decommissioning, nuclear power is not a low-carbon electricity source.[129][130][131]

Arguments of economics and safety are used by both sides of the debate.

Nuclear power organizations

Against

Main article: List of anti-nuclear power groups

- Friends of the Earth International, a network of environmental organizations in 77 countries.[132]
- Greenpeace International, a non-governmental environmental organization[133] with offices in 41 countries.[134]
- Nuclear Information and Resource Service (International)
- Sortir du nucléaire (Canada)
- Sortir du nucléaire (France)
- Pembina Institute (Canada)
- Institute for Energy and Environmental Research (United States)

Supportive

Main article: List of nuclear power groups

- World Nuclear Association, a confederation of companies connected with nuclear power production. (International)
- International Atomic Energy Agency (IAEA)
- Nuclear Energy Institute (United States)
- American Nuclear Society (United States)
- United Kingdom Atomic Energy Authority (United Kingdom)
- EURATOM (Europe)
- Atomic Energy of Canada Limited (Canada)
- Environmentalists for Nuclear Energy (International)

Nuclear renaissance

Main article: Nuclear renaissance

Since about 2001 the term "nuclear renaissance" has been used to refer to a possible nuclear power industry revival, driven by rising fossil fuel prices and new concerns about meeting greenhouse gas emission limits. Being able to rely on an uninterrupted domestic supply of electricity is also a factor. In the words of the French, "We have no coal, we have no oil, we have no gas, we have no choice."[135] Improvements in nuclear reactor safety, and the public's waning memory of past nuclear accidents (Three Mile Island in 1979 and Chernobyl in 1986), as well as of the plant construction cost overruns of the 1970s and 80s, are lowering public resistance to new nuclear construction.[136]

At the same time, various barriers to a nuclear renaissance have been identified. These include: unfavourable economics compared to other sources of energy, slowness in addressing climate change, industrial bottlenecks and personnel shortages in nuclear sector, and the unresolved nuclear waste issue. There are also concerns about more accidents, security, and nuclear weapons proliferation.[18][137][138][139]

New reactors under construction in Finland and France, which were meant to lead a nuclear renaissance, have been delayed and are running over-budget.[140][141][142] China has 20 new reactors under construction,[143] and there are also a considerable number of new reactors being built in South Korea, India, and Russia. At least 100 older and smaller reactors will "most probably be closed over the next 10-15 years".[144]

However, in 2011 the nuclear emergencies at Japan's Fukushima I Nuclear Power Plant and other nuclear facilities raised questions among commentators over the future of the renaissance.[145][146][147][148][149] Platts has reported that "the crisis at Japan's Fukushima nuclear plants has prompted leading energy-consuming countries to review the safety of their existing reactors and cast doubt on the speed and scale of planned expansions around the world".[150] Many countries are re-evaluating their nuclear energy programs and in April 2011 a study by UBS predicted that around 30 nuclear plants may be closed world-wide as a result, with those located in seismic zones or close to national boundaries being the most likely to shut. The UBS analysts believe that 'even pro-nuclear counties such as France will be forced to close at least two reactors to demonstrate political action and restore the public acceptability of nuclear power', noting that the events at Fukushima 'cast doubt on the idea that even an advanced economy can master nuclear safety'.[151] Canadian uranium-mining company Cameco expects the size of world's fleet of operating reactors in 2020 to increase by about 90 reactors, 10% less than before the Fukushima accident.[152]

Future of the industry

See also: List of prospective nuclear units in the United States, Nuclear power in the United States, Nuclear energy policy, and Mitigation of global warming


Brunswick Nuclear Plant discharge canal

As of 2007, Watts Bar 1 in Tennessee, which came on-line on February 7, 1996, was the last U.S. commercial nuclear reactor to go on-line. This is often quoted as evidence of a successful worldwide campaign for nuclear power phase-out. However, even in the U.S. and throughout Europe, investment in research and in the nuclear fuel cycle has continued, and some nuclear industry experts[153] predict electricity shortages, fossil fuel price increases, global warming and heavy metal emissions from fossil fuel use, new technology such as passively safe plants, and national energy security will renew the demand for nuclear power plants.

According to the World Nuclear Association, globally during the 1980s one new nuclear reactor started up every 17 days on average, and by the year 2015 this rate could increase to one every 5 days.[154]

There is a possible impediment to production of nuclear power plants as only a few companies worldwide have the capacity to forge single-piece reactor pressure vessels,[155] which are necessary in the most common reactor designs. Utilities across the world are submitting orders years in advance of any actual need for these vessels. Other manufacturers are examining various options, including making the component themselves, or finding ways to make a similar item using alternate methods.[156] Other solutions include using designs that do not require single-piece forged pressure vessels such as Canada's Advanced CANDU Reactors or Sodium-cooled Fast Reactors.


The CANDU Bruce Nuclear Generating Station in Ontario, Canada is the second largest nuclear power plant in the world.

China has 25 reactors under construction, with plans to build more,[157] while in the US the licenses of almost half its reactors have been extended to 60 years,[158] and plans to build another dozen are under serious consideration.[159] China may achieve its long-term plan of having 40,000 megawatts of nuclear power capacity four to five years ahead of schedule.[160] However, according to a government research unit, China must not build "too many nuclear power reactors too quickly", in order to avoid a shortfall of fuel, equipment and qualified plant workers.[161]

The U.S. NRC and the U.S. Department of Energy have initiated research into Light water reactor sustainability which is hoped will lead to allowing extensions of reactor licenses beyond 60 years, in increments of 20 years, provided that safety can be maintained, as the loss in non-CO_2-emitting generation capacity by retiring reactors "may serve to challenge U.S. energy security, potentially resulting in increased greenhouse gas emissions, and contributing to an imbalance between electric supply and demand."[162]

Following the Fukushima I nuclear accidents, the International Energy Agency halved its estimate of additional nuclear generating capacity to be built by 2035.[163] Platts has reported that "the crisis at Japan's Fukushima nuclear plants has prompted leading energy-consuming countries to review the safety of their existing reactors and cast doubt on the speed and scale of planned expansions around the world".[150] In 2011, *The Economist* reported that nuclear power "looks dangerous, unpopular, expensive and risky", and that "it is replaceable with relative ease and could be forgone with no huge structural shifts in the way the world works".[164]

Climate change

Climate change causing weather extremes such as heat waves, reduced precipitation levels and droughts can have a significant impact on nuclear energy infrastructure.[165] Seawater is corrosive and so nuclear energy supply is likely to be negatively affected by the fresh water shortage.[165] This generic problem may become increasingly significant over time.[165] This can force nuclear reactors to be shut down, as happened in France during the 2003 and 2006 heat waves. Nuclear power supply was severely diminished by low river flow rates and droughts, which meant rivers had reached the maximum temperatures for cooling reactors.[165] During the heat waves, 17 reactors had to limit output or shut down. 77% of French electricity is produced by nuclear power and in 2009 a similar situation created a 8GW shortage and forced the French government to import electricity.[165] Other cases have been reported from Germany, where extreme temperatures have reduced nuclear power production 9 times due to high temperatures between 1979 and 2007.[165] In particular:

- the Unterweser nuclear power plant reduced output by 90% between June and September 2003[165]
- the Isar nuclear power plant cut production by 60% for 14 days due to excess river temperatures and low stream flow in the river Isar in 2006[165]

Similar events have happened elsewhere in Europe during those same hot summers.[165] If global warming continues, this disruption is likely to increase.

See also

- Alsos Digital Library for Nuclear Issues
- Anti-nuclear protests
- German nuclear energy project
- Linear no-threshold model
- List of military nuclear accidents
- Lists of nuclear disasters and radioactive incidents
- Nuclear power phase-out
- Nuclear weapons debate
- Uranium mining debate
- World energy resources and consumption

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Further reading

See also: List of books about nuclear issues and List of films about nuclear issues

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External links

- Reactor Power Plant Technology Education (http://www.acme-nuclear.com/) — Includes the PC-based BWR reactor simulation.
- Alsos Digital Library for Nuclear Issues — Annotated Bibliography on Nuclear Power (http://alsos.wlu.edu/default.aspx)
- An entry to nuclear power through an educational discussion of reactors (http://www.chemcases.com/2003version/nuclear/nc-10.htm)
- Argonne National Laboratory — Maps of Nuclear Power Reactors (http://www.insc.anl.gov/pwrmaps/)
- Briefing Papers from the Australian EnergyScience Coaltion (http://energyscience.org.au/)
- British Energy — Understanding Nuclear Energy / Nuclear Power (http://www.british-energy.com/pagetemplate.php?pid=312)
- Coal Combustion: Nuclear Resource or Danger? (http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html)
- Congressional Research Service report on Nuclear Energy Policy (http://usinfo.state.gov/usa/infousa/tech/energy/nuclear.pdf) PDF (94.0 KB)
- Energy Information Administration (http://eia.doe.gov/) provides lots of statistics and information
- How Nuclear Power Works (http://science.howstuffworks.com/nuclear-power.htm)
- IAEA Website (http://www.iaea.org/) The International Atomic Energy Agency
  - IAEA's Power Reactor Information System (PRIS) (http://www.iaea.org/programmes/a2/)
- Nuclear Power: Climate Fix or Folly? (http://www.rmi.org/rmi/Library/E09-01_NuclearPowerClimateFixOrFolly) (2009)
- Nuclear Power Education (http://nuclearinfo.net/)
- Nuclear Tourist.com (http://www.nucleartourist.com/) , nuclear power information
- Nuclear Waste Disposal Resources (http://pepei.pennnet.com/resource/nuclear%20waste%20disposal)
- The World Nuclear Industry Status Report 2009 (http://www.bmu.de/english/nuclear_safety/downloads/doc/44832.php) .
- Wilson Quarterly — Nuclear Power: Both Sides (http://www.wilsoncenter.org/index.cfm?fuseaction=wq.essay&essay_id=203041)