Generation IV Nuclear Reactors: Safety and Efficiency

Vorwissenschaftliche Arbeit verfasst von

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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.

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.

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

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

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

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. In a critical reaction, the number of neutrons causing a fission event remains constant. If the factor k is less than 1, 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].

$$k = \frac{\textit{number of neutrons involved in fission in generation n}}{\textit{number of neutrons involved in fission in generation n - 1}} \tag{1.4}$$

[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.

In practice the reactivity ρ is used. It describes the change of the reactor away from the critical state. It is calculated using 1.5.

$$\rho = \frac{k-1}{k} \tag{1.5}$$

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

[7] Khalil, 2016, p. 793.
[8] Energy Education, 2022.

facilities or private housing, thereby reducing the amount of wasted, unused energy[9].

1.6. Fuel Cycle

Currently, spent fuel from nuclear reactors is sent to reprocessing facilities. There light actinides are separated from the remaining uranium and plutonium. Currently these actinides are treated as waste and stored in facilities to keep them from contaminating the environment. The uranium and plutonium remain in the form of oxides and are reused for mixed oxide fuels (MOX)[10].

1.6.1. Proliferation

A significant risk in the operation of nuclear power reactors is the proliferation of fission products for use in nuclear weapons. As older fast nuclear reactors produce a great deal of $^{239}_{94}\mathrm{Pu}$. Therefore, proliferation resistance is a big consideration in the construction and development of new power reactors and technologies. A possible mitigation is the early removal of fuel, which is only partially spent, from the reactor. This fuel contains nearly no $^{239}_{94}\mathrm{Pu}$, but instead contains $^{238}_{94}\mathrm{Pu}$, which cannot be used in weapons and cannot practically be turned into $^{239}_{94}\mathrm{Pu}$[11].

1.7. Components of Nuclear Reactors

1.7.1. Fuel

The reactor fuel is the fissile material used in the fission reaction inside of a reactor. In most cases uranium dioxide UO_2 pressed into pellets is used for this

[9] International Atomic Energy Association, 2018.
[10] Schullenberg, 2022, pp. 82–84.
[11] Schullenberg, 2022, p. 87.

purpose. These pellets are put into tubular fuel rods. The whole fuel assembly inside the reactor consists of many such rods[12].

1.7.1.1. Startup Neutron Source

As the fission of uranium produces on average 2.4 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 1.6[13,14].

$$ {}^{9}_{4}\mathrm{Be} \ + \ {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} \ + \ n \tag{1.6} $$

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

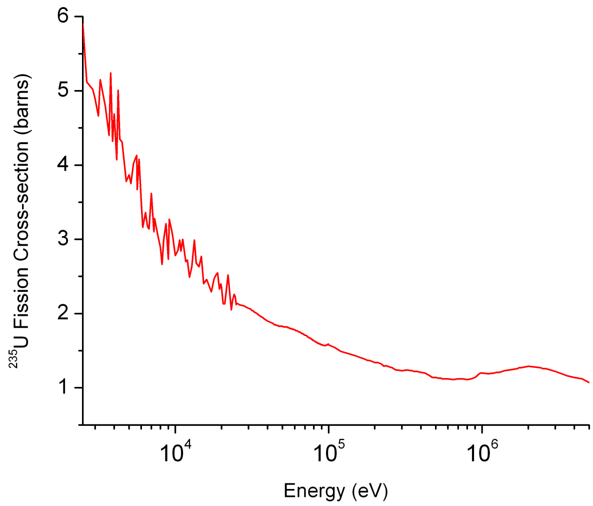

Figure 1.1.: Nuclear cross section of ^{235}U in relation to neutron energy

1.7.2. 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.[15]

1.7.2.1. 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

[15]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.[16]

1.7.3. 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 made up of 20 control rods[17,18].

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[19].

1.7.4. 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

[16] World Nuclear Association, 2022.
[17] Stacey, 2018, p. 72.
[18] Grayson, 2011.
[19] 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[20].

[20]World Nuclear Association, 2022.

2. Historical Generational Developments of Nuclear Reactors

Nuclear reactors are normally categorised into generations. These generations differentiate reactors based on various technological factors such as cost-effectiveness, safety, commercial applicability and fuel cycle. These generations present a useful tool in categorizing nuclear reactors as multiple factors are combined into one single metric. It is important to not that all designs of generations I to III+ consist mainly of designs first developed in the late fourth decade of the 20th century with various improvements added.[1]. Figure 2.1 shows a timeline of nuclear reactor generations along with important notes on the properties of reactors in this generation. The images show representatives of each generation. It is important to note that the example image for gen-

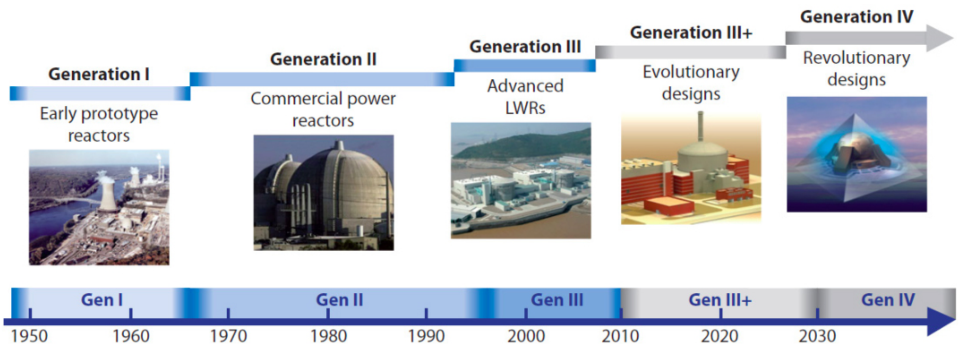

Figure 2.1.: Timeline of nuclear reactor generations

[1]Goldberg and R., 2011, pp. 1, 2.

eration IV is not representative, as the reactors of this generation are still in development and have not been built.

2.1. Generation I

The first generation of nuclear reactors consists primarily of research reactors and primitive nuclear power plants. These reactors are regarded as “proof of concept” in the USA. All reactors of this generation have been decommissioned or are undergoing deconstruction as their technological level is far behind that of newer reactors. Therefore they have very low cost-effectiveness and operational safety[2].

2.2. Generation II

The second generation of nuclear reactors represent the first efforts to produce nuclear reactors primarily designed for commercial viability. The comprise mainly boiling water reactors (BWR), pressurised water reactors (PWR), Canadian deuterium uranium reactors (CANDU) and advanced gas-cooled reactors (AGR). They are designed for an operational lifetime of 40 years. Generation II reactors are the most common generation for boiling water reactors and pressurised water reactors around the world, which can be categorised under the term light water reactor (LWR). These reactors feature more advanced safety features compared to generation I reactors. These safety have the ability to automatically prevent grievous incidents in the operation of a nuclear reactors, as they prevent dangerous incidents in cases such as loss of power or operator error.

Designs from this category require comparatively large electrical power grids. And feature advanced safety envelopes based on western standards. New reactors of this generation are mainly built in China, Russia and the Republic of Korea. Their fuel cycle requires high level waste repositories for ultimate disposition[3].

[2] Goldberg and R., 2011, p. 3.
[3] Goldberg and R., 2011, pp. 4–6.

2.3. Generation III

In essence nuclear reactors of the third generation are the same designs as in the second generation with evolutionary improvements. These reactors feature improvements to fuel economy, thermal efficiency and and safety. These designs shift away from active safety systems to passive safety systems. They also feature a more standardised design, which leads to more economical construction costs. Designs such as the advanced boiling water reactor (ABWR) belong to this generation[4].

2.4. Generation III+

As implied by the name nuclear reactors of the III+ generation feature another set of incremental improvements over the third generation. The main focus of these improvements lay in the improved safety of reactor systems as less operator intervention and fewer active components are utilized in reactor safety systems. These new safety systems utilize effects such as gravity to function. This leads to improved safety as a total failure of these safety systems is very unlikely compared to those of earlier generations. These reactors also have a higher expected operating lifetime of up to 60 years. The power plants of this generation also have increased fuel burn up. This has the consequence of reducing fuel consumption and reduced waste generation. Many reactors of this generation of different designs are in operation and construction around the globe[5].

[4] Goldberg and R., 2011, pp. 5, 6.
[5] Goldberg and R., 2011, pp. 7–11.

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.

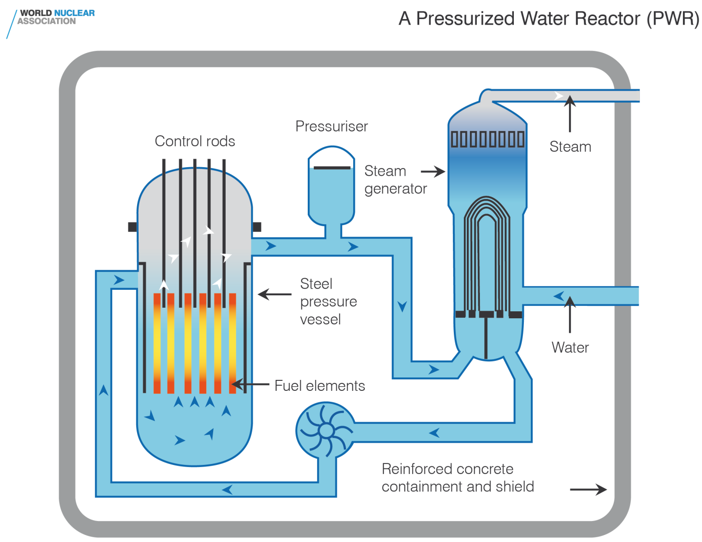

Figure 3.1.: Schematic representation of a pressurized water reactor

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 seconds. 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.

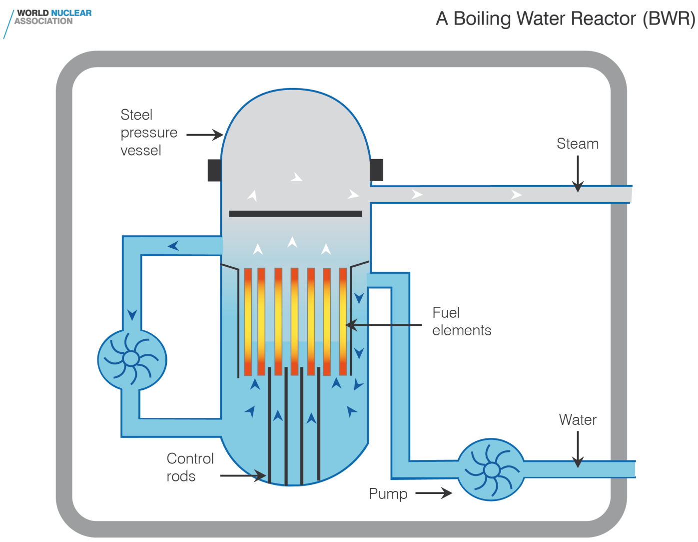

Figure 3.2.: Schematic representation of a boiling water reactor

3.3. PHWR – Pressurized Heavy Water Reactor

Pressurized heavy water reactors also called CANDU for Canadian deuterium uranium reactor, utilize heavy water (${}^{3}_{1}H_2O$ – also called D_2O) 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

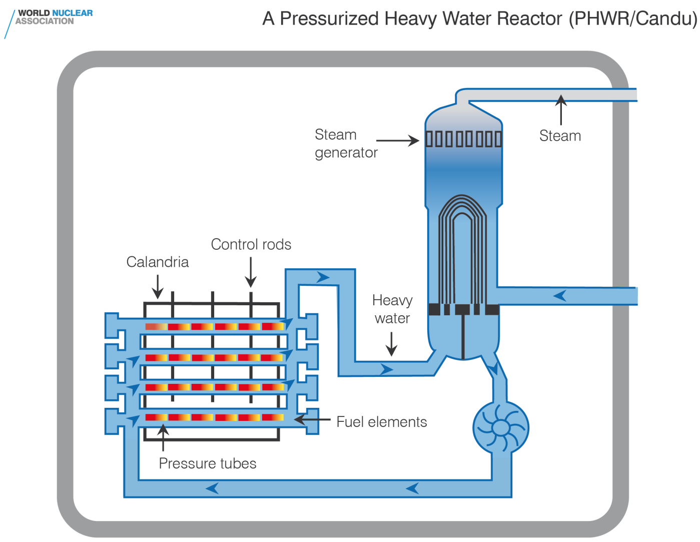

Figure 3.3.: Schematic representation of a pressurized heavy water reactor

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.

4. Generation IV

Nuclear reactor systems of the fourth generation are a set of six novel reactor designs created with set goals in mind. This development effort is lead and governed by the Generation IV International Forum (GIF). The GIF has 14 Members: Argentina, Australia, Brazil, Canada, China, Euratom, France, Japan, Korea, the Russian Federation, South Afrika, Switzerland, the United Kingdom and the United States of Amerika. The GIF goal is to motivate research and development on new reactor systems[1].

4.1. Goals

Goals have been defined for nuclear reactor systems of the fourth generation. These goals can be categorised into four sections: Economics, Sustainability, Safety and Reliability and, Proliferation Resistance[2].

4.1.1. Economics

Generation IV nuclear reactors will have a lower total life-cycle cost when compared to nuclear reactors of previous generations. This means that over the energy produced by these nuclear reactor systems over their lifetime is higher in relation to the cost involved in building such a power plant. Additionally, these reactor systems will have comparable financial risks to other energy projects, which is especially important to make Generation IV systems competitive in

[1]Generation IV International Forum, 2021, p. 6.
[2]Pioro et al., 2016, p. 38.

the marketplace. This also includes viability for a wider range of different ownership models and a wider array of possible energy supply roles[3].

4.1.2. Sustainability

It is important for nuclear reactor systems of the fourth generation to make effective use of the resources involved in building and operating such a system. Another area of importance is the reduction and effective management of nuclear waste[4].

4.1.3. Safety and Reliability

In nuclear reactors of previous generations a compromise between safety and reliability needs to be met, because these designs have not been designed with safety primarily in mind. Therefore an increase in safety mostly coincides with reduced reliability as these measures increase the complexity of the nuclear reactor and also decrease the amount of valid operating states. Because Generation IV nuclear reactors are designed from the ground up with inherent safety systems no compromise needs to be struck. Most of these novel designs feature passive protection against failure modes such as overheating[5].

4.1.4. Proliferation Resistance and Physical Protection

Proliferation resistance and physical protection are important to make the deployment of nuclear reactors attractive. Generation IV reactors are designed to make them the most unattractive option for creating fissile material for use in nuclear weapons. Therefore their fuel cycle mus produce as few actinides as possible, which is also beneficial for the sustainability of such systems[6].

[3]Generation IV International Forum, 2021, p. 6.
[4]Pioro et al., 2016, p. 38.
[5]Generation IV International Forum, 2021, p. 6.
[6]Pioro et al., 2016, p. 39.

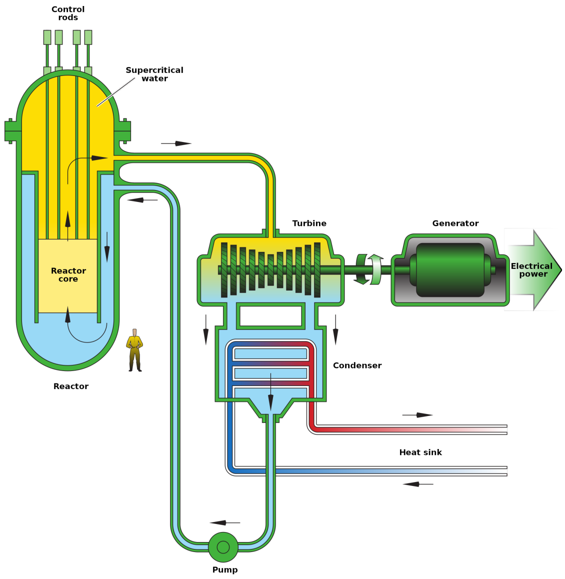

Figure 4.1.: Schematic representation of a supercritical water reactor

4.2. Reactor Types

4.2.1. Supercritical Water Reactors

Construction wise, supercritical water reactors are very similar to boiling water reactors. They use light water for the cooling and moderation of the reactor. The main difference is the aggregate state change of the water used as the coolant. In a boiling water reactor, the water changes aggregate state at the set boiling point. In a supercritical water reactor, the coolant is heated beyond the critical temperature of 374°C. Therefore, there is no difference in the density of liquid particles and steam. This effect creates a homogenous mass of H_2O, where no clear distinction of steam and liquid water can be made. This state is called supercritical and should not be confused with the term of criticality used in nuclear physics[7]. The effect of supercriticality is well illustrated by the phase change diagram of water shown in figure 4.2. A schematic representation of a supercritical boiling water reactor is shown in figure **??**.

[7] Pioro et al., 2016, pp. 206–236.

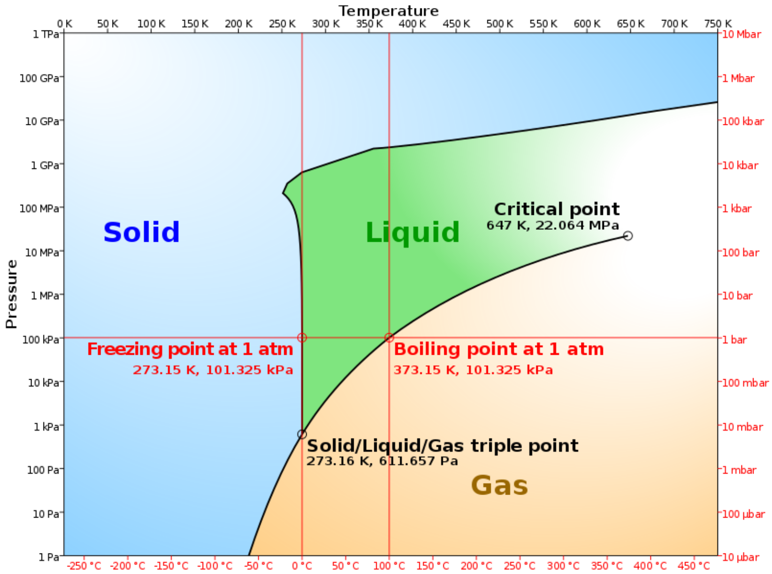

Figure 4.2.: Phase change diagram of H_2O

4.2.1.1. Efficiency

The main advantage of supercritical water reactor lay in the increased efficiency compared to boiling water reactors, because the turbines are operated at higher temperature and pressure and because the turbine exhaust is fed into the reactor without the need to dump thermal energy to liquefy it again. This is expected to increase the thermal efficiency form $\approx 35\%$ to $\approx 45\%$. Such a system is already used for the energy generation of many coal power plants built since 1990[8].

4.2.1.2. Safety

Because of the great similarity to boiling water reactors, supercritical water reactors are comparable in safety to the aforementioned. However, because no reactor of this type has been built to date, little research has been conducted on the practical safety of those systems. reaction Additionally, due to the

[8] Schullenberg, 2022, pp. 30–51.

temperature and density gradient in the coolant inside the core itself, the moderating coolant absorbs fewer neutrons in the top section of the reactor. Therefore, an additional moderator needs to be installed at points of higher coolant temperature[9].

4.2.1.3. Disadvanages

Supercritical water reactors have the same unsustainable fuel cycle of boiling water reactors, because they operate on enriched uranium fuel and generate nuclear waste. Therefore they are not considered appropriate for wide scale adoption. This is also reflected in the small amount of research effort that has gone into this system. An additional disadvantage of such a system is the need for the coolant to be superheated for safe operation and the high operation pressure which is exerted on the reactor vessel[10].

4.2.2. Very High Temperature Reactors

Because usually used in nuclear reactors such as zircalloy or steel corrode or melt at temperatures above 650°C, these materials cannot be used to build reactors, which allow for higher temperatures. Higher reactor temperatures are of advantage because they increase efficiency significantly. The only materials such as ceramics can be used for such a purpose[11].

4.2.2.1. Fuel Elements

To allow for increased temperatures, the fuel elements inside a very high temperature reactor are made from ceramic uranium dioxide spheres and coated with graphite and silicon carbide (SiC). These particles have a diameter of 0.9mm. These gas tight particles are called TRISO (TRistructural-ISOtropic) particles. The particles are then arranged into cylindrical graphite pellets with a diameter of 24mm or spheres with a diameter of 60mm. The pellets are

[9] Schullenberg, 2022, pp. 52–53.
[10] Schullenberg, 2022, pp. 52–53.
[11] Schullenberg, 2022, p. 55.

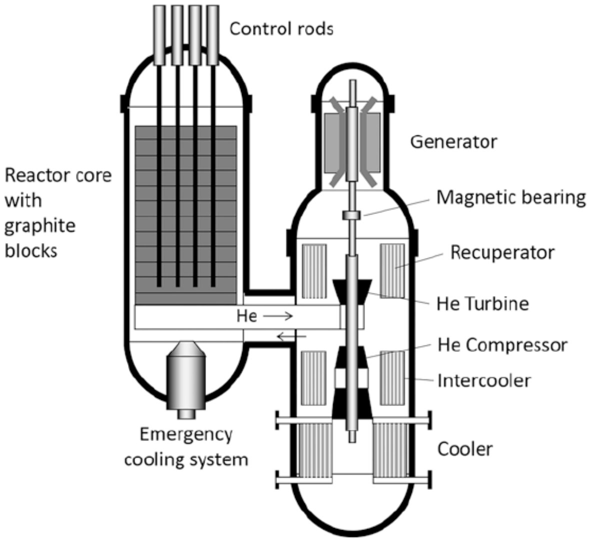

Figure 4.3.: Schematic representation of a very high temperature reactor

usually used in graphite block type reactor cores, which closely resemble those of traditional reactor cores such as RBMK reactors. However, the fuel spheres are used in pebble bed type reactors, which will be explained in a following section[12].

4.2.2.2. Very High Temperature Reactors with Prismatic Core

An example of a reactor, which uses the graphite block type core configuration is shown in figure 4.3. This type of reactor is moderated by graphite and cooled with helium. As a coolant, helium has a lower thermal capacity compared to water, but because helium can be used at higher operating temperatures, it's use is advantageous for high core temperatures. Additionally helium has close to no ablility to moderate neutrons. In such a reactor configuration the prism shaped core is surrounded by a graphite reflector and a pressure vessel. The primary turbine is located in a secondary pressure vessel and directly driven by the helium, which is heated by the reactor core. Heat exchangers are used

[12]Schullenberg, 2022, p. 56.

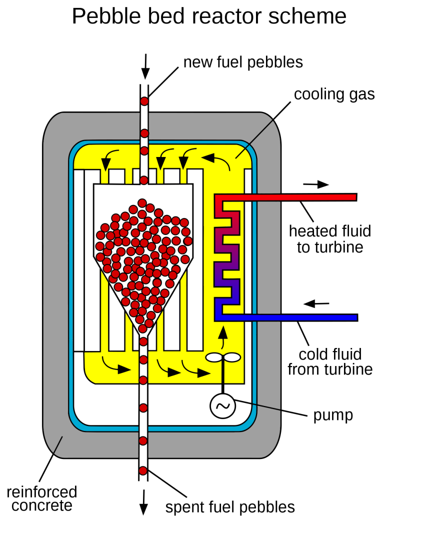

Figure 4.4.: Schematic representation of a pebble bed reactor

to transfer the remaining heat from turbines into a water based cooling loop for additional energy extraction[13].

4.2.2.3. Pebble Bed Reactors

The reactor core of a pebble bed reactor is made up of around 500000 individual fuel spheres. These spheres rest loosely inside the graphite reflector which is contained by a pressure vessel. The graphite reflector contains the control rods, because in previous research efforts the control rods were blocked by jammed spheres. New fuel spheres can be continuously fed in from the top side of the reactor, while spent fuel is extracted from the bottom end funnel. Therefore the reactor can be operated and refueled without the shutdowns normally required in refuelling. Helium is blow through the reactor core by a pump. A heat exchanger is used to extract the generated heat from the nuclear reactor[14]. Such a reactor core is illustrated in 4.4.

[13] Chapin, 2005.
[14] Schullenberg, 2022, pp. 60–62.

4.2.2.4. Safety

A great advantage of such a reactor is the inherent safety it provides. This means that the core need not have a emergency cooling system, because the fuel pebbles can survive heat in excess of 1600°C meaning that a core meltdown is virtually impossible. If the helium cooling fails the core only needs to be cooled from the outside to dissipate the heat created. Another advantage of this reactor type is, that no direct contact between the coolant and fissile material is possible due to the coating of the fuel spheres. Therefore in the event of coolant loss no radioactive material can be leaked into the surrounding environment[15]. Because they utilize fuel, which is only enriched to 8%, they have the same proliferation resistance as the pressurized water reactors currently in use[16].

4.2.2.5. Efficiency

Because very high temperature reactors operate at elevated temperatures and may make use of turbines operated directly by the coolant gas, they have comparatively high thermal efficiencies of 42%. They, however, are expected to reach efficiencies in excess of 50% with further development[17].

[15] Chapin, 2005, pp. 18–21.
[16] Chapin, 2005.
[17] Schullenberg, 2022, p. 62.

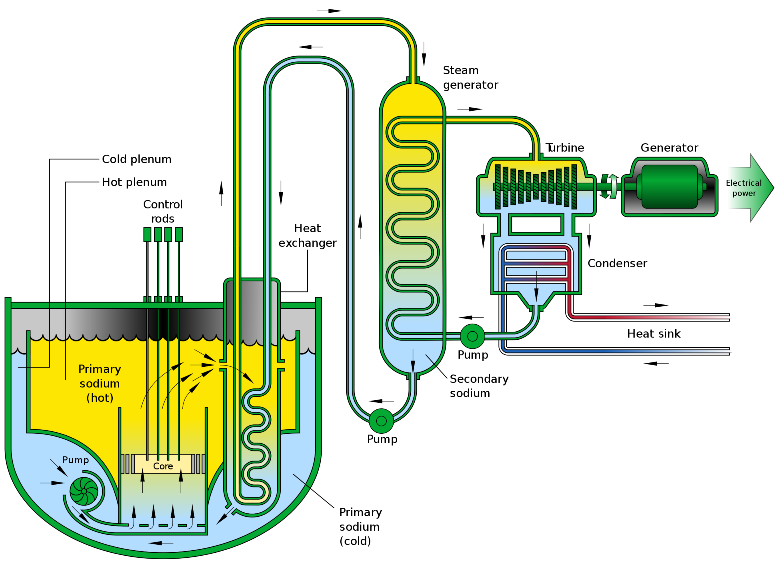

Figure 4.5.: Schematic representation of sodium-cooled fast reactor

4.2.3. Sodium-Cooled Fast Reactors

Sodium cooled fast reactors already have a working history of 60 years. As all fast reactors, they make use of fast neutrons with energies exceeding 3keV. As fast neutrons have a nuclear cross section which is lower than that of thermal neutrons by 500%, a neutron flux ten times greater than that of thermal neutron based reactors is required to achieve a comparable energy density[18]. Sodium-cooled fast reactors utilize sodium as the primary and secondary coolant. Sodium has little capability to interact with neutons. It is therefore well suited for fast reactors. Compared to water sodium has a thermal conductivity greater than that of water by a factor of 100. Because it has a melting point of 98°C and a boiling point of 883°C it is possible to operate the reactor at an entry temperature of 400°C and an exit temperature of 550°C while keeping the pressure at 1atm. Sodium as also very compatible with stainless steel, leading to no erosion of the reactor hull. The core itself is made up of conventional fuel rods and submerged in a circulating pool of liquid sodium. To increase the energy of the neutrons the fuel rods are mounted closer together to minimise

[18] Stacey, 2018, pp. 120–122.

the already small moderating effect of the coolant[19]. Figure 4.5 illustrates such a reactor.

4.2.3.1. Fuel

Because of the high energy neutrons, a large amount of plutonium in the form plutonium dioxide PuO_2 is added to the fuel. The mixed oxide fuel is made up of 15% Pu_2 with the rest being UO_2. During the reactor operation more plutonium is created as a fission product. Additionally the actinides created by the reaction are recycled in further fission reactions leading to a closed fuel cycle. No transuranic waste is created by fast reactors. The primary factor limiting the lifetime of fuel elements is the damage caused to the fuel containing tubes caused by the high neutron flux[20].

4.2.3.2. Safety

Because of the low operation pressure the risk of containment failure is kept at a minimum. Additionally, the chance of environmental pollution is reduced because there remains little to no radioactive transuranic waste to be stored away. The primary operating risk is the high reactivity of sodium, especially with water. Therefore even contact with miniscule amounts of H_2O, such as those in the atmosphere, could lead to catastrophic chemical explosions. Therefore great care needs to be taken to protect the cooling sodium from water. Additionally, caution needs to be exercised to keep the sodium coolant below its boiling point of 883°C to avoid the creation of a positive void coefficient, which would create a fatal super critical state. Lastly, reactors of this type have a self regulating property, as the core expands with increased heat. This allows more neutrons to escape the core reducing reactivity[21].

[19] Schullenberg, 2022, pp. 94–110.
[20] Schullenberg, 2022, p. 111.
[21] Generation IV International Forum, 2021, pp. 30–37.

4.2.3.3. Efficiency

Sodium-cooled fast reactors can reach high thermal efficiencies comparable to those of other fast reactors. Also, to reduce mechanical failures, electrodynamic pumps can be used to propel the molten sodium instead of mechanical pumps, reducing the amount of moving parts and thereby increasing reliability[22].

[22]Generation IV International Forum, 2021, pp. 30–37.

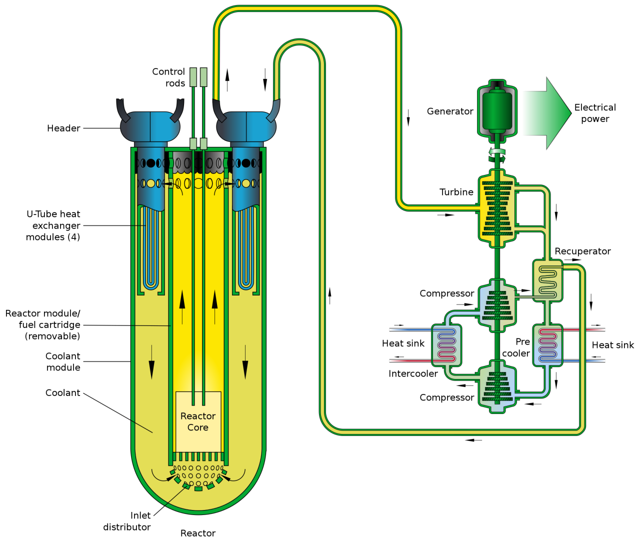

Figure 4.6.: Schematic representation of sodium-cooled fast reactor

4.2.4. Lead-Cooled Fast Reactors

The construction of lead cooled fast reactors is very similar to that of sodium-cooled fast reactors, as can be seen in figure 4.6. For the sake of brevity, only the differences to sodium-cooled fast reactors will be illustrated, while the parallels are omitted.

The two main problems of using sodium as a coolant can be solved by replacing it with another metal. Lead is well suited for such an application due to it't relatively high melting point of 337°C and the high boiling temperature of 1750°C. Therefore it is impossible for the lead to start boiling inside the reactor, because the fuel assemblies and the reactor hull would be destroyed first. Another advantage is the ability of lead to naturally circulate through the core because of the differences in density of lead at different temperatures. Because of the relatively high melting temperature great caution needs to be exercised as to not freeze the coolant inside the reactor. To mitigate this possibility the alloy lead-bismuth may be used. Lead-bismuth consists of 55.5 mass % lead and 44.5 mass % bismuth. This alloy has a low melting temperature 124°C, but also a decreased boiling point of 1670°C. Except for the higher nuclear cross section of lead-bismuth, the two coolants can be used interchangeably.

To further examine lead and bismuth as coolants close attention needs to be drawn towards the individual isotopes of these metals[23].

4.2.4.1. Coolant Isotopes

As can be seen from table 4.2.4.1, ${}^{204}_{82}Pb$ compared to bismuth, but because naturally occurring lead consists of a mixture of the lead isotopes listed in 4.2.4.1 in the ratios given, its total cross section of neutron absorption is lower compared to bismuth. Through neuton capture ${}^{206}_{82}Pb$ and ${}^{207}_{82}Pb$ are converted to ${}^{208}_{82}Pb$ during the nuclear reactor operation. Through further neutron absorption ${}^{209}_{82}Pb$ can be created, which decays to ${}^{209}_{83}Bi$ with a half life of 3.23h. When ${}^{209}_{83}Bi$ absorbs a neutron, ${}^{210}_{83}Bi$ which decays to ${}^{210}_{84}Po$ with a half life of 5 days, a strong alpha emitter with a half life of 124 days. ${}^{210}_{84}Po$ decays to ${}^{204}_{82}Pb$. Thereby the coolant is not only contaminated, but there is a significant safety risk for the operating personell, but due to the short half life of the relevant isotopes, one only has to await the decay of the isotopes if disposal is necessary[24].

Isotope	${}^{204}_{82}Pb$	${}^{206}_{82}Pb$	${}^{207}_{82}Pb$	${}^{208}_{82}Pb$	${}^{209}_{83}Bi$
Abundance (%)	1.4	24.1	22.1	52.4	100
Half-Life (years)	$1.4 * 10^{17}$	Stable	Stable	Stable	$2 * 10^{19}$
Nuclear cross section (mbarn)	703	26.6	622	0.23	32.4

Table 4.2.4.1

4.2.4.2. Safety

Because lead is susceptible to explosive reactions with water and because it mitigates the problem of a positive void coefficient it may be better suited a as coolant for a fast rector. Additionally, in the case of a breach in the reactor vessel, the leaking lead solidifies below melting temperature and thereby stops further evacuation of the reactor chamber. The main problem of safety in operation is the danger of irradiation caused by the contamination of the lead coolant through the generation of radioactive isotopes, mainly ${}^{210}_{84}Po$[25].

[23] Pioro et al., 2016, pp. 137–174.
[24] Schullenberg, 2022, pp. 115–134.
[25] Schullenberg, 2022, p. 132.

4.2.4.3. Efficiency

The efficiency and fuel cycle benefits are identical to those of sodium-cooled fast reactors. See chapter 4.2.3

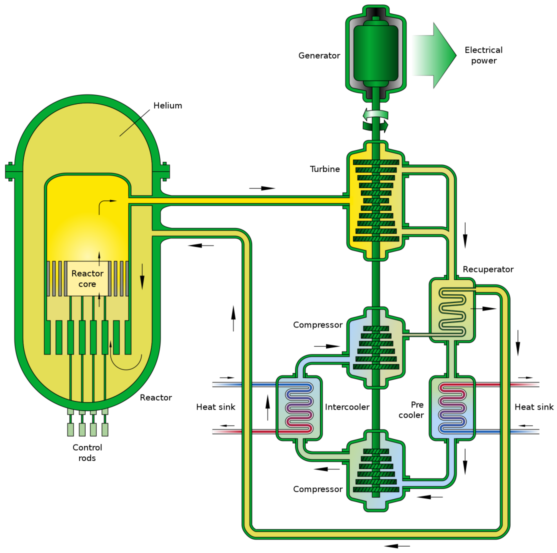

Figure 4.7.: Schematic representation of a gas-cooled fast reactor

4.2.5. Gas-Cooled Fast Reactors

Gas-cooled fast reactors employ a gas, in all relevant cases helium, as the coolant. Thermodynamically, they bear a great similarity to helium-cooled very high temperature reactors. But, because they are fast reactors, the core design varies greatly. The core assembly is very similar to sodium-cooled fast reactors, where mixed oxide fuel is housed in stainless steel tubes. Attempts to use the more economical and safe TRISO pellets have failed because of damages caused by high neutron flux. Because of it's very low density, helium has no ability to moderate neutrons with a cross section of neutron absorption of 0 mbarn. This makes it the ideal coolant for a fast reactor. However, if operated at 70 atm of pressure, the flow rate of the reactor coolant needs to 500 times as high compared to a sodium-cooled fast reactor to achieve comparable heat transfer rates[26].

[26]Schullenberg, 2022, pp. 135–144.

4.2.5.1. Safety

Because of the high flow rates required to keep the reactor operational, active pumps need to be employed to move the coolant helium through the core. Because of the high pressure it is very difficult to design a passive safety system for such a reactor and no tested solution has been found yet, because no such system has ever reached criticality. However, because helium is chemically inert, no corrosion of the reactor vessel can be expected. Additionally, no positive void coefficient can occur because helium already has no ability to moderate neutrons[27].

4.2.5.2. Efficiency

The efficiency and fuel cycle benefits are identical to those of sodium-cooled fast reactors. See chapter 4.2.3

[27] Schullenberg, 2022, pp. 135–144.

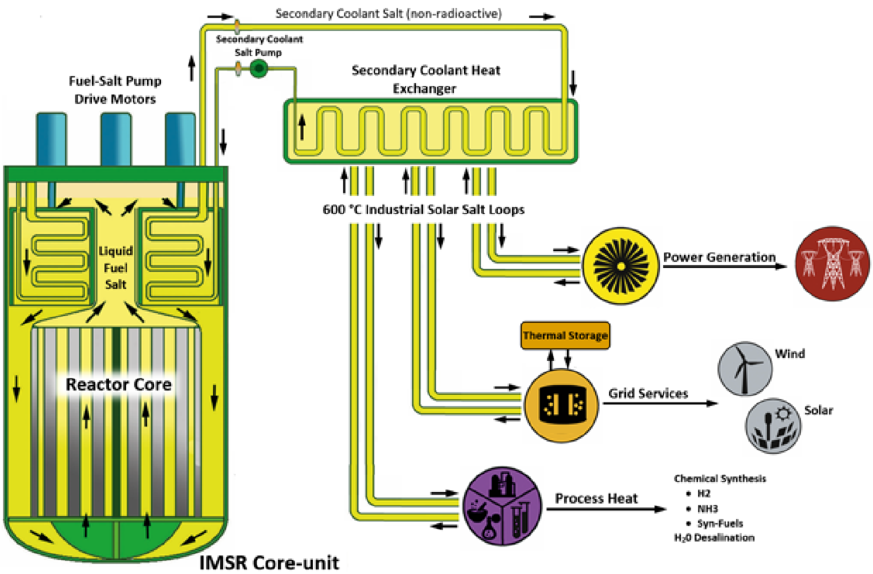

Figure 4.8.: Schematic representation of a molten salt reactor

4.2.6. Molten Salt Reactors

Molten salt reactors are a class of reactors where the fuel is not present inside the core as a solid but rather as a liquid. In such a configuration the salt used as fuel also functions as the primary coolant simultaneously. Because the melting points of the salts used are 400°C to 500°C the core operates at ranging from 650°C to 700°C. However the pressure inside the reactor and coolant systems does never exceed 1atm meaning that the pressure inside the reactor is never above atmospheric pressure. If operation with thermal neutrons is desired, graphite is used as the moderator[28]. An illustrativ schematic of such a reactor is shown in 4.8.

4.2.6.1. Fuel

Uranium dioxide is not suitable as a fuel for molten salt reactors, because it has a melting point around 1000°C. Therefore a mixture of different fluoride

[28]Schullenberg, 2022, pp. 147–152.

containing salts is used. The main salts used are Lithium Fluoride (LiF) and Beryllium Fluoride (BeF_2). The fissile material is present in the form of Uranium Fluoride (UF_4). If the reactor is operated using thermal neutrons, unenriched uranium may be used as fission fuel.

4.2.6.2. Safety

Because the reactor core is already in the liquid phase during normal operation, a core meltdown is not possible. Additional, if an emergency condition is detected, the contents of the core can be dumped into special containers where the reactive mass becomes subcritical and is allowed to cool off. It is also possible to change the fuel contents during regular core operation, thereby making a core shutdown unnecessary. This also allows for more streamlined fuel cycles, as the components composing the molten salt fuel can be separated directly in a secondary plant, thereby bypassing the need for separate reprocessing facilities and creating the possibility to remove fission products and simultaneously introduce new fission fuel during reactor operation. Lastly, because gaseous substances such as Iodine and Xenon Isotopes are not well soluble in liquid salt when compared to water. Therefore it is easier to extract and capture them[29]. If the reactor does not make use of a moderator and instead uses fast neutrons, it has the advantage of a negative void effect. This means that as the heat inside the reactor rises, the reactivity of the reactor decreases, thereby creating a passive safety feature. Fast molten salt reactors are the only fast reactors with such a property[30].

4.2.6.3. Efficiency

Because of the higher operating temperature molten salt reactors are more efficient at generating electrical power. Additionally, because the fuel composition can be varied considerably during operation and because unwanted isotopes can be extracted or eliminated in a targeted fashion, they may also profit from high economic viability[31].

[29] Serp, 2014.
[30] Schullenberg, 2022, p. 164.
[31] Pioro et al., 2016, pp. 159–161.

4.2.6.4. Disadvanages

Because the liquid fuel comes into contact with a greater deal of moving mechanisms such as pumps, a greater area of containment and more remote operation and servicing is needed to operate such a reactor[32].

[32] Serp, 2014.

Appendix

Appendix A.

Rights

A.1. Figures

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A.2. Equations

A.2.1. Own Creation

Equations 1.1, 1.2, 1.3, 1.4 and 1.6 were typeset by the author with information taken from[1].

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

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List of Figures

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