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Review

Nonproliferation improvements and challenges presented by small modular reactors

Shikha Prasad [a,*], Ahmed Abdulla [b], M. Granger Morgan [b], Inés Lima Azevedo [b]

[a] *Indian Institute of Technology – Kanpur, Kanpur, UP 208016, India*
[b] *Carnegie Mellon University, Pittsburgh, PA 15213, USA*

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ABSTRACT

Small modular reactors (SMRs) may provide an energy option that will not emit greenhouse gases. From a commercial point-of-view, SMRs will be suitable to serve smaller energy markets with less developed infrastructure, to replace existing old nuclear and coal power plants, and to provide process heat in various industrial applications. In this paper, we examine how SMRs might challenge and improve the existing nonproliferation regime. To motivate our discussion, we first present the opinions gathered from an international group of nuclear experts at an SMR workshop. Next, various aspects of SMR designs such as: fissile material inventory, core-life, refueling, burnup, digital instrumentation and controls, underground designs, sealed designs, enrichment, breeders, excess reactivity, fuel element size, coolant opacity, and sea-based nuclear plants are discussed in the context of proliferation concerns. In doing this, we have used publicly available design information about a number of SMR designs (B&W mPower, SVBR-100, KLT-40S, Toshiba 4S, and General Atomics EM^2). Finally, a number of recommendations are offered to help alleviate proliferation concerns that may arise due to SMR design features.

1. Introduction

In order to move towards a more sustainable, de-carbonized and reliable energy systems a portfolio of new energy technologies and strategies is needed. Among promising emerging technologies are small modular reactors (SMRs) (Abdulla et al., 2013). The International Atomic Energy Agency (IAEA) defines SMRs as nuclear reactors producing less than 300 MW of electricity (“Small and Medium Sized R, 2013). SMRs might become an energy option which, like today's large reactors, will not emit greenhouse gases while having much lower initial total capital costs, and be more easily deployed (even in remote areas), standardized, and be safer (Abdulla et al., 2013; Liu and Fan, 2014). Such a technology could play a key role in a portfolio of generation technologies for a global reduction in carbon emissions. Since SMRs might be widely deployed if they become economically viable, it becomes imperative to examine the nonproliferation challenges they present and benefits they offer (O'Meara and Sapsted, 2013).

This paper highlights and investigates how SMRs could improve and challenge the existing nonproliferation regime. This regime involves a patchwork of internationally codified and legally binding instruments, informal agreements, national laws, and diplomatic pressure. The main pillars of this regime include: the Nuclear Nonproliferation Treaty (NPT), which bars all but five states from having nuclear weapons, and commits all states to eventual disarmament; Resolution 1540, which commits United Nations (UN) member states to counter nuclear terrorism by preventing nuclear materials from getting into the hands of non-state actors; and the Comprehensive Test Ban Treaty (CTBT), which – upon ratification – would commit member states not to explode nuclear devices in any environment for any purpose (Council on Foreign Relations, 2013). The IAEA is responsible for monitoring and verifying that member states' non-proliferation obligations are met, and is granted the right to monitor nuclear activity in member states, including spot inspections and careful material control and accounting (International Atomic Energy Agency, 2014a,b). An increase in the number of nuclear sites, the total amount of nuclear material in circulation, or the geographic distribution of these sites would greatly expand the amount of work under the IAEA's remit. It would also lead to an increase in the number of potential targets for sabotage, or the possibility of errors in accounting for the increased volume of nuclear material in circulation. Therefore, it is important to investigate whether and to what extent different SMR designs

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* Corresponding author.
E-mail address: shikhap@iitk.ac.in (S. Prasad).

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alleviate these concerns, for example, by eliminating the need for access to nuclear materials or by providing real-time information on core inventory to operators and investigators alike.

To motivate the discussion, we first present survey results from questions related to proliferation that we discussed and posed to forty SMR experts at a workshop on SMRs organized by Carnegie Mellon University (CMU), the International Risk Governance Council (IRGC), and the Paul Scherrer Institute (PSI) on the 18th and 19th of November, 2013 in Villigen, Switzerland. Participants in that workshop were drawn from SMR vendors, nuclear utilities, regulatory bodies, academia, and national laboratories from around the world. During the workshop detailed discussions were held about the path forward for the mass deployment of SMRs in the world, progress made, challenges ahead, and strategies with which they might be overcome. This workshop was divided into eight sessions. In the second session, technical presentations were made on six SMR designs: the integral light water B&W mPower™, the shipborne light water KLT-40S, the liquid metal Toshiba 4S, the high temperature HTR-PM, the high temperature General Atomics (GA) EM^2, and the liquid metal SVBR-100. A brief discussion of the six designs follows.

Two of the six reactors under consideration were light water SMRs. The first of these discussed was the B&W mPower™, a 180 Megawatt-electric (MW$_e$) integral light water reactor (Scarangella, 2012). In the B&W mPower™, the reactor core, the steam generator, the pressurizer, and the associated piping are contained in a reactor module that would be deployed underground (Scarangella, 2012). The mPower™ uses light water reactor fuel assemblies which are half the height of the standard assemblies. Each module has a four-year refueling interval. Babcock and Wilcox argues it should be possible to reduce the Emergency Planning Zone (EPZ) for this reactor to inside the plant perimeter (about 1000 feet) (Mowry, 2013). The refueling equipment is present on-site. At the end of core life, the used fuel is discharged, placed in a spent fuel pool, and the fresh fuel is loaded into the module. The second light water reactor we chose was the OKBM Afrikantov KLT-40S. The design calls for two of these 35 MW$_e$ reactors to be installed in a non-self-propelled ship and is known as a floating nuclear power plant (IAEA Update on KLT–40S). It would be deployed off customers' shores under a build-own-operate scheme, whereby, it is owned by its vendor and staffed by personnel recruited by them (IAEA Update on KLT–40S). At the end of core life, the floating plant is moved to a special handling facility, spent fuel is discharged and temporarily stored on the floating plant, and fresh fuel is then loaded back into the two reactors (IAEA Update on KLT–40S).

Another two of the six reactors discussed were liquid metal reactors. The first of these was the Toshiba 4S, a 10 MW$_e$ (also designed for a 50 MW$_e$ output) fast-neutron reactor that uses molten sodium as a coolant. The reactor has a 30–year refueling interval and Toshiba does not intend to install fuel-handling equipment at 4S deployment sites. The reactor uses fuel enriched up to 19% ^{235}U ("Status report 76 – Super, 2011). At the end of core life, the fuel handling equipment is brought to the site, spent fuel is discharged and removed from site, finally fresh fuel is loaded into the module. Another liquid metal reactor we chose to explore was the lead–bismuth-eutectic cooled SVBR-100, developed by Russia-based JSC AKME. This is a 100 MW$_e$ fast-neutron spectrum reactor with a refueling interval of 7–8 years, uses fuel enriched up to 16% ^{235}U, and can be deployed alone or in configurations of up to 16 modules (Chebeskov, 2010).

The last two of the six reactors were gas-cooled reactors. The first of these is the HTR-PM, a helium-cooled (with a steam-based turbine system), pebble-bed reactor being constructed now in China. This high temperature reactor requires continuous refueling and has a thermal efficiency of 40%. It is slated for deployment with fuel enriched up to 8.5% ^{235}U ("Status report 96 – High, 2011). In the HTR-PM reactor, fuel is contained in tennis-ball size pebbles, refueling is continuous with pebbles recycled through the reactor until an analyzer determines to reject them based on its fuel burnup. The last design is General Atomic's EM^2, a 265 MW$_e$ fast-neutron reactor that utilizes a full helium-cooling cycle. This reactor operates at a thermal efficiency of 53%, and can run for 32 years without refueling. After the end of its core life, the entire module is removed from its underground vault and returned to a special fuel-handling facility (Schleicher and Back, 2012; Small Modular Reactors Wokshop, 2013). The major design features of the six SMRs are shown in Table 1:

We chose designs that spanned a range of technologies, and a range of deployment options, with each novel in at least one respect. This was done because the discussion and exercises that followed these presentations were comparative in nature. Following the technical presentations, the participants were asked to provide their answers to questions posed to them in workbooks. The names of the participants who provided answers for nonproliferation and safeguards related questions, along with their institutional affiliations, are listed in Section 6. However, no specific answers are linked to specific respondents.

In one question, a list of potential SMR advantages related to nonproliferation was presented to the participants. They were asked to select the factor that would most help improve the nonproliferation regime, as well as the second most valuable factor. Some participants added their own suggestions to the list that was provided. The results of this exercise are presented in Fig. 1.

Twenty nine participants answered this question. Of these, more than half believed that making spent nuclear fuel (SNF) unattractive for proliferation, something that is being promised by many SMR designs, would be the best improvement for the nonproliferation regime. This is reasonable because if the SNF composition is such that it is difficult to work with to construct a nuclear weapon, it is less likely to be a target. In Section 2, we discuss how higher content of the isotope Pu-240 can render the SNF less reliable for weapon fabrication purposes.

Sealed designs received the highest number of counts for the second best improvement factor. There was debate among participants as to how "sealed" a reactor could be, but the point was to reduce or eliminate the need for access to the reactor core. Completely sealed designs could ensure that the reactor core is rendered inaccessible throughout its lifetime. Without access, it would not be possible to steal fuel out of the core. Thus, if the reactor vessels can be fueled and sealed during the fabrication, and

Table 1

Major design features of the six SMRs discussed (Scarangella, 2012; Mowry, 2013; IAEA Update on KLT–40S; Status report 76 – Super, 2011; Chebeskov, 2010; Status report 96 – High, 2011; Schleicher and Back, 2012; Small Modular Reactors Wo, 2013; Ingersoll, 2011; Arie and Grenci, 2009; Zhang et al., 2009; Antysheva, 2011).

	B&W™ mPower	KLT-40S	Toshiba 4S	SVBR-100	HTR-PM	GA EM^2
Power output (MW$_e$)	180	2 × 35	10 or 50	101	2 × 105	265
RPV height (m)	25.3	3.9	24	7.9	25.4	10.6
Underground	Yes	Sea	Yes	No	No	Yes
Coolant	H_2O	H_2O	Na	Pb–Bi eutectic	He	He
Breeder	No	No	No	Yes	No	No
Fuel reprocessed	No	Yes	Optional	Optional	No	Optional
Refueling period (yrs)	4	3	30	7–8	Cont.	32
Fuel enrichment (%)	<5	<20	<19	<20	8.5	<17.5
On-site refueling	Yes	Yes	Once	Yes	Yes	No