The Future of Nuclear Reactors

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Abstract

Generation IV (Gen IV) nuclear reactors represent the forefront of nuclear technology, proposed with the goal of enhancing safety, efficiency, and sustainability over their predecessors. This paper examines the development, potential and challenges of six proposed Gen IV reactors. The paper starts by discussing a broad spectrum of technical aspects from the fundamental theories underpinning nuclear fission to important details of reactor operation and control. It addresses the advancements of Generation II and III reactors to the cutting-edge developments in Gen IV technologies, emphasising the lessons learned from past reactor incidents and the forward-looking innovations designed to prevent their recurrence. Finally, we compare the proposed designs and give our view of the situations in which these designs either thrive or fall short.

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1 Introduction

With global warming posing a larger threat than ever, and the stockpile of fossil fuels running out [1], it is clear that alternate ways of generating energy must be explored. Over the past couple of years, there has been a shift towards using more renewable energy sources in the UK, with 51% of our energy coming from these sources in 2023 [2]. These sources include wind, tidal, and solar power but there remains another option, nuclear fission. Nuclear fission is already in use and could serve as a primary power source or a useful supplement to renewables.

Nuclear power has been in use since the 1950's and 60's [3] and remains a cleaner alternative to fossil fuels due to the lack of greenhouse gases emitted in production. As of 2022, only around 15% of the UK's energy was generated through nuclear power [4]. While power generation is currently the main use of commercial nuclear reactors, there are other possible uses in research (e.g. isotope production) and notably hydrogen production. There remains a stigma around nuclear power as many people associate it with the Chernobyl/Fukushima nuclear plant disasters or with the nuclear bombs used in the Second World War. Taking these events into consideration helped shape nuclear power plants today and continues guiding the creation of new technologies.

In 2001, the Generation IV International Forum (GIF) was formed, and a road map to new reactors was set out. This report aims to discuss the principles of nuclear power and reactors, introduce the technology used in past generations of reactors and discuss the outcomes of the GIF Summit in creating the new Gen IV reactors.

2 Theory

In the realm of nuclear physics, reactions such as fission, fusion, and radioactive decay play important roles. Currently fission is the primary reaction harnessed for energy production. Meanwhile fusion, the process of combining atomic nuclei, holds promise for future energy solutions but is currently in experimental stages and not yet viable for commercial energy production. Radioactive decay on the other hand is a natural process used in applications including radioisotope generators, but does not provide the controlled and large-scale energy output suitable for power generation.

2.1 Nuclear Fission

Nuclear fission refers to the splitting of a nucleus into smaller nuclei, typically two. Although fission into three nuclei (ternary) or more occurs, referred to as multiple fission, it is infrequent [5] leading to binary fission being more relevant.

Figure 1 shows how the binding energy per nucleon of a nucleus varies with its mass number A. For mass numbers greater than 56 the binding energy per nucleon decreases with increasing mass number, a result of the long-range electromagnetic repulsion between protons in the nucleus starting to become more significant than the short-range strong nuclear force in nuclei with increasing volume. The binding energy is the energy required to separate a nucleus into its constituent nucleons, hence an increase in binding energy means that energy has been released. Fission releases energy because the binding energy per nucleon of the fission products is greater than that of the original nucleus, the increase in binding energy of the products is released.

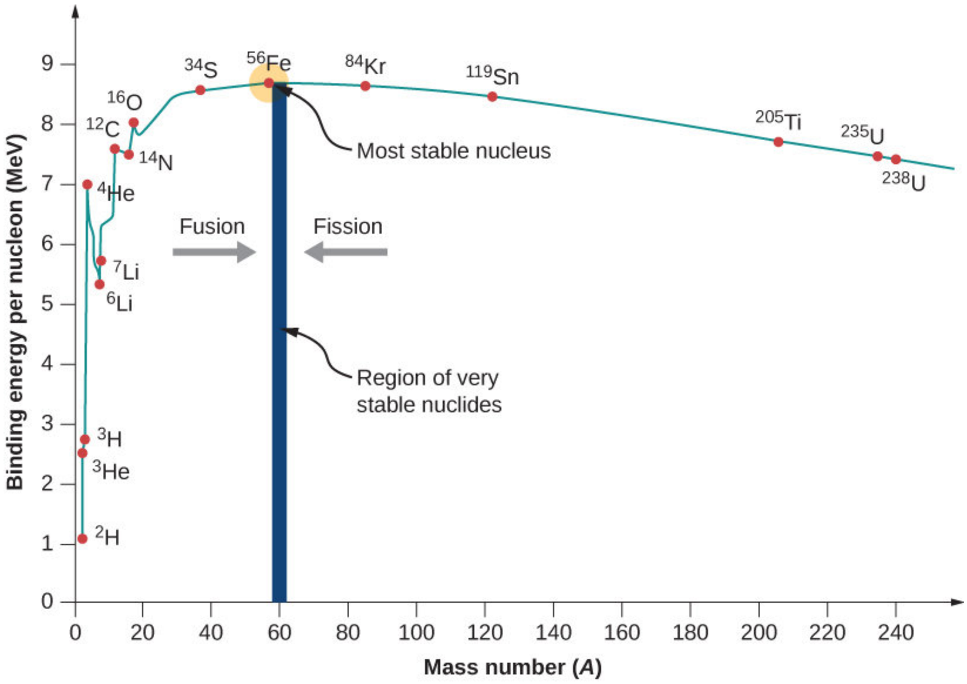

Figure 1: Figure from [6]. Plot of the Binding energy per nucleon in MeV against mass number A. This plot illustrates that fission is energetically viable for nuclei with A greater than 56. Fission releases energy because the products have greater binding energy per nucleon than the original nucleus.

Fission processes can be either spontaneous or induced. Spontaneous fission occurs when a more stable isotope is available to a nucleus via decay. Spontaneous fission becomes more probable for nuclei with high mass number; nuclear stability tends to decrease with increasing mass number. Spontaneous fission differs from induced fission in that it is an intrinsically random process which relies on quantum tunneling to occur.

What spontaneous fission does share with induced fission is its suitability as a source of neutron production. While spontaneous fission is random, due to the large numbers of nuclei in a reactor, the rate of fission is consistent making spontaneous fission a suitable neutron source for a reactor.

Induced fission occurs when nuclei are bombarded by neutrons. When a nucleus absorbs a neutron with sufficient energy, the critical energy or greater, its structure deforms into an excited dumbbell configuration (in the case of binary fission). In such a configuration, repulsive electrostatic forces begin to dominate the short-range attractive strong force which holds nuclei together. This results in a scission - rapid separation of the nucleus into two smaller nuclei, releasing energy and neutrons in the process. Higher mass nuclei are more susceptible to induced fission as they require less energy to deform enough for scission to occur [7].

2.2 Neutron Sources

Neutron sources are important to the operation of a reactor as they allow for the reactor to be started and ensure a minimum neutron flux in the core at all times. There are two types of neutron sources: intrinsic and installed. Intrinsic neutron sources refer to materials with some other purpose in the reactor, which also act as a source of neutrons. One example of this would be the heavy nuclei used to fuel the reactor. These heavy nuclei will spontaneously fission with some probability leading to the production of neutrons and therefore acting as an intrinsic source. Installed neutron sources refer to materials included in the reactor explicitly for the purpose of producing neutrons [7].

2.3 Sustained Fission Chain Reaction

The core mechanism upon which current nuclear reactors operate is the fission chain reaction. A single nucleus fission typically releases energy in the hundreds of MeV, approximately 200MeV in the case of ^{235}U [8]. This means that to generate a significant amount of power, there needs to be a large number of fission reactions occurring rapidly. When a fission reaction occurs neutrons are released, sustaining the chain reaction as the released neutrons induce fission in other nuclei, see Figure 2. However, not all of the released neutrons will go on to induce fission. This is not necessarily an issue though, since fission reactions tend to release multiple neutrons. For example, during a single ^{235}U fission it is typical for two or three neutrons to be released [9]. The condition for a fission chain reaction to be sustainable is that on average at least one of the neutrons released from each fission reaction should go on to induce fission in another nucleus [10]. The vast majority of neutrons are released immediately during the scission, these are referred to as 'prompt neutrons'. There is also a second type of released neutron called 'delayed neutrons' which are released after the scission when one or both of the two product nuclei undergo nuclear decay as they attempt to achieve stability [7].

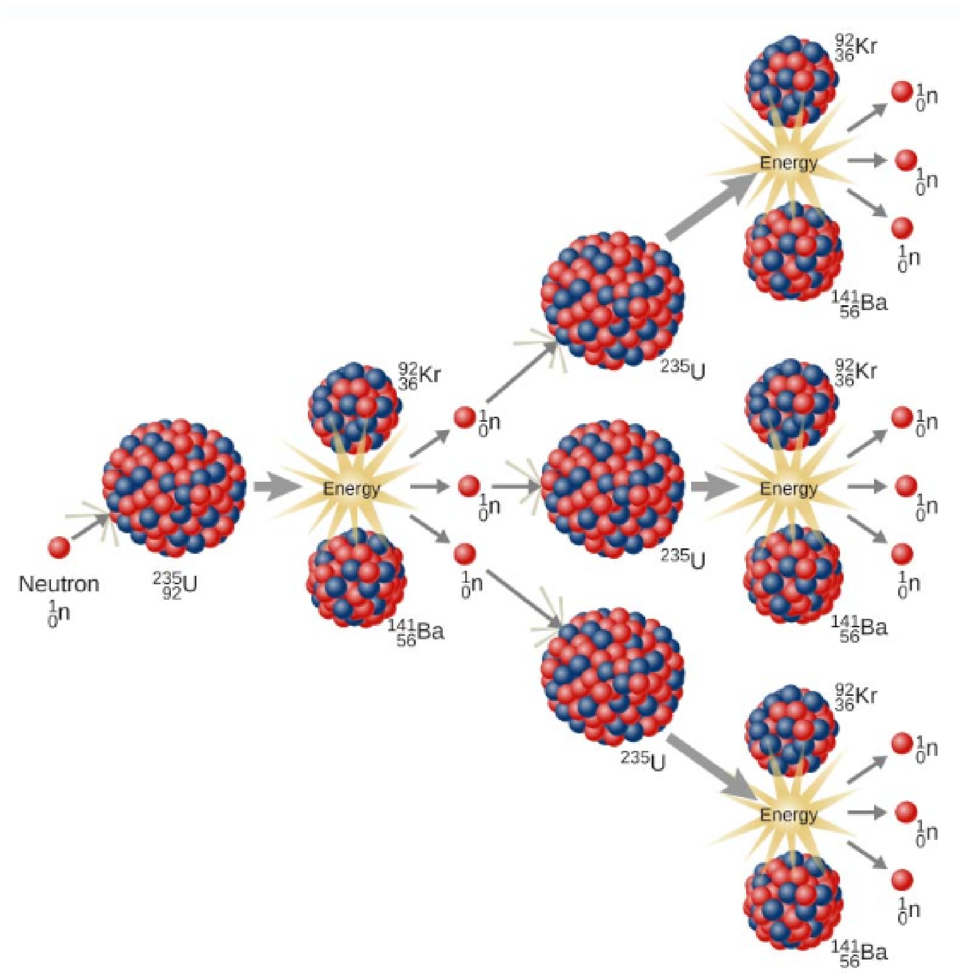

Figure 2: Figure from [11]. Illustrates how a fission chain reaction functions using ^{235}U as an example. When a fission reaction occurs, the neutrons released go on to induce fission in other nuclei creating a chain reaction. Not all of the neutrons released will induce fission in another nucleus, however if an average of at least one released neutron per fission reaction does induce fission, then the reaction will be sustained [7].

2.4 Reactor Control

The generation time is the time for the neutron products of one generation of fission to induce the next generation. Reactor power depends on generation time, so it is important to maintain an average generation time which can be controlled. Without delayed neutrons the generation time would entirely depend on prompt neutrons, this could lead to a reactor experiencing rapid fluctuations in generation time and therefore power, making it uncontrollable. Delayed neutrons are important as they allow for the average generation time to be slowed to a controllable level. Despite delayed neutrons comprising a minority of the neutrons produced by fission, their contribution to the average generation time of the reactor dominates that of prompt neutrons allowing for reactor power to be controlled [7].

It is important that reactor power levels can be directly adjusted. This is done through the use of control rods - rods of neutron absorbing material. The power of a reactor is related to the core neutron flux; a high flux means high power, while a low flux corresponds to low power. When a control rod is inserted into the reactor core it reduces the power of a reactor as it absorbs neutrons decreasing the neutron flux, see Figure 3 'ϕ with control rod'. In contrast, removing a control rod from the reactor core increases the power of a reactor as fewer neutrons are being absorbed leading to an increased neutron flux, see Figure 3 'ϕ without control rod'. Control rods may be used for multiple purposes including safety and providing fine control allowing for the reactor to operate at a specific power if desired. Some reactors may use different control rods for different purposes, while some will use multi-purpose rods [10].

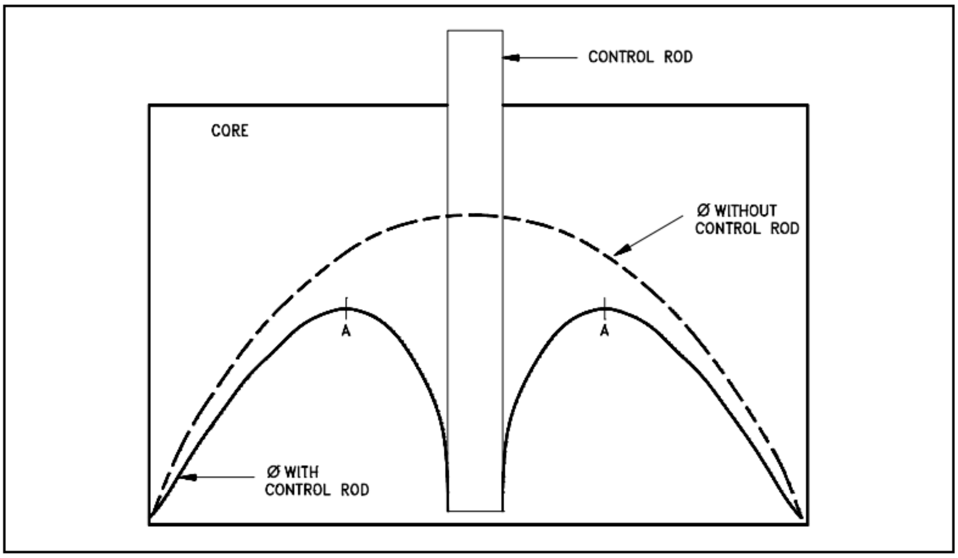

Figure 3: Figure from [10]. Shows the effect of a control rod on neutron flux ϕ in a reactors core. Neutron flux in a reactor core is reduced in the presence of a control rod. It should be noted that the control rod has a maximum effect when inserted at the maximum in neutron flux. It is common for more than one rod to be inserted, in such cases further rods should be inserted at new flux maxima (labeled A in the figure) to maximise their effect [10].

2.5 Neutron Energy Spectrum

An important consideration pertaining to a nuclear reactor is whether fissile or fissionable material should be used as fuel. The distinction is important as it determines whether fission requires thermal or fast neutrons. Fissile material refers to nuclei for which fission is possible after absorbing thermal neutrons (neutrons with low kinetic energies of order kT). For fissile materials, the change in binding energy resulting from the absorption of a neutron is greater than the critical energy meaning fission can occur without additional kinetic energy. Fissionable nuclei include all fissile nuclei but also nuclei which can only fission after absorbing fast neutrons (high-energy neutrons). To fission, such nuclei require fast neutrons as the change in binding energy is less than the critical energy meaning that for fission to occur, the absorbed neutron must have sufficient kinetic energy to supplement the change in binding energy [7].

A critical factor in understanding reactor behavior is the neutron flux spectrum, the distribution of neutron energies shown in Figure 4. The flux spectrum is an important consideration when designing a reactor and choosing a fuel. For example, in a fast reactor, the spectrum is skewed towards higher-energy neutrons. These are more effective in causing fission in certain isotopes not easily fissionable by low-energy (thermal) neutrons. This characteristic enhances the efficiency of material usage reducing waste.

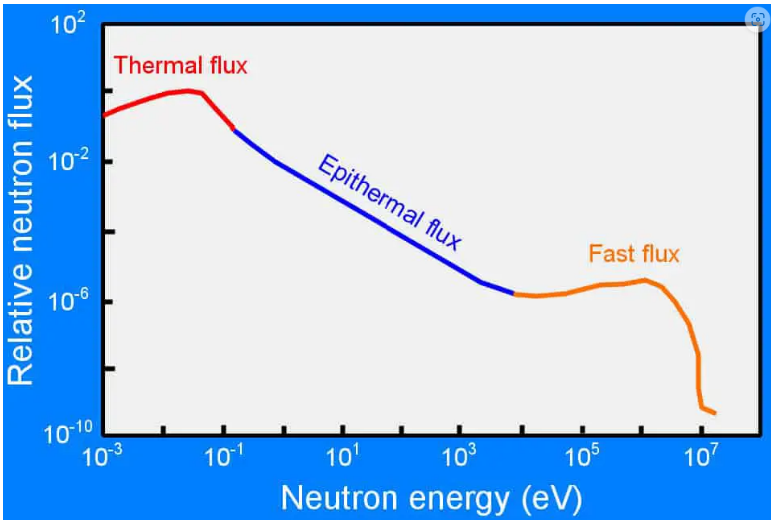

Figure 4: Figure from [12]. This graph shows a neutron flux spectrum characteristic of a thermal reactor. The "Thermal flux" region indicates the prevalence of low-energy neutrons essential for fission in fissile materials like ^{235}U. The "Fast flux" portion shows high-energy neutrons required to fission fissionable materials such as ^{238}U. The spectrum informs whether a reactor will use thermal or fast neutrons to sustain the chain reaction, influencing the efficiency and type of nuclear fuel used [13].

Whether fast or thermal neutrons are used to sustain the fission chain reaction is an important consideration when designing a reactor. Thermal reactors use thermal neutrons to sustain the fission chain reaction, while fast reactors use fast neutrons for this purpose.

2.6 Coolants and Moderators

Some fissile nuclei do not absorb fast neutrons as readily as thermal neutrons, see Figure 5, in such cases a moderator can be used to increase the rate of fission. A moderator is a material used to slow down fast neutrons via scattering. A good moderator has a large scattering cross section and high energy loss per scattering event, while also not absorbing a significant fraction of the scattered neutrons [7].

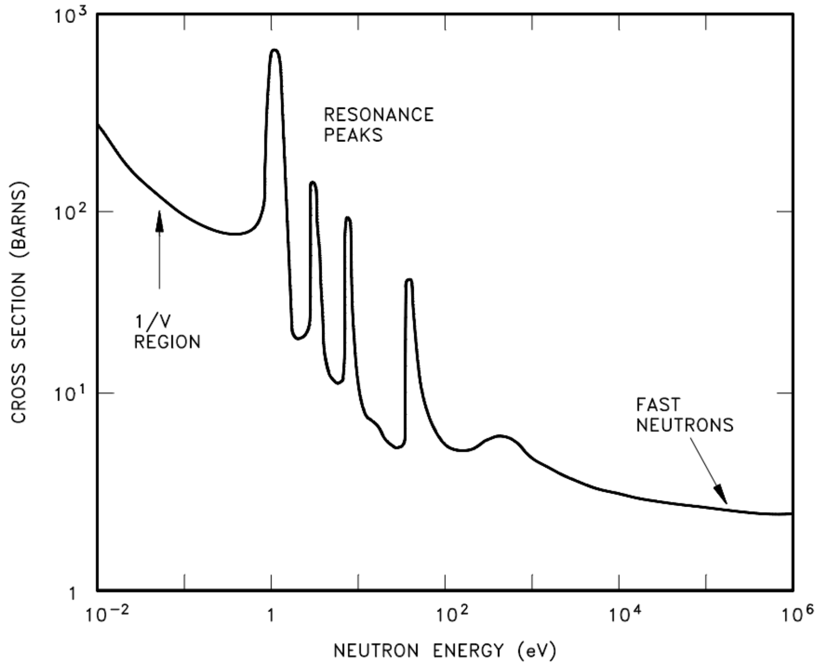

Figure 5: Figure from [7]. Shows a characteristic plot of Neutron Absorption Cross Section against Neutron Energy, it includes three notable features. At thermal energies neutron absorption cross section is high and inversely proportional to neutron velocity. As neutron energy increases, resonance peaks are observed, these correspond to neutron energies matching discrete quantum energy levels of the nuclei. At non-resonance fast neutron energies, the neutron absorption cross section is low and shows a decreasing trend with increasing energy [7].

An important component of any reactor is coolant. Reactor coolant, commonly water, is used to extract thermal energy produced in the reactor core but also to control reactor temperature and pressure. The coolant used may be the same as the moderator but this varies between reactor designs.

2.7 Thermal Power and Efficiency

Thermal power is the immediate measure of the energy generated within the core due to nuclear fission - it represents the heat produced when fissile materials like ^{235}U or ^{239}Pu undergo induced fission after absorbing neutrons. The management of this heat is central to the operation of the reactor core, dictating the design of the cooling systems, the structural materials used, and the overall safety measures employed [13].

We generally categorize the reactor power output into three classifications: nuclear, thermal, and electrical. While the nuclear power quantified by the neutron flux serves as a precursor to thermal power and electrical power is the ultimate output, it is the thermal power that is most critical from an operational standpoint. This is because the reactor core must be designed to handle the heat generated by fission. If the heat is not efficiently removed, it can lead to core damage or meltdown, making thermal power a crucial safety parameter. The thermal energy generated is transferred to a coolant, usually water, which then carries this energy away from the core to be used for electricity generation or other applications.

The efficiency of a nuclear reactor is a measure of how effectively it converts thermal power into electrical power. Typically, only 30% to 40% of thermal power is converted into electrical power, illustrated in Figure 6, with the rest lost as waste heat. This conversion rate is governed by the thermodynamic limitations of the Rankine or Brayton cycles used in the turbines and generators of power plants. The heat-to-electricity conversion efficiency is a key metric for the economic and environmental assessment of a nuclear power plant, as improvements in this area can lead to more power output for the same amount of nuclear fuel and reduced thermal pollution [14].

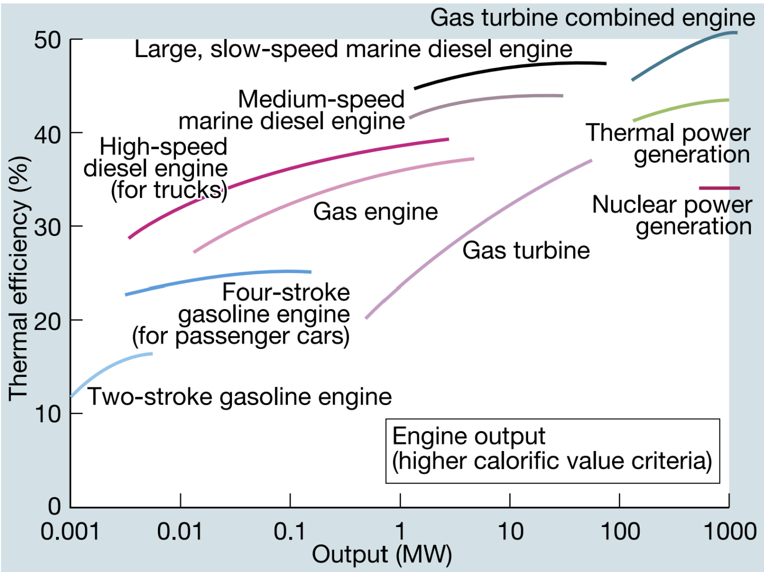

Figure 6: Figure from [15]. The graph displays the thermal efficiency of various engines and power generation systems against their output. Marine diesel engines show the highest efficiency at larger scales, while conventional gasoline engines for cars are less efficient. Gas turbines in a combined cycle exhibit improved efficiency due to waste heat recovery. Thermal and nuclear power generation methods have comparable efficiencies, constrained by the limits of thermodynamic cycles, typically between 30% to 40% at higher outputs [15].

2.8 Hydrogen Production

Hydrogen is a very promising fuel for the near future with a number of applications, global demand for hydrogen is expected to rise to as high as 500 million tonnes per year by 2050. Current hydrogen production stands at around 100 million tonnes per year, with some 95% of this coming from fossil fuels. If the demand for hydrogen is to keep growing, it is clear that less polluting alternatives are needed.

Every technique for producing green hydrogen relies on the splitting of water into hydrogen and oxygen using energy produced by clean sources. The direct electrolysis of water to produce hydrogen is much more expensive than production through hydrocarbons however, so more efficient techniques are needed. These techniques, such as the thermochemical production of hydrogen, require very high temperatures of several hundred degrees Celsius and so a clean method of generating this heat is required [16].

Currently active nuclear reactors do not operate at high enough temperatures to be a viable heat source for the previously mentioned efficient hydrogen production processes. This has motivated the development of high-temperature reactors ($\gtrsim$ 800°C) which could provide the necessary temperatures for such a process. The high temperatures generated by these reactors could also be used in other industrial applications, supplanting the use of gas as a generator of heat. High-temperature reactors could even be used to supply the temperatures required in the production of hydrogen through hydrocarbons, a step which accounts for 30% of present-day emissions due to hydrogen production [17].

2.9 The Nuclear Fuel Cycle

The nuclear fuel cycle is a fundamental aspect of nuclear reactor operation, encompassing the entire journey of nuclear fuel from its initial extraction to its final disposition. This cycle is pivotal in determining the efficiency, sustainability, and environmental impact of nuclear reactors. There are three different nuclear fuel cycles: the once through, reprocessing, and breeding cycles. In the once-through fuel cycle spent fuel is treated as waste and not reused (it contains plutonium and other actinides). In contrast, the reprocessing fuel cycle involves extracting plutonium and uranium from spent fuel, using the plutonium to create mixed-oxide fuel (MOX) for thermal reactors thus altering the nature of the nuclear waste and offering additional energy. The breeding cycle, designed to produce more fissile material than initially provided, increases the range of usable fuels significantly.

Currently most commercial reactors, especially in the U.S., operate on a once-through fuel cycle with some countries including France employing extensive reprocessing programs. The breeder cycle, though previously attempted, is not currently in use. Additionally, there is ongoing interest in thorium fuel cycles due to their potential for proliferation resistance and sustainability. In such a cycle, ^{232}Th serves as the fertile material which leads to the production of ^{233}U, a fissile fuel [16].

3 Historical Reactor Development

3.1 Generation II Reactors

After the end of the Second World War, scientists were tasked with finding peaceful ways of utilizing nuclear energy. One promising application was building power plants which would make use of controlled nuclear reactions to release energy. Multiple small-scale nuclear reactors were built in the late 50s and early 60s to verify the feasibility of nuclear energy production. These early prototype reactors were not powerful enough to be used commercially and served primarily as a proof of concept. These reactors are referred to as Generation I reactors, and their success paved the way for the development of commercially viable Generation II reactors [18].

Generation II refers to multiple reactor designs. Among them are boiling water reactors (BWRs), pressurised water reactors (PWRs), Canada deuterium uranium reactors (CANDU), advanced gas-cooled reactors (AGRs), and water-water energetic reactors (WWERs) [18]. The main difference between these designs is the number of coolant loops and the type of coolant. The two most common types of nuclear reactors are PWRs and BWRs, both of which use exclusively light water (water with no deuterium) as their coolant and are thus called light-water reactors (LWRs) [19].

3.1.1 Pressurised water reactor

Pressurised water reactors consist of four main elements: the nuclear reactor, the primary coolant loop, the secondary coolant loop, and the steam turbine. Figure 7 shows a simplified schematic of a PWR.

A notable feature of the PWR design is that power production decreases with increasing reactor temperature. The neutrons released in the reactor must be moderated to react again with the fuel. In PWRs, neutrons are slowed by colliding with the hydrogen atoms in the water molecules. As the temperature increases, the distances between water molecules increase, thus decreasing the possibility of neutron scattering. As a result, a smaller percentage of neutrons are moderated leading to reduced fission. A downside of PWRs is that they require significant pressure in the primary loop to maintain the water in liquid phase increasing construction and maintenance costs [20].

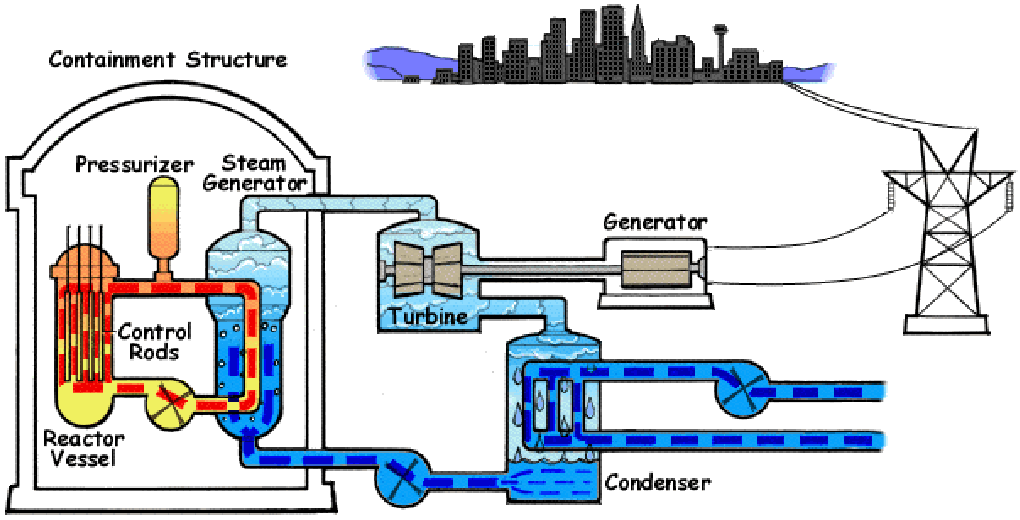

Figure 7: Figure from [21]. Schematic diagram of a PWR. The water in the primary loop is heated at the reactor vessel. The heated water starts moving up the primary loop, thus siphoning the next portion of water into the reactor. This heated and pressurised water comes into thermal contact with the water in the secondary loop, which evaporates and rotates the steam generator, producing electricity. In the primary loop, the water is kept under pressure with the help of a pressuriser to avoid a phase transition, which could cause instability in the coolant's flow. The water in the secondary loop is cooled down in a condenser by water from a nearby reservoir like a lake or a river [19].

3.1.2 Boiling water reactor

The second type of LWR is the boiling water reactor. Such reactors consist of only one coolant loop, significantly reducing the design's complexity and construction costs. Figure 8 presents a simplified design of a BWR.

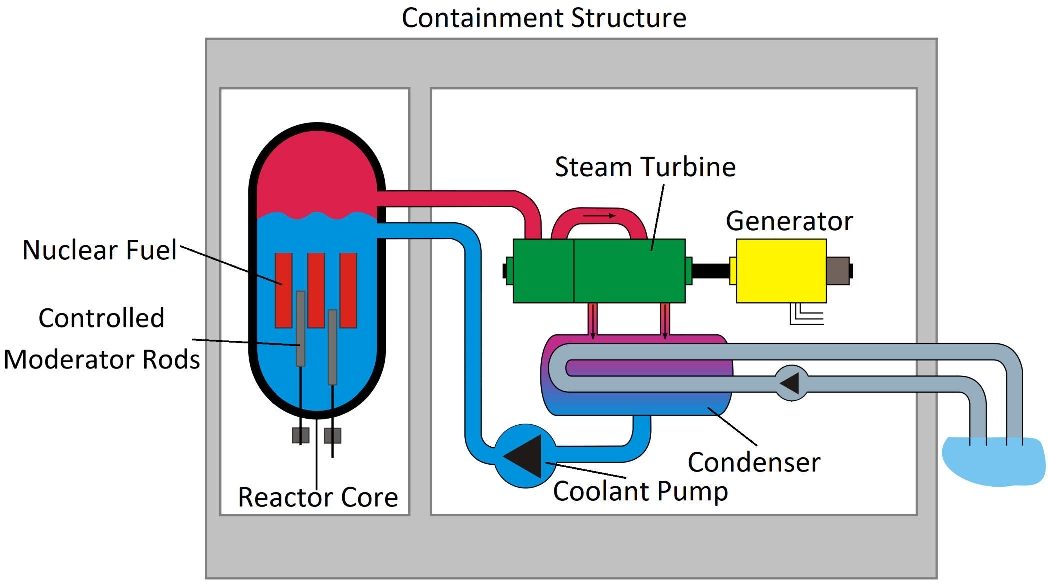

Figure 8: Figure adapted from [22]. Schematic diagram of a BWR. The nuclear fuel and the moderator rods are located inside the reactor core. The moderator rods can be inserted and retracted, allowing for control of the nuclear chain reaction. The coolant is pumped into the reactor core as a liquid. In the reactor, the water evaporates and exits as steam towards a steam turbine, which is connected to a generator. After passing through the steam turbine, the steam is condensed back into liquid at a condenser by water from a reservoir, and the cycle repeats [22].

A significant advantage of a BWR over a PWR is its simplicity. A BWR operates at lower pressures than a PWR does. Moreover, a BWR does not require a pressuriser and various other components, as there is only one coolant loop. The absence of these components reduces the construction cost of a BWR. However, the two-phase coolant loop has more coolant density fluctuations than the one-phase coolant loop in a PWR, leading to BWRs requiring more complex fuel management systems. Additional sensors are needed for the two-phase coolant loop to be appropriately maintained. Furthermore, the steam turbine in a BWR is contaminated with radioactive products of nuclear fission, so additional shielding is necessary [20].

3.2 Generation III Reactors

Generation III reactors are the successors to the Generation II reactors of the late 1950s. Both generations of reactors have the same variants, and the notable differences are from technological advancements spanning over four decades.

The upgrades implemented into Generation III from Generation II reactors are improvements in safety systems, fuel efficiency, thermal efficiency, standardized designs, and modularity of new reactors.

The first Generation III reactor to become operational was the Kashiwazaki-6 reactor in Japan utilising the BWR design (Figure 8) [23]. The safety systems introduced, that would notably go into the upgraded Generation III+ reactors as well, are passive safety features. These included the removal of operator controlled cooling and reactor shut downs in the event of any possible incidents such as the historic failure of the Chernobyl Unit-4 reactor. With the improvements in technology, the Generation III reactors operate at higher temperatures increasing their efficiency.

Generation III reactors also introduced standardized designs and modularity, allowing for the production of components that can fit multiple reactors. This can allow components from two reactors to be interchanged without issue and reduces costs.

3.3 Reactor Failures and Current Developments

There are three well-known instances where nuclear reactors failed under various circumstances, resulting in devastating consequences. These three historic events have influenced how reactors are designed, especially with regard to the implementation of safety protocols and fail-safes for Generation III reactors to avoid or minimise future incidents.

3.3.1 Three Mile Island, Chernobyl and Fukushima Reactors

The first is the Three Mile Island (TMI) Pennsylvania incident which occurred in 1979. This incident was the partial meltdown of the Three Mile Island Unit-2 reactor caused by a malfunction of the coolant temperature circuit resulting in the immediate shutdown of the reactor [24]. Additionally, a valve to relieve pressure failed to close, and the coolant evaporated causing the core to heat up and melt. Due to the core melting and the relief valve remaining open, a release of radioactive ^{133}Xe and radioactive ^{131}I into the surrounding environment occurred [25]. As of 2019, TMI-1 shut down after running since 1985, and the clean-up of TMI-2 was completed in 1991. No fatalities were recorded during the incident or after the radiation release.

The second is the Chernobyl incident that occurred in 1986 where the Reactor-4 night shift operators performed a test they were not trained to do. Mixing of the fuel with the coolant water led to a build-up in pressure. This caused the reactor head to become loose and the control rods to be jammed halfway inside the reactor's core resulting in an uncontrollable chain reaction that caused the fuel rods and control rods to melt into a highly radioactive compound called Corium lava [26]. This lava melted into the base of the reactor and eventually solidified to a solid radioactive mass nicknamed 'The Elephant's Foot'. As of 2023, the mass is still located in the room 15 metres below the rector core where it originally flowed to in 1986. The events that occurred during the test along with poor maintenance of the reactor resulted in the biggest unapproved release of nuclear material in human history [26]. This resulted in the death of an estimated 4000 people and radiation exposure to an estimated 5 million people [27]. The date for the Chernobyl plants complete decommission and destruction is scheduled for 2065 [26].

The third is the 2011 Fukushima incident in Japan, which wasn't as catastrophic as Chernobyl. This incident occurred when a Magnitude 9 Earthquake between the North American and Pacific tectonic plates caused a tsunami to hit the Fukushima Daiichi Nuclear plant. The tsunami breached the water defences and flooded the basement of the power plant shutting down the diesel generators and seawater pumps that provided cooling to the reactor cores. When this occurred, the power supply and cooling to reactors 1, 2, 3 and 4 was cut. In reactor Units 1 and 3, due to the lack of cooling, core temperatures started to rise. This caused steam to react with the zirconium cladding of the fuel rods producing hydrogen, later resulting in a hydrogen explosion releasing hydrogen and a mixture of noble gases. This is similar to the Chernobyl incident where excess heat caused the fuel rods and control rods to melt into Corium lava which flowed into the concrete base of the reactor and solidified [28]. Unit 2 experienced the same processes. After the incident, a leak was found in the Primary Containment Drywell (PCD), a concrete well that is designed to capture any melted fuel in the result of the core melting. This leak appeared to release most of the nuclear contaminants from the plant[28]. In Unit 4, the water level in the core was restored, after dropping 1.2 metres, due to a water reservoir that was located at the top of the Unit 4 building, resulting in the core not melting and allowing for the decommissioning process to begin immediately after the incident[28].

3.3.2 Generation III+ Developments

Following the Fukushima Daiichi incident, nuclear reactor safety was reevaluated. This introduced the development of Generation III+ reactors. These reactors take into account the failed or insufficient safety features of the Fukushima reactors and upgrade the previous Generation III reactors to new reactor standards [29]. Some of the upgrades implemented were the capability to maintain power plant safety after natural disasters such as tornadoes and tsunamis, the ability to deal with core damage in the event of a serious natural disaster and the ability to deal with the reactor in the event of power loss. Another safety feature that was implemented is improved "passive safety", first introduced in the Generation III reactors. This removes the requirement for an operator to function and can automatically detect when the reactor needs cooling or needs to be shut down. Any further reactors such as the proposed Generation IV reactors will utilise and build upon these developments.

As of November 2023, there are currently 62 reactors under construction, 111 planned reactors and 318 proposed reactors around the world [30]. These are all Generation III/III+ and Generation IV reactors, some of which will be for research and testing purposes, while others will be for main power grids. Currently, in China, there are 26 reactors under construction, 42 planned reactors and 154 proposed reactors [30]. For global warming, this is a significant benefit in the reduction of CO_2; China as of 2022 emits 27% of the global emissions through manufacturing and energy production [31].

If all proposed reactors are approved and planned reactors built there will be an estimated 0.53 Tera-Watts of power added to the worlds energy production every year [30]. As of 2022 the worlds energy consumption is estimated at 6.78 Tera-Watts, with the 440 reactors that are already in operation producing an estimate of 390 Giga-Watts [30], so an additional $\sim 8\%$ of the world's energy supply would come from these nuclear sources.

4 Generation IV Reactor Designs

4.1 Generation IV International Forum

In search of a safer and more efficient nuclear reactor the Generation IV International Forum (GIF) was formed in 2001. Its aim was to test the feasibility and performance of a new generation of rectors and their implementation into energy grids by 2030 [30]. The Forum considered many new theoretical designs for future reactors and picked the ones that met one or more of a specified group of criteria. For any reactor to qualify they had to be: more efficient, have the ability to produce hydrogen, reduce nuclear waste, easier to handle, more cost effective, or include improved safety features.

After evaluating all the theoretical designs, six reactors were picked: The Gas-Cooled Fast Reactor (GFR), Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium-Cooled Fast Reactor (SFR), Supercritical Water Cooled Reactor (SCWR) and The Very-High Temperature Reactor (VHTR). The GRFs, LFRs and SFRs are classified as fast reactors, while the SCWRs, VHTRs are classed as thermal reactors. MSRs have both a fast and thermal variant [32].

A further proposition paper was released in 2010 [33] that suggested the use of thorium within Generation IV nuclear reactors by combining the naturally abundant ^{232}Th, instead of ^{238}U, with ^{233}U. This would reduce the amount of enriched ^{238}U that is currently required for Generation IV reactors. The downside of ^{232}Th is the reduced amount of transuranics (elements with atomic number greater than Uranium). This would require an increase of ^{233}U enriched uranium to run the reactors which is a serious concern for nuclear proliferation.

All the reactors have been designed such that they run at much higher temperatures than the previous generations. Reactors can be considered as heat engines where the efficiency (η) is determined by the heat input into the system (Q_H) and the heat transfer out of the system (Q_C), $\eta = 1 - \frac{Q_C}{Q_H}$, therefore with a reactor that produces more heat and with more effective coolants the overall efficiency will increase [34]. This allows for an increased production of electricity from the nuclear fuel in addition to more heat being available for other industrial purposes. These purposes include production of hydrogen through electrolysis, district heating, seawater desalination, and methane reforming. The main issues associated with the construction and testing of these reactors are due to engineering restrictions. These include some coolants having corrosive properties, coolants changing chemical properties at different temperatures and pressures, and the manufacturing of materials that will not chemically interact with the reactor coolant [35].

4.2 Fast Reactors and Breeders

In section 2.5, the idea of fast and thermal neutrons was introduced but now we will briefly consider the implications this has on reactor designs. Older generation reactors primarily use thermal neutrons but with 4 out of 6 of the proposed Gen IV reactors being fast neutron reactors, it is clear that this is an important development in the field. This is not new technology, with papers on the subject dating back to the 1950s [36], however it is only recently that these have become potential systems for commercial reactors.

Fast reactors remove the neutron-moderating material that is present in the older generation thermal neutron reactors. While this reduces the cross section of the chain reaction continuing within a fast reactor, when a fast neutron does hit a nucleus, it will almost always fission. This is due to the increased kinetic energy being absorbed by the nucleus, which makes it more likely to overcome the potential barrier. Figure 9 illustrates this for ^{235}U and ^{238}U. Fast reactors are able to make use of a wider variety of fuels. While the fast reactor was originally designed to use uranium fuel more efficiently than older reactors, they have since started to use plutonium as the main fuel to ensure there is a high enough concentration of fissile material. The advantages of plutonium fuels are that they have a higher fissile cross-section and there is a larger number of neutrons produced per fission event. The current fast neutron reactors are mostly "fast breeder reactors" that output more ^{239}Pu than the amount spent. Each ^{239}Pu fission produces 25% more neutrons than a ^{238}U fission which is how a sufficient number of neutrons is maintained. Subsequently, there are also enough neutrons left over to be captured by a uranium blanket surrounding the core creating ^{239}U which can then beta decay to more ^{239}Pu fuel [37].

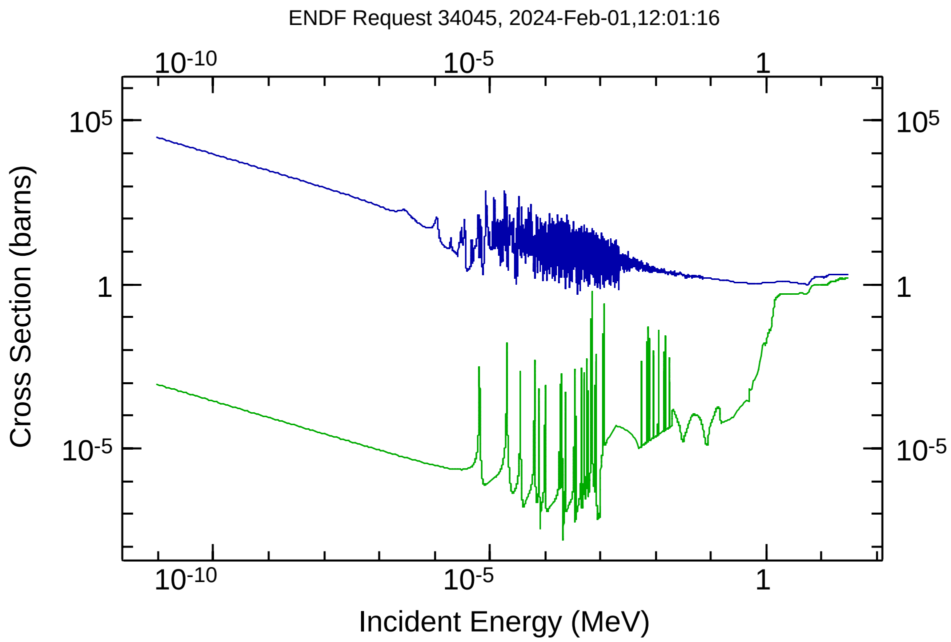

Figure 9: Graph generated on 1/2/2024 from [38]. The cross section of neutron-induced fission in ^{235}U (Top, Blue) and ^{238}U (Bottom, Green). In the thermal neutron regime, it can be seen that the fission cross section for ^{238}U is much lower than that of ^{235}U since it is a more stable nuclei. However, it shows that in the fast neutron regime, both isotopes have nearly the same likelihood of fission, showing that fast reactors can use more unconventional fuels. ^{235}U is a fuel better suited to thermal reactors, however it is less abundant than ^{238}U.

Removal of the moderating material allows for fast reactors to have smaller cores and higher power density. The main challenge for fast neutron nuclear reactors is to efficiently cool them, which is a problem that the Gen IV designs hope to address.

4.3 Design 1: Gas-cooled fast reactors

4.3.1 Gas Cooled Reactors

Gas-Cooled Fast Reactors (GFRs) are helium-cooled reactors that operate at high temperatures (800-850°C) and pressures (7-15MPa) [39]. The proposed design has a 1200MW output while also maintaining a constant amount of fuel by ensuring the breeding rate is equal to (or greater than) the usage rate. The electrical energy can be taken out of the core using an indirect helium cycle on the primary circuit, which powers a gas turbine on the secondary circuit through a process known as the Brayton

Cycle [14] and a steam cycle on the tertiary circuit [39]. Figure 10 shows a schematic diagram of a GFR reactor.

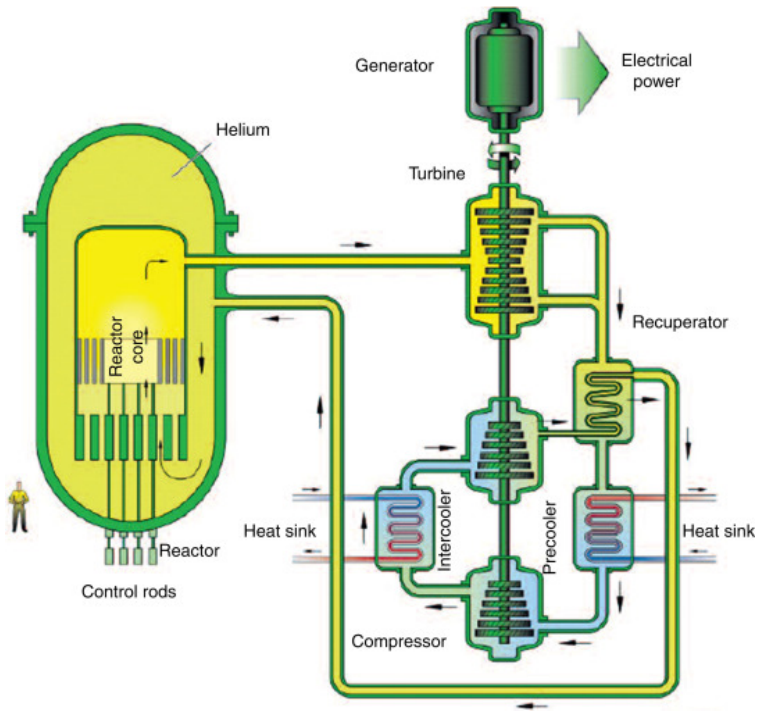

Figure 10: Figure from [40]. Diagram of a potential GFR. The reactor can be seen on the left of the diagram, surrounded by the pressurised helium coolant. On the right are the secondary and tertiary cycles that produce the electricity from these reactors. These additional cycles do however make the system larger than most of the other proposed designs.

The nitride or carbide fuels could be recycled onsite through reprocessing, and the produced actinides can be recycled repeatedly to reduce the long-lived waste [41]. Using helium as a coolant provides many benefits due to its physical properties, inertness and lack of decay modes. The physical properties ensure that the coolant does not undergo a phase change during the operation of the reactor. Since helium has a doubly magic nucleus, it has a very low neutron capture cross section, so it will not become irradiated by the core. Since helium is an inert noble gas, there is no interaction between the coolant and any part of the system including the graphite moderator, fuels or the coolant vessels [42].

A second GFR design was proposed at the GIF summit that runs at 600°C - 650°C with a helium-cooled primary circuit and a supercritical CO_2 secondary system. This reduces the issues with metals and fuels at such high temperatures, however less research has been done regarding this design [39]. Currently, there are no gas-cooled reactors of either variant in use, though there is one being planned by Euratom [39].

4.4 Design 2: Lead-cooled fast reactors

The second proposed design from the GIF conference was Lead-Cooled Fast Reactors (LFRs). The key component of this design is the lead or lead-bismuth liquid metal that cools the system through convection at atmospheric pressure [39]. The submitted designs are incredibly flexible with the ability to use many different fuels (metals or nitrides). These designs can also burn actinides that are produced by the older generation light water reactors. These designs are based on current reactors in Russia, the USA, Japan and Europe [43]. The designs are estimated to be in use by 2025 at a temperature around 550°C, but work is being done to get a larger output from reactors operating at 800°C in use by 2040 [39]. The higher temperature reactors do require research into materials to prevent lead corrosion [44], but they would allow for hydrogen production. These materials are currently one of the two main research focuses surrounding these reactors, with the other being fuels [39].

Adding to the flexibility of these designs, there are three proposed sizes with different uses. The smallest of these are "battery" reactors with 15-20 year life spans for use in small electrical grids or developing countries. Secondly, there are medium-sized modular designs with 300-400MW outputs. Finally, there are large single-plant reactors capable of outputting around 1400MW [39]. For the smaller reactors to have longer lifespans, they must have a positive neutron economy and potentially act as breeders to produce their own fuel [43]. This shows one situation where using fast reactors is beneficial as they are better suited to be used as breeders (Sec. 4.2). These smaller reactors are cheaper than the single-plant ones, making them more economically viable for developing countries which is one of the aims of the Gen IV reactors.

4.4.1 Safety and Sustainability

The use of lead or lead-bismuth mixtures makes these designs safer than previous generation water-based reactors. As mentioned above, LFRs are able to run at near atmospheric pressures which is due to the high boiling point of the coolant, so pressure is not needed to keep it in the liquid phase. Furthermore, the coolants are relatively inert and combined with low pressures required this provides a good degree of "passive safety" in the event of a disaster [43]. Lead is also a readily available element, so the sustainability of these reactors is quite high [43].

The inertness and availability of lead combined with the high boiling point also have a benefit to the economical viability of LFRs. Since the coolant is not going to boil off, there is no chance of complete loss of coolant which increases safety while also meaning lost coolant does not need to be replaced. The chemical inertness also means the reactors do not need extra circuits to keep it separate from other coolant systems as it will not react with them. This means that two more of the GIF criteria, reactor designs being safe and sustainable, are met by LFRs.

4.5 Design 3: Very-High Temperature Reactor

The very-high temperature reactor (VHTR) can be thought of as a high temperature, thermal neutron variant of the gas-cooled reactor. VHTRs use a carbon-moderated core with a once-through fuel cycle and aim to have output temperatures of ~ 1000°C, which makes them highly favourable for providing clean heat for industrial processes or hydrogen production [42].

The technical basis for the VHTR is the high-temperature gas-cooled reactor (HTGR), a design which has been extensively tested since the 1960s with experimental reactors such as the UK's Dragon reactor [45]. These HTGRs, similar to the Gen IV gas-cooled reactors, use helium gas as a coolant since it has a low reactivity even at the high temperatures targeted, as well as minimal interaction with radiation [42]. VHTRs aim to develop this technology and to push the temperatures achieved by HTGRs even higher.

There are two main configurations of the VHTR under development, each with its own distinct fuel structures. These are the pebble-bed and prismatic block designs, both of which utilise ceramic-coated fuel particles, with all currently operational HTGRs of this type using TRISO (tristructural-isotropic) fuel particles [46]. These particles (of diameter ~ 1 mm) consist of a central pellet of fissile material which is coated in four layers of different materials [47], see Figure 11, designed to retain fission products and protect against fuel degradation at the very high temperatures targeted in VHTRs.

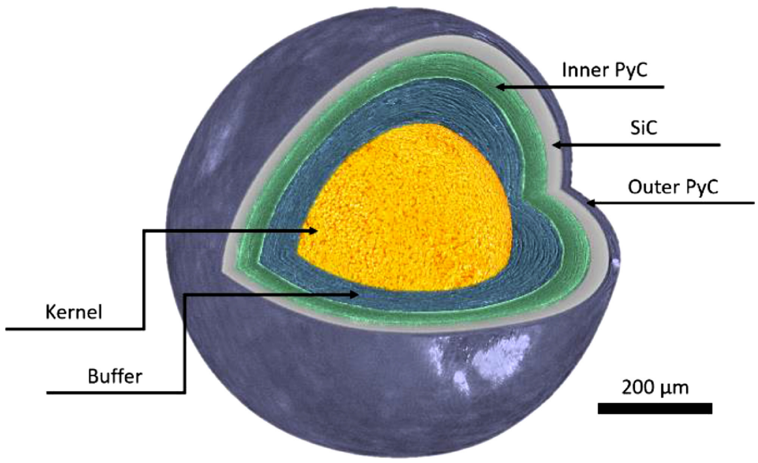

Figure 11: Figure from [47]. X-ray CT imaged and 3D rendered TRISO fuel particle, showing a central kernel of fissile fuel (commonly UO_2) coated with layers of a carbon buffer, pyrolytic carbon (PyC), and silicon carbide (SiC). These coatings allow for radioactive decay products to be contained within the casing and provide structural stability at very high temperatures.

4.5.1 Pebble-Bed Reactor Core

In the pebble bed design, thousands of TRISO particles are embedded in spheres of pyrolytic carbon (graphite with additional covalent bonding between each layer) of diameter $\sim 6\,\mathrm{cm}$ to create "pebbles" of which thousands are amassed to create the reactor core, see Figure 12. This fuel design has a number of advantages compared to traditional fuel rods, with one being that it allows the fuel to be much more mobile - old fuel pebbles can be extracted from the bottom of the core with spent pebbles sorted and disposed of, while new pebbles can be added from the top [48].

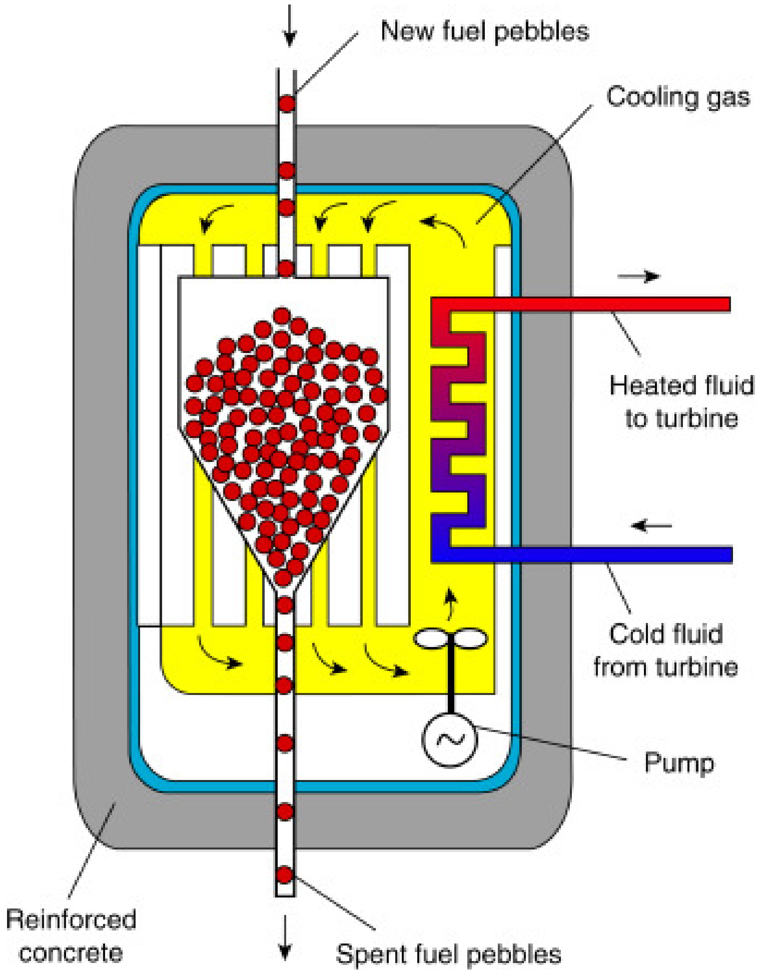

Figure 12: Figure from [48]. A rough schematic of a Pebble-Bed reactor design. Fresh pebbles can be loaded into the reactor from the top of the reactor core, and old pebbles can be extracted from the bottom. Spent pebbles can then be sorted and disposed of while usable pebbles are cycled back into the reactor.

Since each pebble only contains $\sim 9\,\mathrm{g}$ of uranium [49], the power density of a pebble-bed reactor is much lower than that of traditional reactors, meaning even with a total loss of coolant the maximum temperature that could possibly be achieved would still be low enough for radioactive products to be contained by the TRISO particles [50].

This means that even if an immediate accident response was impossible, the reactor would prevent environmental harm for significantly longer than current reactors. The main concerns with this design are that the carbon casing used for the pebbles is flammable, should there be a breach of air into the core, and radioactive dust can be formed by movement of the pebbles which if not managed can contaminate the helium coolant [51]. The technology was first demonstrated in Germany in 1966, and two pebble-bed reactors are currently operational in China [52].

4.5.2 Prismatic Block Reactor Core

The main alternative to the pebble-bed reactor design is the “prismatic block” design, which is more closely related to a traditional reactor core. In this design, the TRISO particles are sintered with pyrolytic carbon into cylindrical rods which are assembled to form fuel rods. These are then loaded into circular cutouts in a graphite block, which is used to form the reactor core [50], see Figure 13. The coolant gas can be run through the blocks in circular cutouts similar to those used to hold the fuel. The Japanese High-Temperature Test Reactor utilises this design variant.

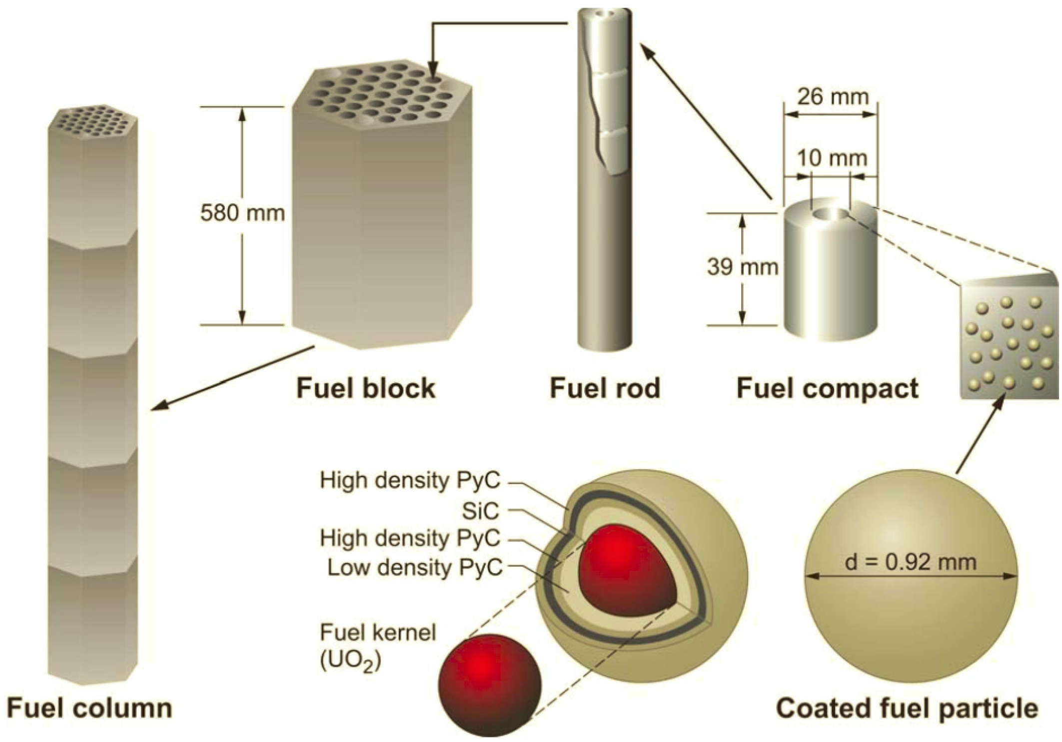

Figure 13: Figure from [53]. Diagram showing how TRISO particles are sintered into modular pellets of fuel, which are used to assemble fuel rods. These are loaded into modular fuel blocks, of which several are stacked to form fuel columns and the reactor core. Extra channels are used to run coolant through the fuel columns or for the insertion of control rods.

4.5.3 Safety

Despite having the highest operating temperature of all Gen IV reactors, the VHTR is an extremely safe design due to its use of helium gas and ceramic-coated fuel. Like the gas-cooled reactor, the use of helium eliminates the possibility of a hydrogen explosion by removing water from the reactor core. The coated fuel particles also allow for easier fuel transportation and can contain fission products within their casing, which provides an immediate containment for spent fuel, requiring minimal additional processing [51].

4.6 Design 4: Sodium-cooled fast reactors

Sodium-Cooled Fast Reactors (SFRs) were also considered at the GIF summit. These reactors have proven to be effective with over 390 years of combined reactor running time across eight countries. This made it the primary design of interest during the summit, and it has since remained as a promising design with significant research being put into it. SFRs use liquid sodium as a coolant which has the benefit of only needing small volumes of coolants and low (near atmospheric) pressures to produce high power densities. Figure 14 shows an example of how these reactors are designed.

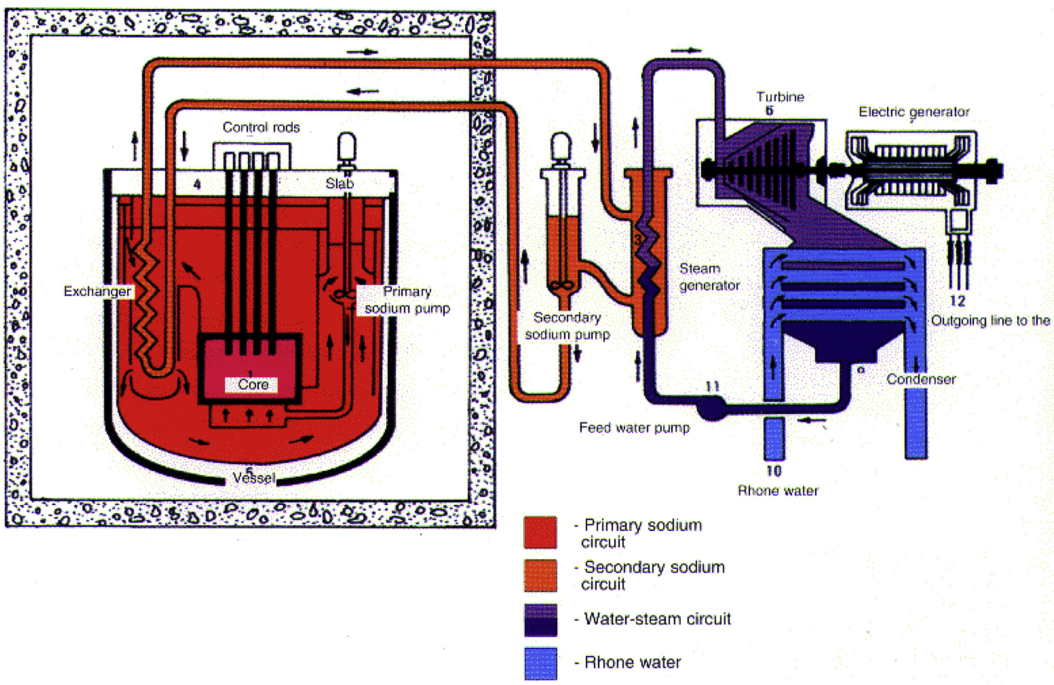

Figure 14: Figure from [54]. Diagram of an SFR that is part of the Phénix plant in France. On the left is the primary reactor, surrounded by the sodium coolant that is being pumped around it. The right half of the diagram shows how the heat from the reactor is used to create steam to turn a turbine and generate electricity.

These reactors typically use a depleted uranium fuel matrix with a variety of fuels including oxides, carbides, nitrides and metallic fuels being used in different reactors [55]. The liquid sodium coolant is kept at around 500°C which is much lower than the boiling point of sodium allowing for the reactors to be operated at low pressures. The primary concern of these systems is the reactivity of sodium with air and water so methods must be in place to limit interactions with water coolant and the environment. In extreme cases such as Fukushima-type disasters, the reactivity could greatly increase the danger of the event.

As with the LFRs, there are three main designs being considered. Firstly, there is a small 50-150MW output modular design using actinides mixed with a Uranium-Plutonium metal fuel. Secondly, there is a similar design using the same fuel but in a pool-type reactor that produces 300-1500MW output [56]; a pool-type reactor is one that has the fuel elements suspended in a pool of coolant. The final design is a mixed oxide (MOX) fuel loop-type reactor producing outputs of 600-1500MW. The loop-type reactors are more compact, cheaper and less likely to experience leakage, however they have not been experimented with as much as pool types [44].

Two reactors currently use this technology to provide energy to a grid in Beloyarsk, Russia: the BN-600 and BN-800 reactors. Other SFRs can be found in Japan, Korea, and the USA, with more being considered in the UK and India [39, 44]. Because of this technology being readily available and well-tested, it has been estimated that the SFRs could be in use more widely very soon. While the BN-800 reactor is connected to the electrical grid, it also serves as an experimental facility for testing types of fuels for use in fast reactors. Other applications of these reactor designs include hydrogen generation and removing salt from seawater [54].

4.7 Design 5: Supercritical Water-cooled Reactors

A supercritical water-cooled reactor is a proposed design for Generation IV reactors based on two proven technologies: boiling water reactors and supercritical fossil-fired burners. Both BWRs and SCWRs are LWRs with only one coolant loop. Figure 15 shows how similar a SCWR design is to a BWR. However, because SCWR has a single-phase coolant loop, it does not require multiple crucial components of a BWR, like jet pumps or steam separators. Replacing a two-phased coolant loop with a single-phased one and increasing the maximum temperature of the coolant improves the thermal efficiency of SCWR to an estimated 45% from 33% for other LWR designs [57].

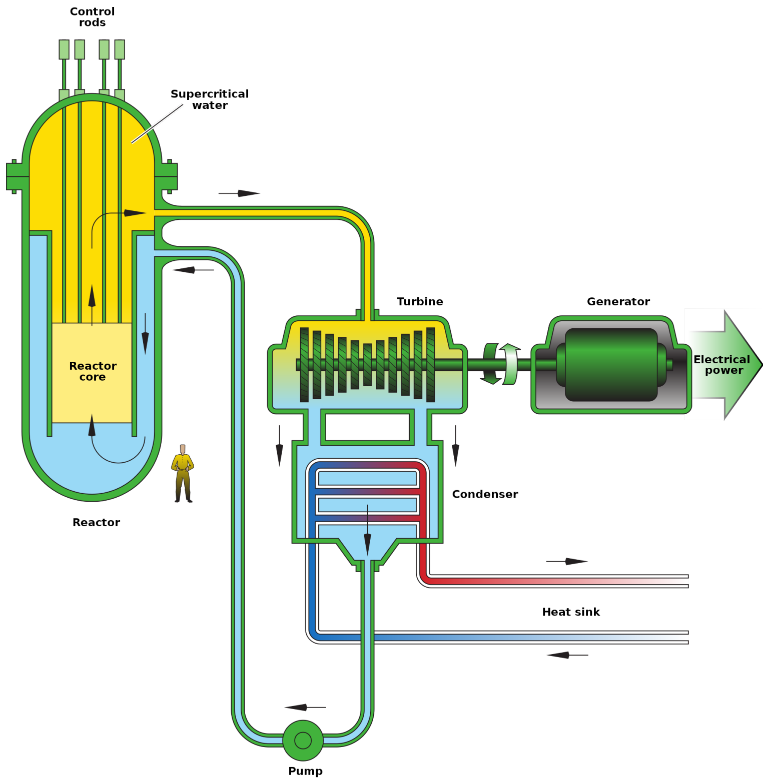

Figure 15: Figure adapted from [57]. Schematic diagram of an SCWR. The SCWR design is similar to that of a BWR. Both reactors feature only one coolant loop. However, in a SCWR, the pressure and the temperature inside the coolant loop reach 25 MPa and 500°C, respectively, significantly higher than in a BWR. Such high pressure ensures that the water in the coolant loop remains supercritical and does not separate into liquid and gaseous phases.

When constructing an SCWR, the main challenge is designing an appropriate core, as most other parts already exist. The technology for containing supercritical water at similar temperatures and pressures has been developed and is currently being used in fossil-fired burners. The containment design for a BWR can be used for an SCWR. For an SCWR to work efficiently, the coolant heat-up is estimated to be around 200°C. In contrast, current BWRs have a coolant heat-up of around 35°C. Using a current BWR's core to heat the coolant in a SCWR is impossible as the cladding material must be heated to unreasonably high temperatures [58].

In 2006, a consortium of 10 different companies and the Universities of Stockholm and Stuttgart created a design concept for an SCWR called the High Performance Light Water Reactor (HPLWR). The core design for the HPLWR was inspired by coal-fired boilers, where the coolant is heated up by about 200°C in multiple stages. Instead of a single-stage coolant heat-up used in most LWRs, the HPLWR heats its coolant in three stages. The first stage is an evaporator, where the coolant is transformed from liquid-like to steam-like conditions at supercritical pressure. After the evaporator, the coolant is sent through two consecutive superheaters. The main difference with a regular LWR, where the coolant steadily rises under thermal expansion, is that in the HPLWR, the coolant is intensively mixed between these stages while heated. The thermal efficiency of the HPLWR is simulated to be 44%, as expected for a SCWR. Despite having a significantly more complex core design than other LWRs, the HPLWR's construction cost is lower: 1000 €/kWe for HPLWR versus 1200 €/kWe for other LWRs, since there are significantly fewer components in SCWRs than in other LWRs [58].

4.8 Design 6: Molten Salt Reactor

Molten Salt Reactors (MSRs) offer a departure from the standard concept of the nuclear reactor by utilising a fluoride salt compound in the reactor core, typically as a fuel carrier or coolant. Having the fuel dispersed in such a salt compound offers a number of advantages compared to traditional reactors, including the possibility of continuous maintenance and refueling without shutdown, as well as heightened safety [59].

While initially proposed as a single Gen IV design variant, research into the molten salt reactor has since branched into two designs, the Molten Salt Fast Reactor (MSFR) and the Advanced High-Temperature Reactor (AHTR). The MSFR utilises a fuel-salt mixture with a closed fuel cycle, while the AHTR uses a fluoride salt coolant and solid fuel [39].

4.8.1 Advanced High-Temperature Reactor

The advanced high-temperature reactor (AHTR) makes use of a number of technologies developed for other Gen IV reactors, including coated fuel particles and molten salt, which in this variant is used only as a coolant [60].

Since the molten salt coolant has a low cross section for neutron absorption [61], similar to a helium coolant, the reactor core bears many similarities to the helium-cooled VHTR. It makes use of the same kind of coated fuel particles which, as outlined in Section 4.5, are beneficial in reactors operating at very high temperatures. With the use of this technology, the AHTR is expected to reach temperatures of 750°C to 1000°C [61], making them viable for hydrogen production. The fissile fuel itself could also be supplied from nuclear waste generated by current reactors, but this has not been well tested for use with coated fuel particles [62]. Other variants of the AHTR where the fuel matrix takes a different shape, analogous to the pebble-bed VHTR, are also being investigated [61].

The key distinction from the VHTR is that AHTRs utilise a molten salt coolant in a pool reactor configuration instead of helium gas, see Figure 16. Molten salt remains a liquid at atmospheric pressure between 400°C and 1400°C [63], which encompasses targeted operating temperatures, meaning AHTRs can operate at atmospheric pressure [62]. The use of molten salt brings about its own challenges, however as these salts are highly corrosive at high temperatures, and so for the reactors to have a substantial lifetime, materials which can endure these conditions are required.

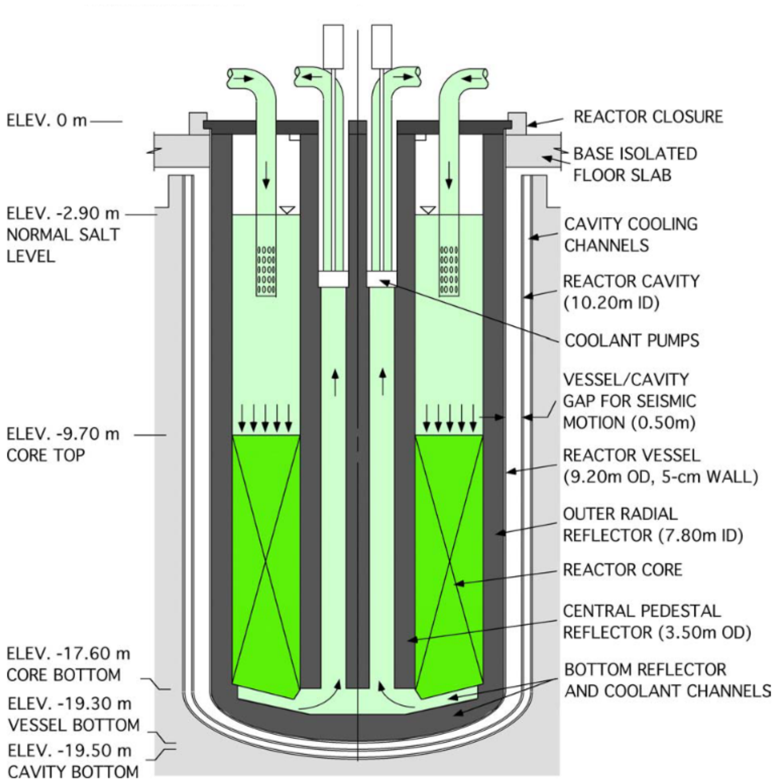

Figure 16: Figure from [61]. Conceptual design of an advanced high-temperature reactor, demonstrating its pool configuration. In this design, the coated fuel particles are embedded in a graphite matrix submerged in the salt coolant, which is continuously pumped through the core, similar to the prismatic block variant of the VHTR.

4.8.2 Molten Salt Fast Reactor

Compared to the AHTR, the molten salt fast reactor (MSFR) is the more conventional molten salt reactor, using a fuel salt as the carrier of the fissile fuel. The fuel salt is typically fluorine-based [59], with fissile fuel dissolved throughout. This is pumped through the reactor to reach criticality while passing through the core.

The core itself has no internal structure and is simply a volume of $\sim 18\,\mathrm{m}^3$ of the fuel salt [59], it has no moderator in order to achieve a fast neutron spectrum. This enables the MSFR to act as a breeder reactor if suitable material is supplied in the salt and enables it to be used to "burn off" actinide waste generated by other reactors. The fuel salt can accumulate waste, however, especially if used in a burner reactor, and so needs to be continually reprocessed at an external plant to prevent excess waste poisoning the reaction [59].

While some more exotic reactor designs use the same salt mixture as both a fuel and coolant salt, the designs under consideration today mainly utilise two different salts, with the second salt isolated from the core to play the role of the coolant, see Figure 17. The coolant salt can then be used to transfer the heat to some industrial process or to a third Brayton gas cycle to generate electricity. Having two distinct salt loops prevents radioactive material from circulating and contaminating the full reactor, which would arise if the radioactive fuel salt were to circulate the complete loop.

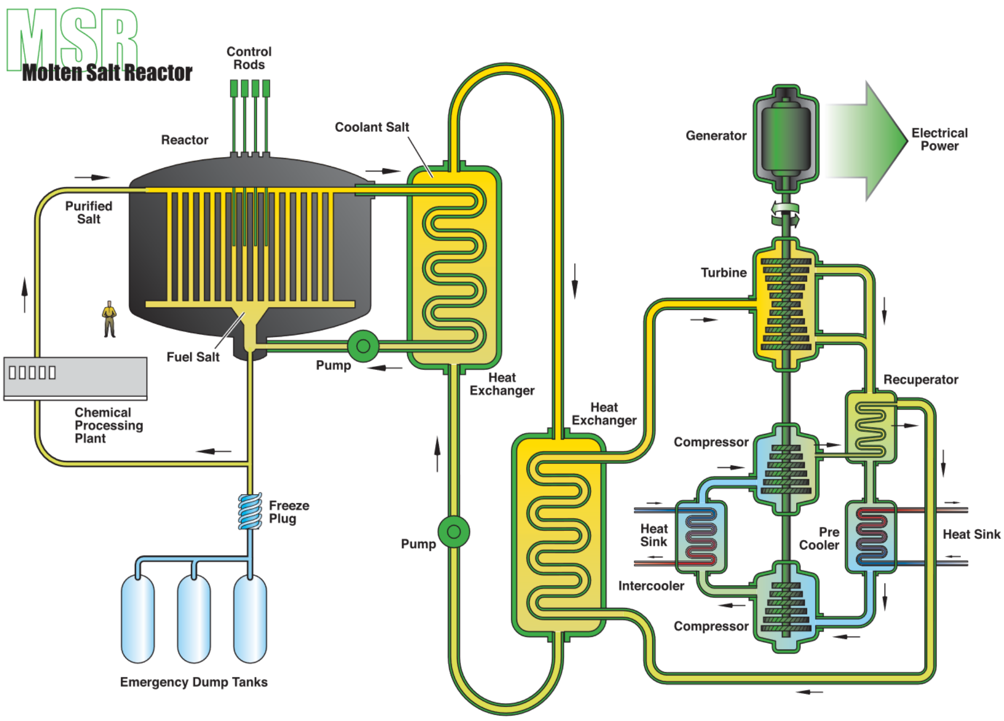

Figure 17: Figure from [64]. Diagram of a "conventional" molten salt reactor, using a primary fuel salt loop and secondary coolant salt loop. The fuel salt passes through the reactor core where it reaches criticality, and is continually processed at an external chemical plant to remove waste products from the salt. The coolant salt does not come into direct contact with the fuel salt, and in this diagram, it takes the heat to a tertiary gas Brayton cycle for electricity generation.

Like the AHTR, the physical properties of the molten salt allow the MSFR to operate at near-atmospheric pressure, in particular the relatively high melting point of the fuel salt ($\sim 400^{\circ}$C) means that in the event of an emergency, the salt can be drained from the reactor core and made to solidify very quickly [65], stopping the reaction. This can be achieved through the use of freeze valves which automatically melt (draining the salt) if there is a loss of power or if the fuel salt breaches some critical temperature.

5 Comparison of Generation IV Designs

Reactor Types	Neutron Spectrum	Temperature (°C)	Pressure	Output (MW)
Gas-Cooled Reactor	Fast	800 – 850	High	1200
Lead-Cooled Reactor	Fast	~ 550	Low	20 - 1400
Very-High Temperature Reactor	Thermal	900 – 1000	High	250 - 300
Sodium-Cooled Reactor	Fast	500 – 550	Low	50-1500
Supercritical Water-Cooled Reactor	Fast / Thermal	~ 500	Very High	300-1500
Molten Salt Reactor	Fast / Thermal	700 – 1000	Low	1000-1500

Table 1: Overview of the specifications for each Generation IV reactor type. The data in the table is taken from throughout the report and also from [39]. As discussed in Section 2.8, the temperature needed for hydrogen production is around 800°C, so from the table above, the reactors capable of hydrogen production can be identified. Here, high pressure is regarded as one in the range of 7 MPa to 15 MPa. It is also important to note that the wide output power ranges are due to some reactors having multiple designs such as the "battery" LFRs.

Table 1 summarises the relevant general properties of each Gen IV reactor design. Each of the reactors discussed has its own merits, allowing for each design to have situations where it may work better. For reactors needing to be replaced or built soon, the most suitable designs to utilise would be the Sodium-cooled Fast Reactors, Supercritical Water-cooled Reactors or Very High Temperature Reactors. This is because these designs have been proven to be operational and are very closely related to existing technologies. These technologies do have their own drawbacks however. SFRs use sodium that can react with any air or water in the environment, SCWRs have a large difference in temperature between the incoming and outgoing coolant, so a core needs to be designed to properly heat the coolant, and VHTRs can't reuse spent fuel and require materials that can withstand the near 1000°C temperatures.

Some of the more experimental reactors may be more suited for use later in the future once the technologies have been refined a bit more. Molten Salt Reactors and Lead-cooled Fast Reactors are prime candidates for this. The use of liquid fuel in

MSRs means that the concentration of the radioactive isotopes can be easily adjusted without excessive downtime in energy production. The reactor can take many different fuels, making it a good burner reactor to use waste products from older reactors, and the waste from MSRs is easily recyclable. These reactors do however need a reprocessing plant on site to do this recycling, and the salt itself can transmute from the radiation leading to unexpected interactions with the materials in the reactor. LFRs can solve some of these problems, the lead coolant is inert and less likely to transmute. It also has a very high boiling point meaning there is no need for it to be pressurised, and the coolant is a relatively abundant metal. The other main advantages to LFRs are the flexibility in the size of the reactors and the fuel they can use, making them incredibly adaptable. The issue with these reactors is that they can only really be used to produce electricity as they do not run at temperatures high enough for hydrogen production. The smaller "battery" type reactors only have lifespans of 15-20 years which may mean that the returns are not as good when comparing to the much larger plant reactors that can run for much longer.

The final reactor considered was the Gas-cooled Fast Reactor. While it does have the advantages of using inert helium coolant, this must be pressurised to prevent boiling off which reduces the safety of the reactor. These reactors can produce hydrogen and act as breeder reactors but neither of these advantages are unique to this design. GFRs also use multiple circuits to produce usable energy which takes a lot of space, and there is no working version of this reactor currently in use. For these reasons, we feel that GFRs are the least suitable Gen IV candidate.

As a whole, Gen IV reactors do provide many additional benefits when compared with the current Gen III+ reactors. It is therefore a worthwhile investment to research these newer designs instead of just building more of the previous generation designs. Gen IV promises two main improvements. The first improvement of Gen IV is the utilisation of fast reactors which can reduce the lifetime of the waste products (potentially to centuries instead of millennia), increase the yield from a given mass of fuel and have increased safety precautions [66]. Secondly, the potential use of small LFR reactor systems would mean less investment is needed to get the benefits of nuclear power, making it more accessible to everyone.

Finally, we must consider renewable energy sources and fusion. These are both potential alternatives to fossil fuels and nuclear fission. Renewables have been heavily invested in over the recent years and as previously mentioned, provided over half of the UK's energy in 2023 [2]. These provide clean energy like nuclear reactors but they don't carry the same stigma of being dangerous as nuclear power does. Nuclear fusion could also provide clean energy but the technology available for this still needs years of development before it is viable. Using only one energy source to completely supply the world's energy in the future is highly unlikely, so a combination of both nuclear fission reactors and renewable energy sources is a highly probable outcome.

6 Conclusion

While the current Gen III+ reactors are well suited for the current nuclear environment, they can still be improved upon. The Gen IV reactors were proposed at the GIF summit to increase safety, reduce waste, make handling and transportation easier and make them more economically viable. At this summit, they decided on six reactor designs that meet these criteria: Gas-Cooled Fast Reactors, Lead-Cooled Fast Reactors, Very High Temperature Reactors, Sodium Cooled Fast Reactors, Supercritical Water Reactors and Molten Salt Reactors. As a whole, these reactors provide many benefits over the older generations. The use of Fast Reactors allows for reduced waste, increased fuel efficiency and the ability to use a wider variety of fuels. Secondly, the adaptability of certain reactors to work in smaller sizes allows for more economic viability. Having more reactors connected to the electrical grid means there are fewer issues if one reactor stops producing energy, compared to there only being a handful of large reactors which each produce a significant portion of energy.

Within the Gen IV reactors, each one has their own situations where they would thrive. We feel that for getting reactors built soon, ones based on existing designs would be better such as SFRs, SCWRs and VHTRs. However given enough research designs like the MSRs or LFRs, may be better suited for the future.

We cannot fully say with certainty that nuclear fission is the way forward, or that one design is better than the other, however, we do feel that Gen IV reactors show significant promise. It is likely that in the future, Gen IV reactors will operate in cooperation other power sources such as renewables.

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