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Review

Nonproliferation improvements and challenges presented by small modular reactors

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A B S T R A C T

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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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

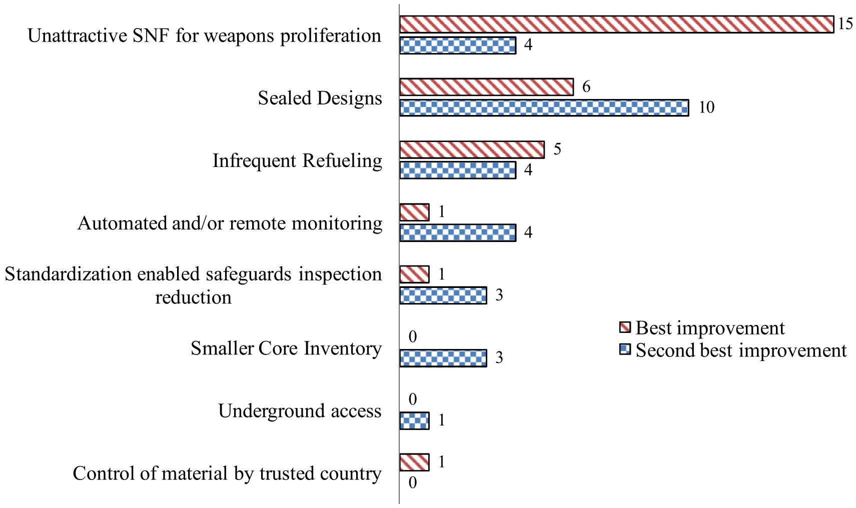

Fig. 1. Distribution of the best and second best nonproliferation improvement aspects of SMRs.

if they can remain sealed until they are safely shipped to a back-end fuel handling facility after being used at a nuclear plant, the security of the fuel during the transport becomes less complicated endeavor.

Some of our workshop participants argued that SMRs with inaccessible cores constitute the only viable option for deploying nuclear reactors in developing countries at acceptable levels of proliferation risk. During the workshop, we heard arguments both more and less extreme than this. Some experts suggested that "sealed" reactors still make excellent targets for sabotage, and any attack – even an unsuccessful one – on a SMR in a developing country would still cause mass panic around the world. Others thought that reactors without "sealed" cores might be viable in developing world settings if other control and verification measures were implemented, such as off-site control rooms, real-time monitoring via sensors and cameras, or off-site storage of spent fuel. These arguments ultimately rest on two premises: 1) that some features yield greater proliferation resistance than others; and 2) that all of these features could be implemented with high reliability. However, existing tools to assess proliferation resistance are inadequate, complicating such discussions (Committee on Improving the Assessment of the Proliferation Risk of Nuclear Fuel Cycles—NationalResearch Council, 2013). Furthermore, a concrete, technical definition of what constitutes a "sealed" core is necessary, along with a better comparative assessment of the potential merits of such an arrangement to determine whether the sealibility of cores dominates potential alternative ways of increasing proliferation resistance. More on the limitations to and challenges raised by such an ideal design are discussed in Section 2.

Infrequent refueling received the third most counts. During refueling, the reactor is shutdown, the core is opened and fuel is accessed. The reactor is in a more vulnerable state in such situations, hence the loading and unloading of fuel during refueling is strictly monitored. Safeguard procedures, such as continuous surveliance camera monitoring ensure that no diversion of special nuclear material takes place during fuel movements to and from spent fuel storage. Infrequent refueling limits the occasions when the reactor core can be opened and the necessary safeguard procedures can be followed to ensure the security of reactor fuel (Whitlock and Sprinkle, 2012).

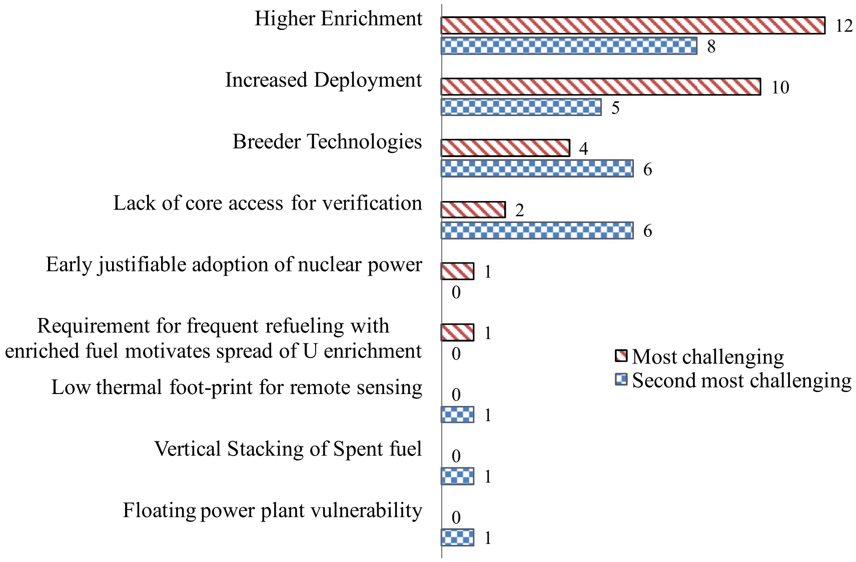

Fig. 2. Distribution of the most and the second most challenging nonproliferation aspects of SMRs.

Other factors such as automated and remote monitoring, standardization enabled by factory fabrications, and smaller core inventory also received some attention.

In another question, participants were asked to identify the most challenging, and the second most challenging design aspects of SMRs from a nonproliferation perspective. Here too, participants added additional factors they thought were important beyond those we provided.

The results summarized in Fig. 2 suggest that higher fuel enrichment presents the greatest challenge. Participants argued that going for higher enrichment levels poses one of the more politically and institutionally sensitive decisions for a reactor designer, despite some of the technical and operational advantages of higher enrichment. In Table 4, we illustrate how going from 5% enrichment to 20% enrichment can reduce the resources needed to construct a nuclear weapon by nearly a factor of three. Yet, many advanced SMR designs are moving towards higher enrichment, because achieving the advantages promised for SMRs is challenging otherwise. The obvious counter argument involves the burdens of commercializing and safeguarding higher enriched fuels. Higher enrichment also received the highest number of second choices as being the most challenging issue.

Increased deployment of reactors was identified by our participants as presenting the next highest level of concern. SMRs are intended for global deployment, in remote and populated areas, as well as in developed and developing countries. Of course, as the number of SMRs increases, the probability of security and safety incidents will also increase. Therefore, there is a need to develop a more robust deployment infrastructure, introducing standardized procedures that can help reduce regulatory and enforcement burdens.

Other factors that concerned our participants were breeder technologies and lack of core access for inspection. Core access or inspection ability can be affected by factors such as the opacity of the coolant and reactor seals, as discussed in the next section. Evidently, reactor seals present both a nonproliferation advantage and a challenge. Similarly, most SMR design features create an element of risk along with the benefits they bring; these are discussed next.

2. Characteristics of SMRs for nonproliferation evaluation

In the discussion below we examine publicly available technical data to understand the improvements and challenges posed by SMR designs in the context of nonproliferation and safeguards.

2.1. Fissile inventory

The critical mass of a fissile isotope is the minimum mass needed to sustain a chain nuclear reaction. A sustained chain nuclear reaction is the first requirement to design a nuclear weapon. Without any supporting material, it takes 52 kg of U-235 (94% enriched) or 10 kg of Pu-239 to achieve a critical mass (Mark, 1993). For nuclear devices which use reflectors to reflect back leaking neutrons and use tampers to keep the nuclear material assembled for a longer time, the above bare-critical masses can be reduced by several factors (Bunn and Wier). These critical masses are much smaller than what is available in a nuclear reactor. If we consider SMRs such as the ones shown in Table 2, we find that these reactors contain significant amounts of special nuclear material (Tsuboi et al., 2012; Email communication with, 2013a). Therefore, it is imperative to give SMRs the same attention as medium or large nuclear reactors receive in regards to safeguards and nonproliferation.

Table 2
End of life fissile inventory in SMR designs.

Reactor	U-235 (kg)	Pu-239 (kg)
Toshiba 4S	1502	156
SVBR-100	884	334

Some advanced SMR designs will produce waste containing plutonium of higher quality from the perspective of weapons production. The reliability of plutonium to construct a nuclear weapon increases as the Pu-239 content increases and as the Pu-240 content decreases (Mark, 1993). This is because Pu-240 has a high ability to spontaneously fission, therefore, the chances of predetonation can increase for high quantities of Pu-240, rendering a weapon unreliable (Mark, 1993). However, a higher Pu-240 doesn't make the fabrication process of a weapon any more technically difficult. In fact, reactor-grade plutonium with any level of irradiation is a potentially explosive material (Mark, 1993).

The SVBR-100 is a lead–bismuth eutectic cooled fast reactor which will contain plutonium with less than 5% Pu-240. Thus, it will be categorized as “weapons grade” plutonium containing less than 7% Pu-240 (Plutonium: The First 50 Y, 1996). However, as a nonproliferation measure, the SNF from SVBR-100 will be stored in dry-casks with solidified lead which should act as a barrier against proliferation (Email communication with, 2013a).

GA EM^2 is a gas-cooled fast reactor that contains “fuel grade” SNF (Email communication with, 2013b). This implies that the plutonium composition of the spent fuel contains higher amounts of Pu-239 when compared to reactor grade spent fuel, and the Pu-240 content is between 7% and 19%, based on the DOE definition (Plutonium, 1996). However, GA's spent fuel contains higher concentrations of fission product than traditional thermal reactors, which the vendor argues will self-protect the spent fuel (Email communication with, 2013b).

It is evident from these examples that SMRs should continue to be subject to stringent safeguard inspections due to their fissile inventories; however, they are likely to benefit from easier material accountancy and balance practices due to their small inventories. For instance, the Toshiba 4S-10 MW(e) reactor has only 18 fuel assemblies as compared to over 150 fuel assemblies present in large reactors such as the AP-1000 (Status report 76 – Super, 2011; ML11171A443). The SVBR-100 fast reactor has a total of 61 fuel assemblies (Chebeskov, 2010). GA EM^2 is designed for 91 assemblies (Schleicher and Back, 2012).

2.2. Core life & refueling

Most SMRs being developed are characterized by longer core lives than existing nuclear reactors (Abdulla et al., 2013; Small and Medium Sized R, 2013; Liu and Fan, 2014). With increased core lives, the reactors and the fuel inside will be accessible less frequently. Infrequent access to the core will enhance safeguards

Table 3
Fuel design parameters (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; Kessler, 2012).

SMR design	Core life (years)	Burnup (GWd/t)	Maximum enrichment
B&W mPower™	4	Not Available	5%
SVBR 100	8	106	20%
KLT-40S	2.3	45.4	20%
Toshiba 4S (10 MWe)	30	34	19%
General Atomics EM^2	32	137	17.5%

protection because the frequency for a threat diversion is reduced. Many SMRs, as shown in Table 3, claim greater than 4 years of core lifetime, which is twice as long when compared to the present fleet of the reactor (Small and Medium Sized R, 2013; Liu and Fan, 2014). A few SMR designs, such as the Toshiba 4S-10 MW(e) and GA EM^2, are able to claim core lifetimes as long as 30 years or more (Status report 76 – Super, 2011; Schleicher and Back, 2012). The Toshiba 4S designers have developed special fuel handling equipment which will be made available at the nuclear power plant only during refueling. In addition, it is envisioned that the fuel handling equipment will be shared between several such nuclear power plants (Status report 76 – Super, 2011). There will be no facilities available for the discharge of fuel from the sealed core, and disassembly of the fuel pins. Thus, the vendors propose that by not having the refueling equipment permanently available at a plant except when it is being refueled, the likelihood of access to core and nuclear fuel at any other time is reduced dramatically (Status report 76 – Super, 2011). Of course, if a State that wishes to proliferate is in control of the refueling equipment this design plan may not be effective.

In addition to refueling outages, there are other occasions, such as maintenance tests, during which access is required for some reactor designs (Clayton and Wood, 2010). Therefore, SMR designers need to find solutions for maintenance and materials inspection to ensure that the reactor cores do not need to be accessed for such purposes between refueling outages. To reduce such occasions the Toshiba 4S design has introduced components such as the static electromagnetic pumps which can operate for longer times without any maintenance. These SMRs will also have material surveillance monitoring external to the vessel, which together with the electromagnetic pumps, should eliminate the need to access the core (Status report 76 – Super, 2011). In short, a greater than 4-year core lifetime will not necessarily reduce the frequency with which the core is accessed unless accompanied by other design features that address the regular maintenance and material inspection challenges.

2.3. High burnup

SMRs such as those shown in Table 3 are marked by longer core lifetimes and higher burnups. The burnup of nuclear fuel is a measure of the amount of energy that was released while the fuel was being used or “burned” in the reactor. Thus, the longer the fuel is used to produce power, the higher its burnup is. With a higher burnup, the reliability of SNF for weapons purposes declines. A higher burnup of uranium fuel yields a greater amount isotope Pu-240 in the spent fuel. As discussed above, this isotope may lead to pre-detonation of a weapon as it spontaneously fissions. However, the technical difficulty to make a nuclear weapon is not changed, as mentioned previously (Mark, 1993).

2.4. Digital instruments and control (I&C) for nuclear material accountancy

Digital I&C may be used for tracing and monitoring the entire fuel cycle and also for ensuring physical protection of a reactor (Dudenhoeffer et al., 2007). Since these units will be standardized and some even factory manufactured, autonomous monitoring could be implemented with greater ease and accuracy, thus, reducing the cost and man-hours (Clayton and Wood, 2010).

Digital I&C could also help reduce the cost of physical protection and proliferation resistance compared to the more traditional human based methods (Clayton and Wood, 2010). Components and activities could be identified and tagged to provide monitoring throughout the fuel cycle. Physical protection such as automated monitoring of real-time video images can prevent access to unauthorized individuals, to alert the security in case of a breach, and to allow mitigation of any unauthorized access (Dudenhoeffer et al., 2007). New technologies are being developed to detect and mitigate the impacts of cyber attacks as well (Clayton and Wood, 2010).

Some SMR designs being proposed, such as those by B&W mPower™, Westinghouse, and Holtec International will be integral light water reactors. These reactors will contain all the primary coolant components such as the reactor, the pressurizer, and the steam generator inside the pressure vessel. The design and development of the in-vessel sensors needed for measurements for such reactors still require significant attention (Clayton and Wood, 2010). Parameters that need to be measured include in-vessel flux/power, primary flow, reactor coolant system temperatures, primary coolant flow-rate etc. Sensors measuring these parameters can play an important role in ensuring that no change is being made in the design of the core. Flow measurement sensors will detect any planned attack to cause a loss-of-coolant accident (LOCA), which could initiate a reactor accident if not mitigated in time (Clayton and Wood, 2010).

Another feature of these integral light water reactors is that there is a large water gap between the core and the vessel. Thus, greatly moderated and reduced neutron signals will limit the use of ex-vessel ion chambers for flux and power measurements. For these designs, more sensitive neutron detectors capable of measuring weak signals while withstanding high temperatures and prolonged radiation exposure, need to be developed and tested (Clayton and Wood, 2010).

For other SMRs that use fast-neutron designs, such as the molten-salt cooled reactors, the digital I&C sensor will need to be tested for such harsh environments. These sensors will need to demonstrate tolerance for high energy neutrons that can damage electronics and materials of these sensors (Clayton and Wood, 2010).

With widespread deployment of SMRs the security and robustness of wireless communication will need to be demonstrated for high reliability (Clayton and Wood, 2010). This will help ensure safety against cyber attacks and tamper-proof data transmission to monitoring bodies such as the IAEA.

2.5. Underground designs

Many SMR designs propose to place the reactor modules below the ground. Such designs include B&W mPower™, Toshiba 4S, GA EM^2, Holtec International's SMR-160, NuScale Power Module, and ACP100 (Small Nuclear Power Reac, 2013). Underground reactor designs can be more difficult, costly, and technically challenging to access, thus, they can claim greater proliferation resistance. However, some critics argue that this difficulty to access can also increase the safeguards burden and reduce the ease of unannounced inspections (Whitlock and Sprinkle, 2012). Underground reactor designs will also need to prepare robust physical protection and combat plans in case of a hostage or infiltration attempt, because they will not be easily accessible to forces from the outside (Lyman, 2013). A possible relief to such a situation would be the location of control rooms above ground, such as that of Toshiba 4S (Email response from Kazuo, 2013).

2.6. Sealed designs

From a nonproliferation and safeguards point of view, sealed reactors which are fueled and sealed by the supplier, and are only unsealed at secure fuel handling facilities at the end of their core-life, would clearly be desirable. Some SMR designers, such as G4M, claim that they can transport a sealed reactor unit with fuel inside to a nuclear plant site, and then return it from the plant site, still sealed after it has been used (Gen4 Energy, 2012). However, there are many technical hurdles that must be overcome if this vision is to be realized.

First, SMR designs will need to maintain the integrity of the fresh fuel while being transported to the nuclear power plant (Small Modular Reactors Workshop, 2013). Bumping and vibration during transport could lead to weaknesses, cracking or displacement of the fuel. Second, for reactors with long core lifetimes such as Toshiba 4S and GA EM^2, it must be demonstrated that these reactors can safely operate for over 30 years, without the need to open the seal. Third, handling and transport of sealed reactors after their operation needs to be carefully designed in order to withstand the decay heat. This third issue greatly limits the size of the reactor.

Any nuclear reactor, even after being shutdown continues to produce decay heat. This decay heat although a very small fraction of the total normal output, needs to be continuously removed. For instance, the decay heat from a typical light water spent fuel, even a year after shutdown, is 10 kW/t of fuel (World Nuclear Association, 2012). Thus, a reactor similar to the Westinghouse AP1000 containing approximately 96 tonnes of fuel, will continue to produce 960 kW of decay heat even after a year. Presently, even some of the best dry cask technologies can only remove up to 35 kW of heat per cask (NAC International, 2013). Thus, assuming that dry casks and shipping containers have similar cooling characteristics, if one were to design an SMR for decay heat up to 35 kW, it would be restricted to producing 40 MW(e) at the maximum (assuming a 33% thermal efficiency and designs similar to AP1000). Therefore, if existing technology is used without any improvements to the end of life cooling, the SMR designs will need to be at least 30 times smaller than existing light water reactors such as AP1000.

The decay heat for sealed SMRs could be addressed in at least two different ways. A simple solution would be to limit the power output and hence the size of the SMR such that additional cooling would not be needed during the transport of the reactor after its core life and some local cooling time. Another solution could be to design sealed reactor units which will have the ability to mechanically cool the spent fuel inside after use. However, such designs would need to be versatile to demonstrate that they can be reliably operational while being transported. Needless to mention, such systems are likely to be more expensive.

2.7. *Enrichment*

In an effort to decrease size and yet increase fuel life, many SMR designs pack more fissile content in their small cores, which means higher enrichment levels (Whitlock and Sprinkle, 2012). Furthermore, some advanced SMR designs are fast-neutron reactor designs that require significantly higher enrichments than traditional thermal-neutron reactors (Waltar et al., 2012). The low-enriched uranium (LEU) limit is no more than 20% enrichment of U-235 (International Atomic Energy, 2002); many SMR designs contain fuel with maximum enrichment just short of this mark as seen in Table 2. While still less than the LEU limit, enrichment up to 20% is nearly a fourfold increase compared to that of the present light water fleet, which generally have enrichment levels less than 5%. If one were to compute the amount of separative work units (SWU) or resources needed to reach 95% enrichment of U-235 for a total mass of 55 kg (more than the U-235 bare critical mass for a weapon production) with a 0.3% concentration of U-235 in waste, we obtain the values in Table 4 (Oelrich).

Table 4
Resources needed to obtain a fixed amount of HEU from various initial samples.

Initial enrichment	Feed Mass (kg)	Product enrichment	Product Mass (kg)	SWU (kg.SWU)
0.711%	12,673	95%	55	112,645
5%	1108	95%	55	3287
20%	264	95%	55	1134

As seen in Table 4, the amount of work needed to enrich up to 95% for the case of 20% LEU is nearly three times easier when compared to the work done to enrich to 95% from 5% LEU (more typically seen in present light water reactors). Therefore, SMR designs that will use enrichment up to 20% will be more attractive as a weapons material than the traditional reactors.

2.8. *Breeders*

Many SMRs are fast-neutron reactor designs. Fast reactors can be particularly useful for conversion of the abundant U-238 in the fuel to Pu-239, which could be used for the production of a weapons-material breeder (Waltar et al., 2012). Therefore, SMR designs which utilize fast spectra need to be cautious and should include safeguards by design elements carefully, so that during its time of operation an SMR cannot be transformed from a power producer to a nuclear fuel breeder.

Some SMR designs such as the Toshiba 4S and SVBR-100 have therefore designed their fast reactors such that there are no explicit blanket regions outside the core where plutonium can be bred (Status report 76 – Super, 2011; Zrodnikov et al., 2011). However, exclusion of the blanket region is not a foolproof measure; it may be technically possible to find some unoccupied space between the core and the baffle, and covertly convert that region into a breeding area. Thus, it is important to calculate the impact of such efforts. For instance, Toshiba 4S calculations show that even if certain portion of the core is deliberately altered to breed, the conversion ratio would remain less than one (Email response from Kazuo, 2013). Furthermore, the Toshiba 4S engineers claim that the reactivity control reflectors placed outside the core eliminate the possibility of a breeding area (Email response from Kazuo, 2013). Clearly such claims will require careful independent assessments.

2.9. *Excess reactivity*

As many SMR designs are targeting low refueling frequency, their core designs start with high excess reactivities. The typical value for excess reactivity present in LWRs for a clean core is typically less than 0.3 $\Delta k/k$(Duderstadt and Hamilton, 1976). Jeremy Whitlock from Atomic Energy Canada Limited has explained that such system might tolerate target irradiation without significantly affecting key operational parameters (Whitlock and Sprinkle, 2012). Thus, to an observer or detection system, there might be no peculiarities apparent, while this may well be a diversion route. Verification of target insertion or removal, Whitlock suggests, could be mitigated by pre-operation design verification, sealing of the reactor vessel, and surveillance measures (Whitlock and Sprinkle, 2012).

2.10. *Fuel element size*

Smaller reactors will have smaller cores and thus smaller fuel elements. While the small size of the fuel elements may be good for portability and could lead to reduction in costs, it can also contribute to proliferation and safeguard concerns. For instance, B&W mPower™ has fuel elements that are almost half the height of the typical large LWR fuel elements (Scarangella, 2012). Thus, for nuclear plants utilizing LWR type spent fuel pools, it would be possible to vertically stack the fuel elements in a spent fuel pool. However, doing so would be a hindrance in the inspection of a spent fuel pool because the inspector would not be able to directly verify the spent fuel stack directly under the top stack. Therefore, mPower™ is planning on not stacking the fuel bundles in the spent fuel pools (Small Modular Reactors Workshop, 2013). A second concern is that if the small fuel elements can be easy to transport, they can also be easy to conceal for those planning on diverting these (Whitlock and Sprinkle, 2012). This provides another incentive for the international safeguards regime to develop monitoring methods specifically for SMRs.

2.11. Coolant opacity

Many SMR designs being developed will use non-traditional coolant materials such as molten sodium or lead that are not transparent. In such reactors, a simple visual or camera inspection will not be feasible. While an underwater telescope can be used in water-cooled reactors to inspect the reactor tank bottom and other surfaces from the top of the tank, such an optical device will not be feasible for opaque coolant types (Application of Non-destructive, 2001). New detection methods need to be deployed to replace traditional LWR cameras. There has been significant development of such cameras for opaque coolants for use with sodium-cooled fast reactors (Karasawa et al., 2000). For instance, ultrasonic visual inspection techniques may provide a solution for fast reactor in-vessel inspection (Karasawa et al., 2000).

2.12. Sea-based nuclear power plants

Some SMRs being developed and studied, such as KLT-40S and Flexblue, will be sea-based technologies. The Russian Akademik Lomonosov is a non-self-propelled vessel, which will house two KLT-40S reactors. It is scheduled to start operation by 2016 as the first Russian floating nuclear power plant station (IAEA Update, 2013; Delivery of floating pla, 2013). Flexblue is a French concept SMR with submersible hull, inspired by nuclear powered submarines, being studied in partnership with AREVA, CEA, and EDF (DCNS; DCNS, 2011). Both these technologies are targeting developing countries as potential customers (IAEA Update, 2013; DCNS, 2011). As sea-based technologies, like KLT-40S, are on the verge of being deployed, it becomes imperative to develop the necessary safeguards and nonproliferation standards addressing various aspects, vulnerabilities, and natural advantages of a sea-based nuclear reactor.

3. Conclusion

Innovative SMR designs promise an affordable, safe, viable, and non-greenhouse gas emitting energy option. However, like their traditional, bulky, and costly predecessors; SMRs too should be subject to scrutiny through the lens of nonproliferation and safeguards guidelines. We have discussed improvements and challenges posed by SMRs to the nonproliferation regime, motivated in part by the results of an SMR workshop for nuclear experts that examined this topic.

SMR designs can boast many improvements, in some cases, even in the field of nonproliferation. However, several SMR designs also introduce new concerns. Although, these concerns may not be exclusive to SMR designs, they are likely to pose greater risks with their deployment. In the preceding discussion, we have identified a number of areas where technical improvements in the nonproliferation regime will help the deployment of SMRs. These include:

- Reduction of service and maintenance requirements for reactor parts to ensure that the reactor does not need to be shutdown for maintenance between outages;
- Development of effective wireless communication systems for automated monitoring;
- Development of in-vessel sensors for integral reactor vessels, which contain the entire primary cooling circuit;
- Development of radiation detectors for the passively safe designs with very large water inventories;
- Sealed design development, such that the fuel remains sealed from factory fabrication to the fuel handling facility at the back-end of the fuel cycle;
- Development of designs with infrequent refueling while keeping enrichment levels low;
- New detection systems for opaque coolants, where visual inspections are infeasible.

With these developments and others, the SMR community will be more confident and prepared to face the nonproliferation challenges. Solutions and improvements made in the light of the above suggestions can help strengthen the road to deployment for SMRs around the globe, providing us with a sustainable and secure base-load energy alternative that does not emit greenhouse gases.

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Appendix A. SMR 2013 Workshop Participants

Table 4
List of participants who ranked nonproliferation improvements and challenges.

#	Name	Institution	Country
1	Kazuo Arie	Toshiba Corporation	Japan
2	Alexey Kondaurov	JSK AKME-engineering	Russia
3	Jamal Al Ahbabi	Emirates Nuclear Energy Corporation	U.A.E.
4	Jay Apt	Carnegie Mellon University	U.S.A.
5	Kazuhito Asano	Toshiba Corporation	Japan
6	Inés Azevedo	Carnegie Mellon University	U.S.A.
7	Kennette Benedict	Bulletin of the Atomic Scientists	U.S.A.
8	Rita Bowser	Westinghouse Electric Company	U.S.A.
9	Chao Fang	Institute of Nuclear and New Energy Technology, Tsinghua University	China
10	Steve Fetter	University of Maryland	U.S.A.
11	Ashley Finan	Clean Air Task Force	U.S.A.
12	Keith Florig	University of Florida	U.S.A.
13	Zhihu Gao	China National Nuclear Corporation	China
14	Alex Glaser	Princeton University	U.S.A.
15	Philipp Hänggi	Alpiq AG, Geschäftsstelle Swissnuclear	Switzerland
16	John Molyneux	Rolls Royce Plc	U.K.
17	M. Granger Morgan	Carnegie Mellon University	U.S.A.
18	James Noel	Babcock & Wilcox	U.S.A.
19	Matt O'Connor	Electric Power Research Institute	U.S.A.
20	David Otwoma	Kenya Ministry of Energy and Petroleum	Kenya
21	John Parmentola	General Atomics	U.S.A.
22	Andreas Pautz	Paul Scherrer Institute	Switzerland
23	Shikha Prasad	Carnegie Mellon University	U.S.A.
24	Michael Rosenthal	Department of Homeland Security	U.S.A.
25	Roger Seban	Électricité de France	France
26	Morello Sperandio	AREVA NP	France
27	Kiril Velkov	GRS	Germany
28	Haitao Wang	Institute of Nuclear and New Energy Technology, Tsinghua University	China
29	Tony Williams	Axpo	
30	Kyun Zee	Korea Atomic Energy Research Institute	Korea

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