POLICY BRIEF NO. 86

Small Modular Reactors: Addressing security and safeguards challenges

ANDHIKA PRAWIRA

OCTOBER 2022

Please direct inquiries to:
Asia-Pacific Leadership Network
APLN Secretariat
4th floor, 116, Pirundae-ro
Jongno-gu, Seoul, ROK, 03035
Tel. +82-2-2135-2170
Fax. +82-70-4015-0708
Email. apln@apln.network

This publication can be downloaded at no cost at www.apln.network.

Cover Photo: Radiation protection areas within a nuclear facility which are properly indicated with caution signs (US Nuclear Regulatory Commission)

SMALL MODULAR REACTORS: ADDRESSING SECURITY AND SAFEGUARDS CHALLENGES

SUMMARY

The global development of Small Modular Reactors (SMR) has been increasing in activity. More than 20 countries are developing SMRs designed to fulfill the need for flexible power generation with a wide range of possible applications. SMRs offer several advantages compared to the large conventional nuclear power plant in operation today, including inherent safety features, the potential to decarbonise and reduce greenhouse gas emissions, lower upfront capital costs, better flexibility, and better economies of scale. However, there are real concerns about the potential security and proliferation risks posed by SMR technologies.

Security and safeguard challenges may arise based on the SMRs design, transportability, potential siting and deployment, and cost reduction measures. Security arrangements need to be made with these unique SMR characteristics in mind. Safeguards implementation is also expected to face specific challenges, as the existing safeguards approaches may not be suitable to reduce the proliferation risks inherent to SMRs. The potential security and safeguards challenges of SMRs need to be assessed accordingly. All relevant stakeholders should address the importance of incorporating security-by-design and safeguard-by-design at the earliest stage.

SMALL MODULAR REACTORS (SMRs) DEVELOPMENT

The "nuclear renaissance" movement seems to be gaining momentum with the current energy crisis and climate change concerns. After South Korean President Yoon Suk-Yeol announced plans to resurrect the nation's nuclear energy industry, South Korea is set to return to the nuclear power stage.[1] France is also set to revive its dormant nuclear industry, as President Emmanuel Macron has pledged to spend €52 billion on six next-generation European pressurised reactors.[2] The UK intends to boost its civilian nuclear energy deployment up to 24 gigawatts (GW) by 2050, including the development of small modular reactors (SMR).[3] SMRs and

[1] Ryall Julian, "South Korea Returns to Nuclear Power," DW Asia, 2022, https://www.dw.com/en/south-korea-returns-to-nuclear-power/a-62349112.

[2] Sarah White, "France Sets Course for a Nuclear Renaissance," Financial Times, 2022, https://www.ft.com/content/ce27b34a-b6d3-4bb3-840b-f4b1c8436641.

[3] UK Government, "UK National Statement to the IAEA 66th General Conference 2022," Speech, 2022, https://www.gov.uk/government/speeches/uk-

advanced reactors are at the forefront of modern nuclear technology development. However, SMR technology may pose several issues and considerations that developers, operators, regulators, interested countries, and the International Atomic Energy Agency (IAEA) need to address.

Small modular reactors are a new generation of nuclear reactors capable of generating electricity of up to 300 megawatts (MW) per module. Their components can be centrally fabricated and then deployed or transported as modules to sites.[4] The main push behind SMR development is the need to transition toward more cost-effective, reliable, and low-carbon electricity generation. There are more than 80 SMR designs with varying degrees of development and range of deployment.[5] Improving the safety of reactor designs is also a core driver of SMR development. However, the security and safeguards aspects have received comparatively less attention. SMR designers often assume that with less accessible nuclear materials and improved safety features compared to large nuclear power plants, the security burdens of SMR technology can be lessened. Thus in the context of safeguards, the responsibility of states and operators, proliferation risks, and the applicability of IAEA safeguards are overlooked in the SMR design process.

As there are many variations to SMR design, this paper identifies general security and safeguard issues that may arise. Several issues are technology-specific, such as the safeguard challenges of molten salt reactors[6] or very high-temperature reactors (VHTR).[7] As most SMR concepts are at the design stage, there are opportunities to emphasise the importance and applicability of the security-by-design (SeBD)[8] and safeguard-by-design (SBD)[9] concepts. Security-by-design is a concept in which security plays an integral role throughout the design process, allowing specific emphasis on security for each SMR concept.

national-statement-to-the-iaea-66th-general-conference-2022.

4 Hadid Subki, "Advances in Small Modular Reactor Technology Developments" (Vienna, 2020), https://aris.iaea.org/Publications/SMR_Book_2020.pdf.

5 IAEA, "Advanced Reactors Information System (ARIS)," 2022, https://aris.iaea.org/sites/SMR.html.

6 Karen Hogue et al., "Domestic Safeguards Material Control and Accountancy Considerations for Molten Salt Reactors". Oak Ridge National Lab (ORNL), Oak Ridge, TN (United States), 2021, https://info.ornl.gov/sites/publications/Files/Pub150852.pdf.

7 Lap-Yan Cheng et al., "White Papers on Proliferation Resistance and Physical Protection Characteristics of the Six GEN IV Nuclear Energy Systems". Brookhaven National Lab (BNL), Upton, NY, United States, 2021, https://www.osti.gov/servlets/purl/1818921.

8 Calvin Dell Jaeger et al., "Security-by-Design Handbook". Sandia National Lab (SNL-NM), Albuquerque, NM, United States, 2013, https://www.osti.gov/servlets/purl/1088049.

9 IAEA, "International Safeguards in Nuclear Facility Design and Construction, Nuclear Energy Series" (Vienna, 2013), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1600_web.pdf.

Safeguard-by-design is important in allowing effective and efficient implementation of safeguards, as safeguard requirements are taken into account as early as possible in the design process, both for vendor states and customer states.

DIFFERENT CHARACTERISTICS OF SMR DESIGN

The potential deployment of SMR design should meet safety, security, and safeguard goals to ensure these technologies' success. Safety, security, and safeguards (3S) considerations of SMRs should be assessed with a focus on the different aspects of reactor designs and the multiple modes of operations that SMRs promise. In the context of safety, most SMR designs are developed with the idea of improved safety through the increased use of innovative technology and inherent safety features.[10]

SMRs offer numerous benefits and advantages compared to the conventional nuclear power plant: transportability of the reactors, remote operations, and siting options, increased automation, power capacity and modularity, and potential reductions in capital and operating costs.

However, those benefits also carry potential security and safeguard concerns. SMRs also face evolving security requirements due to emerging trends and threats.

As SMRs have reduced size compared to large nuclear power plants, the reactor modules can be mass manufactured in a factory and then transported to be installed on-site. Modularity can improve efficiencies in construction as it lowers risks and reduces work on-site. The potential standardised manufacturing and construction methods can also benefit knowledge-sharing in future construction, minimising the risk of construction delays and cost overruns.[11] To reduce costs, reducing operating costs play an essential role. SMRs have a lower power output than large nuclear plants, thus revenues will be lower with the same capacity factor. Hence, one way to reduce operational costs is to reduce the staffing needed, including security personnel.

The proposed solution to reducing the number of personnel on-site is to increase the automation of SMRs to a much higher degree than compared to large nuclear power plants. Increased automation also acts as an enabler for the remote operation

[10] H. Hidayatullah, S. Susyadi, and M. Hadid Subki, "Design and Technology Development for Small Modular Reactors – Safety Expectations, Prospects, and Impediments of Their Deployment," *Progress in Nuclear Energy* 79 (March 1, 2015): 127–35, https://doi.org/10.1016/J.PNUCENE.2014.11.010.

[11] Clara A. Lloyd, Tony Roulstone, and Robbie E. Lyons, "Transport, Constructability, and Economic Advantages of SMR Modularization," *Progress in Nuclear Energy* 134 (April 1, 2021): 103672, https://doi.org/10.1016/J.PNUCENE.2021.103672.

of SMRs by off-site staff. The need to automate means SMRs will need improved digital instrumentation and control systems. This presents a significant change in nuclear power plant operations, allowing humans to enhance their monitoring roles, improve situational awareness, and reduce human error.[12] However, the potential issues of achieving high performance with high levels of automation without degrading human performance and possible cybersecurity requirements all need to be addressed. Increasing the reliance on automated digital systems also means potentially increasing the vulnerability to cyber threats.

Safety improvements in SMRs also come from the use of more advanced fuels. The fuels are designed with passive safety features, which means the reactor will remain safe even without external power, water cooling, and operator input. Lower material inventories for some reactor designs remove the need for refueling. There are different types of nuclear fuels being developed for various SMR designs.[13] These advanced fuels also raise safeguards concerns as they may present potential proliferation challenges.

One of the distinct features of SMR designs is the wide range of deployment, transportability, and potential siting options. Russia and China are developing marine-based SMRs where these miniaturised nuclear power plants will be placed on barges and then transported to sites. Korea is also interested in developing its own marine-based SMRs.[14] Other concepts envision mounting nuclear reactors onto trucks, creating mobile energy systems with much lower power output.[15] The transportability of SMRs offers potential advantages in supplying energy to areas in need, or for providing electricity to remote locations that land-based nuclear power plants cannot reach. Nevertheless, it is important to consider transportation safety, security, and safeguard aspects.

The smaller size of SMRs also offers possibilities to shrink power plant footprints, reducing the site boundary and,

[12] Jacques Hugo, "Human-System Interfaces in Small Modular Reactors (SMRs)," *Handbook of Small Modular Nuclear Reactors: Second Edition*, January 1, 2021, 147–85, https://doi.org/10.1016/B978-0-12-823916-2.00007-2.

[13] IAEA, "Advanced Reactors Information System (ARIS)."

[14] World Nuclear News, "Construction Starts on Russia's next Floating Nuclear Power Plant," 2022, https://www.world-nuclear-news.org/Articles/Construction-starts-on-Russia-s-next-floating-nucl; World Nuclear News, "Korean Collaboration to Research Marine SMR," Energy & Environment, 2021, https://world-nuclear-news.org/Articles/Korean-collaboration-to-research-marine-SMR.

[15] Reuters Events, "VSMRs' Success Hangs on Fuel Supply, Transportation Issues," 2022, https://www.reutersevents.com/nuclear/vsmrs-success-hangs-fuel-supply-transportation-issues.

possibly, the emergency planning zone.[16] This will allow SMRs to be deployed closer to urban areas or industrial complexes. Deploying SMRs close to urban areas or in remote areas under automated controls creates unique security, safeguards, and regulatory challenges. For example, current international safeguard measures may face problems when dealing with the transportability and accessibility of the SMR location, which could reduce the effectiveness of unannounced inspections and potentially increase costs.

POTENTIAL CHALLENGES

SMRs' unique characteristics create physical security implications that need to be addressed. The security approach currently applied to the large nuclear power plant may not be cost-efficient if applied to SMRs with a comparably smaller footprint. The modularity aspect of SMRs, which includes shipping fully-loaded reactors from a centralised production facility, means that these facilities must be appropriately secured. The transportation of reactor modules to sites will also require additional attention, as these nuclear materials will be highly attractive targets for potential threats.

Optimising the operating costs of SMRs without compromising safety, security, and safeguards is essential. The physical protection cost for a nuclear power plant accounts for 7 per cent of the total cost of power generation; it accounts for approximately 15-25 per cent of operational and maintenance costs, with half of that being labor costs.[17] Physical security forces account for nearly 20 per cent of the entire workforce. It is hard for SMRs to generate electricity economically if their security requirements are equivalent to those of large nuclear power plants. IAEA's nuclear security series can be utilised as a foundation for designing SMRs' physical security approaches.[18] However, this still needs to be strengthened with adequate local regulations. The improved safety of SMR reactor designs may help in providing time for detection, delay, and response aspects of physical security. Reducing personnel on-site could also bring potential advantages in terms of insider threat mitigation. The number of individuals who might be compromised is

[16] US NRC, "Emergency Planning Zone Sizing for Small Modular Reactors – Regulatory History & Policy Considerations," 2021, https://www.nrc.gov/docs/ML1817/ML18177A386.pdf.

[17] Pralhad H. Burli and Vaibhav Yadav, "Economic Analysis of Physical Security at Nuclear Power Plants," 2020, https://lwrs.inl.gov/Physical Security/Economic_Analysis_Physical_Security_NPP.pdf.

[18] IAEA, "Nuclear Security Series," 2022, https://www.iaea.org/publications/search/type/nuclear-security-series.

significantly reduced, allowing for better human reliability and trustworthiness.

Increasing automation and remote operations call for strengthened cybersecurity capabilities. Countries should be able to identify emerging threats and trends in their design basis to protect a site effectively. Best practices in digital instrumentation and control and cybersecurity design must be applied in these facilities to secure digital systems from current and future adversary's capabilities. Remote plant operations also add potential vulnerabilities to cyber-attacks. As a large amount of critical data will be exchanged from the sites to the control rooms, ensuring the security and integrity of communication between each site through dedicated hardwired connections, internet-based systems, or other means of communication is critical.

Safeguards implementation also faces several challenges due to the unique nature of SMR designs. Current international safeguards may not easily be implemented, thus SMRs could present potential nuclear proliferation risks. Some SMR designs offer improvements in the area of nonproliferation through a series of proliferation-resistant features.[19] The fuels used in many SMR designs include important proliferation-resistant features, for instance. The operational characteristics of SMRs could also contribute to proliferation resistance. SMRs have a smaller footprint, leading to a smaller inventory of potentially attractive materials on-site. Many SMR designs offer a potentially high degree of safeguardability. The development of the Proliferation Resistance and Safeguardability Assessment Tools (PROSA) methodology by the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is important in ensuring the safeguardability of each reactor design.[20]

SMRs will have unique safeguards issues especially related to novel designs, operation modes, and deployment.[21] Material handling is one of the potential concerns when safeguarding SMRs. The presence of on-load refueled reactors requires safeguards considerations as they will involve significant quantities of nuclear materials transported to a site. The potential uses of advanced nuclear fuel also

[19] Shikha Prasad et al., "Nonproliferation Improvements and Challenges Presented by Small Modular Reactors," *Progress in Nuclear Energy* 80 (April 1, 2015): 102–9, https://doi.org/10.1016/J.PNUCENE.2014.11.023.

[20] IAEA, "INPRO Collaborative Project: Proliferation Resistance and Safeguardability Assessment Tools (PROSA)" (Vienna, 2021), https://www.iaea.org/publications/14895/inpro-collaborative-project-proliferation-resistance-and-safeguardability-assessment-tools-prosa; Brian Boyer, "INPRO Activities on Proliferation Resistance," 2021.

[21] B Boyer, "Understanding the Specific Small Modular Reactor Safeguards Issues," in *INPRO Dialogue Forum on Legal and Institutional Issues in the Global Deployment of Small Modular Reactors*, 2016.

challenge nuclear material accountancy and control (NMAC). NMAC approaches are mainly designed for fixed fuels and do not consider other fuel forms such as liquid fuels or pebble beds with online refueling capabilities. Engagement among stakeholders is needed to ensure that international safeguards can be applied to facilities using advanced fuel materials.

SMR designs also challenge safeguards inspections related to a wider range of refueling intervals and varying refueling methods. They also pose new challenges for IAEA safeguards due to the differences in fuel types, coolant, and configurations. Current international safeguards and inspection practices are designed for 12-24 months intervals, shorter than the proposed SMRs refueling cycles which are designed to occur within a two- to ten-year range.[22] A longer refueling cycle will require different IAEA requirements, including changes in the technology used, inspection activities, inventory requirements, and reporting requirements to assure Continuity of Knowledge (CoK).

SMRs also can lower the barrier of entry for a country aspiring to utilise nuclear power. It could carry potential proliferation risks as a country interested in SMRs has varying governance capabilities, presenting new uncertainties for the global nuclear nonproliferation regime.[23] Stakeholders must establish an integrated assessment methodology to assess proliferation resistance and the physical protection aspects of SMRs to limit security and nonproliferation risks.

RECOMMENDATIONS

As there are many challenges related to the security and safeguards of SMRs, all relevant stakeholders should play their part in ensuring the safe and secure future deployment of these technologies. Companies or institutions interested in developing SMRs **should apply security-by-design (SeBD) and safeguard-by-design (SBD) methodologies as early as possible in the design process**. SeBD and SBD should play an integral role throughout the design process to ensure the delivery of effective security and safeguards in designs, minimise overlapping features, and minimise potential security and safeguards burdens. SMR designers and developers

[22] Subki, "Advances in Small Modular Reactor Technology Developments."
[23] Philseo Kim, Jihee Kim, and Man Sung Yim, "Assessing Proliferation Uncertainty in Civilian Nuclear Cooperation under New Power Dynamics of the International Nuclear Trade," *Energy Policy* 163 (April 1, 2022): 112852, https://doi.org/10.1016/J.ENPOL.2022.112852; Robert J. Budnitz, H. Holger Rogner, and Adnan Shihab-Eldin, "Expansion of Nuclear Power Technology to New Countries – SMRs, Safety Culture Issues, and the Need for an Improved International Safety Regime," *Energy Policy* 119 (August 1, 2018): 535–44, https://doi.org/10.1016/J.ENPOL.2018.04.051.

should also try to assess safety, security, and safeguards (3S) risk in a more integrated manner. For example, passive safety systems can bring potential advantages towards safety and give needed time for the detection and delay of nuclear security problems and to how nuclear material accountancy and control can simultaneously affect the security and safeguards of facilities.

Engagement among SMR designers, regulatory bodies, and the IAEA should start early in the design process. This is important to ensure process efficiency and effectiveness in optimising safety, reliability, cost-effectiveness, and safeguardability. As there is currently no formal international standard on the implementation of safeguard-by-design in the conceptual or design stages, early communication among the stakeholders will improve the efficiency and effectiveness of safeguards implementation, reducing the burden on operators. Designers can also avoid potential redesign challenges toward meeting regulatory requirements.

As SeBD and SBD should be applied in all design phases, regulators can play a big part in engaging with industry groups and research organisations. **Exploring new and revised approaches**, especially in handling new technological approaches to an SMR's design, is essential. The regulatory process of design assessment and licensing should be conducted in an effective and timely manner. Regulatory bodies should ensure that their regulatory requirements are optimised and tailored to SMR capabilities to avoid over-engineered or oversized security arrangements that may compromise the cost-effectiveness of SMRs. However, it is also important for the regulatory bodies to strike a balance between maintaining an adequate level of **reliability and conservatism** in the process.

The IAEA already has a broad range of support for its member states related to developing sustainable energy programs, including the development of SMRs. **The IAEA should continue to host a range of fora and events for SMR stakeholders.** The Technical Working Group on SMR (TWG-SMR), the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), and the Small Modular Reactor Regulators' Forum are some of the initiatives that convene experts from a multitude of disciplines to produce advice and technical guidance that may benefit developers, operators, and regulators.

All stakeholders should consider the security and safeguard challenges that SMRs pose. The wide variety of SMR designs, their specific features and applications, and their deployment and operation may need an innovative and integrated approach to evaluating safety, security, and safeguards risks. More concentrated effort and engagement among designers, regulators, operators, and the IAEA are necessary to **develop assessment methodologies for SMRs** that will help reduce costs while simultaneously ensuring the proliferation resistance and physical protection aspects of SMR designs

ABOUT THE AUTHOR

Andhika Yudha Prawira is a PhD candidate at the Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST) in South Korea. He is also a lecturer at the Department of Nuclear Engineering and Engineering Physics, Universitas Gadjah Mada, Indonesia. Andhika obtained his Bachelor of Engineering from the Universitas Gadjah Mada and Masters in Nuclear and Quantum Engineering from KAIST. His research interests include small modular reactors (SMRs) development, nuclear energy policy in Southeast Asia, nuclear security, and nuclear non-proliferation.

ABOUT APLN

The **Asia-Pacific Leadership Network for Nuclear Non-proliferation and Disarmament (APLN)** is a Seoul-based organisation and network of political, military, diplomatic leaders, and experts from across the Asia-Pacific region, working to address global security challenges, with a particular focus on reducing and eliminating nuclear weapons risks. The mission of APLN is to inform and stimulate debate, influence action, and propose policy recommendations designed to address regional security threats, with an emphasis on nuclear and other WMD (weapon of mass destruction) threats, and to do everything possible to achieve a world in which nuclear weapons and other WMDs are contained, diminished, and eventually eliminated.