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Section M003

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Nuclear Fission in a Nuclear Reactor

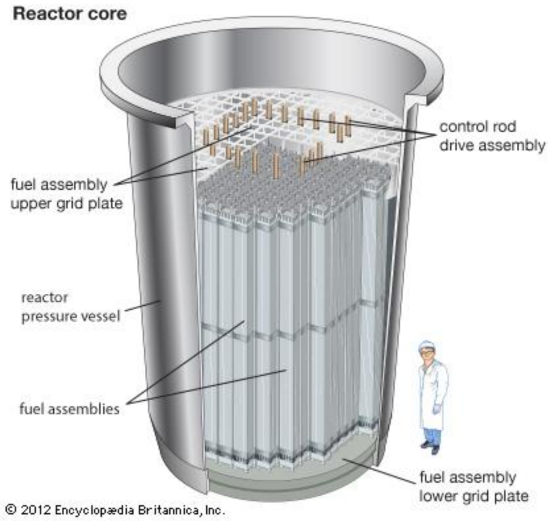
Aside from nuclear fusion, nuclear fission is the most powerful force known to man. At first, fission was used for war, creating the most powerful weapons in history. But then, scientists developed a method of harnessing the immense power of fission for peaceful purposes: the nuclear reactor. Today, nuclear fission reactors play an increasingly large part in America's electricity production. While there currently are many different types of nuclear reactors, they all share a similar basic design and run on the same basic concepts.

The history of nuclear reactors begins with the discovery of nuclear fission. Around 1933, the neutron was discovered by scientists who "bombarded beryllium nuclei with alpha particles (Hobson 2007, 388)." Leo Szilard was the one of the first people to come up with the idea that would later be known as nuclear fission: that a "nuclear reaction would emit neutrons (Hobson 2007, 388)," which would collide with other nuclei, creating a chain reaction. In 1934, Ida Noddack also published a paper predicting that nuclear fission was possible, but the paper was neglected (Hobson 2007, 388). It wasn't until 1938, when Lise Meitner found that Einstein's equation $E=mc^2$ could calculate the work required "to push apart the two fission fragments (Hobson 2007, 391)," that the concept of nuclear fission became a reality (Hobson 2007, 391).

After World War II began in 1939, Einstein and other physicists sent a letter to President Roosevelt urging the United States to "stay informed of further developments and financially support fission research (Hobson 2007, 392)." Despite their efforts, the United States took little action until they joined the war in late 1941. The Manhattan Project, the name for the United States' nuclear program, was established in 1942. By 1945, they had tested one bomb and had two others ready to be used (Hobson 2007, 392). Both of them were capable of catastrophic destruction. The “Little Boy” atomic bomb, dropped on August 6, 1945, had an estimated energy yield of 16 kilotons of TNT (Mahaffey 2009, 179-181). When the bomb exploded, it had a burst temperature of “over a million degrees Celsius (Mahaffey 2009, 179-181)” and created an “840-foot fireball (Mahaffey 179-181).” The “Fat Man” bomb, dropped three days later, had an energy yield of “21 kilotons of TNT (Mahaffey 179-181).”

Almost as soon as the concept of nuclear fission was reported, newspapers discussed the idea that fission could “be exploited as a source of power (“Nuclear Reactor”).” A few years later, the Manhattan Project contained “work on uranium enrichment and research on reactor development (“Nuclear Reactor”).” The objectives of this part were to “learn more about the chain reaction for bomb design (“Nuclear Reactor”),” and to figure out a procedure to produce plutonium. Enrico Fermi was chosen to direct the reactor development. On December 2, 1942, Fermi announced that he had created the “first self-sustaining chain reaction (“Nuclear Reactor”).” His reactor, Chicago Pile No. 1, was the first of its kind. It remained in service until its decommissioning in 1953. The success of Chicago Pile No. 1 led to multiple reactors being assembled, ultimately leading to the Trinity test nuclear bomb. After the war, the U.S. attempted to start a nuclear power program, but they discarded it within two years. In 1953, President Eisenhower revealed the “Atoms for Peace program,” which laid out the blueprints for a “formal U.S. nuclear power program (“Nuclear Reactor”).” The program called for research into various reactor types.

After the mid-1960s, with “an ever-increasing commercial utilization of nuclear power (“Nuclear Reactor”)” expected, orders for larger units were received. By the early 1970s, orders were coming in so quickly it that unit sizes had to be increased. The earlier energy estimates were too optimistic, however. By the late 1970s, future electricity use was predicted to grow slower than expected. That, combined with the rising costs of nuclear plants, led to many of the projects to be cancelled. Public fears about nuclear energy also peaked when the Three Mile Accident occurred in 1979. Afterward, no reactors were approved for construction until 2012, when two were allowed to be built in Augusta, Georgia by the Nuclear Regulatory Commission ("Nuclear Reactor"). Even with only two reactors approved since 1979, nuclear power still plays a significant part in American electricity production. Since 1998, there have been 104 reactors operating in the United States. The total electricity production from 1998 to 2010, however, has gone up. In 1998, nuclear power generated 673,702 kilowatt hours of energy, providing 18.6% of America's electricity production. By 2010, the same number of nuclear plants was producing 790,225 kilowatt hours of electricity, which was 19.2% of the total electricity production of the United States that year (Energy Information Administration 2012). With two upcoming reactors planned and approved, nuclear power's electricity production is sure to continue to rise.



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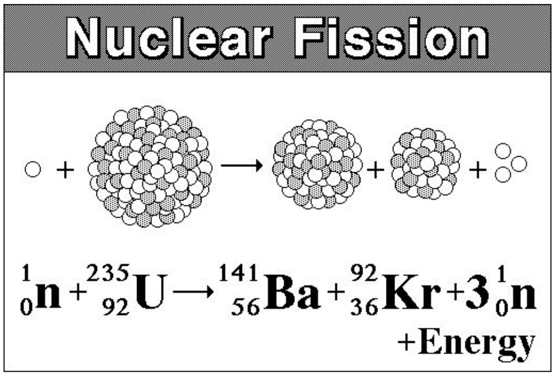
The core of a typical nuclear reactor ("Nuclear Reactor")

Today, while there are various types of nuclear reactors, they all share similar components. An integral part of every reactor is the core ("Nuclear Reactor"). A typical reactor core will be composed of "long, thin, metal-clad fuel rods (Nero 1979, 7)." The fuel rods themselves are actually stacks of "small cylindrical pellets of fuel material (Nero 1979, 7)." The fuel pellets are enclosed by cladding, a metal case that surrounds the stacks of fuel (Nero 1979, 7).

All nuclear fission reactions occur in the core. During nuclear fission, a heavy atomic nucleus is split into two smaller nuclei. In a nuclear reactor, this process occurs when the nucleus is "induced by the excitation of the nucleus ("Nuclear Fission")" with particles such as alpha particles, deuterons, protons or gamma rays, but mainly neutrons, a process called "induced fission" ("Nuclear Fission"). When the neutron enters the nucleus, it increases the excitation energy, the difference between the nucleus' current energy level and the energy level of its ground state, beyond its critical energy, "the minimum excitation energy required for fission to occur (Department of Energy 1993)." This causes the atom to split, resulting in the release of a large amount of energy, radioactive products, and many neutrons ("Nuclear Fission"). These neutrons can induce fission in other nuclei with fissionable material nearby, which also release neutrons that can repeat the process, resulting in a chain reaction. If the chain reaction is contained, it can be used to generate electricity, but if it is not, as in the case of nuclear weapons, it will result in an explosion with enormous destructive force ("Nuclear Fission").



A fission reaction involving a uranium-235 nucleus (Hibbing Community College)

The amount of energy released by fission is based on the mass defect and binding energy. All systems with forces bonding objects together have a mass defect. The mass defect is "the difference between the mass of the constituent parts in a bound state compared with the completely unbound or dismantled state (Marshall 2012, 642)." The mass defect can be calculated by using the equation shown below.

$$\Delta m = [\ Z(m_p + m_e) + (A\text{-}Z)m_n\ ] - m_{atom}$$

The mass defect equation (Department of Energy 1993)

In the equation, Δm is the mass defect, m_p is the mass of a proton, m_e is the mass of an electron, m_n is the mass of a neutron, m_{atom} is the mass of the nuclide $^{A}_{Z}X$, Z is the atomic number, and A is the mass number. All the masses are in units of amu (Department of Energy 1993).

The mass defect is caused by mass converted into binding energy when protons and neutrons are combined to form a nucleus. Binding energy is "the amount of energy that must be supplied to a nucleus to completely separate its nuclear particles (Department of Energy 1993)." Because mass is converted to energy, Einstein's mass-energy relationship, with a couple of conversions, can be used to calculate binding energy. Determining binding energy requires that the amount of energy equivalent to 1 amu of mass be calculated. The mass-energy relationship states that $\mathrm{E} = \mathrm{mc}^2$, where E is energy, m is mass, and c is the speed of light. Given that $1\ \mathrm{amu} = 1.6606 \times 10^{27}\ \mathrm{kg}$, $1\ \mathrm{N} = 1 \frac{\mathrm{kg} \times \mathrm{m}}{\mathrm{s}^2}$, $1\ \mathrm{J} = 1\ \mathrm{N} \times \mathrm{m}$, and $1\ \mathrm{MeV} = 1.6022 \times 10^{-13}\ \mathrm{J}$,

$$\mathrm{E} = (1\ \mathrm{amu})(2.998 \times 10^8\ \frac{\mathrm{m}}{\mathrm{s}})^2 = (1.6606 \times 10^{27}\ \mathrm{kg})(2.998 \times 10^8\ \frac{\mathrm{m}}{\mathrm{s}})^2 \left(\frac{1\ \mathrm{N}}{1 \frac{\mathrm{kg} \times \mathrm{m}}{\mathrm{s}^2}}\right)\left(\frac{1\ \mathrm{J}}{1\ \mathrm{N} \times \mathrm{m}}\right) =$$

$$(1.4924 \times 10^{-10}\mathrm{J})\left(\frac{1\ \mathrm{MeV}}{1.602 \times 10^{-13}\mathrm{J}}\right) = 931.5\ \mathrm{MeV}.$$

Therefore, the binding energy is $\mathrm{BE} = \Delta\mathrm{m}(\frac{931.5\ \mathrm{MeV}}{1\ \mathrm{amu}})$

BE is the binding energy in MeV, and Δm is the change in mass in amu (Department of Energy 1993).

There are two ways to calculate the energy released by fission. The first method involves finding the change in binding energy. During the fission reaction, the total binding energy increases when the nucleus splits into two. In order to increase the stability of the system, it releases energy equivalent to the increase in binding energy. Therefore, the "energy liberated is equal to the increase in the total binding energy of the system." $\mathrm{BE}_{\mathrm{final}} - \mathrm{BE}_{\mathrm{initial}} = \Delta\mathrm{BE}$ (Department of Energy 1993). The second method is to calculate the instantaneous energy, "the energy released immediately after the fission process (Department of Energy 1993)," using the binding energy equation $\mathrm{E}_{\mathrm{Inst}} = \Delta\mathrm{m}(\frac{931.5\ \mathrm{MeV}}{1\ \mathrm{amu}})$. $\mathrm{E}_{\mathrm{Inst}}$ is the instantaneous energy in MeV, and Δm is the mass lost during fission ($\mathrm{m}_{\mathrm{reactants}}$ — $\mathrm{m}_{\mathrm{products}}$) in amu (Department of Energy 1993).

The fuel used in most nuclear reactors today is uranium. The uranium is enriched to the point where it is 3% uranium-235 and 97% uranium-238. Only the uranium-235 is fissionable, while the uranium-238 absorbs neutrons released by fissioning U-235. The uranium fuel needs to be enriched because natural uranium (0.7% U-235 and 99.3% U-238) will not work in the reactor. Because the fuel is only slightly enriched, the chain reaction from the fissioning fuel cannot develop into a large explosion (Hobson 2007, 418).

Enclosing the core is the reflector. The reflector "is a region of unfueled material surrounding the core ("Nuclear Reactor")" that serves to either "scatter neutrons that leak from the core ("Nuclear Reactor")," which allows some of the neutrons to reenter the core, or to absorb escaping neutrons. In the latter case, fertile material is used as the reflector because fertile material that absorbs neutrons can develop into fissile material. For a reactor using uranium-235 as fuel, the fission process results in the creation of plutonium (Reed 2005, 222). A uranium-235 atom that undergoes fission will release approximately 2.5 neutrons. Each of these neutrons can collide with another uranium-235 atom, be absorbed by another uranium-235 atom, or be absorbed by a uranium-238 atom. The first option results in the atom undergoing fission, continuing the reaction. The second option results in neutrons being removed "from circulation (Reed 2005, 222)." When the third option occurs, the uranium-238 atom goes through two consecutive beta-decays, producing fissile plutonium. The amount of plutonium produced varies based on "the power output of the reactor, the degree to which the uranium fuel has been enriched, and the cross-section parameters that characterize the probability that U and Pu atoms will absorb or be fissioned by a bombarding neutron. (Reed 2005, 222)" A commercial reactor with a net electrical energy output of 1 gigawatt "will produce about 200 kg of plutonium. (Reed 2005, 222)"

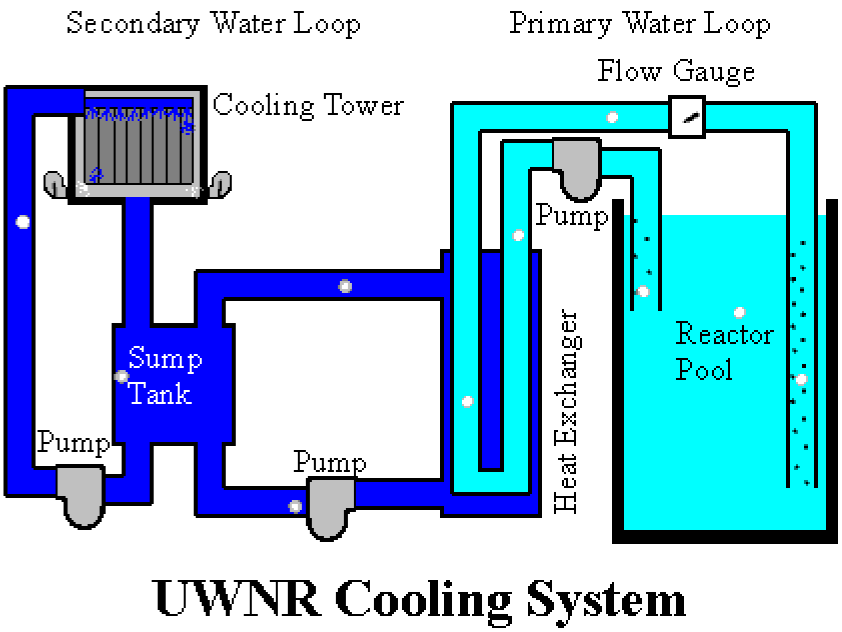
The progression of the chain reaction is based on the probability that neutrons will continue to split atoms. This determines the criticality of the reactor and the reactor's reactivity, the "measure of the state of a reactor in relation to where it would be if it were in a critical state

("Nuclear Reactor")." If the number of neutrons in the reactor and the reactor's fission rate is decreasing until they reach zero, the reactor is in a subcritical state and has a negative reactivity. If the number of neutrons and fission rate is stable, the reactor is in a critical state and has zero reactivity. If the number of neutrons and fission rate is increasing, the reactor is in a supercritical state and has positive reactivity ("Nuclear Reactor").

In order to control the reactivity, and therefore the criticality and fission reaction, in the core, three types of control rods are used: safety rods, regulating rods, and shim rods. Safety rods are used in the activation of the reactor. It's most essential function, however, is to shut down the reactor, whether it is a planned shutdown or an emergency one ("Nuclear Reactor"). The regulating rods can alter the power rate of the reactor but is intentionally designed to be able to change reactivity by only a miniscule amount. This is to ensure that the "added reactivity" is "well within sensible limits ("Nuclear Reactor")" if the rods are accidentally removed. Shim rods compensate for the "changes in reactivity as fuel is depleted by fission and neutron capture ("Nuclear Reactor")," also known as burnup. At times, they must compensate for an enormous change in reactivity, but this change transpires very slowly, often over the course of days to years. Other ways to control the reactivity are to manipulate the amount of fuel in the reactor, increasing or decreasing the number of nuclei that can be fissioned, and changing "the ratio of neutrons that leak out of the system to those that are kept in the system ("Nuclear Reactor")"

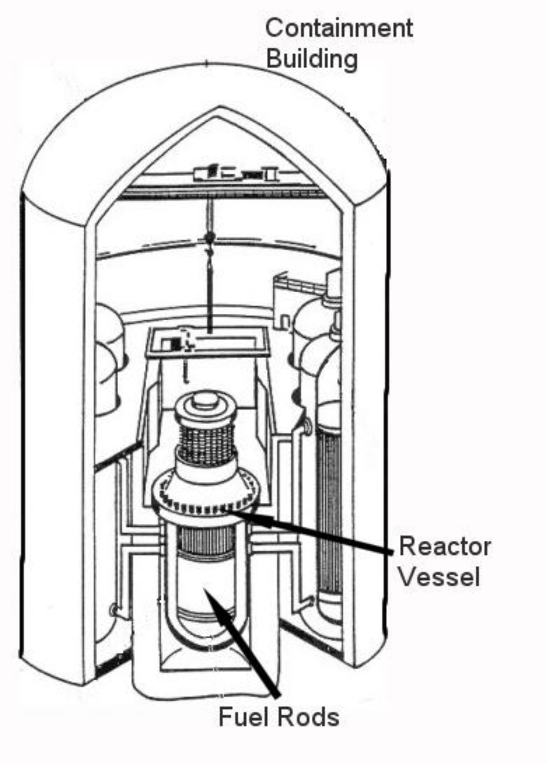
The reactor is held together by various structural components. The reactor vessel is the most integral structural component, housing "the grids for holding the reactor core and solid reflectors, control-rod guide tubes, and internal thermal hydraulic components such as pumps and steam circulators ("Nuclear Reactor")."

The coolant system is designed to remove heat from the core. This is achieved by having coolant fluid enter the core "at a low temperature and exit the core at a higher temperature after collecting the fission energy ("Nuclear Reactor")." However, the fluid that comes into contact with the fuel rods becomes contaminated with radioactivity and cannot leave the reactor. In order to transfer the heat safely without letting any radioactivity escape, two loops of coolant fluid are used. The first loop allows fluid to flow through the core and remove the heat. The first loop then guides the fluid into a "steam generator," where the pipes of the first and second loops come into contact. The heat is transferred to the fluid in the second loop, which is free to take the fluid anywhere without the risk of radioactivity (Hobson 2007,). An assortment of fluids can be used as coolants, including "water, air, carbon dioxide, helium, liquid sodium, liquid sodium-potassium alloy, and hydrocarbons ("Nuclear Reactor")."



The cooling system for a University of Wisconsin reactor. In this diagram, the steam generator is called a "Heat Exchanger (University of Wisconsin)."

Since reactors have the potential to emit radioactivity into the surrounding environment if an accident occurs, there are multiple barriers built around the reactor to prevent this from happening. The first two lines of defense are "the fuel cladding and the reactor vessel ("Nuclear Reactor")." The third line of defense, the shielding, is a barrier surrounding the reactor that protects personnel near the reactor from radiation. For some research reactors, the shielding is a deep pool of water. For other kinds of reactors, the shielding is a "thick concrete structure around the reactor system," which can be reinforced by metals such as lead and steel ("Nuclear Reactor"). The last barrier is the containment dome, which is the building the reactor is contained in. It is composed of "steel-reinforced concrete about a meter thick (Hobson 2007, 418)," and can withstand a tremendous impact.



A drawing of a containment dome (Nuclear Regulatory Commission)

In conclusion, nuclear fission reactors have come a long way since Enrico Fermi's Chicago Pile No. 1. Even though multiple types of reactors have been developed, all of them still are based off the same basic design. And as the public gains more and more confidence in nuclear power, it will continue to play a larger and larger role in the electricity production in the United States. Until nuclear fusion reactors are practical, nuclear fission is the most powerful source of energy Earth has to offer.

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