Generation IV Nuclear Reactors: Safety and Efficiency

Vorwissenschaftliche Arbeit verfasst von

Elias Leitinger

Klasse 8B

Betreuer: Patrick Ritt

BRG Steyr Michaelerplatz
Mühlbergstraße 1
4407 Dietach

Steyr, February 2023

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.

Contents

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.

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

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]

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

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]

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

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].

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

[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. Safety

Safety is particularly important for nuclear power reactors, as they contain large amounts of radioactive material, which could be released into the environment in the case of an accident. During the ongoing fission reaction a large amount of radioactive isotopes, of which actinides are the most dangerous. Thus safety in nuclear power plants has three main objectives. Firstly, the reactor needs to operate normally without exposing operators and the environment to dangerous levels of radiation. Secondly, accidents need to be prevented as much as possible. Thirdly, in the case of an accident the consequences need to be minimized. Therefore for each reactors risks need to be carefully evaluated and their probabilities need to be carefully considered[7].

1.5. Efficiency

Like other power plants, current nuclear power reactors offer efficiencies between 30% and 35%. However with increased heat and cogeneration the efficiency of nuclear power plants could be increased dramatically[8].

1.5.1. Cogeneration

Usually a large amount of energy is lost to the environment in the form of heat. This is usually destructive towards the environment and results in reduced efficiency. This heat could be used in cogeneration to supply heating to other facilities or private housing, thereby reducing the amount of wasted, unused energy[9].

[7]Khalil, 2016, p. 793.
[8]Energy Education, 2022.
[9]International Atomic Energy Association, 2018.

1.5.2. Capacity Factor

1.6. Components of Nuclear Reactors

1.6.1. 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[10].

1.6.1.1. 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 α-particle with ${}^{9}_{4}\mathrm{Be}$ releases a neutron as part of its reaction, as can be seen in equation 1.5[11,12].

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

[10] World Nuclear Association, 2022.
[11] World Nuclear Association, 2022.
[12] Basdevant, Rich, and Spiro, 2005, p. 100.

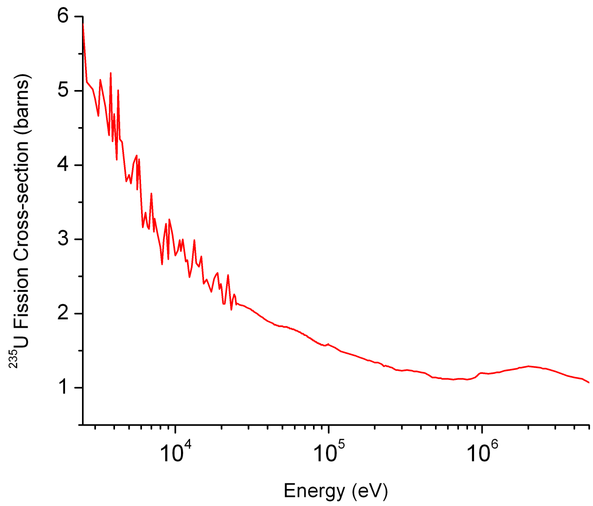

Figure 1.1.: Nuclear cross section of ^{235}U in relation to neutron energy

1.6.2. 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. These are called thermal neutrons. 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.[13]

1.6.2.1. Fast Reactors

However, there is a category of reactors which harness fast neutrons in their nuclear reaction. These have no moderator and instead make use of fuel, which

[13]Stacey, 2018, p. 28.

requires a higher share of ^{235}U as this reduces the chance of neutron capture by ^{238}U and increases the likelihood of a fission event to occur. As actinides are fissile by fast neutrons, fast reactors may reduce the amount of transuranic nuclear waste generated by nuclear power production. There is still ongoing research regarding fast reactors to make them useful for widespread energy production.[14]

1.6.3. 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 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[15,16].

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[17].

1.6.4. 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

[14] World Nuclear Association, 2022.
[15] Stacey, 2018, p. 72.
[16] Grayson, 2011.
[17] Grayson, 2011.

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[18].

[18] World Nuclear Association, 2022.

2. Historical Generational Developments of Nuclear Reactors

2.1. Generation I

2.2. Generation II

2.3. Generation III

2.4. Generation III+

3. Common Nuclear Reactor Types in Current Use

3.1. PWR – Pressurized Water Reactor

Pressurized water reactors harness H_2O as coolant and commonly also as moderator. However they have at least two coolant circuits. The water in the primary coolant circuit is under a large pressure in order to still remain liquid even at the high temperatures generated inside the reactor core. Between the primary and secondary coolant circuit lay a steam generator, which turns the cool water supplied in the secondary circuit into steam used to drive turbines. Special attention needs to be drawn to the fact, that primary and secondary circuit are never directly connected and therefore no radioactive material can be passed from inside the reactor core though the steam generator. Therefore only the reactor components which lay before the steam generator need to be under containment.[1,2] A simplified schematic representation of a pressurized water reactor can be seen in 3.1. The turbine and cooling systems of every schematic are not shown, as this would exceed the scope of the explanations given herein and not contribute to the understanding of the reactor types shown.

[1] World Nuclear Association, 2022.
[2] Khalil, 2016, pp. 14–84.

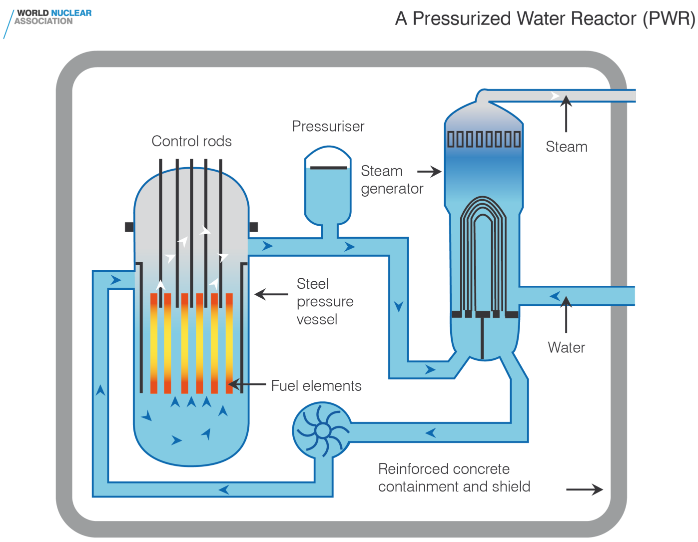

Figure 3.1.: Schematic representation of a pressurized water reactor

3.2. BWR – Boiling Water Reactor

Boiling water reactors are characterized by their mode of steam production. In comparison to pressurized water reactors, these reactors boil the water directly inside the reactor core. This has the advantage of significantly increasing the simplicity of reactor construction, because there is no need for a steam generator or secondary coolant loop. Like pressurized water reactors, boiling water reactors most commonly employ water as their moderator. Because the coolant water unavoidably comes into direct contact with the fuel rods, radioactive isotopes are leaked into the coolant water and therefore turbines. But as these isotopes almost unanimously consist of ^{16}N, which has a short half life of 7 the access radiation is almost completely depleted after power generation. But due to the further spread of radioactive material a greater area of containment needs to be constructed for the nuclear power plant[3]. A schematic representation of a boiling water reactor is shown in 3.2

[3]Khalil, 2016, pp. 85–140.

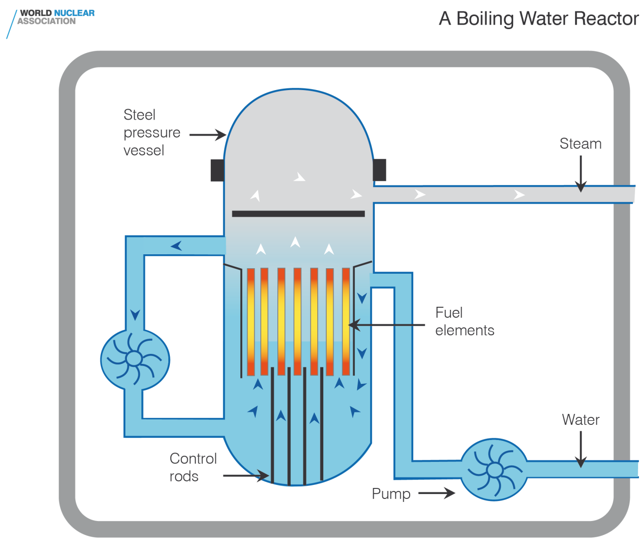

Figure 3.2.: Schematic representation of a boiling water reactor

3.3. PHWR – Pressurized Heavy Water Reactor

Pressurized heavy water reactors also called CANDU for Canadian deuterium uranium reactor, utilize heavy water $({}^3_1\mathrm{H}_2\mathrm{O}\breve{}\, alsocalled \mathrm{D}_2\mathrm{O})$ as coolant and moderator. The cylindrical fuel elements, which consist of multiple small fuel rods welded together, as shown in 3.4, rest inside zirconium alloy pressure tubes, through which the cooling heavy water flows. Many of these tubes are contained inside the calandria. The calandria itself is an enclosed chamber, which contains low pressure, low temperature heavy water used only as moderator. Because only the heavy water inside the zirconium alloy pressure tubes is under high pressure, the calandria need not be able to withstand the pressures, which are exerted upon the vessels housing pressurize water reactors and heavy water reactors. The only parts which need to withstand high mechanical stress are the pressure tubes, which can more easily be mass manufactured, due to their repetitiveness. Another advantage of this design is that single tubes can be refueled during reactor operation, as they can be disconnected, while other reactor designs need to be shut down completely before a change of fuel rods can occur. Pressurized heavy water reactors can also operate on unenriched

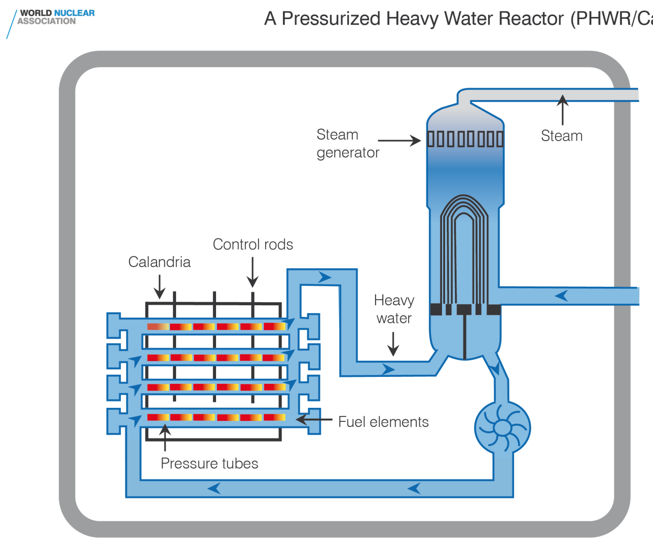

Figure 3.3.: Schematic representation of a pressurized heavy water reactor

natural uranium.[4]. For a simplified representation of a reactor of this type see figure 3.3.

Figure 3.4.: Fuel element as used in PHWR

[4] Khalil, 2016, pp. 141–198.

Appendix

Appendix A.

Rights

A.1. Figures

A.1.1. Public Domain

Figure 1.1 is released into the public domain and can therefore be used for any purpose.

A.1.2. World Nuclear Association

Rights are granted for educational use for figures 3.1, 3.2 and 3.3 as per https://www.world-nuclear.org/furniture/masterpage-items/permission-for-use-of-content.aspx

A.1.3. Canadian Nuclear Association

Rights are granted for educational use for figure 3.4 as per https://cna.ca/terms-of-use/

A.2. Equations

A.2.1. Own Creation

Equations 1.1, 1.2, 1.3, 1.4 and 1.5 were typeset by the author with information taken from[1].

[1]Oka and SpringerLink (Online service), 2014.

Bibliography

Basdevant, J.L., J. Rich, and Michael Spiro (2005). *Fundamentals in Nuclear Physics: From Nuclear Structure to Cosmology*. Advanced Texts in Physics S. Springer. ISBN: 9780387016726 (cit. on pp. 1, 2, 4).

Energy Education (2022). *Energy Education: Nuclear Power*. URL: https://energyeducation.ca/encyclopedia/Nuclear_power_plant (visited on 10/22/2022) (cit. on p. 3).

Grayson, James (2011). *Control Rods in Nuclear Reactors*. URL: http://large.stanford.edu/courses/2011/ph241/grayson1/ (visited on 10/11/2022) (cit. on p. 6).

International Atomic Energy Association (June 2018). *Nuclear Power beyond Electricity: towards Greater Efficiency in Energy Production and Water Management*. URL: https://www.iaea.org/newscenter/news/nuclear-power-beyond-electricity-towards-greater-efficiency-in-energy-production-and-water-management (visited on 10/22/2022) (cit. on p. 3).

Khalil, Yehia F. (2016). *Nuclear Engineering Handbook*. CRC Press. DOI: 10.1201/9781315373829-23 (cit. on pp. 3, 9, 10, 12).

Oka, Yoshiaki. and SpringerLink (Online service) (2014). *Nuclear Reactor Design*. An Advanced Course in Nuclear Engineering, Tokyo : Springer Japan : (cit. on p. 15).

Stacey, Weston M. (2018). *Nuclear reactor physics*. 3rd, revised edition. Weinheim, Germany: Wiley-VCH (cit. on pp. 2, 5, 6).

World Nuclear Association (Aug. 2022). *Nuclear Power Reactors*. URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx (visited on 09/25/2022) (cit. on pp. 1, 4, 6, 7, 9).

List of Figures

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