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Overview of Safeguards Challenges and Opportunities for Small Modular Reactor Technology

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Abstract – *Small Modular Reactor (SMR) technology is increasingly popular for its potential to provide clean, affordable, and dependable energy. However, implementing and adopting SMRs pose unique challenges and opportunities for nuclear safeguards. This paper provides an overview of these issues, including proliferation risk, safeguards implementation, resource constraints, novel technologies/designs, and adapting existing frameworks. SMRs' challenges include increased proliferation risk due to their concealability, complex designs, and the need to adapt existing safeguards frameworks to new reactor types. Resource constraints further exacerbate these challenges. Nevertheless, SMR technology offers opportunities for enhancing nuclear safeguards through intrinsic features such as the use of proliferation-resistant fuel cycles and self-contained fuel designs, standardizing designs, and remote monitoring technologies. International cooperation is crucial in addressing the challenges and harnessing the opportunities presented by SMR technology by sharing best practices, technology, and information. Innovation in safeguards technologies, such as advanced remote monitoring and data analytics, is necessary to address the unique challenges posed by SMRs. These technologies can overcome resource constraints, streamline safeguards implementation, and adapt existing frameworks to accommodate novel SMR designs. In conclusion, while SMR technology presents several challenges for nuclear safeguards, it also offers numerous opportunities for enhancing proliferation resistance, streamlining implementation, and fostering international cooperation. By leveraging these opportunities and addressing the challenges, the global community can ensure the safe and responsible deployment of SMRs as a key component of the future energy mix.*

Keywords: Small Modular Reactor (SMR), Nuclear Safeguards, Nuclear Non-Proliferation

I. Overview of SMR Technology

Small Modular Reactors (SMRs) are a specific classification within the broader nuclear power ecosystem, defined by their reduced scale and adaptable design. The term 'modular' in SMRs refers to their ability to be pre-fabricated at external facilities and subsequently transported to their ultimate installation site. This approach facilitates design standardization and mass production, which can potentially lead to substantial cost savings. SMRs typically produce less than 300 MWe (megawatt electrical), which is significantly less than traditional nuclear reactors that usually generate around 1000 MWe. The reduced output of SMRs grants them a level of adaptability, allowing for their utilization in areas with less grid capacity and lower electricity demand. SMR technology is primarily based on the widely understood light-water reactor (LWR) technology, but with significant improvements in the realms of safety, security, waste management, and operational efficiency **[1, 2]**. For instance, many SMRs incorporate passive safety systems that rely on natural physical phenomena, such as gravity and convection, rather than active mechanical systems, to ensure safety in abnormal conditions.

The concept of compact, portable reactors has its roots in the early era of nuclear energy. The initial nuclear reactors used for electricity generation were relatively small. For instance, the Shippingport Atomic Power Station, the inaugural commercial nuclear power plant in the USA, had a capacity of just 60 MWe when it began operations in 1957. However, the latter part of the 20th century saw a shift towards larger reactors, driven by economies of scale and the need for large-scale electricity production. The notion of small modular reactors started to regain traction in the early years of the 21st century, as the nuclear industry sought more flexible and cost-effective solutions. The International Atomic Energy Agency (IAEA) hosted its first technical meeting on SMRs in 2006, and in 2010, the US Department of Energy (DOE) launched an SMR program to expedite the development and deployment of SMR technology **[1-3]**. Over the next decade, an array of companies, including established nuclear power firms and start-ups, embarked on the development of various SMR designs.

As of 2023, several SMR designs have received licensing or are nearing the completion of the licensing process, and a few have been built and are operational. Below is a list of some of these SMR designs, see Figure 1. However, for more details of the global existing SMRs designs, please review reference **1** and **2.**

- NuScale Power Module (USA): NuScale's design became the first SMR to receive design certification from the US Nuclear Regulatory Commission (NRC) **[1-3]**. The NuScale Power Module is a 77 MWe pressurized water reactor (PWR). The first NuScale plant, consisting of 12 modules for a total capacity of 924 MWe, is projected to be operational at the Idaho National Laboratory site by the mid-2020s **[1-3]**.
- SMART (South Korea): The System-Integrated Modular Advanced Reactor (SMART) is a 100 MWe PWR designed by the Korea Atomic Energy Research Institute (KAERI). The primary application of this design is for desalination and district heating. The design received standard design approval from the Korean regulator in 2012 **[1, 2, 4]**.
- CAREM (Argentina): The Central Argentina de Elementos Modulares (CAREM) is a 25 MWe PWR currently under construction by Argentina's national atomic energy commission. The first unit is undergoing construction at the Atucha site in Argentina **[1, 2]**.
- HTR-PM (China): The High-Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) is a 210 MWe high-temperature gas-cooled reactor (HTGR). The first unit is under construction in Shidaowan, China, and is projected to be operational in the near future **[1, 2]**.

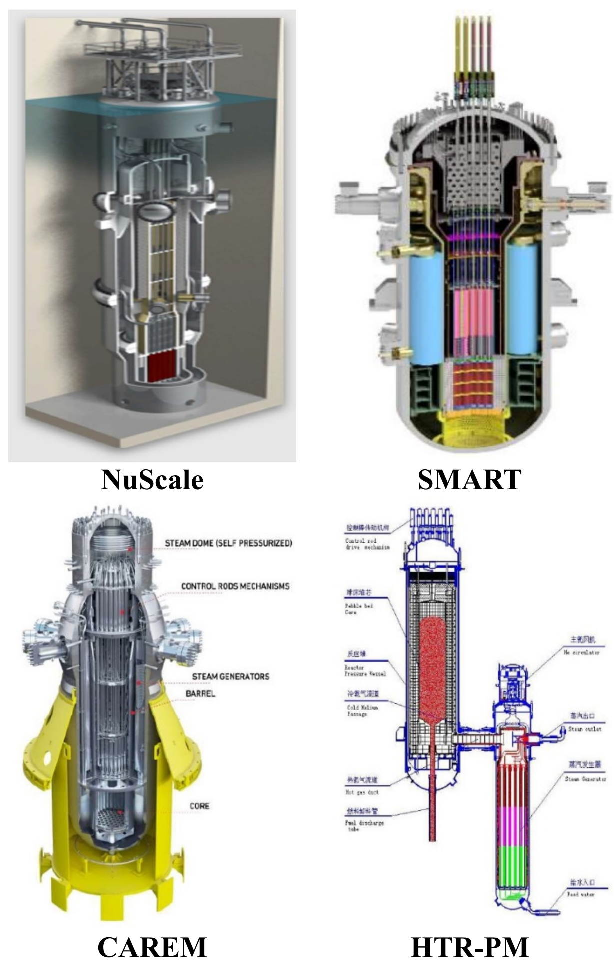

Fig. 1. Dimensional View for some of the SMR design ***[1-6]****.*

II. Advantages of SMR Technology

In recent times, the SMR technology has emerged at the forefront of nuclear energy development, gaining considerable interest from both the scientific community and industry. This progressive technology confers several unique advantages over conventional large-scale nuclear reactors, including enhanced scalability, advanced safety measures, and economic feasibility.

One of the most noteworthy characteristics of SMRs is their inherent scalability. By design, SMRs are engineered to yield less than 300 MWe, rendering them substantially smaller than traditional nuclear reactors, which typically generate around 1,000 MWe. This reduced scale bestows a level of adaptability and flexibility that is unattainable with larger reactors. SMRs can be deployed either as standalone units or in multiples, contingent upon the specific energy requirements of a region. This enables a more customized approach to energy production and can aid in averting overcapacity. Furthermore, the modular design of SMRs facilitates incremental capacity augmentation. As demand escalates, additional modules can be integrated as necessary, a significant advantage over larger reactors, which necessitate substantial upfront investment and protracted construction timelines **[6]**.

SMRs also incorporate a variety of sophisticated safety measures. Numerous SMRs leverage passive safety systems, which depend on natural physical phenomena, such as gravity and convection, instead of active mechanical systems, to maintain safety during abnormal conditions **[7]**. These passive safety systems can drastically reduce the risk of mishaps, rendering SMRs safer than traditional nuclear reactors. Additionally, the smaller scale of SMRs results in less nuclear waste production, and their compact design enables improved containment structures. Certain SMR designs even incorporate features resilient to severe natural disasters, such as earthquakes and tsunamis, further augmenting their safety profile **[7]**.

The economic feasibility of SMRs constitutes another key advantage. Given that they can be mass-manufactured in factories and subsequently transported to their installation site, SMRs offer potential cost savings via economies of scale **[6]**. This can render nuclear power more affordable and accessible, particularly in developing nations that lack the requisite resources to construct and operate large-scale nuclear facilities. Moreover, the shorter construction timelines associated with SMRs can also lead to cost savings. Traditional nuclear reactors can necessitate a decade or more for construction, during which time costs can escalate significantly. Conversely, SMRs can be constructed within a few years, mitigating the risk of cost overruns and facilitating more predictable budgeting.

III. Importance of Nuclear Safeguard for SMR Implementation

The deployment of advanced nuclear technologies, such as Small Modular Reactors (SMRs), brings with it not only the potential for flexible, efficient, and carbon-neutral power but also the solemn obligation of ensuring nuclear security and non-proliferation **[8, 9]**. The indispensability of nuclear safeguards in the context of SMR deployment is undeniable. These safeguards, which constitute a variety of both technical and institutional measures, are instrumental in ensuring that nuclear materials are not misappropriated for non-peaceful uses, thus playing a pivotal role in preserving global security and stability **[8, 9]**.

One of the foremost justifications for the critical role of nuclear safeguards in SMR deployment is the assurance of non-proliferation **[8]**. Due to the nature of nuclear technology, there exists an ever-present risk of nuclear materials being diverted for the fabrication of nuclear weaponry. This risk is not exclusive to large-scale nuclear reactors; it extends to SMRs as well **[9]**. Nuclear safeguards, inclusive of measures such as stringent control over nuclear material, rigorous inspections, and thorough reporting, are essential to thwart such diversion and misuse.

Public confidence in nuclear energy is heavily contingent on the effectiveness of nuclear safeguards. The recollection of nuclear disasters and the inherent risks associated with nuclear technology render public acceptance one of the primary challenges for the deployment of nuclear energy. Effective nuclear safeguards can provide reassurance to the public that nuclear technology, including SMRs, is being utilized safely and responsibly.

Nuclear safeguards also play a crucial role in fostering international collaboration. Many countries, particularly those devoid of nuclear weaponry, are willing to collaborate and share nuclear technology for peaceful purposes only if they are assured of the effectiveness of nuclear safeguards. In the context of SMRs, this could translate to more comprehensive cooperation in the development and deployment of this technology, thereby leading to accelerated progress and wider access to the benefits of SMRs **[8, 9]**.

Also, nuclear safeguards are crucial for regulatory adherence. Both international regulations, such as those set forth by the IAEA, and national laws necessitate stringent safeguards for any nuclear power initiative. These safeguards are even more significant in the context of SMRs, given their potential for deployment in a broader range of locations and environments.

IV. Safeguards Challenges and Opportunities for SMR Technology

SMRs epitomize a significant progression in nuclear power generation, distinguished by their compact dimensions and modular construction. Nevertheless, these unique attributes of SMRs present several challenges and opportunities pertaining to the implementation of nuclear safeguards, the systems designed to prevent the misappropriation of nuclear technology and materials **[8]**.

This article seeks to emphasize and integrate the recurrent challenges and prospects related to safeguards, subjects that have been rigorously examined within the nuclear scientific community. Furthermore, it aims to shed light on the process of converting these challenges into advantageous opportunities, thereby enhancing the safeguarding mechanisms of SMR technology.

Table 1 present a list of safeguards challenges and opportunities for SMR technology. The listed safeguards challenges involves increasing proliferation risk, safeguards implementation, emergent technologies and design, resources constraints, and adaption of existing safeguards frameworks **[8 - 10]**. The listed safeguards opportunities involves inherent proliferation resistance, remote monitoring and data analysis, innovation in safeguards technologies, economies of scale, and international cooperation **[8 - 10]**. The principal aim of Table 1, delineating the safeguards challenges and opportunities inherent to SMR technology, is to elucidate how each perceived challenge may, in fact, represent a potential opportunity for strengthening and bolstering the safeguards measures specifically tailored to SMR technology.

Table I. Safeguards Challenges and Opportunities for SMR Technology.

#	SMR Technology	
	Safeguards Challenges	**Safeguards Opportunities**
1	Increasing proliferation risk	Inherent proliferation resistance
2	Safeguards implementation	Remote monitoring and data analysis
3	Emergent technologies and designs	Innovation in safeguards technologies
4	Resource constraints	Economies of scale
5	Adaption of existing safeguards frameworks	International cooperation

<u>Increasing proliferation risk vs. Inherent proliferation resistance</u>

One of the foremost challenges associated with SMR technology is the augmented risk of nuclear proliferation. The relatively smaller scale and potential for ease of transportation render SMRs potentially appealing to non-state actors or nations harbouring clandestine ambitions to develop nuclear weaponry. Addressing this proliferation risk and ensuring that nuclear materials are not diverted for illicit endeavours is a substantial challenge that demands robust safeguard measures. In contrast, several designs of SMRs incorporate intrinsic features that enhance their resistance to proliferation threats. These features include sealed reactor cores, extended fuel cycles, and the employment of low-enriched uranium. Such design attributes could potentially mitigate the overall risk of nuclear material diversion, thereby augmenting the proliferation resistance of SMRs. Consequently, it is of paramount importance for the nuclear community, particularly nuclear regulatory entities, to amalgamate their efforts to establish robust and appropriate standards that bolster nuclear proliferation resistance for SMR technology at this nascent stage of licensing and construction.

Safeguards implementation vs. Remote monitoring and data analysis

The unique architectural design of SMRs presents another challenge. SMRs commonly feature compact, integrated designs that diverge significantly from conventional large-scale reactors. These design characteristics can complicate the monitoring and verification processes integral to the implementation of nuclear safeguards, necessitating the development of innovative strategies and techniques. However, the unique attributes of SMRs may provide enhanced opportunities for remote monitoring and data analysis. Advanced technologies and data analytics could be leveraged to monitor the operations of SMRs, verify compliance with safeguards, and detect any anomalous activities. This could help to alleviate the burden on safeguard inspectors, augment the overall effectiveness of safeguards implementation, and enhance the ability to detect any potential misuse of nuclear technology or materials.

Emergent technologies and designs vs. Innovation in safeguards technologies

SMRs frequently incorporate emergent technologies and designs absent in traditional nuclear reactors. The unfamiliarity with these novel elements could create gaps in the efficacy of existing safeguard approaches. This necessitates continuous research and development endeavours to thoroughly comprehend these new technologies and develop appropriate safeguard measures. In contrast, the unique challenges posed by SMRs could spur innovation in safeguards technologies and methodologies. The need to monitor and verify the operations of SMRs effectively could drive the development of new technologies and methods for safeguards implementation. This could lead to more effective and efficient safeguards, enhancing the ability to ensure the peaceful use of nuclear technology.

Resource constraints vs. Economies of scale

The potential for widespread deployment of SMRs could lead to an increased number of facilities necessitating safeguard inspections. This uptick could place considerable strain on the resources of regulatory bodies such as the IAEA. Meeting this demand without compromising the effectiveness of inspections poses a substantial challenge, requiring an increase in funding, personnel, and equipment. In contrast, the modular architecture of SMRs potentially facilitates the deployment and maintenance of standardized safeguard measures across multiple facilities. This could engender economies of scale, rendering the implementation of safeguards more efficient and effective, and potentially reducing the overall cost of safeguards implementation.

Adaption of existing safeguards frameworks vs. International cooperation

Current nuclear safeguard frameworks are primarily customized to large-scale nuclear facilities. Adapting these frameworks to accommodate the unique characteristics and needs of SMRs could require significant modifications to existing methodologies. This adaptation is a complex undertaking that requires meticulous consideration to ensure the efficacy of safeguards without hindering the operational efficiency of SMRs. Therefore, the development and deployment of SMRs present a unique opportunity for increased international cooperation on safeguards issues. As nations grapple with the challenges posed by these new reactor designs, there is an opportunity to collaborate to develop effective safeguards approaches, share best practices, and coordinate efforts. This cooperation could lead to more robust and effective safeguards systems, enhancing global nuclear security.

V. Conclusions

Small Modular Reactors (SMRs) represent an innovative stride in the realm of nuclear power, offering a host of advantages including enhanced scalability, improved safety measures, and economic feasibility. However, like all nuclear technologies, they present both challenges and opportunities in terms of nuclear safeguards. The nascent stage of SMR technology development and deployment provides an opportune moment to confront these challenges head-on and leverage the opportunities presented.

Proliferation risks, complexities in safeguards implementation, emergent technologies and designs, resource constraints, and the need for adaptation of existing safeguards frameworks are significant challenges that need to be addressed meticulously. However, each of these challenges presents a potential opportunity for strengthening and bolstering safeguards measures. Inherent proliferation resistance, the potential for remote monitoring and data analysis, innovation in safeguards technologies, economies of scale, and the chance for increased international cooperation are all promising avenues that can be used to fortify the nuclear safeguards system in the context of SMRs.

As the nuclear community, particularly regulatory entities, continue to navigate these challenges and opportunities, it is crucial to establish robust and appropriate standards that bolster nuclear proliferation resistance. This is of paramount importance to ensure the safe, secure, and peaceful use of SMR technology. The journey of SMR technology is just beginning, and it holds the promise of not only transforming the nuclear power landscape but also enhancing the effectiveness of nuclear safeguards to match these developments.

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