STUDY OF SAFETY AND INTERNATIONAL DEVELOPMENT OF SMALL MODULAR REACTORS (SMR)

S. Buchholz, A.-K. Krüssenberg, and A. Schaffrath
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Boltzmannstraße 14, 85748 Garching n. Munich, Germany
sebastian.buchholz@grs.de; anne.kruessenberg@grs.de; andreas.schaffrath@grs.de

ABSTRACT

The European SMR market can open in the next years. Therefore GRS has performed a study [1] on *Safety and International development of Small Modular Reactors (SMR)*. The aims of this study were to set-up a sound overview on current SMR, to identify essential issues of reactor safety research and future R&D projects and to identify needs for adaption of system codes of GRS used in reactor safety research. Basic issues and results of this study are presented in this manuscript.
The sound overview consists of the description of in total 69 SMR (Small and Medium Sized Reactor) concepts (32 LWR, 22 LMR, 2 HWR, 9 GCR and 4 MSR). It provides information e.g. about the core, the cooling circuits and the safety systems. Using current German safety requirements for nuclear power plants [2] and common fundamental safety functions, the safety relevant issues of the selected SMR concepts were identified. Further on, it was evaluated whether these safety systems and measures can already be simulated with the nuclear simulation chain of GRS and where further code development and validation is necessary.

KEYWORDS
SMR, Small Modular Reactors, Small and Medium-Sized Reactors, Passive Safety Features

1. INTRODUCTION

Worldwide the abbreviation SMR is used in two ways. At first, it stands for Small Modular Reactor and describes reactors with low power. One reactor module, composed of primary, secondary and, where necessary, intermediate circuit and auxiliary systems, may be transported to the construction site as a whole or in few parts only and can therefore be built quickly. Various modules can form a larger nuclear power plant and additional modules may be added one by one, while the others are in operation. Secondly, IAEA uses the definition Small and Medium Sized Reactors for the abbreviation SMR. This means, a power of less than 300 MW_e characterizes small reactors while medium sized reactors may have a power between 300 MW_e and 700 MW_e. The modular character is not met by this definition but is also not excluded. Within this paper both definitions are hereinafter collectively referred to as SMR.

Designers anticipate SMR deployment mainly in sparsely populated remote areas or near cities respectively. SMR may here provide electricity, district heating and potable water. The developers expect especially for developing countries a chance to establish a nuclear industry with a fraction of the cost of currently operating nuclear power plant only. One argument for that is a complete prefabrication of the fully equipped module within factories. This may result in short production times, standardization, high qualities and lower cost due to mass production. Some concepts provide a deployment one after another while the yet deployed modules can operate already.

The idea of small reactors is not a new one. Since the mid of the last century the former USSR and the USA have used nuclear reactors as engines for their submarines, merchant vessels and ice breakers. Currently, 3 SMR concepts are operating and 5 are under construction. Information about deployment sites, electrical power output as well as the current status of the design, based on public available information (mainly composed out of [4] and [15]) are given within Table I.

Table I. Considered SMR Concepts (currently operating, under construction)

Name	Type	Manu-facturer	Coun-try	P [MW_e]	Status	Site
Currently operating						
CEFR	LMR	CIAE/ CNEIC	CN	20	Operating, Prototype for CDFR-1000	Tuoli (China)
CNP-300	LWR	CNNC	CN	325	Operating, additional planned	Qinshan 1 (China), Chashma (Pakistan)
PHWR-220	HWR	BARC	IN	236	16 operating, additional planned	Rajasthan, Madras, Narora, Kakrapar, Kaiga (India)
Currently under construction						
CAREM	LWR	CNEA	AR	27	Start of construction: February 2014	Atucha (Argentina)
CNP-300	LWR	CNNC	CN	325	2 blocks under construction	Chashma (Pakistan)
KLT-40S	LWR	OKBM Afrikan-tov	RU	35	2 reactors in Akademik Lomonosov, deployment: 2016	Akademik Lomonosov (Barge)
HTR-PM	GCR	INET	CN	105	Demonstration plant under construction since 2012 (2 modules)	Shidaowan (China)
PFBR-500	LMR	IGCAR	IN	500	Under construction, first criticality planned in mid of 2015	Kalpakkam (India)

In other countries the development of market-ready SMR concepts are pushed. Great Britain is strongly interested in SMR technology [3]. The US Department of Energy (DOE) announced a $452 Mio funding for supporting the realization of licensing processes in order to support the commercial operation of one SMR until 2022. B&W won the first funding round in November 2012 with its concept mPower against concepts of Westinghouse, Holtec and NuScale. A second round was started by the DOE in March 2013. Here the NuScale concept won the funding against Westinghouse, Hybrid Power Technologies, Holtec and General Atomics [4]. Unfortunately, some of the SMR projects were financially reduced because of high costs for development and licensing in the US [5, 6].

Although also non-light water concepts are currently in deployment GRS expects that mainly light water SMR will be deployed in Europe in the near future due to large experience of manufacturer and operators in light water technology. Thus in this paper the focus lies on this kind of SMR concepts and their provided safety systems.

2. STATUS OF DEPLOYMENT OF SMR CONCEPTS

Apart from the currently operating SMR and concepts under construction approximately 50 further concepts are currently under development. In Tables II-III these SMR concepts are listed ordered by the current operating status: planned deployment and no deployment. Information about planned deployment sites, planned electrical power output as well as the current status of the design, based on public available information are given within these tables.

Table II. Selected SMR Concepts with planned deployment

Name	Type	Manu-facturer	Coun-try	P [MW_e]	Status	Site
with planned deployment						
ACP-100	LWR	CNNC	CN	100	Planned construction (Start 2015)	Zhangzhou, later: Jiangxi, Hunan, Jilin
ALFRED	LMR	Int	Int	125	Planned construction (Start 2017)	Mioveni, RO
BREST-OD-300	LMR	NIKIET	RU	300	Planned construction	Beloyarsk, RU
CNP-300	LWR	CNNC	CN	325	Operating, additional construction planned	PK
G4M	LMR	Gen4 Energy	US	25	Planned construction	Savannah River, US
GT-MHR	GCR	Int	Int	285	Planned construction	Seversk, RU
MYRRHA	ADS-LMR	SCK CEN	BE	Heat only	Planned construction (Start 2015)	Mol, BE
PHWR-220	HWR	BARC	IN	236	16 operating, further planned	IN
RITM-200	LWR	OKBM Afrikan-tov	RU	175 MW_{th}	Completion expected: 2018, 2 more in 2019 and 2020	Icebreaker LK-60
SVBR-100	LMR	AKME	RU	101.5	Planned construction	RIAR in Dimitrovgrad
VK-300	LWR	RDIPE	RU	250	Planned construction (Current status unknown)	Kola peninsula, Archangelsk, Primorskaya

Table III. Considered SMR Concepts (without planned deployment)

Name	Type	Manufacturer	Country	P [MW_e]	Status (Site)
4S	LMR	Toshiba/CRIEPI	JP	10-50	Well-developed, possible construction site: Galena (Alaska)
ABV-6M	LWR	OKBM Afrikantov	RU	6	Well-developed
Adams Engine	GCR	Adams Atomic Engines Inc.	FR	10	2010 folded
AHWR300-LEU	HWR	BARC	IN	304	Well-developed, site selection started
ANGSTREM	LMR	OKBM Gidropress	RU	6	n/s

Name	Type	Manufacturer	Country	P [MW_e]	Status (Site)
ANTARES/SC-HTR	GCR	AREVA	US	250	Developing phase
ARC-100	LMR	ARC LLC	US	100	Developing phase
ASTRID	LMR	CEA	FR	600	Conceptional design phase till 2015
ELENA	LWR	Kurchatov Institute	RU	0.1	-
Em²	GCR	GA	US	240	Early state
ENHS	LMR	Uni. of Calif.	US	50-75	Well-developed, demonstration plant till 2025
FBNR	LWR	Fed. Uni. of Rio Grande do Sul	BR	70	Early state
Flexblue	LWR	DCNS	FR	160	Developing phase
Fuji	MSR	TTS	Int	200	Market maturity planned till 2018-2025
GTHTR	GCR	JAEA	JP	274	Development after Fukushima doubtful
IMR	LWR	MHI	JP	350	Licensing earliest 2020
IRIS	LWR	Int	Int	335	Just before licensing of US NRC, needs investors
LSPR	LMR	Titech	JP	53	Developing phase
mPower	LWR	B&W	US	180	Well-developed, DOE funding, financing reduced since 2014
MRX	LWR	JAERI/ JAEA	JP	30	no up to date information available
NHR-200	LWR	INET	CN	Heat only	n/s
NIKA-70	LWR	NIKIET	RU	15	Apparently folded in favour of KLT-40S und VBER
NP 300	LWR	AREVA	FR	300	no current information available
NuScale	LWR	NuScale Power Inc.	US	45	Well-developed, funded by DOE
PB-AHTR	MSR	UCB/ORNL	US	410	Early state
PBMR	GCR	ESCOM	ZA	165	International commercialization
PEACER	LMR	NUTRECK	KR	300-550	Development phase, planned demonstration plant (PATER)
PRISM	LMR	GE-Hitachi	US	311	Well-developed, US NRC licensing pending
RADIX	LWR	Radix Power Systems	US	10-50	n/s
RAPID	LMR	CRIEPI	JP	1	Development phase
RAPID-L	LMR	CRIEPI	JP	0.2	Development phase
RUTA-70	LWR	NIKIET	RU	Heat only	Development phase, lacking funding
SC-GFR	GCR	SNL	US	100/200	Conceptual phase
SCOR600	LWR	CEA	FR	630	Development phase
SHELF	LWR	NIKIET	RU	6	Early design phase
SmAHTR	MSR	ORNL	US	50	Early design phase
SMART	LWR	KAERI	KR	100	Licensing completed
SMR-160	LWR	HOLTEC	US	160	Well-developed, US NRC licensing shall start in 2016
SSTAR	LMR	ANL/LLNL	US	20	Well-developed
STAR-LM	LMR	ANL	US	175	Development phase
STAR-H2	LMR	ANL	US	Heat only	Development phase, construction till 2030 planned

Name	Type	Manufacturer	Country	P [MW_e]	Status (Site)
SVBR-10	LMR	AKME	RU	12	Development phase
TRIGA	LWR	GA	US	11.8	Focus of GA lies on GT-MHR and EM2
TSMR	MSR	SINAP	CN	45	Development phase
TWR	LMR	Terra-power	US	500	Construction of a demonstration plant between until 2022 planned
U-Battery	GCR	Int	Int	5-10	Development phase
UNITHERM	LWR	RDIPE/ NIKIET	RU	2.5-6.0	n/s
VBER-300	LWR	OKBM Afrikantov	RU	295-325	Well-developed
Westing-house SMR	LWR	Westinghouse	US	225	Well-developed, decreased financing since 2014
WWER-300	LWR	OKBM Gidropress	RU	300	n/s

Finally it has to be stated that the operating sites of SMR concepts are not limited to landscapes: The concepts ABV-6M, Flexblue, KLT-40S, MRX, NIKA-70, RITM-200, SHELF and SVBR-10 are intended for operating sites at water surfaces (floating nuclear power plants) or seabed (e.g. Flexblue and SHELF). Additionally an Offshore SMR (OSMR) concept developed by MIT provides a swimming platform (similar to oil platforms) for suited landscape SMR like Westinghouse SMR or others. These platforms could be operated in a distance of 8 to 15 km from the coasts and in water depths of 100 m [7]. Beyond that there are much more changes foreseen in current SMR concepts compared to current operating NPPs. The main topics are discussed in the following two chapters focused on light water SMR concepts. Chapter 3 focuses on operating topics while chapter 4 deals with safety systems.

3. SHORT DESCRIPTION OF THE LIGHT WATER CONCEPTS AND SPECIAL FEATURES

In this chapter, main characteristics and special features of the selected light water SMR concepts are given and summarized.

SMR designs are mainly characterized by **high compactness**. The use of compact designs supports the modularity, which in turn leads to large savings of space, so that consequently the modules can be factory produced and deployed to the site by truck, barge or train. Some light water SMR concepts provide **integral primary circuits** where steam generators, main cooling pumps (when used), pressurizer and, in some concepts, the control rod drives are included inside the reactor pressure vessel (RPV) (see Figure 1). Especially the integration of the steam generators leads to smaller pipe cross sections in the primary loop. Consequently, a large break LOCA may be inherently eliminated. In order to maximize heat transfer areas within small spaces, **special designs for steam generators** were introduced to several concepts. Here, helical steam generators are one usual choice (e.g. CAREM, IMR, IRIS, MRX, NuScale, etc.). Experiments for verification of the effectiveness of such designs were performed for example for the NuScale concept at SIET in Piacenza [8]. CFD calculations of such geometry mentioned in [9] show a strong secondary flow inside the helical tubes, which depends strongly on the torsion ratio (fraction of pitch to radius of the helix) and may have an impact on heat transfer. Another solution is the use of plate heat exchangers for transferring the heat out of the primary loop (e.g. RUTA-70, etc.).

Using **integral control rod drives** (e.g. CAREM, IRIS, mPower, Westinghouse SMR) is another kind of minimizing volume. Integral control rod drives eliminates the threat of an unprotected control rod ejection, since the pressure difference between top and bottom of the control rods is not calculated by ambient and primary pressure but level difference in the reactor pressure vessel only.

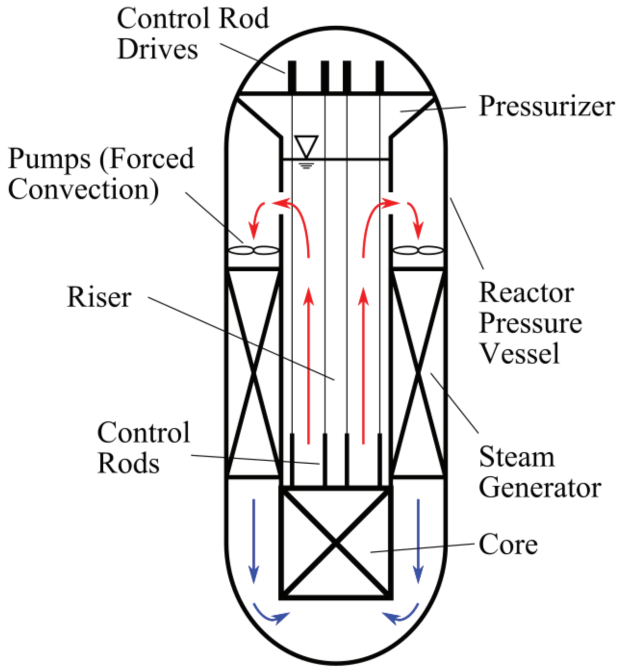

Figure 1. A default SMR with integral primary system

Especially in Russian concepts (e.g. KLT-40S) the main cooling pumps and steam generators are located outside the reactor pressure vessel. In order to minimize the number of flanges, pumps and steam generators are connected with the reactor pressure vessel by coaxial pipes. When using such pipes with steam generators, the hot leg is located in the inner pipe and the cold leg in the outer pipe, in order to minimize the heat losses due to a temperature gradient outwardly.

Some of the selected SMR concepts work with **natural circulation** in the primary loop even in normal operation (e.g. ABV-6M, CAREM, NuScale, etc.). This eliminates the threat of a failure of a main cooling pump or a break of a pump shaft. But this may lead also to disadvantages like instabilities of the flow in start-up phase of the reactor (e.g. geysering, density wave oscillations). Such phenomena are described in [10], where start-up transients of the IMR were tested. Here void fraction and velocity oscillations with cycle durations of 150-200 s at the core were observed. Such void fraction oscillations may also have an impact on the reactivity in such a way, that the power may also oscillate.

Apart from all mentioned improvements in constructing components there are improvements in the **core designs**, too. The negative temperature coefficients of light water reactors for both, primary coolant and fuel, are maintained for light water SMRs, too. Some concepts spare a boron acid system, in order to safe space and lower the temperature reactivity coefficient. Instead of a boron system burnable absorbers like Gd_2O_3, IFBA, Er or B_4C are used. Compensation of excess reactivity is also achieved by using control rods which also provide short time control of the core. Used materials here are e.g. Ag In-Cd, B_4C and $Dy_2Ti_2O_7$. Additionally there are different enrichment values of the fuel ^{235}U. While the concepts ABV-6M, SHELF, RITM-200, KLT-40S, UNITHERM, ELENA and NIKA-70 use enrichment values between 5% and 20% all other concepts consider fuel with enrichments below 5%.

4. CHARACTERISTICS OF SAFETY SYSTEMS USED IN LIGHT WATER SMR

Using current German safety requirements for nuclear power plants [2] and common fundamental safety functions (control reactivity, cool the fuel and contain radioactive substances) the safety relevant issues of the selected SMR concepts were identified. In general a defense-in-depth concept is used to ensure the fulfilment of the fundamental safety functions and the preservation of the barriers and retention functions on several consecutive levels of defense as well as in the case of any internal and external hazards [2].

Table IV. Selected safety systems of light water SMR concepts

Principle		Reactor
Function: Decay Heat Removal		
Passive cooling of steam generator	with water pool	IMR, IRIS, KLT-40S, NuScale, SMART, VBER-300
	with air flow	ELENA, mPower (air flow may be achieved by fan), IMR, NuScale
Passive Cooling of Primary Side	in water pool (two phase natural convection)	CAREM, mPower
	in water pool	ACP-100, Flexblue, MRX
	by extra loop	SCOR600, TRIGA, SMR-160, Westinghouse SMR
Active cooling with auxiliary systems		KLT-40S, SMART, VBER-300
Function: Emergency Injection		
Accumulator		ACP-100, CAREM, CNP-300, IMR, KLT-40S, RITM-200, VBER-300, WWER-300
Active low and/or high pressure injection		KLT-40S, SCOR600, SMART, UNITHERM, VBER-300, WWER-300
Make-Up-Tank		ACP-100, CAREM, CNP-300, IRIS, SMR-160 (poss.), Westinghouse SMR
Higher water pool	Inside containment	ACP-100, mPower
	Outside containment	VK-300
Long-time cooling	Passive with sump/cavity or from top of the RPV	ACP-100, Flexblue, IRIS, NuScale, SMR-160, Westinghouse SMR
	Active with sump/cavity	KLT-40S
	Active with pressure suppression pool	SCOR600
	Passive with external pool	VK-300
Function: Primary Pressure Relief		
Relief in water pools/tanks		ACP-100, CAREM, CNP-300, Flexblue, IRIS, mPower, SMART, TRIGA, VK-300, WWER-300
Relief in containment		ACP-100, NuScale, UNITHERM (poss.), VBER-300 (poss.), Westinghouse SMR
Function: Pressure Suppression in Containment		
Wet well/Pool		CAREM, Flexblue, IRIS, KLT-40S, SCOR600, VK-300
Containment condenser		ACP-100, KLT-40S, VBER-300
Spray in containment		CNP-300, SMART
Containment surrounded by water		NuScale, SMR-160, Westinghouse SMR
Additional special components		
Flow limiter		KLT-40S, VBER-300
Venturi nozzles		SCOR600, TRIGA

The safety systems and measures foreseen in current light water SMR concepts were identified for each of the four levels (1. operation (specified normal operation, undisturbed), 2. anticipated operational occurrences (specified normal operation, incident), 3. accidents and 4. very rare events involving multiple failures of safety equipment and severe fuel assembly damages). In table IV the resulting main safety measures and systems to fulfil the above mentioned fundamental safety functions during level 3 (accidents) are summarized for light water SMR concepts. The specific concepts considering these systems and measures are named in the last column, too.

The principles of the four different functions (decay heat removal, passive emergency injection, primary pressure relief, pressure suppression in containment) and two special components listed in Table IV are explained now in detail.

Decay heat removal in the selected light water SMR concepts is mainly achieved by passive safety systems (see Figure 2 and Figure 3). Unfortunately the term passive is not clearly defined. There are three different definitions by EPRI [12], IAEA [13] and German KTA [14] rules which vary in the degree of passivity. While all definitions consider the use of passive principles like gravity the KTA definition considers only systems without movable parts, signals, external energy support and with or without movable media. In contrast the EPRI definition considers passive systems also when using movable parts, using signals and using external energy support. So the characterization passive is used in this text according to EPRI definition.

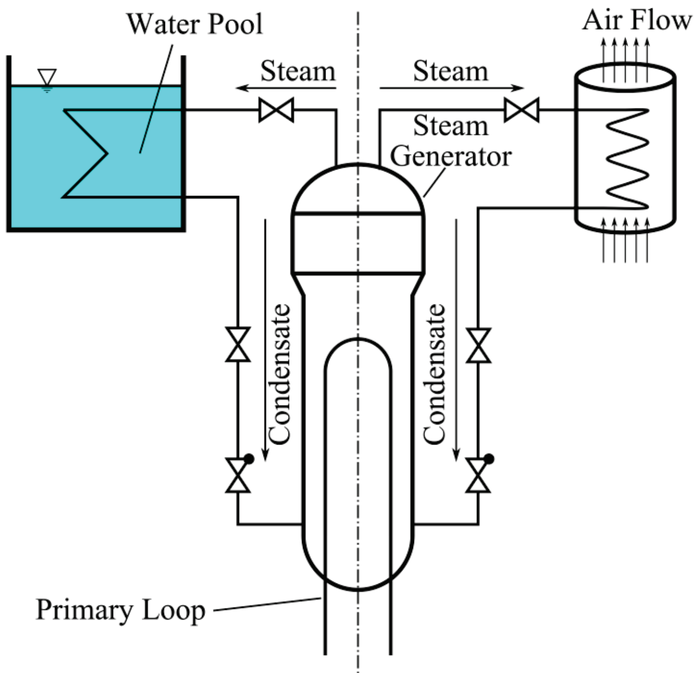

Figure 2. Decay heat removal in light water SMRs by passive cooling of steam generator [11]

As passive safety systems for decay heat removal there are two main ideas realized: cooling of the steam generator fluid or cooling of the primary side fluid. In Figure 2 the passive cooling of the secondary side fluid is sketched. The main steam will be transferred into separate circuits with a heat exchanger and will be condensed either in a water pool or by airflow. In both cases the heat transfer is located above the steam generators to ensure adjusting natural convection due to geodetic pressure losses inside the circuit

during operation. The IMR concept uses a special design by combining both principles: Only after having uncovered the air flow path the water of the also available water pools starts evaporation.
Figure 3 shows the second way for passive decay heat removal: cooling of the primary side. Also, this possibility will be realized in different ways: on the left side of Figure 3 a separate cooling loop is sketched and on the right side natural convection of the primary coolant to a heat exchanger in a higher levelled water pool. In the latter, two or one phase flow is possible. In the two phase flow case, the decay heat is mainly removed by condensation of steam inside the condenser. The condensate drains back passively into the primary system. Again, the water pool is located much higher than the main steam line to ensure natural convection in these cases, too.
Furthermore, some light water concepts provide additional active auxiliary cooling systems with pumps and heat exchanger (see Table IV).

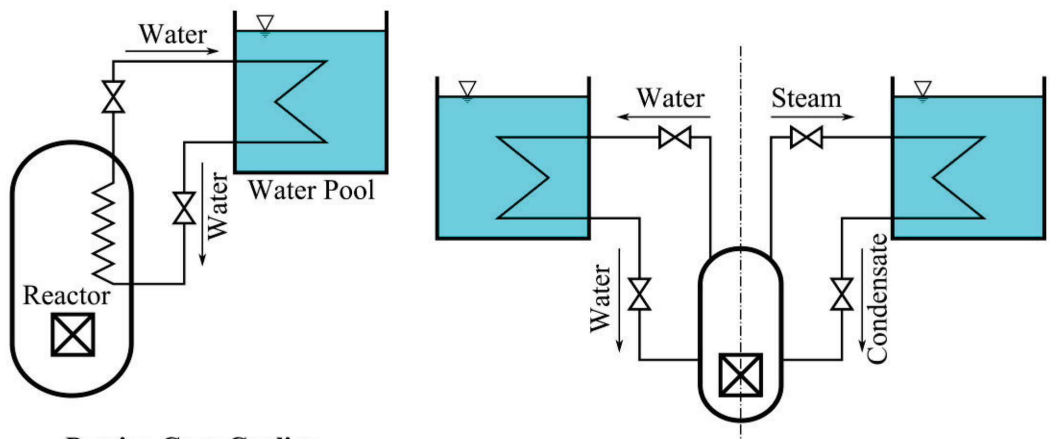

Figure 3. Decay heat removal in light water SMRs by passive cooling of primary side [11]

During loss of coolant accidents it must be ensured that the core is cooled and the water level remains above the core. For this the selected light water SMR concepts uses active and passive safety systems listed in Table IV. The six main systems are summarized in Figure 4 to illustrate the working principles of the different possibilities. The following short description of these different systems based on [11] is focused on passive **emergency injection** of coolant into the primary system.

- The emergency injection can be provided by **accumulators**, which are water filled, and/or by pressurized tanks, connected to the primary system. When the primary pressure drops under certain limit check valves or rupture disks yield and the coolant is injected (system 1 in Figure 4).
- Another possibility is the use of **core make-up tanks (CMT)** which are located above the primary system and completely filled with water. In case of demand the corresponding valves are opened and the water from the tank is injected into the primary system (system 2 in Figure 4).
- Also, water can be injected out of **high-level water pools**. In contrast to the CMT, these water pools are not under primary pressure and the water flow is driven due to geodetic pressure drop (system 3 in Figure 4).
- During a loss of coolant accident (LOCA), the ejected steam condense on the containment structures and flows into the containment sump or cavity. In some concepts this cavity forms a very narrow gap with the RPV. Thus the water level inside the gap is increasing rapidly during LOCA. By **direct vessel injection (DVI) or recirculation valves inside the RPV wall,** the water from the cavity can drain into the cavity passively driven by geodetic pressure drop only (system 4 in Figure 4). In the SMR-160

concept the steam condenses also on the containment inner surface, but the condensate is injected directly from the top of the RPV into the primary system.

- Last, in some concepts active emergency injection systems are also provided (systems 5 and 6 in Figure 4).

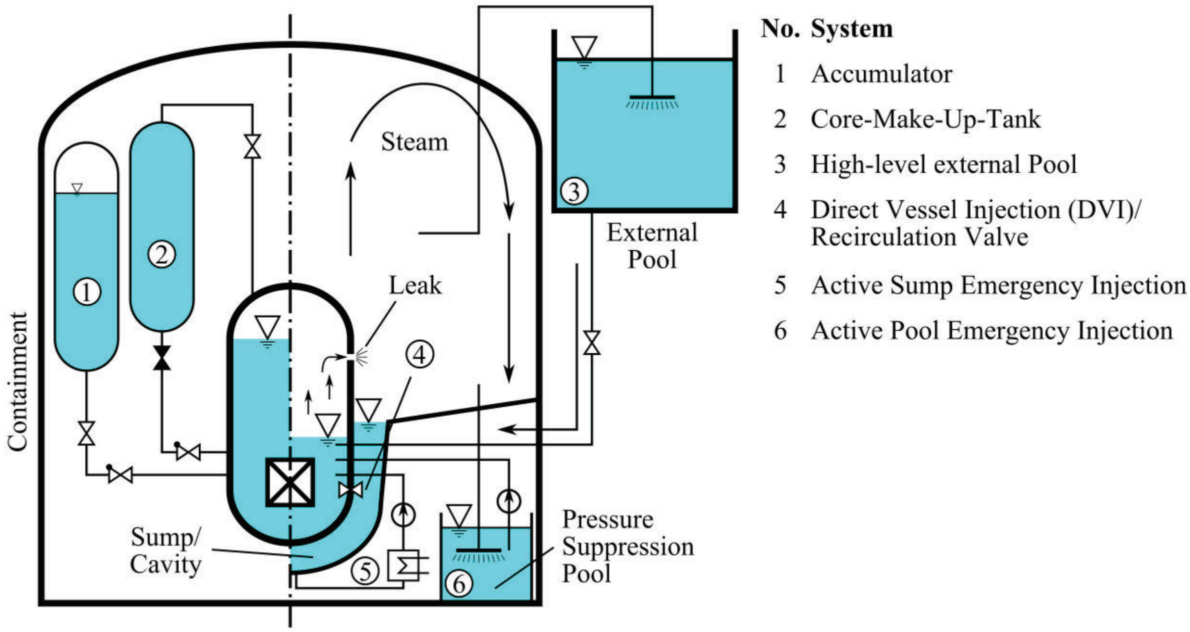

Figure 4. Active and passive safety systems for emergency core cooling

A further task for safety systems are measures for **primary depressurization.** Here steam dumping from the pressurizer into a special tank like a pressure relief tank, pressure suppression pool or into the containment atmosphere is the most common system in the light water SMR concepts. Additionally, some concepts provide a back flow of the coolant out of the relief tank, when this tank is located above the RPV.

The last presented safety measure is **pressure suppression of the containment.** Several light water SMR concepts provide a containment condenser to realize this. Mostly, this condenser is located at the upper part of the containment and is connected with a large water tank (1 in Figure 5). Steam in the containment can condense on the containment condenser tubes while the heat is transported by natural convention into the large water pool. Additionally to that the steam can also be relieved directly into a pressure suppression pool or an external water pool where is condenses (systems 2 and 3 in Figure 5).

In addition to these sketched systems in Figure 5 there are some further safety measures and systems to realize pressure suppression of the containment: Pressure suppression is also possible by spraying steam into the containment atmosphere, which is condensing due to the spraying. Thus the containment pressure decreases. Some concepts also provide a containment surrounded by water. Here steam can condense on the inner containment surface and the heat is released to the surrounding water.

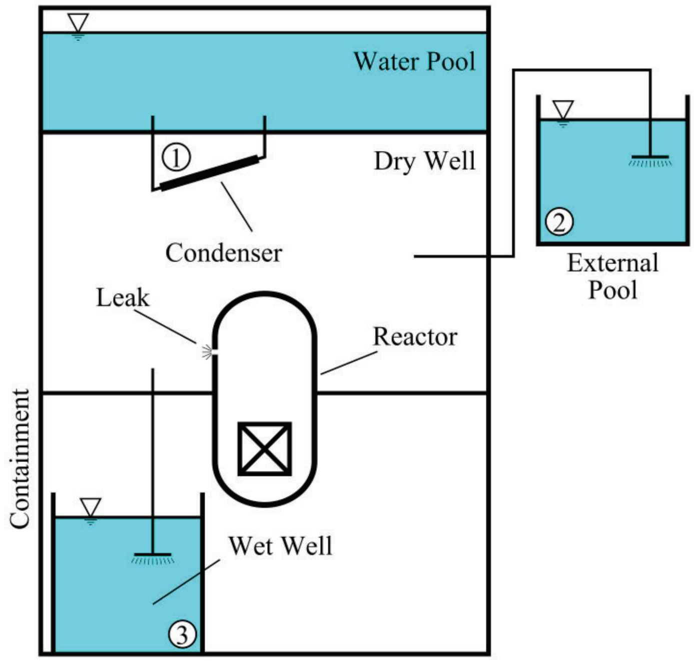

Figure 5. Systems for containment pressure suppression

Additionally to the above mentioned safety measures and systems some concepts consider **special components** supporting safety directed behaviors. Two of these are presented here. At first there are flow limiter located in connecting pipes, which provide a high pressure loss in one and a low pressure loss in the other direction. Used in a cold leg it limits the flow out of the RPV in the case of a cold leg LOCA but in normal flow direction its effect is nearly not noticeable. Other new components are so called venturi nozzles. They are used to block or clear flow paths depending on coolant velocities.

5. NECESSARY IMPROVEMENTS FOR SAFETY SPECIFIC ASSESSMENT OF SMR

Based on the above mentioned comparisons of 69 selected current SMR concepts [1] a broad summary was received on current developments in the complete field of light water, heavy water, gas, liquid metal and molten salt cooled SMR concepts. On the basis of this overview on new construction, operation and safety issues gathered from available public sources necessary enhancement and validation needs for the GRS codes ATHLET, COCOSYS and QUABOX/CUBBOX were identified. While ATHLET (Analysis of Thermal-hydraulic of Leaks and Transients) is used to simulate the fluid behavior inside the cooling circuits, COCOSYS (Containment Code System) calculates the thermo-hydraulic outside the loops (mostly inside the containment). For core calculations neutron kinetic programs (e.g. QUABOX/CUBBOX, etc.) are used. Coupling of all programs is possible and done, too. So, GRS determined the following main topics for improvements of the codes to put code users in the position to access the safety of SMR concepts by verifying the compliance of the common fundamental safety functions control reactivity, cool fuel and contain radioactive substances.

While ATHLET and COCOSYS are validated the last decades especially for current light water reactors there is a strong need to validate the programs for other working fluids. This means not only introducing the components itself but also validating the corresponding models for drift, friction, heat transfer, etc. Additionally, new heat transfer correlations have to be applied and validated, since new concepts of heat exchangers are used within the selected SMR designs even in light water cooled concepts (e.g. helical pipes, plate heat exchangers, horizontal inclined pipes, bayonet pipes, etc.).

An example for further validation work of ATHLET is the simulation of horizontal declined pipes of an emergency condenser used for example in the KERENA reactor concept (AREVA), which in a different configuration may be used in several SMR concepts. Figure 6 compares experimental data and two calculation results achieved with different ATHLET Versions (3.0A and 3.0B) for a transient emergency condenser experiment done at INKA facility in Karlstein, Germany. While in the ATHLET 3.0A case the used heat transfer correlations are mainly valid for vertically arranged pipes, the code was improved in the 3.0B case by a new correlation for turbulent condensation in horizontal tubes based on flow pattern (Dobson and Chato [16, 17]), by adapting the used Chen correlation [18] for convective subcooled and saturated boiling also for horizontal pipes (It was modified in such a way, that the heat transfer due to nucleate boiling is not suppressed by convection on horizontal tubes anymore, which is suitable for vertically arranged tubes) and by replacing an equation for estimating the temperature difference between tube wall and saturation temperature (Thom) by calculated temperatures of preceding time step. Since the heat transfer of the emergency condenser is still underestimated further validation of the used ATHLET heat transfer models for horizontal declined pipes are necessary.

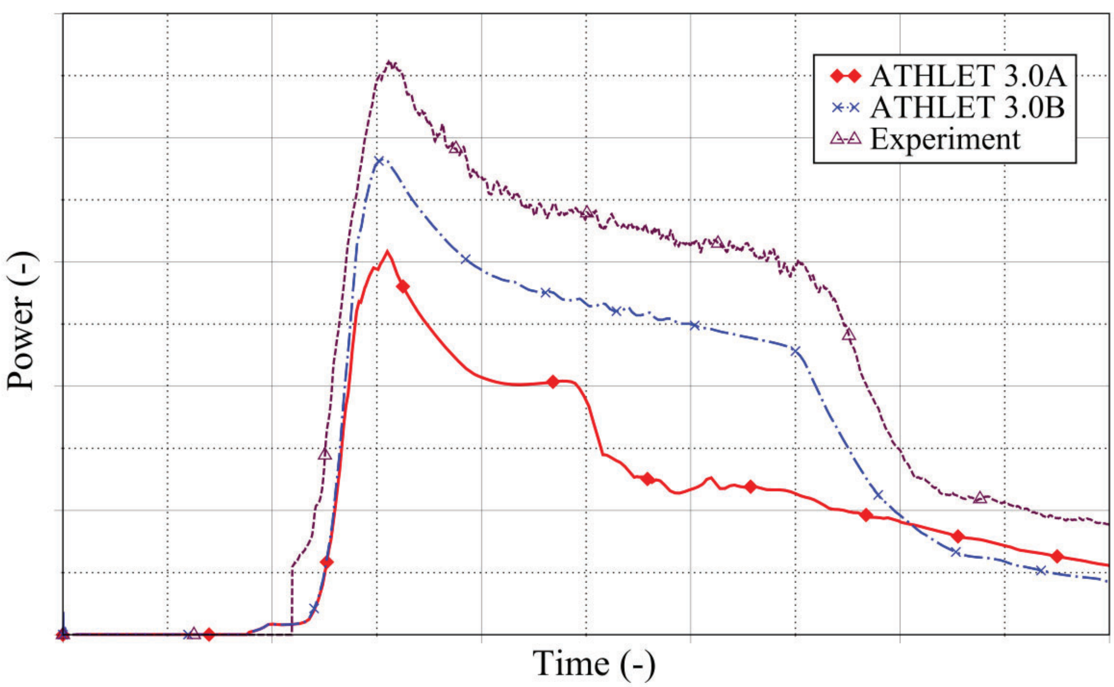

Figure 6. Calculation Results of Emergency Condenser Power

Basic work for the calculation of 3D flow regimes or stratification phenomena in large water pools has been done by introducing a special 2D/3D model into ATHLET. Here some validation work will start in 2015.

Another issue is the correct simulation of natural convection under the compactness of SMR designs. Because natural convection is a basic normal operation and/or safety system issue in the majority of SMR designs this issue has determined to be of high interest and to extend the validation work on it in ATHLET. Since ATHLET was created for assessment of mainly generation II reactors, they consider primarily forced convective flows. Therefore it has to be determined in detail, whether they are also able to simulate free convective flows induced by small pressure differences and small or large temperature differences, which may be characteristic for the starting behavior of passive systems.

Also the models of the containment code COCOSYS have to be validated against new requirements resulting from the SMR concepts. Starting with new components up to new operation phenomena, each used model has to be checked concerning its applicability. And finally, the applicability of the different neutron kinetic simulation codes for simulating behavior of SMR concepts have to be checked. Since neutron kinetic programs used at GRS are primarily validated for light water reactors there is a leak of experience for example in using the nuclear basic data (i.e. ENDF-VII or JEFF 3.1) for materials installed in new reactor concepts under consideration of uncertainties of these data for those materials. Another point is the leak of experience with long fuel cycles up to 4 – 5 years (current experiences: 12 – 22 months) and high burnups up to 70 – 75 MWd/kg_{HM} (current experiences: 50 MWd/kg_{HM}).

Finally it has to be stated that all the determined necessities for code improvements are directed for a basic safety related assessment of different current SMR concepts. But this work is only possible in close interaction with SMR developers because much more construction and operation details are required to perform this validation work for the codes and to provide regulatory authorities the possibility to assess these concepts using the codes.

6. CONCLUSIONS

In this paper an overview about the GRS study for SMR done in 2014 is presented. While in the study a sound overview of about 69 SMR concepts were set up, in this paper a summary about the used safety features of light water SMR are given and a selection of needed improvements of GRS codes are composed, which are basically needed to perform safety assessments of these SMR concepts.

ABBREVIATIONS

ATHLET	Analysis of Thermal-hydraulics of Leaks and Transients
COCOSYS	Containment Code System
CMT	Core-Make-Up Tank
DOE	U.S. Department of Energy
DVI	Direct Vessel Injection
GCR	Gas Cooled Reactor
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HWR	Heavy Water Reactor
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
LMR	Liquid Metal Cooled Reactor
MSR	Molten Salt Reactor
poss.	possibly
RPV	Reactor Pressure Vessel
SMR	Small Modular Reactor Small and Medium-Sized Reactor

Countries

AR	Argentina
BE	Belgium
BR	Brasilia
CN	China
FR	France
IN	India
Int	International Project
JP	Japan
KR	Korea
PK	Pakistan
RO	Romania
RU	Russia
US	United States of America
ZA	South Africa

ACKNOWLEDGMENTS

The presented study was sponsored by the German Federal Ministry of Economic Affairs and Energy (BMWi) within the project RS1521.

REFERENCES

1. S. Buchholz, A. Krüssenberg, A. Schaffrath, R. Zipper, *Studie zur Sicherheit und internationalen Entwicklungen von Small Modular Reactors (SMR)*, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, publishing expected in August 2015.
2. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit BMUB, *Sicherheitsanforderungen an Kernkraftwerke 20. November 2012* (translation: "Safety Requirements for Nuclear Power Plants"), (2012).
3. National Nuclear Laboratory, *Small Modular Reactors (SMR) Feasibility Study*, available under www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf, (2014).
4. "Small Nuclear Power Reactors," http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/ (2014).
5. "Westinghouse SMR progress slows," http://www.world-nuclear-news.org/NN-Westinghouse-SMR-progress-slows-210214ST.html (2014).
6. "Funding for mPower reduced," http://www.world-nuclear-news.org/C-Funding-for-mPower-reduced-1404141.html (2014).
7. J. Buongiorno, M. Golay, N. Todreas, A. Briccetti, J. Jurewicz, V. Kindfuller, "OFFSHORE SMALL MODULAR REACTOR (OSMR): AN INNOVATIVE PLANT DESIGN FOR SOCIETALLY ACCEPTABLE AND ECONOMICALLY ATTRACTIVE NUCLEAR ENERGY IN A POST-FUKUSHIMA, POST-9/11 WORLD," *Proceedings of the ASME 2014 Small Modular Reactors Symposium*, **SMR2014-3306**, (April 15-17, 2014)
8. "Helical steam generator passes test," http://www.world-nuclear-news.org/NN-Helical-steam-generator-passes-test-2702147.html (2014).
9. J. De Amicis, A. Cammi, L. P.M. Colombo, M. Colombo, M. E. Ricotti, "Experimental and numerical study of the laminar flow in helically coiled pipes," *Progress in Nuclear Energy*, **Vol. 76**, pp. 206-215 (2014).
10. A. Dixit, T. Hibiki, M. Ishii, K. Tanimoto, Y. Kondoh, K. Hibi, "Start-up transient test simulation with and without void-reactivity feedback for a two-phase natural circulation reactor," *Nuclear Engineering and Design*, **Vol. 265**, pp. 1131-1147 (2013).
11. International Atomic Energy Agency, IAEA, *Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants*, TECDOC 1624, Chapter 2, IAEA, Austria (2009).
12. Electric Power Research Institute, *EPRI Advanced Nuclear Technology Advanced Light Water Reactor Utility Requirements Document,* Revision 12 16.12.2013
13. International Atomic Energy Agency, IAEA *Safety related terms for advanced nuclear plants* TECDOC 626, Wien, September 1991
14. Kerntechnischer Ausschuss, KTA Nachwärmeabfuhrsysteme von Leichtwasserreaktoren KTA 3301 vom 27.06.1989
15. International Atomic Energy Agency, IAEA, *STATUS OF SMALL AND MEDIUM SIZED REACTOR DESIGNS,* (September 2012)
16. J. R. Thome, *Engineering Data Book III*, Wolverine Tube, Inc. 2010
17. F. Vera-García et. al, "Assessment of condensation heat transfer correlations in the modelling of fin and tube heat exchangers," *International Journal of Refrigeration*, **Vol. 30**, pp. 1018-1028 (2007)
18. J. G. Collier, *Convective Boiling and Condensation*, 2nd Edition, McGraw-Hill Book Company (UK) Ltd. 1972