Nuclear Physics III

Fission. Nuclear power. Reactor Physics

Chapter 9 of the textbook
Elementary Physics 3

This is an article from my home page: www.olewitthansen.dk

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Informative remark: The present chapter is a translation from the Danish textbook: Elementary Physics 3. However, the texts, when it appears in the figures are not translated. On the other hand the figures and the supplementing text should speak for themselves.

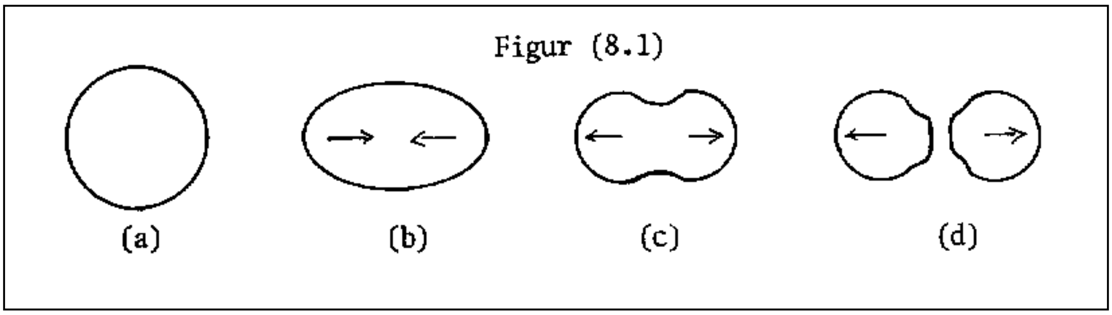
Contents

8. Nuclear energy. Fission and fusion

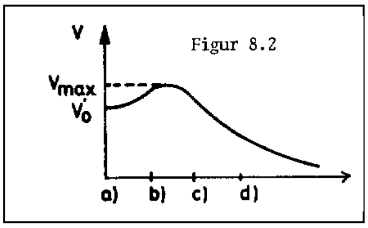
If the aim is to manufacture radioactive isotopes, the usual procedure is to irradiate an atomic nucleus with neutrons. The isotopes are then created by capturing a neutron followed by a β^--, β^+-decay or a *K*-capture.
As early as in 1934 E. Fermi made an attempt to create elements with atomic number $Z > 92$, by irradiating uranium (*U*-238, $Z = 92$) with neutrons.
Even if β radiation was observed, it was not possible to interpret the experimental results.

In 1938 Hahn and Strassman showed, on the basis of extensive chemical analysis that among the residues from the irradiation of the *U*-238, that there were found traces of Barium ($Z = 56$) and Krypton ($Z = 36$).
Now 56 + 36 =92, so shortly after that the experimental results were published, the two physicists Meitner and Frisch suggested, (the rather obvious) that the uranium nucleus (Z = 92) after having captured a neutron, had been split in two nuclei, namely *Ba* ($Z = 56$) and *Kr* ($Z = 36$).

The splitting of a nucleus into two larger fragments is known as *fission*.
Shortly after the discovery of the fission disintegration, Bohr and Wheeler put forward a theory for the occurrence of fission based on the liquid drop model.
In this model the fission process takes place in much the same manner as the splitting of a drop of liquid into two almost equal drops. Illustrated in figure (8.1)



As it is the case for a drop of liquid, we shall assume that the volume of the drop is conserved during the split.
The energy conditions in the process (a) → (d), can therefore only be directed by the surface term and the Coulomb term in the semi empirical mass formula.
The energy grows in the deformation (a) → (b) , because the surface grows, without the Coulomb energy decreases. By the deformation (b) → (c) the Coulomb energy decreases faster than the surface energy grows, and the nucleus is driven towards division (c) → (d) .



In the figure (8.2) it is shown that the nucleus must overcome a certain threshold energy to split. In principle this could be achieved by the tunnel effect, (as is the case of the alpha-decay of *U*-238), and in that case we speak of a *spontaneous fission*.
The spontaneous fission is however very improbable compared to the (equally improbable) alpha-decay.
Using the semi-empirical mass formula Bohr and Wheeler estimated that spontaneous fission would occur only for nuclei having $Z^2/A > 47.8$, but for the heavy nuclei we find values far below this value e.g. $Z^2/A = 35.5$ for *U*-238.

To obtain a disintegration of a nucleus it is necessary to excite it to a energy above the threshold illustrated in figure (8.2). This may be obtained by capturing a neutron in the nucleus, as it was observed experimentally by irradiating uranium with neutrons.
In the experiments, however, there were also observed a distinct β-activity having a half-life of 23 min. Since the β-activity was far above from what could be expected as a consequence of fission, it had to be induced radioactivity by neutron capture in uranium-238 followed by a β-decay.
More specifically:

(8.3) $$^{238}_{92}U + ^{1}_{0}n \;\rightarrow\; ^{239}_{92}U \;\rightarrow\; ^{239}_{93}Np + e^{-} + \bar{\nu}$$

In this process a new element with $Z = 93$ has been created. It is not found in nature and it has acquired the name Neptunium.
Bohr and Wheeler could, however, (using the semi-empirical mass formula), show that the neutron energies were hardly sufficient to excite uranium-238 above the fission threshold.

This explains the β-activity (3.8), whereas the observed fissions seemed inexplicable.

The in nature existing uranium consists, however, of two isotopes, namely $^{238}_{92}U$ (99.3%) and $^{235}_{92}U$ (0.07%), and concerning $^{235}_{92}U$ even slow neutrons are able to instigate a fission of the nucleus. The reason for this is that $^{235}_{92}U$ has an odd number of neutrons, and adding a neutron releases sufficient energy, (caused by the pairing energy $\delta(A,Z)$), to bring the nucleus above the fission threshold. (For $^{238}_{92}U$, which is an (even – even) nucleus it is just the opposite situation).

Thus Bohr and Wheeler proposed that the observed fissions emanated from a disintegration of $^{235}_{92}U$, and not, as was the first conjecture, a disintegration of $^{238}_{92}U$.
The cleavage is then supposed to happen in the following way.

(8.4) $$^{235}_{92}U + ^{1}_{0}n \;\rightarrow\; ^{236}_{92}U \;\rightarrow\; ^{144}_{56}Ba + ^{89}_{36}Kr + 3\,^{1}_{0}n + energy$$

The disintegration of $^{235}_{92}U$ may take place in several different ways. Another possibility is:

(8.5) $$^{235}_{92}U + ^{1}_{0}n \;\rightarrow\; ^{236}_{92}U \;\rightarrow\; ^{140}_{54}Xe + ^{94}_{38}Sr + 2\,^{1}_{0}n + energy$$

For all fissions, however, it is characteristic that the emission of a few neutrons is accompanied by the disintegration. The Neutrons have energy of about 2 *MeV*.
Even then, the disintegration fragments have a large surplus of neutrons, when compared to the β-stability line, and the fragments are thus violently β-active.
As an example, it is shown below the β-decay chain of the fission fragment *Xe*-140.

(8.6) $$^{140}_{54}Xe \rightarrow \beta^{-} + ^{140}_{55}Xe\,(16\,s) \rightarrow \beta^{-} + ^{140}_{56}Ba\,(66\,s) \rightarrow \beta^{-} + ^{140}_{57}La\,(2.8\,d) \rightarrow \beta^{-} + ^{140}_{58}Ce\,(stable)$$

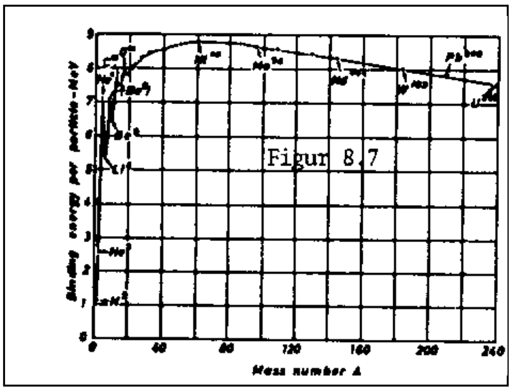
Apart from the β-decay, some fragment also emits neutrons. They are however delayed by several seconds compared to the β-decays, and are therefore called delayed neutrons.
They are however of paramount importance in controlling the activity in a nuclear reactor, and without these neutrons, it would hardly be possible to maintain a stable fission process in a reactor.

Rather early, when it became clear that the neutron induced fission itself was accompanied by neutron emission, it took only a very short time to realize that inducing uranium with neutrons could start a chain-reaction developing in an explosive manner.

From chemistry this kind of explosive chain reactions are well documented, but the crucial difference is the magnitude in release of energy per atom and per nucleus.
This ratio is namely roughly the same as the ration between the binding energies of the outer electrons in an atom (of magnitude 1 eV) and the binding energies of the nucleons in the atomic nucleus (of magnitude 1 MeV) , that is, a million times stronger.
So when constructing a nuclear bomb, one would expect a destructing power of about a million times greater than using ordinary explosives.

Realizing the possibility of constructing a nuclear fission bomb, initiated in the 1930-ties a technological race, both in Nazi Germany, Britain and USA, a race, as it is well known, was won by the Americans who threw the first two uranium based fission bombs which destroyed the cities of Hiroshima and Nagasaki in august 1945.

If you look at a mapping of the binding energy per nucleon for the stable nuclei, shown in figure (8.7) , we observe that it has a maximum for the medium heavy nuclei around A = 60 (Nickel).
From which on may conclude, that energy can be released either by fission of heavy nuclei to medium heavy or to fuse lighter nuclei to medium heavy. The latter is called *fusion*.



Figur 8.7

From the figure it appears that the difference between the binding energy per nucleon for uranium-235 and for its fission fragments is about 0.9 MeV . This results in a release of energy of about 200 MeV per fission.
A fusion between two deuterium ($^{2}_{1}H$) nuclei to a helium nucleus $^{4}_{2}H$, will, however, result in a release of energy of about 6 MeV per nuclear fusion.
From the point of view of providing energy to the society, the fusion process is thus much preferably than the fission. Also because, the radioactivity accompanied by the fusion of hydrogen to helium is very small.
Furthermore the deuterium isotope $^{2}_{1}H$ is abundant in almost unlimited quantities, since 0.0017% of the water in the oceans is “heavy water” D_2O.
On the other hand, the technological difficulties controlling fusion are enormous, (whereas a uncontrolled hydrogen bomb was tested by USA already in the mid fifties).

It seems practically impossible to obtain, maintain and control such enormous temperatures and pressures which are required for initiating the fusion.
The most promising development has been the Tokamak reactor, where the alpha-particle are confined in magnetic fields, and accelerated in variable magnetic fields.
For the time being (1980) it has only been possible to obtain temperatures and densities that are several thousand times below the threshold initiating fusion of deuterium to helium.
(When this text book was first written in 1980, the perspective was that we would have a fusion reactor within 30 - 40 years).

On the other hand, it has been possible to cause uncontrollable fusion in the hydrogen bomb.
In this device a uranium or plutonium bomb is applied to ignite the fusion, since this "ignition" can create the necessary temperatures and pressures to initiate the fusion.

Finally it should be mentioned that the sun and all stars get their radiation of energy from fusion processes (hydrogen to helium) in the core of the stars.
The fusion processes in the stars comes about because the gravitational forces of these very massive stars are sufficient to create the sufficient pressures and temperatures to initiate the fusion processes. Once they have started the production of heat keeps up the pressure and temperature. This is discussed in detail in the section of astrophysics.

9. Exploitation of nuclear energy

The energy which is exploited in a reactor in a nuclear power plant is nuclear energy released from fission of uranium-235 or uranium-238 as fuel.
As described in the previous section the fusion is instigated when an uranium-nucleus captures a neutron following by a disintegration in two fragments, releasing energy together with 2-3 neutrons, and it is the release of these neutrons that maintains the fission processes.

It is the kinetic energy of the fragments that is converted to heat, that is, to the steam that drives the turbines and produce electricity.

There are several possibilities for the fragments from the fission, but common for them all is that the fission is accompanied by the emitting of 2-3 neutrons. Below is shown one of the most common fission processes.

$$^{235}_{92}U + ^{1}_{0}n \;\rightarrow\; ^{236}_{92}U \;\rightarrow\; ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n + Q$$

$Q = \Delta E = -\Delta Mc^2$ is the released energy from the fission. For all fissions of $^{235}_{92}U$ the released energy is about 200 *MeV*.
To lift the released energy coming from one fission to a macroscopic scale, we shall calculate the energy released by fission from all the nuclei in 1 *g* $^{235}_{92}U$.

In one gram of $^{235}_{92}U$ there are 6.02 10^{23}/235 nuclei = 2.55 10^{21} nuclei. By fission of all these nuclei there will be released: 200 *MeV* · 2.55 10^{21} ·1.60 10^{-13} *J/MeV* = 8.16 10^{10} *J*.

So if a power plant consumes 1 g of $^{235}_{92}U$ a day it corresponds to:

$$8.16\ 10^{10}\ J/(3600\ 24\ s) = 0.94\ \text{MW}$$

Roughly 1 MW, which is the power delivered by a medium size power plant.

The calculation is, however, theoretical, since a lot of the energy will end as waste heat.

The energy released from one fission is (in round figures) distributed as follows.

The kinetic energy of the fission fragments:	168 MeV
The kinetic energy of the neutrons	5 MeV
Momentary gamma-radiation	5 MeV
β- and γ-radiations from the fragments	13 MeV
Energy of the neutrinos	11 MeV
	202 MeV

It is the instantaneous emission of neutrons from the fission process that maintain the fissions in the reactor.
Assuming that 3 neutrons are released, and further that 2 of these neutrons induce new fissions, then the number of fissions would increase as 2^n, where n is the number of "generations".
Since the time interval between a fission until it has induced the next is a few milliseconds, then the number of fissions will grow exponentially forming a chain reaction, that is, a nuclear bomb.

We shall now briefly discuss the means to control the fissions in a reactor, so it does not go runaway, which would be a major disaster.

Firstly: ${}^{235}_{92}U$ is only 0.73% of the uranium which is found in nature, the rest is ${}^{238}_{92}U$.
${}^{238}_{92}U$ can also be disintegrated by neutron capture, but it requires neutron energies somewhat above the energies released by the fission neutrons.
For this reason it is in general not possible to maintain a chain reaction process with ${}^{238}_{92}U$.

Secondly: The cross section for neutron capture in ${}^{235}_{92}U$ is strongly decreasing with neutron energy.
The cross section is largest for so called thermal neutrons with energies 0.01 – 10 eV.

Thermal is a reference to the energy atomic particle have, when they are in thermal equilibrium with the surroundings, namely:

$$E_{kin} = \tfrac{3}{2}kT = \tfrac{3}{2}1.38\,10^{-23}\ J/K\ 300K = 6.2\,10^{-21}\ J = 0.04\ eV.$$

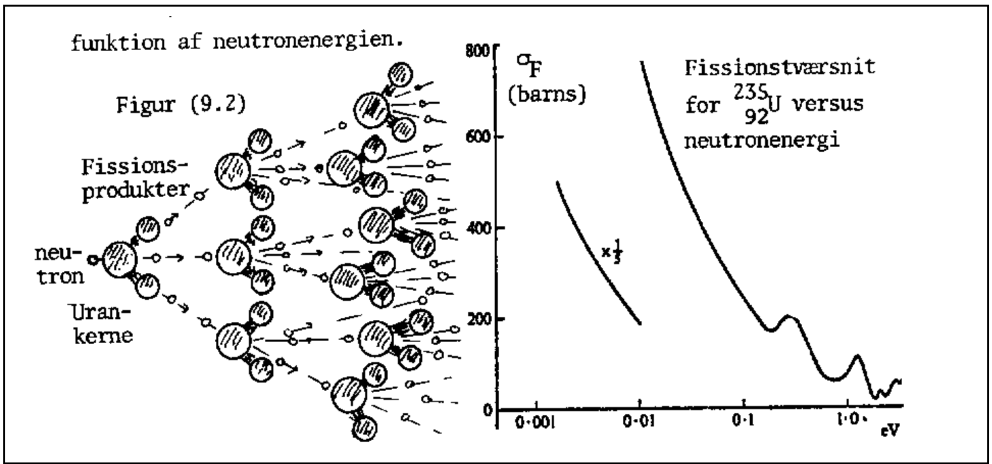
The neutrons, which are released in the fission process are, however, far from thermal, having energies 1 – 3 eV .
So using the fission neutrons to create new fissions they have to be slowed down.
For this reason all reactors have built in so called moderators, containing a substance which is able to brake the fast neutrons.
The energy that a neutron with mass m_n looses when colliding with a nucleus with mass M, can be estimated from the formulas for a central elastic collision between the two particles. The neutrons velocity after the collision is according to these formulas:

$$v_{after} = \frac{m_n - M}{m_n + M} v_{before}$$

So we see that $v_{after} \approx 0$ if $m_n \approx M$. So, if it is the purpose to slow down the neutrons as much as possible, the obvious choice is to use a moderator containing hydrogen.
But using substances containing a lot of hydrogen has a drawback, since the hydrogen nucleus (the proton) has a tendency to capture the neutrons to create deuterium. ${}^{2}_{1}H$.

The cross section for neutron capturing in deuterium is however very small, so albeit a bigger mass it is the most efficient moderator for the neutrons.
When heavy water D_2O is used as a moderator the reactor is called a heavy water reactor.
However, light water reactors do also exists, but they require a substantial enrichment of uranium - 235.
(During the second world war, there was a competition to get hold of heavy water, although only very few knew why. The Norwegian resistance succeeded, on orders from London, to sabotage a heavy water plant in Rjukan to prevent Nazi Germany to get hold of the very scarce heavy water).

In the figures below is to the left schematically illustrated the fission chain reaction, and to the right the fission cross section for $^{235}_{92}U$, as a function of the energies of the captured neutrons.



Uranium-235 is, however, not the only possible candidate to supply fuel in a nuclear reactor.
The absolute dominating isotope of uranium $^{238}_{92}U$ (99.27%) may also be disintegrated by fission, but it requires higher neutron energies than released by the fission process.

The probability of neutron capture in uranium-238 is, however, rather large, and for moderate neutron energies the nucleus will not disintegrate by fission, but decay according to the following schema.

(9.3) $$^{238}_{92}U + ^{1}_{0}n \rightarrow \ ^{239}_{92}U \rightarrow^{23.5\ \text{min}} \ ^{239}_{93}Np + e^- + \bar{\nu}$$ (Neptunium)

(9.4) $$^{239}_{93}Np \ \xrightarrow{2.3\ day} \ ^{239}_{94}Pu + e^- + \bar{\nu}$$ (Plutonium)

By the two β-decays two new elements are created: Neptunium-239 and Plutonium-239, (which are not found in nature).
The interesting fact about Plutonium-239 is, however, that it (like Uranium-235) can disintegrate by fission induced by slow neutrons, since both nuclei have an uneven number of neutrons.
Thus, they both release the pairing energy when absorbing a neutron, which brings the nucleus above the fission threshold. For that reason Plutonium-239 can be used as fuel in a nuclear reactor.

Some reactors are constructed to make use of the production of Plutonium-239. They are called *breeder reactors*.

From one fission of uranium-235 there are on the average released 2.5 neutrons. To maintain the chain reaction it is necessary that one of these neutrons is captured in uranium-235 to induce a new fission. If it, at the same time, is achieved that one neutron is captured by uranium-238, the reactor will produce fissile material at the same rate as it is consumed.
If, however, the uranium-238 which is present in the reactor is not reprocessed, then this extremely high radioactive material will be highly dangerous and useless in the future.

From the point of view of a rational preservation of the energy resources it is therefore not sensible to burn the 0.7% uranium-235 in nuclear power plants, without reprocess the 99.3% uranium-238. Reprocessing the uranium-238 is however, technological demanding, since you will have to deal with extremely radioactive material, which requires very high security precautions.
The devastating consequences of an accident in a nuclear power plant has (as you know), been a persistent issue in the public opinion since the 1960-ties.

10. Reactor physics

In this section we shall line up the neutron accounting, which is totally decisive for controlling a fission chain reaction in a nuclear reactor.
Let us therefore assume that we in a reactor have a momentary production of neutrons n_p.
The neutron accounting is then about to establish what happens to these n_p neutrons.

1. Neutrons are captured in ${}^{235}_{92}U$, causing new fissions. This number we shall call n_F.
To increase the number of these neutrons, one may do the following:

a) Slowing down the neutrons by using a moderator e.g. water H_2O or heavy water D_2O.
The figure (9.2) above shows that the fission cross section σ_F grows dramatically with decreasing neutron energies. Without a moderator it is not possible to induce sufficient fissions to keep the fission processes going at the same rate.

b) Artificially to increase the amount of ${}^{235}_{92}U$ in the natural uranium. This then called enriched uranium. Enrichment of uranium is however an extremely complicated and costly process, since the two isotopes cannot be separated chemically. It must be done in an isotope-separator, diffusion techniques or in advanced centrifuges. (The concept of centrifuges for that purpose has been on the front pages for almost a decade).

2. Neutrons are captured in ${}^{238}_{92}U$ to form ${}^{239}_{92}U$.
This isotope is not β-stable, and it decays to ${}^{239}_{93}Np$ and further to ${}^{239}_{94}Pu$ by another β-decay.
The formed ${}^{239}_{94}Pu$ can, however, like ${}^{235}_{92}U$ disintegrate by fission by capturing a slow neutron.
In the so called breeder reactors the formation of ${}^{239}_{94}Pu$ is exploited to form new fissile material.
(The formation of Plutonium can of course also be (mis-)used to the production of nuclear weapons, known as atomic bombs, a permanent issue in the public debate of establishing nuclear power plants especially in countries without proper democratic control).

${}^{238}_{92}U$ can disintegrate by capturing a neutron, but the threshold energy is above the average neutron energy, which is about 1 MeV. To achieve a reasonable probability of fission it requires higher neutron energies, but at these energies the cross section for neutron capture is too small to make fission of uranium-238 significant.

The cross section for capturing thermal neutrons in ${}^{238}_{92}U$ is quite big, and to avoid that too many neutrons are captured in ${}^{238}_{92}U$ the trick is artificially to increase the content of ${}^{235}_{92}U$ in the reactor fuel. The number of neutrons, which are captured either in ${}^{238}_{92}U$ or in the moderator is denoted n_c.

3. To slow down a fission chain reaction from developing in an explosive manner, one can immerse so called control rods made of strongly neutron absorbing material. The control rods are either made of *Cd* (Cadmium) or *B* (Bor). The number of neutrons absorbed in this manner is denoted n_A.

4. Neutrons escape from the reactor. This number is denoted n_L and it is called the leak.
The leak has nothing to do with physical leaks in the reactor, but is merely an expression of the fact that neutrons can diffuse out from the area without having instigated a nuclear reaction.
The leak is proportional to the surface of the reactor, whereas the neutron production is proportional to the volume. If the linear extension of the reactor is r, then the surface is proportional to r^2 while the volume is proportional to r^3.
The ratio between the leak n_L and the neutron production n_P is therefore: $n_L/n_P = r^2/r^3 = r^{-1}$.
This ratio is seen to diminish with the size of the reactor.
To keep the fission going it is therefore necessary that the volume of the uranium has a certain size called the *critical mass*. (And the same applies for the production of nuclear weapons).
The size of the critical mass is “a secret” but it is probably a few kilograms highly enriched uranium.
In the first nuclear bomb manufactured at Los Alamos in the spring of 1945, two masses of enriched uranium each below the critical mass were cannoned together to initiate the (uncontrolled) chain reaction of the fission bomb.
The leak can be reduced by applying a neutron reflector, which returns the neutrons by elastic collisions against graphite (Carbon) on their way out of the reactor.

Taking all the mentioned factors in consideration, we find the following neutron accounting.
Neutron production: $n_P = n_F + n_C + n_A + n_L$.

1) *F:* Fission
2) *C:* Capture in ${}^{238}_{92}U$ or in moderator
3) *A:* Absorption in control rods.
4) *L:* Leak

To maintain the chain reaction under control, (so it does not develop explosively), then the sum of four terms must be held constant, in which case the function of reactor is called *critical*.

To keep the chain reaction critical, without running wild, the so called delayed neutrons, mentioned earlier are of vital importance. Apart from the neutrons coming from the fissions, a few neutrons are also emitted from the fragments from the fission of uranium-235 or uranium-238, because the fragments have a neutron surplus. While the neutrons from the fission are emitted within 10^{-10} *s*, the delayed neutrons are emitted only within 0.2 – 55 *s*.
These neutrons contribute to the neutron production n_p, and may instigate new fissions.

The average time it takes for a released neutron to induce a new fission is about 10^{-3} *s*, and that means a doubling of the fission activity in 0.1 *s*. So from that perspective it would not seem possible mechanically to lower the control rods to prevent an uncontrollable development (melting down) in the reactor.
The fact is that it would hardly be possible to maintain a critical level in the reactor, without the contribution from the delayed neutrons from the fission fragments.

It is in fact amazing that the "peaceful" exploitation of nuclear energy is based on a rather accidental emission of delayed neutrons from the fragments of the fission of uranium-235.
The neutron production in the reactor can also be viewed more mathematically.
We therefore introduce two constants.
τ is the average life-time of a neutron from it is emitted until it is captured and causes a new fission.
κ is the effective multiplication factor. It is defined as the number of new neutrons, which is emitted (from fission) that an emitted neutron averagely produces.
Using these two constants it is possible to establish a differential equation for the neutron production n_p.
We express simply that the increment/decrement in the neutron production dn_p in the time interval dt is equal to $\kappa n_p - n_p$ times dt/τ . From this follows the equation:

$$dn_p = n_p(\kappa - 1)\frac{dt}{\tau} \quad \Rightarrow \quad \frac{dn_p}{dt} = \frac{(\kappa-1)}{\tau} n_p$$

The equation has the solution:

(10.1) $$n_p(t) = n_p(0)e^{\frac{\kappa-1}{\tau}t}$$

Clearly the reaction is only critical, when $\kappa = 1$.
Which factors determine κ is discussed on the previous pages. It is schematically illustrated below.

1 thermal neutron is captured in ${}^{235}_{92}U$ or ${}^{238}_{92}U$.	→	η fast neutrons are produced by fission.
		↓
The fraction p from the fast neutrons are slowed down in the moderator to thermal neutrons, and the fraction 1-p is absorbed in the moderator, or are captured in ${}^{238}_{92}U$.	←	The number of fast neutrons are increased by a factor ε from fission in ${}^{238}_{92}U$
↓		
The fraction f of the thermal neutrons are captured in ${}^{235}_{92}U$ or in ${}^{238}_{92}U$.	→	The fraction $k_\infty = \eta\varepsilon p f$ of thermal neutrons are absorbed in uranium and the process starts over again.

$k_\infty = \eta\varepsilon p f$ is called the *four factor formula*.
In this formula, however, we have neither considered the leak nor the absorption of the neutrons in the control rods. Let P_L be the probability that, a neutron escapes the reactor, and P_A is the probability that a neutron is absorbed in the control rods.
We can then write the relation between the four factor formula and the multiplication factor κ.

(10.2) $$\kappa = (1 - P_L)(1 - P_A)\, k_\infty$$

11. Nuclear power plants

Quite generally one may say that a nuclear power plant produces neutrons, radioactive nuclear fragments, plutonium, and heat. The heat comes about because the fission fragments transfer their kinetic energies to the atoms in the cooling substance. The heated cooling substance is then applied as an energy source in a steam turbine, driving an electrical generator.

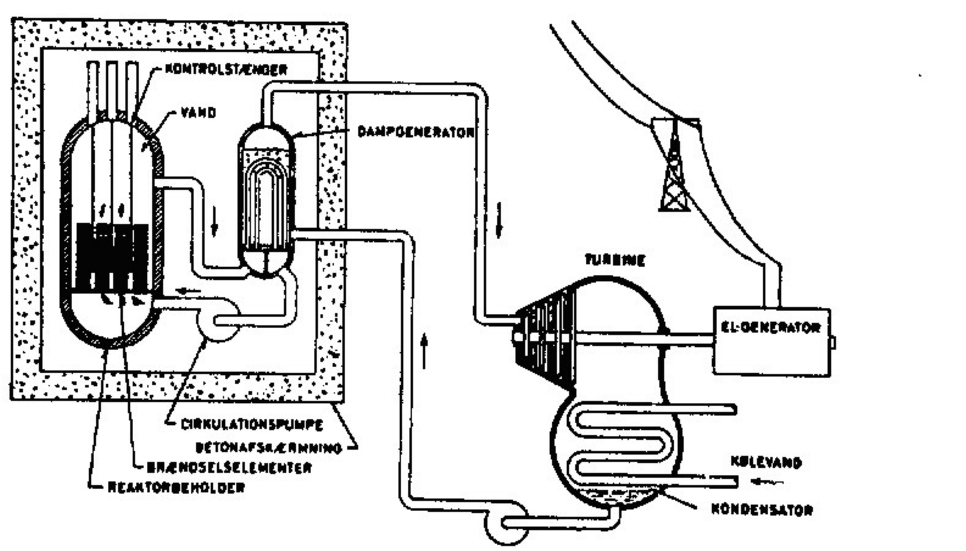
The technology in the various reactor types may be rather different, but in general all reactors consist of the following components.

1) Fuel elements of fissile material (*U*-235*, U*-238*, Pu*-239, *U*-233)
2) Moderator to slow down fast neutrons
3) Control rods to regulate the neutron intensity in the reactor.
4) A cooling substance, which both keeps the reactor at an appropriate temperature, and at the same time transfer the heat from the reactor to a power generating turbine. The cooling substance also serves as a moderator.
5) A neutron reflector (normally graphite) and a shield to protect from the radioactivity (the γ-radiation, which accompanies the fission processes. to penetrate out of the reactor area. The shield is usually 2 meters of concrete).

Decisive for the choice of reactor technology is the choice of moderator. As previously mentioned the possibilities for a moderator are ordinary water (light water), heavy water and in some cases graphite.
However, also generators without moderators are constructed, the so called fast reactors (the same as breeder reactors). In contrast, the other types of reactors are called thermal reactors.

11.1 The light water reactor

High pressure water reactor   Figure (11.1)



The light water reactor has ordinary water, both as moderator and cooling substance, but since the hydrogen nuclei has a tendency to capture the neutrons, it is necessary to enrich the existing uranium-238 with 2-3% uranium-235, to compensate for the weakened neutron intensity. Separation of uranium-235 is technologically a very complicated and costly process, whether it is done in centrifuges or in an isotope separator.
This is considered as the greatest disadvantage of the light water reactor.

In the high pressure water reactor, figure (11.1), the water in the reactor is kept under a pressure of about 150 at, to prevent it from boiling. The water serves both as a moderator and a cooling substance. The overheated water is then led through a steam generator, and the resulting steam drives a turbine.

11.2 The boiling water reactor

In the boiling water reactor the water is boiling, and the steam is led directly through heat exchangers to a steam turbine. The reactor type is shown schematically below.

Figur 11.2

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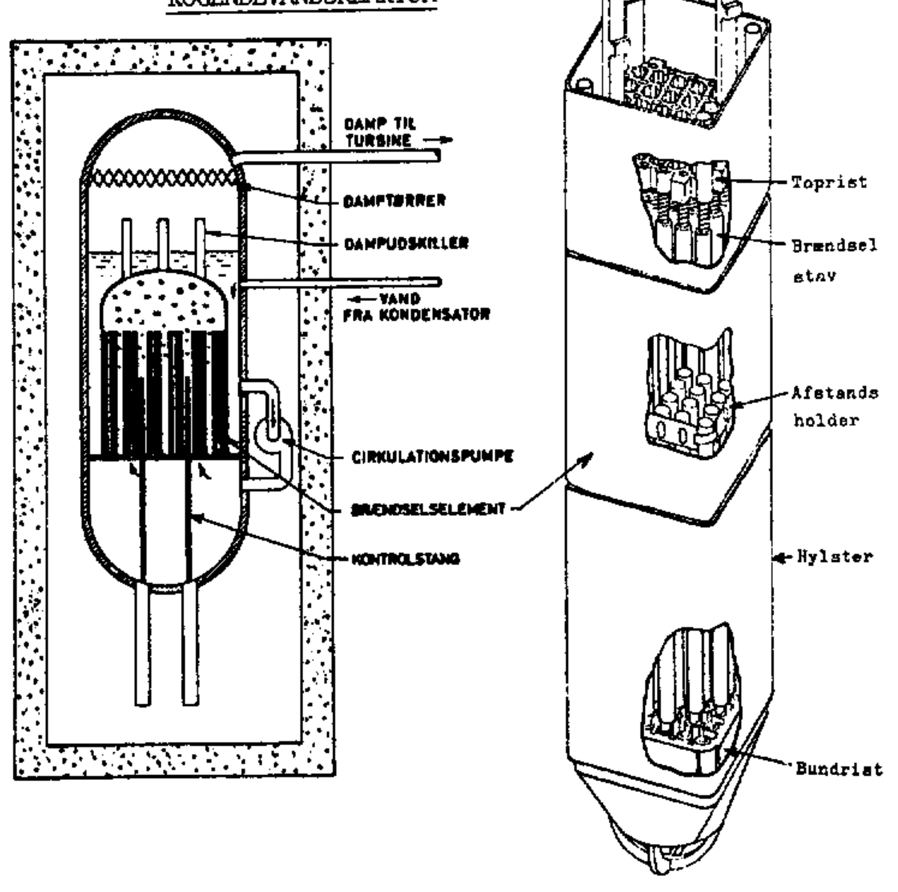


The fissile material is placed in a row of fuel elements, separated by control rods. In the reactor shown it is Bor carbide). The fuel elements are a bundle of fuel sticks, in a quadric sheath.
A fuel stick is a 4 meter long tube made of a zirconium alloy, which only moderately absorbs the neutrons.

The fuel sticks have an external diameter 12.5 *mm*, and they are filled with cylindrical pills of UO_2 (uranium dioxide) enriched with 2% - 3% *U*-235. The fuel sticks are welded tight in both ends, so that the highly radioactive material cannot leak into the cooling substance.

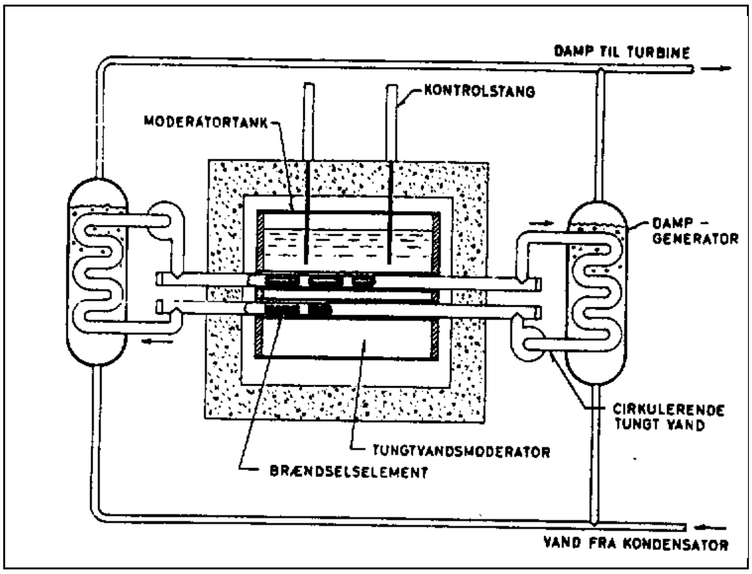
During operation, the fission processes will cause the fuel sticks to glow, and the heat is led through the wall of the sticks, where the surrounding water is brought to a boil. The fuel sticks are kept in their position by a bottom grate and a top grate combined with some distance holders between the two grates.
The control rods have a cross section forming a cross, so the can be inserted between the fuel elements to prevent neutron flux between the individual fuel elements.
Pumps are used to keep the water in circulation in the reactor, so that the water which is heated in the reactor is led out in the top of the reactor. The pressure in the reactor is 70 at.
And this Corresponds to a temperature of 285^0C.
Once a year the reactor is shut down to replace about a third of the fuel sticks. The used fuels sticks represent the most highly radioactive material from a reactor.

11.3 The heavy water reactor

In the heavy water reactor is used heavy water D_2O as the cooling substance instead of light (common) water. This gives the advantage, that the absorption of neutrons is diminished, such that the heavy water reactor can be driven without the (costly) enrichment with *U*-235.

On the other hand the heavy water is costly to produce in larger quantities, since it also must be produced by isotope separation. In figure (11.3) is shown a heavy water reactor of Canadian construction.
The costly heavy water circulates in absolute closed and tight systems, where the heavy water transports the heat from the reactor container to a heat exchanger, generating steam to drive a turbine.
The fuel-elements are 0.50 *m* long bundles of fuel sticks welded into zircaloy pipes.
For this reactor type, however, the fuel elements can be replaced during operation, as two loading machines connected to each end of a pressure pipe can replace the fuel element in one end, and at the same time take out the used one in the other.

Fig (11.3) The Candu reactor

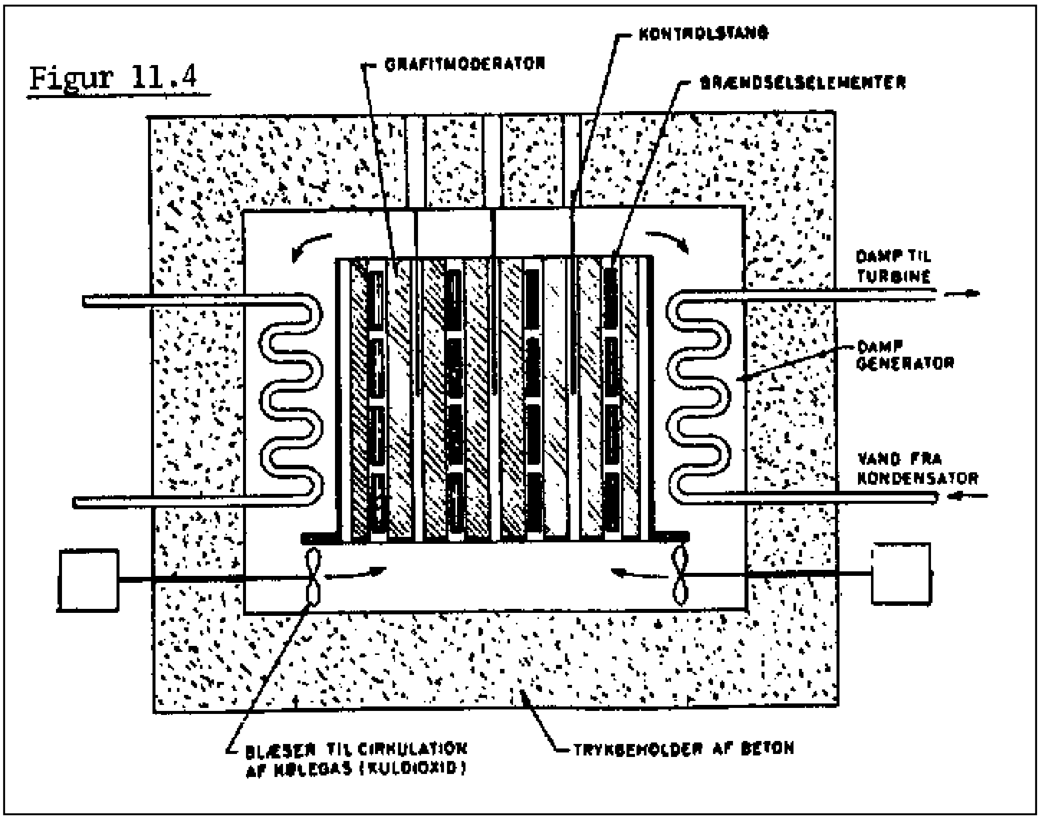


11.4 The graphite moderated reactor

In the graphite moderated reactor, graphite is used instead of water (heavy or light). Graphite has (like heavy water) the quality that it only weakly absorb the neutrons.
Great Britain, which was the first country to build reactors on a larger scale, did not have access neither to heavy water nor enriched uranium (or they did not have the technology to produce either), so instead they developed a technology to construct graphite moderated reactors.

As cooling substance they used CO_2 (Carbon dioxide), and the reactor is therefore denoted as gas cooled.
They applied natural Uranium encapsulated in a magnesium alloy (Magnox) as fuel elements.

The yield from these early reactors were, however, much lower than from the nuclear power plants that were built in the United States and elsewhere in the 60-ties and seventies.
The design and construction of nuclear reactors from the fifties was later changed in some essential aspects.
The first nuclear power plant was put in operation in the vicinity of Moscow in 1954. It was graphite moderated, water cooled reactor.
In the figure (11.4) below is shown schematically a graphite moderated gas cooled reactor.



Figur 11.4

11.5 Breeder reactor

The fast breeder reactors operate without a moderator, and along with the fission processes the fissile material $^{238}_{94}Pu$ is created by the reactions:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \xrightarrow{23.5 \text{ min}} ^{239}_{93}Np + e^{-} + \overline{\nu} \quad \text{(Neptunium)}$$

$$^{239}_{93}Np \xrightarrow{2.3\ day} {}^{239}_{94}Pu + e^- + \bar{\nu} \qquad \text{(Plutonium)}$$

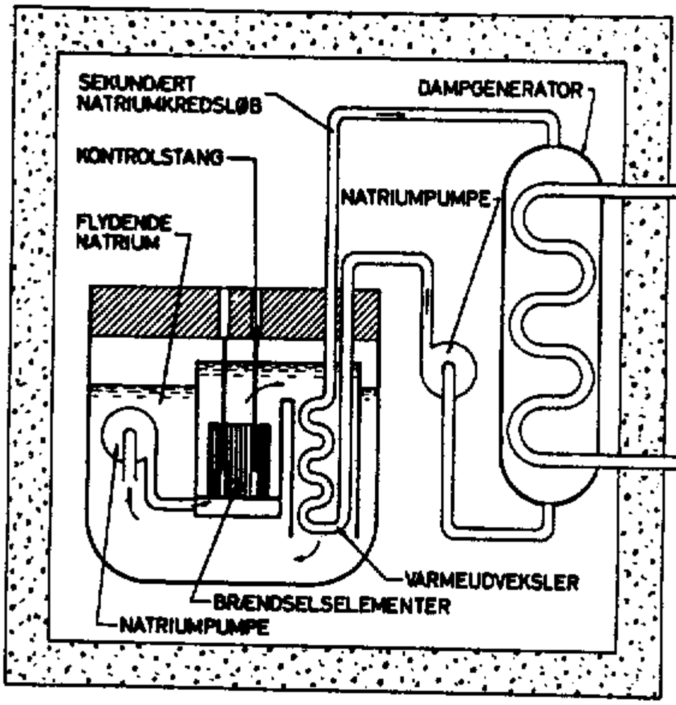
The reason for that it is not possible to obtain breeding using thermal reactors is mainly that the neutron yield by fission of *Pu*-239 is too small.

While the thermal reactors exploits only 1 -2% of the natural uranium to produce energy the fast breeder reactors can achieve a yield of 70 – 80%.
As a cooling substance there must be applied a material, which neither slow down the neutrons nor absorb them. The preference has hitherto been liquid sodium. It has excellent cooling properties, and its low steam pressure causes the reactor to operate under low pressure in the cooling system.

However sodium has the serious hazard, since it reacts explosively with water, and that put further demands to the security system.
So although the breeder reactors are advantageous for the intention of producing energy, only few have been built because of considerations of safety, since the blow up of a power plant is major catastrophe with consequences in years to come.

In figure (11.5) is shown schematically a fast breeder reactor.
The fuel elements, heat exchangers and pumps are placed in a tank of steel and filled with fluid sodium, that circulate and transfer the heat from the fuel elements to the heat exchangers.

In the heat exchangers the heat is for security reasons led to a secondary sodium circuit, which again transfer the heat to a steam generator and on to a turbine.



Figur 11.5

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