# Novel Design features of proposed

# light-water smrs – a swedish perspective

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**Abstract**

Land-based light-water small modular reactors (SMRs) are an option for adding new nuclear capacity in Sweden, mainly to produce electricity but also heat and hydrogen. Compared with the current Swedish reactor fleet, the SMRs entail a number of novel features that could be potential barriers to deploying the SMRs in Sweden. Some of the novelties are or have been in use in nuclear reactors in other countries, whereas some are new to the world. Five proposed land-based light-water SMR designs, one boiling-water reactor and four pressurised-water reactors (PWRs), that are considered relatively likely to be built in Sweden in the near future were selected, and notable novelties needing further investigation were identified based on these designs. Licensing, construction, and operation and maintenance of the SMRs can be affected by the novelties. The pointed-out novelties are modularity, the smaller size of SMRs, integral PWRs, boron-free PWR coolant, enhanced natural circulation, increased passive safety, novel containment designs, increased load-following capability, and dry storage of spent fuel. All of these novelties can affect licensing and almost all of them can affect operation and maintenance of the SMRs. Three of them, the modularity, the smaller size, and the novel containment designs can also affect the construction. Further investigation of the novel features can increase the understanding of them and decrease the barriers to implementing them in the designs and deploying SMRs, in Sweden as well as in other countries.

## INTRODUCTION

Small modular reactors (SMRs) are considered an option for adding new nuclear capacity in Sweden to meet the future electricity demand and to produce heat and hydrogen [1]. Of particular interest for the relatively near future are land-based light-water SMRs. More than 25 such SMR designs have been proposed [2–5]. They contain several novelties compared with the currently and previously operable Swedish reactors, aside the fact that they are SMRs. Such novelties could be potential barriers to deploying SMRs, in Sweden as well as in other countries, if they are not well understood and if adequate measures to handle them are not implemented. Licensing, construction as well as operation and maintenance of the SMRs might meet obstacles because of the novelties.

There are currently six operable commercial nuclear reactors for electricity production in Sweden and six permanently shut down [6]. Of these 12 reactors nine are boiling-water reactors (BWRs) delivered by ASEA Atom or ABB Atom and three pressurised-water reactors (PWRs) delivered by Westinghouse. They started operation between 1972 and 1985 and are generation II plants.

In this work, novelties, based on five proposed SMR designs, are pointed out and described with respect to their potential implications on deployment of SMRs in Sweden. The five designs are considered relatively likely to be built in Sweden in the near future, mainly for the purpose of producing electricity but potentially also to produce heat or hydrogen. Following short design descriptions, notable novelties are discussed on a general rather than design-specific level. The discussion and conclusions in this paper should, at least to a certain extent, be applicable also to other countries.

## considered SMR designs

The SMR designs considered in this work are listed in Table 1. One is a BWR- and four are PWR-type reactors.

TABLE 1. The SMR designs along with general information.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| SMR | Type | Electrical output (MW) | Developer | Country |
| BWRX-300 | BWR | 300 | GE-Hitachi | USA |
| Rolls-Royce SMR | PWR | 470 | Rolls-Royce | UK |
| AP300 | PWR | 300 | Westinghouse | USA |
| VOYGR | PWR | 77/module | NuScale | USA |
| NUWARD | PWR | 2170 | EDF | France |

### Design descriptions

In the following design descriptions focus is on features of interest for the purpose of this work. More detailed descriptions of the SMRs can be found elsewhere [2,4,7–10]. In addition to the features outlined below, there are common features of the designs that (from a Swedish perspective) can be considered novelties. Three notable such are covered in this work. They are that SMRs have a smaller size than conventional nuclear power plants, that they allow for more flexible load-following than the Swedish reactors, and the potential use of an on-site dry storage of spent nuclear fuel. Additionally, all the designs are planned to be built using modular construction (to a degree that is not always specified by the developer).

#### BWRX-300

BWRX-300 [7] is a BWR of 870 MW thermal and around 300 MW electrical capacity developed by GE-Hitachi. It is similar to current BWRs but relies on natural circulation of the coolant and therefore has no primary pumps. The core contains 240 standard fuel assemblies with UO2 fuel pellets and Zr alloy cladding. There is a chimney between the core and the steam separators to enhance the natural circulation. All reactor pressure vessel (RPV) nozzles are located well above the core, and reactor isolation valves integrated to the RPV are located at all nozzles larger than 19 mm to mitigate loss-of-coolant accidents (LOCAs) in case of breaks on the corresponding pipes.

All safety features are passive and specified to be able to keep the core cooled for at least seven days during accident scenarios. An isolation condenser system provides core cooling in accident conditions. There is also passive cooling of the containment, complemented by active cooling during normal operation. In case of malfunctioning normal shutdown of the plant, boron can be injected via a manually initiated system to bring the reactor to a subcritical state.

The containment, a major part of which is located below grade, is planned to be built using steel-plate composite. It is surrounded by a reactor building. Contrary to current BWRs, the containment is dry.

#### Rolls-Royce SMR

The Rolls-Royce SMR [8] is a three-loop non-integral PWR of 1358 MW thermal and 470 MWelectrical capacity similar to current PWRs but smaller. The core contains 121 1717 fuel assemblies, that are slightly shorter than currently used fuel assemblies, with UO2 fuel pellets and Zr alloy cladding. The coolant is boron-free; reactivity control is achieved by control rods (CRs) and burnable absorbers. The RPV has an integrated head package comprising, among other things, the control rod drive mechanisms (CRDMs). There is one pressuriser and three vertical U-tube steam generators (SGs) with a centrifugal reactor coolant pump mounted directly at the outlet nozzle of each SG. The circulation during normal operation is thus forced, but during accident scenarios there are passive safety features (including natural circulation) specified to be able to keep the core cooled for at least three days. The containment is made of steel.

The power plant is planned to be built using a high degree of modularity, meaning that road-transportable modules will be built in a factory and assembled at the construction site.

#### AP300

AP300 [4] is a one-loop non-integral PWR of about 1000 MW thermal and 300 MWelectrical capacity developed by Westinghouse. It is similar to the AP1000 plant of which six now are operational in USA and China. The core contains 121 standard 1717 fuel assemblies planned to employ of chromia- and alumina-doped UO2 pellets and Zr alloy cladding. Soluble boron in the coolant, CRs, and burnable absorbers are used for reactivity control. Like in the Rolls-Royce SMR, there is an integrated RPV head package comprising CRDMs and other components.

The circulation during normal operation is forced, but during accident scenarios there are passive safety features (including natural circulation) specified to be able to keep the core cooled for at least seven days.

The containment is a steel vessel surrounded by an outer concrete vessel with a space between them to allow for convective air-cooling.

#### VOYGR

VOYGR [9] is an integral PWR of 250 MW thermal and 77 MW electrical capacity designed to be built in units of four, six, or twelve modules per reactor building and control room. It is developed by NuScale. The core contains 37 1717 fuel assemblies with UO2 pellets and Zr alloy cladding of half the height of currently used fuel assemblies. Soluble boron in the coolant, CRs, and burnable absorbers are used for reactivity control. In addition to the core, the two SGs, which are of helical-coil type, and the pressuriser are located inside the RPV. The circulation is natural during normal operation, and there are passive safety features specified to be able to keep the core cooled for an infinite amount of time and used fuel in the fuel pool for at least 150 days.

A cylindrical steel containment vessel surrounds each RPV and its associated CRDMs and piping. All modules are located in a common reactor pool in the reactor building in sections separated by concrete walls. The modules are to most part located below grade.

#### NUWARD

NUWARD [10]is an integral PWR of 2540 MW thermal and 2170 MW electrical capacity developed by EDF. There are two reactors per unit. The core contains of 76 1717 fuel assemblies, shorter than those in current reactors, with UO2 fuel pellets. In addition to the core there are CRDMs, six plate-type SGs for normal operation and two for accident conditions, and pressuriser inside the RPV. The coolant is boron-free; reactivity control is achieved by CRs and burnable absorbers. The circulation during normal operation is forced, using six horizontal canned-rotor pumps mounted on the RPV, but during accident scenarios there are passive safety features (including natural circulation) specified to be able to keep the core cooled for at least seven days.

The containment is made of steel and located in the reactor pool. The pool is planned to most part to be located below grade.

### Novelties

Novelties in the abovelisted designs that are important to consider for further investigation are discussed in this section. The novelties considered are modularity, the smaller size of SMRs, integral PWR designs, boron-free PWR coolant, enhanced natural circulation, increased use of passive safety systems, novel containment designs, increased load-following capability, and dry storage of spent nuclear fuel. Licensing, construction, and operation/maintenance of the SMRs might be affected by these novelties. Fuel cycle back-end aspects and decommissioning are here considered to be part of operation/maintenance. Table 2 shows which novelties affect which of these categories.

TABLE 2. Novelties in the SMR designs considered and which of the categories licensing, construction, and operation/maintenance they might affect (as indicated by the Xs).

|  |  |  |  |
| --- | --- | --- | --- |
| Novelty | Licensing | Construction | Operation/maintenance |
| Modularity | X | X | X |
| Smaller size | X | X | X |
| Integral PWRs | X |  | X |
| Boron-free PWR coolant | X |  | X |
| Enhanced natural circulation | X |  | X |
| Increased passive safety | X |  | X |
| Novel containment designs | X | X |  |
| Increased load-following capability | X |  | X |
| Dry storage of spent fuel | X |  |  |

Modularity can refer to modular construction (i.e. fabrication and on-site assembly of individual modules) or the use of more than one reactor module per power-generating unit. The proposed extensive use of modular construction in SMRs is novel compared with most large-scale reactors which have to a much smaller extent been built using pre-fabricated modules. The increased modular construction might require new approaches to quality control, that to some extent needs to be performed both at the module factory and at the reactor construction site. Licensing and construction might thus be affected by the increased modular construction.

The use of several reactors per power-generating unit means that more than one reactor will be placed in the same reactor building and will be controlled from the same control room. Having more than one reactor per reactor building can have consequences in accident scenarios and might restrict when different types of jobs can be performed. Regarding having a common control room for several reactors, the possibility to separate cables etc. for the individual reactors might be affected. There will also be more units for the operators to control, meaning that man–machine interaction aspects need consideration. Licensing, construction, and operation/maintenance might thus be affected by the use of several reactors per power-generating unit.

The smaller size of SMRs can be considered a novelty of potential interest to investigate further. A smaller core leads to a higher neutron leakage and a corresponding worse neutron economy. Higher neutron leakage might also affect surrounding materials, potentially leading to more rapid degradation. A smaller size of the power plant might make it more difficult to separate safety-related cables and equipment. Additionally, it can be more difficult to inspect, repair, or replace components in a smaller-sized plant. The smaller SMR size can thus affect all three of licensing, construction, and operation/maintenance.

Integral PWR designs are significantly different from today’s reactors. The potential problems of smaller-sized plants apply to integral PWRs. Additionally, new types of SGs, PRZ, pumps, and CRDMs are entailed in the designs. Inspections, maintenance, and repairs might be even more difficult when the components are located inside the RPV. Furthermore, integral components are often located closer to the core, potentially exposing them to even higher radiation fields leading to more rapid material degradation. Integral PWR designs can thus affect licensing and operation/maintenance of the SMRs.

The proposed use of boron-free PWR coolant necessitates increased use of control rods and burnable absorbers to control reactivity. It can, at least for certain configurations, be very challenging to maintain core stability and the desired reactivity profile over the whole fuel cycle without boric acid in the coolant [11]. From a materials degradation perspective it is for most materials likely beneficial with a boron-free environment. However, Zr alloy fuel cladding might experience higher corrosion rates in the absence of boric acid if lithium hydroxide is used to control the pH [12]. How severe the degradation will be needs further investigation. A potential remedy could be to instead use potassium hydroxide, as done in water–water energetic reactors (VVERs) [13].

Natural circulation is a much more prominent feature in SMRs compared with current reactors and is for some designs planned to be used both during normal operation and accident conditions. For BWRs, some experience of natural circulation exists from the Dodewaard reactor in the Netherlands, from experiments performed in large-scale BWRs, and from the in USA licensed but never built Economic Simplified Boiling Water Reactor (ESBWR) [14,15]. For PWRs, experience of using natural circulation as part of passive safety systems exists, notably from the AP1000 reactor. The implementation of enhanced natural circulation will need attention from the licensing perspective and potentially also from the operation/maintenance perspective.

Passive safety is featured to larger extent in the proposed SMRs than in current reactors, which use a combination of passive and active safety systems [16]. The extensive use of passive safety systems is largely enabled by the enhanced use of natural circulation. Additional features enabling passive safety are gravity, convection, and pressurised systems. The implementation of increased passive safety needs attention from the licensing perspective. Due to potential difficulties to perform (periodic) testing of the systems, operation/maintenance might also be affected by the increased passive safety.

The containments of the Swedish reactors are made of prestressed concrete [17]. Novelties in the SMR containments include the use of a steel containment (surrounded by concrete) and building the containment using composite materials. Experience of some of the proposed containment designs exists outside Sweden. However, licensing and construction aspects need to be considered for the new types of containments. A BWR-specific case for containment design is the proposed use of a dry containment. Current BWRs use pressure-suppression containments with large water pools. However, the initial BWR containments were dry [18]. Dry containments will likely be advantageous from an operation/maintenance perspective but need attention from a licensing perspective.

Load-following capability is in the SMR designs significantly increased compared with the Swedish reactors. Means to load-follow include control rods, soluble boron (PWRs), coolant temperature, and bypassing the turbine and using the steam for other purposes [19]. The increased load-following capability will need attention from the licensing and operation/maintenance perspectives.

Dry storage of spent fuel is currently not used in Sweden, where the used fuel is stored in water pools at the interim storage facility *Clab* in Oskarshamn [20]. However, dry storage on-site might be an option for SMRs (and any new large-scale reactors). Dry storage might be advantageous because of decreased transportation of spent fuel and no need to expand the capacity of *Clab*. Equipment previously not used in Sweden to handle the spent nuclear fuel might need to be deployed. As on-site dry storage of spent fuel is used elsewhere [21], it should be relatively easy from a technical perspective to implement it in Sweden. However, mainly the licensing aspects need attention.

## Summary and conclusions

SMRs are considered an option for increasing the nuclear capacity in Sweden. Of primary interest in the relatively near future are land-based light-water SMRs, mainly for electricity production but potentially also for heat or hydrogen production. Compared with the current Swedish reactors there are a number of novel features entailed in the SMR designs that could be potential barriers to deploying the SMRs in Sweden. Some of the novelties are already in use in reactors outside Sweden and will thus not need as much further investigation from a technical perspective as those features that are new also to the rest of the world. However, regulatory (notably licensing) aspects need consideration when implementing features that have previously not been used in Sweden.

The novel features of SMRs might affect one or more of licensing, construction, and operation/maintenance of the reactors. Notable novelties compared with the Swedish reactor fleet were in this work identified based on five proposed SMR designs, one BWR and four PWRs. These novelties are modularity, the smaller size of SMRs, integral PWR designs, the use of boron-free PWR coolant, enhanced natural circulation, increased passive safety, novel containment designs, increased load-following capability, and dry storage of spent nuclear fuel. All of these novelties can affect the licensing and almost all of them the operation/maintenance of the SMRs. Construction is more likely affected by the modularity, the smaller size, and the novel containment designs than by the other novelties.

Further investigation of the novel features is needed to increase the understanding of them and to decrease the barriers to implementing them. Such investigation is critical to deploying SMRs in Sweden.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the ANItA collaboration (<https://www3.uu.se/forskning/anita/?languageId=1>) and has been financially supported by the Swedish Energy Agency under project number 52680-1. Stellan Molin, Luca Facciolo, Nici Bergroth, Konsta Värri, and Antti Rantakaulio are acknowledged for fruitful discussions.

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