

State-of-the-art report on water chemistries and structural materials in small modular reactors based on light water technology

Authors: Konsta Sipilä
Aki Toivonen

Confidentiality: VTT Public

Version: Final

Report's title	
State-of-the-art report on water chemistries and structural materials in small modular reactors based on light water technology	
Customer, contact person, address	Order reference
SAFER2028	
Project name	Project number/Short name
SAFER2022_MINERVA_2025	141382/MINERVA
Author(s)	Pages
Konsta Sipilä, Aki Toivonen	33/
Keywords	Report identification code
small modular reactor, water chemistry, light water reactor, structural materials	VTT-R-00292-25
Summary	
<p>The most recent openly available information concerning the construction materials and water chemistries used in land-based light water cooled small modular reactors (SMRs) under development is reviewed in this report.</p> <p>The International Atomic Energy Agency (IAEA) lists 15 land-based light water cooled Small Modular Reactors (SMRs) of which 14 are Pressurized Water Reactor (PWR) type units and only one Boiling Water Reactor (BWR). BWR SMR chemistries are apparently similar to large scale BWRs. PWR type SMR primary water chemistries differ in many cases from those of present day and older large scale PWRs' chemistries (H₃BO₃ + LiOH in western PWRs or H₃BO₃ + KOH + NH₃ in Russian large scale VVERs). The most common PWR SMR primary side chemistry appears to be boron-free, which is utilized in CAL-30, CAREM, HAPPY200, i-SMR, NUWARD, PWR-20, RITM-200N, SMART-P, STAR and Rolls Royce SMR. pH control is planned to be achieved with ammonia, LiOH, or KOH in those PWRs which do not utilize soluble boron for reactivity control.</p> <p>Prospective main structural or fuel cladding materials do not differ significantly from those used in newer generation large scale electricity producing nuclear power plants except that steam generator tubes are reported to be titanium alloy in different SMART versions as well as the steam generator in RITM-200N. RITM-200N is also reported to have Cr-Ni-Mo alloy fuel cladding. No new material or component manufacturing methods, e.g., additive manufacturing, are planned to be applied in light water cooled SMRs.</p>	
Confidentiality	VTT Public
Espoo 19.12.2025	
Written by	Reviewed by
Konsta Sipilä, Senior Scientist	Essi Jäppinen, Research Scientist
VTT's contact address	
Kivimiehentie 3, 02044 VTT	
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Date:

Signature:

Name:

Mikko Vepsäläinen

Title:

Research Team Leader



Preface

This report has been issued as part of the project “Mitigation of corrosion and novel water chemistries in light water reactors” (MINERVA) within the SAFER 2028 -research programme. VYR and VTT are acknowledged for funding this work.

Espoo 19.12.2025

Authors

Contents

Contents	4
Abbreviations	5
1. Introduction	6
2. SMR materials and water chemistries	8
2.1 ACP100	8
2.2 AP300	9
2.3 BWRX-300	10
2.4 CALOGENA CAL 30	11
2.5 CAREM	12
2.6 HAPPY200	13
2.7 i-SMR	14
2.8 NuScale	15
2.9 NUWARD	16
2.10 PWR-20	17
2.11 RITM-200N	18
2.12 SMART	19
2.13 STAR	20
2.14 Rolls Royce SMR	21
2.15 SMR-300	22
3. Discussion	23
4. Conclusions	25
References	27

Abbreviations

ASNR	French Authority for Nuclear Safety and Radiation Protection
BWR	Boiling water reactor
CAREM	Central Argentina de Elementos Modulares
CEA	French Alternative Energies and Atomic Energy Commission
CNEA	National Atomic Energy Commission (Argentina)
CNNC	China National Nuclear Corporation
CRDM	Control rod drive mechanism
CS	Carbon steel
CVCS	Chemical and volume control system
EDF	Électricité de France
EPRI	Electric Power Research Institute
Gd ₂ O ₃	Gadolinium(III) oxide; gadolinia
GE	General Electric
H ₃ BO ₃	Boric acid
HTGR	High temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
i-SMR	Innovative Small Modular Reactor
KAERI	Korean Atomic Energy Research Institute
KHNP	Korea Hydro & Nuclear Power
KOH	Potassium hydroxide
LAS	Low alloy steel
LiOH	Lithium hydroxide
LMR	Liquid metal cooled reactor
LWR	Light water reactors (PWRs and BWRs)
MCP	Main coolant pump
MSR	Molten salt reactor
n	Neutron
NH ₃	Ammonia
NRC (/USNRC)	(United States) Nuclear Regulatory Commission
NUWARD	Nuclear Forward
p	Proton
PTWR	Pressure tube water reactor
PWR	Pressurized water reactor
RPV	Reactor pressure vessel
RR	Rolls-Royce
SG	Steam generator
SMART	System integrated Modular Advanced Reactor
SMR	Small modular reactor
SPIC	State Power Investment Corporation
SS	Stainless steel
STAR	Safe Tiny Atomic Reactor
TT	Thermally treated
VHTR	Very high temperature reactor
VVER	Water-water energetic reactor
ZIRLO®	Zirconium low oxidation

1. Introduction

Small modular reactors (SMRs) are a class of small nuclear fission reactors designed to be built in a factory, shipped to operational sites for installation, and then used to power buildings or other commercial operations. The term SMR refers to the size, capacity, and modular construction of these reactors. IAEA defines the power capacity of SMRs to be up to 300 MWe [1]. Compared to the traditional large nuclear power plants, they display many beneficial qualities such as enhanced safety, unit cost price, flexibility and scalability. Advanced safety features are typically incorporated in SMRs, including passive safety systems that do not require human intervention to operate. This enhances the overall safety of the reactors. SMRs have a lower initial capital investment compared to traditional large-scale reactors. The modular components and factory fabrication can significantly reduce construction costs and duration. SMRs can be deployed in a variety of locations, including smaller electrical markets, isolated areas, and sites with limited infrastructure. This flexibility makes them suitable for a wide range of applications, including industrial processes, district heating, and hydrogen production. Building of SMRs can be implemented incrementally, allowing for additional modules to be added as demand for energy increases. This scalability provides a more adaptable approach to meeting energy needs.

The most common SMRs have similar general designs and operational principles as the conventional large ones:

- liquid metal cooled reactor (LMR)
- molten salt reactor (MSR)
- high temperature gas-cooled reactor (HTGR)
- pressurized and boiling water light water reactors (LWRs)

LMRs use liquid metals or alloys, such as sodium, lead or lead-bismuth, as coolants. These metals have high thermal conductivity and boiling points, which allow operation temperatures around 550 °C [2]. Furthermore, the liquid metal coolant enables the reactor to operate at near atmospheric pressure, which enhances the safety. The high operation temperatures improve thermodynamic efficiency and power output. LMRs are often designed as fast neutron reactors, meaning they make use of fast neutrons to sustain the nuclear fission chain reaction. This allows for more efficient use of nuclear fuel and has the potential to burn long-lived radioactive waste. The main challenges in LMRs are related to the control and properties of the molten coolant. The coolant reacts vigorously with air and water, so all leakages are dangerous. It also sets high demands to the constructional materials and their design due to the coolant's corrosive nature. Finally, the inspection and repair of components are difficult due to the coolant properties. [3] There is currently one pilot demonstration plant under construction in Russia, BREST-OD-300 [4].

MSRs use liquid fuel, typically a mixture of fluoride salts containing fissionable materials, or solid particle fuel where liquid salt acts only as coolant and the fuel is in the form of tiny coated capsules. They operate at high temperatures (700-800 °C), which improves the overall efficiency. They can be used for a range of applications, not just electricity generation, but also thermochemical hydrogen production. MSRs operate at low pressures, reducing the risk of a large break and loss of coolant as a result of an accident. MSRs can adapt to a variety of nuclear fuel cycles, allowing for the extension of fuel resources. They can also be designed as nuclear waste "burners" or breeders. Molten salt fuel comes with an inherent safety feature. If the salt overheats, it naturally expands and makes the fission reaction less effective, which shuts down the reactor. There is currently one low power demonstration plant of this variety under construction in the USA. [4,5]

HTGRs use gas, typically helium, as a coolant and graphite as a moderator. They are capable of operating at very high temperatures. For example, the currently only commercially developed demonstration HTR-PM facility in China has an operation temperature of 750 °C. [2,6] The high operation temperature makes them suitable for a variety of applications, including hydrogen production and industrial processes. The term very high temperature reactor (VHTR) is applied when the temperature is 1000 °C or above. The use of helium as a coolant enables improved safety features due to its inertness. HTGRs can use a variety of fuel types, including uranium and thorium. The reactors also have passive safety features, such as the ability to shut down safely without human intervention. The challenges of HTGR reactors are related to material degradation and corrosion at high temperatures if impurities are present in the coolant, complex fuel handling, and waste management. [7]

The LWR-types of SMRs differ from the above designs by the coolant type and lower operating temperature. Indeed, the operating temperature is significantly lower in LWR designs (or heavy water designs as well), as shown in Figure 1. The relatively low operating temperature can still be applied to other industry processes in addition to electricity generation, such as district heating and seawater desalination. LWR SMRs are mainly scaled down designs of those used in large-scale nuclear plants and rely on an already well-established technology that has been used in the nuclear industry for decades. This familiarity can simplify the licensing process and reduce regulatory hurdles. There is currently one operating pressurized water reactor (PWR) type SMR, the floating Akademik Lomonosov equipped with two KLT-40S reactors with 35 MWe power each. [8] Furthermore, two land-based SMR are under construction in Argentina and China [4].

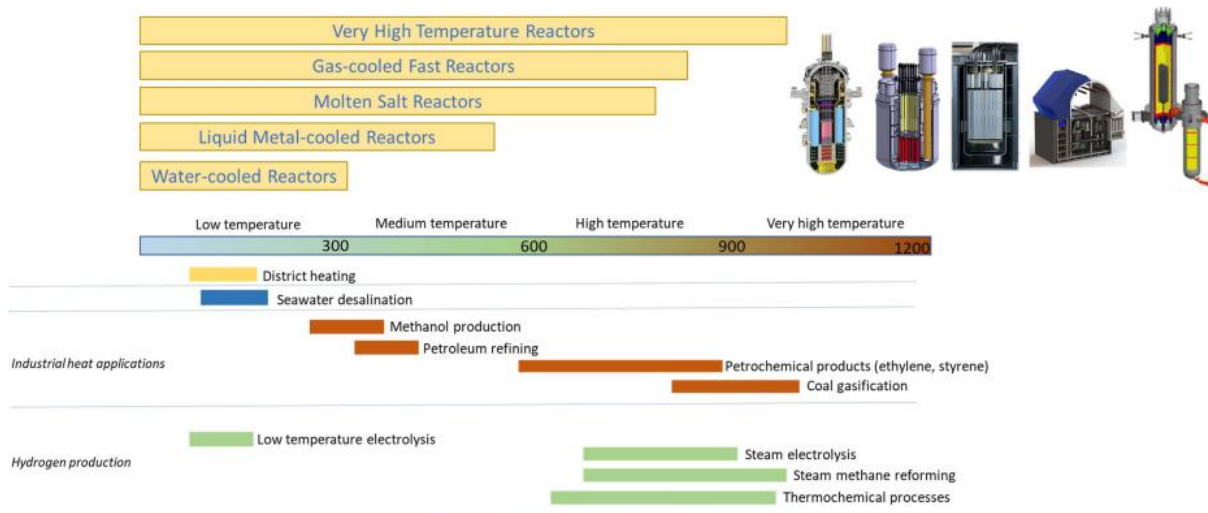


Figure 1. Operating temperature ranges for different types of SMRs and associated industrial processes. [2]

The materials and water chemistry solutions of the LWR SMR designs were summarized within SAFIR2022 ELMO project in 2019 [9]. The report conclusions stated that the materials were similar to the ones used in the larger Gen III plants and water chemistry was apparently in most cases based on boron-free solutions. However, the available literature at the time of the writing of the report was scarce and the conclusions thus somewhat uncertain. Taking into account that in the past six years there has been considerable development in the SMR designs, it should be now possible to conclude a more complete picture of the status on the SMR materials and water chemistries. This report focuses on summarizing the current publicly available knowledge on the land-based LWR-type SMR materials and general water chemistry solutions. Marine and submarine small reactors were excluded, as they probably do not fulfil the present-day safety requirements for civil use.

2. SMR materials and water chemistries

According to IAEA [10], there are around 15 land-based water-cooled SMR designs under development in ~10 countries for energy production (electricity or heat). Some designs are developed for commercial export, but most designs are for domestic production. The present state of the design, output, type, designer, country and design status of the land-based light water cooled SMRs are listed in Table 1. The list in Table 1 is not complete, as for example, the Finnish LDR-50 district heating reactor under development [11] is not listed, but it gives a good overview on the current status of the technological readiness levels of different SMR designs. Most of the reactor types are PWRs, but not all of them use boron for reactivity control as is used in older large electricity production PWRs. There is only one SMR of the boiling water reactor (BWR) type in the list whereas in 2019 there were three [9]. In the following chapters, open-source search results for the construction materials and chemistries of the SMRs shown in Table 1 are reported.

Table 1. Land-based LWR SMRs under development. [10]

Design	Output MW(e)	Type	Designers	Country	Status
PART 1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
ACP100	125	PWR	CNNC	China	Under construction
AP300	330	PWR	Westinghouse Electric Company, LLC	United States of America	Basic design
BWRX-300	300	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America, Japan	Detailed design
CALOGENA*	30MWth	Pool type	Calogena S.A.	France	Conceptual design
CAREM	30	PWR	CNEA	Argentina	Under construction
HAPPY200	200 MWth	PWR	SPIC	China	Detailed Design
i-SMR	170	PWR	KHNP & KAERI	Republic of Korea	Conceptual Design
NuScale Power Module	77	PWR	NuScale Power Inc.	United States of America	Detailed design
NUWARD	170	PWR	EDF, CEA, TA, Naval Group	France	Basic Design
PWR-20	20	PWR	Last Energy	United States of America	Detailed design
RITM-200N	55	PWR	JSC "Afrikantov OKBM"	Russian Federation	Detailed design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea, and Saudi Arabia	Detailed design
STAR	10	PTWR	Star Energy	Switzerland	Basic design
Rolls-Royce SMR	470	PWR	Rolls-Royce	United Kingdom	Detailed design
SMR-300	320	PWR	Holtec International	United States of America	Conceptual Design

2.1 ACP100

ACP100 reactor design (Figure 2) has been under development since 2010. Its preliminary design was completed in 2014. It is an integrated pressurized water reactor in which the major components of its primary coolant circuit are installed within the reactor pressure vessel. ACP100 has passed a safety review by IAEA. The inlet water temperature of ACP100 is 282 °C and outlet temperature 323 °C. Core reactivity is controlled by control rods, solid burnable poison (Gd_2O_3) and boric acid.

Corrosion potential control (dissolved H₂) or pH control are not mentioned, but the design is based on existing PWR technology so it can be assumed that the chemistry is similar. No details of the construction materials are available. The reactor has 16 once-through RPV internal steam generators and forced circulation by four main circulation pumps. Changjiang nuclear power site, Hainan, China, was chosen as the site for the first ACP100 demonstration plant. It has been under construction since 2021. The aim is to begin the commercial operation during 2026. The demonstration plant is land-based, although floating type versions are designed as well. [12-17] On October 16, 2025, the cold functional tests were completed [18].

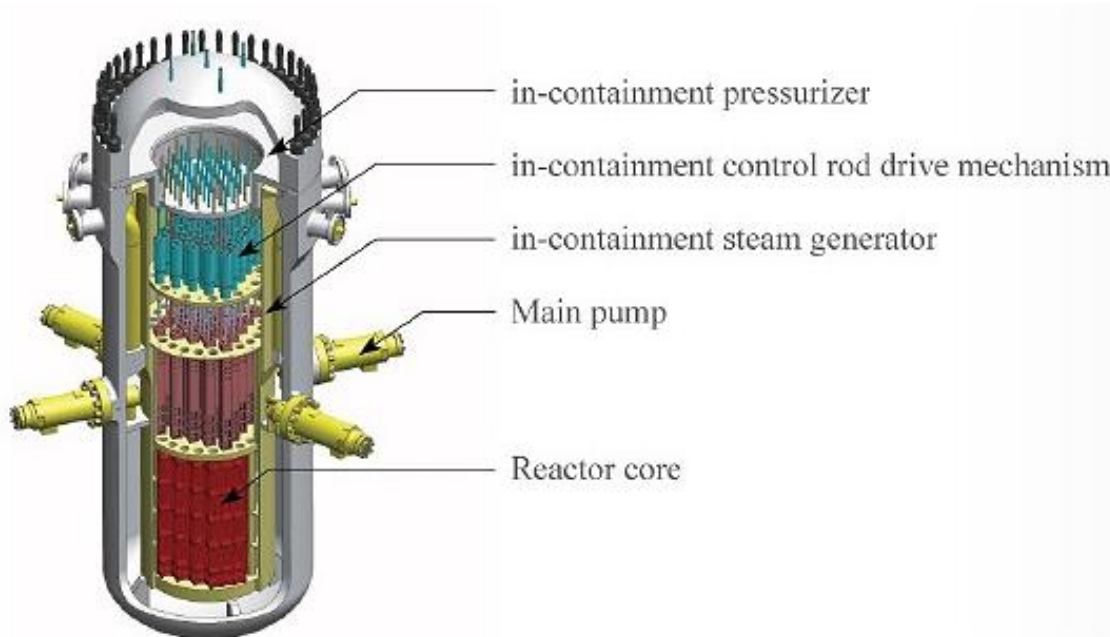


Figure 2. Schematic design of ACP100 SMR. [19]

2.2 AP300

The AP300 SMR, Figure 3, is a 300 MWe single-loop PWR design. It is significantly more compact compared to its predecessor, the AP1000, which provides 1,100 MWe. Smaller scale is claimed to enable efficient construction and integration into various energy systems. The AP300 design aims to gain Nuclear Regulatory Commission (NRC) certification by 2027, with construction of the first unit anticipated to start in the early 2030s. The operational debut of the reactor is projected for 2033. [20]

No specific details on water chemistry or materials are available, but it can be assumed that they are similar to the AP1000 as the design is heavily relying on its user experience, supply chains, engineering and components. AP1000 applies boron in reactivity control and zinc injections for corrosion/corrosion product transport control [21]. Austenitic stainless steels (different Type 304 and/or Type 316 variants), carbon steels and A690 (e.g. steam generator tubes and reactor vessel head penetrations) are typical materials in AP1000 [22-24].

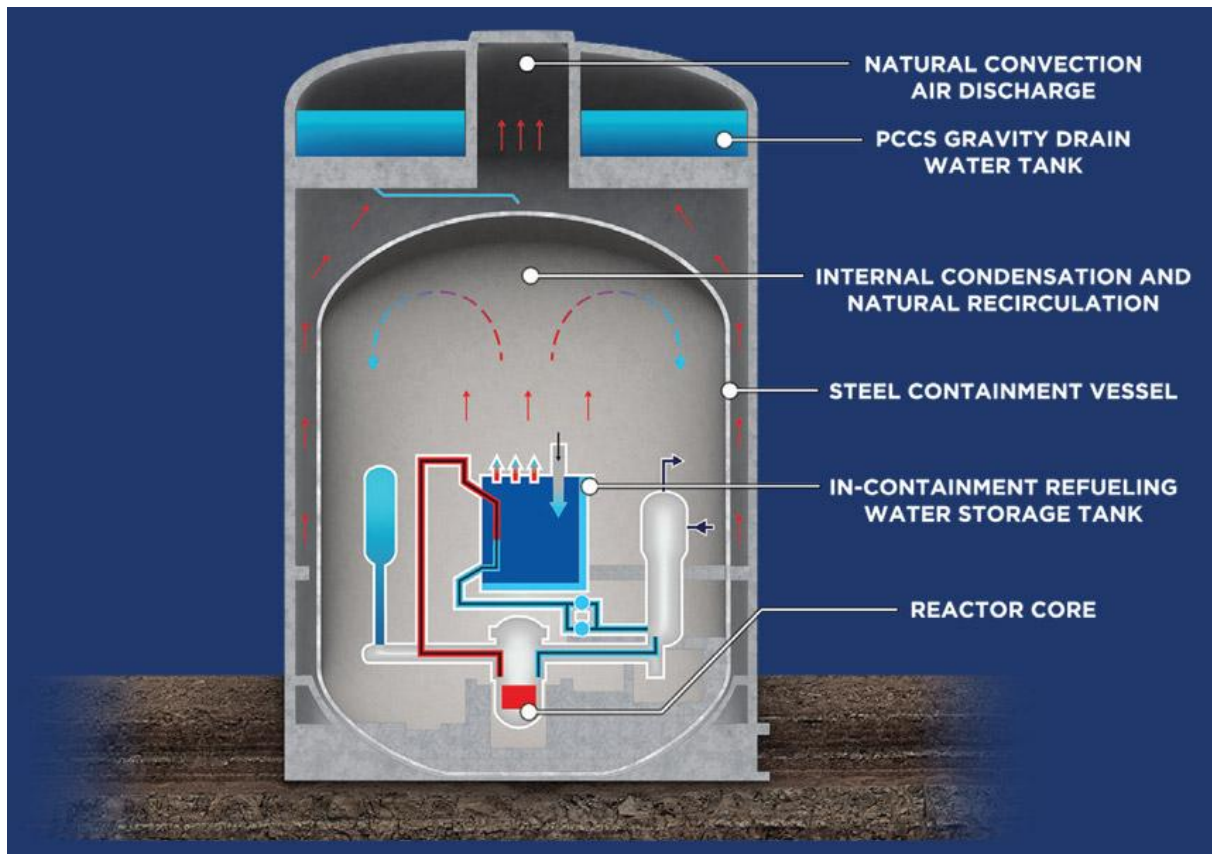


Figure 3. A schematic of the modular nuclear island of AP300. [25]

2.3 BWRX-300

The BWRX-300, Figure 4, is a 300 MWe (870 MWth) BWR-type small modular reactor with passive cooling and natural circulation designed by GE Hitachi. It is an evolutionary version of the U.S. NRC-licensed 1520 MWe ESBWR [26]. Initial commercial operation is expected as early as 2028, with various partnerships established for deployment in locations including the U.S., Canada, and Poland. Licensing is currently under review in the U.S. by the national regulatory commission and completed the first of three general design approval steps in UK at the end of 2024 [27-29].

As the reactor is a BWR, no boron is used in the coolant water during normal operation for reactivity control. Boron is only used for emergency shutdown by injecting it from a separate boron injection system [30]. The BWRX-300 uses cruciform control rods typical for BWRs for reactivity control during normal operation. Additionally, the reactor core is designed to include burnable poisons for the management of the cycle excess reactivity [31]. Otherwise, no more detailed information regarding the water chemistry was found.

The reactor internal materials and piping are stainless steels resistant to stress corrosion cracking or other high alloy steels. Zircaloy is used as a cladding material. [30] No detailed information on the used construction materials was found.

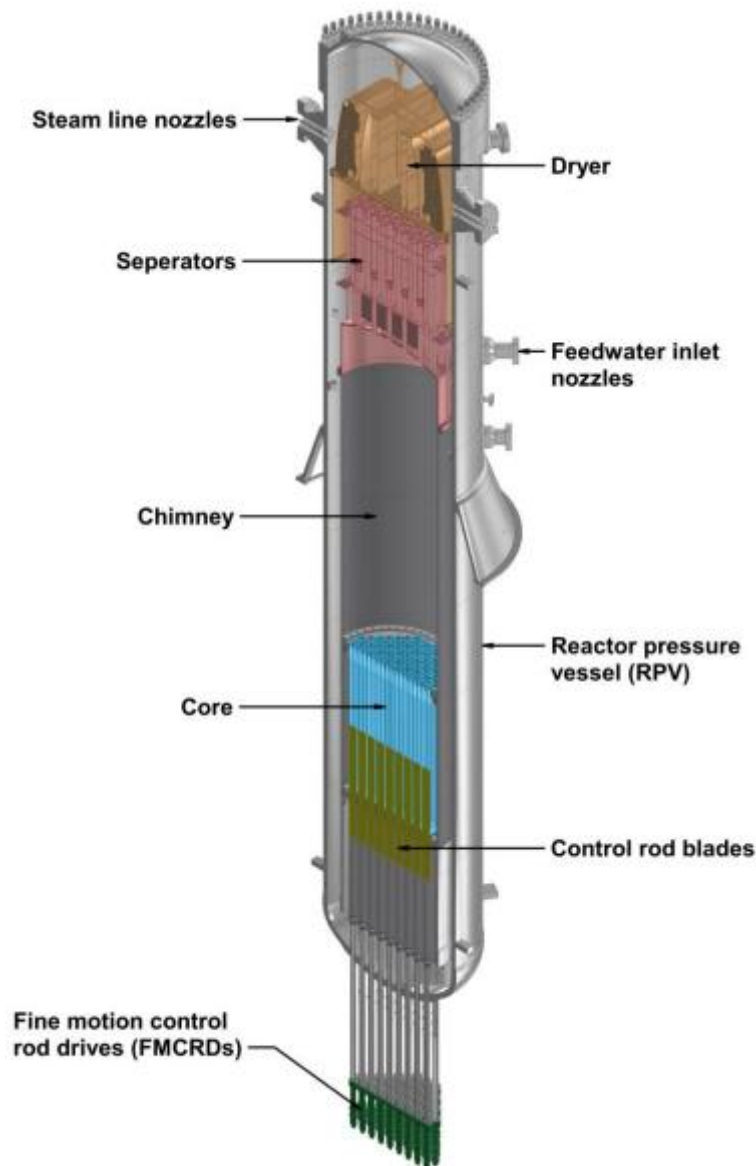


Figure 4. BWRX-300 Reactor Pressure Vessel and Internals. [30]

2.4 CALOGENA CAL 30

Calogena is a subsidiary of the French industrial group Gorgé. Calogena's reactor design, CAL 30, is a 30 MW_{th} district heating reactor relying on natural convection primary circulation with 70-110 °C coolant temperature [10,32], Figure 5. Heat is transferred to district heat network thru an intermediate circuit. The main heat exchangers are integrated to the reactor vessel. The primary side coolant is boron-free demineralized water. Control rods are used for reactivity control. Design status as of 2024 was conceptual design that is under review by the French Nuclear Safety and Radiation Protection Authority (ASNR) [32] and assessment of the conceptual design is underway in Finland [33]. The first plant construction is planned to take place in 2029-2032. [10,32] No mentions about the construction materials were found.

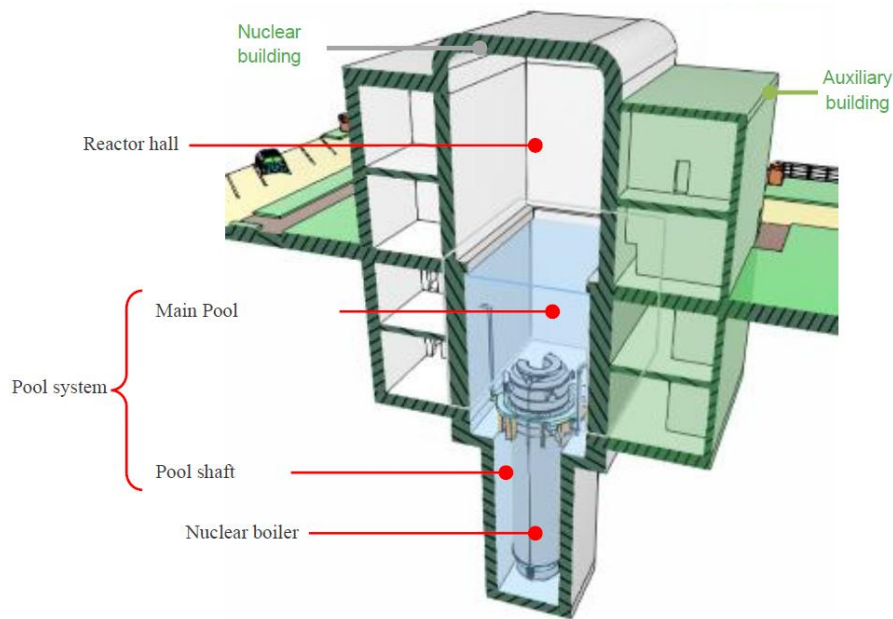


Figure 5. CAL 30 district heating reactor layout. [10]

2.5 CAREM

CAREM is an integral PWR type NPP with natural primary circulation and 100 MWth and ~30 MWe power. Inlet and outlet temperatures are 284 and 326 °C, respectively. Reactivity is controlled using burnable poison (Gd_2O_3) in specific fuel rods and movable absorbing elements. Neutron poison (boron) in the coolant is not used for reactivity control during normal operation or reactor shutdown. The CAREM prototype (Figure 6) is under construction as a new plant on the site of a former heavy water research facility that is adjacent to the Atucha power station in Argentina. The design includes 12 identical helical tube steam generators, which have a common connection flange. The pressure vessel is “forged steel with stainless steel liner”. [10,14,34]

No recent materials or chemistry information were found. However, in an early paper from a conference held in 2000 [35], Alloy 690 is mentioned for steam generators, SS 347 for internals and reactor vessel liner, and Zircaloy-4 for fuel elements. In the same document, primary side water chemistry recommendations were given, Table 2. Chemistry values were based on pH, redox-potential, and temperature effects on oxide structures on different alloys and the solubilities of the oxides and activity transport.

Table 2. Early recommendations for CAREM primary water chemistry. [35]

Parameter	Value
Boron	0
Li	0.27 ppm
pH _{300C}	7.0
pH _{25C}	9.59
O ₂	<0.05 ppm
H ₂	<10 cc/kg
Conductivity	<10 μS/cm
Solids	<0.03 ppm
Chlorides	<0.005 ppm
Fluorides	<0.005 ppm

Sulfate	<0.005 ppm
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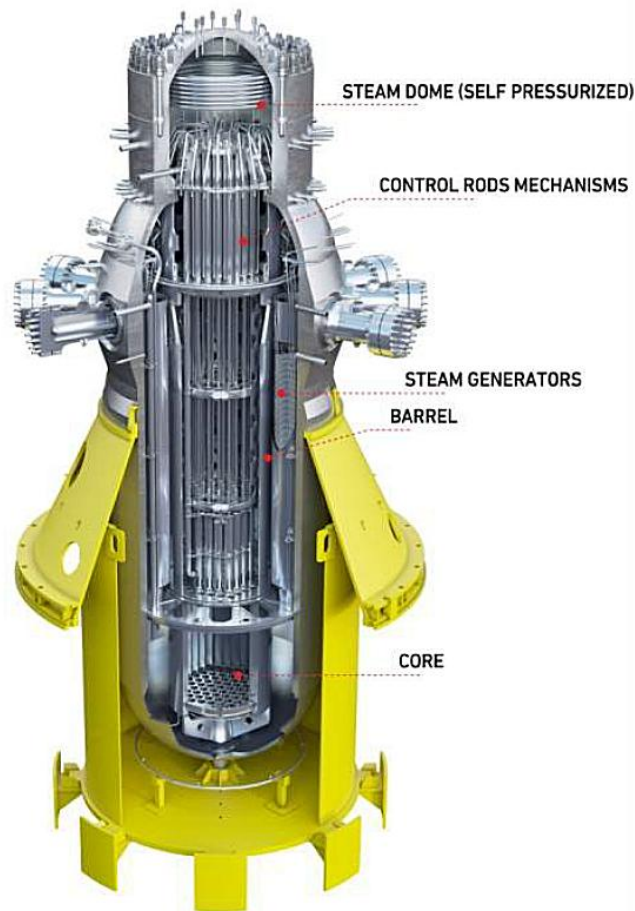


Figure 6. Schematic design of CAREM SMR. [10]

2.6 HAPPY200

HAPPY200 is a heat producing reactor operating at 80/120 °C (primary side inlet/outlet temperatures) and aimed at district heating, desalination, cooling applications, and to operate as an energy storage. The thermal capacity of the reactor is 200 MW. Control rods and Gd_2O_3 in fuel rods are employed to manage reactivity. HAPPY200 has a completed conceptual design. As of 2024, preliminary design is underway. The first project has completed the site selection and preliminary feasibility analysis report review. However, in Small Modular Reactors Catalogue 2024 [10], it is mentioned that the project has been suspended for the time being.

Secondary coolant system separates the primary loop and the tertiary loop (e.g., district heating system) while transfer heat from the primary to the third. The pressure of the secondary loop is designed to be higher than that of the primary loop, so there is low chance that the radioactive primary side water could contaminate the tertiary loop. [10]

No closer information about neither the water chemistry (except that boron is not used for reactivity control) nor construction materials are available from public sources.

2.7 i-SMR

The i-SMR, Figure 7, is a 170 MWe PWR with integrated helical once through steam generators developed in South Korea. It is currently on track to complete its standard design by the end of 2025 and aims to obtain standard design approval by 2028. The first-of-a-kind construction is planned for the early 2030s. [36,37] The design life of the reactor is 80 years [38,39].

The i-SMR has boron-free chemistry, which simplifies the CVCS according to the designers [40]. Control rods that have pressure vessel internal driving mechanisms and Gd_2O_3 in fuel rods are used for reactivity management [36]. It seems that there are currently two options for pH control (KOH and LiOH), but apparently it has not yet been decided which one will be applied. Hydrogen injection is also planned: a constant level of 25 cc/kg is speculated [41]. Zinc injection for radiation field control has been considered as well [42].

The most likely main structural materials are 316L stainless steel, Alloy 690 and a Zr alloy (not defined more closely) as mentioned by Choi et al. [41] in their paper describing planned electrochemical tests in boron-free i-SMR chemistry on the candidate materials and water chemistries. In a later paper, Choi et al. [43] describes results of tests on 316L. The tests were done at 320 °C in water with 25 cc/kg H_2 and pH_T of 7.2 both with LiOH and KOH. Definite information is not available on water chemistry as could be expected since the standard design is not yet completed.

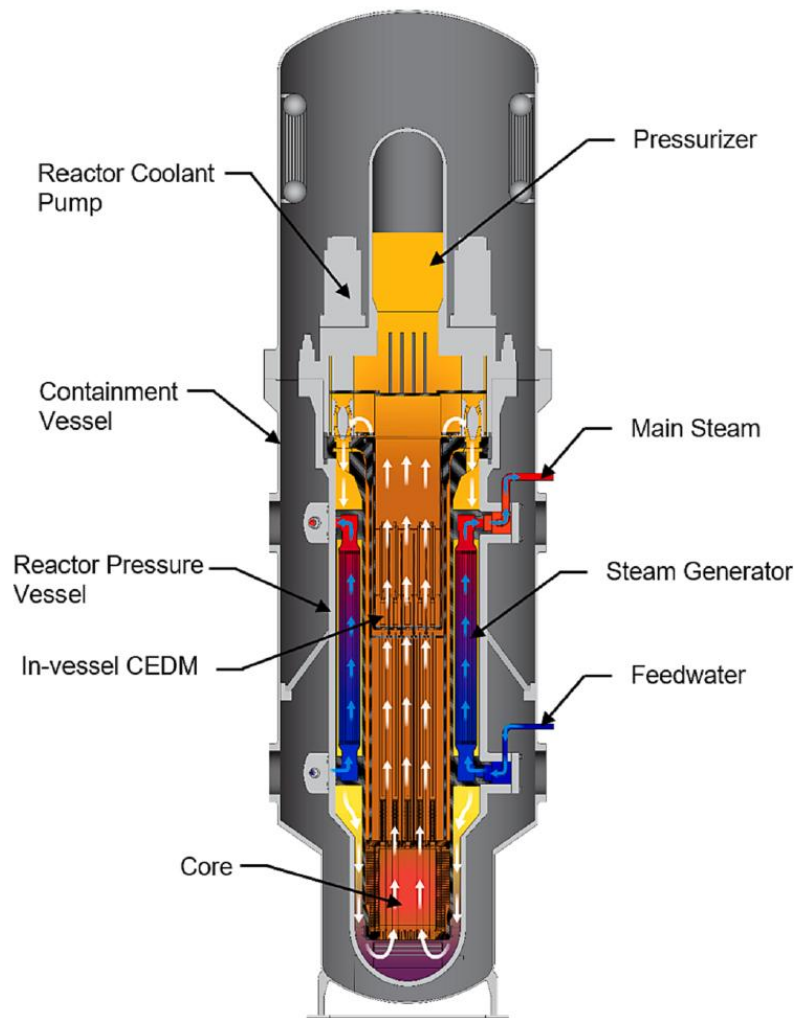


Figure 7. Schematic design of i-SMR. [39]

2.8 NuScale

The United States based NuScale SMR, Figure 8, is a PWR with integral once through helical-coil steam generators, internal pressurizer, and natural primary circulation. Control rods and soluble boron are employed for reactivity management. The core inlet and outlet temperatures are 249/316 °C, respectively. [10] The water chemistry in NuScale follows mostly the EPRI PWR water chemistry guidelines. However, some modifications are required due to the technical differences in SMRs compared to the large scale PWRs. The items recognized requiring modifications in the current guidelines have been identified [44]:

- Control During Shutdown (primary side)
- Timing of Changes in Chemistry Regimes (primary and secondary side)
- Moisture Separator Drain Sampling (secondary side)
- Blowdown Sampling (secondary side)

The reactor type has received design approval from the U.S. Nuclear Regulatory Commission [45,46].

Some material data is available for the NuScale design and shown in Figure 8. The pressure vessel is low alloy steel SA-508 Gr. 3 with stainless steel cladding. The steam generator tubing and tube support material selected are similar to large advanced PWRs, Alloy 690TT tubing with ferritic stainless steel tube supports. [47]

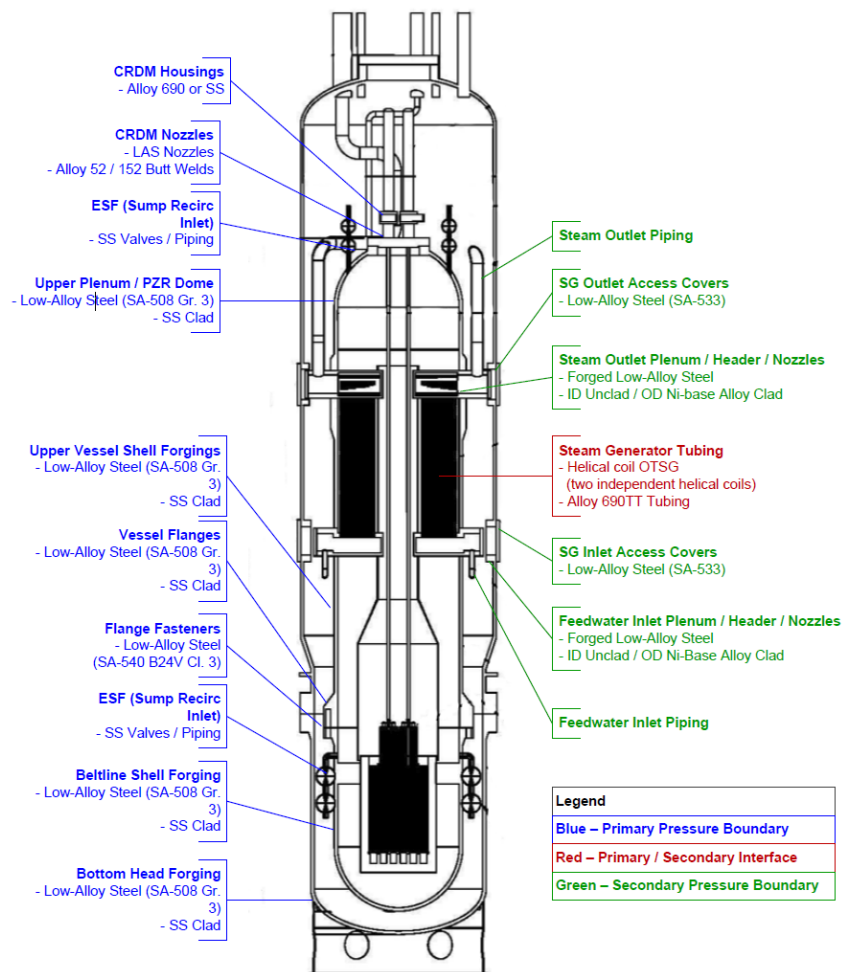


Figure 8. Schematic of NuScale SMR unit and used main materials. [47]

2.9 NUWARD

The NUWARD SMR, Figure 9, is a modular nuclear reactor design with a capacity of 340 MWe, composed of two integrated 170 MWe Pressurized Water Reactor units with forced circulation. Core inlet and outlet temperatures are 280/307 °C, respectively. It can be modified for heat generation, hydrogen production, district heating and water desalination [48]. Currently the reactor conceptual design is planned to be completed in 2026 and provide a ready facility for the markets in 2030s [49].

NUWARD has steam generators, control rod drive mechanisms and pressurizer within the reactor pressure vessel. NUWARD operates with boron-free water chemistry. Reactivity control takes

place by control rods and burnable poison. [10] No detailed information on water chemistry nor materials was found, which may be due to the incomplete conceptual design.

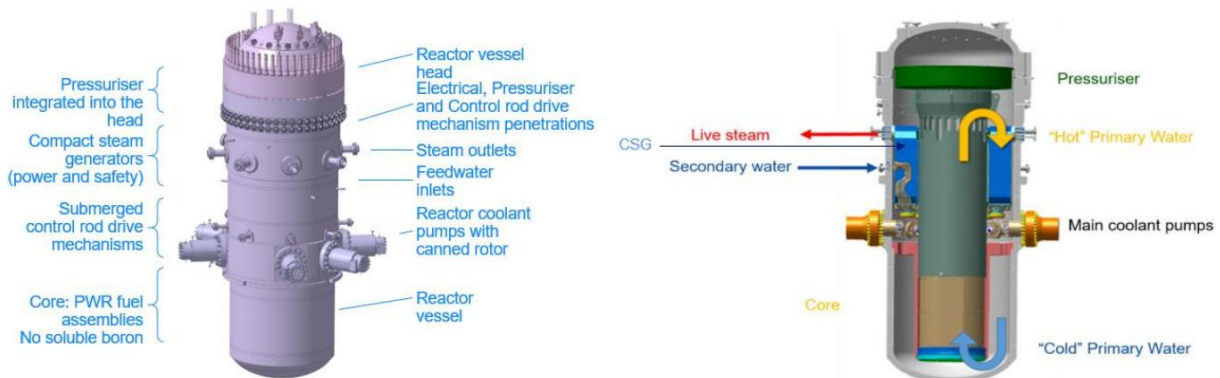


Figure 9. Overall schematics of the NUWARD SMR reactor. [50]

2.10 PWR-20

PWR-20, Figure 10, is an SMR design developed by Last Energy Inc. It has 20 MWe electric output and the concept seems to be fairly well developed. Core inlet and outlet temperatures are 270/331 °C. Reactivity control is done with control rods and burnable poison (no soluble boron mentioned). [10] The design enables direct local delivery of electricity to the end users, and no grid connection is required. First deployment is targeted for 2027 at a former coal plant site in Bridgend, South Wales, UK [51]. The licensing process is currently underway [52]. Despite all the progress with the design, no detailed information was found on water chemistry or structural materials of PWR-20. Last Energy Inc states [53] that the design relies heavily on the current PWRs and is basically a scaled-down multi-loop PWR.

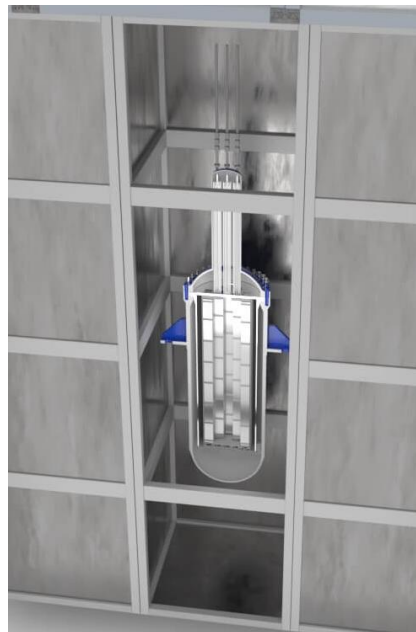


Figure 10. Schematic image on the PWR-20 reactor. [54]

2.11 RITM-200N

The RITM-200N, Figure 11, is a 55 MWe (190 MWth) Generation III+ SMR with core inlet and outlet temperatures of 283/321 °C, respectively. The design is developed by OKBM Afrikantov, a subsidiary of Rosatom, and is a land-based adaptation of the marine RITM-200 reactor used in Russian nuclear icebreakers. Integrated reactor pressure vessel houses the core, steam generators, pressurizer, and primary coolant pumps in a single compact unit. Commissioning of a pilot plant is planned for 2028. [55]

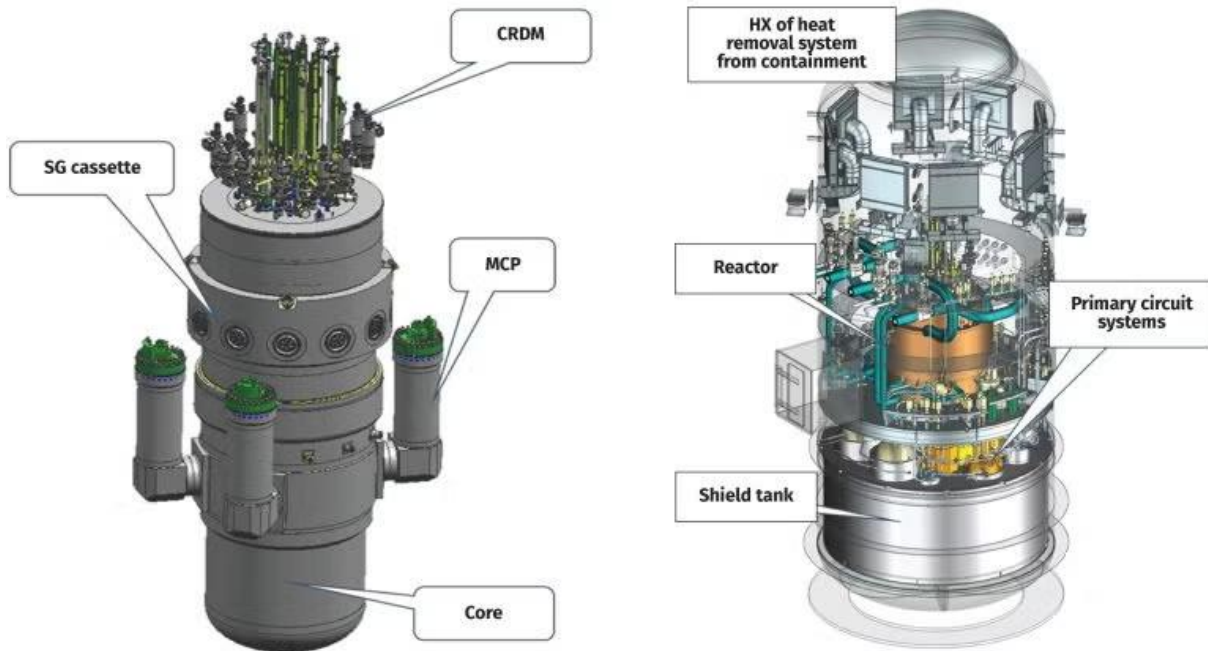


Figure 11. Schematic presentation of the RITM-200N reactor design. [55]

Boron is not used in reactivity control, as it is replaced with “an electromechanical system” (assumedly similar to control rods). Ammonia is used to control the pH in primary circuit and the solution is described as self-sustaining ammonia water chemistry. Such a chemistry can provide several benefits through simplifying chemical dosing and operation and thus enabling reduction in operating costs. There is existing operation experience on ammonia chemistry from the icebreaker design RITM-200. The secondary circuit chemistry is neutral water without any chemical additives. [55, 56]

The available information on structural materials include [56,57]:

- Integral reactor vessel made of 15Kh2MFA low alloy steel (2.5-3%wt. Cr, 0.6-0.8%Mo, ≤ 0.4%Ni, 0.3-0.6%Mn, 0.17-0.37%Si, 0.25-0.35%V, 0.13-0.18% C)
- Steam generator made of titanium alloy
- Fuel cladding material is Cr-Ni-Mo alloy 42KhNM (Cr 42%, Mo 1.5 %, Ni bal. [58])

The cladding material is stated to be more resistant to corrosion during a long fuel cycle compared to zirconium alloys. The same cladding alloy is used in the cores of new nuclear icebreakers and fast reactors in Russia. [55]

2.12 SMART

SMART (System integrated Modular Advanced Reactor) is a Korean design PWR SMR, Figure 12, which has been granted standard design approval from the national nuclear safety regulator in 2024 (SMART100). There are three versions of design: SMART, SMART100 and SMART-P, the latter one being a prototype plant [10,59,60]. The inlet temperature of the coolant for SMART is 295.7 °C and outlet temperature 323 °C. Original SMART is reported to utilize soluble boron and control rods for reactivity control [10] whereas SMART-P is boron-free with control rods [60]. No information was found on SMART100. In SMART-P, ammonia (10-100 ppm) is planned to be used in pH control of primary side, setting the pH value between 9.5 and ~10.6. Upper limit for dissolved nitrogen is 2000 cm³/kgH₂O. Limits for impurities (Cl, F and SO₄) have been proposed to be set to < 0.15 ppm. Dissolved oxygen levels are planned to be set to 0.1 ppm. The operating pressure is 15 MPa and dissolved H₂ content 20-60 cc/kg (the indicated H₂ content was defined in prototype design phase, final H₂ content is not known). [60]

Available material related data for the original SMART is listed below [60-66]:

- Reactor pressure vessel: low alloy steel SA508 Grade 3, Class 1 (≤ 0.25 wt.%C, 1.20% Mn, 0.60%Si, 0.25%Ni, 0.25%Cr, 0.35%Cu)
- Pressure vessel cladding: 321 SS (≤ 0.08 wt. %C, 17-19%Cr, 9-12%Ni, ≤ 2.0%Mn, ≤ 1.0%Si, ≤ 0.7%Ti, ≤0.1%N)
- Mixing head assembly and other internals: 304 SS (C 0.08 %wt)
- Steam generator tubing: titanium alloy or A690
- Fuel cladding: Zircaloy 4
- Fuel channel pressure tube: Zr 2.5% Nb
- Control rod drive mechanism: ball bearings 440 SS, screw Incoloy 925, gear Incoloy 925 (42-46wt.%Ni, ≥22%Fe, 19.5-22.5%Cr, 2.5-3.5%Mo, 1.5-3.0%Cu, 1.9-2.4%Ti, ≤ 1.0%Mn, ≤ 0.5%Si, ≤ 0.5%Nb, ≤ 0.03%C).

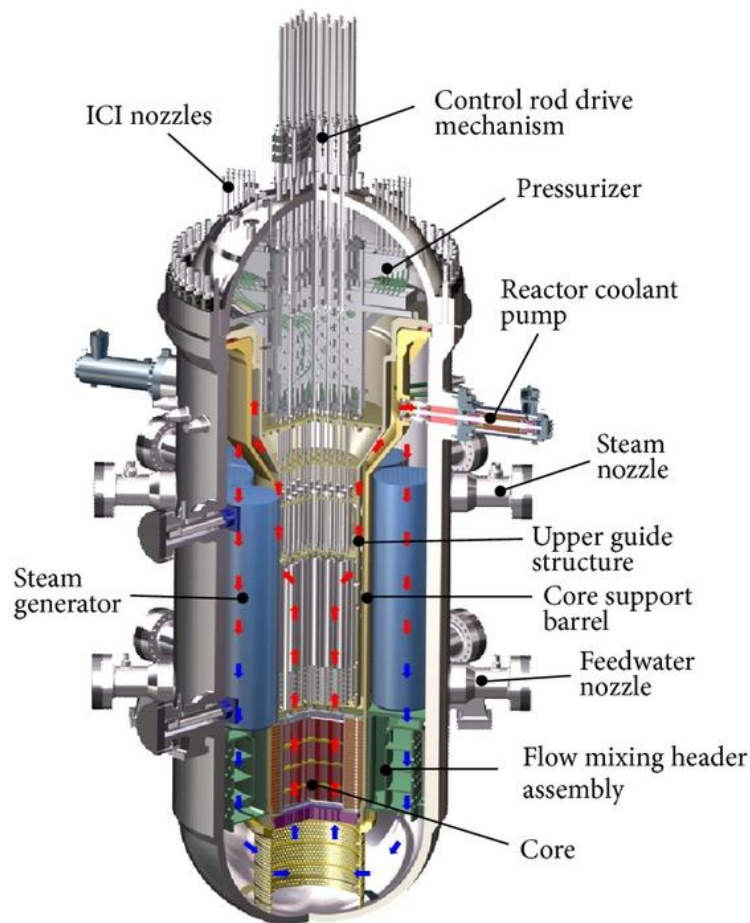


Figure 12. Schematic design of original SMART SMR. [66]

2.13 STAR

The STAR SMR (Safe Tiny Atomic Reactor), Figure 13, is a next-generation pressure channel micro modular reactor developed by STAR Energy SA, a Swiss-based company. It is designed to be extremely compact, transportable, and safe, targeting remote and off-grid applications. Its thermal capacity is 30 MWth and electric 10 MWe. Its core inlet and outlet temperatures are 270/300 °C, respectively. Reactivity control takes place by control rods and burnable poison. A particular feature of the reactor design is its long (10 years) re-fueling interval. The development of basic design is currently on-going according to IAEA 2024 SMR catalogue [10]. However, very little recent information is available concerning the development progress or if the development continues at all.

No detailed water chemistry or structural material information was found on the STAR SMR. This could be expected as the reactor type basic design is not completed yet.



Figure 13. A schematic of Star Energy SA's STAR 10 MWe micro reactor. [10]

2.14 Rolls Royce SMR

The Rolls Royce PWR SMR power station will have the capacity to generate up to 470 MWe and thermal capacity of 1358 MWth. Core inlet and outlet temperatures are 295/322 °C, respectively. The reactor structure comprises of a primary and secondary circuits, in which three steam generators transfer the heat. Rolls Royce has provided a set of documentation covering safety, environment, security and safeguard topics, which can be applied during the licensing process [67]. The pressure vessel (see Figure 14) body material is carbon steel SA-508M Grade 3 [68]. The reactor pressure vessel cladding has a base layer of stainless steel 309L and subsequent layers of 308L. The safe ends are made of stainless steel 316LN. [69] The reactor vessel internals seem to be mostly stainless steel, but a more detailed grade is redacted from the report [70]. The pressurizer has the materials as the pressure vessel (SA 508 Grade 3 with 309L/308L cladding) [69]. The fuel clad is Optimized ZIRLO® [70]. Some speculation on secondary side piping has been made regarding flow assisted corrosion (FAC). The most likely option for the piping is carbon and low alloyed steel, but at regions where FAC has been identified as a potential issue, the use of SA-335M P22 as base material and ER90S-B3 as weld material has been speculated. [71] Otherwise, the secondary side materials were more scarcely available. Based on the currently available documentation, the main steam line piping material is ferritic grade SA335M P22 [72].

Reactivity control is done with control rods. The primary water chemistry is boron-free [73] and KOH is used for pH adjustment. The use of KOH instead of LiOH is argued to have benefits such as more reliable supply chain, less concern regarding accelerated fuel cladding corrosion and reduction in tritium generation. The anticipated $\text{pH}_{300\text{ }^\circ\text{C}}$ is 7.4, where the general corrosion rate is expected to be lower and the solubility of corrosion products reduced. Hydrogen injection is applied to lower the redox potential. Zinc injections are also anticipated from the hot functional testing onwards. Impurities such as chloride, fluoride and sulfate are all control parameters and monitored according to industry guidelines. [71]

In the secondary side chemistry, ammonia is intended to be used for pH control ($\text{pH}_{25\text{ }^\circ\text{C}}=9.8$ to 10.1). Sodium, chloride, sulfate and total iron are control parameters at the secondary side. [72]

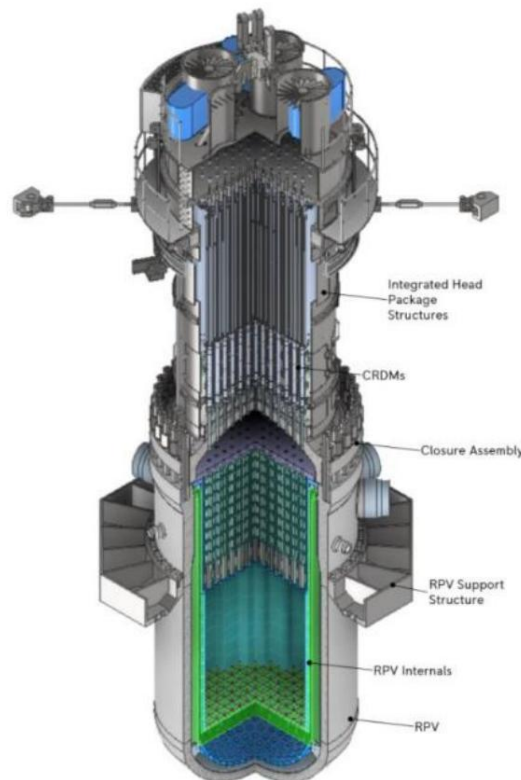


Figure 14. Schematic cut section image on the Rolls Royce SMR reactor and its internals. [70]

2.15 SMR-300

The SMR-300, Figure 15, is a next-generation PWR SMR developed by Holtec International with 292/321 °C inlet and outlet temperatures. It is designed to deliver 300 megawatts of electric power, and has a thermal output of 1050 MWth, and a design life of 80 years. General characteristics of the design include passive safety features, two pumps for forced circulation, and one once-through steam generator. Holtec is engaged in pre-application discussions with the national regulators in U.S. and UK and plans to deploy the first SMR-300 at the Palisades site by 2030. Pre-application documents are available at USNRC web site [74].

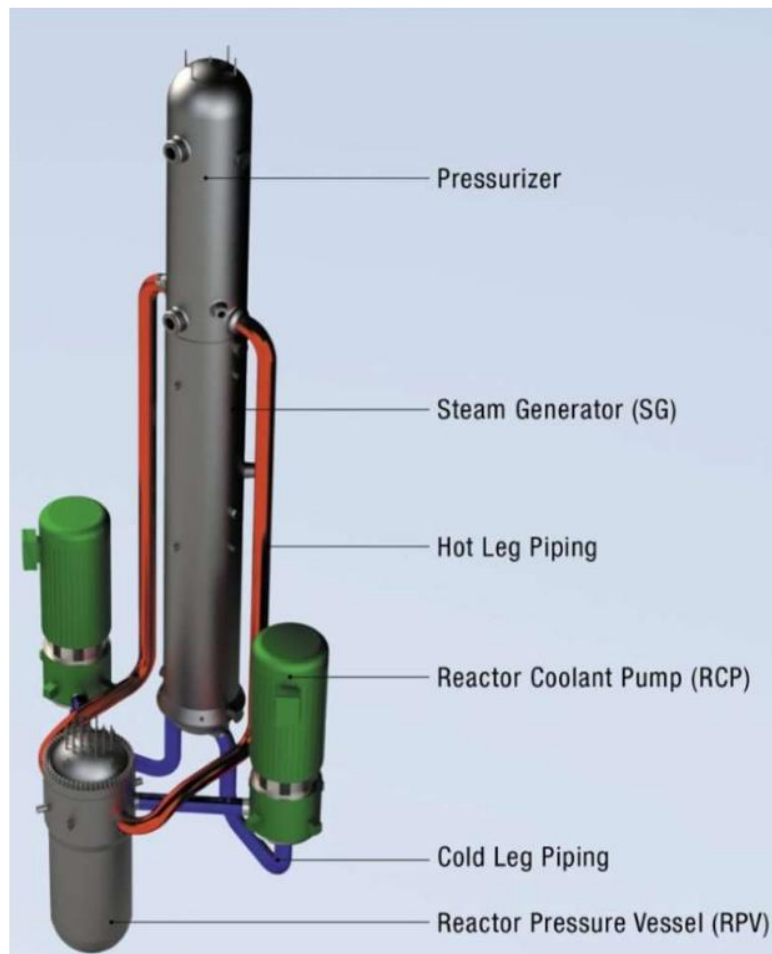


Figure 15. Schematic presentation of SMR-300 configuration. [75]

The reactor employs standard PWR fuel assemblies and utilizes soluble boron, control rods and burnable poison (Gd_2O_3) in fuel assemblies for reactivity control [76]. The $pH_{300^\circ C}$ is maintained alkaline with lithium hydroxide enriched in 7Li . Hydrogen is dissolved in the primary coolant to maintain a low redox potential for control of corrosion and corrosion products transport [77]. No numerical values of the chemistry, or information on SMR-300 structural materials were found.

3. Discussion

There has been progress in the SMR design development in the past six years, and a bit more detailed information is available now (2025) on water chemistry and structural materials. General reactor coolant chemistry plans announced for several designs can be concluded as:

- Boron-free normal chemistry more common than boron chemistry: only ACP100, NUSCALE, SMART (but not SMART-P) and SMR-300 use soluble boron for reactivity control
- Application of KOH instead of LiOH in some cases (RR-SMR, possibly i-SMR)
- Application of ammonia (RITM-200N, SMART, RR-SMR (secondary side))

- Zn injections (AP300, possibly i-SMR, RR-SMR)
- H₂ injections commonly planned

Boron-free chemistry offers certain potentially significant improvements, e.g., the elimination of both boric acid induced corrosion and axial offset anomaly, which is due to the lithium borate enrichment in crud on the fuel cladding and restricted flux in these areas. System and components related to boron control system can be left out from the design simplifying the overall function of the plant. Although, there might still be need for systems related emergency boration, the reduced building and operation costs are estimated to be significant.

Boron-free PWR primary chemistry has been discussed, e.g., by Cheon et al. [78]. Chemistry control for nuclear power plants plays an important role in the degradation of materials, fuel integrity, and radiation field control. Proper range of high temperature pH to reduce the solubility for magnetite and Ni-ferrite is between 6.9 and 7.4. To reach this pH range, application of soluble boron (boric acid) requires simultaneous application of a pH increasing agent, e.g., LiOH, KOH, and/or ammonia (NH₃). pH of pure water at 300 °C is below the optimal range, i.e., ~5.6. The authors of this report assume that for this reason some pH controlling agent might be used also in those boron-free PWR SMRs where no information is provided, even though it might affect to chemistry monitoring, and design of laboratories and CVCS.

LiOH has been traditionally used in western PWRs and KOH (+ ammonia) in Russian design VVERs with good results. However, there has been relatively little confirmed information on the compatibility of KOH and steels, fuel claddings and nickel base alloys used in western PWRs. These issues have been studied extensively in recent years, e.g., by Electric Power Research Institute (EPRI) [79-81], although very little public information is available of the exact results. General consensus seems to be that there are no significant compatibility issues. On the other hand, EPRI studies have been done with soluble boron + KOH, not in boron-free chemistries.

Ammonia have been used in marine-based applications in pH control of the primary circuit and seems to be one potential option also for some SMR designs. Examples of ammonia concentration and pH ranges in marine-based applications are between 10-100 ppm and 9.0-10.5, respectively [82]. The potential benefits of ammonia water chemistry include long-term cycles, simplified water chemistry control and mitigation of corrosion [82, 83]. However, according to Cheon et al. [78], ammonia is not recommended due to possible fluctuation of the pH value by ammonia radiolysis and ¹⁴C production from the ¹⁴N (n,p) ¹⁴C reaction. The uncertainties related to controlling ammonia and its radiolysis products in PWR primary conditions (where the power output is significantly higher than in marine-based applications) seem to be one reason why its use has not been deployed in the western design large-scale PWRs parallel to boron, although some VVERs apply it in small concentrations on a common basis [84].

Structural materials seem to be very similar to large scale PWRs when reported. The least conventional at least from western point of view is titanium used as SG material in RITM-200N and, possibly, in SMART SG tubing. No new component or material manufacturing methods to be applied are reported, e.g., additive manufacturing.

Summary table of specifications of LWR SMRs and found information on materials and water chemistries of those LWR SMRs are presented in Table 3.

Table 3. Summary of specifications of LWR SMRs. In the table “-“ means that no information was available. “NA” means that this category is not applicable for that reactor. For “boron-free” category, “yes” means that no boron is used for normal operation or anticipated transients, but might be used for emergency boration.

Design	Type	Temperature (inlet/outlet) °C	Boron-free (not considering emergency boration)	Water chemistry primary	Water chemistry secondary	Materials	Status
ACP100	PWR	282/323	no	(assumed PWR)	-	-	Under construction
AP300	PWR	-	(assumed no based on AP1000)	(assumed PWR+zinc based on AP1000)	-	(assumed stainless steels, carbon steels and A690 based on AP1000)	Basic design
BWRX-300	BWR	-	yes	BWR	NA	internals and piping: "stress corrosion resistant stainless steels or other high alloy steels" fuel cladding: "zircaloy"	Detailed design
CALOG ENA	Pool type	70-110	yes	boron-free demineralized water	-	-	Conceptual design
CAREM	PWR	284/326	yes	early recommendation: boron-free+LiOH, H ₂ <10cc/kg	-	RPV "forged steel with SS liner", early paper mentioned A690 for SGs, SS 347 for RPV liner and internals, Zircaloy-4 for claddings	Under construction
Happy200	PWR	80/120	yes	-	-	-	Detailed design
i-SMR	PWR	-	yes	boronfree+KOH/LiOH, H ₂ ~25cc/kg, maybe zinc	-	assumed primary structural materials SS 316L, A690 and zr-based fuel cladding	Conceptual design
NuScale Power Module	PWR	249/316	no	PWR	-	RPV: LAS (SA-508 Gr.3) with SS cladding; SG: A690 tubing and ferritic stainless steel tube supports	Detailed design
NUWARD	PWR	280/307	yes	-	-	-	Basic design
PWR-20	PWR	270/331	yes (assumed)	-	-	-	Detailed design
RITM-200N	PWR	283/321	yes	ammonia "self-sustaining ammonia water chemistry"	neutral water without chemical additives	RPV: LAS 15Kh2MFA; SG: titanium alloy; Fuel cladding: Cr-Ni-Mo alloy 42KhNM	Detailed design
SMART	PWR	SMART: 295.7/323	SMART:no; SMART-P:yes; SMART-100: ?	SMART-P:NH ₃ (10-100ppm), H ₂ 20-60 cc/kg (generated from NH ₃)	-	SMART: RPV: LAS SA508 Gr3, Class 1, RPV cladding: 321 SS, internals 304 SS, SG tubing: titanium alloy or A690, fuel cladding: Zircaloy-4, Fuel channel pressure tube: Zr-2.5%Nb, CRDM: ball bearings: 440 SS, screw and gear: Incoloy 925	Detailed design
STAR	PTWR	270/300	assumed yes	-	-	-	Basic design
Rolls-Royce SMR	PWR	295/322	yes	boron-free+KOH, hydrogen and zinc injections	ammonia	RPV: CS SA-508M, Gd 3, RPV cladding: SS 309L and SS 308L, RPV safe ends SS 316LN, internals SS, PZR: same as RPV, Fuel cladding: Optimized ZIRLO [®] , secondary side main steam line piping: ferritic SA-335M P22	Detailed design
SMR-300	PWR	292/321	no	PWR	-	-	Conceptual design

4. Conclusions

PWR type SMR water chemistries differ in many cases from those of present day and older large-scale PWRs' (H₃BO₃ + LiOH or H₃BO₃ + KOH + NH₃). The most common PWR SMR primary side chemistry appears to be boron-free:

- Boron-free chemistry avoids issues related to boric acid corrosion and axial offset anomaly. Another benefit is simplified chemistry control and monitoring. The absence of boron does not necessarily eliminate the need of pH adjustment chemical.

- pH control of SMR primary circuits seem to have three options: KOH, LiOH and ammonia
 - o Extensive user experience exists on KOH in VVER-type of plants and LiOH in western type PWRs. Compatibility of KOH with western type of structural materials have been studied.
 - o Ammonia have been applied in marine-based applications but its use as a sole pH adjusting chemical in land-based reactors has not been demonstrated.
- Hydrogen and Zn injections are planned to be used in SMR primary circuits similarly as in the large-scale plants.
- Not much information available on secondary circuit chemistries but they seem to be similar to the large PWR/VVER plants.

BWR SMR chemistries are apparently similar to large scale BWRs. On the other hand, IAEA presently lists only one BWR SMR that is under development (BWRX-300).

LWR SMR materials do not differ significantly from those used in newer generation large scale electricity producing nuclear power plants except that steam generator tubes are reported to be titanium alloy in SMART-P as well as steam generator in RITM-200N. RITM-200N is also reported to have Cr-Ni-Mo alloy fuel cladding. No new material or component manufacturing methods, e.g., additive manufacturing, are reported to be applied in light water cooled SMRs.

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