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REVIEW ARTICLE

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SMRs – overview, international developments, safety features and the GRS simulation chain

Abstract The Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH as the main technical support organization for the German Federal Government in nuclear safety has been dealing with small modular reactors (SMRs) for about one decade since SMRs are one interesting option for new builds in most countries worldwide which continue to use nuclear energy for commercial electricity production. Currently four different SMR designs are in operation, four in construction, one is licensed, and further 12 are in a licensing process. In this paper, definitions, history, and current developments of SMRs are presented. Subsequently, selected trends of SMR development such as factory fabrication and transport, compactness and modularity, core design, improved core cooling, exclusion of accidents, features for preventing and limiting the impact of severe accidents, economic viability, competitiveness and licensing are discussed. Modeling gaps of the GRS simulation chain programs with a view to applications in nuclear licensing procedures are identified and a strategy for closing these gaps is presented. Finally, selected work on the extension and improvement of the simulation chain and first generic test analyses are presented.

Keywords small modular reactors (SMRs), history, recent developments, safety aspects, simulation chain of the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

1 Introduction

The Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH is a nonprofit, non-governmental and independent research and expert organization. One aspect of GRS' mission on nuclear safety is to identify and address safety research needs and close these gaps, to gain the scientific and technical knowledge necessary to support regulatory authorities with independent expert assessment. For this purpose, GRS reviews and follows relevant nuclear developments mainly in its direct (i.e., European) neighborhood, but also worldwide. This is also valid for the topic of small modular reactors (SMRs).

Stefano Monti, Head of the IAEA's Nuclear Power Technology Development Section states that SMR's unique attributes in terms of efficiency, flexibility, and economics may position them to play a key role in the clean energy transition [1]. The same argument is used by the current US government. It has promised the most ambitious climate program, which is based on the turn away from oil and gas industry. The future power supply shall be completely changed, relying primarily on renewables. Because their global share of energy production is still comparatively small, the US government also plans to invest in nuclear power, especially in new, mobile, and safe SMRs [2].

Reputable media have increasingly reported about further SMR activities in several countries within the last two years. A small selection (without claim to completeness) is listed below.

Argentina: construction of the entirely Argentinian designed CAREM is nearing completion, and start of operation is planned within the next three years [3].

Canada: the Canadian government is investing 20 million CAD to accelerate development of Terrestial Energy's integral molten salt reactor (IMSR) [4].

China: the prototype high-temperature gas cooled HTR-PM located in Shidao Bay is slated to begin operation next year [1]; additionally China has started building the two-unit ACP100 demonstration SMR at Changjiang site on Hainan island by the state-owned China National Nuclear Corporation (CNNC) [5].

France: CEA, EDF, NAVAL Group and TechnicAtome

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unveil their jointly developed SMR project based on the PWR technology with significant innovations and major benefits to the operator and product’s competitiveness such as compactness and simplicity of an integrated design, flexibility for construction and operation, innovative safety approach [6].

Russia: start of operation of two reactor units of KLT-40S aboard the floating nuclear power plant (NPP) Akademik Lomonossov and a project for commissioning a land based SMR in 2027 [1].

UK: the UK SMR consortium led by Rolls-Royce claims to create 6000 jobs in five years if the government commits to a fleet of 16 SMR power stations built by 2040 [7].

Due to the numerous, extensive worldwide activities related to SMR, it is difficult to keep an overview of all activities. GRS has started early (approximately from 2010) with first work on this topic. In the framework of an extensive and broad-based project, GRS has performed and published a study on Safety and International Development of Small Modular Reactors [8]. The large number of SMR designs in operation, under construction, and under development at an advanced state of design required a generic approach and the identification of general trends. This still applies today. Today, five years later, it is a good moment to update the content and, if necessary, also the conclusions of the study and corresponding papers. The basis for this update is freely accessible press releases, papers, and reports (e.g., IAEAs biennial IAEA booklet Advances in Small Modular Reactor Technology Developments [9], according to which currently 72 reactors or reactor designs are under development in 18 countries).

The outline and structure of this paper is adopted from the oral presentation SMR — Overview on International Developments and Safety Features as part of the focus session International Innovation — SMR a Major Element of Future of Nuclear of the Annual Meeting on Nuclear Technology (AMNT) in Berlin in May 2019 [10] and a contribution with the same title in International Journal for Nuclear Power in Oct. 2020 [11]. In this paper, first, common definitions of the term SMR and a rough overview of their history are given. Then, recent developments are presented, considering different project status (SMRs in operation, SMRs in construction and additional SMRs licensed or in a licensing state). Next, the changed political framework in Germany is overviewed. General technical trends, construction and safety trends identified in the GRS study on safety and international development of SMRs are summarized. A description of selected specific details is given mainly for illustrative purposes. Thereafter, considerations concerning economic viability, competitiveness and licensing expounded. Finally, an overview of necessary improvements and validation of the GRS nuclear simulation chain is provided. This is supplemented by an overview on national/international research project of GRS on this issue, a description of current activities for the development of a new neutron kinetics code well suitable for the particularities of SMRs and first safety analyses for a generic SMR design.

2 Definitions, history, and current developments

After a compilation of different SMR definitions in Section 2.1, a short overview on the history (Section 2.2) and current projects (Section 2.3) is provided. This paper deals exclusively with SMRs for energy and/or power generation. Engines for nuclear icebreakers, merchant vessels and submarines, studies of mobile SMRs, propulsion systems for outer space, as well as military applications are out of scope.

2.1 Definitions

There are two different definitions for SMR in the literature. The first one is widely used in North America (e.g., the USA and Canada). There, the abbreviation SMR stands for small modular reactor. The emphasis is on the term modular, which implies that a (larger) production unit consists of several modules which may be added one by one. Generally, one unit can be refueled while the others continue their operation. The term “small” in the definition SMR characterizes an electrical power output of less than 300 MW. On this scale, the primary coolant system, selected parts of the secondary and, where necessary, intermediate circuit and auxiliary systems can be arranged in an integral reactor pressure vessel (RPV) at dimensions well-known from extant larger PWRs. An SMR module may be transported to the construction site in one piece or in few parts [12].

On the contrary, the IAEA defines SMR as small and medium-sized reactor. These reactors can have capacities up to 700 MW of electrical power. The modular character is not addressed by this definition but is not excluded [12]. According to this definition, all reactors ever built within this power range, even the Soviet-type VVER440, are SMRs [11].

For the same reason, different views exist, whether e.g., the CNP-300 and the PHWR-220 (all described in Section 2.3) are SMRs or only NPPs with a low electrical power output. In this paper, the approach described in Refs. [8–11,13,14] are followed to consider these aforementioned SMR designs.

2.2 History

The idea of small (modular) reactors is not a new one. Since the mid of the last century the former USSR and the USA have used SMRs for energy and heat production for remote areas (e.g., Arctic, the Antarctica or Greenland)

[10,11,13] and for engines for their submarines, merchant vessels and ice breakers [10,11,13].

One well-known example is the US Army Nuclear Power Program (ANPP) [15–17], which has achieved numerous pioneering successes. Selected milestones were

- the development of detailed designs for pressurized water, boiling water, gas-cooled and liquid metal reactors,
- the first construction and operation of an NPP in the USA
  - with a boiling water reactor
  - with a containment (equipped with pressure suppression),
  - to supply electricity to a commercial grid,
  - used for district heating
- the development of fuel element assemblies of stainless steel,
- the first replacement of a steam generator in the United States,
- the first portable, prefabricated, modular nuclear power plant to be built, operated and dismantled,
- the first use of nuclear energy for seawater desalination,
- the development of the first mobile, land transportable nuclear power plant,
- the development of the first nuclear-powered gas turbine with closed Brayton circuit and
- the first floating nuclear power plant.

Nuclear ship propulsion has also been tested for the civilian sector. Examples are or were the Soviet icebreakers Lenin, Arktika, and Sibir [18] and the cargo ships Savannah (USA), Otto Hahn (Germany), which notably operated one of the first iPWR designs [19], Mutsu (Japan) and Sevmorput (USSR). The Russian icebreakers Rossiya, Tajmyr, Sovetskiy Soyuz, Waigatsch, Yamal, and 50 Let Pobedy are still in operation today [18].

2.3 SMR overview

Worldwide, there are numerous as well as comprehensive activities on the operation, construction, and development of SMRs which are described in Sections 2.3.1, 2.3.2, and 2.3.3.

2.3.1 SMRs in operation

Apart from nuclear ship propulsion as well as very small modular reactors (vSMR, e.g., for aerospace and military), which are not the subject of this paper, currently four SMR designs are in operation, two in Russia, and one in China and India each (see Table 1). At this point, it should be referred again to the note in Section 2.1, that there are different views whether some of the reactors listed in Tables 1, 2, and 3 are SMRs or only NPPs with a low power output.

The CNP-300 is the first own development of an NPP in China and was built between 1985 and 1991 at the Qinshan site [19]. The CNP-300 is a pressurized water reactor and has a capacity of approximately 999 MW_{th} or 325 MW_e [20]. Additionally, at the Qinshan site there are 4 blocks of the CNP-300 successor CNP-600, mid-scale NPPs, still of Chinese design. Only the steam generators were manufactured by Babcock and Wilcox in Canada. The CNP-300 design was exported to Pakistan. Concerning the IAEA Power Information System (PRIS, available at the website of iaea.org), four reactor units in Chasnupp (or Chasma) were built. Start of construction was between Aug. 1993 and Dec. 2011, first grid connection between Jun. 2000 and Jun. 2017.

The EGP-6, a down-scaled version of the RBMK reactor design, is currently the world’s smallest and northernmost nuclear reactor in operation [21]. Four units of this type were erected at Bilibino NPP. Plans for shutdown have been announced. Unit one was already taken out of service in 2018. The Bilibino NPP shall be replaced by the floating nuclear power station Akademic Lomonosov.

The floating NPP Akademic Lomonosov [9] has been built in a shipyard in St. Petersburg since 2007. It contains two KLT-40S reactors with a thermal power of 150 MW each. These reactors are derivatives of the KLT-40 [22], which were used in icebreakers of the Sevmorput class and the KLT-40M used in icebreakers of the Taymyr class [13]. The Akademic Lomonosov was deployed to Pevek at the East Siberian Sea in order to provide electricity, district heating, and potable water to the region. The first grid connection was in Dec. 2019 [9]. Other reactor designs by OKBM Afrikantov, like the RITM-200 [19,23,24] and VBER-300 [9], are either ship propulsion reactors or derive from ship reactors. The RITM-200 reactors have been installed in new nuclear-powered icebreakers of the Russian federation, so deployment is under way [19].

The PHWR-220 is a pressurized heavy-water reactor indigenously built in India. Sixteen units of this series were

Table 1 SMRs in operation

Name	Type	Manufacturer	Country	P/MW_e	Status	Site
CNP-300	PWR	CNNC	CN	325	5 operating	Qinshan 1 (CN), Chasnupp 1–4 (PK)
EGP-6	RBMK	OMZ Group	RU	12	4 operating	Bilinino 1–4 (RU)
KLT-40S	PWR	OKBM Afrikantov	RU	35	2 operating	Barge Akademik Lomonosov (RU)
PHWR-220	HWR	BARC	IN	236	16 operating	Rajasthan 1–6, Madras 1–2, Narora 1–2, Kakrapar 1–2, Kaiga 1–4 (all IN)

Notes: CN—China; RU—Russia; IN—India; PK—Pakistan.

Table 2 SMRs under construction

Name	Type	Manufacturer	Country	P/MW$_e$	Status	Site
ACP100	PWR	CNNC	CN	100	Site preparation in July 2019	Changjiang at Hainan island (CN)
ACPR50S	PWR	CGNPC	CN	60	Start of construction Nov. 2016	Demonstration offshore nuclear reactor (CN)
CAREM	PWR	CNEA	AR	27	Start of construction: Feb. 2014	Atucha (AR)
HTR-PM	GCR	INET	CN	105	Demonstration plant under construction since 2012 (2 modules)	Shidaowan (CN)

Notes: CN—China; AR—Argentina.

Table 3 Additional SMRs licensed or in a licensing process

Name	Type	Manufacturer	Country	P/MW$_e$	Status	Site (planned)
ACR-100	LSFR	ARC Nuclear	CA	100	Pre-licensing (phase 1 completed)	–
BWRX-300	BWR	GE-Hitachi	USA, JPN	280	Pre-licensing (phase 2* in progress)	(CA)
IMSR	MSR	Terrestial Energy	C	200	Pre-licensing (phase 2 in progress)	(CA)
MMR-5 MMR-10	HTG	Ultra Safe Nuc. Cor.	CA	5 10	Pre-licensing (phase 2 pending)	(CA)
MOLTEX	MSR	Moltex Energy	CA	300	Pre-licensing (phase 1 in progress)	(CA)
NuScale	PWR	NuScale Power and Flour	USA	60	Pre-licensing (phase 2* in progress)	(US)
NuScale 720	PWR	NuScale Power and Flour	USA	77	Ppplication of Standard Design Approval	(US)
SEALER	LMFR	LeadCold Nuclear	SWE	3	Pre-licensing (phase 1 pending)	–
SMART	PWR	KAERI	KR	100	Licensed	–
SMR-160	PWR	Holtec Int.	USA	160	Pre-licensing (phase 1)	(UA)
U-Battery HTG	HTG	U-Battery Canada Ltd.	CA	4	Pre-licensing (phase 1 pending)	–
VBER-300	PWR	OKBM	RU	300	Licensing stage	(KZ, RU)
XE-100	HTG	X Energy	CA	80	Pre-licensing (phase 2* in progress)	–

Notes: CA—Canada; JPN—Japan; SWE—Sweden; RU—Russia; KR—South Korea; USA—United States of America.

constructed at five different sites (Kaiga, Kakrapar, Madras, Narora, and Rajasthan). The PHWR-220 has a power output of roughly 800 MW$_{th}$ and 220 MW$_e$. Kaiga 1 Nuclear Power Plant became a world record holder for running 962 days of continuous operation on Dec. 31, 2018 [25].

2.3.2 SMRs under construction

Four SMR designs (Table 2) are currently under construction. These are the ACP100 and the ACPR50S in China (PWR), the CAREM in Argentina (PWR), and HTR-PM in China (GCR).

The ACP100 is an integral PWR design developed by China National Nuclear Corporation (CNNC) to generate an electric power of 125 MW. It is based on the existing PWR technology, adapting verified passive safety systems. The integral design of its reactor coolant system (RCS) enables the installation of the major primary circuit's components within the reactor pressure vessel (RPV). According to IAEA PRIS, site preparation started in July 2019. In March 2019 World Nuclear News (WNN) reported that first concrete for the site in Changjiang on Hainan island is to be poured on Dec. 31, 2019. Construction is expected to take 65 months. First grid connection is planned for 2025 [26].

In 2015, China decided to build an indigenous modular floating NPP. This SMR is called ACPR50S and has an electrical power output of 60 MW. The reactor is designed to supply energy to islands, remote coastal areas, or offshore oil and gas production facilities [27]. The ACPR50S can also be applied for seawater desalination. On Nov. 4, 2016, CGN announced the start of construction on the first demonstration unit of a floating nuclear power plant with the signing of the purchase contract for the first ACPR50S reactor [28].

In Argentina, a CAREM-25 [29] is currently built by CNEA at the Atucha site north-west of Buenos Aires. A special feature is the integral design of the primary circuit, where the pressurizer, the steam generator, and control rod drives are integrated within the reactor pressure vessel. Since the core is cooled with natural convection even in operation, no pumps are necessary [30]. Construction of CAREM is nearing completion, and start of operation is planned within the next three years [3].

The construction of the HTR-PM started in Shidao Bay Nuclear Power Plant in Dec. 2012. It consists of two high-temperature gas-cooled pebble-bed reactors with an electrical output of 105 MW each. Both reactors are connected to a single steam turbine. The HTR-PM is partly based on the HTR-10 prototype reactor and is expected to be the first Gen IV reactor to enter operation [31]. According to Ref. [1], the reactor pressure vessels of units 1 and 2, which are approximately 25 m high and have a weight of 700 t, were lifted into the reactor building. Afterwards they were connected to the steam generator and the hot gas line. The cold tests are completed at the first HTR-PM unit and start now for the second unit [32]. Start of operation is planned in 2021 [33].

2.3.3 SMRs licensed or in a licensing procedure

According to IAEA [9], there are four additional SMRs with a certified design (SMART), in a licensing state (VBER-300), in a pre-licensing state (BWRX-300) or under regulatory review (NuScale).

The website of the Canadian Nuclear Safety Commission provides information on further pre-licensing activities. The reviews take place in three phases, each of them is conducted against related CNSC regulatory documents and Canadian codes and standards. Here information on review activities on seven further SMR (IMSR, MOLTEX, MMR(5/10), SEALER, SMR-160, U-Battery, and XE-100) can be found.

On the website of the United States Nuclear Regulatory Commission (US NRC), a NuScale720 appears for the first time. In this version of NuScale, the electrical output was increased from 60 to 77 MW. Granting of the Standard Design Approval (SDA) is scheduled for the 3rd quarter of 2021.

Additional information is provided in Table 3. In addition, roughly 60 SMR concepts are at a design state without advanced deployment plans.

3 Re-evaluation of (technical) trends of the GRS study on safety and international development of small modular reactors

Selected results of the GRS study on safety and international development of SMRs [8] were briefly summarized in Refs. [10,11,13]. The aim of this section is to re-evaluate and, if required, to update the respective statements for necessary improvements of the GRS simulation chain (see Section 4). The large number of SMR designs in operation, under construction, under licensing development, and under an advanced state of planning requires a generic approach and the identification of general trends.

In Section 3.1, the current political framework in Germany and the motivation for this paper is presented. In Section 3.2, objectives of the paper as well as identified (technical) trends are summarized. In Section 3.3, estimations concerning economic viability and competitiveness and in Section 3.4, concerning licensing are summarized.

3.1 Current political framework in Germany

After the Fukushima nuclear disaster [34], Germany decided to terminate the use of nuclear energy generation by 2022. According to Ref. [35], new builds of NPP are prohibited by law since 2002, which also applies for SMRs. However, worldwide, national government policies differ. Many countries (e.g., China, Finland, France, Hungary, Saudi Arabia, Turkey, United Arab Emirates, United Kindom, United States of America, and Russia) are planning or constructing new builds of NPPs. SMRs are an interesting option there, but also for other countries.

For asserting of legitimate nuclear safety and/or security interests, German authorities require own and independent expertise for the safety assessment of NPPs and other nuclear facilities worldwide and especially in neighboring countries. Thus, the German Federal Government continues to fund reactor safety research which is in line with national and international framework conditions and obligations. The technical expertise in Germany for promoting comprehensive safety reviews and ambitious safety targets, is essentially built-up and provided by the GRS gGmbH [36]. Studies, as Ref. [8] and its update, substantially contribute to this goal.

3.2 Reevaluated (technical) trends

The aim of the GRS study on Safety and International Development of Small Modular Reactors [8], published in 2015, was

- to setup a sound overview on current SMRs,
- to identify essential issues of SMR reactor safety research and future R&D projects, and
- to identify needs for adaption of system codes of GRS.

In the following sections, selected results (e.g., general trends and safety features) are re-evaluated and updated as necessary. Some of these trends apply for all SMRs (Section 3.2.1 to Section 3.2.2), while others (Section 3.2.3 to Section 3.2.5) are exclusively valid for light-water cooled SMRs. From GRS' point of view, the SMRs based on the LWR technology show best chances of realization in higher numbers because they are based on a long-term operationally proven technology and an already existing fuel cycle. Furthermore, all nuclear stakeholder (especially regulators) have amassed by far the most experience with this technology.

3.2.1 Factory fabrication and transport

Many SMRs facilitate a modular construction, and major components are small enough to be built on a production line in a factory and assembled onsite [37]. Factory production allows for producing several units simultaneously and not, as at present, assembling one single unit at a time [38]. The components of large power reactors (e.g., the reactor pressure vessel, the steam generators, the main coolant pumps, the pressurizer, and the blow-off tank) are large and heavy, so that these items must be manufactured, transported individually to the construction site and assembled here to each other e.g., by piping. However, site construction has a higher risk of sub-standards and/or rejects. The crafts are e.g., exposed to strongly varying weather conditions, dirt, and grime.

The size of many SMR modules often allows for their transport from factory to the construction site as one single unit. Hence, such SMRs do not require huge custom transporters, highway closures, or reinforcement of bridges along the transportation route. With SMRs, getting all the equipment to the construction site is much simplified [39,40]. Additional SMRs are much less demanding in terms of siting. Large reactors require sites with a low population, generally due to a larger emergency planning and exclusion zone, and access to large quantities of cooling water. Therefore, the number of suitable construction sites for SMRs is by far larger.

3.2.2 Integral designs

Many of the SMRs are proposed as an integral (PWR) design [8]. Integral in this context means that the components of the primary coolant circuit (e.g., core, pressurizer, steam generators, main coolant pumps (if the respective SMR has a forced convection cooling)) are arranged within the reactor pressure vessel. This construction mode excludes large break loss of coolant accidents (LBLOCA) by design, since no large connection lines are needed (see Section 3.2.4). In some cases, the control rod drives are also integrated into the reactor pressure vessel [41]. This compact design and the elimination of major plant components give both safety and economics advantages so that integral PWR designs are among the most promising options for SMR deployment [19].

Loop designs with very short coaxial connection nozzles can also be found (e.g., KLT-40S). Here the hot legs are located in the inner pipe while the cold legs are in the outer part of the coaxial pipe in order to minimize temperature losses [22].

However, integral SMR designs typically require new types of compact and highly effective steam generators able to transfer large heat quantities at a low overall height at the same time [11]. For this purpose, bayonet, helical coil, or plate heat exchangers were adapted from the conventional energy technology.

The arrangement of the helical coil steam generators could be, either several steam generators in the downcomer (e.g., in CAREM) or one steam generator around the riser (e.g., NuScale). Common in all designs is that the efficiency is increased by thin walls and highly turbulent flow fields, which makes the steam generators susceptible to flow-induced vibrations.

3.2.3 Core design

The reactor core of a light-water cooled SMR typically consists of 40 up to 80 shortened standard fuel assemblies arranged according to optimized loading patterns. Such core has an active length between 2 and 2.5 m. Most often, the corresponding fuel (UO_2 as well MOX) is higher enriched and shall be burned-up significantly higher to extend refueling cycles. Many SMR cores are designed for fuel cycles between two and ten years [11]. All light-water cooled SMRs by design have a negative temperature coefficient for both primary coolant and fuel. Some concepts waive a boron acid system, in order to save space and to lower the temperature coefficient. Instead of a boron system, burnable absorbers like Gd_2O_3, IFBA, Er or B_4C are used. Additionally, compensation of excess reactivity can be achieved by the use of the control rods which are also applied for short time control of the core. The materials used are e.g., Ag In-Cd, B_4C, and $Dy_2Ti_2O_7$ [8,13].

In NPPs consisting of several modules, one module can be refueled, while the others continue operation. The output of the multi-module production NPPs is reduced only in this time span; but the plant is not entirely powered down. The outage can be planned and carried out at times of low energy demand. At the end of their lives, the modules are returned to the factories for disassembling [11].

3.2.4 Improved core cooling and exclusion of accidents

The reliability of core cooling provisions of many SMR designs was improved as compared to the currently operated LWRs. Therefore, similar design principles as for the advanced Gen III / III + reactors are applied [40]. Concerning [11] these are e.g.,

- the reduction of the power density of the core (up to –50% as compared to currently operated Gen II LWRs),
- a low positioning of the core inside the RPV,
- a high water coverage of the core so that even for a

break of the largest line connected at RPV, no uncovery of core occurs during blowdown,

- increased scaled size of integral pressurizes slows down pressure transients,
- large water inventories in- and outside the RPV, respectively, to ensure slow-acting accident control capabilities,
- large heat storage capacity inside the containment as a result of large water inventories,
- passive equipment for heat removal from the RPV and the containment, and
- passive cooling of the RPV exterior in the event of core melting scenarios to ensure retention of the core melt inside the RPV.

Up to an electrical power output of roughly 200 MW and an appropriate design, decay heat can be safely removed from the RPV with passive safety features in principle. This is an important advantage for a demonstration that a severe accident with complete core melting is practically eliminated. The improved heat removal features result from the larger surface to the volume ration of the RPV. This again results from the diameter to the length ratio of the vessel. Compared to Gen II LWRs, the reactor core has a smaller distance to the RPV wall, which leads to a better heat removal by conduction. Additionally, the heat transfer resistance of an SMR RPV wall is lower than that of the RPV wall of a Gen II LWR, because the wall thickness decreases with the curvature of the vessel [11].

Several SMRs remove selected accidents by design. Many of the light-water cooled SMRs are operating under natural circulation without the use of main coolant pumps (e.g., CAREM, NuScale, etc.). Consequently, for these concepts, no pump trip has to be considered. However, especially during the start-up phase, this may lead to flow instabilities like geysering or density wave oscillations, which the designers have to deal with. Descriptions of such phenomena for the integrated modular reactor (IMR) design can be found in Ref. [42]. Boron dilution accidents, of course, can be excluded for SMRs with boron free cores and switching to burnable neutron poisons. The utility of this approach again depends on reactor power [19]. When using integral control rod drives (e.g., CAREM), the threat of an unprotected control rod ejection is essentially eliminated, since the pressure difference between the top and the lower edge of the control rod is not caused by ambient and primary pressure anymore but by level difference in the reactor pressure vessel only [29]. Finally, the integral design can exclude large break loss-of-coolant accidents (LBLOCA) [43].

SMR concepts typically consider three main design principles for a save control of a postulated LOCA: First, the number of lines connected to the RPV is minimised. Second, the connections of the pipe are far above the top edge of the core and third, the piping with primary coolant outside the RPV is reduced. Since the maximum break sizes of a Gen II LWR (a double ended break leads to a break area of roughly 1 m^2) and an SMR vary by up to three orders of magnitude, LOCA in SMRs can be more easily and thus reliably controlled, and loads on RPV internal and on the containment structure decrease [10].

As mentioned above, in many SMRs, decay heat removal relies on passive safety systems. The operation mode of these systems is based on laws of nature (e.g., free convection, condensation, and evaporation). The decay heat is removed by natural circulation toward large water inventories arranged in- or outside the containment. However, at present, there are neither uniform definitions of passive safety systems nor requirements for experimental and/or analytical evidences [11]. While the definitions of IAEA [44] and EPRI [45] allow an active initiation of operation to classification as a passive safety system, German Safety Requirements for NPPs [46] do not allow for this. Systems with an active initiation of operation would, according to Ref. [46], be an active system, for which a $n+2$ degree of redundancy is required. Due to a current existing lack of operation experience, there are, however, concerns regarding the performance and reliability of passive safety systems [11]. Consequently, the required number of redundancies for passive defense-in-depth level 3 safety features and the inclusion of diverse safety provisions on defense-in-depth level 4 are subject to on-going debate. Decisions will likely have to be taken for each specific safety concept.

The containments of typical light-water cooled SMRs have a passive cooling capacity of at least 72 h. Some SMRs even have an infinite passive containment cooling to an ultimate heat sink which could be either air or water. Four different design approaches currently exist for this issue: These are horizontally or vertically containments arranged in large water pools, subsea-based containments, floating containments, and containment cooled by heat pipes [47].

In many SMRs, the containment is more compact than the containment of currently operated plants. In case of a potential loss-of-coolant accident, this may result in a higher pressure build-up inside the containment as well as in higher heat fluxes through the containment wall. These circumstances have already been considered in several integral test facilities. In the Multi-Application Small Light Water Reactor (MASLWR) test ring of the Oregon State University (OSU), integral tests have already been conducted with pressures far beyond 2 MPa [48,49].

3.2.5 Features for preventing and limiting the impact of severe accidents

In general, the lower amount of nuclear fuel within the SMR cores, the improved core cooling features, and the practical elimination of accidents (both described in Section 3.2.4) lead to a reduction of the probability and consequences of core melting. As a result, the off-site emergency planning requirements can be scaled down to be proportionate to those reduced risks. This includes the possibility that emergency planning zones (EPZ) do not have to extend beyond the plant site boundary [40].

Most SMRs designs include new ideas to increase the resilience against external hazards such as earthquakes, explosion pressure waves, and airplane crashes. This includes i.e., the arrangement of SMR modules in a (water filled) cavern, being partially or completely below the ground level sometimes additionally buried under an earth wall (e.g., French SMR NUWARD [50]) or at the ground of an ocean in a water depth of up to roughly 100 m.

3.3 Economic viability and competitiveness

In general, questions of economic viability and competitiveness are not included in the working fields of GRS, which are the safety and security aspects. GRS has looked into with these aspects for an initial assessment whether SMRs can be an option for new builds in the direct neighborhood of Germany. This would increase GRS's prioritization for detailed analyses on such SMR design.

The evaluation of various studies (e.g., [51]), papers (e.g., [52]) as well as qualitative considerations e.g., by [44] indicates that SMRs can be under certain assumptions competitive compared to Gen II, III and III + LWRs as well as in the medium term to gas powered plants. However, the extent of costs considered widely varies from study to study.

The current initial estimation is as follows: For SMRs, it is the key to offset the economies of scale, which seemed to be in favor of large reactors, with economies of numbers, provided by the concept of modules or entire plants built in factories and shipped to the site [52]. Moreover, construction of multiple units allows for learning effects and associated cost reductions. SMRs have a large application spectrum and can be used for many purposes such as electricity, heat production, and co-generation. Smaller units also allow for an easier integration into existing electricity grids and are more suitable for niche markets (e.g., sparsely populated regions), increasing their viability [19]. Vendors state that an SMR unit requires (due to its smaller size) lower capital costs for construction and commissioning. A production unit could be extended module by module, even after connecting the first module, electricity and/or heat could be generated and sold. The risks of delays could be minimized by factory production of the nuclear island. After transportation to the site, the modules could be immediately connected to grid. This reduction of financing costs and associated financial risks (and their premiums) is one major factor for offsetting the worse economies of scale [19]. SMRs have been designed for longer operating cycles and require less maintenance. Further, vendors argue, that SMRs could be disposed of more easily, since the complete modules could be shipped back to the factory and dismantled there. However, it has to be mentioned that the studies mentioned above indicating the economic feasibility as well as a significant market potential based on certain assumptions, as all entry barriers have been overcome; SMRs are produced in series in factories, which have to be built first; and efficient transnational licensing procedures have been established (see Section 3.4).

With regard to the second bullet, it should be pointed out that it is not clear which company or economy is able and especially willing to realize the necessary investments, respectively. Moreover, costs and associated risks from the frontend of the fuel cycle (fuel supply) and the backend (interim and final repository) have to be taken into account. For that reason, institutional and state investors are more likely to realize an SMR new build, and the host state needs to set favorable boundary conditions.

More generally, with the increased action on climate change by national actors and the ensuing restructuring of energy markets, there is a limited window of opportunity SMR designs need to meet to be part of the energy supply markets of the future. Designs not ready for deployment before 2030 might miss this window.

3.4 Licensing

This section describes global harmonization of rules and regulations and changes in current licensing procedures, desired by manufacturers and operators. Such harmonization could facilitate for SMRs being successful in the market. The decisions necessary for the implementation are taken by respective national governments and regulators. In this sense, the following remarks are only brief summaries of the current discussion in the nuclear community, which may differ from the GRS' point of view.

Studies concerning the economic viability and competitiveness indicate that a cost efficiency of SMRs requires the construction of at least 80 up to 100 identical units worldwide. The word "identical" here means that the same design needs to be deployed in all target markets. Currently, SMR vendors desire to reduce the number, the time, and the financial effort for nuclear licensing procedures. This means that if identical modules are added to a production unit, no new licensing procedure is required for the nuclear island. Furthermore, approvals should be recognized internationally. Another point is that the construction surveillance could be conducted by a Technical Support Organization (TSO) in the country, in which the SMR factory is located. All aspects discussed above require a harmonization of definitions (e.g., for passive safety systems, see Section 3.2.4), rules and regulations (e.g., for experimental and analytical evidence). Discussions on these issues between national regulators are on-going on multiple levels, e.g., via the IAEA SMR regulators forum.

As already mentioned in the introduction of Section 3.2, SMRs based on the LWR technology currently offer advantages, due to the experiences of the nuclear regulators collected with light-water reactor technology in the last decades. Since a licensing process lasts several years, SMRs in operation or even under construction have advantages in the market. Licenses have been granted so far to six light-water cooled SMRs (ACP-100, ACPR50S, CAREM, EGP-6, KLT-40S, and PHWR-200).

4 GRS nuclear simulation chain, necessary improvements, and current work

The numerical simulation of SMRs (e.g., safety analyses to support a safety assessment) necessarily requires SMR know-how and specific technical data as well as qualified simulation tools. Today, a comprehensive, historically grown, and to a large extent in-house developed and validated nuclear simulation chain system is available at GRS [53,54]. This simulation chain originally was developed for light water reactors and in succession, in various degrees, selectively expanded for other coolants (e.g., heavy and supercritical water, gas, liquid metals, and molten salts). The application of the simulation chain requires the identification of modeling gaps, a strategy for filling that gap and of course necessary methodological improvements/expansion as well as, of paramount importance, a subsequent verification and validation.

After a general overview of the GRS nuclear simulation chain in Section 4.1, in Section 4.2, an overview on identified modeling gaps is provided, including an overview on current activities and domestic and international projects in which GRS is currently involved. In Section 4.3, preliminary thermal hydraulic analyses for a generic SMR design are presented. The objective of these analyses was to gain first experiences with the application of the code suite AC^2, especially its herein included thermal hydraulic code ATHLET for these issues.

4.1 GRS nuclear simulation chain

The structure of this nuclear simulation chain is depicted in Fig. 1 [54], which consists of GRS' in house developments (deep blue boxes) and third-party codes (white boxes). Many codes can be coupled simply for data transfer (indicated by the dotted lines) or in a more complex way through interfaces (indicated by red line). The latter option requires the development of appropriate interfaces. The advantages of coupling will be discussed in more detail later in this section.

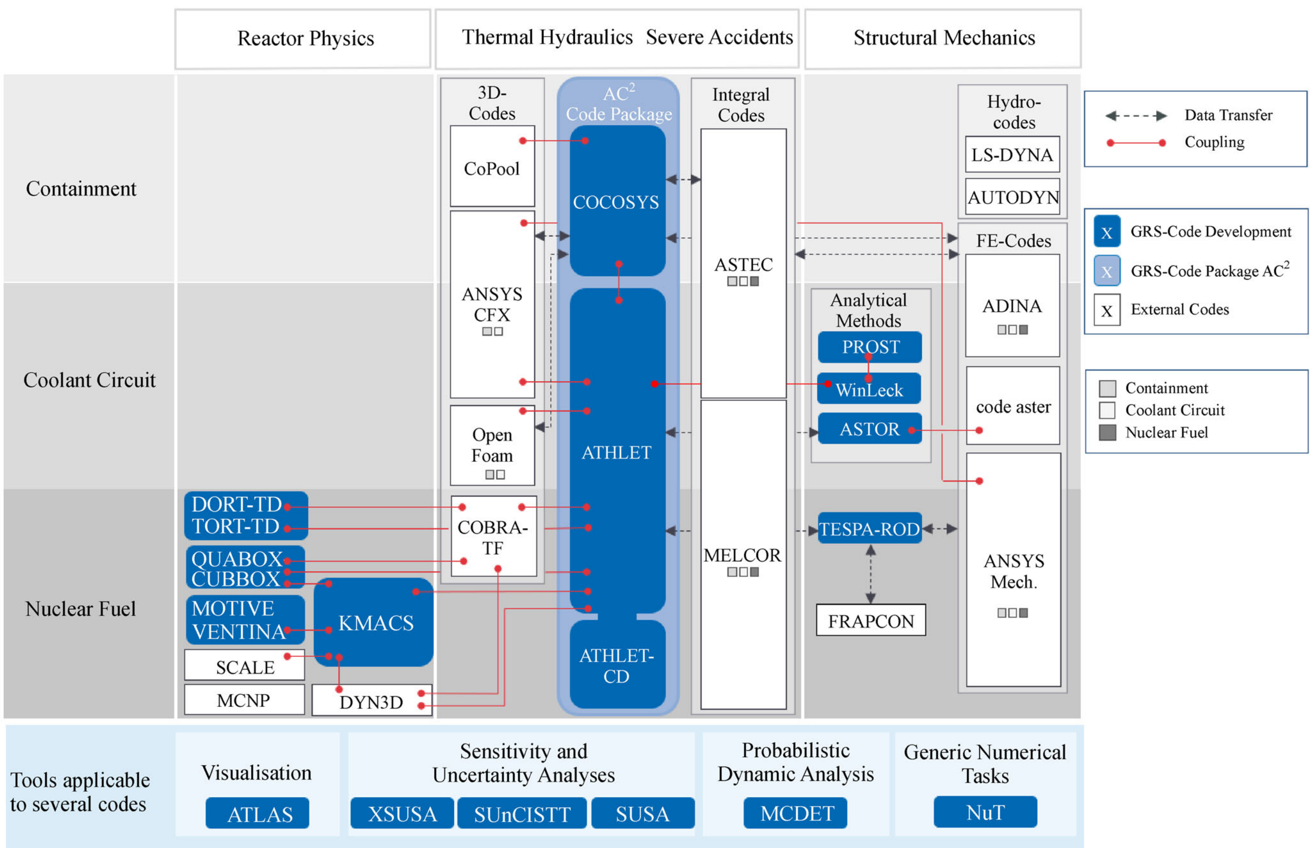

Fig. 1 The current status of the nuclear simulation chain of GRS (adapted with permission from Ref. [54]).

The codes are assigned to the following main thematic areas: reactor physics, thermal hydraulics/severe accidents, and structural mechanics (columns in Fig. 1). The systems/components: nuclear fuel, reactor coolant system (RCS), and containment which can be simulated with the codes arranged in rows and correspond to the respective fundamental safety functions control of reactivity, core cooling, and enclosure of radioactivity. In addition, there is a fourth row which contains other codes (e.g., for visualization, sensitivity, uncertainty, and probabilistic dynamic analysis).

Despite the German nuclear phase-out, the Federal German Ministry of Economic Affairs and Energy strongly supports the further improvement of GRS' nuclear calculation chain, which is kindly acknowledged. It is the basis on which a sustainable and long-term development program is being implemented that delivers added value to GRS' role in supporting national and international competent authorities in the field of nuclear, and national and international users of GRS codes.

4.2 Necessary improvements and current work

From GRS' current perception, safety cases for SMRs by vendors and operators will definitely rely on safety analyses with simulation tools as evidence. The assessment of these safety cases by regulators will include independent confirmatory calculations by TSOs at least for a few selected cases. In both cases, the simulation tools may be identical to those which are already developed, validated, and successfully applied to Gen II LWRs or, if required, dedicated new developments. Already developed tools are e.g., the GRS

- code QUABOX/CUBBOX (a 3-D neutron kinetics core model) and
- the system code package AC^2 [55] consisting of the codes
  - ATHLET (a lumped parameter code for analysis of leaks and transients in the reactor coolant circuit (RCS)),
  - ATHLET-CD (the extension of ATHLET for severe accident analyses in the RCS including core meltdown and fission product release) and
  - COCOSYS (a lumped parameter code for analysis of conditions within the containment and buildings of NPPs in case of accidents and severe accidents).

One example for a recent new development at GRS is the neutron kinetics simulation code FENNECS (finite element neutron kinetics code system), based on modern calculation methods, not yet included in Fig. 1.

Considering the main findings in GRS' SMR study [13], a critical reassessment shows that the main conclusions of the study still hold. While some SMR designs might have been discontinued in the interim, new designs have entered the field, and some have progressed toward licensing and deployment. From the authors' point of view, integral PWR SMRs are still the most promising candidates and should be in the center of GRS' strategic program development and validation activities. However, it is necessary to keep looking for emerging developments (e.g., vSMR and SMR based on liquid metal, molten salt or high temperature gas technology). For all these developments, the questions arise, if, where and in what quantities these plants would be built.

Given the work already achieved in the interim, the following conclusions can be drawn for the next steps. The challenges/simulation requirements for the neutron kinetics codes for both development and validation in terms of SMR conditions are

- long fuel cycle length (>24 month),
- higher burn-up (>50 MWd/kg) and/or higher fuel enrichment,
- advanced loading pattern,
- boron free core under consideration of the behavior of burnable absorber at the beginning of new cycles,
- moveable (steel) reflectors for long-term compensation of excess reactivity
- advanced, more resilient materials for fuel, cladding, and components.

Similarly, the system code package AC^2 requires further improvements: Besides models for non-LWR designs, further model improvements and extended validation is also needed for LWR SMR, and specifically for integral PWR SMRs. The increased reliance of integral PWR SMRs on passive safety features, particularly for core cooling and decay heat removal to an ultimate heat sink, necessitates model improvement for the ATHLET and COCOSYS codes [47,56], for which actively driven safety systems were in focus in the past. Several passive safety features work with small driving forces so that a simplifying treatment of phenomena, engineering level approximations and the coarse nodalisation in a 1D system code need careful application and review. Relevant areas for further model improvements include:

- single/two phase flow natural convection, transition range between single and two-phase natural convection and emergence of flow instabilities,
- heat transfer correlations for passive safety systems in the cooling circuit and in the containment, achieving a better predictive quality for the intended applications as well as improved consideration of different geometries, flow conditions, lower pressures and temperatures, and impact of non-condensables,
- specific models for innovative, high-performance heat exchangers, including compact plate and helically coiled types,
- improved prediction of bundle heat transfers for free convection, subcooled, or saturated boiling conditions both in the cooling circuit and the containment,
- prediction of free convection, stratification, and heat transfer in large water pools used as heat sinks for passive safety systems, including coarse 3D models, and prediction of heat transfer for large structures with Rayleigh (Ra)

numbers $\gg 10^{12}$,

- impact of advanced fuel concepts on heat transfer, critical heat flux, and core degradation,
- improved simulation of passive safety systems considering e.g., special components, start-up behavior, mutual interaction of different passive safety systems or trains of one passive safety system, extension of the scope of correlations for containment heat transfer,
- better heat transfers between the cooling circuit and the containment and improved coupling between AC^2 programs ATHLET and COCOSYS,
- improved thermo-physical properties for both water at a pressure below 1 MPa and temperatures below 180°C, and non-condensables,
- the assessment of occurrence of flow induced vibrations and their effects,
- the operation mode and operation boundaries of heat pipes (viscous, sonic, entrainment, capillary, and boiling limits), enhancement of the parameter ranges of correlations toward low pressures, improvement and validation of the semi-empirical closure correlations for interphase friction, heat and mass transfer and if necessary implementation of properties for new heat pipe working fluids,
- check-valves, in which the opening cross section and the associated form loss is calculated dependent on the pressure difference up- and downstream the valve,
- steam condensation at containment walls, structures and internals especially for the case of small break (SB) LOCA, inertised containment or containment operated under near vacuum conditions,
- infinite passive containment cooling to an ultimate heat sink in ocean environment (influence of seawater, mussel growth, etc.).

Model improvements need to be systematically validated. This is possible in most cases against single-effect or combined effect tests for large LWR. This should be complemented with specific tests, including integral tests, at dedicated SMR facilities. This way, scaling effects can be adequately captured in the code validation. GRS is actively engaging with its international partners and is participating in national and international activities for acquiring access to dedicated SMR tests [19], which unfortunately are often proprietary to the designers and their immediate collaborators.

Current activities in neutron kinetics

The main current neutron kinetic research activity in this working area is the development of the 3D few-energy group neutron kinetics code FENNECS (Finite Element Neutron Kinetics Code System) for the safety assessment of SMR, vSMR, as well as advanced reactors and innovative reactor concepts with complex and irregular geometries within the framework of a national research project Adaptive Geometry Neutron Transport (AGeNT) sponsored by the German Federal Ministry of Economic Affairs and Energy (BMWi). The activities on the latter reactor designs are not included in this paper. In addition, there is plenty of work on fuel rod behavior, advanced materials for nuclear fuel, and cladding for large LWRs, whose results are also important for SMRs in the national research project Accident Tolerant Fuel Analyses (ACTOFAN). ACTOFAN is also sponsored by BMWi. Further work on liquid metal cooled reactors, also relevant for liquid metal cooled SMRs, is performed within the national research project Innovative Systems (INNOSYS) and the European Horizon 2020 Project European Sodium Fast Reactor – Safety Measures Assessment and Research Tools (ESFR-SMART).

The particularity of most SMR cores is their compactness, which may exhibit large neutron flux gradients and increased leakage, long cycle times, complex geometries deviating from regular lattices, and heterogeneous material composition with special fuels, absorbers, and cooling media. The new GRS neutron kinetics code FENNECS solves the time-dependent and steady-state 3-D few-energy group diffusion equation in the Galerkin finite element representation, using upright triangular prisms with linear basis functions as spatial elements [57]. The time integration of both transport and delayed neutron precursor equations is conducted implicitly which provides unconditional numerical stability. Wielandt iteration is applied for convergence acceleration of the eigenvalue problem. FENNECS is also coupled [58] to the GRS thermal-hydraulic system code ATHLET [47] for thermal-hydraulic feedback. FENNECS uses macroscopic cross section libraries in NEMTAB-like format, which may be parameterized with respect to up to six thermal-hydraulic feedback parameters with linear cross section interpolation. For the meshing of regular rectangular or hexagonal lattice arrangements, FENNECS comes with a built-in meshing tool which generates a list of nodes and element connectivity data. SMRs, vSMRs, and micro reactors, however, it may be characterized by significantly more complex, irregular geometries. For the meshing of such geometries, a specialized meshing software implemented in Python has been developed [59] which provides dedicated, problem-dependent node, and element connectivity data for FENNECS.

An early version of FENNECS has been applied first to and assessed against other neutronics codes for the prismatic (or block type) high-temperature reactor MHTGR-350MW within an OECD/NEA benchmark activity [60] and the sodium cooled fast reactor concept ASTRID [61] within the EU project ESNII +. Currently, FENNECS is applied to simulate the neutronic start-up tests of the China Experimental Fast Reactor (CEFR, see also Section 2.3) in the frame of an IAEA Coordinated Research Project [62].

Even if vSMRs are not the subject of this paper, the following simulation of the Heat Pipe-cooled Micro Reactor (HPMR) [63] clearly demonstrates the advanced state of the FENNECS development, its performance as well as its application potential [59]. The HPMR core

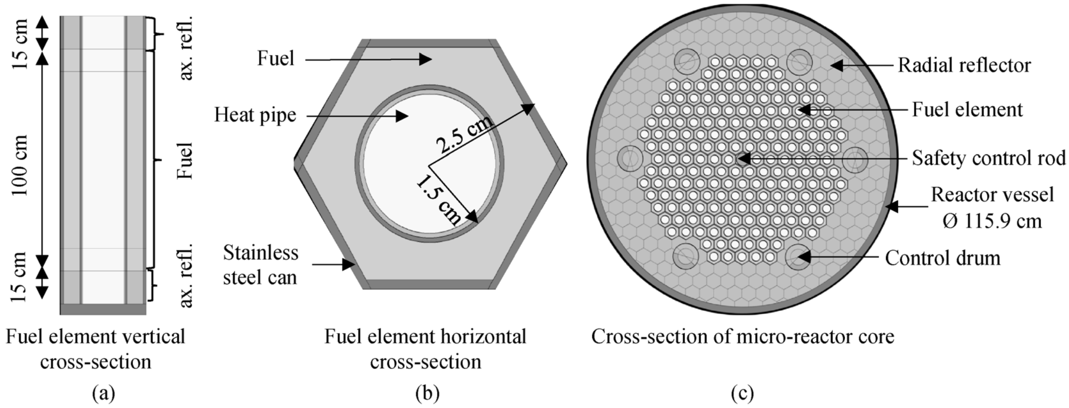

Fig. 2 The HPMR core consisting of 192 hexagonal fuel elements surrounded by six control rod drums.
(a) HPMR fuel element axial section; (b) fuel element radial section; (c) radial section of the micro-reactor core at ARO state.

consists of 192 hexagonal fuel elements surrounded by six control rod drums (see Fig. 2), which are adding or removing neutron reflectivity and thus reactivity to the core, depending on their orientation. Each fuel element has a central cylindrical heat pipe with a 3 cm diameter surrounded by the fuel contained within a hexagonal stainless steel can. Axially, each fuel element consists of two 15 cm axial reflector zones, composed of beryllium oxide (BeO), directly placed above and below the 100 cm fuel zone. The fuel is of metallic type and consists of 18.1% enriched uranium.

The Monte Carlo code Serpent [64] has been used for generation of macroscopic cross sections in 12 energy groups and for providing a 3-D reference solution using continuous energy nuclear data. FENNECS models of the all rods out (ARO) and the all rods in (ARI) state are shown in Fig. 3. The multiplication factors obtained with FENNECS agree to within 39 pcm for the ARO and 142 pcm for the ARI state with the respective Serpent reference solution.

Current thermal-hydraulic activities

As mentioned above, there are multiple challenges for the AC^2 system code package regarding model improvements and validation for SMRs, for which GRS is in the process of resolving. Consequently, GRS' new nationally funded projects for the development and validation of AC^2 put a specific focus on issues related to advanced LWR and integral SMR of PWR type designs. This is accompanied by collaborations with national and international partners on specific topics.

For example, in the already completed EASY project [65], GRS in collaboration with national partners validated AC^2 and particularly its herein included thermal-hydraulic programm ATHLET for the passive safety systems of the Framatome design KERENA® using data of the INKA test facility. First model improvements as to horizontal bundle two-phase heat transfer were implemented with further work still outstanding.

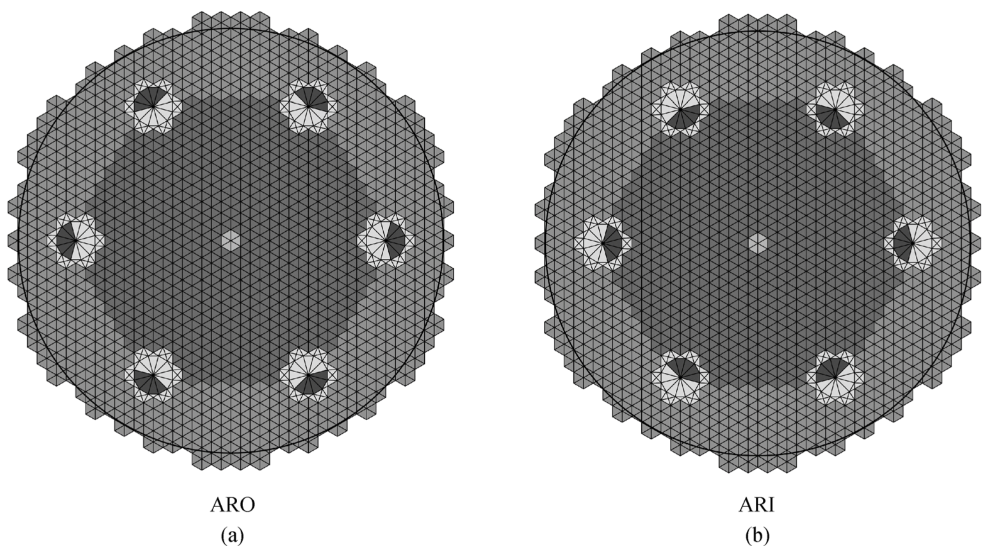

Fig. 3 FENNECS models of HMPR core.
(a) In all rods out state; (b) in all rods in state (control drums rotated).

GRS initiated the national research alliance VASiL. One objective is the implementation and validation of dedicated models for innovative heat exchangers of the compact plate, bayonet, and helically coiled type. In addition, improved models for evaporation from water pools will be implemented. Finally, AC^2/ATHLET is validated by performing test calculations for generic input decks of extant SMR designs and assessing their quality against available information in the literature. Complimentary to VASiL, GRS is also involved in the EU HORIZON2020 ELSMOR (Toward European Licensing of Small Modular Reactors) project, as one of 15 organisations from 8 countries under the lead of VTT, Finland. In ELSMOR systematic methods for the safety assessments especially of SMRs are developed. Furthermore, the project shall intend to utilize the existing European experimental infrastructures and prepare modeling/evidence tools to be ready for use in nuclear licensing procedures [66].

GRS also takes part in the EU HORIZON 2020 project PASTELS (Passive Systems: Simulating the Thermal hydraulics with Experimental Studies), started in September 2020. This project aims at improving passive heat removal technologies for LWR designs (e.g., the safety condenser of a PWR and the containment condenser of a VVER). Respective tests are performed at the PKL and PASI facilities. This is accompanied by extensive work on validation of recent thermal-hydraulics codes, including GRS' AC^2 package, for the simulation of passive safety systems.

Within a joint national R&D project, GRS has improved ATHLET models for water-filled wickless heat pipes (thermosiphons) proposed for long-term passive spent fuel pool cooling and validated them against dedicated experiments at the University of Stuttgart [67]. This work continues with the PALAWERO-II project, where further improvements for ATHLET models will be derived, implemented, and tested against experiments at the ATHOS test facility in Stuttgart.

Zittau-Görlitz University of Applied Sciences is finalising a new implementation of a IAPWS-97 thermophysical properties library for ATHLET, which will provide the backbone of fluid properties calculations for the AC^2 package. The parameter range of this water-steam fluid properties package is extended into the near vacuum range. Besides, Zittau-Görlitz University of Applied Sciences will also provide a real gas model for non-condensable.

Further topics relevant for SMR, which are carried out within the framework of the national ATHLET development project are the development of coupling interfaces (e.g., COCOSYS and ATHLET-CD of the AC^2 suite), the refactoring of heat transfer package, and its alignment with flow maps.

Similarly, ongoing work in COCOSYS development and validation improves models for passive containment cooling systems, covering both heat exchangers with natural circulation heat transfer to external water pools and condensation heat transfer at large containment structures. Moreover, complementary to ACTOFAN activities, improved models for accident tolerant fuel are added to ATHLET-CD and validated within the scope of the OECD/NEA QUENCH and the upcoming QUENCH-ATF project.

Finally, GRS is also pursuing the further improvement of its AC^2 code package for other working fluids than water (e.g., supercritical water, gases, liquid metals, and molten salts).

All activities described above are accompanied by dedicated and planned activities in the continuous AC^2 development and validation projects of GRS.

4.3 Generic application of ATHLET to an SMR design

As mentioned above, AC^2/ATHLET is continuously improved and validated for passive safety features and SMRs. This work was started several years ago, and one of the first generic applications to an SMR design was realized in Ref. [68].

The overall objective was to prepare a generic simulation model for the mPower design with ATHLET based on publicly available information. The model should be capable of calculating the undisturbed stationary operation of the reactor and should simulate selected design basis accidents with plausible results.

The mPower design was an integral PWR of 195 MW_e power, with once-through internal steam generators, internal control rod drives, integrated coolant pumps, and an integrated pressurizer. Decay heat removal was achieved passively via natural circulation to the several potential heat sinks, including an auxiliary steam condenser and a water tank for containment cooling and decay heat removal. A brief description can be found in Ref. [69], and the additional information is available in Ref. [68]. The mPower design has been discontinued in the mean-time due to a lack of buyer interest [19].

For this design, an ATHLET model was established using ATHLET version 2.2C. The nodalisation with a two-channel representation of the primary side in the RPV and a simplified model for the integrated steam generated with its feedwater and steamline pipes is demonstrated in Fig. 4. The core power is set as constant, switching to a generic decay heat curve as soon as scram would be triggered, so there is no neutronics feedback considered in the calculations.

With this model, even without sophisticated active control functions, it was possible to reproduce the stationary operational conditions in the reactor design with acceptable accuracy with respect to values published by the vendor. The stability of these results was investigated with sensitivity cases varying secondary side pressure, temperature, and mass flow boundary conditions. The results showed only minor changes in stationary operating conditions for the reactor predicted by the code.

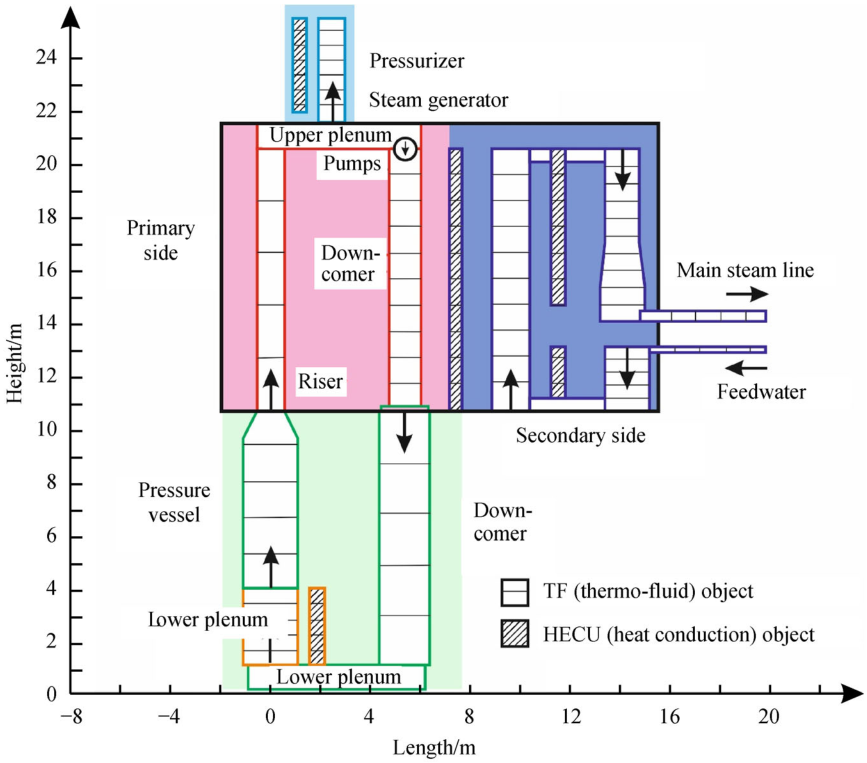

Fig. 4 ATHLET mPower nodalization scheme.

For transient calculations performed in Ref. [68], the lack of information led to somewhat particular assumptions. However, for the postulated initiating event of active coolant pump failure of one or two pumps of the total 8 pumps from normal operation and no additional active interventions aside from scram, the scenarios and the modeling are more adequate. For both pump trips without scram, i.e., constant core power, the calculations show that this triggers overpressure protection and blowdown into the in-containment water storage tank. For a partial pump trip with scram, the temperature evolution in the reactor system is reasonable and shows that stable conditions are reached quite soon. Figure 5 illustrates this with the temperature evolution for a postulated trip of two pumps with scram at 2000 s, showing both the initial short temperature spike and the primary side cooldown by passive safety features with reducing decay heat, approaching stable conditions at approximately 3000 s.

5 Summary

Small modular reactors are one promising option for new builds in most countries continuing to use nuclear energy

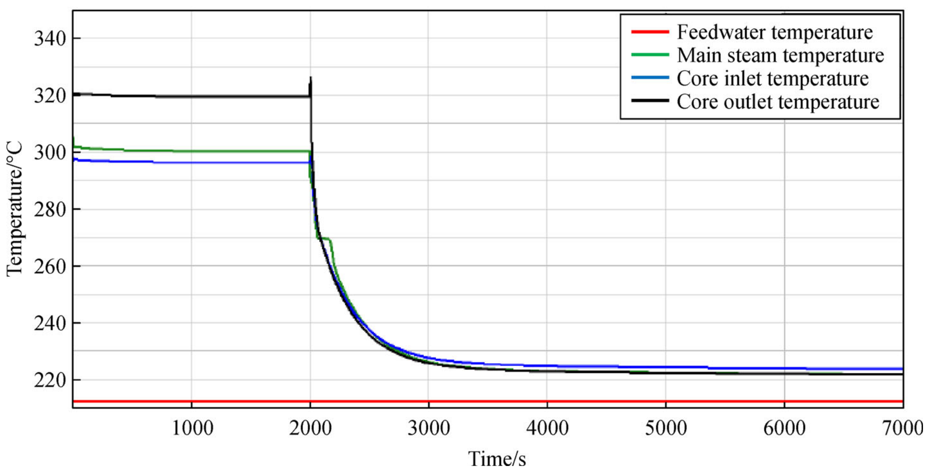

Fig. 5 Temperature evolution for a partial pump trip with scram (modified from Ref. [68]).

for commercial electricity or heat production. Currently four different SMRs are in operation, further four SMRs are under construction, and 13 are licensed or in a licensing process. Various neighboring European countries to Germany (e.g., the UK, Russia, and Poland) are operating, building, or considering building SMRs.

The GRS gGmbH as the main German technical support organization in nuclear safety to German Federal Government, has performed and published a Study on Safety and International Development on SMR in 2015 (GRS-376). Five years later a reevaluation was performed. The results of this update were presented on various topics (selected technical trends, economic viability and competitiveness, and licensing). In summary, while there are some changes in details, the overall strategy for GRS derived in 2015 is still valid. Emerging developments (e.g., the SMR based on liquid metal, molten salt, or the high temperature gas technology) will follow as far as is clear if, where and in what quantities these plants would be built.

GRS is further developing and validating its nuclear simulation chain in such a way that it can be used for independent assessments and confirmatory calculations of safety analyses submitted by vendors and operators. Many SMRs designs have, as compared to currently operated NPPs, new and strongly revised safety concepts with numerous new and innovative safety features. The simulation of these safety features partially requires extensive improvements of existing simulations tools. In some cases, even new developments are necessary.

Currently existing modeling gaps were presented for both neutron kinetics and thermal hydraulic codes. Numerous open issues are currently being addressed as part of national as well international research projects. Furthermore, there is a close connection to the work performed for currently operated or future large NPPs. Due to the particularity of SMR cores (e.g., their compactness, which may exhibit large neutron flux gradients and increased leakage, long cycle times, their complex geometries deviating from regular lattices and their heterogeneous material composition with special fuels, absorbers, and cooling media), GRS has decided to develop a new 3D few-energy group neutron kinetics code FENNECS. This code was briefly introduced and a first application for the Heat Pipe-cooled Micro Reactor was presented. Finally, a first analysis of a generic SMR for testing the GRS simulation chain has been summarized.

The work presented in this paper gives an excellent overview on the scope and depth of GRS activities on SMRs and points out that in future GRS will have the necessary staff, competencies, know-how, and validated evidence tools for safety assessments also for SMRs.

Acknowledgements This paper is largely based on the works and results of the following research projects RS1521, RS1561, RS1574, RS1576, RS1577, RS1578, RS1579 and RS1589 which are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of decisions of the German Bundestag.

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