# Novelties in light-water SMR designs suitable for Sweden’s future electricity production needs: Report ANItA project A2

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## Abstract

Land-based light-water-cooled and -moderated small modular reactors (SMRs) are one option for adding new nuclear capacity in Sweden. This project has investigated such SMRs and compiled a shortlist of four SMRs that are deemed the most probable to be built for (mainly) electricity production in Sweden in the relatively near future. These SMRs are the boiling-water reactor GE Hitachi BWRX-300 and the pressurised-water reactors (PWRs) Rolls-Royce SMR, Westinghouse AP300, and NuScale VOYGR.

In the shortlisted SMRs, as well as in others, there are design features previously not used in Swedish reactors. Some of these features could have an impact on the licensability, constructability, and operability/maintainability of the SMRs and thus be barriers to deploying the SMRs. Better understanding of such features, and therefore further investigation, or at least clarification from the organisations developing the reactors, is necessary for successful implementation of SMRs in Sweden. The following were identified as novel features that need further investigation or clarification: increased modularity, enhanced natural circulation, increased passive safety, novel containment designs, smaller size (of the reactor and power plant), integral PWRs, integral reactor isolation valves, novel types of water chemistry, novelties in the steam and power conversion system, increased load-following capability, dry storage of spent fuel, and novelties in severe accident mitigation and management. Regarding licensability, all identified novel features except some of the novelties in water chemistry and in the steam and power conversion system are deemed to be in need of further investigation or clarification; regarding operability/maintainability, all identified novelties except some of the novelties related to modularity, increased passive safety, containment design, and severe accident mitigation and management are deemed to be in need of further investigation or clarification; and regarding constructability, the increased modularity, the novel containment designs, the smaller size, and part of the novelties in the steam and power conversion system are the novelties that are deemed to be in need of further investigation or clarification.

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# List of abbreviations

| | |
|---|---|
| AC | Alternating current |
| ANItA | Academic-industrial Nuclear technology Initiative to Achieve a sustainable energy future |
| BWR | Boiling-water reactor |
| CCS | Containment-cooling system |
| CNSC | Canadian Nuclear Safety Commission |
| CRDM | Control rod drive mechanism |
| DC | Direct current |
| EPZ | Emergency planning zone |
| ESBWR | Economic simplified boiling water reactor |
| GDA | Generic design assessment |
| IAEA | International Atomic Energy Agency |
| ICS | Isolation condenser system |
| IVR | In-vessel retention |
| LOCA | Loss-of-coolant accident |
| MSHIM | Mechanical shim |
| ONR | Office of Nuclear Regulation |
| PAR | Passive autocatalytic recombiner |
| PRZ | Pressuriser |
| PSAR | Preliminary safety analysis report |
| PWR | Pressurised-water reactor |
| RCP | Reactor coolant pump |
| RPV | Reactor pressure vessel |
| SG | Steam generator |
| SINCAD | Silver–indium-cadmium |
| SMR | Small modular reactor |
| UPS | Uninterruptible power supply |
| USNRC | United States Nuclear Regulatory Commission |
| VVER | Water–water energetic reactor |

# 1. Introduction

This work (project A2) has been performed within the competence centre ANItA (Academic-industrial Nuclear technology Initiative to Achieve a sustainable energy future), jointly sponsored by the Swedish Energy Agency, the nuclear industry, and academia. The purpose of ANItA is to gather competence in technical as well as non-technical areas of nuclear technology specifically relating to small modular reactors (SMRs) [1].

The intended outcome of project A2 is a shortlist of SMR concepts targeting (primarily) electric power production. The shortlist shall consist of designs that have potential to fulfil future Swedish needs as described by the production scenarios defined in project A1 [2] and should thus primarily focus on near-term-deployable land-based light-water SMR designs. The objective is, furthermore, to assemble key design features and plant data that can be provided to other research projects on e.g. core design, fuel, safety systems, and operational systems. The following are the main tasks:

- Establish a shortlist of suitable SMR designs targeting (primarily) electric power production.
- Assemble key design features and plant data of the selected designs.
- Define needs for further investigation, with focus on potential technology development needs.

The International Atomic Energy Agency (IAEA) has compiled a status update on SMR designs under development in 2024 [3] and assembled design descriptions of them [4]. Of these designs, 15 are land-based light-water-cooled SMRs and an additional three are land-based light-water-cooled microreactors with a maximal electric capacity of 10 $MW_e$. Microreactors have not been considered in this project.

In this report, the shortlist compiled in project A2 is presented and followed by descriptions of the shortlisted designs, and a table of design data is provided. The information about the designs comes from the publicly available literature and, in some cases, directly from the reactor developers. The comparison between the SMRs is thus limited by the different amounts of information provided for each of them.

Novel design features compared with current (and previous) commercial Swedish reactors are pointed out, and it is also stated if these novelties are or have been in use outside Sweden or not. Each novelty might affect one or more of licensability, constructability, and operability/maintainability of the reactors. Because of their potential impacts on these aspects, the novelties might need further investigation, or at least clarification by the reactor developers, to successfully deploy SMRs in Sweden. This need for investigation or clarification is discussed in this report. Apart from the new technical design, the reactors could also presently be designed to codes and standards that deviate from the Swedish Radiation Safety Authority’s regulations, e.g. when it comes to safety classification, material requirements and quality control [5].

It should be kept in mind that this report describes the current status. There is a rapid development in the SMR field, so the status in the future will be different.

# 2. Shortlist of SMR designs

SMRs that are deemed to have potential of being built in Sweden in the relatively near future are those that are at a relatively advanced design stage and are being developed by organisations that are based in a country from which it is politically acceptable to acquire nuclear power, currently excluding e.g. Russian and Chinese designs from the shortlist. Based on these criteria, four SMR designs were selected, yielding a shortlist comprising one boiling-water reactor (BWR) and three pressurised-water reactors (PWRs). The shortlisted SMRs are (without any ranking order) presented in Table 1.

*Table 1. Shortlist of SMR designs deemed having the potential of being built in Sweden in the relatively near future.*

| **Reactor** | **Developer** | **Country of developer** | **Thermal capacity ($MW_{th}$)** | **Electrical capacity ($MW_e$)** |
|---|---|---|---|---|
| BWRX-300 | GE Hitachi | USA | 870 | 300 |
| Rolls-Royce SMR | Rolls-Royce SMR | UK | 1358 | 470 |
| AP300 | Westinghouse | USA | 1000 | 330 |
| VOYGR | NuScale | USA | 250[1] | 77[1] |

Note:

[1] Planned to be employed as modules of this capacity in plants consisting of 4, 6, or 12 modules.

Design descriptions of these SMRs are given in Section 3. Features in the designs not previously used in Sweden and the associated needs for further investigation or clarification are then discussed in Section 4.

Additional designs, currently not on the shortlist, might also be of interest in the future, e.g. the three PWRs EDF NUWARD (France), Holtec SMR-300 (USA), and KHNP i-SMR (Republic of Korea) [4]. Although not used as a selection criterion for the shortlist, it can be worth mentioning that it is likely advantageous if the SMRs are developed by large organisations, especially those that have previously built nuclear reactors in Europe.

Although Russian and Chinese reactors were excluded from the shortlist, it is worth mentioning that there are light-water SMRs at an advanced stage from these countries. In China, a first demonstration plant of the integral PWR ACP100 of 125 $MW_e$ capacity is being built at Changjiang [6]. Work is also ongoing to develop a marine-based version of this reactor. In Russia, preparations are ongoing to construct one or two units of the 55 $MW_e$ integral PWR RITM-200N at Ust-Kuyga [7], and a plant with six reactors of the same type is planned in Uzbekistan [8]. The RITM-200N is based on marine reactors that are in operation in several icebreakers. Two marine-based RITM-200S reactors for electricity and heat generation are also under construction [9].

# 3. Descriptions of the shortlisted SMRs

In this section the shortlisted SMRs are briefly described, and references to more detailed descriptions are given. Novelties compared with the current and previous Swedish reactors are pointed out. A table comparing design data of the different designs is provided in the appendix of this report.

Apart from being light-water SMRs, meaning that they use normal water as coolant and neutron moderator and are smaller and more modular than most of today's reactors, the shortlisted designs share some common features. Notably, passive safety to keep the core cooled for varying amounts of time in case of accidents is among those features, although the type and specific design of the safety systems vary between the reactors. Additionally, industry-standard uranium dioxide fuel with a uranium-235 enrichment below 5 wt% and gadolinia burnable absorbers in zirconium alloy cladding is specified to be used in all designs. However, the fuel assembly length is typically not the same as in current Swedish reactors.

## 3.1. GE Hitachi BWRX-300

The main references for this section are the IAEA 2024 SMR catalogue [4], the BWRX-300 design description by GE Hitachi [10], and the GE Hitachi website [11]. Additional references are given in the text.

### 3.1.1. Design description of GE Hitachi BWRX-300

The GE Hitachi BWRX-300 (Figure 1) is a BWR with a thermal capacity of 870 $MW_{th}$ and an electrical capacity of 300 $MW_e$. It is to large extent based on the Economic Simplified Boiling Water Reactor (ESBWR) [12] licensed by the US Nuclear Regulatory Commission (USNRC) but never built. It utilises natural circulation during normal operation as well as transient and accident conditions. There are passive safety features without any need for external power, operator action, or other auxiliary systems to keep the core cooled during accident scenarios for a time that varies depending on postulated scenario. Often, the passive cooling time is stated to be seven days; however, this is under the assumption that only two of three trains of the isolation condenser system (ICS, see below for description) are available, if only one ICS train is available the time is shorter, and if all three ICS trains are available the time is longer. If sufficient water is supplied, the passive cooling time is infinite.

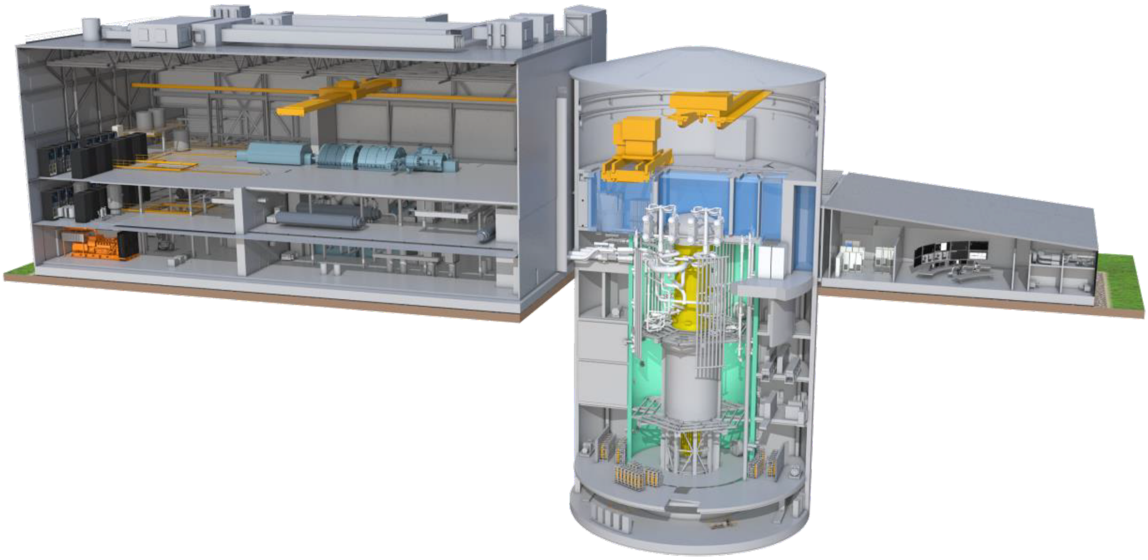

*Figure 1. Schematic of the BWRX-300 plant* [10].

The nuclear steam supply system is that of a conventional BWR. The reactor pressure vessel (RPV) contains the core, steam separators, and steam dryers. The part of the RPV between the core and the steam separators forms a chimney to enhance the natural circulation. Additionally, the presence of a chimney leads to a high water level above the core, a feature increasing the margins in loss-of-coolant accidents (LOCAs) and other transients without compromising core cooling. All RPV nozzles are located well above the top of the active fuel. Reactor isolation valves are integral to the RPV at all nozzles larger than 19 mm in diameter to mitigate all LOCAs due to pipe break larger than this size [10]. These nozzles are for the main steam system, the reactor water cleanup system, the ICS, the head-venting system, and the feedwater system. At each location there are, for redundancy, two reactor isolation valves in series. In case of loss of power, hydraulics, or air to the valves, the reactor isolation valves will passively close, except for the ones located at the ICS lines which fail as is, i.e. normally open. In case of indication of breakage in an ICS train, the corresponding reactor isolation valves will close.

The core is similar to the core of a large-scale BWR. It consists of 240 fuel assemblies located within a core shroud. The fuel planned to be employed is GNF2, a commonly used BWR fuel with uranium dioxide fuel pellets in a a 10 × 10 array of Zircaloy-2 fuel and water rods [13]. Like for other BWRs, it will be possible to use fuel of other designs. Reactivity is controlled by control rods and gadolinia burnable absorbers in the fuel rods. There are 57 control rods, essentially of the same type as in current BWRs. The RPV and its internals are schematically shown in Figure 2.

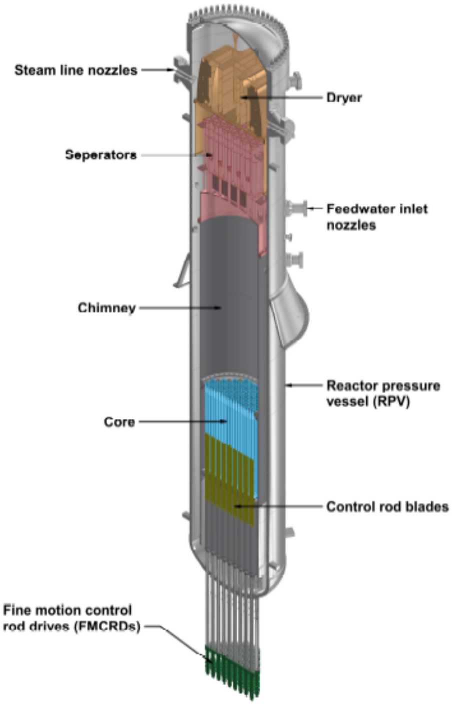

*Figure 2. Schematic of the RPV, including control rod drives, of BWRX-300* [14].

Due to the natural circulation during normal operation, there is no need for primary pumps. The cooling system during normal shutdown, however, consists of two independent lines of pumps and heat exchangers. For emergency core cooling, the ICS is utilised. The ICS comprises three independent loops of isolation condensers. In the ICS, steam is condensed inside the condenser tubes and heat is transferred to a pool that is at atmospheric pressure. The three pools and isolation condensers are located above the steam outlet from the RPV to allow for natural circulation. A schematic of the ICS and its connections to the RPV is shown in Figure 3.

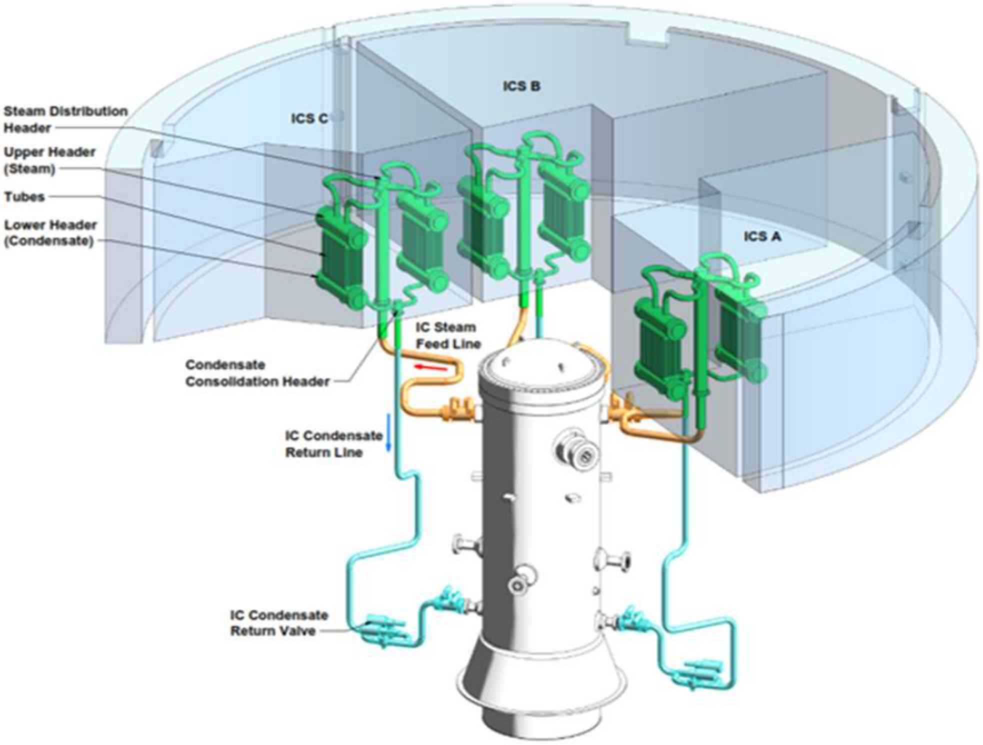

*Figure 3. Schematic of the isolation condenser system (ICS) of BWRX-300 and its relation to the RPV* [14].

The containment is dry and is a cylindrical vessel, to most part located below grade, approximately 38 m in height and 17.5 m in diameter. The ICS in combination with the integral reactor isolation valves allows for not having the commonly used pressure suppression type of containment. A reactor building surrounds the containment. During normal operation, a non-passive containment-cooling system is in use and a passive system (that is in service also during normal operation) provides sufficient cooling during accident or loss-of-active-containment-cooling conditions. The reactor pool is located inside the reactor building and above the containment. Next to it, the three isolation condensers are located in three separate pools. The building technique for the containment is planned to be by steel-plate composite materials (see Section 4.4 for a description of these types of materials) [15].

A manually initiated boron injection system is implemented to reduce reactivity in case of anticipated transients without control rod insertion, i.e. events in which the normal shutdown of the reactor does not function as intended. The capacity is enough to bring the reactor from full-power operation to subcritical cold-shutdown condition.

The steam and power conversion system is of the same type as that typical of BWRs. However, slightly modified "off-the-shelf" turbines are planned to be used, in contrast to current nuclear reactor turbines that are designed specifically for nuclear steam. There is one turbine connected to the RPV via two steam lines, and there is one main condenser. In the condensate and feedwater system there are two condensate pumps and two feedwater pumps, each of 100 % capacity. There are three stages of low-pressure feedwater heaters (two in parallel followed by one in series) and three stages of high-pressure feedwater heaters (all in series).

Hydrogen water chemistry with On-Line NobleChem and zinc addition [16] is the standard option. A combination of hydrogen and noble metals is added to decrease the corrosion potential of the coolant while keeping sufficiently low radiation levels in the steam. Zinc is added to reduce dose rates in the plant by reducing the deposition of cobalt-60 on pipe surfaces [17].

The instrumentation and control systems are divided into three safety classes and a non-safety class. In the highest safety class (Class 1) the systems, which are for reactor shutdown, reactor and containment isolation, and emergency core cooling, are divided into three independent divisions that can be powered by diesel generators if needed.

In case of core melt, there is a core catcher below the RPV. The core catcher is equipped with a liner manufactured of zirconia to contain the corium and prevent molten core–concrete interaction. There is also passively activated containment flooding to quench the corium in the catcher to maintain containment integrity. Sufficient water is available to keep the corium quenched for seven days without refill.

Hydrogen combustion or detonation is to be avoided by having a nitrogen atmosphere in the containment. Filtered containment venting is not included in the standard design.

Safety and operational specifications include an internal-event core damage frequency $< 10^{-7}$/year, a large-release frequency $< 10^{-7}$/year, an availability factor > 95 %, and a load-following range of 50–100 % with a ramp rate of ± 0.5 % per minute.

The proposed fuel cycle length is 12 months for load-following operation and 24 months for non-load-following operation. Anticipated refuelling time is 10–20 days, with 32 or 72 fuel assemblies being replaced depending on fuel cycle length. A longer outage of 25 days for more extensive inspections is anticipated every ten years. Used fuel can be stored in the fuel storage pool in the reactor building, with a capacity of eight years of operation.

The footprint of a single-unit reference site is $260 \times 332$ m$^2$, with the power block (reactor, turbine, control, and radwaste buildings) having a footprint of $140 \times 70$ m$^2$. The reactor building is partly below ground level and is designed to withstand seismic activity. The emergency planning zone (EPZ) radius is specified to be 0.5 km.

### 3.1.2. Novelties in GE Hitachi BWRX-300

Notable novelties (from a Swedish perspective) in BWRX-300 are listed in this section. The main novel features in all shortlisted SMRs are explained in Section 4, where the potential need for further investigation or clarification of them also is discussed. Novel features in BWRX-300 are:

- Natural circulation (passive core cooling)
  - During normal operation
  - During accident conditions
- Reactivity/power control by other means than main-circulation pumps, e.g. feedwater temperature
- Integral reactor pressure vessel isolation valves
- No safety relief valves (because of the ICS)
- Slightly different fuel assembly length than in current BWRs (standard GE length will be used)
- Fixed in-core gamma thermometers for core monitoring, instead of a transverse in-core probe (TIP) system
- On-Line NobleChem
- Dry containment
- Containment of steel-plate composite materials
- 30 of 60 m of containment height below grade
- Passive containment cooling
- Core catcher
- Slightly modified off-the-shelf turbines
- Automatic emergency boron injection not included in the standard version
- Filtered containment venting system not included in the standard version
- Load-following: 50–100 %, 0.5 %/min

### 3.1.3. Design and licensing status GE Hitachi BWRX-300

The BWRX-300 design is made to comply, as much as possible, with IAEA safety standards as well as American and European codes and standards. Local adaptations of the standard design will be made when needed.

The design is at a relatively advanced stage. In Canada, a pre-licensing vendor review has been completed by the Canadian Nuclear Safety Commission (CNSC) [18], and in the USA, a pre-application review of licensing topical reports is ongoing [19]. In the UK, Step 1 of 3 a generic design assessment (GDA) conducted by the Office of Nuclear Regulation (ONR) has been completed, and Step 2 is ongoing [20].

An application for a licence to construct a first unit at Ontario Power Generation's Darlington site was submitted to CNSC in October 2022 and is currently under review [21]. A preliminary safety analysis report (PSAR) for this unit is available [22]. Three additional units at the Darlington site are being planned [23]. BWRX-300 is also considered for deployment in Saskatchewan, Canada, in the UK, in Poland (where decisions-in-principle for construction of a total of 24 units at six locations have been issued by the Polish Ministry of Climate and Environment [24]), and in Estonia [11]. In Sweden, it is among the reactor models considered for deployment at Ringhals by Vattenfall [25], and the potential to build it at Studsvik and outside Valdemarsvik is investigated by Kärnfull Next [26].

## 3.2. Rolls-Royce SMR

The main references for this section are the IAEA 2024 SMR catalogue [4] and the Rolls-Royce GDA website [27]. Additional references are given in the text.

### 3.2.1. Design description of Rolls-Royce SMR

The Rolls-Royce SMR (Figures 4 and 5) is a (non-integral) three-loop PWR with a thermal capacity of 1358 $MW_{th}$ and an electrical capacity of 470 $MW_e$. There are passive safety features without any need for external power, operator action, or other auxiliary systems to keep the core cooled for at least 3 days during accident scenarios. The passive cooling time can be increased if water is supplied.

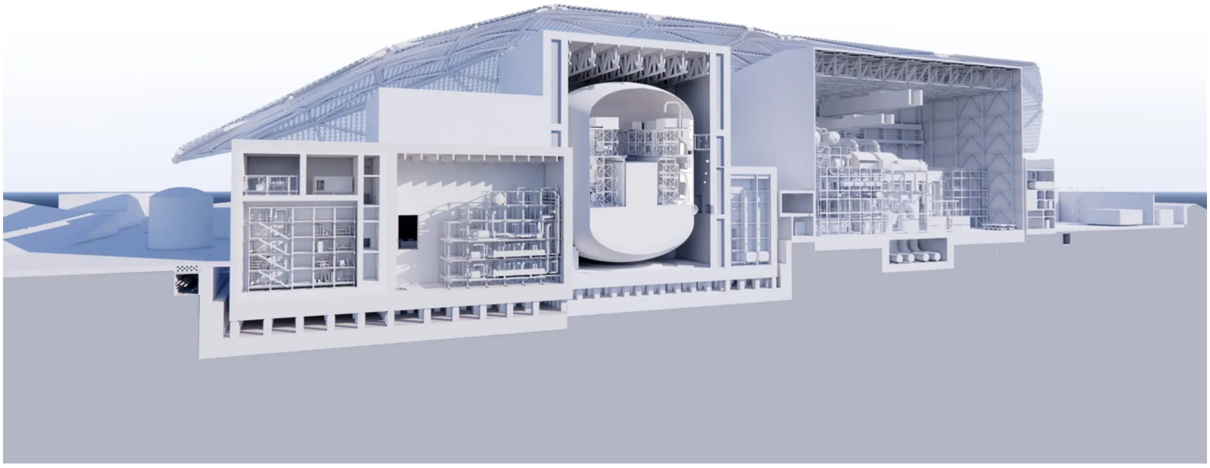

*Figure 4. Schematic cross-sectional view of the Rolls-Royce SMR. Image courtesy of Rolls-Royce SMR.*

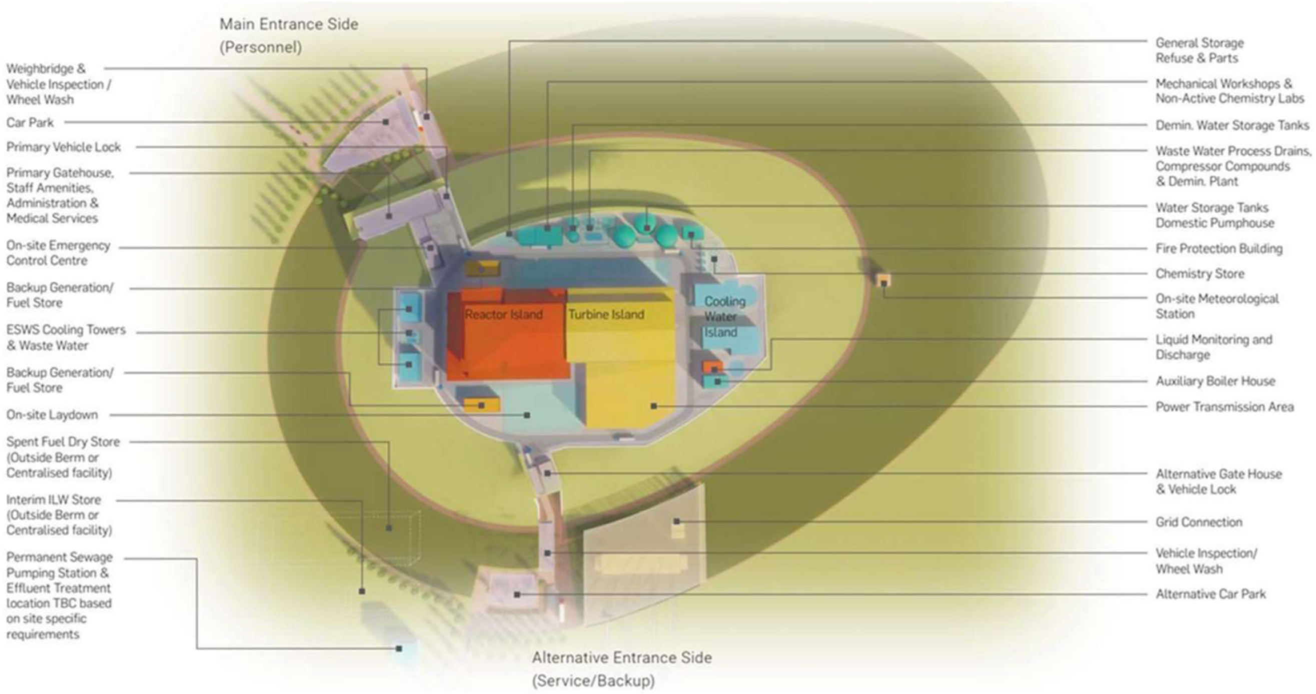

*Figure 5. Plant layout overview of the Rolls-Royce SMR* [14].

The nuclear steam supply system (Figure 6) is that of a conventional PWR. It consists of the reactor core, three centrifugal reactor coolant pumps (RCPs), three vertical U-tube steam generators (SGs), and one pressuriser (PRZ).

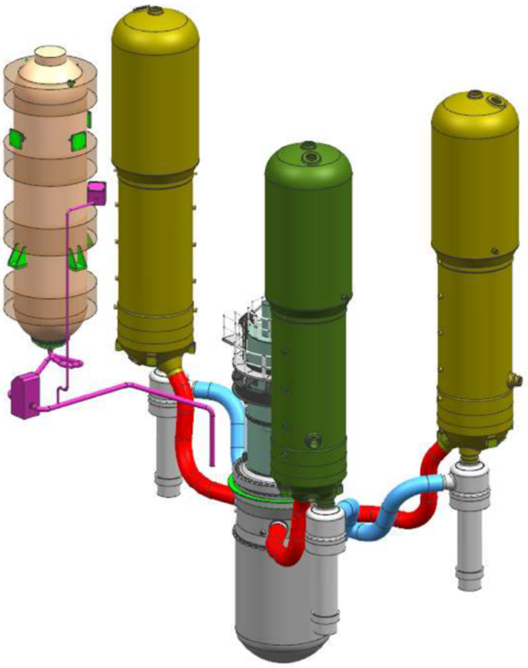

*Figure 6. Schematic of the primary system of the Rolls-Royce SMR, with RPV, PRZ, three SGs, and three RCPs* [14].

In the RPV, there are six reactor coolant nozzles (three inlets and three outlets) and three direct-injection nozzles. The control rod drive mechanisms (CRDMs) are part of an integrated RPV head package additionally comprising in-core instrumentation, fans for CRDM cooling, integral missile shield, and lifting assembly. The core is located in a core barrel, there is a radial neutron reflector, and the control rod housing-columns are located in an upper support barrel above the core.

The core consists of 121 17 × 17 fuel assemblies (that are 1–2 dm shorter than the fuel assemblies of current reactors) using standard uranium dioxide fuel and zirconium alloy cladding and having an active core length of 2.8 m. Reactivity control is provided by gadolinia burnable absorbers in the fuel and control rods. The gadolinia content is different for different fuel rods and assemblies, and there is also axial zoning with the gadolinia content varying for different axial positions. The coolant is boron-free. There are three types of control rods: boron carbide rods for shutdown, silver–indium–cadmium (SINCAD) rods for through-cycle and reactivity-transient control, and stainless-steel rods for load-following and reactivity-transient control.

The SGs are located above the RPV and are connected to it via short pipes. The size of the SGs is minimised by employing a crossflow preheater directing the feedwater to the cold side of the tube bundle. An integrated preheater for the secondary cold-side is incorporated in the design. A centrifugal RCP with a flywheel is located directly at the outlet nozzle of each SG. The purpose of the flywheel is to provide prolonged pump coast-down to give more time for safe shutdown in case of loss-of-flow situations. The PRZ is connected to the hot-leg of one SG and is a vertical cylinder made of low-alloyed steel. A pump-induced spray system in the PRZ can reduce the pressure if needed.

The steam and power conversion system is of the same type as that typical of PWRs. There is one turbine and generator system per reactor. The steam from the SGs is directed to a high-pressure turbine that is succeeded by a reheater and two low-pressure turbines. There is one main condenser, condensate pumps, a condensate polishing system, five low-pressure preheaters (two in parallel followed by three in series), a deaerator, feedwater pumps, and four high-pressure preheaters (two in parallel followed by another two in parallel) before the water is fed back into the SGs.

pH in the primary circuit will be controlled by addition of potassium hydroxide instead of the commonly used lithium hydroxide, in PWRs that are not of the (Russian-designed) type water–water energetic reactor (VVER). Nominal pH is 7.4. Hydrogen gas will be added to lower the redox potential. Additionally, hydrogen peroxide and hydrazine will, during some operating conditions, be added for the same purpose. Zinc will be added to reduce corrosion and dose rates.

Active and passive safety systems are independent and diverse and have multiple trains per system. Decay heat is removed via the SGs and can be transferred from the core through either forced or natural circulation. Emergency core cooling can be achieved via depressurisation of the reactor coolant system and injection of coolant via gas-pressurised accumulators and gravity. There is a water-based passive containment-cooling system.

The containment is made of steel. It is supported by a containment support structure consisting of one central and three outer concrete plinths located on a concrete basemat. A reinforced concrete structure rests on the basemat and surrounds the containment and the rest of the reactor island, thus forming a hazard shield to protect against external impacts by e.g. airplanes or tsunamis. Below the basemat, there is a raft foundation. The top of the raft foundation is located 11.2 m below ground level and the top of the hazard shield approximately 45 m above ground level. An outer roof covers the reactor and turbine islands, mainly for aesthetic reasons. Additionally, there is a berm (with two entrances) surrounding the plant.

There is in-vessel retention (IVR) in case of molten core. Hydrogen combustion or detonation is to be avoided by passive autocatalytic recombiners (PARs). Filtered containment venting is not included in the standard design, but there is space allocated for such a system if required by regulatory bodies.

According to probabilistic safety analysis the internal-event core damage frequency is $< 10^{-7}$/year. The estimated availability factor is > 90 %, and a load-following range of 50–100 % with a ramp rate of ± 3–5 % per minute is possible.

The proposed fuel cycle length is 18 months (18–24 months). Anticipated refuelling time is 18 days, with 44 fuel assemblies being replaced [28]. Used fuel can be stored in the fuel storage pool that is located in the reactor building and has boron-free water and neutron absorbers in the racks.

The footprint of a reference site is 100 000 $m^2$ including the berm, 54 500 $m^2$ inside the berm, and 18 550 $m^2$ under the hazard shield.

### 3.2.2. Novelties in Rolls-Royce SMR

Notable novelties (from a Swedish perspective) in the Rolls-Royce SMR are listed in this section. The main novel features in all shortlisted SMRs are explained in Section 4, where the potential need for further investigation or clarification of them also is discussed. Novel features in the Rolls-Royce SMR are:

- Passive core cooling
    - Natural circulation during accident conditions
- Boron-free coolant
- Shorter fuel assemblies (1–2 dm shorter than current fuel assemblies)
- Integrated RPV head package
- IVR of molten core
- Steel containment
- Passive containment cooling
- Filtered containment venting system not included in the standard version
- High degree of modularity with standardised modules for essentially the whole power plant
- Load-following: 50–100 %, 3–5 %/min

### 3.2.3. Design and licensing status Rolls-Royce SMR

The Rolls-Royce SMR has completed Step 2 of the generic design assessment by ONR in the UK and is currently undergoing the final Step 3. Countries for which the design is intended include the UK, Sweden, Finland, the Netherlands, Poland, and Czechia. It is attempted to, as much as possible, have a standard design that fulfils the requirements of these countries. Among other codes and standards, EUROCODES are implemented in the design.

A Czech–UK collaboration is ongoing to deploy Rolls-Royce SMR in the UK and Czechia [29]. In Sweden, the Rolls-Royce SMR is among the reactor models considered for deployment at Ringhals by Vattenfall [25]. The potential to deploy it at Marviken is also evaluated in collaboration with iPower Group [30].

## 3.3. Westinghouse AP300

The main references for this section are the IAEA 2024 SMR catalogue [4], a general description of AP300 provided by Westinghouse [31], and the Westinghouse website [32]. Additional references are given in the text.

### 3.3.1. Design description of Westinghouse AP300

Westinghouse AP300 (Figure 7) is a (non-integral) one-loop PWR with a thermal capacity of 1000 $\mathrm{MW_{th}}$ and an electrical capacity of 330 $\mathrm{MW_e}$. To large extent, it is based on the two-loop AP1000 design, licensed and operating in the USA and China. There are passive safety features without any need for external power, operator action, or other auxiliary systems to keep the core cooled for at least three days during accident scenarios. The passive cooling time can be increased if water is supplied.

*Figure 7. Schematic peel-away view of AP300* [33].

The nuclear steam supply system (Figure 8) is that of a conventional PWR and consists of the reactor core, one PRZ, one SG, and two RCPs. There is one hot-leg and two cold-legs. The core is located in a core shroud in a core barrel and has 121 fuel assemblies of uranium dioxide fuel pellets in zirconium alloy cladding in a 17 × 17 configuration with an active core length of 3.66 m. Reactivity control is achieved via a combination of burnable absorbers, soluble boron in the coolant, and control rods, one type for shutdown and one type for other reactivity adjustments. There are 45 control rod assemblies [4]. The mechanical shim (MSHIM) operating strategy used for AP1000 is implemented, meaning that the changes in the boron concentration in the coolant are minimised by using control rods for both load-following and reactivity changes due to fuel burnup.

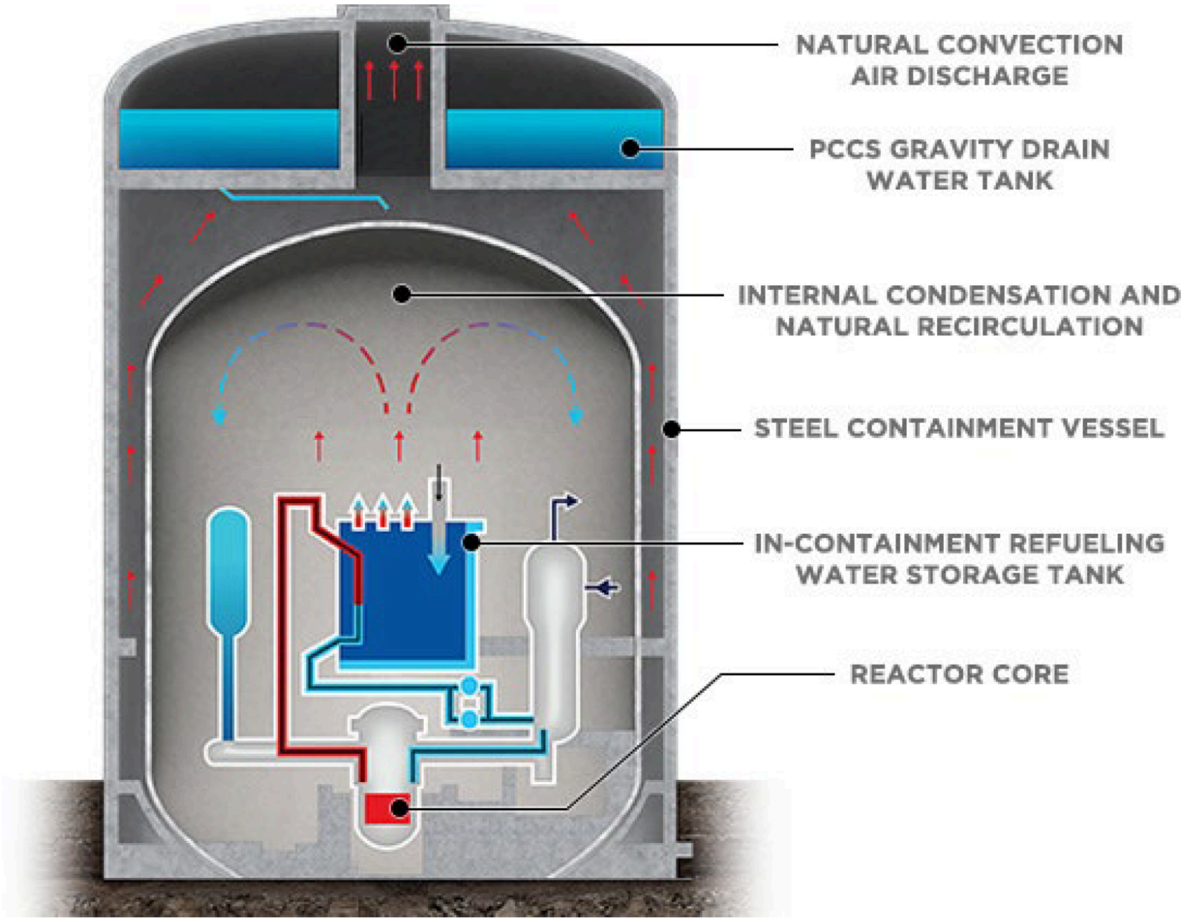

*Figure 8. Schematic of the AP300 primary system and containment* [31].

The RPV (Figure 9) is approximately 11 m in height and 3.6 m in inner diameter. There are two inlet nozzles, one outlet nozzle, and two direct-vessel-injection nozzles (the latter for injection of borated water in off-normal events). All nozzles are located above the core to allow for IVR of molten core. The design includes an integrated head package that comprises a lifting rig, seismic restraints for the CRDMs, a reactor head vent piping support, shroud assembly, and cables and cable supports.

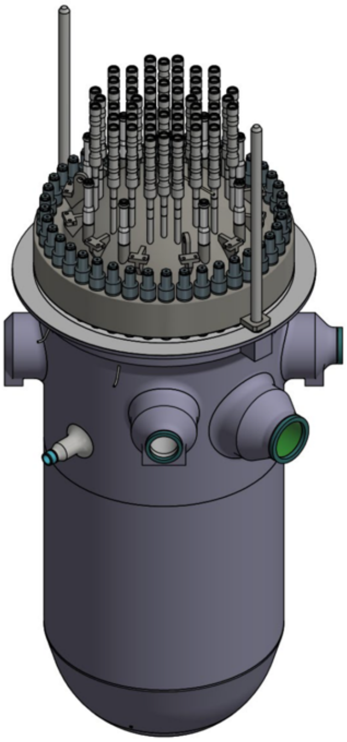

*Figure 9. Schematic of the AP300 RPV* [31].

The AP300 containment is a free-standing steel vessel surrounded by a concrete shield building with room for convective air-cooling between them. There is a water tank for passive containment cooling by gravity at the top. The containment shield building serves to protect the containment vessel and the components located inside it. Additionally, during off-normal conditions, the containment shield building shields the surroundings from radioactivity inside the containment.

The steam and power conversion system is of the same type as that typical of PWRs. There is one turbine and generator system per reactor. It is possible to dump all steam and to operate the plant off-grid; there is thus no need for reactor scram in case of a turbine trip. The condenser in the standard version is water-cooled, but it is also possible to operate the plant using an air-cooled condenser.

All safety-related components and structures are located in the nuclear island. The control room is located in a non-safety-related building.

There are three main power systems: a main alternating-current (AC) power system used during normal and off-normal conditions, the latter in which standby diesel generators may be used; a non-Class 1E [34] direct-current (DC) power and uninterruptible power supply (UPS) system for non-Class 1E instrument AC power; and a Class 1E and UPS system with reduced length of Class 1E cables because of the DC power sources being positioned close to where the power is used instead of being centrally located. Valves and other field-mounted components have been selected to be fail-safe and do thereby not require Class 1E control power.

The combination of a passive core-cooling system, a passive containment-cooling system, and an automatic depressurisation system is stated to keep the reactor safely shutdown during design-basis events. The passive core-cooling system comprises a C-shaped passive residual-heat removal heat exchanger partly located in an in-containment refuelling-water storage tank. There are also three sources of borated water for LOCA conditions: high-pressure core-makeup tanks, intermediate-pressure accumulators, and low-pressure injection and containment sump recirculation. Dedicated direct-vessel-injection lines are used for the emergency boron injection.

The passive containment-cooling system makes use of gravity, air pressure, convection, evaporation, and condensation to keep the containment cooled. It comprises a water storage tank located at the top of the inside of the containment shield building. The surfaces (interior as well as exterior) of the containment steel vessel are coated with zinc to increase wettability, increase heat conduction, promote surface bonding (of released species), and inhibit corrosion.

There is an automatic depressurisation system to depressurise the reactor coolant system during small-break LOCAs. It consists of several valve stages that open sequentially on protection and safety-monitoring system signals. Each group of the first stages has an inlet connected to the top of the PRZ and a discharge connected to the in-containment refuelling-water storage tank via spargers in the tank. If the core makeup tank level drops below a setpoint level, a signal is initiated to open the first stages. Some of the valves open after a time delay not to induce too high pipe loadings. The last-stage valves discharge directly to the containment atmosphere above the anticipated post-accident containment floodup water level. In each of the last-stage lines there are two valves (an isolation valve and a squib valve) in series. A second setpoint level in the core makeup tank initiates opening of the last stages.

There is a hydrogen control system that consists of three subsystems: the hydrogen-monitoring system, the hydrogen recombination system, and the hydrogen ignition system. The hydrogen-monitoring system consists of hydrogen sensors, pressure sensors, and processing and display units. The hydrogen recombination system consists of PARs at two locations in the containment. The hydrogen ignition system consists of hydrogen igniters throughout the containment that will ignite the hydrogen in case more hydrogen is generated than can be handled by the PARs. Initiation of the hydrogen ignition system is to be done manually if the core temperature exceeds an upper limit. This limit is set so that the system is initiated well in advance of the hydrogen concentration increasing above the capacity of the PARs.

Spent fuel can be stored in the in-containment refuelling-water storage tank, at the same elevation as the fuel in the core. This differs from the AP1000 design, where spent fuel is not stored in the containment building. The fuel rack in the tank comprises burnable absorbers. The proposed fuel cycle length is 36 months with flexibility of adopting 24 or 48 months.

The plant footprint is 8 300 m$^2$ for the power block buildings.

### 3.3.2. Novelties in Westinghouse AP300

Notable novelties (from a Swedish perspective) in AP300 are listed in this section. The main novel features in all shortlisted SMRs are explained in Section 4, where the potential need for further investigation or clarification of them also is discussed. Novel features in AP300 are:

- 1-loop PWR (with 1 hot leg, 2 cold legs, 1 SG, 2 RCPs)
- Passive core cooling
    - Natural circulation during accident conditions
- IVR of molten core
- Integrated RPV head package
- Spent fuel pool in containment
- Steel containment
- Passive containment cooling system
- Possibility to use air-cooled condensers
- Hydrogen igniters
- Filtered containment venting system not included in the standard version
- Load-following capability (via the MSHIM operating strategy)

### 3.3.3. Design and licensing status Westinghouse AP300

The preliminary design is planned to be finalised 2025, and USNRC design certification is envisaged for 2027 and possibility to start construction of a first-of-a-kind plant 2030. A GDA application was submitted to the UK Department of Energy and Net Zero in February 2024 [35]. There is an agreement between Westinghouse and Community Nuclear Power to build four AP300 reactors in the UK [36], and deployment of AP300 is also considered in Ukraine [37] and Canada [38]. No information on work to deploy it in Sweden has been found.

In the currently ongoing conceptual design phase, an approach to modularity is developed, where it is foreseen that smaller modules can be used to create larger structures. The aim is to be able to use standard-size shipping containers as much as possible for transportation of the modules.

The design is stated to comply with all international design and licensing regulations.

## 3.4. NuScale VOYGR

The main references for this section are the IAEA 2024 SMR catalogue [4], the NuScale website [39], the NuScale submittal of Revision 1 to standard design approval application available at the USNRC website [40], and an article published in Frontiers of Energy Research [41]. Additional references are given in the text.

### 3.4.1. Design description of NuScale VOYGR

NuScale VOYGR (Figures 10–12) is an integral PWR, i.e. a PWR in which the primary-circuit components are located inside the RPV. A VOYGR plant is based on power-generating modules of 250 $MW_{th}$ thermal and 77 $MW_e$ electrical capacity that can be combined in various numbers; plants of four, six, or twelve modules are the standard versions offered.

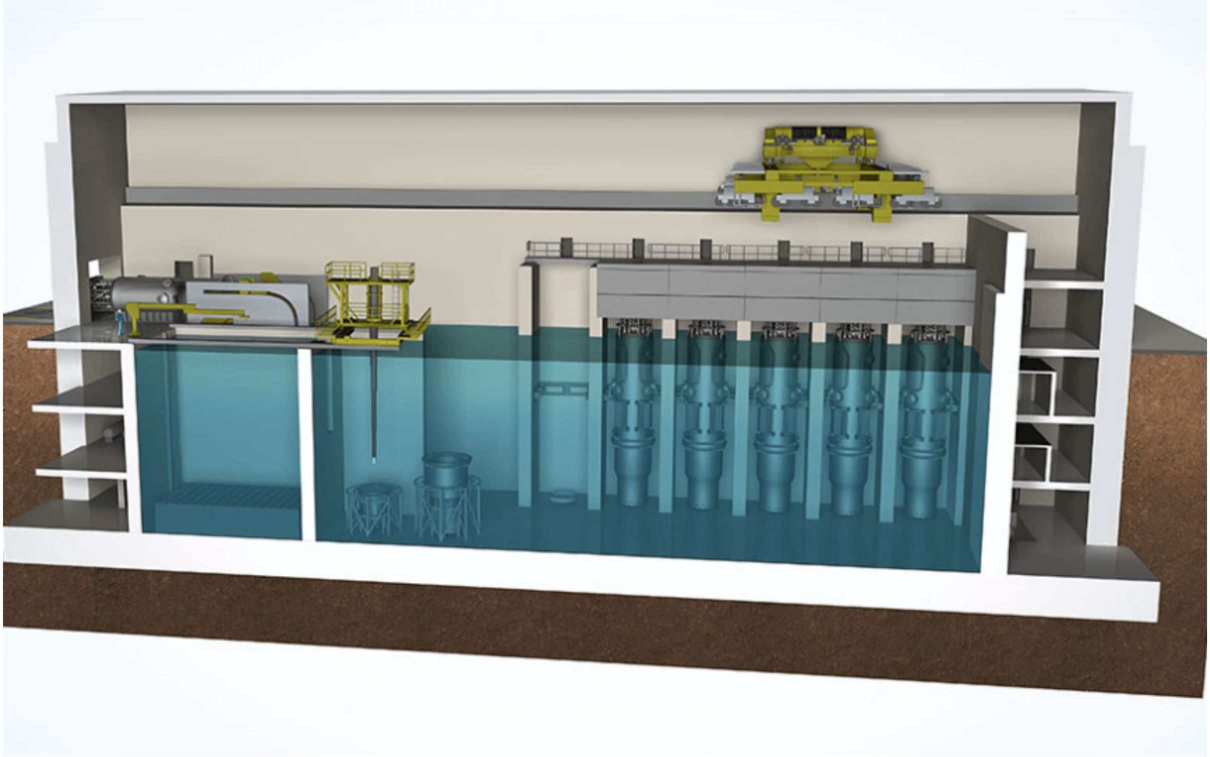

*Figure 10. Schematic of the reactor building of a VOYGR plant with six modules* [39].

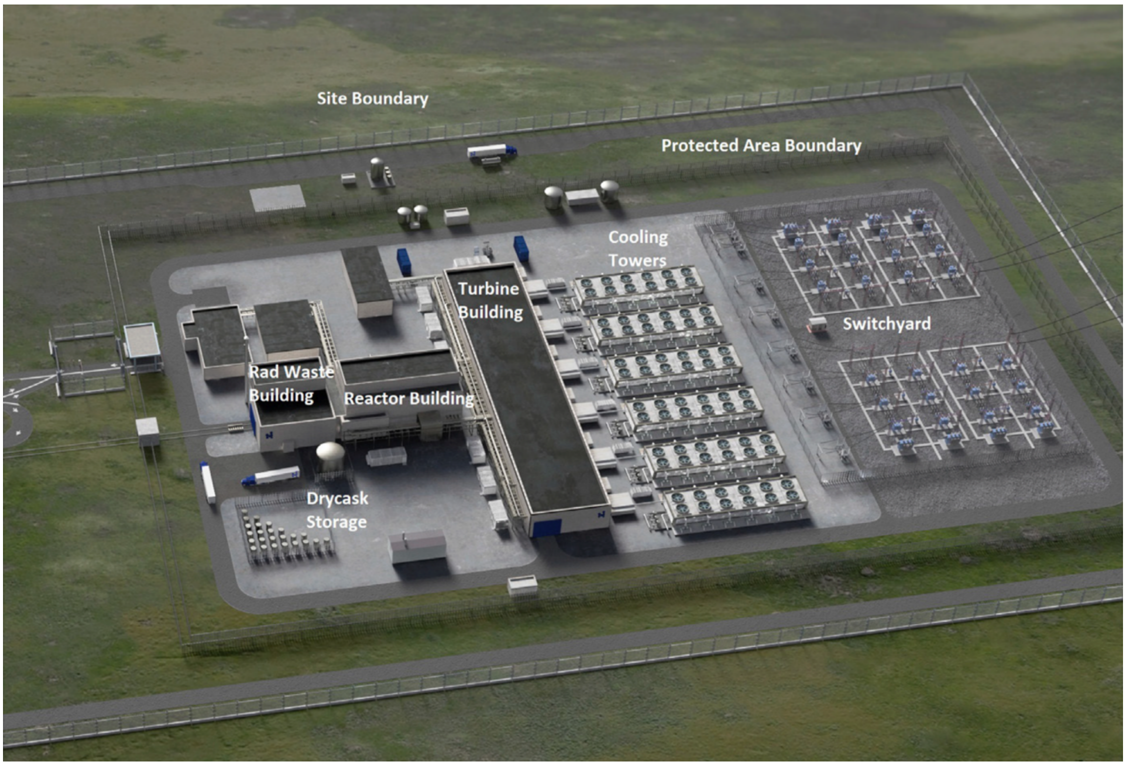

*Figure 11. Layout overview of a VOYGR plant with six modules* [41].

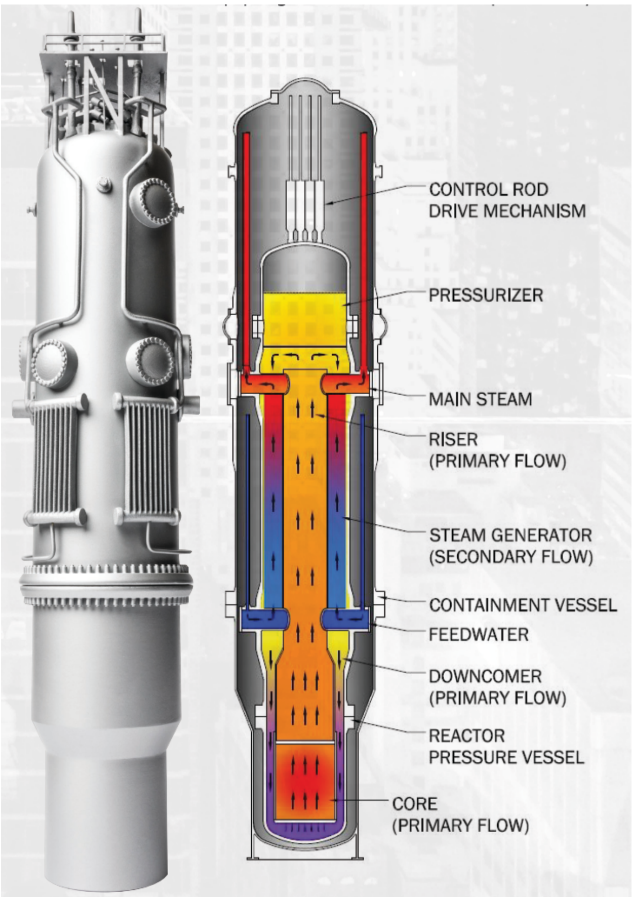

*Figure 12. Schematic of the VOYGR power module* [42].

One control room is used to control all the modules, which are located in the same reactor building. Coolant flow is provided using natural circulation. According to the IAEA SMR Catalogue 2024, there are passive safety features without any need for external power, operator action, or other auxiliary systems to keep the core cooled for an infinite amount of time during accident scenarios [4], and, according to the 2022 version of the same publication, used fuel in the fuel pool can be passively cooled for at least 150 days without additional water supply [14]. According to the standard design approval application, the passive safety can be maintained for at least three days [40].

The nuclear steam supply system consists of the reactor core, the two SGs, and the PRZ, all located inside the RPV. The core consists of 37 fuel assemblies of a 17 × 17 design, of approximately half the length of currently used fuel. The fuel is standard uranium dioxide with gadolinia burnable absorbers. There are 16 control rod assemblies comprising 24 control rods of SINCAD and boron carbide in stainless-steel cladding. 12 assemblies are for shutdown and the remaining four for other reactivity adjustments. Additionally, boron is dissolved in the coolant for reactivity control.

The RPV is 2.67 m in diameter and 17.7 m in height and designed for an operating pressure of 13.8 MPa. A cylindrical steel containment vessel of 4.5 m diameter and 23.1 m height surrounds each RPV and associated CRDMs and piping. A common reactor pool in the reactor building houses all modules side by side in separate sections divided by concrete walls.

The SGs are of helical-coil type with the primary-side water on the outside of the tubes. Part of the RPV forms the SG shell. The primary coolant flows downward outside the tubes, and the feedwater inside the tubes flows upward. The steam is specified to have a maximum moisture content of 0.10 weight-% during full-power operation.

There is one steam and power conversion system, including turbine generator and condenser, per module. The turbine is a 3 600 rpm, 16-stage, single-flow, condensing turbine. This differs from current nuclear power plants, where dual-flow turbines are used. Either water- or air-cooled condensers can be used.

The plant is passively cooled during all scenarios. There are three primary passive safety systems: the decay heat removal system, the emergency core-cooling system, and the containment system.

The decay heat removal system is a secondary-side system and has one train of 100 % capacity per SG. There is one decay heat removal condenser (located in the reactor pool) per train. An actuation signal leads to opening of the valves to this condenser and closing of the main steam and feedwater valves. The condensate from the decay heat removal condensers is used as the secondary-side medium in the SGs to keep the core cooled before being recycled to the condenser again.

The emergency core-cooling system is a primary-side system that comprises vent valves in the PRZ region at the top of the RPV and recirculation lines and valves. If the valves are opened, steam will leave the RPV at the top, condense inside the containment vessel, and return to the downcomer region of the RPV at a height above the core via the recirculation lines. The system also comprises soluble boron pellets at the top of the containment. These are dissolved by the steam/liquid water in an accident so that the boron concentration in the core is increased.

The containment system comprises the steel containment vessel and its isolation valves, which passively close at failure. The containment is designed to tolerate borated water, which is the normal environment during shutdown. The reactor pool surrounds the containment, and heat is removed from the containment via the water. If the water starts boiling, the boil-off followed by passive air cooling can provide sufficient cooling of the reactor.

The nominal fuel cycle length is 18 months with replacement of one third of the fuel, but there is flexibility to adjust if desired. It is possible to refuel one reactor module while the others are in operation. 10 years of used fuel can be stored in the spent fuel pool located adjacent to the reactor pool. There is room for dry-storage casks for at least 60 years of spent fuel onsite.

The estimated availability factor is > 95 % with an outage time for refuelling of ten days.

The reference size of a 12-module plant site is 140 000 $m^2$ [14].

### 3.4.2. Novelties in NuScale VOYGR

Notable novelties (from a Swedish perspective) in VOYGR are listed in this section. The main novel features in all shortlisted SMRs are explained in Section 4, where the potential need for further investigation or clarification of them also is discussed. Novel features in VOYGR are:

- Integral PWR
- Several reactors per reactor building and control room
- Natural circulation (passive core cooling)
    - During normal operation
    - During accident scenarios
- Helical-coil SGs
- Fuel assemblies of approximately half the length of the ones currently used
- Most part of the reactor pool located below ground level
- Steel containment
- Single-flow turbine
- Possibility to use air-cooled condensers
- Soluble boron pellets in the emergency core-cooling system
- Filtered containment venting system not included in the standard version
- Load-following capability

### 3.4.3. Design and licensing status NuScale VOYGR

A twelve-module version of 50 $MW_e$ electrical capacity per module has received standard design approval and design certification by USNRC. A standard design approval application review of a 6-module plant consisting of 77-$MW_e$ modules is currently being conducted by USNRC, with anticipated conclusion by the end of July 2025 [43].

A planned VOYGR plant at Idaho National Laboratory, the so-called Carbon Free Power Project launched by Utah Associated Municipal Power Systems and supported by the US Department of Energy, was cancelled in November 2023 [44]. Another plant is planned in Doicești in Romania in collaboration with RoPower Nuclear [45]. Manufacturing of RPVs and SG tubing for six modules began in 2023.

The design has been made to conform to US standards and codes.

# 4. Novelties in the shortlisted designs and associated needs for further investigation or clarification

Notable novelties, compared with existing and previous commercial reactors, in the shortlisted designs are listed and briefly described in this section. The descriptions are at a general, rather than design-specific, level. Each novelty might affect one or more of licensability, constructability, and operability/maintainability of the plants. Spent fuel management and (severe) accident mitigation and management are here considered part of operation/maintenance. It is, furthermore, stated if the novel features are new to commercial nuclear reactors in Sweden or worldwide. The information is summarised in Table 2. The need for attention for each novelty is briefly described in the succeeding sections. Minor novelties with minor need for attention regarding licensability, constructability, and operability/maintainability are not included in Table 2 or the succeeding descriptions.

*Table 2. Notable novelties in the shortlisted designs that might affect one or more of licensability, constructability, and operability/maintainability (as indicated by the Xs) of the SMRs.*

| **Novelty** | **Subcategory** | **Novel to Sweden or the world** | **Licens-ability** | **Con-struct-ability** | **Operability / maintain-ability** | **SMRs** |
|---|---|---|---|---|---|---|
| **Increased modularity** | | | X | X | X | |
| | Extensive modular construction | World | X | X | | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| | Several reactors per reactor building and control room | World[1] | X | X | X | VOYGR |
| **Enhanced natural circulation** | | | X | | X | |
| | Normal operation | Sweden[2] | X | | X | BWRX-300, VOYGR |
| | Transient and accident conditions | Sweden[2] | X | | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| **Increased passive safety** | | | X | | X | |
| | Passive core cooling | Sweden[2] | X | | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| | Passive containment cooling | Sweden[2] | X | | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| | Other passive safety features | Sweden/world[2] | X | | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |

| Novelty | Subcategory | Novel to Sweden or the world | Licens-ability | Con-struct-ability | Operability / maintain-ability | SMRs |
|---|---|---|---|---|---|---|
|  | New approach to safety-class components | Sweden/world[2] | X |  |  | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| **Novel containment designs** |  |  | X | X | X |  |
|  | New construction techniques | Sweden/world[3] | X | X | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
|  | Dry BWR containment | Sweden[4] | X |  |  | BWRX-300 |
| **Smaller size** |  | Sweden[5] | X | X | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| **Integral PWRs** |  | World | X |  | X | VOYGR |
| **Integral reactor isolation valves** |  | World | X |  | X | BWRX-300 |
| **Novel types of water chemistry** |  |  | X |  | X |  |
|  | Boron-free PWR coolant | World | X |  | X | Rolls-Royce SMR |
|  | Other novelties in water chemistry | Sweden |  |  | X | BWRX-300, Rolls-Royce SMR |
| **Novelties in the steam and power conversion system** |  |  | X | X | X |  |
|  | Novel turbine types | World |  |  | X | BWRX-300, VOYGR |
|  | Air-cooled condensers[6] | World[7] | X |  | X | AP300, VOYGR |
|  | Standard design adapted for cooling towers | Sweden |  | X | X | ?[8] |
| **Increased load-following capability** |  | Sweden/world | X |  | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| **Dry storage of spent fuel** |  | Sweden | X |  | X | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |

| Novelty | Subcategory | Novel to Sweden or the world | Licens-ability | Con-struct-ability | Operability / maintain-ability | SMRs |
|---|---|---|---|---|---|---|
| **Novelties in severe accident mitigation and management** | | | X | | X | |
| | Strategies to handle molten core[9] | Sweden | X | | | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| | Absence of automatic boron injection[10] | Sweden[11] | X | | X | BWRX-300, VOYGR[12] |
| | Absence of filtered containment venting[10] | Sweden[13] | X | | | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |
| | Hydrogen management | Sweden[14] | X | | X | AP300 |
| | Smaller EPZ | Sweden[15] | X | | | BWRX-300, Rolls-Royce SMR, AP300, VOYGR |

Notes:

[1] Experience of having more than one reactor per control room, but not as many as proposed for VOYGR, exists outside Sweden.

[2] Natural circulation and passive safety is to some extent used in Swedish and other reactors and to large extent in a few reactors outside Sweden.

[3] Some of the proposed containment concepts are used outside Sweden.

[4] Dry BWR containments were used in early, small BWRs outside Sweden.

[5] Some experience exists from the Ågesta reactor.

[6] Air-cooled condensers are an optional feature in AP300 and VOYGR.

[7] Air-cooled condensers are only used in a few very small nuclear power plants in Russia.

[8] Not clear from the design descriptions if the standard designs are adapted to cooling towers.

[9] IVR is proposed for the PWR SMRs and core catcher for BWRX-300. In VOYGR, damaged core is stated to be retained in the containment vessel [41]; because of the different design of the VOYGR containment, this can be classified as IVR rater than a core catcher. IVR is also to some extent aimed for in current Swedish reactors.

[10] Per standard design.

[11] Automatic emergency boron injection was previously not implemented in Swedish reactors.

[12] The soluble boron pellets in VOYGR provide automatic boron injection but are a novel solution.

[13] Filtered containment venting systems have been added to all Swedish reactors.

[14] Hydrogen igniters previously not used in Sweden.

[15] There are small emergency planning zones for nuclear facilities in Sweden that are not reactors.

## 4.1 Increased modularity

Modularity can refer to two different things, construction of reactors using pre-fabricated modules or the use of several reactor modules per reactor building and/or control room. It is, of course, possible to adopt both types of modularity for the same power plant.

For the construction using pre-fabricated modules one aspect needing attention is quality control, which is needed both for the modules themselves and for their correct attachment to one another. The control of the modules will thus likely (to some extent) need to be performed both at the factory where they are produced and at the reactor construction site. The implementation of quality control will be of importance for licensability and constructability.

Having several reactor modules per reactor building can have consequences in severe accident scenarios and might need consideration when performing work inside the reactor building (and potentially also other buildings). Licensability and operability/maintainability can thus be affected.

Having several reactors per control room is related to human performance and man–machine interaction. The possibility to separate cables and other safety-related components for the different reactors also needs consideration. Having several reactors per control room might thus impact all three of licensability, constructability, and operability/maintainability. Some experience of having more than one reactor per control room exists outside Sweden [46,47], but not as many as proposed for the VOYGR plants.

## 4.2 Enhanced natural circulation

Natural circulation is to some extent featured in current reactors but is typically a more prominent feature in SMR designs, where it is proposed for both normal operation and transient and accident conditions. BWR experience of using only natural circulation exists from the 220 $MW_{th}$/65 $MW_e$ Humboldt Bay and 183 $MW_{th}$/60 $MW_e$ Dodewaard reactors in the USA and the Netherlands, respectively, and from tests performed in larger BWRs (e.g. Forsmark 1) [48,49]. For example, flow instabilities, which could be of concern in natural-circulation BWRs, have been investigated [50,51]. The ESBWR reactor developed by GE Hitachi (but never built) is designed for natural circulation. In natural-circulation-only BWRs it is, obviously, not possible to use main-circulation pumps for reactor power control; instead, other means, e.g. feedwater temperature, have to be used. Natural circulation is, to some extent, implemented also in conventional PWRs, notably in conjunction with cooling via SGs for non-LOCA accidents [52].

Natural circulation, during normal operation as well as part of passive safety systems, needs consideration regarding licensability and operability/maintainability. The need for attention regarding passive safety systems is mentioned in Section 4.3.

## 4.3 Increased passive safety

Conventional reactors typically have a combination of active and passive safety systems [53] (with the AP1000 reactor relying on passive systems to keep the core cooled for three days [54]). The extensive use of passive safety systems in SMRs, being able to keep the core and the containment cooled for a few days or more, can thus be considered a novelty from a Swedish perspective.

The enhanced natural circulation is one of the reasons passive safety systems can be implemented in SMR designs. Additionally, heat conduction and convection, gravity, and pressurised systems are utilised to maintain the passive safety. Periodic and non-periodic (full-scale or non-full-scale) testing of the passive systems might be challenging and in some cases maybe impossible to perform. Thus, licensability and operability/maintainability might be affected by the extensive use of passive safety systems.

Because of the increased passive safety, it is possible to have a new approach to safety-class components. In the shortlisted SMRs, as well as in others, there are fewer safety-class components. The use of fewer safety-class components and different ways of separating and dividing electrical systems needs attention from the licensability and potentially also from the operability/maintainability perspective.

## 4.4 Novel containment designs

All Swedish reactors have containments of prestressed concrete [55]. Thus, the use of steel containments and the use of modular steel-plate composite systems to construct the containments or the surrounding shield buildings are novelties, although experience of steel PWR containments and steel-plate composite shield buildings exists outside Sweden [56,57]. The steel-plate composite materials (Figure 13) typically consist of steel plates connected to each other via tie bars with studs on the side of the plate facing the other plate [58]. Several plates can be welded together to form modules of various sizes. The modules can be produced in a factory and transported to the reactor construction site where they can be welded together before concrete is poured in them.

New standards/codes for the (composite) materials used might be needed, and quality control procedures need to be implemented. Additionally, long-term operation aspects need consideration, both for the steel containments and the steel-plate composite materials. Leak tightness is one such aspect. The new ways of constructing the containment thus need consideration from the perspectives of licensability and constructability and to some extent also from the perspective of (long-term) operability/maintainability.

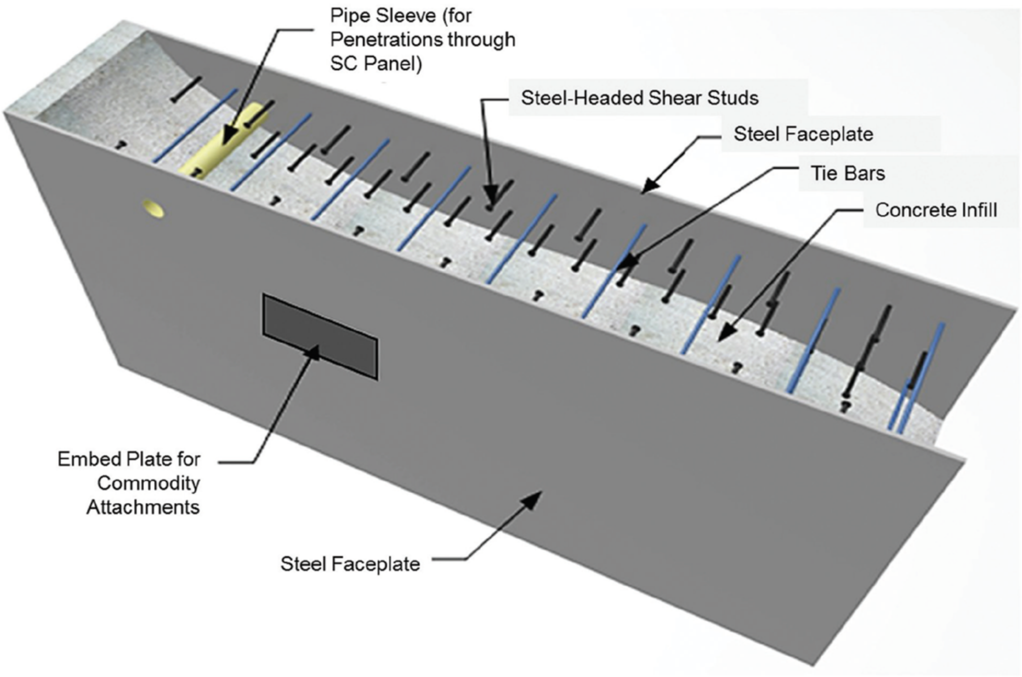

*Figure 13. Schematic of typical steel-plate composite material for walls* [56].

Additionally, the implementation of a dry BWR containment in BWRX-300 can be considered a novelty, although dry containments were used in early, small BWRs outside Sweden [49]. It mainly could mainly affect licensability (in addition to likely leading to simpler operability/maintainability because of the reduced number of in-containment components).

## 4.5 Smaller size

The smaller size of the SMR power plants might be problematic mainly from three aspects, the first being difficulties separating/dividing safety systems and components, the second being difficulties inspecting/repairing/replacing components, and the third being the smaller core. The former two aspects relate to all three of licensability, constructability and operability/maintainability of the plants. The latter of the three aspects is explained in this section.

Making the core smaller than in current reactors will imply some differences that need attention. Notably, the neutron leakage is higher from a smaller core. This makes the neutron economy worse, often leading to a lower achievable burnup and more activation by neutrons in materials surrounding the core. There will thus likely be more radioactive waste from smaller reactors, considering spent nuclear fuel as well as activated materials. However, to determine whether this is the case, detailed calculations are needed for each specific design and fuel cycle length. In relation to waste, the different fuel assembly length proposed for the SMRs will need adaptation of the fuel cannisters used for transportation and final repository.

In addition to generation of waste, neutron activation could potentially lead to more rapid material degradation. The neutron flux experienced by the various components should be relatively easy to estimate by calculations, but the potential material degradation might need experimental studies.

In conclusion, the smaller size of the core and its immediate surroundings needs consideration mainly from an economic perspective, and potentially also from a long-term operation perspective, and licensability and operability/maintainability can be affected. It should be noted that if SMRs, in contrast to large-scale reactors, are used also for purposes other than electricity production the amount of waste per used unit energy can be smaller for the SMRs.

## 4.6 Integral PWRs

The use of integral PWRs is a major difference compared with current PWRs. Components that are altered are RPV, SGs, PRZ, and CRDMs. Pump types not previously used in nuclear reactors have been considered for forced-circulation integral PWRs, e.g. in the previous version of the NUWARD reactor [4]. Functionality of all new components needs to be verified.

The use of an integrated PRZ eliminates the risk of pipe breaks between it and the RPV, thus enhancing safety. There might, however, be other failure modes because of the integrated PRZ that could need consideration. The same is valid for the integrated SGs.

In the VOYGR reactor, the CRDMs are located outside the RPV but inside the power module. The location of the CRDMs in this manner, or potentially inside the RPV in other integral SMRs, might lead to difficulties regarding inspections, maintenance, and repairs.

Integral PWRs need attention mainly from the perspectives of licensability and operability/maintainability. In addition to the abovementioned aspects, the potential difficulties relating to the smaller size, as described Section 4.5, apply also to integral PWRs.

## 4.7 Integral reactor isolation valves

The integral reactor isolation valves of BWRX-300 and their attachment to the RPV are shown in Figure 14. These valves play a key role in the overall plant safety design, and, together with the ICS, secure isolation of the reactor system in case of accidents, which is the main reason BWRX-300 can be designed with a dry containment. As this overall RPV isolation solution is new, it will likely be reviewed from an operability/maintainability point of view; thus the overall licensability of the design might be impacted. Also, the long-term operability of the RPV needs to be verified with valves attached to it.

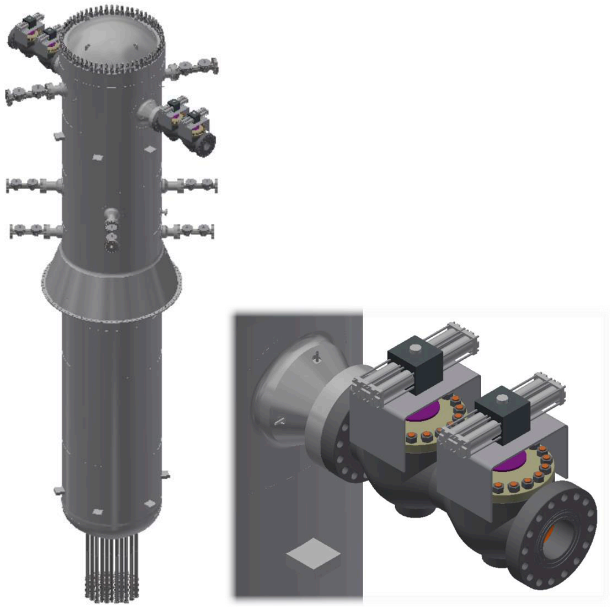

*Figure 14. Schematic of the integral reactor isolation valves of BWRX-300 and their connection to the RPV* [10].

## 4.8 Novelties in water chemistry

The most notable novelty in water chemistry is the proposed use of boron-free PWR coolant in the Rolls-Royce SMR. Not using soluble boron means that reactivity control needs to be managed relying only on burnable absorbers and control rods.

The benefits of not using boron are that the risk of boron dilution accident is eliminated, that the system for chemical control can be simplified, and that the risk of boron leaking out from that system and potentially causing corrosion damage is avoided. Additionally, less liquid waste will be generated, but at the cost of more solid waste due to the additional reactivity control by control rods and burnable absorbers.

To manage the reactivity control and core stability without B in the coolant can be challenging [59–61]. Detailed core calculations for each specific core are needed to clarify if burnable absorbers and control rods will be enough to maintain the desired reactivity. Furthermore, increased use of control rods leads to altered power distribution, and use of burnable absorber rods leads to increased power burden on the surrounding fuel rods [61]. Thus, the fuel performance can be affected by the use of boron-free PWR coolant.

The water chemistry of the plant needs to be carefully chosen so that corrosion of various systems does not occur. Commonly, potassium hydroxide is used to control the pH in VVERs and lithium hydroxide in non-VVER-type PWRs. An advantage of using potassium hydroxide instead of lithium hydroxide, as planned for the Rolls-Royce SMR, is that lithium hydroxide in absence of boric acid might lead to increased zirconium alloy fuel cladding corrosion [62].

## 4.9 Novelties in the steam and power conversion system

Three novelties in the steam and power conversion system are discussed here. They are novel turbine types, air-cooled condensers, and SMR standard designs being adapted for the use of cooling towers.

There are two main novelties regarding turbines. The first is the size of the turbines, ranging from 77 $MW_e$ for VOYGR to 470 $MW_e$ for Rolls-Royce SMR, and the other is the use of turbine types not commonly used in the nuclear industry, i.e. the only slightly modified off-the-shelf turbine proposed for BWRX-300 and the single-flow turbine proposed for VOYGR.

Regarding the size, there should not be much difference compared with other sources of electricity production having turbines in the same range. Additionally, the Rolls-Royce SMR turbine is similar in size to some of the turbines that previously have been used in Swedish nuclear power plants. There will thus not be much need for further investigation, although it could be useful to understand how the electricity system behaves with turbines of different sizes.

For the use of off-the-shelf turbines, more information about how the turbines are modified and the properties of the steam are needed to assess how well the turbines will work. Steam from light-water reactors is, in contrast to steam produced from combustion processes taking place at higher temperatures, not superheated. Therefore, in light-water reactors reheaters are used between the high- and low-pressure turbines [63]. If the temperature of the steam is too low, water droplets might form and cause erosion damage to the turbine blades. For the use of single-flow turbines, it needs to be verified that they will function as intended. For conventional nuclear reactors, single-flow turbines are not suitable, mainly because of the large steam volume.

Air-cooled condensers are proposed as one option for AP300 and VOYGR. While air-cooled condensers are used for non-nuclear power plants, they are only used for very few and very small nuclear reactors [64]. It might be easier to use air-cooled condensers for SMRs than large reactors, but they need to be assessed from technical as well as economic and regulatory perspectives.

If the standard version of an SMR is adapted for the use of cooling towers, there are likely differences in the planned height of the condensers compared with what is optimal for a plant using cooling water from the sea. Design modifications might thus be necessary to make full use of the cooling advantages offered by the sea.

The novelties in the steam and power conversion system thus mainly relate to operability/maintainability, but also to licensability and constructability.

## 4.10 Increased load-following capability

All shortlisted and most other SMR designs are claimed to have load-following capability, i.e. capability to alter the electric power output depending on electricity demand. To some extent there is load-following capability in the current Swedish reactors [65], but the SMRs typically have design features for increased load-following operation.

There are two main ways of load-following, one being to divert the steam flow from the turbine, and potentially use the heat for other purposes, and the other to change the reactor power output [66]. This latter option is achieved by varying the reactivity. Control rods and/or soluble boron can be used for this purpose. Typically, specific control rods (commonly referred to as “grey rods” in PWRs) that do not absorb too many neutrons are used for load-following, whereas other control rods that absorb more neutrons are used for shutdown. Grey rods have so far not been used in Swedish reactors but are in use elsewhere [67]. It is additionally possible to control the reactivity by controlling the feedwater temperature.

The main known disadvantage of load-following operation (not using the steam for purposes other than electricity production) is that the fuel utilisation is not as efficient as in non-load-following operation [65]. There might also, depending on the load-following characteristics, be a need for new requirements on the fuel. Additionally, load-following can potentially lead to increased wear on various components, e.g. RPV and turbine. The potential use of load-following will thus have practical and economic implications, and needs consideration from the perspectives of licensability and operability/maintainability.

## 4.11 Dry storage of spent fuel

In Sweden all spent fuel is stored in water pools at the interim storage facility Clab in Oskarshamn [68]. Dry storage of spent fuel is, however, common in other countries [69]. In a dry storage, passively cooled cannisters of metal and concrete are typically used to contain the spent fuel.

If many SMRs will be built in Sweden the capacity of Clab will not be enough. It could thus be beneficial from economic and practical aspects to have dry fuel storage at the reactor sites (as is proposed by the reactor designers). Even if there is wet-storage capacity in Clab, dry storage might be advantageous if SMRs are deployed at locations not easily connected to the current transportation system by sea. In addition to new legislation and safety analyses, equipment that is new to Sweden might be needed for handling the fuel onsite. Dry storage of spent fuel could mainly affect licensability, and to some extent also operability/maintainability.

## 4.12 Novelties in severe accident mitigation and management

The new approach to safety and safety systems, notably using passive features, makes it easier to mitigate severe accidents. In case of accidents in which the integrity of the containment is broken, the resulting release of radioactivity will likely be smaller in SMRs than in large-scale reactors. The combination of the lower risk of accidents and the expected lower impact on the environment (including humans) might make it possible to implement less strict regulatory requirements on some reactor systems and emergency planning procedures.

Strategies to avoid hydrogen explosions to decrease the risk of severe accidents are implemented in current reactors. In the SMRs, passive systems in the form of low-oxygen environment and/or PARs and active systems in the form of hydrogen igniters are proposed. Most of the proposed measures are used in current Swedish reactors, but the use of hydrogen igniters is a novelty.

In case of accidents leading to core melt, IVR of the molten core or a core catcher, i.e. ex-vessel, in-containment retention of the molten core, will lead to lower risk of releasing radioactivity to the surroundings. Typically, IVR, which can be achieved by cooling the RPV from the outside, and potentially also by injecting water to the RPV [70], is easier to implement in small reactors because of their lower core power. Because of the control rods being inserted from below the RPV in BWRs, it is typically more difficult to design BWRs for IVR. In addition to handling of the molten core, a lower pressure buildup in the containment compared with conventional reactors is needed to minimise the risk of radiaoctive release.

Because of the lower risk of accidents and resulting release of radioactivity, novel approaches to emergency boron injection are proposed for some designs. Notably, the use of soluble boron pellets in the VOYGR containment is a feature that is new. Additionally, the absence of automatically initiated boron injection in the standard design of BWRX-300 is worth mentioning here. Although non-automatic emergency boron injection has previous been used in Swedish reactors, it has been implemented to fulfil updated regulations [71]. Also, filtered containment venting, which currently is required by the Swedish regulations [72], is not included in the standard designs of the SMRs.

The lower risk of accidents in combination with the expected smaller radioactive release in accident scenarios might allow for having a smaller emergency planning zone. This is what is proposed by the reactor designers, and it is often seen as important from the perspective of utilising SMRs for more than electricity production, where it is beneficial to have the steam produced close to the consumer.

The new approaches to severe accident mitigation and management are mainly related to the licensability of the SMRs, but at least the absence of automatic boron injection and the hydrogen igniters could also be of importance for the operability/maintainability. If required, it should be relatively easy to change the designs to implement automatic emergency boron injection and add a filtered containment venting system.

# 5. Summary and conclusions

In this research project performed within the Swedish competence centre ANItA, proposed designs of land-based light-water SMRs have been reviewed. A shortlist of four SMRs that, based on the currently available information, are deemed the most probable to be built for electricity production in Sweden in the relatively near future has been established. The shortlist (without any ranking order) consists of the following four SMRs:

- GE Hitachi BWRX-300
- Rolls-Royce SMR
- Westinghouse AP300
- NuScale VOYGR

Each of the designs incorporates a number of features that are novel compared with the currently (and previously) operable nuclear reactors in Sweden; some of the features are novel also to the world. The implementation of many of the novelties necessitates improved understanding of them. Additionally, there is a need to make sure that there are no contradictions between regulations and the new features. Therefore, these types of novelties in the shortlisted SMRs were identified, and the need for further investigation or clarification of them was pointed out. Each of the novelties could have an impact on the licensability, constructability, and operability/maintainability of the SMRs.

The identified novelties are the following:

- increased modularity
- enhanced natural circulation
- increased passive safety
- novel containment designs
- smaller size (of the reactor and power plant)
- integral PWRs
- integral reactor isolation valves
- novel types of water chemistry
- novel features in the steam and power conversion system
- increased load-following capability
- dry storage of spent fuel
- novel features in severe accident mitigation and management

All of these, with some subcategories excepted, need further investigation or clarification to better understand how they will impact the licensability and the operability/maintainability of the SMRs. For assessment of the constructability, the increased modularity, the novel containment designs, the smaller size, and part of the novelties in the steam and power conversion system are the novelties that need further investigation or clarification.

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# Appendix: Design data of the shortlisted SMRs

Design data of the shortlisted SMRs are shown in Table A1.

*Table A1. Design data of the shortlisted SMRs.*

| | **BWRX-300** | **Rolls-Royce SMR** | **AP300** | **VOYGR** |
|---|---|---|---|---|
| **Type of reactor** | BWR | PWR | PWR | PWR |
| **Integral PWR design** | -[1] | No | No | Yes |
| **Power ($MW_{th}$ / $MW_e$)** | 870 / 300 | 1358 / 470 | 990 / 330 | 250 / 77 (gross, per module) |
| **Core inlet / outlet temperature (°C)** | 270 / 288 | 295 / 325 | 302 / 325 | 249 / 316 |
| **Operating pressure, primary / secondary side (MPa)** | 7.2 / -[1] | 15.5 / 7.8 | 15.4 / 7.35 | 13.8 / 4.3 |
| **Coolant volume ($m^3$)** | 1 820 | -[2] | -[2] | -[2] |
| **Natural circulation during normal operation** | Yes | No | No | Yes |
| **Natural circulation during transient and accident conditions** | Yes | Yes | Yes | Yes |
| **Passive cooling time (days)** | 7[3] | 3 | 3 | Infinite (150 days passive cooling of used fuel) |
| **RPV height (m)** | 26 | 7.9 | 10.9 | 17.7 |
| **RPV diameter (m)** | 4 | 4.2 | 3.6 (inner diameter) | 2.7 |
| **RPV wall thickness (mm)** | 136 | -[2] | -[2] | -[2] |
| **RPV weight (ton)** | 485 | 150 | 275 | -[2] |
| **RPV material** | SA-508 | SA-508 Grade 3 Class 1 + 309L and 308L cladding, safe ends of 316LN | -[2] | SA-508 Grade 3 Class 1 (Class 2 for top head) |
| **Fuel type** | $UO_2$ | $UO_2$ | $UO_2$ | $UO_2$ |

| | BWRX-300 | Rolls-Royce SMR | AP300 | VOYGR |
|---|---|---|---|---|
| **Fuel enrichment (wt% $^{235}$U)** | < 4.95 (avg 3.81) | < 4.95 | < 5 | < 4.95 |
| **Number of fuel assemblies** | 240 | 121 | 121 | 37 |
| **Fuel assembly length (m) / length of fuel stack (m)** | 4.468 / 3.810 | -[2] / 2.8 | -[2] / 3.66 | 2.4 / 2.0 |
| **Fuel cycle length (months)** | 12–24 | 18 | 24–48 | 18 |
| **Part of core replaced (%)** | 13–30 | 33 | ~26 (2 year fuel cycle)<br>or<br>50 (3 year fuel cycle) | 33 (flexible) |
| **Refuelling time (days)** | 10–20 | 18 | -[2] | 10 (possible to operate the cores not being refuelled) |
| **Average discharge burnup (GWd/t)[4]** | 60 | ~65[5] | -[2] | 50–55[5] |
| **Maximum discharge burnup (GWd/t)[4]** | 65 | ~65[5] | -[2] | 50–55[5] |
| **In-plant storage capacity of used fuel (years)** | 8<br>+<br>1 cycle used and new fuel | -[2] | -[2] | 10 |
| **In-plant storage capacity of used fuel (#fuel assemblies)** | 660 | 160 | -[2] | 600 |
| **Means of reactivity control** | Control rods, burnable absorbers | Control rods, burnable absorbers | Soluble boron, control rods, burnable absorbers | Soluble boron, control rods, burnable absorbers |
| **Burnable absorber material** | $Gd_2O_3$ | $Gd_2O_3$ | $Gd_2O_3$ | $Gd_2O_3$ |
| **Number of control rods (BWR) / control** | 57 | 89[6] | 45 | 16 (4 + 12) |

| | **BWRX-300** | **Rolls-Royce SMR** | **AP300** | **VOYGR** |
|---|---|---|---|---|
| **rod assemblies (PWR)** | | | | |
| **Primary water chemistry** | H, NobleChem, Zn | No B, KOH, Zn | B, LiOH, Zn | B, LiOH |
| **Number of SGs** | -[1] | 3 | 1 | 2 |
| **SG type** | -[1] | Vertical U-tube | Vertical | Integral helical coil |
| **SG material** | -[1] | -[2] | -[2] | Tubes: SB-163 Alloy 690 |
| **Number of primary pumps** | 0 | 3 | 2 | 0 |
| **Containment design** | Steel-plate composite materials | Steel containment | Steel containment | Steel containment module surrounding the integral reactor |
| **Large part of containment below grade** | Yes | No | No | Yes |
| **Number of reactors per reactor building / control room** | 1 / 1 | 1 / 1 | 1 / 1 | 4, 6, 12 / 4, 6, 12 |
| **Total concrete ($m^3/MW_e$)** | 198.3 | -[2] | -[2] | -[2] |
| **Safety-related concrete ($m^3/MW_e$)** | 61.7 | -[2] | -[2] | -[2] |
| **Cooling water need ($m^3/s$)** | 10.16 (with 13 °C temperature rise) | -[2] | -[2] | -[2] |
| **Plant footprint, buildings ($m^2$)** | 9 800 | 18 550 | 8 300 | -[1] |
| **Plant footprint, fence ($m^2$)** | 27 100 | 100 000 | -[1] | 140 000[7] |
| **Load-following capability** | Yes, 50–100 %, 0.5 %/min | Yes, 50–100 %, 3–5 %/min | Yes | Yes |
| **Estimated EPZ radius (km)** | 0.5 | -[2] | -[2] | Within or at the site boundary |
| **Designed for 50 or 60 Hz** | 50 and 60 | 50 | 50 and 60 | 60[8] |
| **Designed according to metric/imperial system** | Metric | Metric | Metric | Imperial[9] |
| **Design life (years)** | 60 | 60 | 80 | 60 |

| | BWRX-300 | Rolls-Royce SMR | AP300 | VOYGR |
|---|---|---|---|---|
| **Design based on previous design** | Yes (ESBWR) | No | Yes (AP1000) | No |
| **Developer has previously delivered reactors** | Yes | Yes | Yes | No |
| **Developer has previously delivered commercial reactors** | Yes | No | Yes | No |
| **Developer has previously delivered commercial reactors in Sweden** | No | No | Yes | No |

Notes:

[1] Not applicable.

[2] Not found in literature or provided by reactor developer.

[3] Assuming only two of three ICS trains available.

[4] Burnup can vary depending on fuel design and cycle characteristics.

[5] Not specified what is average and what is maximum discharge burnup.

[6] According to Reference [A1].

[7] For a 12-module plant.

[8] Based on the information that the rotational speed of the turbine is 3 600 rpm.

[9] Based on the design descritions in the NuScale submittal revision 1 to standard design approval application to USNRC.

## References

[A1] ONR, Generic Design Assessment of the Rolls Royce SMR – Step 2 assessment of Fuel and Core, 2024. https://www.onr.org.uk/generic-design-assessment/assessment-of-reactors/rolls-royce-smr/step-2-gda-statement-for-the-rolls-royce-smr/.