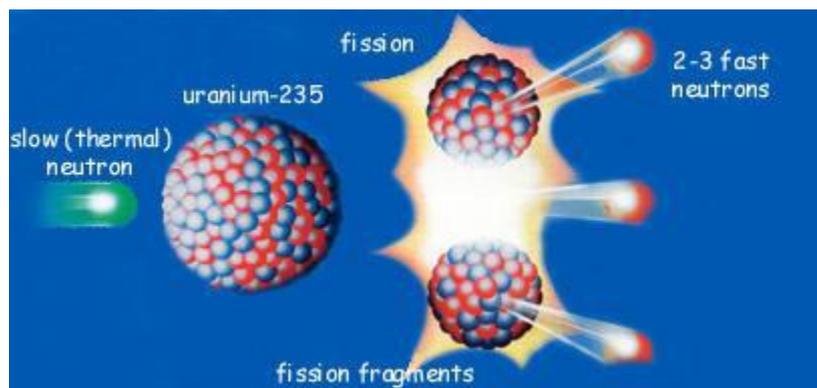


# Nuclear fission

The phenomenon of fission was discovered by Hahn, Strassman and Meitner in 1939. In the process, the uranium nucleus splits up into two medium sized nuclei upon neutron collision. Later it was found that there are a few uranium and plutonium isotopes which can undergo fission if they interact with neutrons. These isotopes reach an energetically more favourable state after fission, i.e. more energy is released than the amount that was necessary to cause the fission.

Natural uranium consists of 99.3%  $^{238}\text{U}$  and 0.7%  $^{235}\text{U}$  isotopes.  $^{238}\text{U}$  can only undergo fission if a neutron of high velocity hits its nucleus.  $^{235}\text{U}$  is much more significant in practical applications: the majority of the reactors operating today utilize the  $^{235}\text{U}$  fission reaction.

If a slow (i.e. low energy or so-called thermal) neutron collides with a  $^{235}\text{U}$  nucleus, the neutron is captured and an excited nucleus ( $^{236}\text{U}$ ) is created. In 85% of cases fission occurs within a very short time (10-14s), while in the rest of the cases the nucleus gets rid of its excitation energy by emitting gamma radiation. There are very many types of fission products: the number of known fission product isotopes is approximately 200 of 35 elements.



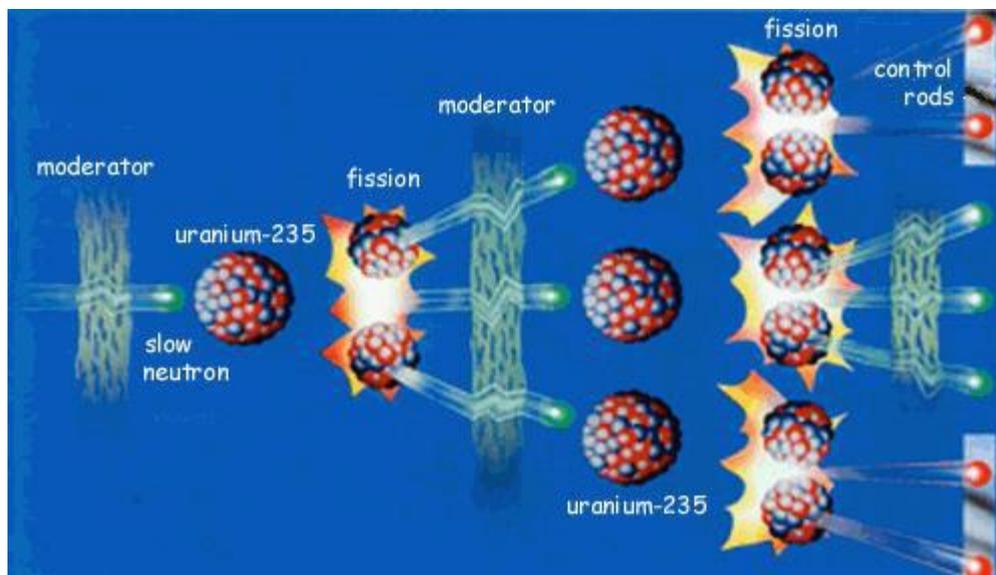
Upon fission of one U-235 nucleus, approximately  $200 \text{ MeV} = 3.2 \cdot 10^{-17} \text{ J}$  energy is released.

It might be more interesting to examine how much uranium has to be fissioned in order to produce a certain amount of energy. The annual electrical energy consumption of Hungary is about 44,000-45,000 GWh. To release so much energy, about 19 tons of pure U-235 must be fissioned. The same amount of energy is obtained if one fires  $47 \cdot 10^6 \text{ t}$  black coal (that is 2.5 million times the quantity). Now the reader can understand how huge energy hides in atomic nuclei.

# Nuclear chain reaction

In a fission reaction, besides the two fission products, a few (in the case of U-235, 2.47 on average) neutrons are emitted. The principle of chain reaction is very easy therefore: a U235 nucleus is hit by a neutron, upon which fission occurs at a high probability. The neutrons produced in this process can cause more fissions, moreover, the already mentioned 200 MeV energy is released each time. Consequently, the process becomes self-sustaining and no external neutron source is needed any longer.

If the neutrons produced from a fission induce only one new fission (because of escaping from the system or being captured inside) we say that the chain reaction is of constant intensity. If the neutrons generated from a fission reaction induce more than one fission, then more and more fission reactions will take place in a unit time and the chain reaction will be diverging.



The probability that a high energy neutron emitted in a fission reaction can directly cause fission is quite low. In order to build a system in which fast neutrons sustain the chain reaction, very highly enriched uranium is needed, which is very expensive. A more easily feasible way is to use materials that slow the neutrons down to such low energies at which the probability of causing a fission is significantly higher. These neutron slowing down materials are the so-called moderators. With the aid of some adequate moderator one might as well achieve chain reaction using natural (0.7% U-235 content) uranium.

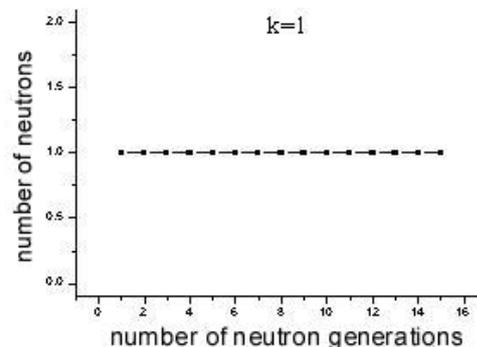
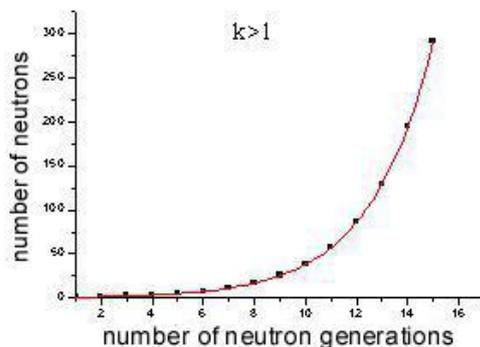
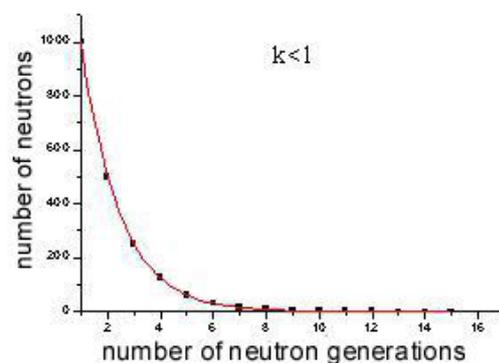
If we simplify things a little, there are two major requirements that a moderator material should meet: it should have as low an atomic mass number as possible and its neutron absorbing ability should be as low as possible. In practice four elements meet these requirements: water (H<sub>2</sub>O), heavy-water (D<sub>2</sub>O), graphite (C) and beryllium (Be). Among these water is the most widespread moderator. The properties of heavy-water are actually better, but its disadvantage is its very high price.

If we start to put together more and more uranium (of course, mixed with some moderator), the expected chain reaction will not start for a good while. The reason for this is that in the case of a small amount of fissile material a large part of the neutrons that originate in fission

will leak out of the pile and therefore they will not be able to cause fission. By increasing the amount of fissile material there will be a moment when we reach the so-called *critical mass* and a self sustaining reaction starts. For example, for pure metal U-235 (without moderator) the critical mass is somewhat less than 50 kg. Because of the very high density (19.2 g/cm<sup>3</sup>) this amount of uranium makes a sphere whose diameter is about 17 cm.

As we have already mentioned, at the fission of U-235 on average 2.5 neutrons are released, but not all of these cause fission. The neutronic state can be characterized by the so-called *multiplication factor* ( $k$ ). This is the ratio of the number of neutrons in a neutron "generation" and the number of neutrons in the preceding generation. (Neutron generation is the time that elapses between the birth of a neutron and the birth of neutrons from the subsequent fission which is caused by the given neutron. Its typical value is about 10<sup>-9</sup> s [i.e. 1 nanosecond] for pure U-235.)

If the value of the multiplication factor is 1, we talk about a *critical reactor*. In this case the number of neutrons in the system is constant, i.e. they cause the same number of fissions in every second. If  $k < 1$ , the reactor is *subcritical* and the number of neutrons is going down. On the other hand, if  $k > 1$ , the system is *supercritical*.



Very often the notion of *reactivity* is used instead of the multiplication factor. The definition of reactivity is  $\rho = (k-1)/k$ .

Correspondingly, for a subcritical reactor  $\rho < 0$ , for a supercritical  $\rho > 0$ , and for a critical  $\rho = 0$ .

Obviously, the number of neutrons present in the reactor must be regulated or controlled since this determines the rate of fission and thus the energy released per second. In order to *control* the chain reaction one should use materials which tend to capture neutrons at a high probability. The most widespread neutron absorbers are cadmium (Cd) and boron (B).

The so-called *control rods* are important tools of control and can be found in every reactor. These are made of neutron absorbing materials and can be moved between the fuel assemblies. For example, if one wishes to decrease the power of the reactor it is sufficient to push in a control rod a little further. The control rods are particularly useful for short-term

control and stopping the reactor. For long-term regulation usually boric acid dissolved in the coolant is used.

The majority of the emitted neutrons leave the place of fission within an extremely short time. However, about 0.64% of them (in the case of U-235) only leave the fission product significantly later. These are the so-called delayed neutrons, which play a vital role in the controllability of reactors.

Change in the power results in changes in temperatures (fuel, coolant, etc.). The temperature changes in turn modify the reactivity through different nuclear physics processes, which has a well defined influence on the number of neutrons ready to induce fission and thus on power. For example, when the power rises, the temperature of fuel will rise, too. However, the higher the temperature, the higher the ability of U-238 to absorb neutrons. Therefore, due to the presence of more neutron absorbing material reactivity is lower and the number of neutrons and accordingly power will decrease. Finally we may say that a change in power caused a change in reactivity and this in turn had an effect on power. If the change in reactivity is such that the processes caused contradict the originating ones, we talk about **negative feedback**. In the above example, the feedback was negative: the power increase induced a negative change in reactivity.

In terms of reactor safety it is an obvious intention that all feedbacks should be negative. In this case, any power increase would cause a drop in reactivity and this will make the reactor sub-critical sooner or later, without external interaction. In such cases we say that the reactor has so-called **inherent safety**. Such inherent safety is characteristic for all PWRs and among them the reactors of the Paks NPP.

As a counter-example for inherent safety we may mention the RBMK type reactors, because in these positive feedback can occur in certain operational states. This contributed largely, among other factors, to the accident of the Chernobyl power plant.