Nuclear Power

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Nuclear power From Wikipedia, the free encyclopedia. A nuclear power station. Non-radioactive water vapor rises from the hyperboloid shaped cooling towers. The nuclear reactors are inside the cylindrical containment buildings.

Nuclear power is the use of nuclear reactions to generate power, usually electrical, such as in an atomic battery or a nuclear power plant.

Nuclear power plants generate power by nuclear fission reactions which occur when sufficient amounts of uranium-235 and/or plutonium are confined to a small space, often in the presence of a neutron moderator. The reaction produces heat which is converted to kinetic energy by means of a steam turbine and then a generator for electricity production. Nuclear power provides about 20% of the U.S.'s electricity [1], 17% of the world's and 7% of total global energy. An international effort into the use of nuclear fusion for power is ongoing, but not expected to be available in commercially viable form for several decades.

After a period of decline following the 1979 Three Mile Island accident and the 1986 incident at Chernobyl, there is currently a renewed interest in nuclear energy because on the one hand nuclear energy produces electricity without requiring fossil fuels or releasing green house gasses (except for the mining veicles and coal-fired plants used to process the fuel); on the other, it produces long term nuclear waste, the method of disposal of which has not come to consensus; on the one hand nuclear power resulted in the Chernobyl disaster and three mile island; On the other, far more people die in coal mines each year than uranium mines and nuclear plants.

The use of nuclear power is controversial because of the problem of storing radioactive waste for indefinite periods, the potential for possibly severe radioactive contamination by accident or sabotage, and the possibility that its use could in some countries lead to the proliferation of nuclear weapons. Proponents, including some national governments, claim that these risks are small and can be lessened with new technology. They further claim that France and all of the industrialised economies of Asia [2] see nuclear power as a key economic strategy, that the safety record is already good when compared to other energy forms, that it releases much less radioactive waste than coal power, and that nuclear power is a sustainable energy source. Many environmental groups claim nuclear power is an uneconomic, unsound and potentially dangerous energy source, especially compared to renewable energy, and dispute whether the costs and risks can be reduced through new technology.

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Origins

The first successful experiment with nuclear fission was conducted in 1938 in Berlin by the German physicists Otto Hahn, Lise Meitner and Fritz Strassman.

During the Second World War, a number of nations embarked on crash programs to develop nuclear energy, focusing first on the development of nuclear reactors. The first self-sustaining nuclear chain reaction was obtained by Enrico Fermi on December 2nd,1942, and reactors based on his research were used to produce the plutonium necessary for the "Fat Man" weapon dropped on Nagasaki, Japan. Several nations began their own construction of nuclear reactors at this point, primarily for weapons use, though research was also being conducted into their use for civilian electricity generation.

Electricity was generated for the first time by a nuclear reactor on December 20, 1951 at the EBR-I experimental fast breeder station near Arco, Idaho, which initially produced about 100 kW.

In 1952 a report by the Paley Commission (The President's Materials Policy Commission) for President Harry Truman made a "relatively pessimistic" assessment of nuclear power, and called for "aggressive research in the whole field of solar energy". [3]

A December 1953 speech by President Dwight Eisenhower, "Atoms for Peace", set the US on a course of strong government support for the international use of nuclear power. [edit]

Early years

On June 27, 1954, the world's first nuclear power plant that generated electricity for commercial use was officially connected to the Soviet power grid at Obninsk, USSR. The reactor was graphite moderated, water cooled and had a capacity of 5 megawatts (MW). The second reactor for commercial purposes (1956) was Calder Hall in Sellafield, England, a gas-cooled Magnox reactor with an initial capacity of 45 MW (later 196 MW). The Shippingport Reactor (Pennsylvania, 1957), a pressurised-water reactor, was the first commercial nuclear generator to become operational in the United States.

In 1954, the chairman of the United States Atomic Energy Commission (forerunner of the US Nuclear Regulatory Commission) famously declared that nuclear power would be "too cheap to meter" [4] and foresaw 1000 nuclear plants on line in the USA by the year 2000.

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).

Thanks to the presence of the nearby Bettis Laboratory and the Shippingport power plant, Pittsburgh, Pennsylvania became the world's first nuclear powered city in 1960. [edit]

Development

Installed nuclear capacity initially rose relatively quickly, rising from less than 1 gigawatt (GW) in 1960 to 100GW in the late 1970s, and 300GW in the late 1980s. Since the late 1980s capacity has risen much more slowly, reaching 366GW in 2005, primarily due to Chinese expansion of nuclear power. Between around 1970 and 1990, more than 50GW of capacity was under construction (peaking at over 150GW in the late 70s and early 80s) - currently around 25GW of capacity is planned. More than two-thirds of all nuclear plants ordered after January 1970 were eventually cancelled.[5]

Rising economic costs (related to vastly extended construction times) and falling fossil fuel prices gradually made nuclear power less economically competitive during the 1970s and 1980s. In the 1980s (US) and 1990s (Europe), electricity liberalization also played a part in increasing the financial risks of investing in nuclear power.

A popular movement against nuclear power also gained strength in the World, based on the fear of a possible

nuclear accident and on fears of latent radiation, and on the opposition to nuclear waste production, transport and final storage. Those risks on the citizens health and safety, the 1979 accident at Three Mile Island and the 1986 Chernobyl accident played a key part in stopping new plant construction in many countries. Austria (1978), Sweden (1980) and Italy (1987) voted in referendums to oppose or phase out nuclear power, while opposition in Ireland prevented a nuclear programme there. The Brookings institution suggests that nuclear power may have been phased out for primarily economic reasons rather than fears of accidents. The use of nuclear power for electricity generation have been suspected of encouraging nuclear proliferation in some countries like recently in Iran.
[edit]

Future plans

The countries which shut down nuclear power plants have to find alternatives for energy generation. Therefore, the discussion of a future for nuclear energy is intertwined with a discussion of renewable energy development. The most discussed alternatives to nuclear power include hydroelectricity, fossil energy, solar energy, and biomass (see also alternative energy).

However nuclear power still continued in many other countries, notably France, Japan, the former USSR and recently China. The 1600MW EPR reactor being built in Olkiluoto, Finland, will be the largest in the world. The U.S. is planning new plants (see Current and Planned Use below). [edit]

Current and planned use

In 2005, there were 441 commercial nuclear generating units throughout the world, with a total capacity of about 368 gigawatts.[6] 111 reactors (36GW) have been shut down.[7] 80% of reactors (and of generating capacity) are more than 15 years old.[8]

In 2004 in the United States, there were 104 (69 pressurized water reactors and 35 boiling water reactors) commercial nuclear generating units licensed to operate, producing a total of 97,400 megawatts (electric), which is approximately 20 percent of the nation's total electric energy consumption. The United States is the world's largest supplier of commercial nuclear power. Future development of nuclear power in the U.S. (see the Nuclear Power 2010 Program) was enabled by the Energy Policy Act of 2005 [9]. As of 2005, no nuclear plant had been ordered without subsequent cancellation for over twenty years, thus the desire for programs to promote new construction. However, on September 22, 2005 it was announced that two sites in the U.S. had been selected to receive new power reactors (exclusive of the new power reactor scheduled for INL) - see Nuclear Power 2010 Program.

In France, as of 2005, 78% of all billed electrical energy was generated by 58 nuclear reactors, the highest share in the world. Some sources cite Lithuania as the world's most nuclear-dependant nation, generating 85% of its power from nuclear reactors. However, this is mostly a testament to the country's low power demand, as Lithuania runs only a single 1500MWe RBMK-2 at its Ignalina Nuclear Power Plant.[10]

Argentina, Brazil, Canada, China, Finland, India, Iran, Japan, North Korea, Pakistan, Romania, Russia, South Korea, Taiwan, Ukraine, and the U.S. are currently planning or building new nuclear reactors or reopening old ones. Bulgaria, Czech Republic, Egypt, France, Indonesia, Israel, Slovakia, South Africa, Turkey, United Kingdom and Vietnam , are considering doing this. Armenia, Belgium, Germany, Hungary, Lithuania, Mexico, Netherlands, Slovenia, Spain, Sweden, and Switzerland have nuclear reactors but currently no advanced proposals for expansion. [11] [12][13]. Belgium, Germany, Italy, Spain and Sweden have decided on a nuclear power phase-out.

According to the EIA and the IEA, nuclear power is projected to have a slightly declining 5-10% share of world energy production until 2025, assuming that fossil fuel production can continue to expand rapidly (which is controversial). See Future energy development. [edit]

Reactor Types [edit]

Current Technology

There are two types of nuclear power sources in current use:
- The nuclear fission reactor produces heat through a controlled nuclear chain reaction in a critical mass of fissile material. All current nuclear power plants are critical fission reactors, which are the focus of this article. The output of fission reactors is controllable. There are several subtypes of critical fission reactors. All reactors will be compared to the Pressurized Water Reactor (PWR), as that is the standard modern reactor design.
- a. Pressurized water reactors (PWR): These are reactors cooled and moderated by high pressure, liquid (even at extreme temperatures) water. They are the majority of current reactors, and are generally considered the safest and most reliable technology. Three Mile Island is a reactor of this type. This is a thermal

neutron reactor design.

- b. Boiling water reactors (BWR): These are reactors cooled and moderated by water, under slightly lower pressure. The water is allowed to boil in the reactor. The thermal efficiency of these reactors can be higher, and they can be simpler, and even potentially more stable and safe. Unfortunately, the boiling water puts more stress on many of the components, and increases the risk that radioactive water may escape in an accident. These reactors make up a substantial percentage of modern reactors. This is a thermal neutron reactor design.
- c. CANDU: An indigenous Canadian design, these reactors are heavy-water-cooled and -moderated Pressurized-Water reactors. Instead of using a single large containment vessel as in a PWR, the fuel is contained in hundreds of pressure tubes. These reactors are fuelled with natural uranium and are thermal neutron reactor designs. CANDUs can be refueled while at full-power, which makes them very efficient in their use of uranium (it allows for precise flux control in the core), and also makes it possible to misuse them as plutonium breeders. Most CANDUs exist within Canada, but units have been sold to Argentina, China, India (pre-NPT), Pakistan (pre-NPT), Romania, and South Korea. India also operates a number of 'CANDU-derivatives', built after the 1974 Smiling Buddha nuclear weapon test.
- d. RBMKs: A design unique to the Soviet Union built to produce plutonium as well as power, the dangerous and unstable RBMKs were water cooled with a graphite moderator. RBMKs are similar to CANDU in that they are refuelable On-Load and employ a pressure tube design instead of a PWR-style pressure vessel. Notably, they were too large and powerful to have containment buildings. Chernobyl was an RBMK.
- e. Gas Cooled Reactor (GCR) and Advanced Gas Cooled Reactor: These are generally graphite moderated, and CO2 cooled. They have a high thermal efficiency compared with PWRs and an excellent safety record. There are a number of operating reactors of this design mostly in the United Kingdom, older designs (i.e. Magnox stations) are either shut down or will be with in the near future. However the AGRs have an anticipated life of a further 10 to 20 years. This is a thermal neutron reactor design.
- f. Super Critical Water-cooled Reactor (SCWR): This is a theoretical reactor design that is part of the Gen-IV reactor project. It combines higher efficiency than a GCR with the safety of a PWR, though it is perhaps more technically challenging than either. The water is pressurized and heated past its critical point, until there is no difference between the liquid and gas states. A CWR is similar to a BWR, except there is no boiling (as the water is critical), and the thermal efficiency is higher as the water behaves more like a classical gas. This is a epithermal neutron reactor design.
- g. Liquid Metal Fast Breeder Reactor (LMFBR): This is a reactor design that is cooled by liquid metal, and totally unmoderated. These reactors can function much like a PWR in terms of efficiency, and don't require much high pressure containment, as the liquid metal doesn't need to be kept at high pressure, even at very high temperatures. Superphénix in France was a reactor of this type, as was Fermi-I in the United States. The Monju reactor in Japan suffered a sodium leak in 1995 and is approved for restart in 2008. All three use/used liquid sodium. These reactors are fast neutron, not thermal neutron designs. These reactors come in two types:
- g-I. Lead Cooled: Using lead as the liquid metal provides excellent radiation shielding, and allows for operation at very high temperatures. Also, lead is (mostly) transparent to neutrons, so fewer neutrons are lost in the coolant, and the coolant does not become radioactive. Unlike sodium, lead is mostly inert, so there is less risk of explosion or accident, but such large quantities of lead may be problematic from toxicology and disposal points of view. Often a reactor of this type would use a lead-bismuth eutectic mixture. In this case, the bismuth would present some minor radiation problems, as it is not quite as transparent to neutrons, and can be transmuted to a radioactive isotope more readily than lead.
- g-II. Sodium Cooled: Most LMFBRs are of this type. The sodium is relatively easy to obtain and work with, and it also manages to actually remove corrosion on the various reactor parts immersed in it. However, sodium explodes violently when exposed to water, so care must be taken, but such explosions wouldn't be vastly more violent than (for example) a leak of superheated fluid from a CWR or PWR. Some of the sodium will be converted to Na-22 by the neutrons in the reactor, so the risk in an accident is somewhat greater, as the sodium itself is fairly dangerous for a few years, after being removed from the core. The difference between fast-spectrum and thermal-spectrum reactors will be covered later. In general, fast-spectrum reactors will produce less waste, and the waste they do produce will have a vastly lower halflife, but they are more difficult to build, and more expensive to operate. Fast reactors can also be breeders, whereas thermal reactors generally cannot.
- The radioisotope thermoelectric generator produces heat through passive radioactive decay. Some radioisotope thermoelectric generators have been created to power space probes (for example, the Cassini probe), some lighthouses in the former Soviet Union, and some pacemakers. The heat output of these generators is diminishes with time; the heat is converted to electricity by thermocouples.

For more details on this topic, see Nuclear power plant. [edit]

Experimental Technologies

A number of other designs for nuclear power generation are the subject of active research and may be used for practical power generation in the future. A number of advanced nuclear reactor designs could also make critical fission reactors much cleaner and safer.

- Integral Fast Reactor - The link at the end of this paragraph references an interview with Dr. Charles Till, former director of Argonne National Laboratory West in Idaho and outlines the Integral Fast Reactor and its advantages over current reactor design, especially in the areas of safety, efficient nuclear fuel usage and reduced waste. The IFR was built, tested and evaluated during the 1980's and then retired under the Clinton administration in the 1990's due to nuclear non-proliferation policies of the administration. Recycling spent fuel is the core of its design and it therefore produces a fraction of the waste of current reactors. [14]
- Pebble Bed Reactor - This reactor type is designed so high temperatures reduce power output by doppler broadening of the fuel's neutron cross-section. It uses ceramic fuels so its safe operating temperatures exceed the power-reduction temperature range. Most designs are cooled by inert helium, which cannot have steam explosions, and which does not easily absorb neutrons and become radioactive, or dissolve contaminants that can become radioactive. Typical designs have more layers (up to 7) of passive containment than light water reactors (usually 3). A unique feature that might aid safety is that the fuel-balls actually form the core's mechanism, and are replaced one-by-one as they age. The containment makes fuel reprocessing expensive.
- Subcritical reactors are designed to be safer and more stable, but pose a number of engineering and economic difficulties.
- Controlled nuclear fusion could in principle be used in fusion power plants to produce safer, cleaner power, but significant scientific and technical obstacles remain. Several fusion reactors have been built, but as of yet none has produced more energy than it consumed. Despite research having started in the 1950s, no commercial fusion reactor is expected before 2050 [15]. The ITER project is currently leading the effort to commercialize fusion power.

Nuclear power primarily produces concentrated heat. This can be converted to electricity and this currently constitutes a small but significant percentage of worldwide electricity generation. The heat can also be converted to mechanical work and this is the power source for many large military ocean going vessels (and a few commercial or government vessels). Other possible uses for the heat is in chemical processes, such as in the production of hydrogen, desalination [16], or direct heating of houses, especially by the massive amount of low grade waste heat generated by power plants. [edit]

Life cycle

Nuclear fuel cycle begins when uranium is mined, enriched and manufactured to 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). Nuclear fuel - a compact, inert, insoluble solid.

Main article: Nuclear fuel cycle

A Nuclear Reactor is only a small part of the life-cycle for nuclear power. The process starts with mining. Generally, uranium mines are either open-pit strip mines, or in-situ leach mines. In either case, the uranium ore is extracted, usually converted into a stable and compact form such as yellowcake, and then transported to a processing facility. At the reprocessing facility, 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 years inside the reactor, generally until about 3% of their uranium has been fissioned, then they will be moved to a cooling pond where the short lived isotopes generated by fission can decay away. After about 5 years in a cooling pond, the spent fuel is radioactively cool enough to handle, and it can be moved to dry storage casks or reprocessed. [edit]

Fuel resources

At the present rate of use, there are 50 years left of low-cost known uranium reserves - however, given that the cost of fuel is a minor cost factor for fission power, more expensive lower-grade sources of uranium could be used in the future [17] [18]. Other ideas include extraction from seawater and granite - although there is controversy on this issue. Arguments for and against these ideas can be found at [19], [20] (for), and [21] (against).

Another alternative would be to use thorium as fission fuel in breeder reactors - thorium is three times more abundant in the Earth crust than uranium [22].

Current light water reactors make relatively inefficient use of nuclear fuel, leading to energy waste. More efficient reactor designs or nuclear reprocessing [23] would reduce the amount of waste material generated and allow better use of the available resources.

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 anywhere from 10,000 to five billion years worth of Uranium-238 for use in these power plants [24]. Breeder technology has been used in several reactors [25]. Currently (December 2005), the only breeder reactor producing power is BN-600 [26] 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.

Proposed fusion reactors assume the use of deuterium, an isotope of hydrogen, as fuel and in most current designs also lithium. 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. [27] [edit]

Reprocessing

For more details on this topic, see Nuclear reprocessing

Reprocessing can recover up to 95% of the remaining uranium and plutonium in spent nuclear fuel, putting it into new mixed oxide fuel. Reprocessing of civilian fuel from power reactors is currently done on large scale in England, France and (formerly) Russia, will be in China and perhaps India, and is being done on an expanding scale in Japan. Iran has announced its intention to complete the nuclear fuel cycle via reprocessing, a move which has led to criticism from the United States and the International Atomic Energy Agency. [28] Reprocessing of civilian nuclear fuel is not done in the United States due to proliferation concerns. [edit]

Solid waste

For more details on this topic, see Nuclear waste.

Nuclear power produces spent fuel, a unique solid waste problem. Because spent nuclear fuel is radioactive, extra care and forethought are given to facilitate their safe storage (see nuclear waste). The waste from highly radioactive spent fuel needs to be handled with great care and forethought due to the long half-lives of the radioactive isotopes in the waste. Also, during reactor operation, the reaction chamber is bombarded with high-energy neutrons - this makes the decommissioning process more expensive when the reactor reaches the end of its life cycle (40 to 60 years for many current designs). However, spent nuclear fuel becomes less radioactive over time - after 40 years 99.9% of radiation disappears [29].

Spent fuel 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 made of fission products. 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. It is possible through reprocessing to separate out the actinides and use them again for fuel, but this often requires special fast spectrum reactors, which produce a reduction in long term radioactivity within the remaining waste. In any case, 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. Even in the most optimistic scenarios (complete consumption of all actinides, and using fast spectrum reactors to destroy some of the long-lived non-actinides as well), the waste must be segregated from the environment for at least several hundred years, and therefore this is properly categorized as a long term problem.

The average nuclear power station produces 20-30 tonnes of spent fuel each year.[30] As of 2003, the United States had accumulated about 49,000 metric tons of spent nuclear fuel from nuclear reactors. Unlike other countries, U.S. policy forbids recycling of used fuel and it is all treated as waste. 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.

The safe storage and disposal of nuclear waste is a difficult challenge. Because of potential harm from radiation, spent nuclear fuel must be stored in shielded basins of water, or in dry storage vaults or dry cask storage until its radioactivity decreases naturally ("decays") to safe levels. This can take days or thousands of years, depending on the type of fuel. Most waste is currently stored in temporary storage sites, requiring constant maintenance, while suitable permanent disposal methods are discussed. Underground storage at Yucca Mountain in U.S. has been proposed as permanent storage. See the article on the nuclear fuel cycle for more information.

The nuclear industry produces a 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, etc. Much low-level waste releases very low levels of radioactivity and is essentially considered radioactive waste because of its history. For example, according to the standards of the NRC, the radiation released by coffee is enough to treat it as low level waste. Overall, nuclear power produces far less waste material than fossil-fuel based power plants. Coal-burning plants are particularly noted for producing large amounts of radioactive ash due to concentrating naturally occurring radioactive material in the coal.

In addition, the nuclear industry fuel cycle produces many tons of depleted uranium (uranium from which the easily fissile U235 element has been removed, leaving behind only U238). This material is much more concentrated than natural uranium ores, and must be disposed of. U238 is a very tough metal with several commercial uses, for example aircraft production and radiation shielding. In particular, depleted uranium is much sought after for making bullets and armor, as it has higher density than even lead. There has been some concern that this may be causing health problems in some groups exposed to this material excessively, such as tank crews.

The amounts of waste can be reduced in several ways. Both nuclear reprocessing and fast breeder reactors can reduce the amounts of waste and increase the amount of energy gained per fuel unit. Subcritical reactors or fusion reactors could greatly reduce the time the waste has to be stored [31]. Subcritical reactors may also be able to do the same to already existing waste. It has been argued that the best solution for the nuclear waste is above ground temporary storage since technology is rapidly changing. The current waste may well become valuable fuel in the future, particularly if it is not reprocessed, as in the U.S.

In countries with nuclear power, radioactive wastes comprise less than 1% of total industrial toxic wastes (which remains hazardous indefinitely) [32]. [edit]

Economy

Opponents of nuclear power claim that any of the environmental benefits are outweighed by safety compromises and by the costs related to construction and operation of nuclear power plants, including costs for spent-fuel disposition and plant retirement. Proponents of nuclear power state that nuclear energy is the only power source which explicitly factors the estimated costs for waste containment and plant decommissioning into its overall cost, and that the quoted cost of fossil fuel plants is deceptively low for this reason. The cost of some renewables would be increased too if they included necessary back-up due to their intermittent nature.

A UK Royal Academy of Engineering report in 2004 looked at electricity generation costs from new plants in the UK. In particular it aimed to develop "a robust approach to compare directly the costs of intermittent generation with more dependable sources of generation". This meant adding the cost of standby capacity for wind, as well as carbon values up to £30 (€45.44) per tonne CO2 for coal and gas. Wind power was calculated to be more than twice as expensive as nuclear power. Without a carbon tax, the cost of production through coal, nuclear and gas ranged £0.22-0.26/kWh and coal gasification was £0.32/kWh. When carbon tax was added (up to £0.25) coal came close to onshore wind (including back-up power) at £0.54/kWh - offshore wind is £0.72/kWh. Nuclear power remained at £0.23/kWh either way, as it produces negligible amounts of CO2. Nuclear figures included decommissioning costs. [33] (see also [34]). (See also the MIT report.) [edit]

Capital costs

Generally, a single nuclear power plant is significantly more expensive to build than a single steam-based coal-fired plant. A coal plant is itself more expensive to build than a single natural gas-fired combined-cycle plant, making it possible for a utility to build additional natural gas plants in smaller increments, and in areas of low power consumption. (However, coal is significantly more expensive than nuclear fuel, and natural gas significantly more expensive than coal - thus natural gas-generated power is the most expensive.)

In many countries, licensing, inspection and certification of nuclear power plants has added delays and construction costs to their construction. In the U.S. many new regulations were put in place after the Three Mile Island partial meltdown. Building gas-fired or coal-fired plants has not had these problems. Because a power plant does not yield profits during construction, longer construction times translated directly into higher interest charges on borrowed construction funds. However, the regulatory processes for siting, licensing, and constructing have been standardized since their introduction, to make construction of newer and safer designs more attractive to companies.

In Japan and France, construction costs and delays are significantly less because of streamlined government licensing and certification procedures. In France, one model of reactor was type-certified, using a safety engineering process similar to the process used to certify aircraft models for safety. That is, rather than licensing individual reactors, the regulatory agency certified a particular design and its construction process to produce safe reactors. U.S. law permits type-licensing of reactors, a process which is about to be used [35].

To encourage development of nuclear power, under the Nuclear Power 2010 Program the U.S. Department of Energy (DOE) has offered interested parties the opportunity to introduce France's model for licensing and to subsidize 25% to 50% of the construction cost overruns due to delays for the first six new plants. Several applications were made, two sites have been chosen to receive new plants, and other projects are pending. [edit]

Operating costs

In the U.S. coal and nuclear power plants must operate more cheaply than natural gas plants to be built. In general, coal and nuclear plants have the same operating costs (operations and maintenance plus fuel costs). However, nuclear and coal differ in the source of those costs. Nuclear has lower fuel costs but higher operating and maintenance costs than coal. In recent times in the United States these operating costs have not been low enough for nuclear to repay its high investment costs. Thus new nuclear reactors have not been built in the United States. Coal's operating cost advantages have only rarely been sufficient to encourage the construction of new coal based power generation. Around 90 to 95 percent of new power plant construction in the United States has been natural gas-fired. These numbers exclude capacity expansions at existing coal and nuclear units.

To be competitive in the current market, both the nuclear and coal industries must reduce new plant investment costs and construction time. The burden is clearly greater for nuclear producers than for coal producers, because investment costs are higher for nuclear plants, which also have the same operating costs. Operation and maintenance costs are particularly important because they represent a large portion of costs for nuclear power.

One of the primary reasons for the uncompetitiveness of the nuclear industry has been the reluctance of the U.S. government to tax carbon emissions which causes global warming. Only when the negative externalities of coal and gas consumption in the form of carbon emissions is taxed will nuclear industry become competitive. The U.S. government has been unwilling to join Kyoto protocol which would have ensured that the free market would dictate efficient quantities of nuclear power production but has instead been willing to ensure that the Government decides behind closed doors in an untransparent manner how subsidies are doled out. [edit]

Subsidies

Critics of nuclear power claim that it is the beneficiary of inappropriately large economic subsidies — mainly taking the forms of taxpayer-funded research and development and limitations on disaster liability — and that these subsidies, being subtle and indirect, are often overlooked when comparing the economics of nuclear against other forms of power generation. However, competing energy sources also receive subsidies. Fossil fuels receive large direct and indirect subsidies, like tax benefits and not having to pay for their pollution [36]. Renewables receive large direct production subsidies and tax breaks in many nations [37].

Energy research and development (R&D) for nuclear power has and continues to receive much larger state subsidies than R&D for renewable energy or fossil fuels. However, today most of this takes places in Japan and France: in most other nations renewable R&D get more money. In the U.S., public research money for nuclear fission declined from 2179 to 35 million dollars between 1980 to 2000 [38] - however, in order to restart the industry, the next six U.S. reactors will receive subsidies equal to those of renewables and, in the event of cost overruns due to delays, at least partial compensation for the overruns (see Nuclear Power 2010 Program).

According to the DOE, insurance for nuclear or radiological incidents in the US, is subsidized [39] by the Price-Anderson Nuclear Industries Indemnity Act - in July 2005, Congress extended this Act to newer facilities. In the UK, the Nuclear Installations Act of 1965 governs liability for nuclear damage for which a UK nuclear licensee is responsible. The Vienna Convention on Civil Liability for Nuclear Damage puts in place an international framework for nuclear liability. [edit]

Other economic issues

Nuclear Power plants tend to be most competitive in areas where no other resources are readily available - France, most notably, has almost no native supplies of fossil fuels [40]. The province of Ontario, Canada is already using all of its best sites for hydroelectric power, and has minimal supplies of fossil fuels, so a number of nuclear plants have been built there. India too has few resources and is building new nuclear plants. Conversely, in the United Kingdom, according to the government's Department Of Trade And Industry, no further nuclear power stations are to be built, due to the high cost per unit of nuclear power, compared to fossil fuels [41]. However, the British government's chief scientific advisor David King reports that building one more generation of nuclear power plants may be necessary [42]. China tops the list of planned new plants, due to its rapidly expanding economy and fervent construction in many types of energy projects [43].

Most new gas-fired plants are intended for peak supply. The larger nuclear and coal plants cannot quickly adjust their instantaneous power production, and are generally intended for baseline supply. The market price for baseline power has not increased as rapidly as that for peak demand. Some new experimental reactors, notably pebble bed modular reactors, are specifically designed for peaking power.

Any effort to construct a new nuclear facility around the world, whether an older design or a newer experimental design, must deal with NIABY objections. Given the high profile of both the Three Mile Island and Chernobyl accidents, few municipalities welcome a new nuclear reactor, processing plant, transportation route, or experimental nuclear burial ground within their borders, and many have issued local ordinances prohibiting the development of nuclear power. However, a few U.S. areas with nuclear units are campaigning for more (see Nuclear Power 2010 Program).

Current nuclear reactors return around 40-60 times the invested energy when using life cycle analysis. This is better than coal, natural gas, and current renewables except hydropower [44].

The Rocky Mountain Institute gives other reasons why nuclear power plants may be uneconomic. In the U.S. this includes long lead times on risky investments, and the more cost effective approach of investing in efficiency instead of new power plants.

Nuclear power, coal, and wind power are currently the only realistic large scale energy sources that would be able to replace oil and natural gas after a peak in global oil and gas production has been reached (see peak oil). However, The Rocky Mountain Institute claims that in the US increases in transportation efficiency and stronger, lighter cars would replace most oil usage with what it calls negawatts. Biofuels can then substitute for a significant portion of the remaining oil use. Efficiency, insulation, solar thermal, and solar photovoltaic technologies can substitute for most natural gas usage after a peak in production.

Nuclear proponents often assert that renewable sources of power have not solved problems like intermittent output, high costs, and diffuse output which requires the use of large surface areas and much construction material and which increases distribution losses. For example, studies in Britain have shown that increasing wind power production contribution to 20% of all energy production, without costly pumped hydro or electrolysis/fuel cell storage, would only reduce coal or nuclear power plant capacity by 6.7% (from 59 to 55 GWe) since they must remain as backup in the absence of power storage. Nuclear proponents often claim that increasing the contribution of intermittent energy sources above that is not possible with current technology [45]. Some renewable energy sources, such as solar, overlap well with peak electricial production and reduce the need of spare generating capacity. Future applications that use electricity when it is available (e.g. for pressurizing water systems, desalination, or hydrogen generation) would help to reduce the spare generation capacity required by both nuclear and renewable energy sources[46]. [edit]

Risks

Opponents of nuclear power, such as Greenpeace, argue against its use due to issues like the long term problems of storing radioactive waste, the potential for severe radioactive contamination by an accident, and the possibility that its use will lead to the proliferation of nuclear weapons. They point to the nuclear accidents.

According to a 1978 finding by the Supreme Court of the United States, comprehensive testing and study had not yet removed the risk of a major nuclear accident [47]. In the 1980s and 1990s each US nuclear plant underwent an Individual Plant Examination process using Probabilistic Risk Assessment to quantify the risks and identify and address high-risk areas. Such PRAs have been criticized by Oldberg, stating they lack mathematical rigor and involve subjective assessments.

Oldberg and Christensen (1995) and Oldberg (2005) claim that consistent units of probability are not maintained in the computation of the catastrophic bursting risk of coolant pipes in pressurized light water reactors. Also, according to the USNRC Inspection Handbook, plant inspectors are required to provide a variety of subjective assessments without empirical bases or confidence intervals, which are used in the derivation of hazard risk probabilities.

To highlight what they believe are the risks, opponents quote the situation in the United States, where under the Price-Anderson Nuclear Industries Indemnity Act corporations requested and were granted immunity beyond (in 2005) $10 billion (all the available insurance plus pool monies combined) from civil liability (including from possible criminal behavior, although that would be subject to criminal prosecution) from a nuclear incident which causes harm to the public. (Beyond the $10 billion, Congress is required by law to act.)

Proponents argue that the risks are small and that fear has been the single largest obstacle to the widespread use of nuclear power. Assessment of nuclear risk was last done in the 1991 NUREG-1150 report. Additionally, competing technologies may have equivalant risks. Coal currently contributes significantly to problems like global warming, acid rain, various diseases due to airborne pollution, and the storage of large amounts of ash. Contrary to popular belief, coal power actually results in more radioactive waste being released into the environment than nuclear power [48].

[edit]

Accident or attack

Opponents argue that a major disadvantage of the use of nuclear reactors is the threat of a nuclear accident or terrorist attack and the possible resulting exposure to radiation. Proponents argue that the potential for a meltdown, as in the Chernobyl accident is very small due to the care taken in designing adequate safety systems, and that the nuclear industry has much better statistics regarding humans deaths from occupational accidents than coal or hydropower [49]. However, the Chernobyl accident caused great negative health, economic, environmental and psychological effects in a widespread area. The accident at Chernobyl was caused by a combination of the faulty RBMK reactor design, the lack of a containment building, poorly trained operators, and a non-existent safety culture. The RBMK design, unlike nearly all designs used in the Western world, featured a positive void coefficient, meaning that a malfunction could result in ever-increasing generation of heat and radiation until the reactor was breached. [50] Even in Three Mile Island, the most severe civilian nuclear accident in the Western world, the reactor vessel and containment building were never breached so that very little radiation was released into the environment.

Design changes are being pursued in the hope of lessening some of the risks of fission reactors; in particular, automated and passively safe designs are being pursued. Fusion reactors which may come to exist in the future theoretically have little risk since the fuel contained in the reaction chamber is only enough to sustain the reaction for about a minute, whereas a fission reactor contains about a year's supply of fuel. Subcritical reactors never have a self sustained nuclear chain reaction.

Opponents of nuclear power express concerns that nuclear waste is not well protected, and that it can be released in the event of terrorist attack, quoting a 1999 Russian incident where workers were caught trying to sell 5 grams of radioactive material on the open market [51], or the incident in 1993 where Russian workers were caught selling 4.5 kilograms of enriched uranium [52][53][54] . The UN has since called upon world leaders to improve security in order to prevent radioactive material falling into the hands of terrorists [55], leading to the guarding of nuclear shipments by thousands of police [56]. (Other energy sources, such as hydropower plants and liquefied natural gas tankers, are more vulnerable to accidents and attacks) Proponents of nuclear power contend, however, that nuclear waste is already well protected, and state their argument that there has been no accident involving any form of nuclear waste from a civilian program worldwide. In addition, they point to large studies carried out by NRC and other agencies that tested the robustness of both reactor and waste fuel storage, and found that they should be able to sustain a terrorist attack comparable to the September 11 terrorist attacks [57]. Spent fuel is usually housed inside the reactor containment building [58].

According to the Nuclear Regulatory Commission, 20 American States have requested stocks of potassium iodide which the NRC suggests should be available for those living within 10 miles of a nuclear power plant in the unlikely event of a severe accident.[59]. [edit]

Air pollution

Like renewables (except biomass), nuclear generation does not directly produce carbon dioxide, sulfur dioxide, nitrogen oxides, mercury, and other pollutants associated with the combustion of fossil fuels (pollution from fossil fuels causes many times more deaths each year in the US alone [60]).

This has led some environmentalists to advocate increased reliance on nuclear energy as a means to reduce greenhouse gas emissions (which contribute to global warming).

However, just like any power source (including renewables like wind and solar energy), the facilities to produce and distribute the electricity require energy to build. Nuclear fuel must also be collected and processed to extract it from ore. The collection, construction, and transportation equipment used in these processes are either directly powered by diesel and gasoline engines, or draw electricity from the power grid, which in most countries is fed mostly by fossil fuel-powered generators.

Various parties have tried to estimate the amount of energy consumed by these processes (given today's mix of energy resources) and calculate, over the lifetime of a nuclear power plant, the amount of carbon dioxide saved (related to the amount of electricity produced by the plant) vs. the amount of carbon dioxide used (related to construction and fuel acquisition).

Some life cycle studies of nuclear power show emissions per kilowatt-hour to be around one third of those of a mid-size gas-fired power station [61], [62]. However, according to one life cycle study (van Leeuwen and Smith 2001-2005 [63]), carbon dioxide emissions from nuclear power per kilowatt hour are from 20-120% of those for natural gas-fired power stations depending on the availablity of high grade ores. The study goes on to say that these high grade ores are becoming more scarce and indeed there are not enough to supply the world's current power plants for the next decade let alone any future plants. The study was criticized in 2001 by the World Nuclear Association [64], with a detailed rebuttal [65] by van Leeuwen and Smith. Other life cycle analyses show similar emissions from nuclear power and renewables like wind power [66], but because of the relative cost of nuclear energy, the abatement costs of renewables are 3-4 times more favourable [67], and that is without taking into account having to deal with radioactive waste.

It is difficult to know what will happen to the carbon dioxide balance of nuclear power in the future. For instance, if energy production systems changed over entirely to renewable or nuclear sources, and transportation systems used this "clean" electricity (or stored electricity in the form of hydrogen) instead of burning fossil fuels directly, there would be no carbon dixoide emissions from construction, fueling, and distribution operations. The energy efficiency of these tasks is also a major consideration. More efficient methods may be found in the future, but this is difficult to predict, and may require funding for research.

Fission reactors do produce gases such as iodine-131 or krypton-85 which have to be stored on-site for several half-lives until they have decayed to levels officially regarded as safe. However, according to several independent organizations, a person receives more radioactivity from household appliances than from nuclear power [68]. [edit]

Waste heat in water systems

Nuclear reactors require water to keep the reactor cool. The process of extracting energy from a heat source, called the Rankine cycle, requires the steam to be cooled down. Rivers are the most common source of cooling water, as well as the destination for waste heat. The temperature of exhaust water must be regulated to avoid killing fish; long-term impact of hotter-than-natural water on ecosystems is an environmental concern.

The need to regulate exhaust temperature also limits generation capacity. On extremely hot days, which is when demand can be at its highest, the capacity of a nuclear plant may go down because the incoming water is warmer to begin with (and is thus less effective as a coolant, per unit volume). This was a significant factor in the European heat wave of 2003. Engineers consider this in making better power plant designs because increased cooling capacity will increase costs.

This is also a problem for coal power plants[69]. [edit]

Health effect on population near nuclear plants

Most of the human exposure to radiation comes from natural background radiation. Most of the remaining exposure comes from medical procedures. Several large studies in the US, Canada, and Europe have found no evidence of any increase in cancer mortality among people living near nuclear facilities. For example, in 1990, the National Cancer Institute (NCI) of the National Institutes of Health announced that a large-scale study, which evaluated mortality from 16 types of cancer, found no increased incidence of cancer mortality for people living near 62 nuclear installations in the United States. The study showed no increase in the incidence of childhood leukemia mortality in the study of surrounding counties after start-up of the nuclear facilities. The NCI study, the broadest of its kind ever conducted, surveyed 900,000 cancer deaths in counties near nuclear facilities.

However, in Britain there are elevated childhood leukemia levels near some industrial facilities, particularly near Sellafield, where children living locally are ten times more likely to contract the cancer. The reasons for these increases, or clusters, are unclear, but one study of those near Sellafield has ruled out any contribution from nuclear sources. Apart from anything else, the levels of radiation at these sites are orders of magnitude too low to account for the excess incidences reported. One explanation is viruses or other infectious agents being introduced into a local community by the mass movement of migrant workers. Likewise, small studies have found an increased incidence of childhood leukemia near some nuclear power plants has also been found in Germany [70] and France [71]. Nonetheless, the results of larger multi-site studies in these countries invalidate the hypothesis of an increased risk of leukaemia related to nuclear discharge. The methodology and very small samples in the studies finding an increased incidence has been criticized. [72] [73] [74] [75]. Also, one study focussing on Leukaemia clusters in industrial towns in England indicated a link to high-capacity electricity lines suggesting that the production or distribution of the electricity, rather than the nuclear reaction, may be a factor.

Aside from the immediate effects of the Chernobyl accident (see above), there is continuing impact from soils containing radioactivity in Ukraine and Belarus. For this reason a Zone of alienation was established around the Chernobyl plant. [edit]

Nuclear proliferation For more details on this topic, see Nuclear proliferation.

Opponents of nuclear power point out that nuclear technology is often dual-use, and much of the same materials and knowledge used in a civilian nuclear program can be used to develop nuclear weapons. This concern is known as nuclear proliferation and is a major reactor design criterion.

The military and civil purposes for nuclear energy are intertwined in most countries with nuclear capabilities. In the US for example the first goal of the Department of Energy is "To protect our national security by applying advanced science and nuclear technology to the Nation’s defense." [76]

The enriched uranium used in most nuclear reactors is not concentrated enough to build a bomb. Most nuclear reactors run on 4% enriched uranium; Little Boy used 90% enriched uranium; while lower enrichment levels could be used the minimum bomb size would rapidly become infeasibly large as the level was decreased. However, the technology used to enrich uranium for power generation could be used to make the highly enriched uranium needed to build a bomb. In addition, designs such as CANDU can be more easily misused to generate plutonium suitable for bomb making. It is believed that the nuclear programs of India and Pakistan used CANDU reactors to produce fissionable materials for their weapons, however, this is a myth. India used a research reactor named CIRUS, based on the Canadian NRX design, which was donated by Canada under the condition that it not be used for weapons production[77]. Pakistan is believed to have produced the material for its weapons from an indigenious enrichment program [78].

To prevent weapons proliferation, safeguards on nuclear technology were published in the Nuclear Non-Proliferation Treaty (NPT) and monitored since 1968 by the International Atomic Energy Agency (IAEA). Nations signing the treaty are required to report to the IAEA what nuclear materials they hold and their location. They agree to accept visits by IAEA auditors and inspectors to verify independently their material reports and physically inspect the nuclear materials concerned to confirm physical inventories of them in exchange for access to nuclear materials and equipment on the global market.

Several states did not sign the treaty and were able to use international nuclear technology (often procured for civilian purposes) to develop nuclear weapons (India, Pakistan, Israel, and South Africa). South Africa has since signed the NPT, and now holds the distinction of being the only known state to have indigenously produced nuclear weapons, and then verifiably dismantled them[79]. Of those who have signed the treaty and received shipments of nuclear paraphernalia, many states have either claimed to or been accused of attempting to use supposedly civilian nuclear power plants for developing weapons, including Iran and North Korea. Certain types of reactors are more conducive to producing nuclear weapons materials than others, and a number of international disputes over proliferation have centered on the specific model of reactor being contracted for in a country suspected of nuclear weapon ambitions.

New technology, like SSTAR, may lessen the risk of nuclear proliferation by providing sealed reactors with a limited self-contained fuel supply and with restrictions against tampering.

One possible obstacle for expanding the use of nuclear power might be a limitated supply of uranium ore, without which it would become necessary to build and operate breeder reactors. However, at current usage there is sufficient uranium for an extended period - "In summary, the actual recoverable uranium supply is likely to be enough to last several hundred (up to 1000) years, even using standard reactors." [80] (see Fuel resources above). Breeder reactors have been banned in the US since President Carter's administration prohibited reprocessing because of what it regarded as the unacceptable risk of proliferation of weapon grade materials.

Some proponents of nuclear power agree that the risk of nuclear proliferation may be a reason to prevent nondemocratic developing nations from gaining any nuclear technology but argue that this is no reason for democratic developed nations to abandon their nuclear power plants. Especially since it seems that democracies never make war against each other (See the democratic peace theory).

Proponents also note that nuclear power (like some other power sources) provides steady energy at a consistent price without competing for energy resources from other countries, something that may contribute to wars. [edit]

List of atomic energy groups

- American Nuclear Society (United States)
- Department of Energy (United States)
- The Nuclear Energy Institute (United States)
- Atomic Energy of Canada Limited (Canada)
- Areva (France)
- EDF (France)
- MinAtom (Russia)
- EnergoAtom (Ukraine)
- KazAtomProm (Kazakhstan)
- Egyptian Atomic Energy Authority
- United Kingdom Atomic Energy Authority (UKAEA)
- EURATOM (Europe)
- International Atomic Energy Agency (IAEA) [edit]

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- Ionizing radiation for a table of radiation exposures
- List of countries with nuclear weapons
- Nuclear physics
- Nuclear power in Canada
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- Uranium
- Wind Power [edit]

USAEC/USNRC studies of risk at nuclear power plants

- WASH-740 (1957)
- WASH-1400 (1975)
- CRAC-II (1982), based on WASH-1400 results
- NUREG-1150 (1991) [edit]

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- Nuclear Files.org Criticisms of nuclear power by an anti-nuclear organization
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- Discussion of the Economics of Nuclear Power
- Freedom for Fission
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