Title: Licensing Challenges for Small Modular Reactor Designs in European Deterministic Regulatory Frameworks

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*Abstract: Small Modular Reactors (SMRs) represent a promising advancement in nuclear technology, offering enhanced safety features, scalability, and flexibility compared to traditional large-scale reactors. The use of passive safety features combined with the lower source term make an SMR inherently safer than a large Nuclear Power Plant (NPP) and opens the possibility for optimization of the design through a graded approach. Explicit guidance for the grading down of SMR related requirements and recommendations is lacking. Certain SMR-designs have used a risk-informed approach to achieve an overall optimization of safety measures, supporting the effective and balanced implementation of the defence in depth concept. However, their deployment faces significant licensing challenges in countries with deterministic regulatory frameworks, which prioritize prescriptive safety standards over risk-informed approaches. This paper explores the complex interplay between risk-informed design methodologies and deterministic regulatory requirements in the licensing process for SMRs. It examines the tension between the desire for innovation and the regulatory imperative for rigorous safety assurance, highlighting a balanced approach that integrates risk assessment principles into existing regulatory frameworks. Through a comparative analysis, this paper identifies key barriers and licensing challenges associated with risk-informed SMR designs within deterministic regulatory environments. Additionally, it underscores the importance of stakeholder engagement, regulatory harmonization, and knowledge sharing to foster a conducive regulatory environment that promotes the safe and efficient deployment of SMRs while ensuring regulatory compliance.*

**The future of nuclear technology in Europe**

Nuclear power plants are and always have been a climate friendly, low to zero-emission and clean energy source. Since the beginning of the war in Ukraine, uncertainty on energy security and dependence on Russian oil and gas have boosted action a nuclear revival in Europe. On May 16th, at the Nuclear Alliance meeting in Paris, ministers of the participating member states acknowledged that nuclear power may provide up to 150 GW of electrical capacity by 2050 in the European Union (vs roughly 100 GW today). With several of the current nuclear plants being in decommissioning, only about 35 GW out of this 150 GW capacity is expected to be produced from existing units going to LTO. This leaves about 115 GW to be realized from new build projects([[1]](#footnote-1)). These figures do not even account for nuclear new build project for non-electrical applications like hydrogen production, district heating or desalination.

And these numbers may even further increase as nuclear technology keeps gaining ground. As an example, 3 years ago our Belgian power plants were heading for a complete phase out. Meanwhile, the previous government has granted a 10 year life time extension for 2 of our 7 units, while in the negotiations for a new government, a further extent the lifetime to 20 years for these 2 units, a life time extension for additional units and a plan to develop for 8 GW of new nuclear capacity are on the table, according the VRT news.

**How realistic are these numbers and what could be the role of SMR?**

Looking back in history, over a period of 20 years (1970-1990), about 127 GW was added in Europe([[2]](#footnote-2)) ([[3]](#footnote-3)) with a development time of 5 to 10 years for the majority of these projects. From these numbers, the European ambitions seem high, but still manageable.

But times have changes. Ever since, lessons learned from accidents like Chernobyl and Fukushima have significantly impacted the licensing framework and trajectory, as well as public acceptance. This has significantly increased the duration and cost new build projects. The recent example of the Olkiluoto 3 new build project in Finland showed a project duration of 17 years and a cost that was approximately 3 times higher than initially estimated. Such uncertainty on the return of investment makes it difficult to find the necessary resources for such large Nuclear Power Plant (NPP) new build programs.

Besides, in an energy landscape where the share of renewables becomes increasingly important, new large NPP designs still don’t have the desired flexibility, even if improved compared to former designs. In this context, Small Modular Reactors (SMR) represent better performance. With a power output between 50 and 300 MW, a nuclear fleet composed of SMR is more flexible in terms of switching off (or on) 1 or more reactors, and therefore more compatible in an energy system with a high share of renewables.

And last but not least, the reduced core inventory and source term combined with the use of passive safety systems or inherent safety characteristics lead to better safety performances and increased safety margins, compared to the traditional large NPP. Two other basic benefits of an SMR that reduce cost and construction time, are the limited footprint and its modularity, i.e. the possibility for complete modules to be factory-assembled and transported and installed as such. This modularity also allows to systematically add new SMRs in function of the energy demand, of course if the site layout allows it.

The combination of the above characteristics should significantly increase the number of potential locations, including locations closer to the its final destination. But even then, there are still a set of issues that question the operational reliability of the technology and may cause increased costs and an uncertain investment climate.

**The licensing issue**

Historically, the international and European regulatory framework has been developed for large NPP, considering the lessons learned from all types of operational experience feedback. In the absence of tailored licensing approach, applying this regulation for licensing SMR can be seen as a logic and obvious choice. However, considering the improved safety performances of an SMR compared to large NPP, imposing the same safety requirements would lead to excessive design options that are not commensurate to the radiological risk from an SMR.

Besides, and despite initiatives inside the Western European Nuclear Regulators Association (WENRA) to harmonize safety requirements, there are still some significant differences in the overall safety approach and the interpretation of some basic nuclear safety principles between different member states in the European context.

An example of such difference is the application of the Single Failure Criterion (SFC) to safety features for Design Extension Conditions, mandatory in a number of member-states, even for DEC-B, but not in all. The combination of this criterion with a strict implementation of independency between the safety systems in different DiD levels, as presented by WENRA O3.2 Position 2([[4]](#footnote-4)), and the principle that each module of a multi-module unit shall have its own safety systems and features, could, for a two-module SMR and in most conservative interpretation lead to a design with 12 emergency diesel generators per reactor([[5]](#footnote-5)). This number will be reduced in countries where one ore more of the above requirements are not valid. Even if individual Safety Authorities are generally open for discussions on a case by case basis, it is clear that such differences complicate the concept of standardization. All stakeholders would benefit from a balanced, common regulatory framework. To obtain such set of technology-specific requirements for SMR, the inherent safety features, like passive system, resulting in considerably lower accident frequencies (DBA/DEC) and the reduced consequences if such conditions occur, should allow a waiving of excessive conservatisms in the existing framework and a reduction of the overall development and construction costs of an SMR, without concession to nuclear safety.

The differences with the existing regulatory framework can be even more pronounced for non-Light Water Reactor (LWR) SMR, like the High Temperature Reactor (HTR-SMR). For example, HTR designs pretend to represent even significantly lower source terms from the use of Accident Tolerant Fuel (ATF). Some designers challenge even the existence of Defence-in-Depth (DiD) levels 4 and 5, as no Design Extension Conditions with core melt will occur. In extreme accident conditions, the fuel effects would typically be limited to a degradation of the fuel, potentially leading to some permeation through the coating as the worst case consequences. This represents reduced and delayed releases, allowing to conclude that the HTR technology meets the safety objectives in DiD level 4 by design and avoiding the need for DiD level 5. As a consequence, the requirements on the leak tightness of the containment for an LWR can be excluded or at least reduced for HTR as its’ role in the confinement function as the 3rd barrier is limited compared to an LWR NPP.

**Risk-based graded approach**

The above examples give an impression on the complex European licensing landscape and indicate the interest for a unified, graded regulatory approach between European member states to simplify the licensing of SMR and optimize the design, obviously always without concessions to the overall nuclear safety objectives. Overall safety requirements should be tailored commensurate to the design-specific risk and the European sensitivities. Such approach is for example available in the American regulation, more specifically 10 CFR 53 “Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors”. IAEA 1436, “*Risk informed regulation of nuclear facilities: Overview of the current status*” may be outdated (it dates from 2005), but provides also a generic basis for understanding the philosophy behind the development of integrated decision making process. In such approach, a crucial role is typically reserved for the Probabilistic Risk Assessment (PRA), a well established practice in the United States, e.g. to justify a relaxation of Operating Licensed Conditions. It can however be noted that 10 CFR 53 also foresees a second possibility, based on a more deterministic, Alternative Evaluation for Risk Insights (AERI). This approach is considered by the US NRC as being particularly useful for design applications representing small fission product inventories, like SMR, and seeking to market design internationally, like the European context.

Both approaches however represent a set of challenges. Obviously, the level of maturity of the technology and the design is also be important in a traditional regulatory framework, but uncertainties about the SMR technology-dependent transients and accident conditions or the behaviour of the passive safety features under such conditions complicate a reliable estimation of the risk. This becomes particularly complex when aiming for a graded approach-based regulatory framework that is expected to be technology-inclusive. As such, further R&D on these phenomena is necessary to develop confidence in the technology as a basis for waiving some requirements. This challenge may be surmounted by capturing this uncertainty by applying conservatisms, but the risk exists that it would lead back to the traditional approach.

Even if the risk-based approach would not be applied to grade the framework overall but rather be allowed as a basic principle to optimize an individual design, it would require for the designer to start modelling the PRA in parallel with the design. The European Utility Requirements strongly promote the development of such PRA as early as possible in the design stage, but it is recognised as an significant cost in the development phase, with relatively limited added value in the current, deterministic European context.

Besides, the benefits of a risk-based approach may seem obvious, but may not be straightforward. E.g. if Design Extension Conditions are minor contributor to the Core Damage Frequency (CDF), the benefit of reducing the number of safety features like the emergency diesel generators mentioned earlier, may not stand out. Also, the passive systems should lead to better CDF values, but it may be complex to demonstrate it if the risk profile is dominated by active components. As such, the advantage of SMR designs may be more obvious in level 2 or level 3 PRA.

Finally, there may be discussions on how and compared to which objectives the grading should be aligned. While European Safety Authorities tend to impose more stringent overall safety objectives to SMR([[6]](#footnote-6)), existing PRA-risk metrics may become obsolete as the definition of core damage becomes vague like in the example of the HTR and even more for advanced technologies using e.g. liquid fuels.

**Hazards**

A specific point of attention in the design of SMR concern the protection against hazards. In Europe, the general approach is to define hazard intensities with a return period of at least 10.000 years as Design Basis Events (DBE). Events that are more severe than the design basis events are identified as part of DEC analysis, to demonstrate the robustness of, and the margin in, the protection concept against the hazard.

Considering the operating experience from existing hazard PRAs and the expected risk metrics for internal events for SMR, hazards may become very dominant in the risk profile of an SMR, if specific safety features like the passive systems show insufficient robustness against the extreme loads induced by hazards. Even for conditions resulting from extreme hazards, the boundary conditions for successful operation of the passive systems should still be met. If the overall safety objectives for SMR would become more stringent, this may lead to the conclusion that more extreme hazards levels must be considered in the safety demonstration for SMR compared to traditional large NPP. Also, SMRs have the potential to be sited at locations that are typically not selected for large NPP, like remote locations with limited power demand, adjacent to non-electrical end-users (like a hydrogen production plant) or closer to high populated areas. Hence, designers may define a broader standard plant parameter design envelope then for large NPP.

As such, grading for hazards may rather be found in the hazard characterization of the site-specific hazard. E.g., as most SMR standard designs use a design basis earthquake representative for a peak ground acceleration of 0.3g (or more), no full Probabilistic Seismic Hazard Analysis should be required to characterize the seismic hazard in low seismic areas like Western or Northern Europe. An example of such approach has been developed in IAEA-TECDOC-2042, “Optimization of Safety Measures for Protection of Nuclear Installations Against External Hazards”

**Conclusion**

The existing European regulatory framework is typically inspired by safety requirements developed for large Light Water Reactors (LWR). Although the preferred option to demonstrate compliance to these requirements in the European context is the deterministic safety analysis, representing the mandatory application of a set of prerequisites, significant differences exist in the interpretation and practical implementation of these requirements and prerequisites. The current paper provides a set of examples, that show the challenge of such situation for the licensing process of SMR designs.

To make the SMR-technology market competitive and tackle the European ambitions on the development of nuclear energy by 2050, the current regulatory context needs to be adapted commensurate with the radiological risk it represents, enable designers to optimize their SMR design and give room for risk-based approaches. The possibility for grading should be included in a global, balanced European framework that accounts for the specific context.

Overall, one could draw the parallel with the ‘modern portfolio theory’ developed by the American economist Harry Markowitz in 1927. One of the basic principles of this theory was that an efficient portfolio meets two conditions: first, if two portfolios represent the same efficiency, take the one with the lowest risk; second, if two portfolios represent the same risk, choose the one with the highest efficiency. Markowitz received the Nobel Prize for economics for this simple but efficient principle in 1990.

1. Source: Presentation NuclearEurope ‘*Overview of nuclear new build in EU with 2050 perspective*’ at SNETP forum 2024 [↑](#footnote-ref-1)
2. Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Italy, Lithuania, Netherlands, Romania, Slovakia, Slovenia, Spain and Sweden [↑](#footnote-ref-2)
3. Source – NuclearEurope chart based on IAEA PRIS data base [↑](#footnote-ref-3)
4. WENRA (RHWG) Report “Safety of new NPP designs” (March 2013) [↑](#footnote-ref-4)
5. 3 levels of DiD x 2 EDG for redundancy per level of DiD x 2 modules/unit = 12 EDG/unit [↑](#footnote-ref-5)
6. WENRA Report “Applicability of the Safety Objectives to SMRs”, 2021 [↑](#footnote-ref-6)