# Generation IV Nuclear Reactors: Safety and Efficiency

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# Abstract

This is a placeholder for the abstract. It summarizes the whole thesis to give a very short overview. Usually, this the abstract is written when the whole thesis text is finished.

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# 1 Basic concepts of nuclear power

Nuclear power reactors harness the heat generated by splitting atoms of certain elements in a controlled and predictable way. This heat is used to create electrical power[1].

## 1.1 Fission

Nuclear fission is the spontaneous or induced reaction, by which an atom is broken up. In the case of nuclear power reactors these reactions are exothermic. Nuclear radiation such as in equation 1.1 already liberates a large amount of energy.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th}, \quad P = 8 \cdot 10^{-9}\ \frac{W}{g} \tag{1.1}$$

This power is increased in nuclear reactors by 10 orders of magnitude. Although the effective lifespan is lowered from $4.468 \cdot 10^9$ years to a few months. Therefore fission is the main reaction trough which nuclear reactors generate the majority or their power output. An example of such a reaction is given in equation 1.2.[2]

$$\begin{aligned} ^{235}_{92}\mathrm{U} + n &\rightarrow {}^{236}_{92}\mathrm{U} \\ ^{236}_{92}\mathrm{U} &\rightarrow {}^{144}_{56}\mathrm{Br} + {}^{39}_{36}\mathrm{Kr} + 3n + 177\ MeV \end{aligned} \tag{1.2}$$

It is important to note that 1.2 is a simplification of the actual decay series of $^{236}_{92}\mathrm{U}$ into stable end products. 1.2 is sufficient to understand the principle

[1] World Nuclear Association, 2022.
[2] Basdevant, Rich, and Spiro, 2005, p. 286.

behind nuclear fission. The decay series of $^{236}_{92}$U with no intermediates removed is given in 1.3.[3]

$$
\begin{aligned}
^{236}_{92}\mathrm{U} &\rightarrow {}^{137}_{53}\mathrm{I} + {}^{96}_{39}\mathrm{Y} + 3n \\
^{137}\mathrm{I} &\rightarrow {}^{137}\mathrm{Xe} + e^{-} \; + \; \bar{v}_e, \;\; t_{1/2} = \; 24.5s \\
^{137}\mathrm{Xe} &\rightarrow {}^{137}\mathrm{Cs} \; + \; e^{-} \; + \; \bar{v}_e, \;\; t_{1/2} = \; 3.818m \\
^{137}\mathrm{Cs} &\rightarrow {}^{137}\mathrm{Ba} \; + \; e^{-} \; + \; \bar{v}_e, \;\; t_{1/2} = \; 30.07y \\
^{96}\mathrm{Y} &\rightarrow {}^{96}\mathrm{Zr} + e^{-} \; + \; \bar{v}_e, \;\; t_{1/2} = 5.36s
\end{aligned} \tag{1.3}
$$

## 1.2 Nuclear Cross Section

Nuclear cross section describes the probability of a certain nuclear reaction to occur. This aspect needs thorough consideration in the design of nuclear reactors, as the nuclear cross section generally increases with the inverse of the velocities of the reactants[4].

## 1.3 Criticality

Criticality is the operating condition of a nuclear reactor, in which the neutrons produced by fission events is sufficient to sustain a chain reaction. It is measured using the multiplication factor $k$. It is defined as in 1.4. If the factor $k$ equals 1 the reaction is said to be critical as the number of neutrons remains constant. If the factor $k$ is less than 1, therefore the number of neutrons is decreasing and the chain reaction is said to be subcritical. If the factor $k$ is grater than 1 the number of neutrons is increasing exponentially and the reaction is supercritical.[5,6].

$$
k \; = \; \frac{number\ of\ neutrons\ in\ one\ generation}{number\ of\ neutrons\ in\ previous\ generations} \tag{1.4}
$$

[3] Basdevant, Rich, and Spiro, 2005, p. 287.
[4] Basdevant, Rich, and Spiro, 2005, p. 108.
[5] Basdevant, Rich, and Spiro, 2005, p. 308.
[6] Stacey, 2018, p. 39.

## 1.4 Components of Nuclear Reactors

### 1.4.1 Fuel

The reactor fuel is the fissile material used in the fission reaction inside of a reactor. In most cases uranium oxide $UO_2$ pressed into pellets is used for this purpose. These pellets are put into tubular fuel rods. The whole fuel assembly inside the reactor consists of many such rods[7].

#### 1.4.1.1 Startup Neutron Source

As the fission of uranium produces three neutrons per reaction, there does not need to be a constant external influx of neutrons. However, to start this chain reaction inside a new reactor equipped with newly made fuel rods a neutron source is needed. Usually beryllium combined with an alpha emitter is used for this purpose, as the collision of an $\alpha$-particle with ${}^{9}_{4}\mathrm{Be}$ releases a neutron as part of its reaction, as can be seen in equation 1.5[8,9].

$$ {}^{9}_{4}\mathrm{Be} \; + \; {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} \; + \; n \tag{1.5} $$

[7] World Nuclear Association, 2022.
[8] World Nuclear Association, 2022.
[9] Basdevant, Rich, and Spiro, 2005, p. 100.

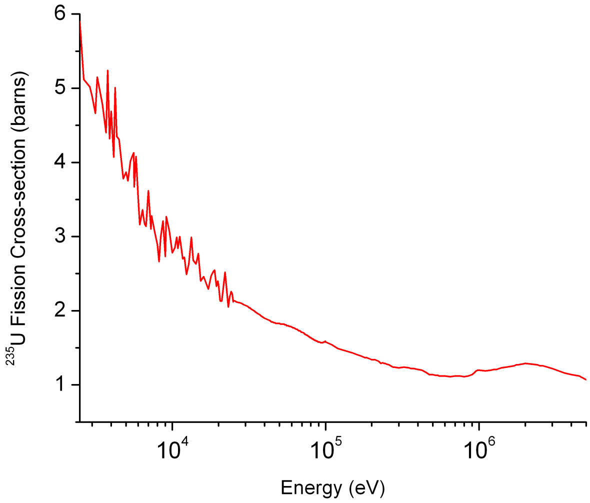


Figure 1.1: Nuclear cross section of $^{235}U$ in relation to neutron energy

### 1.4.2 Moderator

Nuclear fission events release neutrons with energies in excess of multiple MeV, or speeds higher than $10^7\frac{m}{s}$. However at these speeds the nuclear cross section of the fission reaction is quite low as can be seen in figure 1.1.

Therefore the emitted neutrons need to be slowed down in order to be useful.l This is done using a moderator. When passing through a moderator the neutrons are slowed down through collisions with the aforementioned. Although it is important to note that the moderator should absorb as few neutrons as possible to not hinder the chain reaction. For this reason $H_2O$ and graphite are commonly used.[10]

### 1.4.3 Control Rods or Blades

In order to regulate the reaction speed inside of a nuclear reactor the number of neutrons inducing nuclear fission needs to be regulated. This is accomplished

[10] Stacey, 2018, p. 28.

using control rods. As a single control rod with a circular cross section would lead to very nonuniform fission and temperature dynamics, the control rods are either arranged into cruciform blades or evenly spaced across the reactor in the form of clusters. A typical reactor contains around 50 clusters, each make up of 20 control rods[11,12].

These rods or blades contain materials which readily absorb neutrons, such as boron or cadmium. They may either be made of steel enriched with boron or hollow tubes filled with a brittle salt like material such as cadmium isotopes. Because the amount of fuel inside reactor steadily decreases, the amount of neutrons absorbed needs to be regulated in order for the chain reaction to continue. Therefore the control rods or blades are mounted on a movable apparatus, which extends or retracts the control rods into or out of the reactor, thereby regulating the amount of neutrons absorbed[13].

### 1.4.4 Coolant

The coolant is a liquid which circulates inside the nuclear reactor core to extract the thermal energy generated form the fission reactions. In most cases today this liquid is $H_2O$. In the case of boiling water reactors the water is boiled directly inside the core. In all other reactor types, such as pressurized water reactors at least a secondary, separated, coolant circuit is used, which transports the heat away from the primary circuit. When the water is not boiled inside the reactor core, a separate steam generator is used to create the steam, which drives the turbine. The same water which is used as a coolant may also be used as the rector moderator[14].

[11] Stacey, 2018, p. 72.
[12] Grayson, 2011.
[13] Grayson, 2011.
[14] World Nuclear Association, 2022.

# Appendix

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# Eidesstattliche Erklärung

Ich, Elias Leitinger, erkläre hiermit eidesstattlich, dass ich diese vorwissenschaftliche Arbeit selbständig und ohne Hilfe Dritter verfasst habe. Insbesondere versichere ich, dass ich alle wörtlichen und sinngemäßen Übernahmen aus anderen Werken als Zitate kenntlich gemacht und alle verwendeten Quellen angegeben habe.

Dietach, am ____________________ ________________________

Datum Unterschrift