

# Design Review of future UK Civil PWRs

## Assessment of EDF UK EPR and RR SMR designs in 2025

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### SUMMARY

- Early assessment of EDF UK European Pressurised Reactor (UK EPR) and the Rolls Royce Small Modular Reactor (RR SMR) designs in 2025.
- This study conducts an overall plant design review using Safety Case documentation mostly to evaluate plant characteristics, primary reactor systems, secondary power generation systems and safety systems.
- Generates a base understanding of modern nuclear reactor designs in the United Kingdom.

### 1. BACKGROUND

The UK's nuclear power landscape is due to shift from being dominated by designs of gas cooled reactors, moving to Light Water Reactor technology, considering information from World Nuclear Association [1].

Existing UK-grown Advanced Gas-Cooled Reactor (AGR) technology is reaching the end of its operational lifespan in 2030, from its Cold War period rapid development and deployment. Meanwhile, various attempts have been made to adopt LWRs, starting with Dungeness and then to the UK Standard PWR Power Station Design built at Sizewell B. Now a stream of Pressurised Water Reactors (PWRs) are under construction and under regulatory design assessment are due to dominate the landscape (see Table 1, Table 2 and Table 3).

A review of these designs will provide a benchmark for further investigation, including validating design standardisation and forming conclusions about future skills of the workforce in the UK. This is important because UK nuclear power projects have failed to replicate designs at scale, noting that seven AGR twin unit plants involve four different designs, and that a series of ten PWR designs were originally promised by the UK government yet only Sizewell B was constructed.

AGR	Hartlepool 1
	Hartlepool 2
	Heysham A 1
	Heysham A 2
	Heysham B 1
	Heysham B 2
	Torness 1
Torness 2	
PWR	Sizewell B

**TABLE 1: Operating Reactors in United Kingdom (2024) [1]**

PWR	Bradwell B
	Hinkley Point C
	Sizewell C
<i>PWR Cancelled</i>	Moorside
<i>BWR Cancelled</i>	Oldbury
<i>Sodium Cooled Fast Reactor Cancelled</i>	Sellafield
<i>Candu Cancelled</i>	Sellafield
<i>BWR Cancelled</i>	Wylfa Newydd

**TABLE 2: Under Construction Reactors in United Kingdom (2024) [1]**

BWR	GE Hitachi BWRX-300
	GE Hitachi UK ABWR
PWR	EDF UK EPR
	Holtec International SMR-300
	General Nuclear System Ltd UK HPR1000
	Rolls Royce 470MW SMR
	Westinghouse AP1000®

**TABLE 3: Reactor Generic Design Assessment (GDA) Submissions (2024) [2]**

## 2. INTRODUCTION

In this paper, a design review is conducted for UK EPR (design selected for use at Hinkley Point C and Sizewell C) and RR SMR (design selected for use at Wylfa).

The intent of this review is to develop on the ideas of Moore et al. [3], which was a safety focussed review. This review will perform a technology-focussed review of only these civil-specific case studies and across a greater scope of comparison.

The review covers primary reactor plant systems, secondary power generation systems and safety systems. The evaluation of reactor plant systems is conducted through the interrogation of safety functions and the methods that are in place to achieve those safety functions within each chapter. This covers fuel system, reactivity control, containment, heat removal from the reactor core (in normal operation, excluding Decay Heat Removal), production of steam, systems supporting the removal of heat from the core, steam and feed transfer, cooldown (during shutdown and methods supporting Decay Heat Removal) and emergency plant protection.

GDA submissions including Safety Case documentation forms the basis of reliable reactor plant systems information.

## 3. DESIGN REVIEW

### 3.1. Plant Characteristics

#### Safety functions for investigation:

- Fuel system – neutronic core design to generate heat energy.
- Reactivity control – to enable a nuclear chain reaction to be controlled or stopped under all circumstances.
- Containment – barriers for limiting radioactive material release.

#### 3.1.1. Fuel System

Both UK EPR and RR SMR have standard 17x17 fuel rod arrays, each fuelled with standard Uranium Dioxide (UO<sub>2</sub>) pellets within a zirconium alloy cladding [4] [5]. However, UK EPR design permits use of Mixed Oxide (MOX) fuel, with a core able to accommodate up to 50% of MOX1 fuel assemblies, and with some plant modifications, 100% MOX fuel assemblies [6]. This is underpinned by EDF's operational experience of using MOX in PWRs [7] and understanding the adaptations to accommodate this change.

Slight differences in enrichment are noted: UK EPR fuel enriched up to 5% [4], while RR SMR fuel is enriched up to 4.95% [5], which permits access to IAEA Low Enriched Uranium (LEU) Bank [8] (storage of material enriched up to nominally 4.95%) to assure fuel security in case of disruption of supplies of LEU.

UK EPR has a reactor power of 4,500 MWth [9]. It has a design life of 60 years and is intended for full power operation of up to 18 months before refuelling [10]. RR SMR has a reactor power of 1,358 MWth [5]. It also has a design life of 60 years and is intended for full power operation of up to 18 months before refuelling [11].

Having noted the differences in core makeup, the discrepancy in thermal power is related to the size of the core; UK EPR core contains double the number of fuel assemblies and 50% greater active core length. (241 fuel assemblies [4], while RR SMR core contains 121 fuel assemblies [11]. UK EPR core has 420 cm active core length [12], while RR SMR has 280.0 cm active core length [5]).

#### 3.1.2. Reactivity Control

Lamarsh and Baratta [13] state that the kinetic characteristics of the reactor core determine its response to changes in reactivity

caused by plant conditions or operator adjustments. Neutron interactions in the core determine the criticality of the reactor. The effective multiplication factor (*K<sub>eff</sub>*) mathematically expresses factors in the neutron lifecycle.

$$K_{eff} = \eta \epsilon p f P f P t$$

Neutrons that escape resonance absorption and remain in the core will be thermalised. *f* indicates how effectively thermal neutrons are absorbed in the fuel (number of thermal neutrons absorbed in the nuclear fuel per number of neutrons absorbed in all materials that make up the core).

The macroscopic thermal absorption cross-section ( $\Sigma_a$ ) is the total of cross sections for all absorbers:

$$\Sigma_a = \Sigma_a F + \Sigma_a M + \Sigma_a P + \Sigma_a CR + \Sigma_a B + \dots$$

$$f = \Sigma_a F / \Sigma_a$$

Each factor contributing to absorption of thermal neutrons within the core includes the fuel (F), moderator (M), poisons (P), control rods (CR) and boron (B).

Reactivity in both reactor cores is controlled by insertion and withdrawal of neutron absorbing control rods (dubbed 'mechanical shim') [4] [5]. Rod Cluster Control Assemblies (RCCAs) are now industry standard advanced control designs used in UK EPR and RR SMR, comprised of a group of neutron absorber rods fastened at the top end to a common spider assembly [Figure 1].

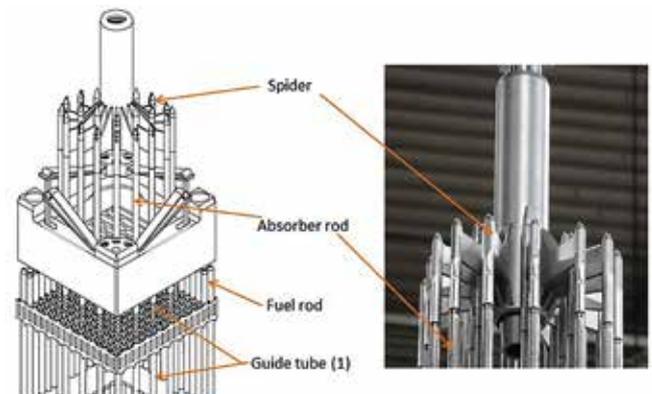


Figure 1: Standard design of AIC Rod Cluster Control Assembly [53]

Control RCCAs, silver/indium/cadmium (AIC) alloy absorbing material, compensate for the reactivity effects of the fuel and water temperature changes accompanying power level changes.

Shutdown RCCAs, boron carbide (B<sub>4</sub>C) absorber material, are fully withdrawn during powered operations, capable of making the core subcritical rapidly providing the majority of shutdown reactivity worth.

RR SMR use additional 'Grey Rods' made of stainless steel, absorbing less neutrons than other types of rods, used to control power peaking within the core and support transient control [5].

Only UK EPR controls slow reactivity changes with soluble boron in the reactor coolant as boric acid [14]. Increasing the concentration of enriched boric acid (dubbed 'chemical shim') adds new absorbing material to the core therefore decreasing the thermal utilisation factor. It does this via the Chemical and Volume Control System which has many safety functions including the controlled injection of water (dilution) or boric acid (boration), responding to signals from the reactor control system

or operator action to adjust the soluble poison content [15]. Boron compensates for all reactivity changes due to xenon transients – such as that following power changes or changes in rod cluster control position – and changes in moderator density and temperature – during warm up or cooldown.

RR SMR does not use soluble boron to control reactivity during normal operations. Instead, this feature is reserved as a safety system initiated upon the reactor failing to trip / SCRAM. This is consistent with Rolls Royce's research, development and experience producing soluble-boron-free (SBF) submarine PWRs for over fifty years [16], and several research articles [17] [18] and feasibility studies [19] [20] that describe SBF SMRs with optimised burnable neutron absorbers, optimised control rod design, and development of a secondary shutdown system.

### 3.1.3. Containment

The shielding and containment of radiation is of key safety significance to eliminate the dose risk to workers and the public and avoid the unplanned release of radioactive material into the environment. The containment systems and containment structures provide multiple levels of protection (INSAG-10 [21]) and are investigated in this chapter.

Containment characteristics include:

- There must be no direct leakage paths from the reactor building into the environment.
- Shielding designed to attenuate the energy of gamma waves and escaped neutrons, minimise irradiation damage to components.
- Accident sequences involving containment bypass (via steam generators or via circuits connected to the primary cooling system which exit the reactor building) should be practically eliminated, by design or by isolation.
- Containment atmosphere must be maintained to avoid over-pressurisation of the containment vessel and to reduce airborne activity inside the containment.
- Containment systems in operation during reactor plant power operation are maintained through hot shutdown and no longer required to maintain containment in cold shutdown.

Containment is primarily provided by the reactor building. Images of the containment cross sections can be seen in the safety case documents for UK EPR [9] and RR SMR [54]. The UK EPR reactor building comprises of a double concrete containment structure.

The inner concrete layer is a pre-stressed concrete dome, designed to withstand potential over pressure which could occur as the result of an accident, lined with welded steel plate sections covering the entire internal surface of the inner containment walls and floors, to maintain leak-tightness in the event of an accident. The outer containment is reinforced concrete which protects all contents of the reactor building from environmental hazards ranging from normal pressure and temperature deviations and fluid system loads, to extreme external loads [22].

RR SMR houses the reactor in a 60mm thick steel containment vessel which promotes leak tightness. This sits within the reactor building. The internal containment structure is not bolstered with concrete due to its thickness [23].

Both designs feature an annulus or interspace between the inner and outer containment layers, establishing another layer of protection. Leak tight penetrations cross the interspace provide

services to and from the reactor systems within the containment. The inner containment comprises electrical and mechanical penetrations, and non-safety critical fluid systems require isolation valves to activate shut automatically on containment breach.

The in-containment structures contribute to shielding and protection. UK EPR has concrete walls in the inner containment to divide dedicated areas for major reactor vessels and tanks. These safety zones protect the containment from any failure in the primary system (pipe whip or missiles) and reduce radiation in accessible zones during operation [9]. RR SMR has a similar arrangement of its containment internal structures; concrete walls and supports below the main floor level form the Reactor Pressure Vessel (RPV) cavity, supports for primary components and system and the base of refuelling pools and LOCA sumps [23].

Maintaining the containment atmosphere is achieved in the same way in both UK EPR and RR SMR designs in normal operation and in fault scenarios by air conditioning [22] [24]. Both UK EPR and RR SMR use standard hydrogen recombiners to provide an in-containment method of reducing hydrogen concentration below the lower flammability limit of 4% volume in air [25] and minimising severe accident hazard of hydrogen combustion that could challenge the integrity of containment. Chemical monitoring and alarms alert operators to parameters outside of defined limits.

## 3.2. PRIMARY REACTOR SYSTEMS

### Safety functions for investigation:

- Heat removal from the reactor core - produced from fission in the fuel transferred to coolant.
- Production of steam – useful steam to power turbines.
- Systems supporting the removal of heat from the core. – maintain within mechanical limits.

### 3.2.1 Heat Removal from the Reactor Core

The process of nuclear fission generates energy upon the splitting of large, unstable atoms. Approximately 200 MeV is produced per uranium fission event [26]. This energy manifests as heat generated in the core, which would cause the fuel cladding to buckle and the fuel to melt – known as a Loss of Coolant Accident (LOCA) in PWRs – if coolant was not present to provide a method of heat sink. In PWRs, water is used as a coolant, pressurised to prevent boiling within the core.

The purpose of the Reactor Coolant Circuit (Loop) is to remove the heat generated by fission in the reactor core by the continuous circulation of pressurised water through the core. This transports the heat to the Steam Generator (SG) where energy is transferred to secondary coolant and steam is produced for powering turbines. UK EPR plant efficiency is stated at 36% [10] while RR SMR plant efficiency is unavailable. RR SMR has three loops [27] while UK EPR has four [9]. The US NRC Reactor Concepts Manual cites Westinghouse civil designs, whereby it is observed that the number of loops positively correlates to the core size and power: plants with two loops (500MWe) (14x14 core), three loops (700-900MWe) (15x15 core), or four loops (950-1250MWe) (17x17 core) [28].

Under normal operating conditions, forced circulation through the core is provided by the reactor coolant pumps. For both UK EPR and RR SMR, if pumps are unavailable, convective flow of coolant is achieved, and residual heat is removed by 'natural

circulation' through the core. Natural circulation is achieved by a difference in density of the water when there is a heat source and heat sink. D'Auria and Galassi evaluate natural circulation, noting that the thermal driving head caused by the difference in density between two areas of fluid requires the correct geometry by locating a heat sink at a higher elevation than the heat source [29]. Figure 2 shows UK EPR and RR SMR loop layouts.

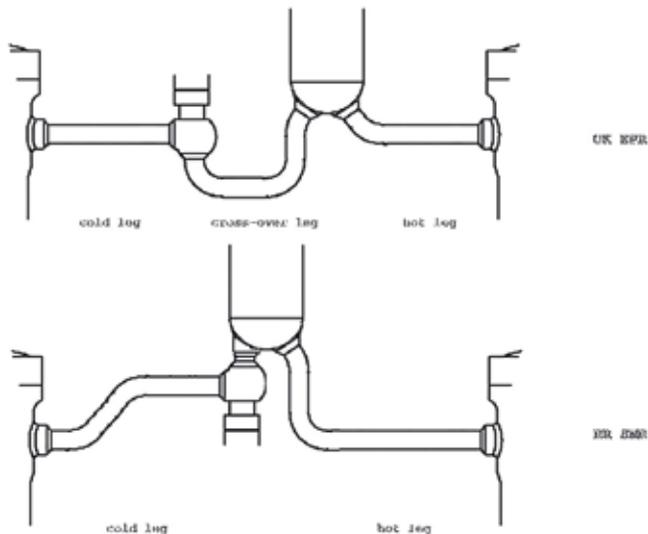


Figure 2: Loop Layouts

The SGs in both designs are located within the containment vessel in an elevated position relative to the RPV to provide a robust thermal driving head for flow in faulted operations. Both plants use SGs to cool down the plant to 120°C before a dedicated heat removal system is initiated [27] [30].

3.2.2. Production of Steam

Both designs use very similar vertical shell and inverted-U tube SGs to generate steam. Inside the outer shell are centrifugal moisture separators to dry the steam, which is subsequently transferred to the Main Steam System for onward distribution to the Turbine Island. However, the pre-heater design is different. Pre-heaters preferentially direct feedwater to the cold side of the tube bundle, to obtain higher steam pressure and increase steam system efficiency. Pre-heaters can be axial or crossflow; UK EPR utilises axial flow preheaters [30], whilst RR SMR uses integral crossflow preheaters [27]. In axial flow preheaters, the feedwater flow is parallel to the tubes, or axial. In crossflow preheaters, flow is perpendicular to the tubes [55].

3.2.3. Supporting Systems

Pressurising system

The pressuriser maintains coolant pressure above saturation pressure, with a pressurised steam bubble in the upper pressuriser maintained by controlled heating at a constant temperature and consequently a constant pressure. This allows temperatures above 100°C to be achieved in the reactor coolant, preventing boiling within the core [31]. A single pressuriser is used. To increase plant pressure, steam is generated by pressure-actuated

immersion-type electrical heaters contained within the lower section of the pressuriser. To reduce plant pressure, main coolant pump-induced spray condenses steam and reduces pressure.

The standard pressure control design illustrated in the US NRC Reactor Concepts Manual is shown in Figure 3. UK EPR closely follows this design, having three safety pressure relief valves (PRVs) and two dedicated severe accident PRVs that relieve to a pressure relief tank. UK EPR has three spray nozzles (two normal operation spray lines from Loop 3 cold and hot legs, one auxiliary spray) that penetrate the top of the pressuriser [30]. Whilst in RR SMR, two spray lines from cold legs of the reactor coolant circuit, each with their own spray initiation valve, converge and allow coolant to enter the top of the pressuriser via a single spray nozzle [27].

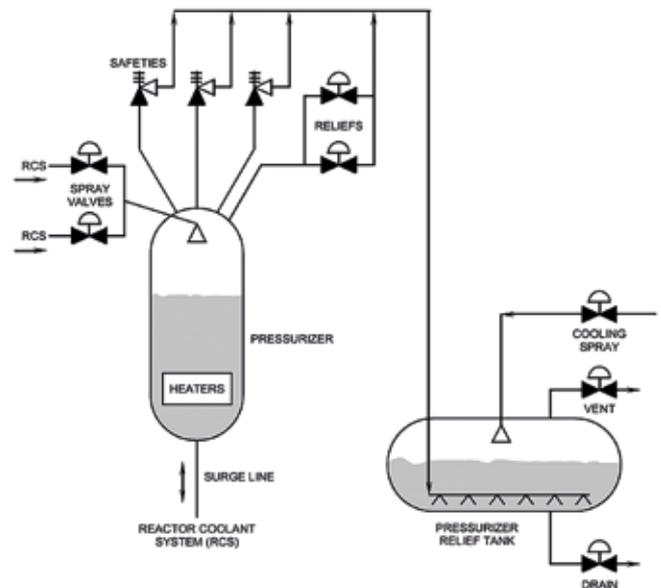


Figure 3: Pressuriser and Pressuriser Relief Tank [28]

RR SMR design has only two primary PRVs. According to Rolls Royce, two steam reliefs located on top of the pressuriser provides protection during power operations because each valve has 100% capacity to achieve primary circuit depressurisation [27]. Design simplification and flexibility is shown by using the in-containment refuelling pool as a receipt tank. In both designs, auxiliary spray is provided by the coolant make-up pumps.

UK EPR documents cite the size of their pressuriser to be 75 m³ [32]. The volume of RR SMR pressuriser is unavailable. A size comparison in relation to their plant power rating and pressuriser heater power rating would be important to investigate, specifically because a larger volume ensures better control of coolant volume transients without breaching Performance Related Design Bases Events (PRDBEs) (also referred to as Postulated Initiating Events (PIEs)) such as low pressuriser level or initiating overpressure protection.

Chemical and Volume Control System

Main functions of the Chemical and Volume Control System are to maintain reactor coolant within strict chemistry limits to minimise rate of corrosion and manage coolant volume, including volume-

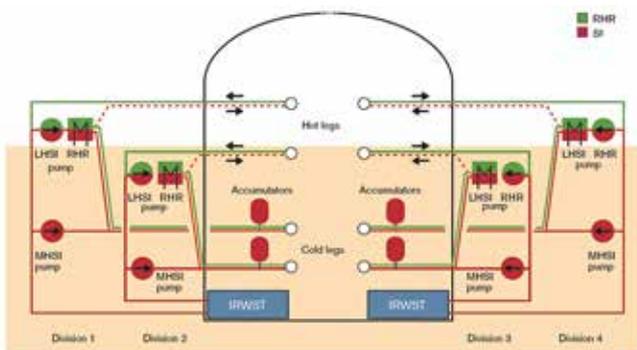


Figure 4: UK EPR ECCS [56]

temperature changes throughout warm-up and cooldown. In both UK EPR and RR SMR plants, reactor coolant is drawn through a regenerative cooler and non-regenerative cooler, having the ability to adjust chemistry, dissolved gases and remove suspended solids before return via the regenerative cooler to the loops. Coolant can be discharged along this route, or added via two charging pumps. pH control is done differently.

There are numerous degradation mechanisms for reactor plant materials and fuel cladding, with pH and reduction-oxidation (redox) potential having the largest impact on material selection. The Austenitic Stainless Steels and nickel-based alloys

chosen have good corrosion resistance in alkaline conditions, so maintaining high pH chemistry regime and deoxygenated conditions in reactor coolant is key [33]. UK EPR injects lithium-7 hydroxide (Li-7 OH), a common pH raiser, into the primary coolant via the charging pump suction header [34]. The pH of water is reduced by the addition of boric acid. Lithium must be enriched from Li-6 to Li-7 to increase effectiveness and decrease neutronic effects – Li-7 has a very low neutron absorption cross section [35]. Lithium usage comes with sustainability and demand concerns, shared by both the United States [36] and United Kingdom [37].

However, RR SMR controls primary coolant pH with two parallel mixed bed ion exchange columns (IXCs) [27] using resins carrying potassium hydroxide (KOH) [35]. The design decision accounted for reduced rate of fuel cladding corrosion, which is present in concentrated lithium hydroxide. This is supported by corrosion sensitivity research [38]. Neutron interactions with boron and lithium make up the highest and second highest contributors to tritium production in PWR coolant, hence KOH would result in substantially lower amount of tritium in coolant and in discharges [35]. Instead, potassium-42 (from irradiated potassium-41) has a 12.4-hour half-life, much shorter than tritium [12.3 years] therefore is considered a significant benefit in minimising decommissioning work.

UK EPR still utilises ion exchange in the form of coolant purification mixed bed demineralisers, whose purpose is to extract solid and ionic impurities (such as fission and activation products) [34].

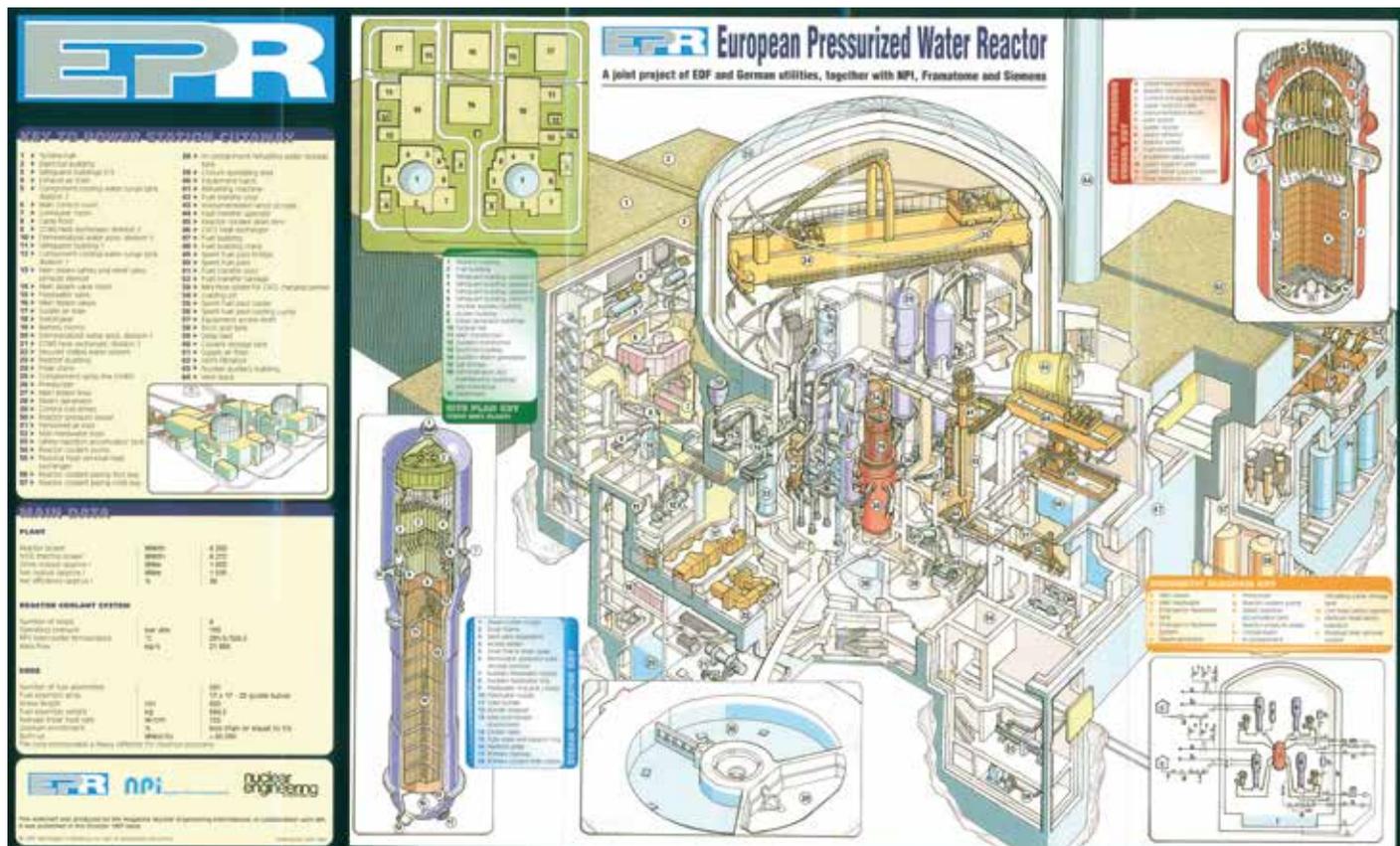


Figure 5: EPR Plant Layout [57] Published with permission for Nuclear Engineering International (www.neimagazine.com)



**Figure 6: RR SMR Plant Layout [58]** This image is a visualisation for illustrative purposes and may not represent the final appearance of the plant

### 3.3. SECONDARY REACTOR SYSTEMS

#### Safety functions for investigation:

- Steam and feed– transfer steam from the SGs to the condenser via steam consumers and feed to the SGs.
- Reactivity control – control of the SG feed and steam during transients and fault scenarios.

#### 3.3.1. Steam and Feed

The secondary system is a closed system. All steam outlets from the SGs converge before entering a turbo-generator (TG) set. The UK EPR design uses a GE Arabelle steam turbine system that rotates at 1500 revolutions per minute (rpm) [39] in line with the UK 50Hz grid, coupled to a generator delivering 1,600 Mwe [40]. RR SMR design states that the TG will spin at 3000 rpm, coupled to a generator that will deliver 470 MWe [41].

Both designs are a double-flow high-pressure turbine, in series with drier/reheater feeding double-flow low-pressure turbines. The drier/reheater removes moisture and uses hot steam, extracted between the main steam isolation valve and the high pressure (HP) turbine throttle valves, to reheat the exhaust steam coming from HP turbine to turn low pressure (LP) turbines. RR SMR has two LP turbines and UK EPR has three LP turbines, and in both designs, the Main Condenser consists of a condenser for each LP turbine in one contained unit [41] [42]. During start-up or on turbine shutdown, main steam is dumped directly into the condensers via the turbine bypass.

The feed system discharges water from the deaerated feed water tank to the SGs via a set of pumps and pre-heaters. To ensure heat removal from the primary plant, both designs have three main systems to achieve this: Main Feedwater System, Start-up and Shutdown Feedwater System (UK EPR) or Auxiliary Feedwater System (RR SMR), and Emergency Feedwater System. Steam is used to re-heat feedwater before and after the feedwater pumps.

Both designs have four main feed pumps (three operational, one backup) where varying motor output speeds is necessary, better meeting the load requirements. RR SMR uses electric variable speed drive (VSD) centrifugal pumps [41]. The UK EPR design uses hydrodynamic VSD (fluid coupling) [43]. A comparison article by MB Drive Services concludes that the fluid coupling presents a simple and compact mechanical system that delivers reliable control and damping, but requires awareness of oil and cooler management,

greater mean repair time and high motor starting current, compared to variable frequency drive system where the motor is inherently soft started and high starting current is completely avoided, in addition to high efficiencies and accurate speed control [44].

A lack of information was available on the Start-up and Shutdown/Auxiliary Feedwater and Emergency Feedwater systems to determine credible differences between designs.

#### 3.3.2. Reactivity Control

The heat exchange taking place within the SG has a direct effect on the reactivity of the reactor core.

#### Increased heat removal

For a critical PWR at constant pressure, the rate that heat is produced in the reactor ( $Q$ ) equals the rate that heat is removed in the SG, for a mass flow rate through the SG ( $m$ ), temperature difference across the SG ( $\Delta T$ ) and specific heat constant of the coolant ( $c_p$ ) [45]:

$$Q=mc_p \Delta T$$

The design of PWRs is load following: the reactor follows the steam demand (turbine) where increased heat transfer in the SG to produce more steam decreases reactor inlet temperature and increases reactivity. The reactor maintains greater reactivity and greater average temperature in the core.

An increase of heat removal by the secondary circuit is mainly caused by temperature reduction of feedwater supply, excessive feedwater flow, or excessive steam demand [46].

To mitigate against this, both designs control final feedwater temperature at the feedwater outlet of the high pressure feedwater heat exchangers, controlled by the rate of HP turbine steam extraction in normal operation, and both designs control rate of feedwater delivery through flow control valves. It is necessary to isolate all main steam lines on demand. To isolate the main steam system from the SG, the main steam isolation valve is automatically tripped to shut responding to viable demand. The UK EPR valve design is hydro-pneumatic, controlled by four (two pairs in series) fail-open pilot solenoid valves. An oil reservoir and pump provide pressure to open, while a nitrogen bubble provides the header to close the valve when triggered by opening the solenoid pilot valves [47]. RR SMR materials are unavailable in the current version of the safety case [41].

### Decreased heat removal

A decrease of heat removal by the secondary circuit is mainly caused by loss of SG feed or a turbine trip [47].

The turbine trip PIE is a key fault. The unmitigated sequence is if no turbine bypass function is available, where the loss of function of the secondary heat sink reduces heat removal from primary plant, increasing reactor pressure and temperature, risking fuel melt.

The first line of defence is the actuation of the turbine bypass. This immediately relieves pressure build-up and maintains plant conditions without necessitating reactor shutdown. The second line of defence is pressure relief valves. There are two main steam safety valves (spring loaded relief valves) per SG in both UK EPR and RR SMR designs [41] [48]. Valve position indication is available to tell operators the condition of the relief valves. RR SMR and UK EPR designs have downstream temperature indication and pressure indication respectively. However, UK EPR design has a fast operating pilot operated relief valve line positioned between each SG and main steam isolation valve, which lifts before the two safety valves at 50% rated steam flow to deal with bulk steam and provide more transient control [42]. A normally open motor-driven isolation valve is located downstream of the relief valve, providing backup protection.

## 3.4. SAFETY REACTOR SYSTEMS

### Safety functions for investigation:

- Cooldown - the ability to cool the shutdown reactor and remove heat produced by radioactive decay (Decay Heat Removal).
- Emergency plant protection – backup core cooling or core shutdown measures.

#### 3.4.1. Cooldown

Safety systems are required to cool the reactor after shutdown due to decay heat production [49]. Both plants use SGs to cool down the plant by transferring steam to the condenser, reducing plant temperature to 120°C before a dedicated cooldown system is initiated as SG heat transfer and steam production becomes too low to operate efficiently [27] [30].

If a route to the condenser is unavailable, then the UK EPR design switches off main feedwater pumps consecutively, initiates the Start-up and Shutdown System pump which takes over SG feed and atmospheric steam dumping commences. Redundancy is assured by, if the Start-up and Shutdown system is unavailable, SG feed from the Emergency Feedwater System [42]. The RR SMR design differs that it can use main feed pumps or auxiliary feed pumps to supply the SGs, and further redundancy is provided by a passive decay heat removal (DHR) method [24].

Low temperature DHR in the UK EPR design is assured by four 'residual heat removal system' units, one in each of the four safeguard buildings surrounding the reactor island, each containing an LP centrifugal pump and a U-tube heat exchanger [50]. Each cooling train is fed from a reactor coolant circuit hot leg and returns to the corresponding cold leg. The layout of the RR SMR design of the 'cold shutdown cooling system' differs by having one system, in one building, with two pump and heat exchanger legs in parallel separated by a partition wall to provide segregation [27]. The coolant is drawn from a single reactor coolant circuit hot leg connection to a single cold leg connection, and this system can provide spray flow from the cold shutdown pumps to the top of the pressuriser.

#### 3.4.2. Emergency Plant Protection

System failures causing the depletion of the reactor coolant circuit inventory and/or loss of core heat removal can lead to the core becoming uncovered. If specific safety systems designed to recover from such events fail, the plant may progress to an accident condition, where the core uncovers. This exposes the fuel cladding to high temperature steam, resulting in clad oxidation; the oxidation of zirconium in steam is a highly exothermic process which produces hydrogen and releases significant quantities of heat [51]. The specific safety systems designed for emergency core make up and cooling are therefore essential to prevent core melt and a severe accident.

A passive backup DHR system is initiated in the RR SMR plant on loss of normal heat sink. Passive DHR provides natural circulation of steam generated in the SG (with main steam isolation valves and feedwater isolation valves shut), condensing in the Local Ultimate Heat Sink, returning via gravity drains to the SG feedwater inlet. The body of water in the heat sink tank will start to evaporate and transfer the decay heat to atmosphere, sufficient to provide 120 hours of heat removal. The use of SGs in this way ensures a short transfer time to initiate the DHR system [24].

### Emergency core cooling

Emergency core cooling systems (ECCS) are designed to accommodate for major leaks, greater than the capacity of normal make-up, indicative of a LOCA. A key difference is that the RR SMR ECCS is passive – pumpless – which automatically and rapidly depressurises the reactor plant following a LOCA to enable accumulator injection following a phased sequence of events. RR SMR describe the three phases of ECCS as: firstly, the rapid automatic depressurisation of the primary plant via blowdown valves in three HP automatic depressurisation lines off the pressuriser head. These discharge to the Refuelling Pool which quenches the heat within the coolant. Low pressure injection of coolant via nitrogen pressurised accumulators (positioned outside of containment) feeds directly into the head of the RPV as reactor coolant pressure reduces below accumulator pressure, to reflood the core. Secondly, once the accumulators are empty, they are isolated, and three LP automatic depressurisation lines off the hot legs vent steam to atmosphere. Plant pressure equalises with containment pressure. A gravity drain from the refuelling pool (potassium tetraborate dosed water pool positioned above the primary plant) provides the driving head to supply the primary circuit with a continuous supply of coolant into the direct head injection nozzles. Containment cooling heat exchangers condense steam, collecting in the containment sump. Thirdly, the hydrostatic head of coolant collected in the containment sump forces coolant through recirculation lines with strainers to provide a continuous DHR method. No further operation is required once ECCS has been initiated. However, component actuation values and sizes of water tanks are unavailable [24].

UK EPR show their ECCS design [Figure 4] not to be phased or directly depressurising plant. The design simply initiates the Medium Head Safety Injection (MHSI) pumps (455 kW, 111 bar), the Low Head Safety Injection (LHSI) pumps (340 kW, 81 bar) and accumulators to inject coolant into the reactor coolant circuit at their operating pressure set points. Both the MHSI pump and LHSI/DHR cooling train are located in the Safeguard Buildings positioned circumferentially around the containment building and take suction

from the refuelling water tank and inject cooling water into the reactor coolant circuit cold legs. The refuelling water tank contains 1894 m<sup>3</sup> of borated water in a leak tight stainless steel liner on the internal lower surface of the containment wall [50]. Because this tank is supported by the containment sump, this design gains the benefit of suction from the refuelling tank requiring no switchover to containment sump recirculation. Each LHSI/DHR shell and U-tube heat exchanger downstream of each LHSI/RHR pump are continuously cooled by the plant's cooling water system. In the long term following a LOCA, the low head discharge will switch over to the hot legs to reduce the risk of boron crystallisation in the upper part of the core [50]. Should the pressure of the reactor coolant circuit drop below 47 bar, each of the four accumulators will inject 30-35 m<sup>3</sup> of borated water under nitrogen pressure via cold leg injection. These are located inside the containment.

**Emergency reactivity control**

Both plants also compensate for elevated reactivity caused by cooldown (cooling water injection) to reach a safe shutdown state. This system initiates on failure to trip and terminates when the boron concentration required for safe shutdown is achieved. Both have two supply lines with HP metering pumps.

The UK EPR Extra Boration System also initiates on low SG pressure. Each supply line has its own borated water tank. Its tanks hold water and boric acid mixed to 7000 ppm and injects into two reactor coolant circuit cold legs, with the ability to switch over to another available cold leg if a reactor coolant loop becomes "inactive" (i.e. there is no coolant circulation) [52]. The RR SMR plant does not utilise soluble boron in normal operation but has an Emergency Boron

System with a single boron storage tank. A concentrated boron-10 potassium tetraborate solution is used, delivered directly into the RPV head via direct head injection nozzles [24].

**4. CONCLUSIONS OR CONCLUDING REMARKS**

The review is a detailed assessment of UK EPR and RR SMR reactor plant systems. Designs are shown and described and supported by current theory. This was achieved through EDF Safety Case Pre-Construction Safety Report (PCSR), Rolls Royce Environment, Safety, Security and Safeguards Case (E3S) documents, UK Office of Nuclear Regulation (ONR) and US Nuclear Regulatory Commission (NRC) publications and available research supporting each investigation topic.

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Functions/Systems/Parameters	Unit	UK EPR	RR SMR
<b>General Remarks</b>			
Net Electrical Output	MWe	1630	470
Thermal Output	MWth	4500	1358
Efficiency	%	35.5	34.6
Life	Years	60	60
Load Follow Range	% of nominal power	60-100	50-100
<b>Main Primary System</b>			
Number of loops		4	3
Operating pressure of primary system	MPa	15.5	15.5
Design pressure of primary system	MPa	17.6	17.6
Vessel inlet temperature in nominal conditions	°C	295.6	295
Vessel outlet temperature in nominal conditions	°C	329.8	325
<b>Secondary Side</b>			
Feedwater temperature at 100% power	°C	230	230
Nominal steam temperature	°C	Unavailable	289.6
Steam piping nominal pressure	MPa	7.5	7.4
Steam mass flow rate	kg/s	645	766
Moisture content at SG outlet	%	≤0.25	Unavailable
<b>Reactor Core</b>			
<b>Fuel Assembly</b>			
Geometry of fuel assemblies		17x17	17x17
Number of fuel assemblies		241	121
Number of Rod Cluster Control Assemblies (RCCAs)		89	89

Control rod types		AIC control rods, B4C shutdown rods	AIC control rods, B4C shutdown rods, Stainless steel grey rods
Active length of fuel assembly (in cold service conditions)	cm	420	280
<b>Fuel Rods</b>			
Number of rods		63865 (265 rods / assembly)	31944 (264 rods / assembly)
Cladding		Zirconium alloy	Zirconium alloy
<b>Fuel Pellets</b>			
Composition		UO <sub>2</sub> and / or MOX	UO <sub>2</sub>
In-fuel neutron poison		Gd <sub>2</sub> O <sub>3</sub>	Gd <sub>2</sub> O <sub>3</sub>
Max design enrichment U235	%	5	4.95
Fuel cycle		18-24 months (burnup dependent)	18 months
<b>Core Instrumentation</b>			
Ex-core instrumentation		Neutron flux measurement channels (source, intermediate, power range)	None
In-core instrumentation		Within RCCAs: - Aeroball Measurement System - Self-Powered Neutron Detector probes - Core exit thermocouples	Within RCCAs - Self-Powered Neutron Detector probes - Core exit thermocouples
<b>Reactor Pressure Vessel</b>			
Material		Low-alloy steel (16 MN D5)	Low-alloy steel (SA508 Grade 3 Class 1). Clad with austenitic stainless steel (309L/308L)
Design temperature	°C	351	Unavailable
Internal diameter	m	4.87	4.2
<b>Primary Pipework</b>			
Material		Austenitic Stainless Steel (X2 CrNi). (Surge Line - X2 CrNiMo)	Austenitic Stainless Steel (316LN)
<b>Primary Pumps</b>			
Material		Stainless Steel (Z3 CN)	Low-alloy steel (SA-508 Grade 3 Class 2)
Type		Centrifugal	Centrifugal, hermetically sealed
Number of speeds		Single	Single (VFD for start-up and cooldown)
Features		Integrated flywheel to elongate run-down time following a loss of primary flow fault	Integrated flywheel to elongate run-down time following a loss of primary flow fault
Flow rate (best estimate)	m <sup>3</sup> /h	28320	Unavailable
Shaft seals		3 seals, 1 standstill seal	Hermetically sealed
<b>Pressuriser</b>			
Surge line connection		Axial Vertical	Axial Vertical
Internal volume	m <sup>3</sup>	75	Unavailable
Total heating power	kW	2600	Unavailable
<b>Plant Overpressure Protection</b>			
Primary Plant	Pressuriser	- 3 steam pilot operated PRV trains - 2 severe accident depressurization trains (2 solenoid valves per train) - 2 PRVs cold overpressure protection - Discharge flow to Pressuriser Relief Tank and via rupture disc into containment.	- 2 steam PRV trains - 2 water PRVs cold overpressure protection - Discharge flow to in-containment refuelling pool. Open-vented.
Secondary Plant	Per SG	- 1 PRV train sized at 50% full load of one SG - 2 back-up safety valve trains sized at 25% full load of one SG	2 safety valve trains each designed for 100% capacity
<b>Steam Generator</b>			
Secondary pressure boundary design pressure	MPa	10.0	Unavailable
Steam pressure at hot shutdown (0%NP)	MPa	9.0	Unavailable
Saturation pressure at full power at SG tube bundle outlet	MPa	7.8	Unavailable
Water mass in secondary section of SG at full load	t	77.2	Unavailable
Tube sheet material		Inconel 690 (NiCrFe clad)	Unavailable

<b>Shutdown and Heat Removal</b>			
<b>Plant Heat Removal</b>			
Method of High Temperature Decay Heat Removal (DHR) >120 °C		Pumped flow / natural circulation Steam Generator - Steam dump to condensers - Steam dump to atmosphere	Pumped flow / natural circulation Steam Generator - Steam dump to condensers - Steam dump to atmosphere - Circulation through SG via Local Ultimate Heat Sink (in-containment heat sink)
Low Temperature DHR system <120 °C		Safety Injection/Residual Heat Removal System	Cold Shutdown Cooling System
Location of cooling system		Outside Reactor Building	Outside Reactor Building
Number of pumps		4 (Low Head Safety Injection (LHSI) pumps)	2
<b>Containment Heat Removal</b>			
Containment cooling		Containment heat removal system (spray system + sump cooling)	Containment heat removal system (spray system + sump cooling)
<b>Emergency Core Cooling</b>			
<b>Injection System</b>			
Emergency Core Cooling System		Safety Injection/Residual Heat Removal System	Emergency Core Cooling System
Number of Safety Injection Pumps		4 Medium Head 4 Low Head	None
Location of injection		In cold leg - LHSI (short term), MHSI In hot leg - LHSI (long term)	Direct Head Injection – Accumulator injection & containment sump recirculation
<b>Accumulators</b>			
Number of Safety Injection Accumulators		4 (one per loop)	3 (one per loop)
Location of injection		In cold leg	Direct Head Injection
Location of accumulators		In containment	Out of containment
<b>Boration System</b>			
System used in normal operation		Chemical and Volume Control System (boric acid)	None
Safety system		Extra Boration System (2 trains) (boric acid)	Emergency Boron System (2 train) (potassium tetraborate)
<b>Feedwater Supply</b>			
Feed tank volume	t	Unavailable	360
Total feedwater flow	kg/s	645	720
Start-up and shutdown conditions		Dedicated system for start-up and shutdown operation (1 pump)	Dedicated system for start-up and shutdown operation (2 pumps)
Emergency system		Emergency feed water system - 4 separate independent trains - Pumps driven by emergency supplied motors and by 2 backup diesel generators	Unavailable
<b>Containment</b>			
Containment structure description		Double concrete structure: - Inner pre-stressed concrete, lined with welded steel plate sections - Outer reinforced concrete	60mm thick steel containment vessel

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