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Neutronic study of a new generation of the small modular pressurized water reactor using Monte-Carlo simulation

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ABSTRACT

Small Modular Reactors (SMRs) are the innovative design of nuclear reactors making remarkable interest during recent years. Since there is not enough available operating experience on SMRs, it might be possible to initiate extensive investigations on these types of reactors for the purpose of improving the current performance level of these systems, significantly. The main purpose of this present study is neutronic study of a typical small modular pressurized water reactor via Monte-Carlo method using the MCNPX code. The CAREM25 is chosen as the reference SMR. The reactor core geometry is simulated and neutronic parameters are visualized and analyzed via high qualified 3-D figures. They are figure out neutronic nature of the chosen case study. They capture the simulation of the reactor core geometry, and skim the neutron flux and power distribution, radial and axial power peaking factors and the influence of the control rods on the thermal flux. Central fuel assembly is determined as the hottest fuel assembly with power peaking factor of 1.778. The hottest fuel rod power peaking factor is calculated as 1.846 in the hottest assembly. The maximum calculated axial power peaking factor of the hot rod is 2.85. Results show that the maximum axial power along the fuel rods occurred below the mid-plane of the rod. The ratio of the hot to average rod axial power peaking factor as a safety parameter used to calculate the maximum heat flux in the hottest channel, is calculated close to 2 in almost 70% of the core height.

The core reactivity at cold and hot shut down without safety injections of boron acid is calculated as $0.09712 \left(\frac{\Delta k}{k}\right)$ and $-0.00103 \left(\frac{\Delta k}{k}\right)$, respectively.

Results show suitable neutronic behavior and responses during virtual tests and analyses.

1. Introduction

During the past few years, there has been remarkably widespread interest in SMRs (small modular reactors). The SMRs would generate between 10 and 300 MWe of electricity, with power levels much smaller than those of the current status operating reactors (Ingersoll, 2009; NEA, 2011; Vujic et al., 2012; Yan et al., 2012). In specific, integrated PWRs, encapsulate all PWR primary coolant system components such as pressurizer, steam generators, pumps and control rod drive mechanism into a tall reactor pressure vessel.

Because of high capital cost of large nuclear reactors, as well as endangering the grid operation and stability due to large power additions in many areas, SMRs technology could be an attractive option only if their cost of electricity is proven to be competitive with the market (Carelli et al., 2010; Ingersoll, 2009).

SMRs are aimed at solving some of the multiple problems plaguing the nuclear industry and allow the possibility of using nuclear power in market niches that have previously been difficult to enter. These market niches include developing countries with smaller electric grids, remote locations, water desalination, and industrial heat supply (Ingersoll, 2009; NEA, 2011; Vujic et al., 2012; Yan et al., 2012).

There are very wide varieties of SMR designs with distinct characteristics that are being developed. Several countries are developing and planning to construct SMRs, including the United States, Russia, China, France, Japan, South Korea, India, and Argentina. One global assessment from predicts that there would

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be between 43 and 96 operating SMRs around the world by 2030 (WNA, 2012).

All SMRs, despite different designs, provide inherent and passive safety features to assure security during operation and accident conditions; proliferation resistance; economic competitiveness with other power generation technology; probability of severe accident below 10E-5; ease of operation and maintenance; transportability from the factory to the field (Chang and Pierre, 2007; Sefidvash, 1996).

The summary of various SMR technologies is listed in Table 1. In comparison to larger units, the common feature among SMRs is smaller power density, which means that the amount of heat needed to be removed to surface area is smaller; therefore, it is possible to use passive cooling system to maintain the heat removal from the reactor vessel. The other advantage of the integrated design is elimination of large Loss Of Coolant Accident (LOCA) due to small pipes diameters that leave the vessel (Liu and Fan, 2014). On the other hand the small power density causes lower efficiency of the design in comparison to larger units; especially in case of water reactors it is noticeable.

Light Water Reactors (LWRs) are the most common nuclear designs in the world, currently there is 357 LWRs of total 437 reactors in operation including 273 Pressurized Water Reactors (PWR). Moreover, PWRs are the majority in SMR and the only type of LWRs, almost every country is pursuing this technology i.e. Argentina, Brazil, China, France, Republic of Korea, Russian Federation and United States of America. In order to ensure inherent and passive safety with compact reactor size we can find that most of LWRs designs are integrated pressurized reactors. Table 2 shows summary of the SMR pressurized light water reactors(Alkan, 2013; Chang et al., 2000; Chung et al., 2003; Chung, 2008; Franceschini and Petrovic, 2008; Hibi et al., 2004; Hong and Song, 2013; Kim, 2011; Koroush and Kazimi, 2012; Mitenkov and Polunichev, 1997; Sahin et al., 2010; Sahin, 2009; Standring, 2009).

Although small modular light water reactors are currently receiving significant interest, there is not enough available operating experience especially for those new ones that include integrated phenomena and passive safety features. Therefore, it might be possible to initiate extensive investigations on these types of reactors for the purpose of improving the current performance level of these systems, significantly.

In spite of a few published studies in literature, there are a few neutronic studies have been conducted on any type of SMRs. The main purpose of the present study is neutronic study of an advanced SMR which is nominated as a near term option of the generation IV reactors. This study is conducted throughout accurate Monte-Carlo simulation of neutrons using MCNPX code. The neutronic calculations aims at the simulation of the reactor core geometry in details, high qualified 3-D visualization of neutron flux and power distribution, radial and axial power peaking factors, and studying the influence of the control rods on the thermal flux. Provided figures reflex the neutron behavior in an integrated small PWR as well as scanning core materials and structures in interaction with neutrons.

2. Material and methods

In order to conduct a detailed neutronic investigation of an advanced SMR, firstly, the CAREM 25 is chosen as our reference case study. Secondly, the whole reactor core is simulated in details using MCNPX.

The MCNP code (Briesmeister, 2000) is the internationally recognized code for analyzing the transport of the reactor nuclear particles based on the Monte Carlo Simulations. It deals with transport of neutrons, gamma rays, and coupled transport, i.e., transport of secondary gamma rays resulting from neutron interactions in any complex geometric structure and nuclear material compositions. It also has criticality calculation and the perturbation

Table 1
Summary of various SMR technologies.

Technology	Light water reactor (LWR)	Heavy water reactor (HWR)	Gas cooled reactor (GCR)	Sodium fast reactor (SFR)	Lead fast reactor (LFR)/Lead bismuth eutectic fast Reactor (LBEFR)
Fuel type	UO_2. TRISO or CERMET	$(Th^{232}$–$U)O_2$, $(Th\text{-}Pu)O_2$ or UO_2	TRISO UO_2	U–Pu–Zr alloy or $(Pu$–$U)O_2$	PuN–UN, UN, UO_2
Enrichment (%)	1.8–19.75	Natural – 4%	8.5	16.6–19.75	16.4–19.75
Efficiency (%)	25–35	30–35	40–50	30–40	35–45
Thermodynamic cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle or Bryton Cycle	Steam Rankine Cycle	Steam Rankine Cycle
Refueling period (months)	14–240	Constant or 24	10-Constant	6-End of design life	84–120
Reactor vessel circulation	Forced or natural	Forced	Forced	Forced	Forced or natural
Design life (years)	25–60	40–100	40–60	30–40	35–43

Table 2
Summary of small modular pressurized light water reactor.

Design name	CAREM	FBNR	CNP-300	FLEXBLUE	IMR	SMART	KLT40-S	UNITHERM	IRIS	mPower	NuScale	Westinghouse
Origin country	Argentina	Brazil	China	France	Japan	Korea	Russia	Russia	International	USA	USA	USA
Fuel type	UO_2	TRISO or CERMET	UO_2	UO_2	UO_2	UO_2	UO_2	CERMET	UO_2/MOX	UO_2	UO_2	UO_2
Electric power (MWe)	25	40	325	160	350	100	35	6.5	335	150	45	225
Efficiency (%)	25	33	25	35	30	30	23	21	33	30	28	28
Reactor pressure (MPa)	12.25	16	15.2	15.5	15.51	15	12.7	16.5	15.5	14.1	8.72	15.5
Core outlet temperature (°C)	326	326	302	310	345	323	316	325	330	320	329	310
Design life (years)	60	N/A	40	60	60	60	40	25	60	60	60	60
Enrichment (%)	1.8, 3.4	5–9	2.4–3	5	4.8	4.8	<20	19.75	4.95	<5	4.95	<5
Refueling period (months)	14	36–84	18	36	26	36	28	240	48	48	24	24
Circulation in RPV	Natural	Forced	Forced	Forced	Forced	Forced	Forced	Natural	Forced	Forced	Natural	Forced
Thermo-dynamic cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle	Steam Rankine Cycle