An overview of safeguard challenges and opportunities for small modular reactors

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**Abstract**

Small Modular Reactor (SMR) technology is gaining momentum for its ability to provide reliable, eco-friendly, and cost-efficient energy solutions. However, its adoption presents distinct challenges and opportunities at the intersection of technological innovation and regulatory considerations. This review explores key aspects, such as the nuanced discussion of proliferation risk, challenges in safeguards implementation, resource constraints, exploration of novel technologies and designs, and the necessary adaptation of existing frameworks. SMRs pose challenges due to their inherent characteristics, including potential concealability and intricate designs. The need to tailor existing safeguards frameworks to accommodate these features adds complexity, exacerbated by resource constraints hindering effective implementation. Despite these challenges, SMR technology offers opportunities to enhance nuclear safeguards. Proliferation-resistant fuel cycles, self-contained fuel designs, standardized reactor designs, and remote monitoring technologies are avenues to fortify safeguards. International cooperation is crucial in navigating SMR challenges and maximizing benefits. Sharing best practices, collaborative technological advancements, and exchanging critical information are essential for a cohesive global approach. Advanced remote monitoring and data analytics become indispensable in this new era of safeguards technology, overcoming resource constraints and facilitating the adaptation of frameworks to novel SMR designs. In conclusion, while SMR technology introduces challenges, it also presents avenues for substantial progress. Emphasizing opportunities to enhance proliferation resistance, streamline implementation, and foster international collaboration is vital. The global community's concerted efforts are essential for the secure and responsible deployment of SMRs within the evolving future energy mix, striking a strategic balance between technological advancements and rigorous safeguards measures.

## INTRODUCTION

Small Modular Reactors (SMRs) are an innovative category of nuclear reactors designed with a smaller scale and greater flexibility compared to traditional nuclear reactors. SMRs are defined by their reduced size, typically producing less than 300 MWe (megawatt electrical), in contrast to the approximately 1000 MWe generated by conventional reactors [1]. This compact size allows SMRs to be more adaptable, catering to regions with limited grid capacity and lower electricity demand. The term 'modular' refers to SMRs' ability to be pre-fabricated in external manufacturing facilities and then transported to the installation site. This approach enables significant design standardization and mass production, which can lead to substantial cost savings. Pre-fabrication also reduces construction time and complexity, as well as onsite labor requirements, further contributing to economic efficiency. Additionally, the modular nature allows for incremental capacity expansion by adding more modules as demand grows, providing a scalable solution to power generation. SMR technology primarily builds on the well-established light-water reactor (LWR) technology, incorporating significant advancements in safety, security, waste management, and operational efficiency. One of the key features of many SMRs is the inclusion of passive safety systems [2]. Unlike traditional active mechanical systems, passive safety systems rely on natural physical phenomena such as gravity and convection to maintain safety during abnormal conditions, reducing the risk of human error and mechanical failure. The idea of compact, portable reactors is not new. The earliest nuclear reactors used for electricity generation were relatively small. For instance, the Shippingport Atomic Power Station, the first 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 toward larger reactors, driven by economies of scale and the need for large-scale electricity production. This trend continued until the early 21st century, when the nuclear industry began to revisit the concept of smaller reactors as a means to achieve greater flexibility and cost-effectiveness.

Interest in SMRs resurfaced in the early 21st century. The International Atomic Energy Agency (IAEA) held its first technical meeting on SMRs in 2006, marking a significant step towards recognizing their potential. In 2010, the US Department of Energy (DOE) launched an SMR program aimed at accelerating the development and deployment of SMR technology. Over the following decade, a diverse array of companies, from established nuclear power firms to innovative start-ups, embarked on developing various SMR designs, each offering unique features and advantages. As of 2023, several SMR designs have received licensing or are nearing the completion of the licensing process, with a few already operational. Here are some notable designs:

**NuScale Power Module (USA):** NuScale's design became the first SMR to receive design certification from the US Nuclear Regulatory Commission (NRC). 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, was projected to be operational at the Idaho National Laboratory site by the mid-2020s [3, 4]. The project was then cancelled in July 2023 due to escalating costs and a lack of firm commitments from utilities to purchase the power generated by the plant [5].

**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 [3, 4, 6].

**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 [3, 4].

**HTR-PM (China):** The High-Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) is a 210 MWe high-temperature gas-cooled reactor (HTGR) located in Shidaowan, China. The first unit of the HTR-PM achieved grid connection in December 2021 and has since entered commercial operation in 2022. The project represents a significant milestone in the development of next-generation nuclear reactors and is fully operational [4, 7].

SMRs hold the potential to revolutionize the nuclear power industry by providing a versatile and cost-effective alternative to traditional large-scale reactors. Their adaptability makes them particularly suited for use in remote areas, island nations, and developing countries with emerging electricity needs. As the world moves towards cleaner energy sources to combat climate change, SMRs could play a crucial role in the global energy transition by offering a reliable and low-carbon energy solution. The future of SMRs looks promising, with continued advancements in technology and growing interest from governments and private companies worldwide. As more designs receive regulatory approval and move towards commercial operation, SMRs are likely to become an integral part of the global energy landscape, contributing to a more sustainable and resilient energy future.

## Advantages of SMR Technology

Recently, SMR technology has gained significant attention in the nuclear energy sector, attracting interest from both the scientific community and industry. This innovative technology offers several advantages over conventional large-scale nuclear reactors, including enhanced scalability, advanced safety measures, and economic feasibility. One of the most notable features of SMRs is their inherent scalability. Designed to produce less than 300 MWe, SMRs are considerably smaller than traditional nuclear reactors, which typically generate around 1,000 MWe. This smaller size provides a level of adaptability and flexibility that larger reactors cannot achieve. SMRs can be deployed as standalone units or in multiples, depending on a region's specific energy needs. This allows for a more tailored approach to energy production and helps prevent overcapacity. Additionally, the modular design of SMRs enables incremental capacity expansion. As demand increases, additional modules can be added as needed, unlike larger reactors, which require significant upfront investment and lengthy construction periods. SMRs also feature advanced safety measures. Many SMRs utilize passive safety systems, which rely on natural physical phenomena such as gravity and convection rather than active mechanical systems to maintain safety during abnormal conditions. These passive safety systems significantly reduce the risk of accidents, making SMRs safer than traditional nuclear reactors. Furthermore, the smaller size of SMRs results in less nuclear waste production, and their compact design allows for improved containment structures. Some SMR designs even include features that can withstand severe natural disasters, such as earthquakes and tsunamis, enhancing their overall safety profile. Another key advantage of SMRs is their economic feasibility. Mass-manufactured in factories and then transported to their installation site, SMRs offer potential cost savings through economies of scale. This can make nuclear power more affordable and accessible, especially in developing countries that lack the resources to build and operate large-scale nuclear facilities. Additionally, the shorter construction timelines associated with SMRs can lead to further cost savings. Traditional nuclear reactors can take a decade or more to construct, during which costs can rise significantly. In contrast, SMRs can be built within a few years, reducing the risk of cost overruns and allowing for more predictable budgeting.

## Significance of Nuclear Safeguards in SMR Deployment

Deploying advanced nuclear technologies like Small Modular Reactors (SMRs) offers the promise of flexible, efficient, and carbon-neutral power. However, it also necessitates a strong commitment to nuclear security and non-proliferation [4, 8]. The essential role of nuclear safeguards in SMR deployment cannot be overstated. These safeguards, encompassing a range of technical and institutional measures, are critical in ensuring that nuclear materials are not diverted for non-peaceful purposes, thereby maintaining global security and stability. A primary reason for the crucial role of nuclear safeguards in SMR deployment is the assurance of non-proliferation. Given the nature of nuclear technology, there is a constant risk of nuclear materials being misappropriated to create nuclear weapons. This risk is not limited to large-scale reactors but also applies to SMRs. Effective nuclear safeguards, including stringent control over nuclear materials, rigorous inspections, and comprehensive reporting, are vital to prevent such diversion and misuse. Public confidence in nuclear energy heavily depends on the effectiveness of nuclear safeguards. Memories of nuclear disasters and the inherent risks associated with nuclear technology make public acceptance a significant challenge. Robust nuclear safeguards can reassure the public that nuclear technology, including SMRs, is being used safely and responsibly.

Nuclear safeguards also play a pivotal role in fostering international cooperation. Many countries, especially those without nuclear weapons, are willing to collaborate and share nuclear technology for peaceful purposes only if they are confident in the effectiveness of nuclear safeguards. In the context of SMRs, this could lead to broader cooperation in the development and deployment of the technology, accelerating progress and increasing access to the benefits of SMRs. Furthermore, nuclear safeguards are crucial for regulatory compliance. Both international regulations, such as those established by the International Atomic Energy Agency (IAEA), and national laws require stringent safeguards for any nuclear power initiative. These safeguards are particularly important for SMRs, given their potential for deployment in a wide variety of locations and environments.

## Safeguards Challenges and Opportunities for SMR Technology

Small Modular Reactors (SMRs) represent a significant advancement in nuclear power generation, characterized by their compact size and modular design. However, these distinctive features also present unique challenges and opportunities related to the implementation of nuclear safeguards—systems designed to prevent the misuse of nuclear technology and materials [8]. This section focuses on highlighting and integrating the recurring challenges and prospects associated with safeguards, topics that have been extensively studied within the nuclear scientific community. Additionally, it aims to explore how these challenges can be transformed into opportunities to enhance the safeguarding mechanisms for SMR technology. Table 1 outlines the safeguards challenges and opportunities for SMR technology. The identified challenges include increased proliferation risk, difficulties in safeguards implementation, emerging technologies and designs, resource constraints, and the adaptation of existing safeguards frameworks. Conversely, the opportunities encompass inherent proliferation resistance, remote monitoring and data analysis, innovations in safeguards technologies, economies of scale, and international cooperation. The primary objective of Table 1, which details the safeguards challenges and opportunities associated with SMR technology, is to illustrate how each challenge could potentially be turned into an opportunity to strengthen and improve the safeguards measures specifically designed for SMR technology.

TABLE 1. Safeguards Challenges and Opportunities for SMR Technology

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| **#** | **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 |

### Proliferation Risk vs. Proliferation Resistance

A primary challenge with SMR technology is the increased risk of nuclear proliferation. The smaller size and ease of transport of SMRs can make them attractive targets for non-state actors or nations with secretive nuclear weapon ambitions. Tackling this proliferation risk and preventing the diversion of nuclear materials for illicit purposes is a significant challenge that necessitates stringent safeguard measures. Conversely, many SMR designs feature intrinsic characteristics that enhance their resistance to proliferation threats. These include sealed reactor cores, extended fuel cycles, and the use of low-enriched uranium. These design features can mitigate the risk of nuclear material diversion, thereby improving the proliferation resistance of SMRs. Hence, it is crucial for the nuclear community, particularly regulatory bodies, to collaborate on establishing robust standards that enhance proliferation resistance for SMR technology during its early stages of licensing and construction.

### Safeguards Implementation vs. Remote Monitoring and Data Analysis

The unique architecture of SMRs presents another challenge. SMRs often have compact, integrated designs that differ significantly from traditional large-scale reactors. These design aspects can complicate the monitoring and verification processes essential for implementing nuclear safeguards, requiring the development of innovative strategies and techniques. However, these unique SMR attributes may also provide opportunities for advanced remote monitoring and data analysis. Technologies and data analytics can be utilized to monitor SMR operations, verify compliance with safeguards, and detect any anomalies. This can reduce the burden on safeguard inspectors, improve the overall effectiveness of safeguards implementation, and enhance the detection of potential misuse of nuclear technology or materials.

### Emergent Technologies and Designs vs. Innovation in Safeguards Technologies

SMRs often incorporate new technologies and designs not found in traditional reactors. This unfamiliarity can create gaps in the effectiveness of existing safeguard approaches, necessitating ongoing research and development to understand these new technologies and develop appropriate safeguard measures. However, the challenges posed by SMRs can also drive innovation in safeguards technologies and methodologies. The need to effectively monitor and verify SMR operations can lead to the development of new technologies and methods for safeguards implementation, resulting in more effective and efficient safeguards that ensure the peaceful use of nuclear technology.

### Resource Constraints vs. Economies of Scale

The potential widespread deployment of SMRs could lead to an increased number of facilities requiring safeguard inspections, straining the resources of regulatory bodies like the IAEA. Addressing this demand without compromising inspection effectiveness requires additional funding, personnel, and equipment. On the other hand, the modular nature of SMRs allows for the deployment and maintenance of standardized safeguard measures across multiple facilities. This can create economies of scale, making the implementation of safeguards more efficient and potentially reducing the overall cost of safeguards.

### Adapting Existing Safeguards Frameworks vs. International Cooperation

Current nuclear safeguard frameworks are primarily tailored to large-scale facilities. Adapting these frameworks to suit the unique characteristics and needs of SMRs may require significant modifications to existing methodologies. This complex adaptation process demands careful consideration to maintain the efficacy of safeguards without hindering SMR operations. However, the development and deployment of SMRs present an opportunity for enhanced international cooperation on safeguards. As nations address the challenges of these new reactor designs, there is potential for collaboration in developing effective safeguards approaches, sharing best practices, and coordinating efforts. This cooperation can lead to stronger and more effective safeguards systems, enhancing global nuclear security.

## Conclusion

Small Modular Reactors (SMRs) represent a significant innovation in nuclear power, offering numerous benefits such as increased scalability, enhanced safety measures, and economic viability. However, like all nuclear technologies, SMRs come with both challenges and opportunities concerning nuclear safeguards. The current early stage of SMR development and deployment presents an ideal opportunity to address these challenges proactively and harness the opportunities available. Key challenges include proliferation risks, the complexities of implementing safeguards, new technologies and designs, resource limitations, and the need to adapt existing safeguards frameworks. However, these challenges also offer opportunities to strengthen and enhance safeguard measures. Features such as inherent proliferation resistance, capabilities for remote monitoring and data analysis, innovations in safeguards technologies, economies of scale, and increased international cooperation are promising avenues for bolstering the nuclear safeguards system in the context of SMRs. As the nuclear community, particularly regulatory bodies, continues to navigate these challenges and opportunities, it is crucial to establish robust and appropriate standards to enhance nuclear proliferation resistance. This is essential to ensure the safe, secure, and peaceful use of SMR technology. The development of SMR technology is just beginning, and it holds the potential not only to transform the nuclear power landscape but also to improve the effectiveness of nuclear safeguards in response to these advancements.

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