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High-level Analysis of Radiological Protection Challenges Related to the Deployment of Small Modular Reactors

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Table of contents

Executive summary

The Nuclear Energy Agency (NEA) Committee on Radiological Protection and Public Health (CRPPH) Task Force on Small Modular Reactors (TFSMR) conducted a high-level analysis of radiological protection (RP) challenges related to small modular reactor (SMR) deployment. Ten key RP challenges were identified: Small Compact Design, Source Terms, Environmental Impact Assessments (EIA), Siting, Staffing Issues, Lack of Operating Experience (OPEX), Emergency Preparedness and Response (EPR), Transport, Public Risk Perception and Risk Communication, and Environmental Monitoring.

A prioritisation exercise assessed these challenges based on their potential impact on RP frameworks, regulatory compliance and public confidence. Lack of OPEX, Source Terms, and Public Risk Perception were identified as the most critical, given their influence on operational safety, emergency preparedness, and stakeholder engagement. Many challenges, including Lack of OPEX and Source Terms, were found to be cross-cutting, requiring multi-faceted approaches that consider safety, operational constraints, and public acceptance.

International initiatives addressing SMRs primarily focus on technical safety and licensing requirements, often without fully integrating RP considerations. While several international efforts examine emergency planning zones (EPZs), other key RP areas, including occupational exposure and environmental monitoring, require further attention. Strengthening collaboration with international SMR initiatives, like the Nuclear Energy Agency (NEA) Expert Group on SMRs (EGSMR), Focus Group on the Back-End of Advanced Reactors (FG-BEAR) and the International Atomic Energy Agency (IAEA) Regulators' Forum, can enhance RP-focused dialogue within global SMR deployment frameworks.

The TFSMR's analysis of RP challenges was conducted from three key perspectives: i) evaluating the necessity of graded approaches to RP based on the risk profiles of different SMR designs, ii) identifying gaps in existing RP regulations and guidance for new SMR technologies, deployment strategies, and operational models, iii) assessing the implications of RP challenges on worker protection, emergency response strategies, and public engagement, particularly for SMRs near population centres.

At the March 2024 CRPPH meeting, several key agreements were made to address these challenges. The creation of an expert group under the Working Party on Nuclear Emergency Matters (WPNEM) was approved to study graded approaches to EPR and protective strategies for SMRs [Expert Group on Emergency Preparedness for Small Modular Reactors (EGEPSMR)]. The CRPPH also endorsed continued monitoring of SMR-related RP challenges through workshops and engagement with international partners.

Future work should investigate and identify SMR design characteristics that are most impactful from an RP perspective across the SMR class.

List of abbreviations and acronyms

3S	Safety, security and safeguards
AHJ	Authority Having Jurisdiction
ALARA	As low as reasonably achievable
AMR	Advanced modular reactor
ANT	Advanced nuclear technology
AOO	Anticipated operational occurrence
BDBA	Beyond design basis accident
CDLM	Committee on Decommissioning of Nuclear Installations and Legacy Management (NEA)
CNRA	Committee of Nuclear Regulatory Activities (NEA)
CNSC	Canadian Nuclear Safety Commission
CORDEL WG	Cooperation in Reactor Design Evaluation and Licensing Working Group
CRP	Coordinated Research Project
CRPPH	Committee on Radiological Protection and Public Health (NEA)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DBA	Design basis accident
DiD	Defence-in-depth
EGEPSMR	Expert Group on Emergency Preparedness for Small Modular Reactors (NEA)
EGSMR	Expert Group on Small Modular Reactors (NEA)
EIA	Environmental impact assessments
EP	Emergency preparedness
EPR	Emergency preparedness and response
EPZ	Emergency planning zone
EU	European Union
FG-BEAR	Focus Group on the Back End of Advanced Reactors
FOAK	First-of-a-kind
HERCA	Head of European Radiological Protection Competent Authorities
HLG-SET	High-Level Group on Stakeholder Engagement, Trust, Transparency and Social Sciences (NEA)
HTO	Halden Human Technology Organisation
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection

IRPS	International Radiation Protection School
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (French Institute for Radiological Protection and Nuclear Safety [ASNR since January 2025])
ISOE	Information System on Occupational Exposure
LLWR	Large light water reactor
LR	Large reactor
LWR	Light water reactor
MEREIA	Methods for Radiological and Environmental Impact Assessment
NEA	Nuclear Energy Agency
NHSI	Nuclear Harmonization and Standardization Initiative
NTE	Division of Nuclear Technology Development and Economics (NEA)
ONR	Office for Nuclear Regulation
OPEX	Operating experience
PCA	Permanent Court of Arbitration
PH	Public health
PIANOFORTE	European Partnership for Radiation Protection Research
RP	Radiological protection
RIPB-DM	Risk-Informed and Performance-Based Decision-Making
RPV	Reactor pressure vessel
RWMC	Radioactive Waste Management Committee
RWMD	Division of Radioactive Waste Management and Decommissioning (NEA)
SMR	Small modular reactor
SMRAG	SMR Ad-hoc Group
SMRTF	SMR Task Force (under WNA)
SSC	Systems, structures and components
STEM	Science, technology, engineering and mathematics
TFSMR	Task Force on SMR (under CRPPH)
TNPP	Transportable nuclear power plants
TWG-SMR	Technical Working Group on Small and Medium-Sized or Modular Reactors (NEA)
WC	Water-cooled
WGHOF	Working Group on Human Factors (NEA)
WISARD	Waste Integration Small Advanced Reactor Designs
WNA	World Nuclear Association
WPNEM	Working Party on Nuclear Emergency Matters (NEA)

1. Introduction and background

Small modular reactors (SMRs) are innovative nuclear reactors that are gaining attention worldwide. These reactors are smaller than conventional large reactors (by measures of physical size and power output) and can meet diverse geographic and market needs. Energy security, environmental, and economic considerations are the main drivers behind their development and deployment in many countries.

SMRs can be categorised by coolant and moderator, including traditional light water reactors (Generation III) and Generation IV reactor concepts. SMR technologies also feature diverse fuel types, enrichment levels, output temperatures, and fuel cycles. The flexibility offered by this class of nuclear reactors, combined with modular design and advanced manufacturing processes, positions SMRs as a potential solution to meet the diverse needs of a broad range of end-users and applications.

To ensure these benefits can be realised swiftly, challenges related to radiological protection (RP), and also nuclear safety, security, and safeguards aspects must be characterised and addressed for a comprehensive and balanced cost-benefit analysis. This report, based on expert discussion, identifies ten aspects of potential RP challenges for SMRs. By raising awareness of RP challenges early in the process, design mitigation measures can be incorporated which can reduce contingent risks during development, licensing, operation and decommissioning.

Identifying potential RP challenges is also a crucial step in determining the regulatory justification for introducing new radiological management practices or technologies, such as SMRs. This ensures that radiation exposure to workers, the public and the environment will comply with regulatory requirements.

1.1. Creation of task force

In March 2022, during a topical session of the 80th annual meeting of the Committee on Radiological Protection and Public Health (CRPPH), the CRPPH discussed anticipated RP challenges associated with the deployment of SMRs in Nuclear Energy Agency (NEA) member countries. The diversity of SMR designs and the potential for innovation in the design, regulation and operation of these facilities provide an opportunity to re-examine the approach to RP. On this basis, the CRPPH decided to establish the Task Force on SMRs (hereinafter "TFSMR") to assess and report on whether there are areas of added value for CRPPH-led work with regards to RP aspects of SMRs.

1.2. Purpose and scope

As a main outcome of the dedicated topical session held at the 80th annual meeting of CRPPH, the committee recommended the development of a preliminary reflection on the following topics:

- The current approach of emergency preparedness and response (EPR) with an analysis of whether it supports a changing risk profile or whether a new approach would be better suited, i.e. do the traditional views around emergency planning zones (EPZ) still apply?
- The concept of RP by design and how to apply it for the many types of SMRs (e.g. the nature of compact designs that may result in higher neutron fluxes to key

components and possibly less core shielding; and consequent complications for RP, notably for inspection, maintenance, decommissioning; possibly other source term and therefore dose-rate contributions for occupational and environmental exposures, depending on factors including fuel and coolant).

- The topical areas where more robust science-based demonstration of protection of workers, the public and the environment in the three types of exposure situations (planned, emergency, existing) is needed, according to the strategy and scale of deployment of such new technologies, including the issue of siting.

The CRPPH tasked the TFSMR to provide a high-level analysis report on the RP challenges related to safety, licensing and any operational issues (e.g. maintenance, decommissioning) that may apply to SMRs. The CRPPH also asked for the report to include a ranked list of topics of interest to NEA member countries, if possible.

Responding to the CRPPH request, the TFSMR identified ten RP challenges associated with the deployment of SMRs, prioritising them in terms of importance from an RP perspective. These challenges were presented at the CRPPH 81st annual meeting in April 2023.

As a result of the discussion at the CRPPH 81st annual meeting, it was agreed to extend the TFSMR for another year and to task the TFSMR to identify where the RP challenges can be integrated into existing mechanisms and where they are specific to the CRPPH. This would be accomplished by communicating with other NEA divisions and committees, as well as international organisations. The CRPPH asked for the report to be aimed at publication.

During 2023, the TFSMR engaged with other NEA expert groups and international organisations to share the results of the high-level analysis, gather feedback, and identify areas of overlap and areas where value may be added by the work of the CRPPH. The TFSMR engagements in 2023 included a presentation to the Heads of the European Radiological Protection Competent Authorities (HERCA) on 8 June, the Expert Group on Small Modular Reactors (EGSMR) on 4 October, and a presentation to the Information System on Occupational Exposure (ISOE) on 6 December. In addition, as an outcome of the 48th meeting of the Working Party on Nuclear Emergency Matters (WPNEM) on 21 November, it was suggested to co-ordinate EPR topics between CRPPH and WPNEM. Feedback from the TFSMR interaction with these groups is reflected in this report.

1.3. Interpretation of high-level analysis result

A TFSMR of experts in the fields of RP, emergency preparedness (EP), and public health was established to identify and assess RP challenges for SMRs. The TFSMR members who contributed to this report are listed in Appendix A. They are regulatory experts actively involved in assessing and regulating SMRs in their respective countries. It is important to note that this analysis is based on expert elicitation in assessing and regulating specific SMR projects that involves unique combination of application, technology and design[1]. In

[1] In this context, "application" refers to operational purposes (e.g. electricity generation, industrial process heat, desalination), output scale, deployment area (e.g. remote region, industrial zones), "technology" refers to reactor type (e.g. Light Water Reactor, High-Temperature Gas-Cooled Reactor, Sodium-Cooled Fast Reactor, Lead-Cooled Fast Reactor, Molten Salt Reactor), fuel type (HALEU, LEU, TRISTO), and "design" refers to modularity (e.g. factory-fabricated modules), placement (e.g. underground, on the sea), safety feature (e.g. passive system, cooling without external power).

this context, this analysis reflects the experts' individual views and introduces a bias towards those SMR projects. Accordingly, experts recognise that the group analysis does not apply uniformly to the entire SMR class of nuclear reactors and should be regarded as guidance for further analysis of RP challenges.

2. Radiological protection challenges

2.1. Identification

The TFSMR identified the following ten areas where RP aspects should be considered because they could impact the deployment of some SMR projects. In this report, the radiological protection challenges[2] are defined as RP aspects in the ten areas, and the areas are used to indicate the RP challenges without referring to their own RP aspects.

- Small compact design;
- Source terms;
- Environmental impact assessments (EIA);
- Siting;
- Staffing issues;
- Lack of operating experience (OPEX);
- Emergency preparedness and response (EPR);
- Transport;
- Public risk perception and risk communication;
- Environmental monitoring.

The TFSMR developed and used a template based on three questions to standardise the analysis of RP challenges:

- "What are the associated RP aspects?"
- "What are the benefits if the challenge is explored?"
- "What is at stake if the challenge is not explored?"

In addition, this template allowed the task force to characterise when each RP challenge emerges, i.e. in which exposure situation (planned, emergency, and existing) and where it applies within the facility's life cycle (pre-operational, operational and decommissioning).

The analyses of the RP challenges based on this template are given in Appendix B. They are the starting points for the TFSMR's analysis and discussions in the following sections.

2.2. Prioritisation

The TFSMR classified the ten RP challenges according to their priority for radiological protection. It is important to note that this exercise was largely subjective due to the number of aspects that were considered (safety-relevance, timeliness, necessity, difficulty, technology maturity, etc.) and the diversity of backgrounds of the TFSMR members (expertise area, knowledge, country-specific circumstance, etc.). However, this exercise

[2] In this context, "radiological protection challenge" refers to an RP issue that national governments, regulators, industry, and other key stakeholders, such as the local community, could experience with the deployment of new nuclear technologies. Such challenges may need to be addressed at the pre-operational phase to reduce the potential impacts and maximise opportunities for ensuring appropriate radiological protection.

provided a useful indication for further exploration of the RP challenges, as requested in the original task set by CRPPH.

The views of TFSMR members are presented in the table below. Members classified the RP challenges by importance based on three grades: 3 – high, 2 – medium, and 1 – low. Three groups emerge from this approach:

- Most important RP challenges include "Lack of OPEX", "Source terms", and "Public risk perception and risk communication".
- Important RP challenges include "Siting", "EPR", "Small compact design", "Staffing issues", and "EIA".
- Least important RP challenges include "Transportation" and "Environmental monitoring".

Table 2.1 Prioritisation of RP challenges

Highly important | Important

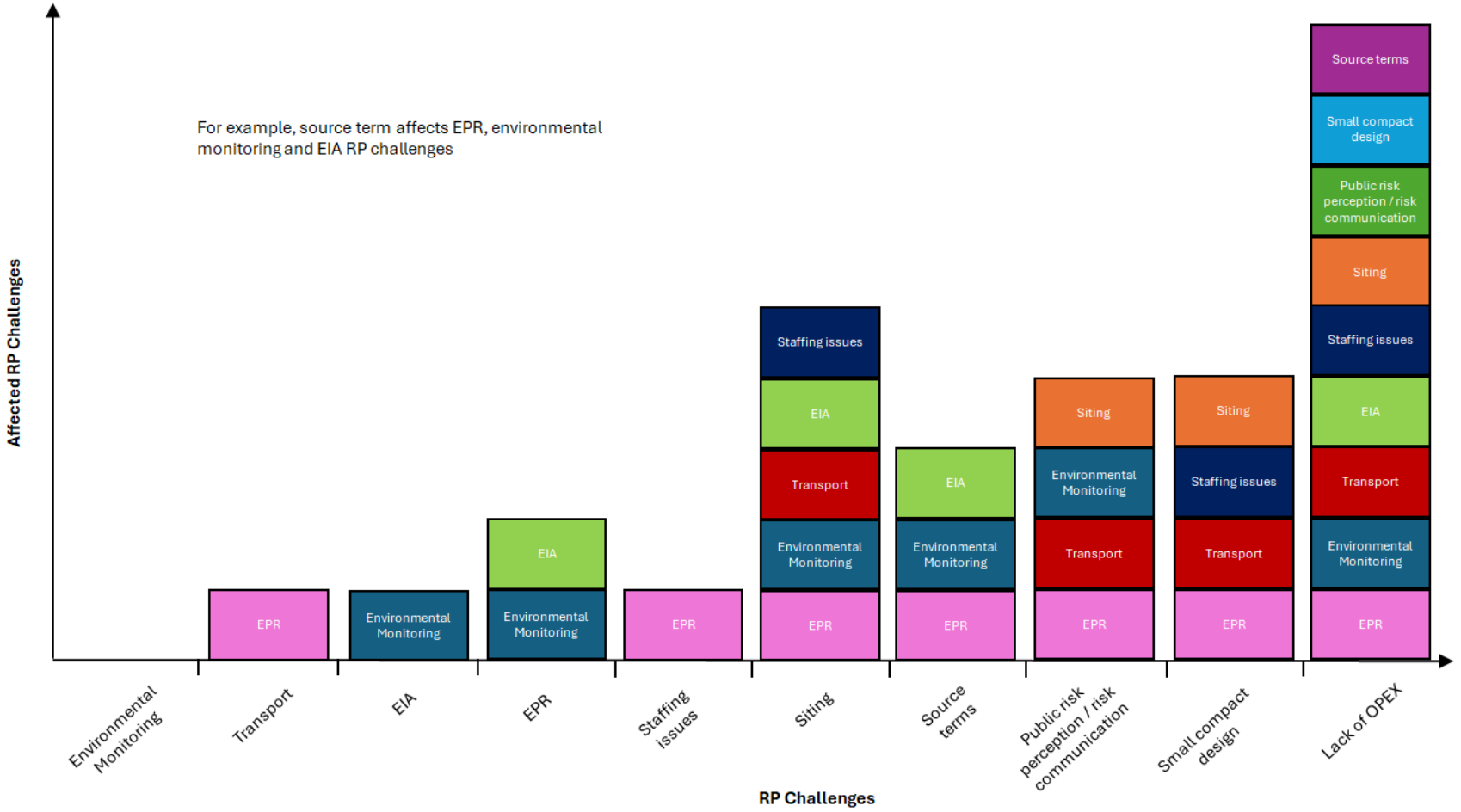
TF member	Lack of OPEX	Source terms	Risk	Siting	EPR	Small compact design	Staffing issues	EIA	Transport	Environmental monitoring
a	3	3	3	2	3	2	2	2	1	1
b	3	3	2	2	3	3	2	2	1	1
c	3	3	3	2	2	3	2	2	1	1
d	3	3	3	2	2	3	2	2	1	1
e	2	2	2	3	2	2	2	3	1	0
f	3	3	3	2	1	1	3	1	1	1
g	3	2	3	2	3	2	2	2	1	1
h	3	3	2	3	2	3	2	1	1	1
i	3	3	3	2	2	1	2	1	1	1
Score	25.0	24.1	23.2	19.4	19.1	19.0	18.5	15.4	8.7	7.6

Note) As total rating scores distributed to the challenges varied from 19 to 22, they are normalized to 20.

2.3. Cross-cutting nature

It is important to note that many "areas" are interrelated and overlap. For example, "Lack of OPEX" affects all phases of SMR design, operation and decommissioning, and influences other areas, making it a "cross-cutting" area. In contrast, areas such as "Environmental monitoring" are more specific to local conditions and the reactor design and have little influence on decisions about other challenges. Accordingly, the following figure illustrates the links and cross-cutting nature of the ten RP challenges.

Figure 2.1 Cross-cutting nature of RP challenges



3. International SMR initiatives

Many international initiatives have started to address challenges related to the development and deployment of SMRs. The TFSMR surveyed and summarised these initiatives with links to the latest publications in the following sections.

3.1. Within the NEA

The NEA SMR Strategy

This Strategy is the Agency's cross-cutting approach to carry out its mission and deliver on member countries' priorities related to SMRs. The NEA SMR Strategy creates an analytical framework for understanding and analysing the conditions for successful development and deployment of SMRs across various power and non-power markets. It facilitates gap analysis and work planning across the Agency, to ensure the current and future NEA programmes of work directly support the priorities of member countries related to SMRs, and it supports dialogue and co-operation with member countries as well as partners and stakeholders. For more information, visit: www.oecd-nea.org/jcms/pl_26297/the-nea-small-modular-reactor-smr-strategy.

Accelerating SMRs for Net Zero

Accelerating SMRs for Net Zero will leverage the NEA's network of industry leaders, government officials, researchers and experts to establish a practical, solutions-oriented platform with a defined plan of work for collaboration and knowledge exchange to support decision makers in maximising the full potential of SMRs. It will focus on pragmatic tools, economic analyses and policy recommendations to help inform policy and investment decisions by governments, industry and the financial sector. For more information, visit: www.oecd-nea.org/jcms/pl_88539/accelerating-smrs-for-net-zero.

Expert Group on SMRs (EGSMR)

This expert group was established under the NEA Committee on the Safety of Nuclear Installations (CSNI) to evaluate NEA members' needs for SMR safety research and assessments and to recommend the CSNI efforts to be conducted to address them. It identified four areas of interest for further consideration by CSNI and suggested actions. The outcomes are compiled in "CSNI Technical Opinion Paper No. 21: Research Recommendations to Support the Safe Deployment of Small Modular Reactors".

Waste Integration for Small and Advanced Reactor Designs (WISARD)

This is a project set in the frame of the NEA Joint Project by the Division of Radioactive Waste Management and Decommissioning (RWMD) to establish a sustainable waste management strategy for SMRs and advanced nuclear technologies, focusing on disposal, transportation, treatment and recycling and storage. It is now under preparation and will start the tasks in 2025. Visit: www.oecd-nea.org/jcms/pl_86832/joint-project-on-waste-integration-for-small-and-advanced-reactor-designs-wisard.

Focus Group on the Back-End of Advanced Reactors (FG-BEAR)

This group was created for waste management and decommissioning issues related to SMRs and advanced reactors to review relevant work, explore the potential for international collaboration and provide recommendations for a possible structured approach to the NEA Radioactive Waste Management Committee (RWMC) and the NEA Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM). It commenced in July 2024. See e.g. NEA (2025a).

NEA SMR Dashboard

This is an assessment of the progress towards commercialisation and deployment of SMR projects by the NEA Division of Nuclear Technology Development and Economics (NTE). Progress is assessed in the areas of licensing readiness, siting, financing, supply chain, engagement and fuel qualification and production. Progress of SMR deployment worldwide is accessible on the NEA website: www.oecd-nea.org/jcms/pl_107879/nea-small-modular-reactor-digital-dashboard, and in NEA (2025b). There may be the opportunity to expand the *NEA SMR Dashboard* database for data relevant to RP.

Working Group on Small Modular Reactor Economics (SMR-ECON)

The SMR-ECON working group focuses on studying the cost and economics of deploying small modular reactors by examining learning processes from comparable industries. The group will consolidate evidence from industries that have achieved economies of scale through serial production and share lessons learnt from their experiences. These insights will be analysed for their relevance to SMR deployment, exploring how cost reductions can be achieved as the deployment process progresses. The group will also consider the interplay between SMR costs, regulatory frameworks, and other policy influences, aiming to provide analysis for policymakers and industry stakeholders. The outcome will be a report offering insights and recommendations to improve the competitiveness and cost-effectiveness of SMRs. For more information, visit: https://www.oecd-nea.org/jcms/pl_79842/expert-group-on-small-modular-reactors-egsmr.

SMR Industrial Case Studies

The *SMR Industrial Case Studies* are a series of reports that estimate the global addressable market of SMRs for specific industrial applications and provide a guide to the barriers SMRs face before adoption can be realised in these markets. For each case study, a global estimate of the addressable market will be calculated that provides an outlook for how much nuclear capacity and when could realistically be deployed to meet this sector's demand. Then, an expert group of end-users will be assembled, surveyed and interviewed to better understand the opportunities and challenges of each market. The goal of the addressable market and structured surveys is to provide a meaningful look into each market sector and provide nuclear audiences with the background needed to address these market sectors with nuclear technologies. See e.g. NEA (2004).

3.2. Outside the NEA

SMR Regulators' Forum

This forum was created in March 2015 by the International Atomic Energy Agency (IAEA) to identify and resolve common safety issues challenging regulatory views associated with SMRs. It aims to facilitate robust and thorough regulatory decisions by enabling discussions among Member States and other stakeholders to share SMR regulatory

knowledge and experience. Its activity develops through Pilot Project Phase (2015-2017), Phase 2 (2018-2020), Phase 3 (2021-2023) and Phase 4 (2024-2026).

Nuclear Harmonization and Standardization Initiative (NHSI)

This initiative was launched in March 2022 by the IAEA to facilitate the safe and secure deployment of SMRs and other advanced technologies. It aims to maximise the contribution of SMRs to achieving the goals of Agenda 2030 by bringing together policymakers, regulators, designers, vendors and operators to develop common regulatory and industrial approaches to SMRs. It is composed of two tracks: the Harmonization of Regulatory Approaches Track and the Standardization of Industrial Approaches Track. Outcomes will be available in 2025.

Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and Small Modular Reactors

This review was published in November 2023 by the IAEA to document the areas of novelty of non-water-cooled reactors and SMRs in comparison with the existing fleet of reactors. It provides an assessment of the impact of SMRs on the applicability and completeness of the IAEA standards and covers a wide range of aspects relevant to the lifetime of the facilities, including EPR and RP.

Coordinated Research Project (CRP) I31029

The title of this IAEA project is "The Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for EPZ for SMR Deployment". It started in July 2022 with the participation of some Member States. The outcomes are expected to be compiled as an IAEA TECDOC in 2025, and then a new EPR Series document will be developed to provide guidance on EPR for SMRs.

Coordinated Research Project (CRP) T13021

The title of this IAEA's project is "Challenges, Gaps and Opportunities for Managing Spent Fuel from Small Modular Reactors"; it started in 2023. Participating countries will collaborate to enhance their knowledge, identify gaps, and support the development of effective SMR spent fuel management strategies tailored to their specific needs of back-end programmes.

SMR Task Force (SMRTF)

The SMRAG evolved into this task force to explore the expectations of design and technology maturity of SMR design in relation to the regulatory pre-licensing and licensing process. It produced an overall picture of the relationship between licensing processes and design phases while highlighting the key technology challenges associated with licensing SMRs.

European SMR pre-partnership

This was created by the European Union (EU) as a collaboration among industrial stakeholders, research and technological organisations, interested customers, and European policymakers and regulators to create enabling conditions for the first SMRs to start operation in Europe by the early 2030s. It resulted in outlining a strategy for the actions to be undertaken to support the launch of the initiative.

European Industrial Alliance on SMRs

This alliance launched in 2024 as a successor of the European SMR pre-partnership, focusing on incentivising the market, financing SMRs, ensuring that the nuclear industry is well-equipped and supporting innovation, research and development.

European Partnership for Radiation Protection Research (PIANOFORTE)

Some projects relevant to RP on SMRs started in 2024.

3.3. Insights from international SMR initiatives

Elements of discussions within international SMR and nuclear wide initiatives on the areas identified by the TFSMR are summarised in Appendix C. This exercise was useful to separate the RP challenges that can be addressed within existing initiatives and those that should be addressed by the CRPPH. The following paragraphs summarise the main insights.

Not focused on RP aspects

While international SMR initiatives are addressing most of the areas identified by the TFSMR in Section 2.1, they generally do not consider them from an RP perspective, except for sizing the EPZ. In this regard, the TFSMR highlights that addressing specific RP challenges from the outset would facilitate the adoption of industry best practices aligned with international guidance. To achieve this, it is necessary to establish mechanisms for disseminating specific RP challenges and exploring the RP aspects of these initiatives.

Sizing EPZs

Many international SMR initiatives focus on the importance of the sizing of EPZs for SMRs (EGSMR, SMR Regulators' Forum and CRP I31029). SMRs have the potential to have smaller or no EPZs due to possibly smaller radionuclide inventories and inherent and passive safety systems. However, the TFSMR raises the concern there is often a mischaracterisation of the EPZ as being related to design safety, rather than as a planning tool for EP. The TFSMR notices a gap on protective strategies for SMRs, especially in scenarios like co-location with industrial and residential areas, where the emphasis should be on the facility context and site-specific risks and hazards. The TFSMR highlights that conceptual or high-level approaches for protective actions would be valuable.

Waste management

Due to the variety of SMR spent fuel and their proximity to communities or industrial facilities, having comprehensive characterisation and strategies for SMR spent fuel management is essential. Spent fuel management considerations are not included in the scope of this report, as they are covered by other groups. Now that the FG-BEAR has started to cover the issue, the TFSMR recommends collaboration with the FG-BEAR to ensure the development of a comprehensive approach to spent fuel and waste management from an RP perspective.

Stakeholder involvement

Early on, international SMR initiatives focused either on the regulatory side (SMR Regulators' Forum, 2015) or the industry side (SMRAG, SMRTF, 2013). Since then, initiatives have evolved to being more collaborative. Additional stakeholders, including newcomers (both countries and vendors) have joined the initiatives to discuss the wide

range of SMR types and their potential applications. The TFSMR stresses the importance of pursuing joint work between the industry and other stakeholders to address RP challenges.

Grouping SMR types

There is considerable variation among SMR technologies and many designs under development. This makes it impracticable to treat the RP challenges as similar across all designs. Some initiatives distinguish SMRs into groups (EGSMR by deployment timeline, WISARD by fuel cycle) considering their technology maturity/readiness and near-term deployment. The TFSMR recognises that this approach enhances the ability to address RP challenges in a practical and timely manner.

Collaboration with international SMR initiatives

As listed below, the areas identified in Section 2.1 are also identified by the other international SMR initiatives. Although they do not address those areas through an RP perspective, the TFSMR insists that collaboration is worth considering to avoid overlap, maximise resources and enhance the compatibility of proposed solutions. Close communication with the EGSMR and Regulators' Forum would be specifically crucial.

3.1 TFSMR identified areas covered by international SMR initiatives

	EGSMR	Regulators' Forum	IAEA Safety Standards	CRP I3 1029	SMRAG	SMRTF	pre-Partnership
Small compact design	○	○			○		○
Source terms		○					
EIA							
Siting		○			○		
Staffing issues	○	○					○
Lack of OPEX	○	○				○	
EPR	○	○	○	○			
Transport	○	○					
Public risk perception / risk communication					○		○
Environment monitoring							

4. Challenge analysis

Considering the points discussed in Sections 2 and 3.3, the TFSMR analysed the RP challenges in the ten areas to develop recommendations for the CRPPH.

4.1. Small compact design

While the small compact design is often viewed as an advantage in other international SMR initiatives, the TFSMR highlights that it raises new challenges for radiological protection. The TFSMR discussed measures that can be used to reduce neutron leakage, higher gamma radiation, neutron activation levels, coolant corrosion, fuel leakage, core inventory, and risk to workers caused by unique SMR types.

It is the TFSMR's opinion that the most effective way to disseminate the importance of considering RP challenges of small compact design is to have a workshop with SMR designers and operators.

4.2. Source terms

Source terms are fundamental for all safety analyses and are directly linked to EPR, EIA and environmental monitoring.

The TFSMR discussed recommendations to characterise source terms in SMR designs and to propose approaches to mitigate potential design-related challenges.

Source terms will vary depending on SMR types and applications and will directly contribute to occupational exposure, accident dose, and environmental impacts. The TFSMR considers that disseminating the importance of considering source terms from the beginning of the design phase is crucial, and this could be facilitated through a workshop or similar forum to discuss the importance of considering RP aspects of source terms early in the design phase.

4.3. Environmental impact assessment (EIA)

The EIA is not addressed in other international SMR initiatives. The TFSMR considers that exploring it from an RP aspect could also contribute to optimise scoping of EIAs for different SMR types, including appropriate consideration of safety features as well as non-radiological risks and benefits[3].

The TFSMR does not consider that this challenge should be treated independently as it intersects with the source terms, small compact design, EPR and siting aspects.

[3] Following the Expert Group on International Recommendations (EGIR) evaluation of International Commission on Radiological Protection's (ICRP's) proposed review of the system of radiological protection, the CRPPH agreed to establish an Expert Group on Radiological Protection of the Environment (EGRPE) in March 2024. The EG will provide an understanding of the implementation of radiological protection of the environment recommendations and identify needs for improvement for the next set of General Recommendations

4.4. Siting

The global deployment of SMRs is expected to lead to SMRs on many new sites and potentially deployed in short time frames. The TFSMR discussed guidance for SMR siting that could be developed:

- To help with regulatory decisions regarding siting criteria and public engagement.
- To provide siting considerations specific to SMRs and proposed approaches to meeting regulatory siting criteria.
- To provide a framework for discussion and provide information to the public on the benefits and risks of SMRs that may be sited in the community.

As discussed in Section 4.9, the TFSMR considers the SMR siting should be addressed together with public risk perception and risk communication.

4.5. Staffing issues

Though the staffing issues are common to the nuclear industry, many international SMR initiatives address it as a challenge for SMR. The TFSMR insists on the RP dimension of staffing issues, such as RP professional shortage and optimisation of RP professional staffing. Additionally, there is a lack of information regarding the number of staff that will be needed for the operation of novel designs[4].

The TFSMR discussed:

- a study required to develop a method for determining the minimum RP staffing levels to include interaction with human and operational factors; and
- developing guidance, including recommending solutions related to staffing issues. Such guidance might define: i) required RP staffing for different technologies and applications, and under different operational states and exposure scenarios, ii) necessary training and minimum qualifications required for RP staff at the facility and for the regulator, and iii) sustainable training programmes to enhance the number of RP professionals available.

To address the challenge of staffing issues the NEA is reinvigorating the conversation about future generations and the need to get more young people into the RP field. Initiatives that contribute to addressing this challenge include the NEA's International Radiation Protection School (IRPS), which is designed to provide participants with a thorough understanding of the international RP system, and the NEA's international mentoring workshops, which encourage female students to study and work in science, technology, engineering and mathematics (STEM).

The TFSMR considers that a study for occupational exposure optimisation and guidance would be valuable for designers, operators and regulators in the safety review process to determine and confirm the optimal RP staffing level for the operation of SMRs.

4.6. Lack of operating experience (OPEX)

Lack of OPEX applies especially to molten salt reactor technology, whereas there is more experience with water-cooled, high temperature gas-cooled and liquid metal-cooled

[4] Vancouver call for action to strengthen expertise in radiological protection worldwide, Radiation and Environmental Biophysics (2023) 62:175–180 (https://doi.org/10.1007/s00411-023-01024-5)

reactors. The cross-cutting nature of a lack of OPEX affects all areas of SMR applications. The TFSMR advises that other international SMR initiatives should consider the lack of OPEX through an RP perspective and advises adopting a collaborative approach, for example, with the EGSMR, the SMR Regulators' Forum and the ISOE.

The TFSMR discussed the possibility of developing regulatory guidance, determining new radiological hazards, understanding the appropriateness of software modelling, creating a database for sharing knowledge/OPEX, and improving the sharing of OPEX related to sensitive information.

The TFSMR considers that collecting information on regulatory approaches that NEA member countries are taking to regulate the implementation of RP in the design and development of SMRs will be useful in supporting the activity. Another potential task for the CRPPH is to document radiological hazards in current nuclear power plant designs and to identify commonalities that might apply to SMRs, which could aid in understanding how SMR vendors can anticipate and address similar issues.

4.7. Emergency preparedness and response (EPR)

EPR has been identified by other international SMR initiatives, but the TFSMR considers that sizing EPZs is overly emphasised. The TFSMR considers the actual RP-related challenge for SMRs to be the management of accident scenarios. Attention should be put on effectively addressing accident situations where protection strategies different from those in place for large reactors (LRs) may be required. Canada, the United Kingdom and the United States presented their graded approaches to EP at the WPNEM annual meeting in November 2023, so comparing regulatory approaches to EP for SMRs is beneficial.

The TFSMR also discussed:

- There is a lack of educational materials about SMRs that are targeted at emergency managers, public officials and the general public.
- An overview report on graded approaches to EP in various countries is necessary.
- Conceptualising high-level approaches to protective action is valuable.

4.8. Transport

Some international SMR initiatives address transport issues, but no RP aspects have been clearly identified.

The TFSMR considers that a communication guide to address public concerns can be developed. However, if necessary, the TFSMR considers it would be treated as part of the public risk perception and risk communication aspect.

4.9. Public risk perception and risk communication

The proposed siting of SMR projects close to industrial and residential areas highlights the importance of the public risk perception and risk communication topic for SMRs. This area is closely linked to siting, EPR and environmental monitoring.

The TFSMR discussed guidance that could be developed on effective communication strategies, public education, and improved community engagement, resulting in a better trust-building process. Guidance would also benefit EPR procedures by supporting risk-informed decision making for protective actions.

The TFSMR considers communication strategies tailored for SMRs based on their uniqueness would be useful.

4.10. Environmental monitoring

The TFSMR highlights that guidance on environmental monitoring in relation to SMR operations can be developed. This can be complemented by policies and guidance on adequate monitoring strategies with appropriate configuration of radiation monitoring networks for the environment and occupational exposure of SMR staff, as well as on cost optimisation, all in response to properly established legislative requirements.

As discussed in Section 4.9, the TFSMR considers treating this challenge as part of the public risk perception and risk communication challenge. An environmental monitoring strategy for SMRs could be valuable in considering the disturbances to industries and populations with which SMRs are co-located.

5. Recommendations and agreements

5.1. TFSMR recommendations

Based on the above, the TFSMR recommends the following actions for the CRPPH to further address the identified RP challenges.

Tasks

- Regarding the challenge "EPR": Study EP and protection strategies applicable to SMRs and include a comparative analysis of regulatory graded approaches to EP. (By an expert group under the WPNEM and possibly interaction with the NEA's Committee of Nuclear Regulatory Activities [CNRA] through the expert group).
- Regarding the "Staffing Issues" and "Lack of OPEX" challenges: Develop a risk-informed approach for RP and optimisation of exposures in design, licensing and operation of SMRs by using existing RP exposure programme OPEX. This approach should account for significantly different operating, maintenance and support regimes. (By an expert group under the CRPPH).
- Regarding the "Public Risk Perception and Risk Communication", "Siting", "Transport" and "Environmental Monitoring" challenges: Develop guidance for public communication of SMRs and related guidance (communication challenges arising from the novelty of the technology, public concerns regarding unconventional siting and revised stakeholder engagement process).

Supporting activities

- The TFSMR's final report of the outcomes, including next steps related to RP and SMRs and incorporating the views from CRPPH country delegates will be published.
- A workshop could be organised between RP experts and SMR stakeholders (designers, operators and regulators) to disseminate the outcomes and enhance stakeholder awareness of RP issues, including the importance of considering RP aspects of "Source Terms", "Small Compact Design" and "EIA" early in the design phase (possible close co-ordination with the NEA's Working Group on Analysis and Management of Accidents [WGAMA]).
- Closer exchange and discussion with the EGSMR and the FG-BEAR and sharing information from the SMR Regulators' Forum and NHSI with the NEA expert groups could also help raise awareness of RP issues to be addressed.

5.2. CRPPH agreements

The TFSMR presented the high-level analysis result and recommended the CRPPH actions above at the annual CRPPH meeting in March 2024. The CRPPH thanked the TFSMR for its efforts, which suggested actions for more in-depth analysis and highlighted the importance of integrating RP considerations early in the design phase, fostering collaboration among stakeholders. The CRPPH agreed to approve the creation of a new expert group under the WPNEM to address graded approaches for EP and SMR protective strategies by 2024 to early 2025. The CRPPH also endorsed continued monitoring of SMR-related RP challenges through workshops and engagement with international partners.

6. Conclusion

In response to a request by the NEA Committee on Radiological Protection and Public Health, the Task Force on SMRs discussed ten RP challenges (RP aspects in ten areas) associated with the deployment of SMRs, which were prioritised based on their importance from an RP perspective. In this report, RP challenges are considered generically while they may apply to only specific combinations of SMR concepts, technologies and designs. Future work should investigate and identify the SMR design characteristics that are the most impactful from an RP perspective across the SMR class.

The TFSMR surveyed international SMR initiatives conducted by the NEA's divisions and committees and other international organisations. It was found that many areas were already addressed in other international SMR initiatives but rarely through a RP perspective, except for the sizing of EPZs. The *NEA SMR Dashboard* database could be leveraged to collect data and identify the groups of SMRs of interest to RP.

Based on the insights obtained from the survey, the TFSMR analysed the ten areas, focusing on RP aspects. As a result, the TFSMR suggests three tasks and three supporting activities for the CRPPH's consideration.

At the annual meeting in March 2024, the CRPPH approved the creation of a new expert group on EP and protective strategies applicable to SMRs with objectives including an international workshop.

Appendix A. List of CRPPH Task Force on SMRs members

October 2022 – March 2023

Ulrich Buchner	Federal Office for Radiation Protection, Germany
Christina Dodkin	Canadian Nuclear Safety Commission, Canada
Bernard Ellaschuk	Canadian Nuclear Safety Commission, Canada
Martin Fogel	VUJE, Slovak Republic
Tomasz Gulinski	Canadian Nuclear Safety Commission, Canada
Ladislav Haluska	Nuclear Regulatory Authority of the Slovak Republic, Slovak Republic
Branislav Hatala	VUJE, Slovak Republic
Grant Ingham	Office for Nuclear Regulation, United Kingdom
Stuart Johnson	Office for Nuclear Regulation, United Kingdom
Zhanat Kenbayeva	World Health Organization
Sheri MacDonald	Canadian Nuclear Safety Commission, Canada
Michal Melichárek	Nuclear Regulatory Authority of the Slovak Republic, Slovak Republic
Debora Quayle	Radiation Protection Bureau, Canada
Todd Smith*	US Nuclear Regulatory Commission, United States
Stefan Wenzel	Swiss Federal Nuclear Safety Inspectorate, Switzerland

(*) Chair of the Task Force

April 2023 – March 2024

Ulrich Buchner	Federal Office for Radiation Protection, Germany
Branislav Hatala	VUJE, Slovak Republic
Stuart Johnson	Office for Nuclear Regulation, United Kingdom
Zhanat Kenbayeva	World Health Organization
Sheri MacDonald	Canadian Nuclear Safety Commission, Canada
Debora Quayle	Radiation Protection Bureau, Canada
Todd Smith*	US Nuclear Regulatory Commission, United States
Michael Tichauer	Institut de Radioprotection et de Sûreté Nucléaire, France
Stefan Wenzel	Swiss Federal Nuclear Safety Inspectorate, Switzerland

(*) Chair of the Task Force

Appendix B. Task Force discussions on 10 radiological protection challenges

This Appendix provides the raw input from the TFSMR on the RP challenges related to SMRs[5]. Each challenge is described in a standard template.

The descriptions may contain topics related to only some specific SMR types and go beyond SMRs and RP. However, they are kept as the TFSMR actually discussed because they would provide the TFSMR with a broad and comprehensive understanding of each challenge. However, the TFSMR focused on SMRs and RP aspects in analysing the challenges afterwards, keeping in mind that grouping SMR types is necessary in the next steps to make the results universal.

Note:

As shown below, the table in the top right corner shows when in a facility's life cycle each challenge appears and which exposure situation each challenge should be considered as defined by ICRP.

1. Small Compact Design

	Planned	Emergency	Existing
Pre-operational	X	X	
Operational	X	X	
Decommissioning	X	X	

What are the associated RP aspects?

The small, compact design of SMRs gives rise to significant potential benefits to the nuclear industry, including reduced costs with economies of scale and reduced build times. These benefits can result in potential radiological protection (RP) impacts that require resolution so far as is reasonably practicable so that an optimal balance between benefits and impacts is achieved. The most significant (RP) impacts

	Planned Exposure Situation*1	Emergency Exposure Situation*2	Existing Exposure Situation*3
Pre-operational*4			
Operational*5			
Decommissioning*6			

*1) An exposure situation resulting from the deliberate introduction and operation of radiation sources, used for their radioactive properties. For this type of situation, the use of the source is understood, and as such the exposures can be anticipated and controlled from the beginning.

[5] The wording for the challenges identified by the CRPPH Task Force on SMRs are those captured during their discussions and are not supported by evidence in the report.

*2) An exposure situation resulting from a loss of control of a source, or from intentional misuse of a source, which requires urgent and timely actions in order to avoid or mitigate exposure.

*3) An exposure situation resulting from a source that already exists, with no intention to use the source for its radioactive properties, before a decision to control the resulting exposure is taken. Decisions on the need to control the exposure may be necessary but not urgent.

*4) Planning, designing and constructing phases.

*5) Operation phase.

*6) Decommissioning phase.

1. Small Compact Design

	Planned	Emergency	Existing
Pre-operational	X	X	
Operational	X	X	
Decommissioning	X	X	

What are the associated RP aspects?

The small, compact design of SMRs gives rise to significant potential benefits to the nuclear industry, including reduced costs with economies of scale and reduced build times. These benefits can result in potential RP impacts that require resolution so far as is reasonably practicable so that an optimal balance between benefits and impacts is achieved. The most significant RP impacts are:

A. Compact designs are likely to result in less core shielding leading to elevated gamma and neutron radiation dose rates leading to:
   a. Higher neutron fluxes to key components and structures with increased activation within the hazard shield, reactor pressure vessel and potentially the nuclear island.
   b. Increased activation which is likely to lead to:
      - higher activity levels of waste for disposal, and
      - elevated radiation exposure during decommissioning.
   c. Affects to 'in-core instrumentation' and any location where these instruments may be taken for maintenance or calibration.
   d. Higher gamma and neutron dose rates are likely within all areas of the nuclear island:
      - reducing and restricting access to operators during SMR operation,
      - resulting in higher operator radiation exposure during maintenance, outages, and other such tasks,
      - delaying commencement of maintenance tasks following reactor shutdown until dose rates decay to acceptable levels, and
      - give rise to increased direct shine radiation exposures to members of the public off-site.

B. Limited working space due to compact designs is likely to complicate RP and operational procedures. For example, it may be difficult to use temporary shielding if work is required close to pumps, valves, flanges etc.

C. The limited space available could impact design considerations such as:
   a. The number of valves, flanges or joints, or the use of small pipework lengths, leading to junctions, sharp bends, or dead legs. These could all lead to the accumulation of activation products and crud.
   b. Penetrations through shielding (for instrumentation or cables) could create streaming or leakage paths where additional shielding or containment is difficult.

D. The small compact design could result in:
   a. Problems associated with controlling contamination at the source (insufficient space to provide containment or ventilation if required for radioactive contamination or vapours such as tritium).
   b. Reduced containment (primary, secondary or building structure) should a radiation emergency arise leading to higher on-site and off-site radiation exposures.
   c. Reduced space and distance for evacuation routes (following an emergency such as a criticality where it is important to move away quickly from the hazard.)
   d. Inadequate shielding of spent fuel and waste, for storage or transport purposes.

What are the benefits if the challenge is explored?

The potential to implement measures to:

A. Use materials to minimise neutron activation, such as titanium for steam generators (rather than Inconel).
B. Use chemistry that minimises coolant corrosion, such as boron/lithium free, which also reduces the generation of tritium.
C. Use modern fuel cladding materials to reduce fuel leakage.
D. Reduce the core inventory, which implies a smaller fuel source term for faults and fuel transfer.

E. Use 'canned primary pumps' (which are electro-magnetically driven rather than by shaft/motor which have no seals). F. Use of low cobalt materials such as Norem for valves and seals. G. Investigate the use of concrete with high-density material, boronated or additional hydrogenated material). H. Develop the use of remote tools (ROVs) or instrumentation rather than operators working in high-dose rate areas I. Use 'quick fit lagging' for pipework (assisting in removal for inspections and maintenance). J. Minimise crud and contamination traps in coolant pipework and auxiliary plant circuits. K. Use a modular design to assist in removing items, structures, or components during decommissioning. L. Use of passive safety measures such as a containment spray around the reactor pressure vessel (RPV).
What is at stake if the challenge is not explored?
If this is not explored fully, the radiation exposure to operators may (on a pro rata MWe basis) be significantly higher than current modern-day operating PWRs.
Other ongoing work
n/a
Any other notes
n/a

2. Source Terms

	Planned	Emergency	Existing
Pre-operational	X	X	X
Operational	X	X	X
Decommissioning	X	X	X

What are the associated RP aspects?

A. Fuel and Activation Products

a. Some SMR types proposing large varieties of fuel types with various chemical and physical properties (ceramic, metallic, TRISO, molten salt, etc.) would impact operation programs and cycles. The chemistry and in-containment behaviour of released fission products in an anticipated operational occurrence (AOO) or accident are expected to differ from existing large light water reactors (LLWRs) and thus can affect the source term. Also, the chemico-physical properties of the fuel must be taken into account during deployment and with regard to the fuel supply chain, including fabrication and transportation. Certain SMR types envisage high burnup rates (>150 GWd/Mt) far above those of LLWRs and higher fuel enrichment which may affect levels of specific fission products. New reactor designs may also hold the potential for new postulated initiating events and hazards (graphite dust, mixture of fuel salt and coolant, sodium-water reaction etc.) that ultimately could result in releasing radionuclide inventory to the environment or staff being exposed.

b. Materials chosen for the reactor design (e.g., coolant, piping material, shielding, etc.) will be another important determinant for evaluating source terms. Other novel materials may be used within some SMR types. Their behaviour will need to be substantiated. A lack of experience with corrosion and activation products of novel materials and their behaviour in combination with non-standard operational conditions (e.g., load following, frequency of outages, etc.) should be considered in the assessment of source terms.

c. The material and fuel-related issues described above should also be considered for operational RP during operation, maintenance, and outages, as well as for the plant's decommissioning and waste management.

B. Siting

Some SMR types propose sites which are smaller in size and in closer proximity to a large population centre. This could result in comparable (collective) offsite doses even for smaller expected source terms compared to LLWRs and in elevated control room doses due to a smaller nuclear island (location of control room and air intake relative to release locations). Possible interferences of modules at a multi-module SMR site and their implications on the size of the source term should be investigated.

C. Small Compact Design

A more compact design of SMRs with smaller piping potentially changes conditions for fission product deposition and accumulation and may change pathways for radionuclide release. This could have implications for RP and mitigation in emergency situations due to relative differences in activity inventories of auxiliary systems and releases in case of failure compared to current LLWRs. Regarding decommissioning questions on sources of radionuclides (i.e., accumulation, deposition, auxiliary systems, etc.) as well as composition and location of activation products (e.g., tight workspaces) should be considered.

D. Regulatory Requirements

a. Some SMR types do not offer a safety class filtered ventilation system in the reactor building and or active containment post-accident systems (i.e., spray and fan coolers) and therefore will affect the regulatory acceptability and EPR planning.

b. It has to be assured that security or intellectual property reasons could not hinder a full provision of the source term and the safety case can be evaluated.

E. Waste

The storage of lifetime inventory of spent nuclear fuel onsite must be accounted for as well as of potential differences in onsite management of radioactive waste inventories and possible differences in the chemico-physical form of radioactive waste.

What are the benefits if the challenge is explored?

The various topics, issues and challenges for RP that are related to the composition and possible release of source terms in new SMR types may be already addressed during the design process as well as in the

elaboration of regulations and guidance by regulators in stakeholder countries. Recommendations for material usage could be elaborated to reduce operational leakage and corrosion (e.g., titanium steam generator tubes, low cobalt levels, boron-free coolant in light water reactor (LWR) types) which could reduce source terms in both power operation and accidental situations. Further benefits may arise for emergency preparedness and mitigation planning if differences to source term related challenges in current LLWR designs were identified.

What is at stake if the challenge is not explored?

New fuel types may challenge current models for calculating dispersion, transport, and deposition of fission products. This could potentially lead to higher uncertainties in onsite and offsite dose calculations. Simplified designs with omission of active systems influencing a fission product release during AOO or accidents may be incompatible with current regulatory rules in stakeholder countries. This may result in the need to review and eventually revise regulations and guidance, delaying deployment and increasing costs. Challenges on RP and public health (PH) related to source term and associated with siting, engineering, and technical design (component size, smaller diameters and radii influencing fission product deposition and release) could impact the assessment of accident analyses, leading to delays or costly design adaptations. Onsite storage and conditioning of radioactive waste from fuels that differ from the uranium oxide fuels currently used in commercial LLWRs could also lead to new challenges in source term assessment.

Other ongoing work

- U.S. Department of Energy / Pittsburgh Technical LLC (DE-NE0008835, PT-PR-19-021, Source Term Reduction for Advanced and Small Modular Boiling Water Reactors)
- Nuclear Energy Institute NEI (U.S.) Small Modular Reactor Licensing Task Force (ML13004A390, position paper on small modular reactor source terms)
- U.S. NRC (SECY-16-0012, Policy Issue on Accident Source Terms and Siting for Small Modular Reactors and Non-Light Water Reactors)
- IAEA on Technology Roadmap for Small Modular Reactor Deployment (No. NR-T-1.18) - Technical Working Group for Small and Medium-sized or Modular Reactors (TWG-SMR)
- UK Committee on Radioactive Waste Management "Development of small modular reactors (SMRs) and advanced modular reactors (AMRs): CoRWM position paper"

Any other notes

Challenges related to the source term are influenced by a variety of factors and impact many aspects of the design, deployment, operation, and decommissioning of a nuclear power plant as well as on storage, conditioning, transport, and disposal of radioactive waste and spent fuel. Releases of radionuclides have to be assessed not only for emergency situations but also for planned and existing exposure situations of the public and of plant staff. The identification and evaluation of potential differences to current commercial LLWRs in the composition of source terms and potential release pathways for SMR/AMR designs are expected to be beneficial with regard to RP&PH.

3. Environmental Impact Assessments (EIA)

	Planned	Emergency	Existing
Pre-operational	X	X	X
Operational	X	X	X
Decommissioning	X		X

What are the associated RP aspects?

A. Variability of designs, deployment strategies, siting environments will all mean that there is a requirement for a lot of information to complete all of the parameters in an EIA. For example:
   - Design-specific parameters related to how the SMR is deployed: e.g., above or below ground? On land or at sea? Harsh environments (e.g., arctic, jungle, desert)?
   - Design-specific parameters related to emissions (routine and in case of failure): e.g., different, non-traditional fuel types, different coolant types (gas, light water, liquid metal), different wastes, different advanced safety features, different pathways.
   - Site-specific environmental parameters for modelling potential impacts: e.g., different substrates (soil types, water salinity), different flora and fauna, etc.

   a. Many of the parameters required may not be readily available and will need to be gathered. Is there an international platform to collect them?
   b. Models (e.g., environmental transport and food chains) may need significant updates to be useful for new circumstances. New models will need peer review and QA; and
   c. The lack of long-term experience with some novel designs/features means that there may be significant uncertainty regarding predicted impacts, which could lead to over/under-conservatism and hinder communication with the public.

B. For units designed/manufactured in one country and deployed in another, information from the manufacturer relevant to environmental compliance may not conform to national requirements.

C. Stakeholder engagement: Different SMR types and environments will require site-specific communication products for productive engagement with different audiences. Preparing these could be a challenge, especially for audiences who have no background in nuclear technology and/or limited vocabulary for discussing it.

D. Deployment to remote sites could be hampered by limited formal/published information about the environment and non-human biota. Traditional knowledge may be important to avoid inadvertent negative effects. Strategies may be required to collect and integrate this.

What are the benefits if the challenge is explored?

A. Exploring issues around gaps in data and modelling tools could lead to the development of databases for sharing parameters and best practices (if they do not currently exist), which could support operators conducting EIAs and regulators who review them.

B. Developing publicly accessible materials that can support productive dialogue on SMRs will facilitate stakeholder engagement and public confidence.

C. Exploration might also contribute to optimised scoping of EIAs for different types of SMR deployment – e.g., narrowing or expanding requirements for different designs or siting locations. It may also raise awareness of significant non-radiological considerations associated with novel designs (e.g., turbines). This might develop organically as regulators and operators gain more experience; however, early exploration could help countries develop guidance and frameworks for preparing and evaluating EIAs.

What is at stake if the challenge is not explored?

A. If we are not prepared for the EIA process, it could lead to delays in deployment and a loss of public confidence. For example, where a NEA member country requires public acceptance for siting an SMR (or related project, such as the long-term disposal of fuel waste), a fearful public can be an obstacle to development.

B. Furthermore, if the deployment overhead is too high, it may discourage the technology's adoption, potentially negatively impacting our ability to phase out fossil fuels and meet climate change targets.

Other ongoing work

• IAEA-TECDOC-1915. *Considerations for Environmental Impact Assessment for Small Modular Reactors* (2020) • IAEA's programme on Methods for Radiological and Environmental Impact Assessment (MEREIA) may be a source of some technical data. Studying a scenario involving SMRs in remote locations with harsh environments was proposed but may not be a priority for this year.
Any other notes
n/a

4. Siting

	Planned	Emergency	Existing
Pre-operational	X	X	X
Operational			
Decommissioning			

What are the associated RP aspects?

A site survey and evaluation are an analysis of factors at a site that could affect the safety of a facility. A site evaluation considers many factors, including consideration of impacts on public dose (e.g., dispersion characteristics and proximity to population centres) and emergency preparedness (impediments to development of an emergency plan). Historically, LLWRs were sited away from population centres and other hazardous facilities. However, potential uses for some SMR types include supplying electricity and process heat for industrial applications and electricity to communities within a microgrid. Siting regulations were developed decades ago and are based primarily on LLWR technology. Some SMR types will have source terms and design features inherently different from LLWRs. While siting considerations may be the same (e.g., seismology, hydrology, geology, meteorology), it should be anticipated that some SMR types will be co-located with other industrial facilities, which may present contiguous hazards, and closer to population centres or in areas of high population density. Conversely, some SMR types may be sited in remote locations that require development of supporting infrastructure and labour skills. IAEA Specific Safety Guide No. SSG 35 notes that the approach to siting for nuclear power plants can be applied to other facilities through a graded approach, but guidance for applying a graded approach to siting for SMRs is lacking. Specific challenges in RP&PH include:

A. Dose criteria
Some siting regulations rely on dose criteria to reference individuals to specify adequate distances for the exclusion area, low population zone, and to population centres. However, dose criteria developed for LLWR technologies may not be the most useful for application to some SMR types for siting analyses due to differences in source term (including multi-modular or multi-unit and potential siting locations). Dose criteria should be assessed for applicability to various SMR designs and compatibility with modern health physics.

B. Extent of siting analysis
The analysis of various siting criteria is often conducted within certain distances (or screening values) or specifies acceptable proximities to the nuclear facility. Criteria established primarily for LLWRs may be limiting to some SMR types, particularly when siting is intended to bring the SMR closer to other facilities or populations. Guidance is needed on a graded approach to siting some SMR types to address the extent of various distances used in siting analyses needed to meet regulatory. Additional consideration may be needed to address potential siting issues near national boundaries.

C. Siting considerations
Some SMR types may benefit from siting on existing locations approved for nuclear power operations or where existing infrastructure and availability of local trade skills would facilitate deployment of the SMRs. Conversely, siting in remote locations may prove a challenge. Such factors have not been widely identified and addressed to support siting decisions.

D. Licensing approach
Some countries are considering a consent-based approach to siting nuclear/radiological facilities. While this is intended to promote public acceptance and trust, this could potentially create issues if public concern outweighs safety considerations related to site characteristics of suitable locations or if SMRs are sited in locations where public sentiment is not in favour of the facility. Guidance is needed to support consent based siting approaches and communicating with the public on RP&PH and EP issues associated with siting SMRs.

E. Migration of radionuclides to cogeneration facilities
SMRs may be connected to on-site or off-site cogeneration facilities for the production of resources including hydrogen, ammonia, and district heat. Some radionuclides produced by SMRs have the potential to migrate into these downstream facilities and enter their products.

What are the benefits if the challenge is explored?

A. Developing SMR-specific considerations and guidance for siting would provide a technical basis for meeting siting criteria and facilitate making timely siting decisions in licensing.
B. Developing guidance for communicating RP&PH and EP issues to communities throughout the siting process will help educate the public on the differences between SMRs and LLWRS and will help the public to understand both the potential risks and the benefits of SMRs.

What is at stake if the challenge is not explored?

A. Without a basis for a graded approach to siting for SMRs, the potential exists for siting considerations based largely on LLWRs to preclude SMR siting in locations which would otherwise be adequate considering SMR technologies. This would be particularly limiting in the case where SMRs are relied upon to provide electricity or process heat to a co-located facility or a community in close proximity.
B. Different approaches to siting across countries and differences in public opinion may raise questions of safety that limit SMR deployment. Community preferences may preclude siting if the public does not fully understand the benefits and risks of SMRs.

Other ongoing work

- The U.S. Nuclear Regulatory Commission is considering alternative siting criteria for SMRs and AMRs.
- The U.S. Department of Energy is pursuing a consent-based approach to siting for interim waste storage facilities.

Any other notes

US NRC: SECY-16-0012, Accident Source Terms and Siting for Small Modular Reactors and Non-light Water Rectors, February 7, 2016.

5. Staffing Issues

	Planned	Emergency	Existing
Pre-operational	X	X	
Operational	X	X	
Decommissioning	X	X	

What are the associated RP aspects?

A. Staffing could be considered problematic in similar ways to issues that currently exist in the nuclear industry. There is a diminishing number of persons available in the field of RP to support SMR development and deployment. This would apply across the industry, including applicant/vendor/operations/emergency RP staff as well as sufficiently trained and knowledgeable regulatory RP professionals (including inspectors and design reviewers).
B. The use of automated processes in new designs (to reduce the number of supporting staff) may be a challenge to determine an appropriate number of qualified RP staff onsite for safe operation. It will need to be determined how many RP staff will need to be available if automated processes fail. This would be of particular concern for those SMRs planned for remote locations. Additionally, staffing may be different for a single SMR on one site to several or more on another site (for example, there may be one central control room for shift or emergency purposes). Enough qualified RP personnel need to be available for emergency response.
C. Generally, it will be a challenge to ensure that trained and qualified RP staff are available prior to the commencement of and throughout operations. RP staff will need to have sufficient knowledge, training, and experience in RP issues relevant to the specific design for the safe operation of the facility and managing upset conditions and emergencies. This may be difficult given current uncertainties in automated processes, the type of fuel, safety systems and containment structures.

What are the benefits if the challenge is explored?

A. Guidance for NEA member countries on expected staffing levels for different technologies under different operational states and exposure scenarios.
B. Recommendations on training and staff qualifications for the facility and the regulator.
C. Possible development of training programs to enhance the number of RP professionals available.

What is at stake if the challenge is not explored?

A. There may be a lack of guidance in RP staffing levels for NEA member countries for different types of SMRs at all phases of the lifecycle and accident scenarios.
B. Lack of drive to actively pursue and establish training programs for RP professionals.

Other ongoing work

n/a

Any other notes

n/a

6. Lack of Operating Experience (OPEX)

	Planned	Emergency	Existing
Pre-operational	X	X	
Operational	X	X	
Decommissioning	X	X	

What are the associated RP aspects?

A. A lack of OPEX for new and novel SMR designs could potentially impact several areas related to RP. While NEA member countries may have regulations requiring the demonstration of the application of As Low As Reasonably Achievable (ALARA) in the physical design of the facility, a lack of OPEX can be problematic from an RP perspective in the assessment of these designs by the regulator. The applicant/vendor must demonstrate that they meet the intent of the requirements without supporting OPEX and the regulator must determine whether to accept or reject their methodology in accordance with existing regulatory requirements. There could be gaps in knowledge, regulatory requirements, and oversight. Further complicating this are issues preventing the release of OPEX such as intellectual property rights for some countries and security issues (ex. naval power plant).

B. Under normal operating conditions, there could be RP-related concerns for storage of the waste generated (short and long term). Unexpected or unanticipated RP issues may arise through the handling and management of fuel defects. For example, systems may be impacted by failed/defect novel fuels, resulting in unanticipated dose rates, which could be of concern for maintenance activities given the smaller footprint. The decontamination of these systems and how the collected contaminants are handled/stored/disposed of will be of RP interest.

C. Other areas for which there is a lack of OPEX that could be of concern to RP are the assessment and response to possible small—or large-scale accident or malfunction scenarios with novel source terms. This could include the appropriate determination of the EPZ, emergency management requirements (including appropriate RP training), and appropriate passive and active emergency systems. There may be potential gaps in the existing modelling systems for AOO/Design Basis Accident (DBA)/Beyond Design Basis Accident (BDBA) and how they apply to new designs/technologies/fuels.

D. Automated processes for new designs may pose a challenge for RP in ensuring that qualified staff are available and knowledgeable. (See Challenge 5 – Staffing)

What are the benefits if the challenge is explored?

If explored, the results could support:

A. Development of regulatory guidance and licensing review materials for NEA member countries.

B. Determining areas of radiological hazards which may not have previously been considered or identified.

C. Understanding whether current software modelling for AOO/DBA/BDBA is appropriate or if new software needs to be developed.

D. Possible development of a database for sharing or knowledge/OPEX for regulatory bodies for the different technologies.

E. Improvements in sharing OPEX related to sensitive information.

What is at stake if the challenge is not explored?

NEA member countries may not have sufficient guidance for the consideration of RP and PH or the means to validate and verify RP assumptions (i.e., novel software, fuel fabrication, training))

Other ongoing work

- TWG-SMR – IAEA
- Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for Small Modular Reactor Deployment - IAEA

Any other notes

Ties to all other areas

7. Emergency Preparedness and Response (EPR)

	Planned	Emergency	Existing
Pre-operational		X	
Operational		X	
Decommissioning		X	

What are the associated RP aspects?

Emergency preparedness ensures protective actions for emergency workers and the public can and will be taken in the event of an emergency. Emergency preparedness for various nuclear facilities applies a graded approach. The characteristics of potential accidents, including the timing and types of radionuclides released, are used to scope the planning efforts. Significant experience exists with emergency planning for LLWR and smaller nuclear facilities, but the planning needs for an SMR will need to be commensurate with the specific risks for those facilities. Challenges to this approach include:

A. Emergency Planning Zones (EPZs)
The EPZ is a planning tool used to facilitate protective action decision-making and implementation, but not all licenced nuclear facilities use EPZs in their planning. Whether or not an SMR needs an EPZ to support the planning has been a topic of considerable discussion. Even so, most of the discussion only centres around purely technical approaches to sizing the EPZ or assuming an EPZ is needed on the grounds of public assurance. However, little work has been done to explain the purpose of the EPZ and its relation to the planning and to explore whether an EPZ would even benefit the planning for an SMR. As such, the topic of EPZs will continue to be one with substantially disparate views.

B. Protective Actions
Emergency planning for LLWRs relies on evacuation and expedient sheltering-in-place as prompt protective actions. Yet protective actions are not without their own risks, and the non-radiological consequences of evacuation and relocation are well documented. SMRs are expected to have design features that would result in much smaller releases of radionuclides and extended times to release. In addition, some intervention levels are based on LLWR source terms and an expected mix of radionuclides. Such intervention levels might not be suitable for some SMRs. This suggests that protective action strategies for SMRs should be different from the strategies relied on for LLWRs. However, there is little guidance on how to develop effective protective action strategies for SMRs.

C. Defence-in-Depth (DiD)
EP is the last and final layer of DiD. While SMR designers are eager to prove the safety case of their designs, the enhanced safety can lead to a false assumption that the design is so safe as not to require planning. Furthermore, while safety criteria for designs can be demonstrated through analysis, EP is not based on risk and there is no calculation to determine whether or not EP is needed. Even for some SMR types in which the likelihood of an accident is very low, EP is still needed as the final layer of defence. But this creates a unique challenge in balancing the extent of planning needed to ensure safety for very low likelihood high consequence accidents against the regulatory burden of maintaining the readiness to respond. This is particularly challenging in that the risk profile of the SMR may be dominated by extreme external events, which needs to factor into the planning.

D. Technology Inclusive Approaches
EP programs and guidance for nuclear power plants are largely based on LLWR (PWR and BWR) technology. However, some SMR types include non-light water reactors and/or contain design features that will make the source terms and accident characteristics significantly different from LLWRs. Planners will be challenged to develop response tools for each unique design. In addition, traditional tools like dose projection software may not be essential to SMR emergency planning and response and new approaches may be needed. While EP requirements can be prescribed in a technology-inclusive framework, little work has been done to provide guidance for developing effective emergency plans for specific SMR types.

E. Education
Emergency managers and the public are mostly familiar with EP for LLWRs. Establishing a protection culture for SMRs that promotes a reasoned response to accidents at SMR facilities will require extensive education on SMR technologies. However, educational materials targeted to emergency managers, public

officials, and the general public are lacking. Without education on SMRs, experience with LLWRs is likely to form the basis for action.

What are the benefits if the challenge is explored?

A. Additional guidance in the areas of EPZs, protective actions, severe external events, and technology-inclusive approaches to EP for SMRs would benefit the deployment of some SMR types by providing consistent and acceptable methods for addressing the planning needs.
B. Right-sizing the planning efforts for SMRs will provide cost-savings to communities and operators of SMRs without compromising public health and safety.
C. Educating emergency managers, public officials, and the public on SMR technologies and the associated risks and benefits will promote a protection culture that supports informed decisions during emergencies.

What is at stake if the challenge is not explored?

A. Significant differences in approaches to EP for SMRs will affect perceptions of the safety of SMRs. Overly conservative approaches with expansive EPZs, and massive drill and exercise programs are likely to be a huge burden on response agencies in both time and money with little gain for public health and safety.
B. Without a practical and sustainable approach to EP for SMRs, as the number of SMR reactor sites increases, the burden on response organisations will significantly increase.
C. Without additional work to explore creative, technology-inclusive approaches to EP, the planning needs for SMRs and response tools will need to be developed specifically for each application.
D. Without education on the risks of SMRs compared to other types of nuclear facilities, response actions during emergencies may result in more harm than good.

Other ongoing work

- The U.S. Nuclear Regulatory Commission has developed a final rule for EP for SMRs that is performance-based, technology-inclusive, consequence-oriented, and risk-informed. The final rule includes guidance for a scalable approach to EPZ sizing.
- The IAEA initiated a coordinated research project on the development of approaches, methodologies, and criteria for determining the technical basis for EPZs for SMRS. An IAEA TECDOC is forthcoming.

Any other notes

n/a

8. Transport

	Planned	Emergency	Existing
Pre-operational			
Operational	X	X	
Decommissioning	X	X	

What are the associated RP aspects?

A. Safeguards and security aspects: SMR technology results in increased number of smaller reactors (compared to common NPP) in probably more remote places. Therefore, it can be harder to control the transport routes. Are the aspects of Safeguards and security comparable to regular NPP?
B. Modes of transportation: Different SMR types result in different fuels/fuel types. Also, the transport of whole modules has to be considered (marine based SMRs, battery-type SMRs). Can transport of fuel/waste/modules be conducted with the same modes of transportation as for common NPP? (vehicles, routes, packages, fixing)
C. Higher/Lower risk of transport accidents because of increased/lowered (lifecycle cores) number of transports and different modes of transports?
D. Regulations/Laws for transport: Can we apply the same rules/laws that are already established for transport or do we need a new set of rules/laws; Cross-border regulations – established or need to establish?
E. Communication of transports – communication aspects should be explored

What are the benefits if the challenge is explored?

A. Safeguards and security aspects should be explored, to reassure the public, that there is no increased risk due to safeguards and security in the context of SMR deployment.
B. Modes of transportation should be explored, to develop new transportation packages or modes if necessary for some SMR types. The benefits of this would also be to increase public acceptance.
C. The risk of an increased number of transport accidents should be explored. Is there a way to reduce these risks?
D. Regulation/lawmaking always has to be involved in the development of new SMR types. This is to set the regulatory framework and to take responsibility as a regulatory authority.
E. Communication aspects should be explored to assure the trust of the public.

What is at stake if the challenge is not explored?

A. If Safeguards and security aspects are not explored, the public acceptance could be weakened and SMRs could be seen as more dangerous compared to regular NPP.
B. If modes of transportation are not explored, then these problems might become apparent during operation, which is a worse way to explore these problems.
C. If a possible increased risk for the number of transport accidents is not explored, then these increased risks might manifest themselves during operation.
D. A lack of regulation/lawmaking might be perceived as a lack of taking responsibility on the part of the regulatory authority.
E. If there is no good communication strategy, there is a risk of conflict concerning transport aspects

Other ongoing work

- Germany: research projects concerning safety of SMRs and possible source terms and affected areas

Any other notes

- UK-Study on "Transportation of small modular reactor modules: What do the experts say," Proceedings Paper: Mignacca, B, Alawneh, AH and Locatelli, G (2019); In: Proceedings of ICONE27. 27th International Conference on Nuclear Engineering (ICONE27), 19-24 May 2019, Tsukuba, Japan. Japan Society of Mechanical Engineers

9. Public Risk Perception and Risk Communication

	Planned	Emergency	Existing
Pre-operational			
Operational	X	X	X
Decommissioning	X	X	X

What are the associated RP aspects?

A. According to the literature, one of the primary determinants that influences perception of risk is trust. Trust between experts and the public is dependent upon effective risk communication and a mutually respectful relationship. Other determinants of risk perception include: familiarity with the subject, voluntary versus involuntary actions, and perceived benefit. These, and other determinates, play a key role in ensuring that public doses are communicated in an effective manner whereby the benefits are compared to the perceived risks of the technology.

B. Some challenges that are associated with public dose and perception of risk are:
   a. Risks are perceived differently between experts and members of the public.
   b. Lack of collaboration between radiation protection specialists and social scientists.
   c. Socially divisive political decisions, where economic benefit may appear more important than community benefit.
   d. Understanding what the perceptions of risk and fears are of the local community to focus education or resources into empowering these groups to make an informed decision.
   e. Obtaining stakeholder engagement at all parts of an SMR licensing process by providing the necessary resources and education to have informed stakeholders. This may require a look at the education curriculum to teach people about nuclear technology.
   f. Ensuring that stakeholders have a mechanism to influence the decision of the authority having jurisdiction (AHJ).
   g. Educating the public on the technology, this takes human and financial resources, and may not draw large segments of the population who may or may not be keen to learn.
   h. Developing a risk communication strategy that is effective and includes experts readily available to inform the public and answer their questions/concerns. This risk communication strategy requires a feedback mechanism to evaluate the effectiveness and make improvements where necessary.
   i. Having a forum for the public to interact with experts and voice their concerns prior to any decisions on key milestones are made in the licensing process.
   j. The regulator being in good standing with the public, so that it can be trusted.

What are the benefits if the challenge is explored?

A. Given the multitude of SMR technologies and their portability/use, it is important that these challenges are explored in further detail. Past experience with nuclear technology has shown that events and incidents could have a significant psychosocial impact on the public. That being said, new technology has greatly increased the safety envelope. Thus, it is necessary to educate the public on the safe and clean energy generation potential of nuclear power and the robust regulatory framework that ensures their protection. Accordingly, public doses have been greatly reduced even under the most severe accidents and therefore pose a smaller risk to the public and environment.

B. Further exploration of the RP and risk perception challenge has the potential to bring the following benefits:
   a. A more informed public (i.e., helping citizens make informed decisions).
   b. Improving radiological risk governance (i.e., regulation and operation).
   c. Greater understanding of SMR technologies (i.e., including the unlikeliness of radioactive releases).
   d. Reduced fear of nuclear technologies (i.e., which may not increase acceptance).
   e. A greater understanding of how regulatory and operator actions can impact the lives of members of the public.
   f. Improved relationships and levels of trust.
   g. Improved collaboration between diverse stakeholders.

What is at stake if the challenge is not explored?

A. Not exploring this challenge further risks having a public that is fearful of nuclear technology and mistrustful of the nuclear community (e.g., Regulators, operators, vendors, etc.) that their safety is not the number one concern. B. Where an NEA member country requires public support/acceptance for siting an SMR (or related project, such as the long-term disposal of fuel waste), a fearful public can be an obstacle to development.
Other ongoing work
There is an activity going on in the NEA High-Level Group on Stakeholder Engagement, Trust, Transparency and Social Sciences (HLG-SET).
Any other notes
This topic is not specific to any one country, all countries are battling climate change and are exploring greener forms of generating energy. The perceived risk of all new technologies is a hurdle for any form of electricity generation to get over. The risk vs reward equation is something that needs to be addressed by all forms of electricity generation and nuclear has perhaps the largest psychosocial impact of all forms of energy generation.

10. Environmental Monitoring

	Planned	Emergency	Existing
Pre-operational			
Operational	X	X	X
Decommissioning	X	X	X

What are the associated RP aspects?

The nature of environmental impacts originating from SMRs may not differ greatly, but relatively high neutron flux results in a higher generation of activated products. New management of such materials will need to be established, during all the stages of the lifecycle of the facilities. Current licensing frameworks and human and environmental monitoring requirements rely on the extensive experience of large units that use Uranium Oxide fuel. Some SMR types are marked by longer core lifetimes and higher burnups. Higher burnup of uranium fuel yields a greater amount of ^{240}Pu. That may cause difficulties in characterising radioactive waste during decommissioning processes, which can lead to non-fulfilment of monitoring plans. Therefore, minor legislation changes, including licensing regimes, will be necessary, especially in relation to the scope and content of individual and environmental monitoring programs. Identification of all the possible pathways will be one of the crucial steps that should be taken.

What are the benefits if the challenge is explored?

Most SMRs being developed have longer core lives than existing nuclear reactors. With increased core lives, the reactors and the fuel inside will be accessed less frequently. Infrequent access to the core will enhance safeguards protection because the frequency of threat diversion is reduced. This results in a higher level of radiation protection for workers and the population, and it lowers the risk of an emergency situation.

What is at stake if the challenge is not explored?

Poor public understanding of new nuclear technology and a lack of regulatory experience.

Other ongoing work

Future projects can benefit from international collaboration, exchanging information about lessons learned, and difficulties and best practices identified by early adopters through public engagement with local communities.

5. Any other notes

n/a

Appendix C. International discussions on TFSMR-identified areas

The descriptions are extracted from the related reports of each international SMR initiatives and summarised for the ten challenges the TFSMR identified.

Small compact design

EGSMR

- SMRs are characterised by their small size and modular nature, offering the potential for increased safety and economies of series production.
- The modular design allows for transportability and assembly on site, contributing to predictability and construction time savings.

SMR Regulators' Forum Pilot Project Phase

- Small core power leads to reduced decay heat load, increased core stability, a smaller inventory of radionuclides, and passive safety.
- Passive cooling mechanisms include natural circulation, gravity-driven injection, and unique designs like ceramic materials and molten salt fuel.
- An integral design incorporating primary system components into a single vessel and non-traditional or different numbers of barriers to fission product release.
- Compact and simplified design can practically eliminate severe accidents, offer inherent safety features such as more extended grace periods, and require fewer structures, systems and components. The modular design also introduces new events internal to single and between modules and new construction techniques. SMRs are produced, assembled, and tested in a factory, and facilities can consist of multiple modules.

SMR Regulators' Forum Phase 2

- The use of modularity in building and operating SMRs has safety implications. Licensees must be able to address these implications to ensure nuclear safety. This includes addressing aspects of manufacturability, inspectability, operability, and maintainability of the modules, especially in the context of alternative or novel configurations such as compact modular systems, structures and components (SSCs).
- The compact design of SMRs affects various aspects of their commissioning and operation. This includes documenting the regulatory views on expected commissioning issues, implications for licensee oversight and regulatory inspection programmes, and the implications on in-service inspection programmes due to factors like compact system design, sealed vessels, or inaccessible systems.

SMR Regulators' Forum Phase 3

- The compact size of SMRs poses challenges in achieving the independence of barriers for containment compared to larger reactors. Despite these challenges, designs should include multiple independent and diverse means to ensure the

function of containment is met for all operating states, aligning with the DiD approach.

- The compact design of SMRs presents new regulatory considerations, including the potential for entire plants to be delivered as a single package or for reactors to be refuelled.
- The advent of modular design and construction for SMRs means that whole safety system modules may be manufactured. This modular approach, facilitated by the small compact design of SMRs, could impact regulatory oversight, particularly in ensuring the safety integrity of these modules.
- SMRs often have a lower inventory of nuclear material, which can lead to reduced residual heat and a smaller potential source term for radioactive releases. The reduced power capacity of SMR cores lessens overall cooling requirements, enabling a broader selection of sites by optimising the number of modules per site. This feature aids in easier decay heat removal, which is particularly beneficial in single-phase flow scenarios.
- Due to their smaller cross-section, SMRs' inherent compactness offers increased resistance to earthquakes and a smaller target for missile strikes. Additionally, the compact design facilitates the use of natural circulation for decay heat removal and simplifies safety systems, reducing the likelihood of common mode failures.
- The design and location of SMRs often allow for smaller safety zones, exclusion zones and EPZs. This flexibility also enables SMRs to be utilised for various purposes beyond electricity generation, such as industrial heat production, district heating, desalination, energy storage, hydrogen generation, or combinations thereof (cogeneration).
- Certain SMR designs utilise coolants with higher heat capacity and higher boiling points, leading to simplified systems with compact coolant and heat transport loops. This results in lower fluid pumping requirements and stable energy transport at near-constant temperatures.

SMRAG

- SMRs have a small power output and compact architecture, often employing passive safety systems, reducing the reliance on active safety systems and additional pumps.
- The compact architecture allows for modularity in fabrication, which facilitates higher quality standards.
- Lower power leads to a reduced source term and smaller radioactive inventory in the reactor.
- SMRs can be located sub-grade (underground or underwater) for added protection against natural or man-made hazards.
- The modular design and small size make having multiple units on the same site feasible.
- SMRs require less cooling water, making them suitable for remote regions and specific applications like mining and desalination.
- SMRs offer the potential for removing the reactor module or in situ decommissioning at the end of its lifetime.

- These features make SMRs adaptable for niche applications, including isolated electrical systems, district heating, and chemical processes.

European SMR pre-partnership

- One key advantage of SMRs is their small size and modularity. This allows them to be delivered in a series of reactors.
- The small and modular nature of SMRs provides many possibilities for different technologies and vendors. This aspect is similar to the aerospace industry, where a limited number of identical aircraft are delivered worldwide.

Source terms

SMR Regulators' Forum Pilot Project Phase

- Regulators require input and output files to verify source terms and offsite consequences. Suppose applicants use methodologies or codes that are not pre-approved. In that case, they must provide all supporting input, output files, and source codes for computer modelling that support the analysis and determination of source terms.
- The need for estimating source terms for accident scenarios identified in safety analyses. Designers may use mechanistic source terms for design-specific accident scenarios and progression. This approach can influence the request for a smaller EPZ than a LR site.
- The source term includes a list of all radionuclides that would be released into the environment following the selected accident and the functioning of all safety systems as expected under accident conditions. The source term also encompasses the release duration and other parameters, such as stack height. The source term is critical for effectively establishing emergency planning policies and procedures, including determining the EPZ.

SMR Regulators' Forum Phase 2

- There is a need to identify criteria against which specific event sequences and accident scenarios in SMRs are considered severe, especially considering the potential for barrier failure leading to radioactive release or fuel relocation. This is crucial for some SMR designs where the concept of "core melt" is not applicable, and the potential for severe consequences arising from actions required for clean-up following an accident, including in the case of multi-module units and co-located facilities, should be considered.

Environmental impact assessment (EIA)

None.

Siting

SMR Regulators' Forum Phase 2

- The licensing process for nuclear facilities, as outlined in IAEA safety standards and guides, applies to licensing regulated activities associated with the siting of SMR facilities. The licensee is responsible for the safe conduct of licenced activities, including siting, and must establish safety and control provisions consistent with DiD requirements. It is important to integrate safety and security considerations in the design assessments of SMRs, including aspects such as underground siting.

SMR Regulators' Forum Phase 3

- The design must consider different elevations, including above-ground and below-ground constructions. The containment systems and structures must be designed to ensure safety across these varying elevations.
- For containment structures built below grade, considerations must include material types, siting restrictions, and the impact of below-grade construction on seismic responses. The design must protect against water intrusion, submergence, and consequential effects, taking into account the presence of naturally occurring gases or vapours in underground structures.
- Siting considerations cover evaluating the site's ability to support safe nuclear operations. This involves assessing seismic and hydrological conditions, geotechnics, and groundwater, including the effects of climate change. Critical considerations include the stability of the reactor facility's foundations and the integrity of below-grade structures. Additionally, the design must withstand weather conditions and consider the reasonably foreseeable effects of climate change over the facility's lifetime.
- Designs must include provisions to prevent accidents related to internal and external hazards, including natural and man-made events. This may involve specific design requirements for containment systems based on siting considerations such as underground/submerged containments or floating SMR installations.

SMRAG

- The site approval process for SMRs would be similar to that for current nuclear power plants (e.g. Early Site Permit in the United States).
- There is a need to consider how the unique features of SMRs impact site selection, such as smaller output, lower source material, and sub-grade installation, and their effects on the site size, environmental impact, and emergency planning.
- Many new sites may be required, some possibly close to cities, emphasising the importance of public acceptance.

Staffing issues

EGSMR

- The impact of significantly reduced or no on-site operations staff for remote operations maintenance and emergency preparedness, as well as the control of multi-unit/multi-module plants by a team of operators.
- The importance of considering the impacts of shared control rooms in the case of remote operations or multi-unit/multi-module plants.
- The EGSMR suggests a review of efforts in this area, most suitable by the Working Group on Human Factors (WGHOF), whose participants are skilled and have already begun research. Such a review could form a foundation for developing guidance on addressing human factor challenges to mitigate issues that may arise in these areas.
- The document highlights important connections to activities being conducted at the Halden Human Technology Organisation (HTO).

SMR Regulators' Forum Pilot Project Phase

- A single operator may operate multiple modules.
- Staffing in the control room is crucial. Operators may need to perform emergency response tasks simultaneously across multiple modules.
- A lack of operational data is a concern related to staffing and operations.

SMR Regulators' Forum Phase 2

- Multiple modules or units at a site could exacerbate plant personnel's challenges during an accident. Events and consequences of an accident at one unit may impact the progression or management of an accident at a neighbouring unit. This scenario highlights the need to carefully consider available resources, including personnel, and ensure that staff are adequately prepared and equipped to handle such complex situations.

SMR Regulators' Forum Phase 3

- It is crucial for all stakeholders, including vendors, the supply chain, licensees, and regulators, to recruit staff with nuclear safety experience. This is vital for the safe execution of SMR projects and to mitigate the risk of delays in project schedules and regulatory processes.
- Organisations new to the nuclear sector may lack experience in the regulatory environment or licensing processes, which could lead to challenges in understanding their responsibilities, especially regarding supply chain oversight.
- The introduction of SMRs is driving an increased demand for skilled and experienced resources across the nuclear industry. This demand requires short-term innovative solutions, such as shared resources or technology and service-based models, and long-term strategies, including education and training programmes to fill knowledge gaps and establish a safety culture among licensees, vendors, and the supply chain.

- Capability assessment, an objective and outcome-based process, should include benchmarking as a key component. This approach helps in developing a comprehensive understanding of capabilities, covering not just the competence of personnel but also the tools and processes employed to ensure safety. The document suggests leveraging existing large nuclear power plant licensees' experiences and regulatory standards to inform the capability assessment for SMR licensees, acknowledging that benchmarking information specific to SMRs might be limited initially.

European SMR pre-partnership

- Insufficient human resources may be the most important bottleneck for developing and deploying SMRs. Suggesting that requesting a planned and structured preparatory programme involving universities and research centres could be important. This programme would aim to address the staffing challenges by developing the necessary skills and capacities.

Lack of operating experience (OPEX)

EGSMR

- There is a need for new analytical tools or validation of current tools for new reactor technologies due to limited OPEX.
- First-of-a-kind (FOAK) SMRs should be equipped with comprehensive instrumentation to collect data, aiding in developing OPEX.
- Extensive research and OPEX supporting the safe operation of conventional reactors are potentially applicable to water-cooled (WC) SMRs. However, further investigation is needed for specific phenomena like natural circulation and passive cooling.
- The applicability of water-cooled operating knowledge is less relevant for advanced nuclear technology (ANT)-SMRs, which include designs like gas-cooled, molten salt, or liquid metal-cooled reactors (e.g. sodium lead).
- While new designs of both WC-SMRs and ANT-SMRs promise safer operations than existing reactor fleets, their safety cases have yet to be fully demonstrated to regulatory authorities.
- Building evidence for the safety claims of these new SMR designs requires experimental support, experience, and sound safety assessments.

SMR Regulators' Forum Pilot Project Phase

- The intent of gathering OPEX is to demonstrate the integrated performance of SMRs and support safety claims and the effectiveness of plant features.
- Lack of OPEX for novel features of SMRs increases uncertainties. These uncertainties are reflected in safety analyses and affect overall outcomes.
- The regulatory process aims to understand and address these uncertainties in the design and operation phases until sufficient OPEX has been generated and reviewed.

- Historically, the lack of OPEX has led to implementing supplemental measures in demonstration plants. These measures include increased safety margins, additional SSCs, and restrictions on the operating envelope.

SMR Regulators' Forum Phase 2

- FOAK facilities, the demonstration of practical elimination of severe accidents needs to consider the absence of OPEX.
- Licensees of SMRs are expected to demonstrate how their commissioning programme accounts for uncertainties due to the lack of OPEX. This includes managing deviations and non-conformances, using safety classifications, and recognising that suppliers with modular design experience might not have nuclear sector experience.
- Most SMR technologies have limited OPEX, if any. The substantiation of safety claims by technology developers is often still in progress, and in some cases, early OPEX is emerging from technology assessment, construction, and operation.
- For FOAK facilities, it is necessary to systematically identify, account for, and address uncertainties in performance claims, especially for passive and inherent safety features. This involves using validated computer models, experimental systems, compensatory design enhancements, control provisions, and other activities necessary to demonstrate or support functional performance claims.

SMR Regulators' Forum Phase 3

- The varied nature of SMRs means existing regulatory arrangements and protocols may require reconsideration to ensure sufficient regulatory assurance. This may involve adjusting to novel technology not covered by existing design codes and facilitating regulators' access to vendor manufacturing facilities, potentially in other jurisdictions.
- Given the unique challenges presented by SMRs, there is an emphasis on the importance of sharing experiences and regulatory practices among Member States. This collaborative approach is vital for effectively addressing the challenges associated with SMRs.
- SMRs present novel technological features that lack extensive OPEX, posing challenges in reliably informing Risk-Informed and Performance-Based Decision-Making (RIPB-DM). The report recommends recognising these limitations in implementing an integrated 3S (safety, security and safeguards) approach.
- Early fundamental design decisions for SMRs aim to meet safety objectives, learning from OPEX, among other factors. Systems engineering integrates various aspects to develop comprehensive plant-level and system-level objectives. The process aims to identify potential conflicts and synergies between safety, security and safeguards (3S) early on.
- The inherent novelty of SMR technology means there might be insufficient reliable data to inform the RIPB-DM process effectively. This limitation is acknowledged as one that needs recognition in the application of the integrated 3S approach.
- The emergence of operators and vendors with less traditional nuclear industry experience, coupled with the potential difficulties in performing inspections of integrated systems post-assembly, underscores the challenges and learning

opportunities faced by the advent of SMRs. These issues highlight the importance of adapting regulatory, safety, and operational frameworks to accommodate the unique characteristics of SMRs.

SMRTF

- When selecting safety options, it is important to consider feedback from OPEX, including lessons learnt from significant events in previous reactors. Licence applicants must explain how these experiences and corrective actions have been applied or considered in new designs. This includes innovative features or techniques proposed to enhance the safety and reliability of new reactor concepts or technologies.
- For unproven designs or deviations from established engineering practices, safety must be demonstrated through supporting research programmes, performance tests, and examining OPEX from other relevant applications.
- Pre-licensing and licensing activities associated with Fast Neutron Reactors SMRs as significant or primary challenges. This includes, limited to no design, little regulatory or OPEX with reactor technology, the necessity for research and development, challenges in fuel design and demonstration, and the need for material development.

Emergency preparedness and response (EPR)

EGSMR

- Identified the investigation of EPZs and emergency response requirements for SMRs as a cross-cutting safety issue. Many SMR designs aim to reach an accident robustness level sufficient to demonstrate that EPZs would be limited to the site boundary, with no off-site emergency response requirements needed. This is a challenging position to attain, and further actions are required to address emergency preparedness and response issues for SMRs. It is aware of ongoing efforts by the IAEA and NEA's CRPPH in this area.

Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and SMRs

- The use of novel materials and the proximity to industrial facilities that might be co-located with some SMRs might exacerbate non-radiation related hazards (chemical, explosions, fires) that would need to be considered in the overall emergency arrangements.
- New or reduced source terms associated with some SMRs can reduce the off-site consequences of a severe emergency, thereby decreasing the size of EPZs and distances and associated level of planning for off-site emergency response.
- Some SMRs are claimed to be designed to be self-sufficient and, thus, can have the capability to be located in remote areas. Such a location would increase the response times needed by external (off-site) emergency services (e.g. firefighting, medical teams) to mount an effective response and, in general, would impact the associated emergency arrangements.
- There are claims that for some SMRs, the slower accident kinetics leading to releasing radioactive material into the environment might allow for less urgency in implementing off-site public protective actions.

- Co-locating Enhanced Inspection Devices with existing nuclear power plants and multi-module plants could lead to simultaneous events impacting several modules and units, straining resources needed for emergency mitigation on and off-site. This may limit the use of dedicated emergency facilities. SMRs may depend more on remote services, challenging emergency arrangements for SMRs.
- The use of novel materials (e.g. liquid metal coolants and molten salts) might pose new or different non-radiation-related hazards that might jeopardise the effectiveness of the emergency response and might drive the emergency response goals differently. This will impact the design of the necessary emergency arrangements for these reactors.
- Transportable Nuclear Power Plants (TNPPs) may require emergency arrangements that differ from those of stationary reactors. This is particularly relevant for the arrangements needed to respond effectively along the transport route of the components loaded with fuel or containing activated primary coolant or effluent. These arrangements have to cover the route from a factory to the deployment site and, if applicable, to a service and refuelling facility in an integrated manner.

SMR Regulators' Forum Pilot Project Phase

- EPZs are controlled by external authorities, separate from the onsite exclusion zone controlled by the licensee, with their size and implementation informed by safety considerations and local factors.

SMR Regulators' Forum Phase 2

- The presence of multiple modules or units at a site could exacerbate the challenges faced by plant personnel during an accident. Events and consequences of an accident at one unit may affect the progression or management of an accident at a neighbouring unit. This necessitates considering whole site risk and developing methods for aggregating risk from different on-site sources.

SMR Regulators' Forum Phase 3

- Emergency preparedness and response involve co-ordination between nuclear safety and nuclear security measures, particularly in command and control during emergencies. Comprehensive co-ordination is necessary to address decision-making and responsibility allocation.
- Licensees are encouraged to integrate safety and security procedures and emergency response and security response plans as part of their emergency preparedness and response strategy. This is particularly crucial for SMRs due to potential challenges associated with remote operation, siting, and other aspects. Identifying and minimising potential conflicts between safety and security measures is vital in developing emergency preparedness procedures.
- SMRs' unique aspects, such as their potential for remote operation and specific siting considerations, add complexity to emergency preparedness and response efforts. It is important to tailor emergency preparedness procedures to address these unique challenges effectively.

Transport

EGSMR

- Safety and security aspects related to the transport of fuelled nuclear modules and transportable/floating SMRs. Some SMR designs involve transportable fuelled nuclear cores or floating vessel configurations, raising safety and security concerns.
- Recommendations include consulting with the IAEA initiative on the design safety of Transportable Nuclear Power Plants and a joint assessment of this issue by multiple CSNI Working Groups.

SMR Regulators' Forum Pilot Project Phase

- There is potential for damage to modules during transport and size limitations for transport. These factors need to be considered in the design and logistics of transporting SMR modules.

SMR Regulators' Forum Phase 2

- The report identifies the need to determine the integration of safety and security considerations in SMR design assessments, including aspects like the transport of factory-fuelled modules.

Public risk perception and risk communication

SMRAG

- Acknowledgement of the importance of public acceptance, and it should not be underestimated.

European SMR pre-partnership

- It emphasises that this initiative's analyses and resulting concepts must be subject to wide public scrutiny and communication to address public risk perception effectively.

Environmental monitoring

None.

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