12 Nuclear Power Plants

> *"The laboratory technician has succeeded in implementing by means of the atomic pile the Einsteinian principle of inertia of energy."*
>
> *Gaston Bachelard*

annihilation processes

In nuclear power plants mass is converted into energy according to the famous equation $E = mc^2$. However, mass can only be completely converted into energy in annihilation processes, e.g. in electron–positron annihilation into two photons,

$$e^+e^- \rightarrow \gamma + \gamma \ , \tag{12.1}$$

antimatter

or in proton–antiproton annihilation processes. Since large quantities of antimatter are not available, nuclear power plants usually transform only part of the mass of atomic nuclei into energy, mostly in fission processes.

binding energy per nucleon

fission products

Fission power plants take advantage of the dependence of the binding energy per nucleon on the mass of nuclei. The binding energy of uranium is about 7.5 MeV/nucleon, that of the fission products is about 8.5 MeV/nucleon. Since the fission products are more tightly bound, they have a smaller mass per nucleon. The fission of a uranium nucleus, therefore, liberates a mass equivalent of 1 MeV/nucleon. This energy is set free in form of kinetic energies of the fission products (84.5%), kinetic energies of prompt fission neutrons (2.5%), energy of prompt and delayed γ rays (5%), kinetic energy of electrons (2.5%), and, finally, the energy of electron antineutrinos (5.5%).

The efficiency of mass-to-energy conversion therefore amounts to

$$\eta = \frac{\Delta E/\text{nucleon}}{m_{\text{nucleon}}\, c^2} \approx 1‰ \ , \tag{12.2}$$

recycling

where m_{nucleon} is the rest mass of the nucleon (938.3 MeV for protons and 939.6 MeV for neutrons). In fission reactions highly radioactive and also long-lived fission products are generated. Fission nuclear power plants use mostly the relatively rare uranium isotope ^{235}U which has a natural abundance of only 0.7%. Natural uranium (99.3% ^{238}U, 0.7% ^{235}U) therefore has to be enriched to be economically fissionable. The recycling of spent nuclear-fuel rods and their transport may imply certain safety problems.

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_12,

Nuclear energy can also be gained by fusion. Indeed, in contrast to fission reactors one can gain 6.6 MeV per nucleon in the fusion of hydrogen to helium, corresponding to a conversion efficiency of 0.7%. In the Sun, hydrogen is fused according to $4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e$, while nuclear-fusion plants intend to use deuterium–tritium fusion ($d + t \rightarrow {}^{4}\mathrm{He} + n$)[1], which has a conversion efficiency of only 0.3%. The radiation-protection problems with fusion reactors are believed to be much less severe since the fusion product, the result of hydrogen burning, is stable helium. It must, however, be considered that radioactive isotopes will be produced by neutron activation, where the neutrons are emitted as a consequence of deuterium–tritium fusion. This activation concerns not only the reactor material but also the steel and concrete shielding.

fusion of hydrogen

deuterium–tritium fusion

neutron activation

12.1 Nuclear-Fission Reactors

The most frequently used isotope in nuclear-fission power plants is ${}^{235}\mathrm{U}$. It breaks up under bombardment of slow neutrons according to, for example,

$$n + {}^{235}\mathrm{U} \rightarrow {}^{236}\mathrm{U}^{*} \rightarrow {}^{141}\mathrm{I}^{*} + {}^{95}\mathrm{Y}^{*} \ . \qquad (12.3)$$

The radioactive fission products created in these reactions partially decay by emission of prompt and/or delayed neutrons and/or successive β^- decays. The decay of the highly excited fission products, in our example iodine and yttrium, will provide further neutrons which will initiate more fission reactions. By using materials with a high neutron absorption coefficient (control rods) the neutron yield can be regulated. This makes possible a safe operation of the nuclear power plant at constant power.

neutron absorption coefficient

control rods

The distribution of the fission products for fission with thermal and fast neutrons on ${}^{235}\mathrm{U}$ is plotted in Fig. 12.1. It is evident that the fission yield is highly asymmetric. This asymmetry can be understood in the framework of the nuclear shell model. Nuclei with proton and neutron numbers corresponding to closed shells are very tightly bound. These 'magic' numbers are 2, 8, 20, 28, 50, 82, and 126. Nuclei with magic proton *and* magic neutron numbers, so-called 'doubly magic' ones, are particularly tightly bound. Examples are ${}^{4}\mathrm{He}$, ${}^{16}\mathrm{O}$, or ${}^{40}\mathrm{Ca}$. The peaks in the fission-yield distribution originate from nuclei around the magic neutron numbers 50 (mass numbers of ≈ 90) and 82 (mass numbers of ≈ 140).

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[1] deuterium: ${}^{2}_{1}\mathrm{H} = d$, tritium: ${}^{3}_{1}\mathrm{H} = t$

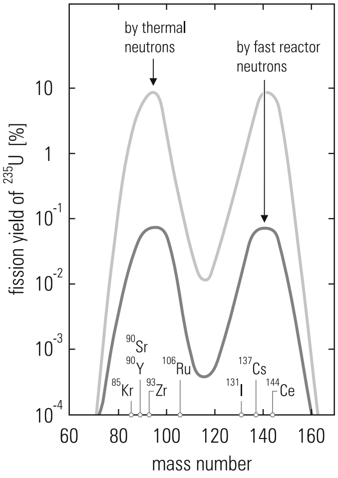


Figure 12.1
Fission yield from ^{235}U by fast and thermal neutrons

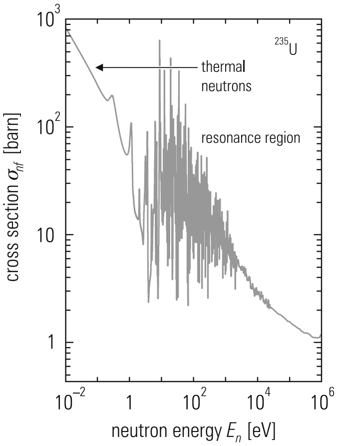


Figure 12.2
Cross section for neutron-induced fission of ^{235}U as a function of the neutron energy

fission cross section

The cross section for fission is particularly large for slow neutrons. It can be parametrized by the $1/v$ law (v – velocity of neutrons). Since neutrons created in the fission process are normally quite energetic (typically several MeV), they have to be moderated to slow them down to thermal energies. The fission cross section of thermal neutrons ($E_n = kT \approx 25\,\text{meV}$) for ^{235}U is $\sigma_\text{f} \approx 700\,\text{barn}$ ($1\,\text{barn} = 10^{-24}\,\text{cm}^2$), much larger than that of fast neutrons ($\sigma_\text{f}(1\,\text{MeV}) \approx 1\,\text{barn}$). The dependence of the fission cross section for ^{235}U is shown in Fig. 12.2 as a function of the neutron energy.

moderation of neutrons

safety aspect

The moderation of fast neutrons is best done by light materials, because a relatively large amount of energy can be transferred in the interaction of neutrons with lighter atomic nuclei. Water (H_2O) is ideally suited for moderation and can be used as a cooling agent at the same time. This provides a very important safety aspect since, if the cooling water should evaporate due to some power excursion, the fast neutrons from the fission products will no longer be moderated thereby reducing the efficiency for the chain reaction or even interrupting it. It presents a safety risk, if different materials are used for cooling and for the moderation. A fission reactor operated with water as cooling agent and graphite as moderator must be considered inherently unsafe. If the cooling agent is lost or evaporates, disrupting the cooling, while neutrons continue to be thermalized by the graphite moderator thus sustaining the chain reaction, this type of reactor can get out of control. Such a situation can easily lead to a core meltdown (see Chernobyl accident, Chap. 14).

Water-cooled and water-moderated reactors therefore represent a reactor design of high security as was also demonstrated by the

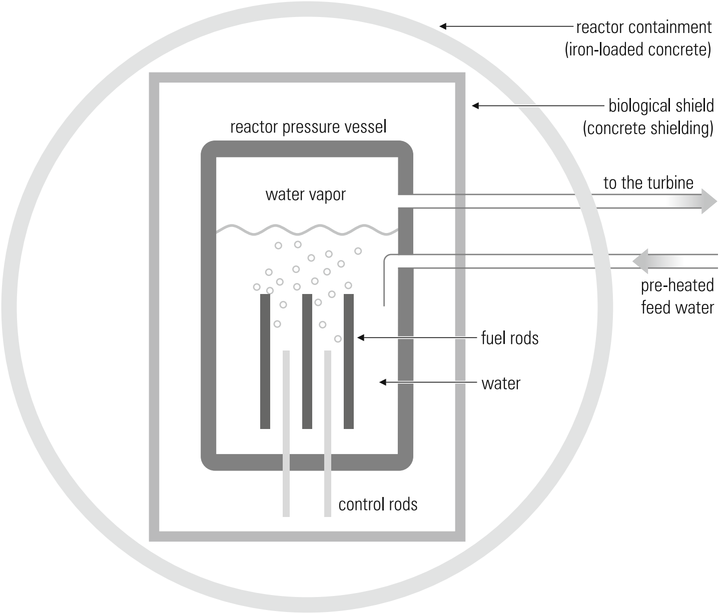


Figure 12.3
Schematic diagram of a boiling-water fission reactor which is water-cooled and water-moderated

natural reactor Oklo in Gabon in Africa, see also Example 2 in this chapter.

natural reactor Oklo

One has to distinguish between boiling-water reactors (Fig. 12.3) and pressurized-water reactors (Fig. 12.4). In both cases the heat generated is used to evaporate water, and the hot water vapor then powers a generator via a turbine. In boiling-water reactors the water vapor from the primary circuit is used to feed the turbine. In this case the possibility that some contaminated water from the reactor might leak into the mechanical equipment for power generation cannot be completely excluded.

boiling-water reactor

pressurized-water reactor

primary circuit

To circumvent such a problem, the primary energy can be transferred via a heat exchanger into a secondary water circuit as in the pressurized-water reactor. The water from the secondary circuit will then feed the turbine without risk of contamination. Pressurized-water reactors have large safety advantages, although the construction of a secondary water circuit is much more complex and also more expensive. An additional safety aspect of a pressurized-water reactor is that the control rods are mounted on top of the fuel elements, which is impossible in boiling-water reactors for reasons of construction. In case of emergency, the control rods would have to be moved up into the reactor core against gravity in boiling-water reactors, while, in contrast, in pressurized-water reactors, they fall down into the reactor core following the gravitational pull.

secondary water circuit

fuel elements

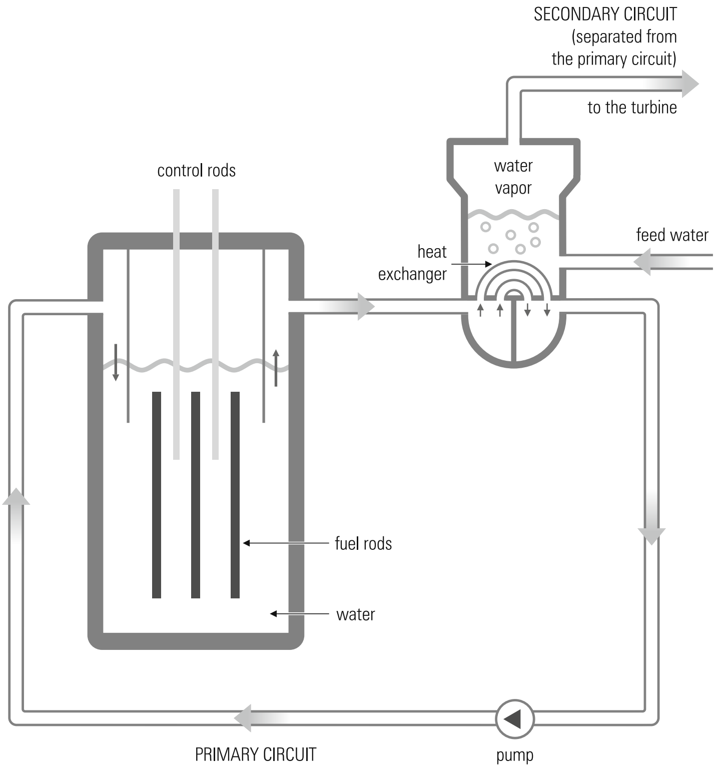
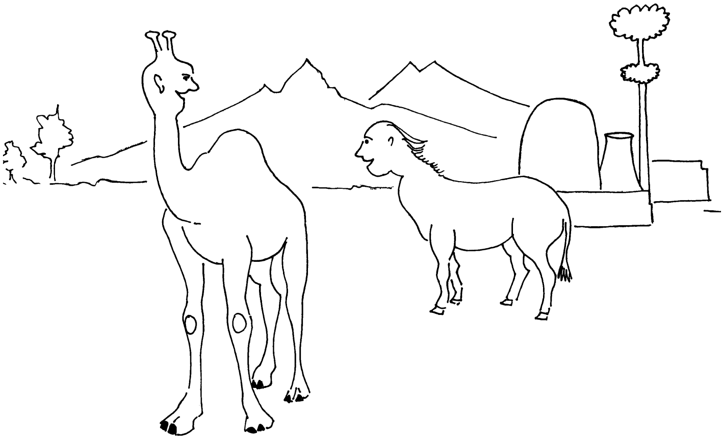


Figure 12.4
Schematic diagram of a pressurized-water reactor. The water is not allowed to boil in the core but rather produces steam behind a heat exchanger to feed a generator



"Since the introduction of nuclear energy the variety of species has obviously increased."

© by Claus Grupen

The complete schematic setup of a pressurized-water reactor is shown in Fig. 12.5. Figure 12.6 shows a view of the inner part of a fission reactor in which the fuel rods are clearly visible.

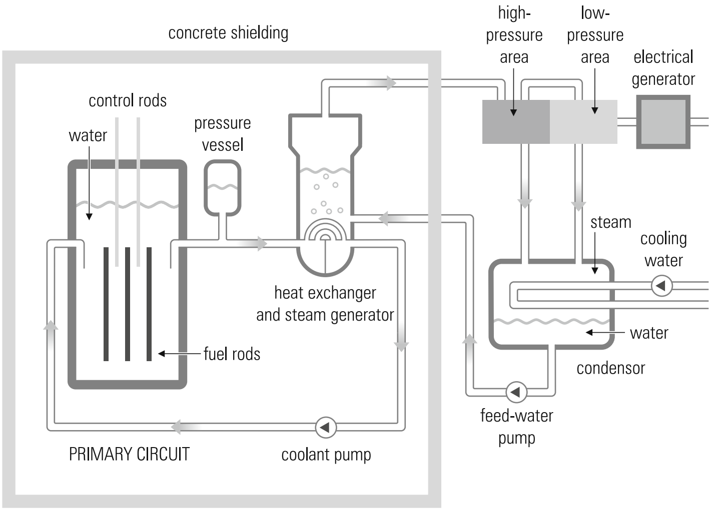


Figure 12.5
Complete schematic setup of a pressurized-water reactor

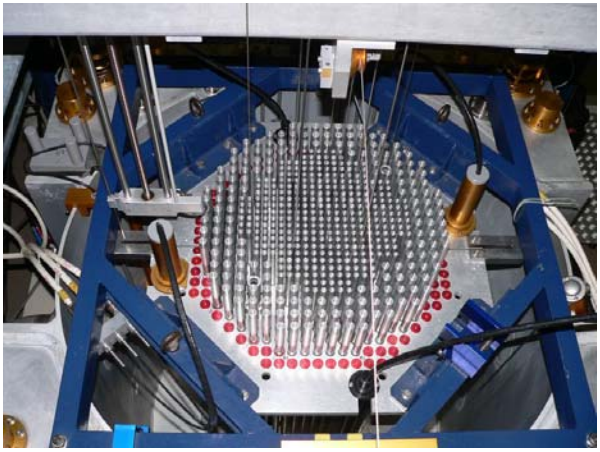


Figure 12.6
Image of fuel elements in the core of a fission reactor. Photo credit: Wikimedia Commons, Ecole Polytechnique Fédérale de Lausanne

high-temperature reactor (pebble-bed reactor)

graphite moderation

It is conceivable that the high-temperature reactor, also called pebble-bed reactor, has a bright future because of its excellent safety aspects. High-temperature reactors are characterized by their efficient use of uranium and by a high operating temperature (≈ 1000 °C) compared to boiling-water reactors (≈ 300 °C). High-temperature reactors use graphite as moderator and helium as coolant.

Highly enriched ^{235}U serves as fuel. The fuel pebbles also contain ^{232}Th, from which the fissile ^{233}U is bred.

graphite pebbles

The uranium fuel is contained as ceramic oxide in graphite pebbles along with the thorium isotope. The fissile material is distributed uniformly as small spheres in a graphite matrix. The graphite pebbles are of tennis-ball size and feel hot to the touch because of their α activity. The reactor core contains several hundred thousand of these graphite pebbles. During reactor operation the fission neutrons breed another easily fissile uranium isotope by neutron attachment to ^{232}Th according to the following reaction:

$$^{232}\mathrm{Th} + n \rightarrow {}^{233}\mathrm{Th} + \gamma \tag{12.4}$$

with the subsequent β decays

$$^{233}\mathrm{Th} \rightarrow {}^{233}\mathrm{Pa} + e^- + \bar{\nu}_e \ \ (T_{1/2} = 22.3\,\mathrm{min}) \ , \tag{12.5}$$

$$^{233}\mathrm{Pa} \rightarrow {}^{233}\mathrm{U} + e^- + \bar{\nu}_e \ \ (T_{1/2} = 27.0\,\mathrm{d}) \ . \tag{12.6}$$

Spent pebbles can simply be removed from the reactor core at the bottom of the reactor container and replaced by fresh ones at the top without problems, guaranteeing a continuous supply of fuel.

helium cooling

Helium gas is an excellent coolant. With its doubly magic numbers, neutrons will not attach to it and therefore it will not be activated. The hot helium evaporates water, and the water vapor drives the turbine. The high operating temperature (1000 °C) guarantees an excellent thermodynamical efficiency. It is even conceivable for the hot helium to drive the turbine directly.

Figure 12.7 shows the design principle of a pebble-bed reactor.

negative reaction coefficient

High-temperature reactors exhibit a negative reaction coefficient, i.e., a temperature increase in the reactor decreases its reactivity. This again provides an automatic stabilization. A number of subtle reasons is responsible for this phenomenon: An increase in temperature leads to a thermal expansion of the graphite pebbles thereby reducing its uranium density. The pebbles are designed in such a way that this effect reduces the criticality and thereby the reaction rate, with the result that the energy-production rate decreases, so that eventually a stable maximum operation temperature is obtained. In terms of physics the temperature increase leads to a Doppler broadening of the resonance-absorption lines of the fuel isotopes. As a result ^{238}U nuclei will also attach some neutrons, which then are missing for ^{235}U fission.[2] In addition, the cross sec-

reducing fuel density

neutron attachment to ^{238}U

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[2] In the language of reactor builders: the fraction of neutrons escaping resonance capture (the p factor), decreases with increasing temperature. With rising temperature, an increasing number of neutrons cannot escape capture by the isotope ^{238}U. These neutrons then are missing for fission of ^{235}U.

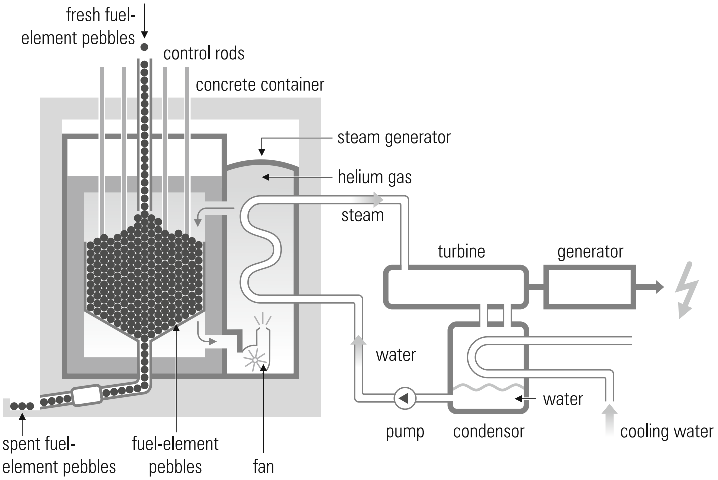

Figure 12.7
Sketch of a pebble-bed reactor

tion for neutron-induced fission is reduced because of the $1/v$ law. A temperature rise increases the thermal energy of neutrons, and – because $v \sim \sqrt{E}$ – also their velocity, thereby reducing the reaction cross section. These effects therefore guarantee a negative feedback and an automatic self-stabilization. These arguments do not hold for 'normal' reactors, since a core meltdown will happen there before the limiting operation temperature is reached, because uranium melts at 1132.2 °C (1405.3 K).

reduced cross section

The self-stabilization in pebble-bed reactors works because the ceramic graphite pebbles can withstand much higher temperatures (2000 °C). Due to the negative temperature coefficient in pebble-bed reactors, the maximum operating temperature stabilizes at 1600 °C, removing the possibility of a core meltdown, at least in theory. A pebble-bed reactor could in principle function without neutron-absorbing control rods which normally regulate the neutron amplification factor. Instead, the operation temperature could be controlled by the flow rate of the coolant. Nevertheless, control and safety rods will be employed for safety redundancy. They will also be used for reactor shutdown.

self-stabilization

no core meltdown

The power density in high-temperature reactors (around 6 MW/m^3) is significantly lower than that of boiling-water reactors (typically 100 MW/m^3). Therefore passive cooling should be sufficient to keep the fuel rods below the melting temperature under all circumstances. For reasons of safety, active cooling will nevertheless be installed to prevent an unforeseen power excursion. Since the activation cross section of helium is extremely low, it is even conceivable to operate this type of reactor only with a primary circuit without a heat exchanger.

passive cooling

heat of reaction

The production of heat in nuclear-fission reactions at high temperature is also considered as advantage.

Countries like Japan, China, and South Africa will use this type of reactor in the near future. China has announced that it will build thirty pebble-bed reactors before 2020.

inherent safety

Because of their inherent safety, pebble-bed reactors do not necessitate a pressure container. Therefore they can be constructed in smaller units economically. A possible disadvantage is that this reactor type requires highly enriched weapons-grade ^{235}U (enrichment up to 97%). Also the recycling of ceramic graphite pebbles containing the fuel needs further study.

One problem of fission reactors is the processing and storage of nuclear waste (see also Sect. 8.12). In nuclear fission enormous amounts of solid and liquid radioactive waste are generated. The liquid waste is usually stored in large tanks. The storage of the radioactive material would be must easier if it could be concentrated. Strontium-90 is a particularly harmful component of nuclear waste with a half-life of about 30 years. It can replace calcium in bones if it gets into the food chain and causes health problems including cancer. A new material that can extract radioactive strontium ions from solutions could help to clean up nuclear waste. A sponge-like material, which looks like a brown powder, has been shown to be able to remove 99.8 per cent of the strontium from a sodium-rich solution of strontium.[3]

12.2 Fusion Reactors

fusion reactor

energy sources of stars

Fusion reactors provide the energy that makes the stars shine. If this source of energy could be made available on Earth, all energy problems would be solved. In the 1930s hydrogen fusion was discovered to be the energy source of all stars.[4]

***pp* cycle**

The main fusion mechanism in stars of the size of the Sun is based on the following reactions:[5]

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[3] `www.rsc.org/chemistryworld/News/2008/March/03030802.asp`

[4] About the discovery of the principles of the hydrogen fusion chain that powers the stars the following anecdote is being told: Carl Friedrich von Weizsäcker was taking a walk with a girl on a nice summer night. The girl, who later became his wife, remarks on how nice the stars are shining. “Yes”, says Weizsäcker, “and right now I am the only one who knows why.” Sometimes this anecdote is also attributed to Hans Bethe.

[5] In high-mass stars, the Bethe–Weizsäcker cycle (CNO cycle) also operates.

$$p + p \rightarrow d + e^+ + \nu_e \ , \tag{12.7}$$

$$p + d \rightarrow {}^3\mathrm{He} + \gamma \ , \tag{12.8}$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p \ . \tag{12.9}$$

In addition to these basic reactions, certain processes with lower probability occur, such as:

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma \ . \tag{12.10}$$

${}^7\mathrm{Be}$ can either transform into ${}^7\mathrm{Li}$ by electron capture,

$${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e \ , \tag{12.11}$$

or it can capture one of the plentiful protons according to

$${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma \ . \tag{12.12}$$

boron decay

${}^8\mathrm{B}$ is unstable and decays under positron emission,

$${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e \ , \tag{12.13}$$

where ${}^8\mathrm{Be}$ decays almost immediately into two α particles. In the same way, ${}^7\mathrm{Li}$ captures a proton and is transformed into helium nuclei,

$${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} \ . \tag{12.14}$$

conditions for hydrogen fusion

Hydrogen fusion requires three important conditions:

- high temperatures,
- high plasma densities, and
- sufficiently long confinement times of the plasma.[6]

tunnelling probability

The two protons fusing in the initial process are both positively charged and repel each other. High temperatures are required so that these two protons can get as close as possible. Still the protons will not be able to get over the Coulomb barrier, they have to tunnel through the Coulomb barrier of the other collision partner. The tunnelling probability increases with the energy of the protons interacting in this process, i.e., the tunnelling probability increases with temperature ($E \sim T$). High plasma densities and long confinement times are, of course, given in the interior of stars.

deuterium–tritium fusion

For fusion reactors on Earth, deuterium–tritium fusion seems to be most appropriate (see Fig. 12.8)

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[6] A plasma is an ionized gas. In the case of fusion reactors, the atoms are fully ionized.

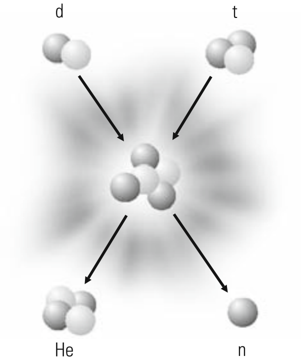

Figure 12.8
Principle of the deuterium–tritium fusion reaction

$$d + t \rightarrow {}^4\mathrm{He} + n \ . \tag{12.15}$$

This interaction allows the tunnelling of deuterium and tritium at relatively large mutual distances compared to the other fusion processes.

In this fusion process, the unstable compound nucleus ^{5}He is initially formed, which decays into ^{4}He and a neutron. The α particle leaves with a kinetic energy of 3.5 MeV and the neutron gains 14.1 MeV. The α particle has a very short range and will deposit its energy in the immediate vicinity, heating up the plasma. If the heating by α particles is sufficient to compensate the energy-leakage rate of the plasma, a self-sustaining fusion can be maintained. The neutron will escape because of its low cross section for interactions in the plasma.

self-sustaining fusion

deuterium and tritium extraction

Deuterium can be extracted from sea water by electrolysis. Tritium can be bred from lithium by neutron bombardment according to

$$n + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He} + {}^3\mathrm{H} \ . \tag{12.16}$$

If the reaction plasma is surrounded by lithium blankets, the neutrons emerging from the (d, t) fusion can breed further tritons.

inertial fusion

There are two fundamentally different proposals to maintain the fusion process on Earth in a controlled fashion. The technique of inertial fusion is predominantly being followed in the United States while fusion with magnetic confinement is mainly being tested and investigated in Europe.

12.2.1 Inertial Fusion

laser fusion

heavy-ion beams

laser pulse

The technique of inertial fusion, also called laser fusion, uses hollow spheres (made, for example, of plastics) which are filled in equal proportions with deuterium and tritium at high pressure and which are cooled down to cryogenic temperatures (i.e. temperatures at which noble gases become liquid). This causes the deuterium–tritium mixture to freeze as thin solid coating on the inner wall of the hollow sphere. These deuterium and tritium pellets are injected into a target chamber, where they are bombarded by intense laser or heavy-ion beams. The high energy deposition by the laser pulse evaporates the shell of the pellet which expands rapidly outwards. This causes a pressure in an inward direction which accelerates the deuterium–tritium layer to the center of the pellet. That part of the deuterium–tritium gas which had remained at the center of the pellet will be compressed by the deuterium–tritium component streaming under high pressure to the center. In this process temperatures on the order of more than 10^8 K are produced for a short period, which is sufficient to initiate the fusion process. The expanding fusion wave started in this way will reach the formerly solid, residual deuterium–tritium component and cause it to fuse as well.

It is possible to generate laser beams of extremely high power density. The NOVA laser at the Lawrence Livermore National Laboratory reaches 100 terawatts per square centimeter. Figure 12.9 shows a battery of high-power lasers which are used for laser fusion.

high-power laser

The reaction products of this type of fusion, however, might deteriorate the optical system used to steer the beam. This disadvantage could be overcome if, instead of laser beams, heavy-ion beams were used: these can be focused by magnetic lenses. Magnetic lense systems are not very susceptible to possible damage by the reaction products from the fusion.

focusability of heavy ions

A fusion reactor based on inertial fusion is a strong source of neutrons. Because of the low interaction probability of neutrons – they are electrically neutral – they will deposit part of their energy at large distances from the fusion chamber. It is unavoidable that radioactive isotopes are formed in the process of neutron absorption in the surrounding material. By adequate selection of materials with low neutron activation cross section and short decay times, the production of radioactive waste can be limited.

neutron activation

The burning plasma (temperatures of $\approx 10^8$ K) will, of course, emit its natural characteristic blackbody radiation which at these

blackbody radiation in the X-ray range

Figure 12.9
Giant high-power lasers (terawatt range) are required to enable hydrogen fusion. Shown are some of the lasers which are used in the National Fusion Facility, USA (source: Lawrence Livermore National Laboratory). The size of the lasers can be judged from the technician in the middle row between the lasers

temperatures is in the X-ray range[7]

$$kT = 1.38 \times 10^{-23}\,\mathrm{J/K} \times 10^{8}\,\mathrm{K}\,\frac{1}{1.6 \times 10^{-19}\,\mathrm{J/eV}} = 8.6\,\mathrm{keV}\ . \tag{12.17}$$

In this way, part of the reaction energy will be lost (about 10% to 15%) by this process of thermal X-ray production. The X-ray photons escaping from the fusion plasma will also interact substantially with the material of the reaction chamber. In these X-ray interactions part of the coating of the chamber walls might be ablated, i.e. detached, thereby polluting the target chamber. The continuous neutron bombardment will also cause some brittleness of the reactor materials.

Altogether one would expect that the pollution of the environment by radioactive waste from fusion nuclear plants to be much less than that from fission reactors.

injection of hydrogen D–T pellets

The energy production in a fusion reactor following the principle of inertial fusion is obtained by a high repetition rate of injecting the hydrogen pellets (see Fig. 12.10) into the fusion chamber.

Figure 12.11 sketches a fusion power plant based on the working principle of inertial fusion.

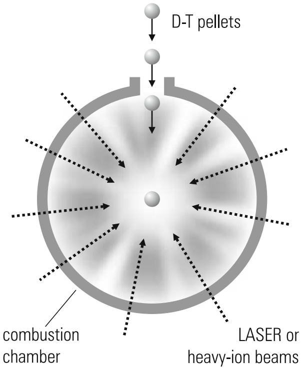

Figure 12.10
Sketch of a fusion reactor by inertial fusion using laser bombardment

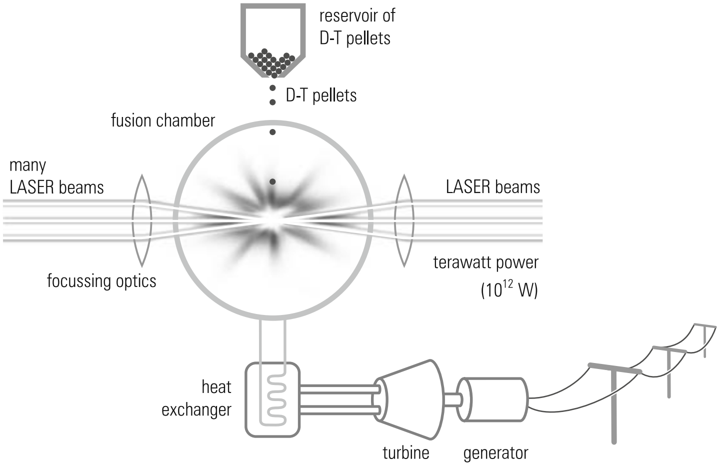

Figure 12.11
Sketch of a fusion power plant based on inertial fusion

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[7] A blackbody at temperature T emits exactly the same energy spectrum which would be present in an environment at equilibrium at temperature T. This spectral intensity distribution is described by Planck's law, $P(\nu)\,\mathrm{d}\nu = \frac{2h\nu^3}{c^2}\frac{1}{\mathrm{e}^{\frac{h\nu}{kT}}-1}\,\mathrm{d}\nu$, where ν is the frequency, k Boltzmann's constant, and h Planck's constant.

12.2.2 Fusion by Magnetic Containment

tokamak principle

fusion by magnetic confinement

In a fusion reactor based upon the tokamak principle, a high-temperature plasma is produced, and then stored by magnetic confinement over a longer period of time (several seconds). For this technique, temperatures of about 100 to 200 million kelvin, confinement times of 1 to 2 seconds, and plasma densities (particle densities) of 2–3 × $10^{20}\,\mathrm{m}^{-3}$ are required.

plasma confinement

Energy losses from the plasma are mainly caused by radiation. Since the radiation loss of a plasma is proportional to its surface area, while the energy content of the plasma depends on the volume, one gains in confinement time with increasing size of the plasma. (The ratio of surface to volume (assumed to be spherical) varies as $1/r$, where r is the radius of the plasma, which means that for small radii the losses are largest.) The plasma confinement is obtained by a rather sophisticated arrangement of magnetic fields: the goal is to store the plasma in a closed torus. To confine the charged particles in a torus, a toroidal magnetic field is produced which causes the plasma particles to move on spiral orbits inside the torus. Furthermore, an additional polar magnetic field causes the plasma to pinch, i.e. to be compressed and confined by magnetic forces, and to keep it away from the walls of the torus (see Fig. 12.12).

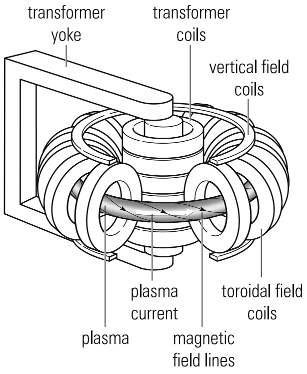

Figure 12.12
Working principle of a tokamak reactor

The heating of the plasma can be performed in various ways, where in most cases all of the following methods will be applied (see Fig. 12.13).

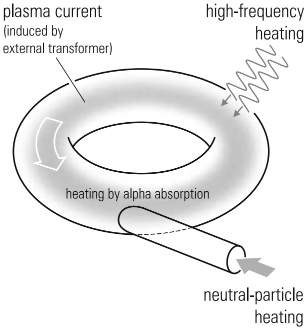

Figure 12.13
Methods of plasma heating in a tokamak fusion reactor. Neutral particles are injected against the plasma stream to increase their absorption

- A powerful transformer with a high current on the primary winding will induce a high current in the plasma, which acts as secondary winding (ohmic plasma heating). The power dissipated into the plasma in this way is proportional to the square of the induced current.
- Deuterium and tritium ions are first accelerated in a linear accelerator up to energies of typically 150 keV/nucleon. Because of the magnetic field, they will not be able to enter the plasma. Therefore the deuterium and tritium ions are neutralized by electron capture allowing them to enter the plasma. The injection of energetic neutral particles increases the plasma temperature (heating by neutral particles).
- In the same way, electromagnetic radiation can heat up the plasma, as long as the frequency of the radiation is tuned in such a way that the radiation will be absorbed in a resonance-like fashion by the charged particles of the plasma.
- Finally, some of the reaction products of fusion, namely, the α particles produced, will be stopped in the plasma leading to further heating.

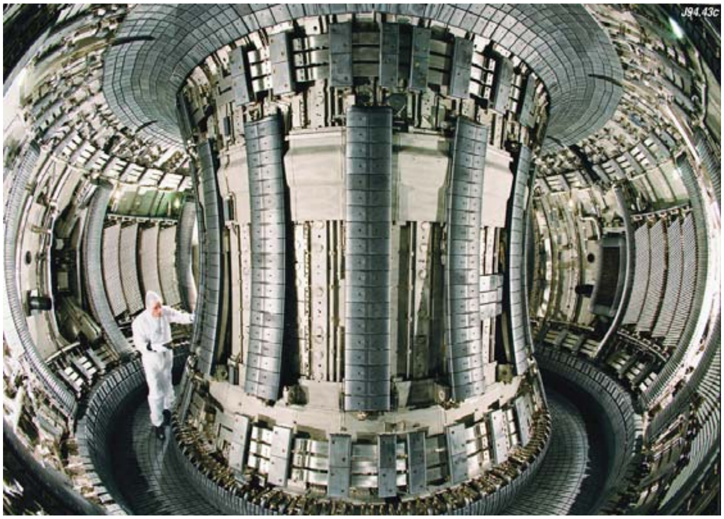

Figure 12.14
Photo of the interior of the Joint European Torus. The dimensions of the fusion reactor can be estimated from the size of the technician in the left-hand part of the photo. Photo credit: JET Culham, England

neutron capture

energy production of a fusion reactor

In very much the same way as in inertial fusion, the neutrons produced in the fusion process in the plasma will escape from the burning plasma. These neutrons have substantial energy: they present the basis for the energy production of a fusion reactor.

Joint European Torus

Figure 12.14 shows a photo of the plasma chamber of a reactor built on the principle of tokamak fusion.

ITER

The follow-up project after the JET[8] fusion facility is the International Thermonuclear Experimental Reactor, ITER. ITER is a joint European–American–Japanese–Russian fusion project to demonstrate the feasibility of producing fusion energy economically. The American participation was, however, significantly reduced in 2008 due to financial cuts to this field of science.

energy gain

10 g of deuterium which can be extracted from 500 l of water, and 15 g tritium which can be produced from 30 g lithium, contain about 3×10^{24} atomic nuclei each. Per fusion process one neutron with energy 14.1 MeV is produced. If the kinetic energy of neutrons can be transformed into the production of electrical power, one will obtain

$$\Delta E = 3 \times 10^{24} \times 14.1\,\mathrm{MeV} = 6.77 \times 10^{12}\,\mathrm{J} = 1.88 \times 10^{6}\,\mathrm{kW\,h}\ . \tag{12.18}$$

This energy is sufficient to cover the energy consumption of a single person over his entire life. This example of energy production shows

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[8] The Joint European Torus JET is to date the world's largest nuclear-fusion research facility, built in Culham, England. It is operated as a collaboration between all European fusion organizations with the participation of scientists from around the globe.

that the efficiency of transformation of mass into energy is given by

efficiency of energy production

$$mc^2\,\eta = 6.77 \times 10^{12}\,\mathrm{J}\ , \tag{12.19}$$

$$\eta = \frac{6.77 \times 10^{12}\,\mathrm{J}}{25 \times 10^{-3}\,\mathrm{kg} \times \left(3 \times 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}\right)^2} \approx 3‰\ . \tag{12.20}$$

Even though this efficiency is somewhat smaller than the efficiency of the proton–proton fusion in the Sun, it is much better than the efficiency that one gets from nuclear power plants based on fission.

neutron-activated reactor material

safety

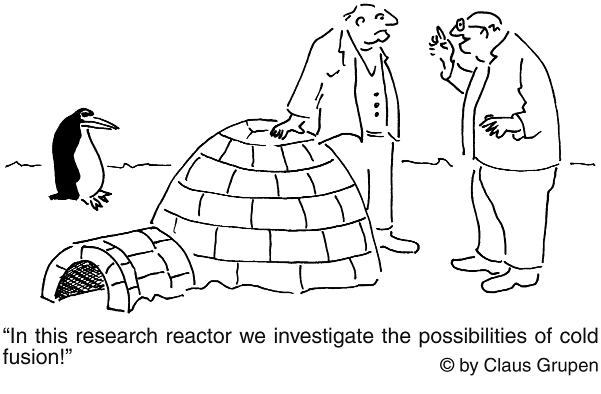
Apart from the neutron-activated reactor material, fusion reactors produce no nuclear waste. In addition to the avoidance of nuclear waste, the improved safety of fusion reactors is a very important aspect. In contrast to fission reactors, a fusion reactor can never suffer a severe radiation accident as happened in the Chernobyl disaster. If the conditions for the fusion of hydrogen nuclei are no longer given, the fusion reactions will terminate and the reactor will shut down all by itself. Since there are no chain reactions in the fusion reactor, it is impossible for the fusion reactor to get out of control. Also events from outside, e.g. a plane crashing into the fusion reactor, cannot cause a sudden uncontrolled fusion.

hydrogen bombs

fission bomb

One might object that hydrogen bombs have been built which work along the fusion principle. However, a fusion bomb, i.e. a hydrogen bomb, needs to be ignited by a normal fission bomb. The overall fusion process is started in the following fashion: Initially, subcritical amounts of uranium or plutonium are brought together by a mechanical implosion, which then start to explode as a standard nuclear-fission bomb. In such an explosion the conditions are created under which nuclear fusion can occur. Only a normal atomic bomb, as it is frequently called, enables the ignition of a hydrogen bomb. Since in a fusion power plant no fission reactions are initiated, a fusion power plant can never undergo a large radiation accident.

inherent safety



"In this research reactor we investigate the possibilities of cold fusion!"

© by Claus Grupen

Also a nuclear-fission bomb thrown in a terrorist attack onto the fusion reactor cannot cause the fusion reactor to get out of control since the fission energy must be liberated in a relatively small volume, otherwise the fusion plasma would simply decay. A normal atomic bomb would dilute and pollute the plasma, thereby destroying the conditions for the burning of the plasma. Also smallest amounts of air entering the plasma would stop the burning plasma immediately. Air entering the fusion chamber during normal reactor operation must be avoided under all circumstances. This extreme sensitivity of a fusion reactor represents an important safety aspect, because it will prevent the reactor running out of control in critical emergency situations. In such situations, the reactor will simply stop working without polluting the environment.

safety aspect

These safety aspects are a strong argument for a fusion reactor. It appears possible to master the solar fire and use it on Earth, in this way avoiding the possible risks which are related to the production of nuclear energy by fission.

12.3 Supplementary Information

Example 1

first nuclear reactor

Enrico Fermi

On December 2nd 1942 the first nuclear reactor went critical. Enrico Fermi and his colleagues succeeded to maintain a self-sustaining chain reaction in a graphite-moderated reactor with uranium oxide as fuel. The reactor was set up under the grandstand of the squash court on the site of the sport stadium of the University of Chicago (Fig. 12.15).

self-sustaining chain reaction

This first reactor was constructed as a uranium–graphite matrix. The uranium blocks and the high-purity graphite modules were arranged in the form of a cubic lattice. The reactor was meant as an experiment to demonstrate the feasibility of a self-sustaining chain reaction. There was no cooling.

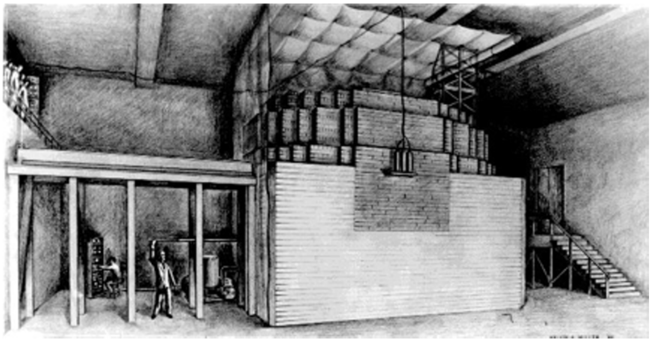


Figure 12.15
Sketch of the historic reactor in Chicago, in which the first controlled, self-sustaining chain reaction was maintained. Image credit: Argonne National Laboratory

Before the reactor was built in Chicago and before it was set into action, thirty subcritical reactors had been tested to measure the neutron yield and to determine the critical mass for a reactor with self-sustaining chain reactions. The reactor was equipped with a three-fold security system by control rods for neutron absorption and further devices which were designed to regulate the neutron flux. There was an automatic system consisting of cadmium control rods and a special safety rod for emergency situations. This hand-operated emergency safety rod was connected to a rope which was held by a physicist. The rope could simply be dropped or cut by an axe if it should turn out to be necessary, e.g. if the automatic shutdown system was not working properly. The third security system consisted of a team of technicians, who were standing by, and would flood the reactor in an emergency situation with a cadmium-salt solution, if the automatic shutdown system and also the hand-operated control-rod system should fail.

three-fold security system

The chain reaction was initiated by withdrawing the cadmium control rods slowly out of the reactor. While this was being done, the neutron yield and neutron flux as a function of the position of the control rods was measured. When the neutron rate increased exponentially, it became obvious that a self-sustaining chain reaction had developed in the reactor. In this way it was demonstrated that a controlled, self-sustaining chain reaction in a uranium reactor would definitely work.

cadmium control rods

controlled chain reaction

Example 2

Oklo, Gabon

natural reactor

1.7 billion years ago, a natural reactor started to operate in Oklo, Gabon in West Africa, and produced energy, with some interruptions, over a period of several million years. In 1970, French scientists found a very unusual ratio of isotopic abundances of $^{235}\mathrm{U}/^{238}\mathrm{U}$ in a mine in Oklo. On Earth, in meteorites, and in lunar rock – just as in the whole solar system – the uranium isotope $^{238}\mathrm{U}$ occurs with an abundance of 99.3% and that of $^{235}\mathrm{U}$ with an abundance of 0.7%. Other uranium isotopes ($^{233}\mathrm{U}$, $^{234}\mathrm{U}$) are quite rare in comparison. The present isotopic ratio $r = \frac{N(^{235}\mathrm{U})}{N(^{238}\mathrm{U})}$ is consistent with the assumption that these two isotopes were of equal abundance during the formation of our solar system. Because of the different half-lives of the isotopes ($T_{1/2}(^{238}\mathrm{U}) = 4.5 \times 10^9$ yrs, $T_{1/2}(^{235}\mathrm{U}) = 7.1 \times 10^8$ yrs), these isotopes developed the currently observed abundance over the course of time.

It came as a surprise that the isotopic abundance of $^{235}\mathrm{U}$ was only 0.35% in the Oklo mine. Comparable values of $^{235}\mathrm{U}$ are also found in spent fuel elements of modern nuclear power plants. Since the observed isotopic abundance of other elements also corresponded to those which are found in nuclear power plants, it was natural to assume that a natural chain reaction and nuclear fission

isotopic abundance

isotopic anomaly

had been running in the Oklo mine. If the present global ^{235}U abundance is extrapolated back in time to the time when the Oklo reactor was in operation, one arrives at a ^{235}U concentration of about 3%.

rainwater

moderator for neutrons

chain reaction

The rocks in the Oklo mine are very porous and they have many cracks. They are therefore very permeable to rainwater (see Fig. 12.16). Rainwater entering the uranium-containing mineral is an ideal moderator for neutrons. Due to spontaneous fission, or also by cosmic rays, there are always some neutrons available which can initiate nuclear-fission processes. Neutrons created in fission processes are relatively fast, but they will be moderated by the rainwater and initiate a chain reaction and sustain it for a while. The energy created in this way will lead to evaporation of the water, thereby interrupting the chain reaction, because the fast fission neutrons are now no longer moderated. Only if further water enters the rock or if the evaporated water condenses, will the chain reaction restart. Apart from this natural phase transition of the water the natural reactor was certainly also modulated by the alternating rainy and dry seasons in West Africa at the time. It is assumed that the Oklo reactor reached thermal powers of about 100 kW. From the fission products one can estimate that several tons of uranium were processed and also a substantial quantity of plutonium was bred. Of course, the Oklo reactor stopped working when the abundance of ^{235}U fell below a certain critical limit.

thermal powers

natural deposit

The fission products of the natural reactor and the transuranic elements bred (e.g. ^{244}Pu, $T_{1/2} = 8.26 \times 10^7$ yrs) migrated only a few meters from where they had been created. They stayed essentially where they were produced. They were also not distributed or washed away by the ground water. In this experiment, which cannot be repeated in a laboratory, nature demonstrated that over a period of 1.7 billion years, certain geological formations are suitable as natural deposit for radioactive waste.

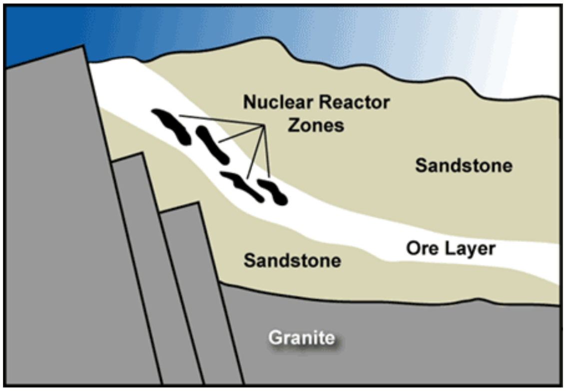


Figure 12.16
Sketch of the uranium-containing deposits held in position in the surrounding geological formation over a long period in the Oklo reactor. Image credit: U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Project

Example 3

cooling after shut down

Even after shutdown of a nuclear reactor, still a significant quantity of energy is produced in the form of beta and gamma radiation. This radiation is the result of radioactive decays of highly radioactive fission products produced in fission reactions. It is therefore important to maintain the cooling even after the reactor has been shut down. Immediately after shutting down a reactor, about 7% to 10% of the nominal power is still created by radioactive decays. This activity, responsible for the energy generation after shutdown, will decrease quite rapidly because many fission products are quite short-lived. The cooling system of the reactor, however, should stay in operation for a period of several hours after the reactor has been shut down. If cooling after shutdown is not provided, the temperature of the reactor might increase in an uncontrolled fashion and might even cause the uranium to melt.

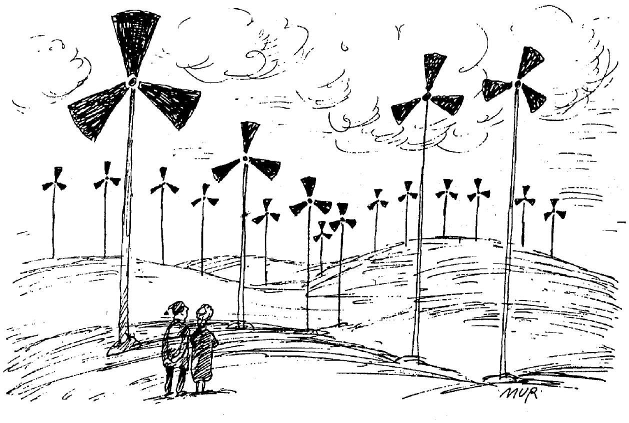
Harrisburg

Three-Mile-Island reactor

fast reactor shutdown

containment system

Exactly that happened near Harrisburg in the Three-Mile-Island reactor in the year 1979. After a fast automatic reactor shutdown the cooling water pumps were also switched off due to an erroneous interpretation of the state of the reactor. Since the heat generated by the radioactive decays of the fission products could no longer be dissipated, the fuel elements got very hot and some even melted. As a consequence of this accident, fission products of high radioactivity entered the primary circuit. Furthermore, gaseous fission products (e.g. $\approx 40\,\mathrm{PBq}$ of $^{133}\mathrm{Xe}$) were directly discharged into the atmosphere. Luckily the molten reactor core was retained in the reactor tank by the primary containment system, so the radioactive exposure for the environment was rather small.



Windy Alternative

© by Luis Murchetz

Summary

Nuclear fission discovered by Hahn and Straßmann in 1938/39 and correctly interpreted by Meitner and Frisch has led to military and civil use of nuclear power. The transformation of mass into energy can be realized by fission of heavy elements but also by the fusion of hydrogen to helium, the energy production mechanism which makes the stars shine. There are a number of different ways to put nuclear fission and fusion into practice. Carefully designed fission reactors based on water-cooled, water-moderated reactor types or pebble-bed reactors guarantee a high degree of safety. The design, implementation, and specific construction of a fusion reactor, however, is still under research and development. In the long term, the energy demand of mankind will very likely have to include the mechanism of gaining energy with the help of nuclear fusion, as it is demonstrated by the stars in a natural way.

12.4 Problems

Problem 1 After the shutdown of a boiling-water reactor, the cooling was also switched off by mistake. Let us assume that 10% of the original reactor power (1 GW) will be provided by radioactive decays of the fission products. About 70% of this fraction will be released typically over a period of 200 seconds. By how much will the temperature of the reactor increase (50 tons of uranium)? The specific heat of uranium at 25°C is 116 J/(kg K).

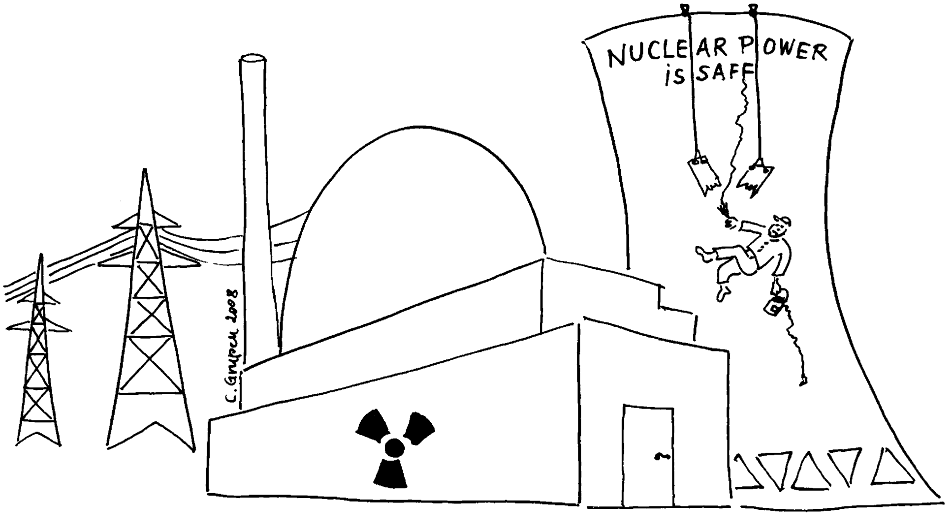
Problem 2 It is assumed that the Oklo reactor produced energy intermittently over a period of 10^6 years, with peak powers of up to 100 kW. Work out the amount of ^{235}U processed, if one assumes that the reactor had an average power of 50 kW over a period of half a million years.

Problem 3 The present isotopic abundance of ^{235}U in the Oklo reactor is 0.35%. Work out the age this uranium deposit would have if this particular value of the isotopic abundance had been caused only by normal radioactive decay. For the solution of this problem it is natural to assume that the uranium isotopes ^{235}U and ^{238}U were originally of equal abundance.

Problem 4 **dose rate** The dose rate after a nuclear accident or a nuclear-weapon explosion decays with time according to

$$\dot{D}(t) = \dot{D}(t_0) \left(\frac{t}{t_0} \right)^{-\alpha} \quad ,$$

where $\alpha = 1.2$ and $\dot{D}(t_0)$ is the dose rate at the time t_0. Assume that $\dot{D}(t_0 = 6\,\text{h}) = 10\,\text{mSv/h}$, and work out
a) the dose rate after one further day;
b) the integral dose which one obtains if one stays in this area over a period from $t_1 = 30\,\text{h}$ to $t_2 = 40\,\text{h}$.



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