Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting
August 23-26 & August 30-September 1, 2021

CONSIDERATIONS FOR PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION OF SMALL MODULAR REACTORS

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ABSTRACT

Global interest in small modular reactors (SMRs) has been increasing due to their prospects to meet the needs of a wider range of users and applications. In addition to exhibit advanced design and safety features, SMRs also provide adaptability in terms of location of deployment since they may serve regions that are more difficult to support with other clean energy systems, like large nuclear power plants. These can be off-grid areas difficult to access, remote islands, or sparsely populated regions with small electric grids and limited infrastructure. This is the case of some nuclear embarking countries. Furthermore, SMRs have specific design characteristics, deployment schemes and associated fuel cycles that may have an impact on the proliferation resistance and physical protection (PR&PP). These deployment schemes with high degree of modularity have to be carefully examined due to the required higher enrichment and/or long refueling intervals in several designs. In general, marine-based SMRs and microreactors adopt long life reactor core with the purpose to achieve long refueling intervals that may also enhance proliferation resistance. Some designs adopt a containment system shared by multiple modules installed underground. These may enhance PR&PP yet complicate safeguards inspection. Hence, focus will be put on understanding the implication of such design features on PR&PP, with potential implementation of the safeguards-by-design (SBD) approach. The paper will also emphasize specific design features and characteristics that can have impact on PR & PP of SMRs.

INTRODUCTION

The assessment of inherent Proliferation Resistance and Physical Protection (PR&PP) characteristics of advanced nuclear power systems including SMRs with innovative designs has become essential to support their early deployments. Several new SMR designs require higher enrichments, and fuel forms significantly different from those manufactured for the current Light Water Reactors (LWRs). The LWR based designs, such as integral pressurized water reactors (PWRs) will be able to utilize fuel similar to that used in the current generation of LWRs, enriched to less than 5% uranium-235. However, many advanced non-LWR SMR designs require enrichments between 5% and 20%, called High Assay Low Enriched Uranium (HALEU) fuel. Manufacturing such fuels might require facilities with security requirements under Category II Special Nuclear Material (SNM), and the plant security requirements could be different for portions of the facility with Category II and III SNM which could create complexity in the plant modifications (Nuclear Energy Institute, 2018).

Proliferation resistance is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices. The degree of proliferation resistance results from a combination of, inter alia, technical design features, operational modalities, institutional arrangements and safeguards measures (International Atomic Energy Agency, 2002). It is important to understand that the technical design features aimed at improving the safety of SMRs might not lead to better proliferation resistance characteristics or support better physical protection. Not all design solutions improving safety and reliability will necessarily improve robustness against acts of sabotage, it might actually be the other way round; hence, any design solutions must balance the trade-off for the different objectives and goals as well as consider economical aspects (Generation IV International Forum, 2011). Physical protection incorporates various measures (including structural, technical and administrative protective measures) taken to prevent an adversary from achieving an undesirable consequence (such as radiological sabotage, or the unauthorized removal of nuclear or other radioactive material in use, storage or transport) and to mitigate or minimize the consequences if the adversary initiates such a malicious act. (International Atomic Energy Agency, 2012). Where many SMRs are currently designed to be factory fabricated and then transported to site, and in cases where it is transported with fuel, the transportation will also require added security measures. For deployment in remote locations and increased number of distributed units, the difficulty to access the site could provide some inherent physical protection measures, but, at the same time, could also pose challenge to IAEA safeguards to conduct any unannounced inspection. Remote monitoring could provide a plausible solution in such siting with an increased emphasis and measures for cybersecurity. Several of the design characteristics, common to many SMR designs, such as compact reactor coolant boundary, below grade installation, lower source term, minimized operator involvement etc. lead to enhanced SMR physical security (Nuclear Energy Institute, 2012). Considering security requirement early in the design stage of new reactors can result in nuclear security (for these facilities) that is more efficient, more effective and better integrated with other safety, safeguards, operational and other measures (International Atomic Energy Agency, 2019). Some of these design characteristics and features are discussed in the next section.

SMALL MODULAR REACTORS, THEIR DESIGN CHARACTERISTICS AND APPLICATIONS

A discussion on the design characteristics can help identifying advanced and innovative features of SMRs which enhance the safety compared to traditional large commercial reactors while preserving economic competitiveness in the energy market. A discussion on SMR applications can help figuring out their role as a flexible power and heat source and a wider range of users and applications.

Design Characteristics

Advanced designs consist of evolutionary designs and designs requiring substantial development efforts. The latter can range from moderate modifications of existing designs to entirely new design concepts. An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining design proveness to minimize technological risks. The development of an evolutionary design requires at most engineering and confirmatory testing. An innovative design is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and a prototype or demonstration plant are probably required (International Atomic Energy Agency, 1997). SMRs are advanced nuclear reactors designed to generate electric power typically up to 300 MWe, whose structures, systems and components can be fabricated in factories and deployed as demand arises. Modularization enables the economy of serial production, shorter construction duration and lower capital cost. The much smaller plant footprint and the application of advanced or novel technologies (in both design and manufacturing) can be considered as significant differences as compared to large Nuclear Power Plant (NPP). The majority of the SMR designs possess passive and/or inherent safety features and are deployable either as a single or multi-module plant. The nuclear industry considers SMRs a game changer for the decades to come. Near-term deployable SMRs will have safety performance comparable or even better to that of evolutionary reactor design.

a) Safety by design

Integral design

Integral design concept provides the basis of some light water-cooled SMR designs (e.g. ACP100, NUWARD, SMART, RITM-200 and NuScale). The term 'integral' refers to the reactor coolant system (RCS) or nuclear steam supply system (NSSS) by incorporating the steam generators (SG) and pressurizer into the reactor pressure vessel (RPV), where the majority of coolant exists, providing the reactor with a higher heat capacity. It is well known that the most serious threat to the safety of large LWRs is the primary coolant pipe rupture which leads to loss of coolant accident (LOCA). The design characteristics of integral design eliminates large coolant piping and connections in the primary circuit, which practically eliminates large break LOCA events. In short, the integral design signifies a conversion from the water injection strategy to reduction of loss of water strategy.

Passive Engineered Safety Design

By reducing the reliance on active safety systems and adopting safety systems using passive features (e.g. gravity, pressure differences, natural heat convection), SMRs on one side rely less on external power sources, and on the other side achieve a cost reduction by excluding unnecessary and dependent systems and equipment. The safety system of CAREM contains a passive residual heat removal system (PRHRS), consisting in parallel horizontal U-tubes coupled to common headers and functioning through natural circulation. In the design of HTR-PM, a reactor cavity cooling system (RCCS) is capable of removing the decay heat to heat sink under accident conditions. Similarly, in BREST-OD-300, a lead-cooled fast reactor, the emergency core cooling system (ECCS) is used to cool down the reactor by natural circulation while emergency heat removal is required. The passive safety features play a pivotal role in accident prevention and mitigation.

b) Modularisation

Modularisation is an advanced approach of construction in which structures, systems and components are prefabricated and transported to the site as modules. Modularisation reduces on-site activities during construction and aims for shortening construction time. Thus, modularisation can also be implemented as subdivision of a SMR power plant or heat-power hybrid plant into modules to form a multi-reactor module SMR power plant. SMR has greater opportunity to adopt modular build; up to 80% of on-site work can be moved to a factory for a fully modular SMR, compared with only 20% for a large reactor (Clara A. Lloyd, 2021). The smaller size of components give rise to the opportunity for modularisation and factory manufacturing.

c) Economic attractiveness

Firstly, SMR adopts design simplification and modularity to enable lower upfront capital cost for potential users, considering its small size, shorter construction time and site adaptability. Secondly, different from the economy of scales reflected in large commercial reactors, the economic attractiveness of SMR is embodied in the economy of serial production, defined as accentuating the advantage on economics after a certain production threshold and especially on the basis of standardization.

d) Resilience

The relatively small size of SMR favours its transportability (by trucks, ships, railways, airplanes), hence enabling enhanced mobility. With this feature, SMR can be quickly transported to destinations and deployed as emergency power sources, in conjunction with microgrids. This characteristic can be applied to strengthen the energy resilience of remote communities, mining areas, and military bases. The “black start-up,” referring to starting up from a thoroughly de-energised state without any external power, also adds to the resilience of some SMR designs.

e) Lower radionuclide inventory

The radionuclide inventory of SMR is much lower than large commercial reactors, due to small inventory of fuel, low fuel burnup thus lower source term. The lower radionuclide inventory contributes to potential opportunities for safety assessment of Defense-in-Depth (DiD) as applied to SMR. Together with the enhanced safety and siting features of SMR, smaller radionuclide inventory is a supporting factor for specific considerations to emergency preparedness and response (EPR), in particularly to potentially reduce the emergency planning zone (EPZ).

Applications

The demand for generating electricity and industrial process heat continues to grow exponentially, both in developed and developing economies. In particular, there are tangible needs for flexible power generation for a wide range of users and non-electric applications, replacing ageing fossil-fired units, enhancing safety performance and offering better economic affordability. Non-electric applications include but are not limited to seawater desalination, district heating, heat for industries and hydrogen production. The major contributing factors to a variety of applications of SMR are its flexibility and high output temperature.

a) Electric applications

In the context of the net zero challenge, SMR can play a pivotal role or even become the backbone of the energy system in achieving this global objective. Besides, many SMRs are envisioned for niche electricity or energy markets where large reactors would not be viable. It is also widely recognised as a partial solution to the phase-out of fossil fuel plants. Some SMR designs can operate either connected to the grid or independently, as they can continue operating in the case of loss of external power. This leads SMRs to be a resilient power source even in situations where grid connection is at risk by natural hazards. Some SMR designs are also able to operate in load-following mode. For example, CAP200 is capable of load following without boron dilution; load-following of SMART is said to be simpler than that of large PWR because only a single bank movement and small insertion is required to induce small reactivity change. The fact that SMR can meet various needs for end-users is attributed to its scalability and versatility, which will be discussed in the next sub-section by introducing multiple non-electric applications.

b) Non-electric applications

In the area of wider applicability, SMR designs (including sizes) are better suited than conventional large LWRs for partial or dedicated use in non-electrical applications such as providing heat for industrial processes, hydrogen production or seawater desalination. The required temperatures for SMRs are strongly related to the applications. In this way, different types of SMR with different output temperatures fit different applications. Industrial processes require a temperature range up to 600°C. For any processes requiring temperatures of up to 300°C, water-cooled SMRs can already meet this need. For other processes requiring temperatures of up to 450°C, fast neutron spectrum SMRs or Molten Salt Reactors (MSRs) are required. HTGR designs, with relatively high outlet temperatures of approximately 750°C, can extend the application of nuclear energy to process heat, water desalination, district heating, oil recovery, petroleum refinery, coal liquefaction and hydrogen production. A study regarding the cogeneration of SMR states that they can use cogeneration options to perform load-following, and SMR with a desalination capability is viable from both a technical and economic perspective (Giorgio Locatelli, 2014). Another study on district heating with SMRs shows that one NuScale SMR unit could fit to the Espoo district heating system with high utilization ratio and the estimated time to return on investment would be between 10 and 20 years, depending on assumed costs and prices (Tulkki, 2017).

PROLIFERATION RESISTANT FEATURES OF SMRS

The proliferation resistance of a design can be defined as “characteristic[s] of a Nuclear Energy System that [impede] the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices” (Generation IV International Forum, 2011). Many advances in reactor technology have proven to be useful in improving the proliferation resistance of reactors. These innovations include materials, operational parameters, and facility and are as varied as SMR designs.

The fuels used in many of these SMR designs include proliferation resistant features. Tristructural isotopic (TRISO) particle fuels are designed to be accident resistant to prevent release of radionuclides at high temperatures in gas-cooled reactors, which also makes the fuel particles difficult to breakdown for any kind of reprocessing and isotopic separation. Liquid fuels such as those used in some molten salt reactors require specialised equipment to transport and process, making covert diversion an unlikely pathway to material proliferation. Not only do these fuel forms provide barriers to proliferation but the fuel composition of spent fuel frequently has sufficient ratios of fission products to make reprocessing more intricate and costly (Shikha Prasad, 2015). Coolant fluids used in liquid metal and molten salt cooled reactors lends to further difficulties in diversion of fuel material as the fuel must be cleaned before being placed in cooling areas or transport casks. This additional step to clean fuel assemblies requires the use of specific equipment, further complicating a process which should be as simple as possible to avoid detection.

Operational characteristics of SMRs are another aspect which contributes to the proliferation resistance of each design. The fact that SMRs are, by definition, smaller than conventional reactors leads to a smaller inventory of potentially attractive material on-site. Even with a spent fuel pool, many SMR designs have long refuelling periods, ranging from four to 30 years, to improve operational costs associated with refuelling and outages which leads to less spent fuel inventory. These long refuelling periods mean that opportunities to place targets or divert fuel from the reactor are limited (Shikha Prasad, 2015). This also places limits on access to internal vessel components outside of scheduled maintenance, which would impact availability of other potential locations for irradiation targets, particularly for fast reactor and LWR designs.

While the size of SMR fuel may make covert transportation easier, it also means that more units are required to achieve certain amounts of material.

Some SMR designs use a cartridge core design. Cartridge cores are designed to be fabricated, tested and sealed in a factory and shipped to a plant location to then be connected to plant systems. Once sealed, these cores should have clear indication of any tampering or broken seals, and upon completion of core lifetime, are returned to the manufacturer for decommissioning and waste disposal. While diversion of an entire core is possible, it would be quickly detected, as would the potential diversion of small amounts of fuel or target placement within the core.

PHYSICAL PROTECTION FEATURES OF SMRS

The physical protection of SMR nuclear power plants stands mostly on technical features and sufficient and effective onsite responses to a potential threat. Those two aspects should be considered at the initial conceptual design phase.

Many physical protection features of SMRs are inherently included in their design as safety or security improvement systems or characteristics. Those features are also meant to deter and delay adversarial actions. The first feature common to many SMR design is the compactness and integration of the primary coolant boundaries within the RPV. Other common features are the increased passive physical barriers and the simplification of the systems required for safe shutdown. According to the designs, it includes such features such as RPVs and containments vessels entirely immersed in water or below grade, reactor buildings partially or completely below grade, fewer required safe shutdown systems, fewer components requiring physical protection.

The below grade construction approach is adopted in some SMR designs which will provide several security benefits, such as limiting access to vital areas, limiting the communications abilities and limiting aircraft impact hazard.

Another major physical protection feature of SMR stands in the human operational factor. Due to their lower power densities, larger heat sinks and longer grace period for operator intervention under design basis accident, safe shutdown usually requires little or no immediate operator action. Thus, the likelihood of an attack targeted on the control room is greatly reduced, as well of the number of target elements to be incorporated in the site's protection program.

SMR designs include methods and features to guarantee an extended adversary delay time in the frame of a sufficient and effective onsite response to a threat. Those methods include:

- Location and configuration of vital components so as to make access extremely difficult and time consuming for an intruder,
- Impossibility to destroy a target from a single point due to their location and configuration,
- Multilayer of intruder delay barriers, minimization of access points to vital components
- Redundant detection systems
- Use of modularity in physical security systems to minimize impact on security staffing.

OVERVIEW OF PR&PP EVALUATION METHODOLOGIES

PR&PP evaluation methodologies, such as the "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems" (Generation IV International Forum, 2011)as well as IAEA's International Project Innovative Nuclear Reactors and Fuel Cycles (INPRO) "Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems – Physical Protection" (International Atomic Energy Agency, 2008) are two major international efforts in this area which can provide insights for the designers and developers of SMRs. The design concept characteristics of the six Generation IV nuclear energy systems (NESs) lead themselves to PR&PP characteristics. GIF proposed a methodology which organises evaluations to be performed at the earliest possible stages of systems design and to become more detailed and more representative as design progresses.

Evaluation Methodology for PR&PP of GEN IV NESs

PR&PP Methodology developed by the Proliferation Resistance and Physical Protection Evaluation Methodology Working Group (PRPPWG) provides a comprehensive framework and guidance for carrying out a system evaluation. The methodology defines a set of challenges, analyzes system response to these challenges and assesses outcomes. For a given system, analysts define a set of challenges, analysze system response to these challenges, and assess outcomes. The challenges to the NES are the threats posed by potential proliferant States and by sub-national adversaries. The technical and institutional characteristics of the Generation IV systems are used to evaluate the response of the system and determine its resistance to proliferation threats and robustness against sabotage and terrorism threats. The outcomes of the system response are expressed in terms of PR&PP measures and assessed. However, when undertaking a specific case study, difficulties arise from either the lack of specific information in the early stages of design or the proprietary nature of detailed information for mature designs (Generation IV International Forum, 2011). A major thrust of the PR&PP evaluation is to elucidate the interactions between the intrinsic (the physical and engineering aspects of the system) and the extrinsic (institutional aspects such as safeguards and external barriers) features, study their interplay, and then guide the path toward an optimized design.

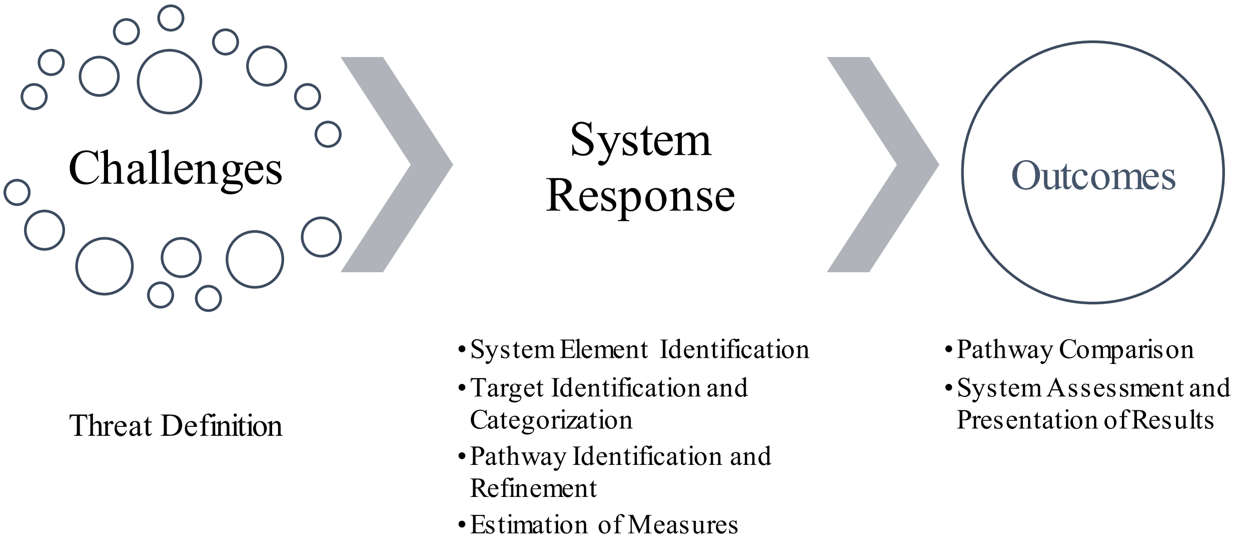

Figure 1 Framework for the PR&PP Evaluation Methodology *(Generation IV International Forum, 2011)*

The methodology is organized as a progressive approach to allow evaluations to become more detailed and more representative as system design progresses. An outline of the methodology is presented in *Figure 1*. The first step is threat definition, which describes the challenges that the system may face and includes characteristics of both the actor and the actor's strategy. In the earliest stages of conceptual design, where detailed information is likely limited, relatively stylized but reasonable threats must be selected. Conversely, when design has progressed to the point of actual construction, detailed and specific characterization of potential threats becomes possible. When threats have been sufficiently detailed for the particular evaluation, analysts assess system response, which has four components (1) System Element Identification, (2) Target Identification and Categorization, (3) Pathway Identification and Refinement, (4) Estimation of Measures. The final steps in PR&PP evaluations are to integrate the findings of the analysis and to interpret the results. Evaluation results should include best estimates for numerical and linguistic descriptors that characterize the results, distributions reflecting the uncertainty associated with those estimates, and appropriate displays to communicate uncertainties.

Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems (INPRO Manual – Proliferation Resistance and Physical Protection)

The IAEA published the manuals on Proliferation Resistance (vol 5) (International Atomic Energy Agency, 2008) and on Physical Protection (vol 6) (International Atomic Energy Agency, 2008) of the Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems (International Atomic Energy Agency, 2008), as an output of the of the INPRO's final report of Phase 1. The manual provides guidance to the assessor of an Innovative Nuclear Energy System (INS) in a country that is planning to install a nuclear power program (or maintaining or enlarging an existing one), describing how to apply the INPRO methodology in this specific area. The manual on Proliferation Resistance (vol 5) focuses on the subject of how to assess an INS embedded in an existing (or planned) non-proliferation regime. It primarily guides the INPRO assessor to confirm that adequate PR has been achieved in the INS, but gives also some guidance to the developer of nuclear technology on how to improve PR. Whereas the manual on Physical Protection (vol 6) provides guidance to the assessor of an INS under a physical protection regime in a country that is planning to install a nuclear power program. The manual is not intended to provide guidance on how to create a physical protection regime (PPR), rather it focuses on the subject of how to assess an INS embedded in an existing or planned regime. For proliferation resistance the guidance identifies five user requirements, which are the conditions that should be met to achieve Users' acceptance of a given INS. Users encompass a broad range of groups including investors, designers, plant operators, regulatory bodies, local organizations and authorities, national governments, NGOs and the media, and last, but not least, the end users of energy (e.g., the public, industry, etc). Several corresponding criteria are also listed for each user requirement to determine whether and how well a given User Requirement is being met. For physical protection there are eleven user requirements and several corresponding criteria.

SAFEGUARD BY DESIGN CONSIDERATIONS FOR SMRS

Many SMR designs already have a high degree of safeguardability. This primarily comes from the proliferation resistance characteristics and physical protection inherent to many of the designs. The overall scope of SBD is wide, and it is mainly an approach whereby early consideration of international safeguards is included in the design process of a nuclear facility, allowing informed design choices that are the optimum confluence of economic, operational, safety and security factors, in addition to international safeguards.

Designers can engage with regulators and the IAEA early in their design process to identify inherent features to increase safeguardability. With this information, they can further optimize their designs for safety, reliability, cost-effectiveness, and safeguardability. By enhancing the inherent safeguardability, designers can reduce the need of potential redesigning required by regulators to meet requirements.

SMR designs have built on many innovations in fuel forms and materials. Some of these pose unique challenges for material accounting, like the sealed cartridge core. While a sealed core makes the scenario of misuse of the core or diversion of fuel material more difficult, Continuity of Knowledge (CoK) is vital for material accounting within the facility. If the sealed vessel is designed with this in mind, remote monitoring and verification methods can be built into the vessel and reduce burden on later instrumentation and inspection requirements (J. Whitlock, 2012).

SBD is expected to be applied to all phases of design, including basic reactor and overall facility designs. While some designers are still in early conceptual phases, many have progressed to demonstration plant design and licensing. At this stage, a higher, facility-level view can be taken, and a facility safeguard approach designed. In some respects, this simplifies the potential approach, as many of the basic design choices have been made and will influence the necessary steps. The strategic planning of fuel handling paths can optimize material balance areas (MBA) and strategic points to improve material accounting, containment, and surveillance. This will further reduce unnecessary redesign or excess monitoring equipment.

Work has been ongoing to provide more understanding between regulators and designers, particularly in this age of nuclear innovation. Designers have emphasised a need for additional guidance in applying SBD methods, as the current guidance provides limited applicable details (Coles, 2013). Many frameworks and steps have been proposed, but a more comprehensive work that can provide functional design requirements for earlier stages in the design process has yet to be performed (Coles, 2013; F Sevini, 2011; T. Bjornard R. B., 2008; T. Bjornard R. B., 2010).

CONCLUSIONS

Many SMR designs from major lines of technology are under different stage for near term deployment. The variety of designs, their specific features and applications make it difficult to formulate a unified approach to evaluate the systems from proliferation resistance and physical protection viewpoint. The existing methodologies from GIF and IAEA-INPRO can provide some good references; however, a more concentrated effort is needed in this area to develop methodologies specific to SMRs. There are also associated difficulties encountered by designers with safeguard requirements and available resources recommend to further need to open cooperation opportunities between designers, regulators, operators and the international organizations like the IAEA.

REFERENCES

Clara A. Lloyd, T. R. (2021). Transport, constructability, and economic advantages of SMR modularization. *Progress in Nuclear Energy*, Volume 134.

Coles, G. A. (2013). *Trial Application of the Facility Safeguardability Assessment Process to the NuScale SMR Design.* Pacific Northwest National Laboratory.

F Sevini, G. R. (2011). A Safeguardability Check-List for Safeguards by Design. *Proceedings ESARDA 33rd Symposium* (pp. 482-489). Luxembourg: Publications Office of the European Union.

Generation IV International Forum. (2011). *Evaluation Methodology for Proliferation Resistance and Physical Protection of Gen IV Nuclear Energy Systems.* GIF/PRPPWG/2011/003.

Generation IV International Forum. (2011). *Proliferation Resistance and Physical Protection of the Six Generation IV Nuclear Energy Systems.* GIF/PRPPWG/2011/002.

Giorgio Locatelli, S. B. (2014). Load following with Small Modular Reactors (SMR): A real options analysis. *Energy*, 41-54.

International Atomic Energy Agency. (1997). *Terms for describing new, advanced nuclear power plants.* Vienna.

International Atomic Energy Agency. (2002). *Proliferation Resistance Fundamentals for Future Nuclear Energy Systems.* STR-332.

International Atomic Energy Agency. (2008). *Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Overview of the Methodology.* Vienna: Volume 1 of 9 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) .

International Atomic Energy Agency. (2008). *Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Physical Protection.* IAEA-TECDOC-1575 Rev. 1, Volume 6 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), Vienna.

International Atomic Energy Agency. (2008). *Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Proliferation Resistance.* Vienna: Volume 5 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

International Atomic Energy Agency. (2012). *Identification of Vital Areas at Nuclear Facilities.* Vienna: IAEA Nuclear Security Series No. 16.

International Atomic Energy Agency. (2019). *Security during the Lifetime of a Nuclear Facility.* IAEA Nuclear Security Series No. 35-G (SSG 35-G), Vienna.

J. Whitlock, J. S. (2012). Proliferation resistance considerations for remote small modular reactors. *AECL NUCLEAR REVIEW*, pp. 9-12.

LAZARD. (2018). *LAZARD's Levelized Cost of Energy Analysis — Version12.0.*

Mark R. Weimar, A. Z. (2020). *Techno-economic Assessment for Generation III+ Small Modular Reactor Deployments in the Pacific Northwest.* Richland: Pacific Northwest National Laboratory.

Nuclear Energy Institute. (2012). *Position paper on Physical Security for Small Modular Reactors.*

Nuclear Energy Institute. (2018). *Addressing the Challenges with Establishing the Infrastructure for the front-end of the Fuel Cycle for Advanced Reactors.* Washington D.C.: Nuclear Enerngy Institute.

Shikha Prasad, A. A. (2015). Nonproliferation improvements and challenges presented by small modular reactors. *Progress in Nuclear Energy*, 102-109.

T. Bjornard, R. B. (2008). *Achieving the Benefits of Safeguards by Design.* Idaho National Laboratory.

T. Bjornard, R. B. (2010). *Implementing Safeguards-by-Design.* Idaho National Laboratory.

Tulkki, V. P. (2017). *District heat with Small Modular Reactors (SMR).* VTT Technical Research Centre of Finland.