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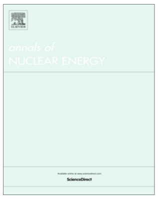

Post-operation radiological source term and dose rate estimates for the Scalable LIquid Metal-cooled small Modular Reactor

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ABSTRACT

The Scalable LIquid Metal cooled small Modular (SLIMM-1.2) reactor has recently been developed at the University of New Mexico's Institute for Space and Nuclear Power Studies, for generating 10–100 MW_{th} continuously without refueling for ~66–6.3 full-power years, respectively. The SLIMM reactor is cooled by natural circulation of in-vessel liquid sodium during nominal operation and after shutdown. It is assembled, fueled, and sealed in the factory, and transported by rail, a heavy-duty truck, or a barge to the site and installed below ground on seismic isolation bearings. Following end of life (EOL) shutdown, the SLIMM reactor remains temporarily on site until the external dose rate decreases to an acceptable level for safe handling. The conducted analyses calculate the post-operation radiological source term, the photon and neutron emission rates, and the biological dose rates in the reactor and outside the guard vessel at EOL and as a function of time after shutdown. When operating at 100 MW_{th} before shutdown, the calculated biological dose rate outside the SLIMM reactor guard vessel ~65 days after EOL shutdown is slightly lower than the US federal transportation limit of 0.2 rem/h. It decreases to 0.069 and 0.036 rem/h, 6 months and 1 year after EOL shutdown, respectively. These rates ensure safe handling, removal and transportation of the post-operation SLIMM-1.2 reactor back to the factory or a processing facility, and subsequent replacement by another unit loaded with fresh fuel. Results also show that for the same thermal power of 100 MW_{th} and operation life of 6.3 full power years, the SLIMM reactor generates ~179% more ^{239}Pu and ~72–100% less minor actinides than a comparable PWR. The former decreases the fissile depletion during reactor operation, while the latter decrease the toxicity of used fuel at EOL.

1. Introduction

Small Modular Reactors (SMRs) designation is for those capable of providing for generating an electrical power of 15–300 MW_e and having modular designs, assembly, and construction (IAEA, 2007, 2012). SMRs could supply high and low temperature process heat for multitude of industrial applications. Examples are steam for oil and natural gas exploration using hydraulic fracturing, production of hydrogen fuel by thermochemical processes and electrolysis, biofuels processing, oil refining, seawater desalinization, and district heating. These energy needs may not be practically met with medium (>300–600 MW_e) or large (>600–1000 MW_e) nuclear reactor plants. SMRs are also better suited for integration into the electrical grid with renewable energy sources.

A wide variety of SMR designs, with thermal or fast-neutron energy spectra, are being developed worldwide (Table 1) for meeting future needs of electricity and process heat for isolated communities, with limited or no access to an electrical grid and fossil fuel supply year round. Many of these SMR designs offer passive operation and safety features, in-vessel heat exchanger or steam generator, and a few reactor vessel penetrations. Some employ passive means for removing the decay heat generating in the core after reactor shutdown, such as heat pipes, water evaporation and natural circulation in a large tank surrounding the reactor vessel (Ingersoll et al., 2014, Reyes, 2012) and natural circulation of ambient air (Palomino and El-Genk, 2016; El-Genk et al., 2017).

Owing to their small size and modular construction, SMRs could be factory fabricated and assembled. Some would be transported by rail, truck or barge to the site and installed below ground, to avoid impact by an airplane or missile, and mounted on seismic isolation bearings to resist earthquakes (IAEA, 2007, 2012, 2016; El-Genk et al., 2017; El-Genk and Palomino, 2014; Arie, 2009;

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Nomenclature

B_4C	Boron Carbide
BeO	Beryllium Oxide
BOL	Beginning-Of-Life
CAREM	Central ARgentina de Elementos Modulares
DUN	Depleted Uranium Nitride
EM^2	Energy Multiplier Module
EOL	End-Of-Life
FP	Fission Products
FPY	Full-Power Years
G4M	Gen4 Module
GFR	Gas cooled Fast Reactor
GT-MHR	Gas Turbine Modular Helium Reactor
GTHTR	Gas Turbine High Temperature Reactor
HEX	Heat Exchanger
HTR	High Temperature gas cooled Reactor
HTR-PM	High Temperature Reactor–Pebble bed Module
IMSR	Integral Molten Salt Reactor
kgHM	kilograms of heavy metal in fresh fuel
LFR	Lead- or Lead-bismuth eutectic alloy-cooled Fast Reactor
MA	Minor Actinides
MSR	Molten Salt Reactor
MSTW	Molten Salt Thermal Waste burner
MTHM	Metric Tons of Heavy Metal in fresh fuel
UN	Uranium Nitride
UO_2	Uranium Dioxide
PWR	Pressurized Water Reactor
RC	Reactor Control
RSS	Reactor safety shutdown
SFR	Sodium-cooled Fast Reactor
SLIMM	Scalable LIquid Metal-cooled small Modular
SMART	System Integrated Modular Advanced Reactor
SMR	Small Modular Reactor

Table 1
A partial list of SMRs designs and types worldwide.

SMR Name	Type	Plant (MW_e)	Developer, Country	Capital Cost Estimate (USD Million)	Status
CAREM	PWR	27	CNEA, Argentina	97	Licensing Stage
SMART	PWR	100	KAERI, ROK	497	Licensed
VBER-300	PWR	295	OKBM Afrikantov, Russia	910	Licensing Stage
KLT-40S	PWR	35	OKBM Afrikantov, Russia	259–294	Under Construction
mPower	PWR	180	BWX Technologies, USA	1007, twin units	Under Development
NuScale	PWR	45	NuScale Power, USA	816	Licensing Stage
Westinghouse SMR	PWR	225	Westinghouse, USA	668	Under Development
AVB-6	PWR	3–10	OKBM Afrikantov, Russia	NA	Under Development
SMR-160	PWR	160	Holtec, USA	NA	Under Development
PRISM	SFR	311	GE-Hitachi, USA & Japan	NA	Licensing Stage
4S	SFR	10	Toshiba, Japan	NA	Under Development
SLIMM	SFR	4–40	University of New Mexico's ISNPS, USA	NA	Under Development
G4M	LFR	25	Gen4 Energy, USA	NA	Under Development
EM^2	GFR-He	265	General Atomics, USA	NA	Under Development
GT-MHR	HTR-He	286	General Atomics. USA – Prismatic	NA	Under Development
GTHTR300	HTR-He	275	JAEA, Japan – Prismatic	NA	Under Development
Xe-100	HTR-He	50	X-Energy, USA – Pebble Bed	NA	Under Development
HTR-PM	HTR-He	2 × 105	Tsinghua Univ. & Shandong Shidaowan Nuclear Power, PRC – Pebble Bed	NA	Under Construction
IMSR	MSR	192	Terrestrial Energy, Canada, USA, & UK	< 1000	Under Development
Stable Salt Reactor	MSR	300	Molex Energy UK	NA	Under Development
ThorCon	MSR	250	Martingale Consortium, International	1200	Under Development
MSTW	MSR	115	Seaborg Technologies, Denmark	NA	Under Development

Horie et al., 2008; Salemo et al., 1988). Some SMRs would be fueled onsite, while others would be fueled and sealed in the factory to enhance nuclear safeguards and alleviate nonproliferation concerns (El-Genk et al., 2017; El-Genk and Palomino, 2014). For the latter, there is no need for on-site storage of either used or fresh fuel. In addition, the simplified designs and the modular construction of SMRs would enhance operation reliability and plant capacity factor. The lower unit capital cost and the short construction time (<2 yr) would reduce financial risk to investors. Furthermore, multiple SMR units could be installed and operated at a single site, allowing the total generation capacity of electricity and process heat to grow, commensurate with the increase in the regional energy needs (Sun, 2013; Ingersoll et al., 2014; Reyes and Lorenzini, 2010; Salemo et al., 1988). Thus, while a new unit is being constructed or an existing unit is shut down for maintenance, other operating units at the site continue to provide a revenue stream, enhancing plant reliability and decreasing the overall investment risk (Locatelli et al., 2014; Samalova, et al., 2017).

Currently, there are SMRs in the licensing stage while others are under development or construction (Table 1). These include pressurized water reactors (PWRs), high-temperature gas cooled reactors (HTRs), gas-cooled fast reactors (GFR), molten-salt reactors (MSRs), sodium fast reactors (SFRs), and lead and lead–bismuth eutectic cooled reactors (LFR) (Arie, 2009; Babcock and Wilcox Nuclear Energy, 2011; Chun et al., 2013; El-Genk, et al. 2017, El-Genk and Palomino, 2014; General Atomics, 1996, 2010; Horie et al., 2008; IAEA, 2007, 2012, 2016; Ingersoll et al., 2014; Kuznetsov, 2008; Kyoko et al., 2011; Liu and Fan, 2014; Samalova, et al., 2017; Salemo et al., 1988; Singh, 2013; Sun, 2013; Ueda et al., 2005; Westinghouse Nuclear, 2016).

Nonetheless, future uses of SMRs require dealing with a number of challenges. These include, but not limited to: (a) developing functional central control rooms and providing personnel training