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Author(s):	Badwan, Faris M. Demuth, Scott Francis Miller, Michael Conrad Pahakin, Gennady
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Safeguards and Security by Design (SSBD) for Small Modular Reactors (SMRs) through a Common Global Approach

Faris Badwan/U.S.
Scott DeMuth/U.S.
Michael Miller/U.S.
Gennady Pshakin/Russia

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ABSTRACT

Small Modular Reactors (SMR) with power levels significantly less than the currently standard 1000 to 1600-MWe reactors have been proposed as a potential game changer for future nuclear power. SMRs may offer a simpler, more standardized, and safer modular design by using factory built and easily transportable components. Additionally, SMRs may be more easily built and operated in isolated locations, and may require smaller initial capital investment and shorter construction times. Because many SMRs designs are still conceptual and consequently not yet fixed, designers have a unique opportunity to incorporate updated design basis threats, emergency preparedness requirements, and then fully integrate safety, physical security, and safeguards/material control and accounting (MC&A) designs. Integrating safety, physical security, and safeguards is often referred to as integrating the 3Ss, and early consideration of safeguards and security in the design is often referred to as safeguards and security by design (SSBD).

This paper describes U.S./Russian collaborative efforts toward developing an internationally accepted common approach for implementing SSBD/3Ss for SMRs based upon domestic requirements, and international guidance and requirements. These collaborative efforts originated with the Nuclear Energy and Nuclear Security working group established under the U.S.-Russia Bilateral Presidential Commission during the 2009 Presidential Summit. Initial efforts have focused on review of U.S. and Russian domestic requirements for Security and MC&A, IAEA guidance for security and MC&A, and IAEA requirements for international safeguards. Additionally, example SMR design features that can enhance proliferation resistance and physical security have been collected from past work and reported here. The development of a U.S./Russian common approach for SSBD/3Ss should aid the designer of SMRs located anywhere in the world. More specifically, the application of this approach may lead to more proliferation resistant and physically secure design features for SMRs.

INTRODUCTION

The Nuclear Energy and Nuclear Security working group was established under the U.S.-Russia Bilateral Presidential Commission during the 2009 Presidential Summit. In the President's Joint Statement on Nuclear Cooperation the special responsibility of the United States and Russia for security of nuclear weapons and material, recognized and agreed to broaden and deepen U.S.-Russian long-term cooperation to further increase the level of security of nuclear facilities around the world. They also stated their common vision for the growth of clean, safe, secure, and affordable nuclear energy for peaceful purposes. Within the working subgroup on civil nuclear energy development Small Modular Reactors were selected as subject for joint study efforts.

SMRs offer the advantage of lower initial capital investment, scalability, and siting flexibility at locations unable to accommodate more traditional larger reactors. The term "modular" in the context of SMRs refers to the ability to fabricate major components of the nuclear system in a factory environment and ship to the point of use. Even though current large nuclear power plants incorporate factory-fabricated components (or modules) into their designs, a substantial amount of field work is still required to assemble components into an operational power plant. SMRs are envisioned to require limited on-site preparation and substantially reduce the lengthy construction times that are typical of the larger units. SMRs provide simplicity of design, enhanced safety features, the economics and quality afforded by factory production, and more flexibility (financing, siting, sizing, and end-use applications) compared to larger nuclear power plants. SMRs may also provide safety, security, and potential proliferation resistance benefits. Many SMRs concepts involve installation below grade for safety and security enhancements, enhancing resistance to both sabotage and natural phenomena hazard scenarios. Some SMRs will be designed to operate for extended periods without refueling. These SMRs could be fabricated and fueled in a factory, sealed and transported to sites for power generation or process heat, and then returned to the factory for defueling at the end of the life cycle. This approach could help to minimize the transportation and handling of nuclear material.

The implementation of safeguards and security requirements early in the design process of a nuclear facility is essential for an efficient design and operations, and is generically known as SSBD. More often than not, and despite the good intentions of all parties involved, realizing SSBD goals during the design and construction of new nuclear facilities are largely unmet primarily as a result of a lack of formality to the SSBD process. The current interest in SMRs provides an excellent opportunity to further SSBD as there are many new designs under development. Historically, safeguards have been retrofitted into existing facilities and have been applied late in the design/build/operate sequence, thus leading to a perception that safeguards are beyond the scope or concern of the facility/process design team. Without adequate planning and preparation, both the added cost and the disruption to the construction and licensing process can be significant.

This paper describes the early development of a U.S./Russian common approach to implementing SSBD for domestic and international SMR applications. The initial step for SMR SSBD is identification of the key domestic and international regulatory requirements and guidance. The second step is to identify component and facility intrinsic design features that satisfy U.S. and Russian domestic and international MC&A/safeguards and security requirements, and that have the potential to enhance proliferation resistance and physical security. The third step is to identify safeguards and security extrinsic design features that satisfy

U.S. and Russian domestic and international MC&A/safeguards and security requirements, and that have the potential to enhance proliferation resistance and physical security. ***The final step is the preparation of a U.S./Russian common approach to implementing SSBD based on the identified component, facility, safeguards, and security design features, for domestic and international SMR applications.***

Example U.S. & Russian SMR Concepts[1]

The following Tables 1 and 2 identify SMR concepts considered for the U.S. and Russian Federation respectively, and selected design features that will influence MC&A and physical protection requirements.

Table 1. SSBD-Related Design Features for Selected U.S.-considered SMRs

Reactor	Design	Type	MWe	Fuel	Enrich-ment (%)	Refuel Interval (yr)	Under Ground	Burn-up (GWd/T)
NuScale	NuScale	PWR	45	UO_2	4.95	2	Yes	
PBMR	W	HTGR	250	UO_2 Triso	10	On-load		
4S	Toshiba-W	LMR	10-50	U-Pu-Zr	variable	30	Yes	34
Hyperion	Hyperion	LMR	25	UN	<20	7-10	Yes	
PRISM	GE-Hitachi	LMR	311	U-Pu-Zr	variable	2	Yes	6
mPower	B&W	PWR	125	UO_2	5	5	Yes	<40
IRIS	W	PWR	335	UO_2	5	4		
MHR	GA	HTGR	285	UCO Triso	<20	1.5		220
ANTARES	AREVA	HTGR	275	UCO Triso	19.8	1.5		
ARC-100	ARC	LMR	100	U-Zr	10-17	20		20

An extensive, updated list of commercially proposed SMRs can be found on the website of the World Nuclear Association (www.world-nuclear.org/info/inf33.html). Other than the ten SMRs listed in Table 1, most SMR designs will require considerable R&D, including substantial work on fuels, reactor materials, sensors, instrumentation, and system components. In other words, they are years away from design maturity.

[1] P. Pan, M. Mullen & S. DeMuth, Preliminary Analysis of Safeguards & Security by design for Small Modular Reactors, Los Alamos National Laboratory, LA-UR-11-05030, September 2013.

Table 2. Small Capacity (≤ 50 MWe) Russian-considered SMR Designs

Name	VKT-12	KLT-40C	SVBR-10	ABV-3 ABV-6M	UNITERM	RUTA-70
Designer	OKBM	OKBM	Hydropress	OKBM		
Electricity (MWe) Heat (MWt)	12	2x19.5 2x85	12 58	18-45	1.5 4.6	0 70
Fuel Enrichment (% ^{235}U)	2.4 – 4.8	<20	16.5	16.5	15	<20
Type of Fuel	Metal-Ceramic	U-Al-Si	UO_2	U-Al-Si	Metal-Ceramic	U-Al-Si
Reloading Period (yrs)	10	3-4	20	8-10	25	10-12

MC&A/SAFEGURDS & SECURITY REQUIREMENTS AND GUIDANCE

US domestic requirements for Material Control and Accounting (MC&A) are contained in Nuclear Regulatory Commission (NRC), Code of Federal Regulations 10CFR Part 74, Material Control and Accounting of Special Nuclear Materials. For Physical Protection, domestic requirements are contained in NRC code of Federal Regulations 10CFR Part73, Physical Protection of Plants and Materials. International guidance on the fundamental elements of Material Control and Accounting (MC&A) is contained in the IAEA's Guidelines for States' Systems of Accounting (SSAC) for and Control of Nuclear Materials (IAEA/SG/INF/2). For physical protection, international recommendations are contained in the IAEA Nuclear Security Series No. 13: Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Rev 5).

In the Russian Federation, procedures for managing nuclear material and radioactive substances are regulated by legislative and regulatory documents, which include:[2]

- The Constitution of the Russian Federation, Article 71. (The Russian Federation has the jurisdiction over: federal power systems, the nuclear power generation industry, fissile materials, federal transportation, information and communications, activities in outer space.)
- The Law of the Russian Federation of November 21, 1995, No. 170-FZ (including modifications of 02.10.1997; 02.10.2001; 12.30.2001; 03.28.2002; 11.11.2003; 08.22.2004; 12.18.2006; 02.05.2007) "On the Use of Nuclear Energy."
- Decree of the President of the Russian Federation of September 15, 1994, No. 1923 "On Priority Activities to Develop and Implement the State System of Nuclear Materials Accounting and Control for 1995."

[2] M.C. Miller, S.F. DeMuth, and G.M. Pshakin, Safeguards and Security by Design: Considerations for Small Modular Reactors, Los Alamos National Laboratory, LA-UR-13-23917, May 2013.

- Federal Law of the Russian Federation of 11.21.1995 No. 170-FZ "On the Use of Atomic Energy."
- Federal Law of the Russian Federation of02.05.2007 No.13-FZ"On the Specifics of Management and Disposition of the Assets and Shares of Organizations Conducting Operations Involving the Use of Atomic Energy; and on Amending Certain Legislative Acts of the Russian Federation."
- Federal Law of the Russian Federation of 01.12.2007 No. 317-FZ "On the State Nuclear Energy Corporation "Rosatom."
- The Decree of the President of the Russian Federation of 04.27.2007 No. 556 "On Restructuring the Nuclear Power Industrial Complex of the Russian Federation."
- The Decree of the President of the Russian Federation of 03.20.2008 No. 369 "On the Measures to Establish the State Nuclear Energy Corporation "Rosatom."
- The Government Decree of 06.05.2008 No. 352 "On Approving the Regulations for the System of State Accounting and Control of Nuclear Materials."
- Federal Rules and Regulations In the Area of the Use of Nuclear Energy "Basic Rules for Accounting and Control of Nuclear Materials." (NP-030-12) [7] (Enacted on 17.04.2012 by the RosTechNadzor Decree of No. 255).
- A number of by-laws and regulatory documents adopted at the agency level.

SMR DESIGN CONSIDERATIONS FOR MC&A/SAFEGUARDS & SECURITY

The overall objective of a nuclear security program is to protect persons, property, and the environment from malicious acts involving nuclear material and other radioactive material. The objectives of a physical protection program (including MC&A) for LWRs include protection against unauthorized removal, theft, and other unlawful taking of nuclear material; protection of nuclear material and nuclear facilities against sabotage; and mitigation or minimization of the effects of sabotage.

The two SMR technologies selected by the U.S. DOE for funding support related to design certification and NRC licensing, mPower and NuScale,[3] use reactor fuels that are within the standard enrichment of large LWR fuel (i.e., less than 5 percent enrichment, NRC Category III SNM). The security and MC&A requirements for a material license to manufacture these SMR fuels addresses the risks associated with the possession of, use of, and activities involving Category III SNM. The transportation of these SMR fresh fuels (i.e., NRC Category III SNM) and irradiated nuclear fuels is not expected to differ from the transportation of fuel for current large LWRs, and thus the current security regulatory framework is therefore adequate for the licensing of transportation activities. These SMRs designs will use reactor fuel that is similar to standard large LWR fuel assemblies (i.e., less than 5 percent enrichment, 17x17 assemblies), with less than the standard length. It is anticipated that designers will apply current knowledge and experiences from approved, certified, or licensed Independent Spent Fuel Storage Installations (ISFSIs) for the storage of these SMR irradiated nuclear fuel.

The IAEA provides recommendations and guidance for implementation of safeguards and security at nuclear facilities including nuclear power reactors large or small. The two main international guidance documents are: Guidelines for States' Systems of Accounting for and

[3] http://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors

Control of Nuclear Materials (IAEA/SG/INF/2) and the IAEA Nuclear Security Series No. 13: IAEA Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Rev 5).

Based on applicable domestic and international requirements and guidance for safeguards and security, preliminary observations have been developed to help guide SMR designs for U.S. and Russian domestic as well as international applications.

- Generally, the performance goals and objectives for both U.S. and Russian domestic and international requirements and guidance are similar for both safeguards and security. However, in many cases, the level of details of these requirements and guidance varies. The domestic requirements are prescriptive and detailed, whereas the international guidance (e.g. IAEA) is more generic.
- Implementation of domestic requirements may be more consistent and uniform than for international requirements, since the U.S. and Russian domestic regulation is more matured and well established than IAEA.
- The approach and methodology for implementing domestic and international security requirements and guidance are similar. The steps in the process are the same; however, the maturity level of the tools used for target setting, threat and vulnerability assessments, and consequences analysis may vary to some extent.
- The physical security for SMRs may rely on sufficient and effective adversary delay times that could be incorporated into the design to include for example:
  - Locate and configure vital components such that gaining access to these items is extremely difficult and time consuming to an intruder,
  - Locate and configure the critical safety systems such that there is not the capability to destroy a target set from a single location,
  - Incorporate multiple layers of intruder delay barriers into the design and minimize the number of access points to areas containing vital assets.
- Analysis of IAEA guidance "Design Measures to Facilitate Implementation of Safeguards at Future Water Cooled Nuclear Power Plants" TRS No. 392, as applicable to the SMR resulted in identifying numerous recommended guidelines that are not presently implemented at the nuclear power plants.[4]

SMR Design Considerations for Security[5]

The design of reactor fuels, safety systems, and physical configurations will have a significant impact on the physical protection against theft and sabotage. For instance:

- An underground or a shallow buried hardened structure may provide excellent protection against large explosive and aircraft impact.
- Simplified active and passive safety system design results in limited number of vital areas.
- Passive safety features can increase delay times, when analyzing effects on nuclear systems from sabotage events.
- Smaller fission product inventory implies smaller radiological releases.

[4] IAEA Guideline, Design Measures to Facilitate Implementation of Safeguards at Future Water Cooled Nuclear Power Plants, IAEA Technical Reports Series No. 392.

[5] P. Pan, M. Mullen & S. DeMuth, Preliminary Analysis of Safeguards & Security by design for Small Modular Reactors, Los Alamos National Laboratory, LA-UR-11-05030, September 2013.

- Long refueling period results in less frequent opening of reactor core, hence, less opportunity for sabotage and material diversion events.
- Replacing the entire reactor core and pressure vessel with a factory manufactured integral unit minimizes onsite handling of core fuels.

SMR Design Considerations for MC&A/Safeguards[6]

The physical type and fission content of the fuel will have a significant impact on the MC&A requirements. For instance:

- A well-established MC&A methodology for pebble-bed fuel, which is being considered for certain advanced SMR designs, does not currently exist. Consequently, pebble fuel will likely require greater safeguards design effort upfront than conventional ceramic pellets.
- The frequency of reloading fuel, the amount and time duration during storage of fresh fuel prior to reloading, its fissionable content and fissionable species will all impact MC&A requirements.
    - The frequency of loading will impact how often fresh fuel will be present on-site.
    - The amount of fresh fuel required for reload and its fissionable content will affect how much SNM material is at risk.
    - The length of time fresh fuel is stored will determine how long the fissionable material is at risk.
- High burn-up fuel, while desirable for economic reasons, will produce higher Pu content in the used fuel. This higher Pu content may make the used fuel more attractive for theft. On the other hand, higher burn-up implies a greater concentration of fission products which can make the fuel less attractive for theft.
- Some SMR designs (Hyperion is one example) do not need onsite re-fueling. Instead, the entire core is removed at the end of fuel life, which may significantly reduce the MC&A requirements.

In general, for use and storage of all Categories I, II, and III nuclear materials, designers should consider, for example, the following safeguards concepts.

- Construct the barrier wall to be unbreachable without detection.
- Limit penetration size to less than the fuel assembly dimensions.
- Provide adequate and reliable illumination for containment and surveillance (C/S) and non-destructive assay (NDA).
- Allow space for installation of C/S equipment for un-obstructed line-of-sight viewing.
- Use non-intrusive and remote measures to minimize personnel exposure and collect information at difficult access areas.
- Ensure adequate storage capacity to provide unblocked viewing and inspection of nuclear materials.
- Use sealing systems for secure containment during periods of inactivity.

In addition to the previous recommendations, for use and storage of Categories I nuclear material, designers should also consider, for example, the following.

[6] P. Pan, B. Boyer and C. Scherer, Safeguards by Design (SBD): Safeguards Guidance for GEN III/III+ Light Water Reactors, LA-UR-10-05336, Los Alamos National Laboratory, August 2010.

- Design the layout of the fresh fuel storage area to allow inspectors to verify and progressively seal groups of fuel assemblies as they are put into storage without affecting the Continuity of Knowledge (CoK) of the fuel already in inventory.
- Provide an indexing mechanism on the refueling machine with a device which can identify the location of each assembly.
- Design a sealing system for the nuclear material contained in the reactor core. Such a system should be accessible for inspection, easy to install and protected against damage.
- Provide capabilities that facilitate the annual physical inventory verification that consists of counting the total number of spent fuel items and verifying spent fuel attributes by NDA.

BILATERAL PATH FORWAD

The substance of this paper is not intended to describe a common U.S./Russian approach for SMR SSBD, but rather through this paper identify work to date that will form the basis of this common approach for the future collaboration. An aspect of this common approach is an appreciation for specific design features that can increase proliferation resistance and physical security for SMRs. Consequently, described here in this paper are the relevant U.S. and Russian domestic regulatory requirements, and international (e.g. IAEA) requirements and guidance, as well as example design features that can enhance proliferation resistance and physical security. As a follow-up to efforts leading to this paper, is the following set of recommendations for future U.S. and Russian bilateral efforts related to SMR SSBD.

1) Select a common U.S./Russian generic SMR design to use as the model for further SSBD development.
2) Identify for the generic SMR concept, component and facility intrinsic design features, and MC&A/safeguards and security extrinsic design features, that can enhance proliferation resistance and physical security.
3) Develop a U.S./Russian common approach for SSBD consistent with their domestic regulatory and IAEA requirements, that encourages the use of component and facility intrinsic design features, and MC&A/safeguards and security extrinsic design features, that can enhance proliferation resistance and physical security.