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On the applicability of the IAEA documentation to innovative reactors

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ABSTRACT

Selected findings of a high-level review on the applicability of IAEA Safety Standards to small modular reactors (SMRs) and Generation IV designs are presented. The evaluation has been performed in the framework of the HARMONISE project covering twenty high-level IAEA documents focusing on nuclear safety issues. The study has taken into consideration both conducted and ongoing initiatives that evaluated document applicability to innovative technologies and SMRs, while it has been complemented with a gap analysis leading to the formulation of proposals for amended as well as novel paragraphs and requirements for the IAEA documentation.

1 INTRODUCTION

The European Commission has recognized the need to "… *facilitate the establishment of a common understanding on licensing methodologies for advanced technologies between nuclear safety regulators, contributing to harmonisation of licensing methods of future installations.*" [1]. It is the enhanced interest in designing and constructing novel nuclear reactor concepts – collectively identified as 'evolutionary and innovative designs' (EIDs) – that has spurred the requirement to examine the current IAEA safety standards under the prism of their appropriateness to innovative reactor designs, while also recognizing potential gaps that may exist within the IAEA documentation [2]. On that matter, IAEA has performed

comprehensive reviews on the applicability of a number of safety standards to various types of non-water-cooled reactors (non-WCRs) and SMRs [2].

In this framework, HARMONISE [3] has carried out a high-level review of the applicability of IAEA Safety Standards to SMRs and Generation IV reactor concepts identified by the Gen-IV International Forum (GIF) [4], namely: gas-cooled fast reactor; lead-cooled fast reactor; molten salt reactor; sodium-cooled fast reactor (SFR); supercritical-water-cooled reactor; very-high-temperature reactor. The EIDs selected for the study have been designed with various types of coolant, fuel, neutron spectrum, inherent safety features and modular concepts. A number of research and development projects worldwide are focusing on these EIDs having achieved various maturity levels.

The evaluation performed covered several among the high-level IAEA documents from the IAEA Safety Standards, i.e., Safety Fundamentals (SFs), General Safety Requirements (GSRs), Specific Safety Requirements (SSRs) and Specific Safety Guides (SSGs). The works addressed issues related to safety without examining nuclear security, while also considering the findings of similar studies performed by IAEA, WENRA, GIF and the SMR Regulators' Forum as well as the outcomes of pertinent Euratom-funded projects. Despite their generic nature, in particular for GSRs and SSRs, the publications examined are not completely technology neutral, which motivates the recommendations that are formulated in order to make them applicable to all nuclear facilities and activities.

The review considered crucial technical aspects such as multi module SMR concepts, factory-built and potentially factory-fuelled designs that ought to be transported as well as cogeneration. Functional and technical topics contemplated include the employment of passive systems, consideration of inherent safety in the implementation of the defence-in-depth (DiD) concept, deliberation on the term 'core melt', recognition of the consequences of low-level operating experience, along with facility commissioning, operation and decommissioning. The work was supplemented by a gap analysis and subsequent proposals of new as well as amended paragraphs and requirements. The suggestions emerging from the HARMONISE findings should be viewed as proposals put forward for further perusing.

The following section sketches the approach followed to review the IAEA documents and provides an indicative example of its output. Selected findings from the review outcome are discussed in Section 3, where the gaps or areas for additional consideration discerned in twenty IAEA documents are summarised and recommendations are made. The conclusions drawn from these works are discussed in the last section.

2 EVALUATION METHODOLOGY

The evaluation assumed as a starting point an IAEA document as shown in Figure 1, while the evaluation was restricted to SFs, GSRs and SSRs and a number of SSGs. Notions that appear in various documents (e.g., DiD, core degradation, containment integrity) were discovered and analyzed individually resulting in 'generic' proposed strategies for reformulation of each evaluated IAEA document. In a typical example, a technical category (i.e. SFR) and a relevant topic (i.e. DiD) appear at the bottom of Figure 1 where SFR concepts need specific requirements (i.e. consideration of sodium fires) and the topic is discussed in several IAEA documents. Thus, it becomes essential to assure the consistency of the recommendations made on a certain topic.

A number of finalized and on-going activities examining the applicability of IAEA standards and assessing the harmonisation needs of regulations and expectations have been recognized. In this framework, the assessment of novel technologies mandates the formulation of requirements and expectations in a technology neutral manner. Thus, for document segments under review that are not applicable to specific reactor designs, proposals are made for requirement modifications endowed with generalization by using, for

example, more general terms. Identified gaps due to reactor design peculiarities could be eliminated either, by adding design specific requirements or, by keeping the requirements more general and developing additional design specific documents.

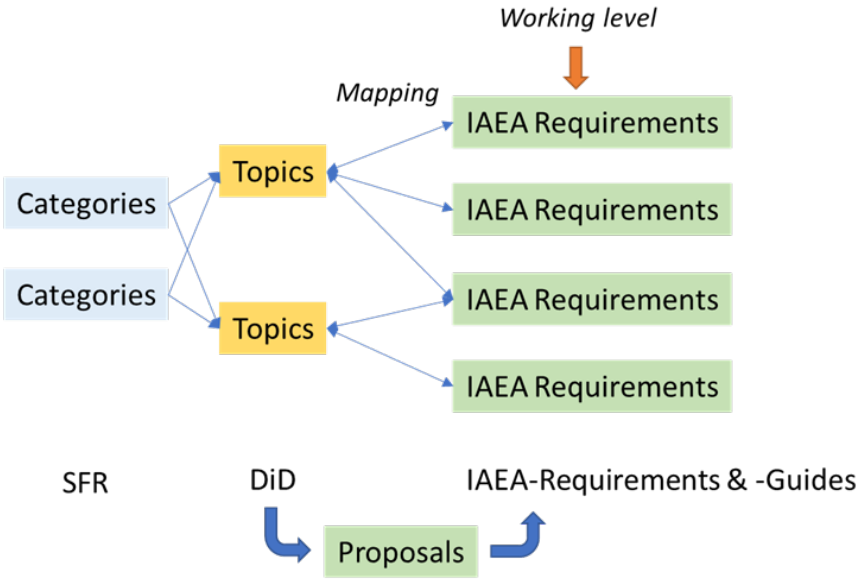

Figure 1: A graphic illustration of the IAEA document evaluation process

An example of a proposed amendment appears in Table 1, where the discovered issues inspired a proposal for an amended requirement statement.

Table 1: Example of a proposed requirement amendment

Requirement in SSR-2/1 (Rev. 1)	Issues / Gaps / Applicability	Proposal
Requirement 48: Overpressure protection of the reactor coolant pressure boundary. Provision shall be made to ensure that the operation of pressure relief devices will protect the pressure boundary of the reactor coolant systems against overpressure and will not lead to the release of radioactive material from the nuclear power plant directly to the environment.	Some terms, such as “overpressure” and “pressure boundary” are not appropriate for designs operated with unpressurized primary coolant circuit. For high temperature gas cooled reactors “the release of radioactive material” is changed to “an unacceptable release of radioactive material”.	Requirement 48: ~~Overpressure~~ Protection of the reactor coolant ~~pressure~~ boundary <u>against excessive pressure loads.</u> Provision shall be made to ensure that the operation of pressure relief devices will protect the ~~pressure~~ boundary of the reactor coolant systems against ~~overpressure~~ <u>excessive pressure load</u> and will not lead to ~~the~~ <u>an unacceptable</u> release of radioactive material from the nuclear power plant directly to the environment.

3 SELECTED REVIEW FINDINGS AND RECOMMENDATIONS

A thorough narrative of the task fulfilled and its outputs has been documented in deliverable D1.5 “Assessment of the IAEA safety objectives in advanced fission reactors” that is to become publicly available. A succinct presentation of selected review outcomes appears in the following subsections for illustration purposes.

3.1 Safety Fundamentals

3.1.1 Fundamental Safety Principles (No. SF-1) [5]

The definition of a “core” provided in the document mainly refers to designs (e.g., light water reactor (LWR), FBR) whose core is formed as a sum of multiple fuel assemblies. Such a definition is not suitable for specific technologies under development in SMRs and multi module reactors. A number of principles, such as the references to “chain reactions’’ and “loss of control of the reactor core” are specific to fission technologies and ought to be made more general to encompass all radiation sources. Furthermore, the document does not adequately address the issue of reactor transport through different States and the need to keep all parties informed. Siting degradation is not taken into consideration although during a life span that is longer than 60 years (as is the case for new reactor designs and SMRs) the site may become, in an extreme case, not suitable for hosting a plant. The gaps or areas for additional consideration have driven the formulation of a few recommendations.

3.2 General Safety Requirements

3.2.1 Governmental, Legal and Regulatory Framework for Safety (No. GSR Part 1, Rev. 1) [6]

The requirements posed in the document are practically technology independent and thus applicable to EIDs and their deployment, while areas of non-applicability were not detected. However, a few EID deployment models require a close interaction and collaboration among regulatory bodies in different jurisdictions. For instance, according to the safety standards, an EID fuelled in a foreign factory must be licensed to operate by the regulator in the vendor’s State as well as the regulator in the hosting State. It is recommended that the document provides guidance with respect to effective cooperation, assistance and sharing of experience among regulatory bodies as well as guidance on transferring or sharing of oversight from one regulatory body to another and potentially sharing of regulatory responsibilities for the different stages of a facility lifetime. These areas of further consideration stimulated a proposal for two additions in the document.

3.2.2 Leadership and Management for Safety (No. GSR Part 2) [7]

Leadership and management constitute an important part of any organization and should be independent of the technology used. Thus, the requirements listed in IAEA GSR Part 2 are, in general, applicable to EIDs. The gap analysis did not notice areas of non-applicability and therefore no recommendations were made.

3.2.3 Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (No. GSR Part 3) [8]

The document is applicable to all facilities and activities that give rise to radiation risks. It addresses the protection of workers, patients, the public and the environment in all exposure situations: planned, emergency and existing. The requirements listed in IAEA GSR Part 3 are built on the three general principles of radiation protection (i.e., justification, optimization and dose limitation) and application of the “graded approach”. Although EIDs are not specifically mentioned, many of the requirements in the document are applicable and the review revealed no gaps or areas for additional consideration.

3.2.4 Safety Assessment for Facilities and Activities (No. GSR Part 4, Rev. 1) [9]

The document is technology neutral and thus applicable to EIDs. While areas of non-applicability as well as major gaps were not discovered, a proposal has been put forward for a modification taking under consideration multi module facilities.

3.2.5 Predisposal Management of Radioactive Waste (No. GSR Part 5) [10]

IAEA GSR Part 5 is applicable to all technologies considered. It states that waste treatment must consider different physical, chemical, biological, geometrical forms in order to achieve the safety goals in compliance with IAEA SF-1 [5]. Thus, the document applies to all radioactive waste types and covers all steps in its management, while the analysis revealed no issues deserving further consideration.

3.2.6 Decommissioning of Facilities (No. GSR Part 6) [11]

The document lists the safety requirements for all decommissioning aspects. The list of facilities to which it is applicable includes nuclear power plants (NPPs), research reactors, other nuclear fuel cycle facilities, former military sites and relevant medical facilities, industrial facilities as well as research and development facilities. The identified gaps or areas for additional consideration motivated two proposals.

3.2.7 Preparedness and Response for a Nuclear or Radiological Emergency (No. GSR Part 7) [12]

The document was drafted – similarly to all GSR publications – in a technology neutral manner and it is applicable to all facilities, activities and sources "*with the potential for causing radiation exposure, environmental contamination or concern on the part of the public warranting protective actions and other response actions*" [12] (para. 1.14), irrespective of the cause ("*whether the emergency follows a natural event, a human error, a mechanical or other failure, or a nuclear security event"* [12] (para. 1.16)). The requirements also apply "*to off-site jurisdictions that may need to take protective actions and other response actions*" [12] (para. 1.15). The document assessment revealed no points of non-applicability of the requirements posed, while no gaps or areas for additional consideration were found.

3.3 Specific Safety Requirements

3.3.1 Site Evaluation for Nuclear Installations (No. SSR-1) [13]

Whereas IAEA SSR-1 specifically refers to facilities related to the nuclear fuel cycle, all facilities producing radioactive waste should follow the same disposal methods. Additionally, the safety objectives apply to all stages of a facility's lifetime – ranging from planning to decommission – and may also apply to future nuclear facilities that have yet to be defined. However, the "graded approach" outlined for research reactors is incomplete, as it only mentions thermal power. The discovered gaps or areas for additional consideration have led to three proposals.

3.3.2 Safety of Nuclear Power Plants: Design (No. SSR-2/1, Rev. 1) [14]

Parts of the document are written in a technology neutral manner being applicable to SMRs and non-WCRs. A few requirements in the document are rather specific to WCRs and need modification, clarification or interpretation to become more widely applicable. Some features or characteristics, specific to innovative designs, are not covered by the existing requirements and additions are needed to close the gaps. Its scope is restricted to land

based, stationary, WCRs and this should be broadened to include non-WCRs and mobile facilities. The document has already been subjected to different reviews (by IAEA and GIF) for its applicability to advanced reactor concepts and SMRs. For those parts of the document that are not applicable to a number of reactor designs IAEA and GIF have made proposals on how to modify the requirements and use more general terms. Gaps have been found that occur due to peculiarities of reactor designs which were not initially considered by the safety standard. These could be eliminated either by adding design specific requirements or by keeping it more general and developing additional design specific documents. The detected gaps or areas for additional consideration derived more than one hundred proposals.

3.3.3 Safety of Nuclear Power Plants: Commissioning and Operation (No. SSR-2/2, Rev. 1) [15]

The document is, in general, technology neutral and thus applicable to EIDs. Nevertheless, an analysis performed by IAEA [2] has listed a number of gaps while the review revealed issues in relation to the fuel integrity of EIDs with liquid fuel for which two proposals were made.

3.3.4 Safety of Research Reactors (No. SSR-3) [16]

Most of the design and safety requirements listed in IAEA SSR-3 are technology neutral and therefore are generally applicable to all types of nuclear technologies considered. The mentioned possibility of relying on a “graded approach” in enforcing requirements adds an ulterior level of flexibility to the applicability field of the document. The analysis findings resulted in six proposals.

3.3.5 Safety of Nuclear Fuel Cycle Facilities (No. SSR-4) [17]

Most of the safety requirements established in IAEA SSR-4 are technology neutral and hence generally applicable to all types of nuclear fuel cycle facilities, including those foreseen to implement advanced nuclear technologies and SMRs. However, there are a few requirements specific to certain types of nuclear fuel cycle facilities. The review outcome has recognized issues in need of further consideration.

3.3.6 Disposal of Radioactive Waste (No. SSR-5) [18]

The document describes, in a general manner, the safety objectives and criteria for the disposal of all radioactive waste, while it lists the requirements to be met for radioactive waste disposal. It does not make a particular reference to a specific technology thus it is applicable to all technology types under consideration. However, it refers to the DiD concept that is, to some degree, specific for a few technologies such as the definition of “physical barriers”. The review found no gaps in IAEA SSR-5.

3.3.7 Regulations for the Safe Transport of Radioactive Material (No. SSR-6, Rev. 1) [19]

The document is applicable to the technologies under consideration and does not require significant adjustments for the transport of conventional radioactive materials from stationary and mobile nuclear facilities employing new technologies. Problems that may arise during radioactive material transport from facilities employing novel technologies due to the hazardous chemical characteristics of these materials (especially liquid) can be resolved by converting the radioactive materials into a form suitable for safe transport. Furthermore, it is recommended to draft a separate document listing the requirements for the safe transport of objects, especially mobile nuclear facility modules, in order to address the issues noticed.

3.4 Specific Safety Guides

3.4.1 Deterministic Safety Analysis for Nuclear Power Plants (No. SSG-2) (Rev.1) [20]

The general considerations provided in the document are written in a technology neutral manner and are applicable to all EID types. The analysis found a number of differences in a few EIDs mandating the document formulation in a more general manner and prompting a number of proposed amendments.

3.4.2 Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants (No. SSG-3) [21]

IAEA [2] considers the general considerations provided in Section 2 of IAEA SSG-3 as applicable to all EID types. However, for a few reactor concepts the meaning of “core damage/melt” might not be applicable or even different and a more generic view has to be developed for the link between Level 1 and Level 2 PSAs. Sections 3 and 4 are applicable to all EID types, while most requirements in Section 5 are applicable to all EIDs. According to [2] the recommendations in Sections 6 to 8 for Level 1 PSA for internal and external hazards appear to be applicable to all reactor technologies. Section 9 offers recommendations for Level 1 PSA for low power and shutdown modes while for EIDs more plant states/modes might be relevant and a more generic view might be necessary.

3.4.3 Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants (No. SSG-4) [22]

Section 2 of IAEA SSG-4 is applicable to all EID types, while Section 3 implies LWR designs as is the case in Section 4. In addition, Sections 4 and 5 rely on a containment used as the last barrier. The description regarding “source terms” for severe accidents is based on water-cooled concepts thus the process of “source term” categorisation has to be described in a more generic manner. Sections 7 and 8 are mostly applicable to all EIDs.

3.4.4 Licensing Process for Nuclear Installations (No. SSG-12) [23]

The document recommendations on the licensing process are mainly technology neutral and standardized plant designs are considered (i.e. Section 2.6) thus, rendering IAEA SSG-12 mostly applicable to new technologies. IAEA has stated that the document is in need of being updated with the target publication set for 2026 [24]. The revised document needs to take into consideration – among others – the recently published new versions of the related Safety Requirements and Safety Guides, provide additional recommendations related to SMR licensing and consider the lessons learned in States embarking on an NPP program and States building new NPPs.

3.4.5 Safety Classification of Structures, Systems and Components in Nuclear Power Plants (No. SSG-30) [25]

All requirements listed in the IAEA SSG-30 are applicable to EIDs and their deployment. This safety guide is formulated in a neutral manner covering all steps of a system life span: design, manufacturing, construction, installation, commissioning, test, operation, inspection and maintenance. The analysis has not detected areas of non-applicability, whereas clarification may be needed especially in the form of examples illustrating the purpose. The review has discerned gaps and areas in need of further consideration and made a number of proposals.

4 CONCLUSIONS

A concise depiction of the evaluation performed on a set of twenty IAEA SFs, GSRs, SSRs and SSGs on the basis of their applicability to advanced reactor technologies that are currently under development has been presented. A comprehensive account of the results found is given in deliverable D1.5 “Assessment of the IAEA safety objectives in advanced fission reactors” that will be openly accessible. The review is accompanied by a gap analysis that has taken under consideration the findings of similar activities. Because these documents are of high-level, large part of them is technology neutral. For a few of the reviewed documents (e.g. IAEA GSR Part 5) the evaluation has not produced proposals, while for others (e.g. IAEA SSR-2/1 (Rev. 1)) the need for updates was identified and proposals have been put forward. However, these proposals are to be viewed as suggestions made for further consideration and analysis.

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REFERENCES

[1] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-euratom-2021-nrt-01-06, retrieved on 5 September 2023

[2] IAEA, Safety Report on Applicability of Safety Standards to Non-Water-Cooled Reactors and Small Modular Reactors, IAEA Safety Reports Series No.123 [IAEA Preprint], 2022

[3] https://harmonise-project.eu/, retrieved on 5 September 2023

[4] Gen-IV International Forum (GIF), Technology Roadmap Update for Generation IV Nuclear Energy Systems, OECD/NEA, January 2014

[5] European Atomic Energy Community et al., Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna, 2006

[6] IAEA, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), IAEA, Vienna, 2016

[7] IAEA, Leadership and Management for Safety, IAEA Safety Standards Series No. GSR Part 2, IAEA, Vienna, 2016

[8] European Commission et al., Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna, 2014

[9] IAEA, Safety Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSR Part 4 (Rev. 1), IAEA, Vienna, 2016

[10] IAEA, Predisposal Management of Radioactive Waste, IAEA Safety Standards Series No. GSR Part 5, IAEA, Vienna, 2009

[11] IAEA, Decommissioning of Facilities, IAEA Safety Standards Series No. GSR Part 6, IAEA, Vienna, 2014

[12] FAO et al., Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSR Part 7, IAEA, Vienna, 2015

[13] IAEA, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSR-1, IAEA, Vienna, 2019

[14] IAEA, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), IAEA, Vienna, 2016

[15] IAEA, Safety of Nuclear Power Plants: Commissioning and Operation, IAEA Safety Standards Series No. SSR-2/2 (Rev. 1), IAEA, Vienna, 2016

[16] IAEA, Safety of Research Reactors, IAEA Safety Standards Series No. SSR-3, IAEA, Vienna, 2016

[17] IAEA, Safety of Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. SSR-4, IAEA, Vienna, 2017

[18] IAEA, Disposal of Radioactive Waste, IAEA Safety Standards Series No. SSR-5, IAEA, Vienna, 2011

[19] IAEA, Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. SSR-6 (Rev.1), IAEA, Vienna, 2018

[20] IAEA, Deterministic Safety Analysis for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-2 (Rev.1), IAEA, Vienna, 2019

[21] IAEA, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-3, IAEA, Vienna, 2010

[22] IAEA, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-4, IAEA, Vienna, 2010

[23] IAEA, Licensing Process for Nuclear Installations, IAEA Safety Standards Series No. SSG-12, IAEA, Vienna, 2010

[24] https://www.iaea.org/sites/default/files/dpp539.pdf, retrieved on 5 September 2023

[25] IAEA, Safety Classification of Structures, Systems and Components in Nuclear Power Plants, IAEA Safety Standards Series No. SSG-30, IAEA, Vienna, 2014