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Design Maturity and Regulatory Expectations for Small Modular Reactors

Cooperation in Reactor Design Evaluation and Licensing Working Group - SMR Task Force and Licensing and Permitting Task Force

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World Nuclear Association is the international organization that represents the global nuclear industry. Its mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing to the energy debate.

The Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group of the World Nuclear Association was created in January 2007 with the mission of establishing an international nuclear reactor design approval and certification process through the harmonization and worldwide convergence of safety standards and licensing approaches. CORDEL is currently working with its six task forces covering a wide range of technical areas, while maintaining close cooperation with the OECD Nuclear Energy Agency, the International Atomic Energy Agency, and standards developing organizations (SDOs), in pursuit of the CORDEL goals.

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Foreword

Since its inception in 2007, the Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group of World Nuclear Association has promoted a worldwide nuclear environment where internationally accepted standardized reactor designs can be deployed globally without major design changes. In practice, this would mean that safety evaluations of a reactor design and generic design certification approved by a recognized competent authority would be acceptable in other countries.

Over the past several years, advanced reactors, including small modular reactors (SMRs), have been seen as a promising option to support the clean energy transition and deepen the levels of decarbonization through their versatile applications including electricity generation, district and process heat production, and desalination.

Numerous SMR designs have been developed for potential deployment in both emerging and mature nuclear markets. The wide variety of innovative designs, technologies and applications will require adaptation of existing regulatory frameworks to ensure that they are capable of appropriately assessing the innovative features of SMR designs. Fully realizing the potential benefits SMRs could provide to the energy transition will require greater collaboration internationally across industry sectors and amongst national regulators.

In September 2013, CORDEL convened the Small Modular Reactor Ad-hoc Group (SMRAG) which evolved into the Small Modular Reactor Task Force (SMRTF) two years later (September 2015). The SMRTF mandate is to establish a path towards harmonized and standardized regulatory requirements leading to global SMR deployment.

In its August 2015 publication, *Facilitating International Licensing of Small Modular Reactors*, SMRAG found that current regulatory environments within established nuclear markets are designed for traditional larger (water-cooled) nuclear power plants, and could constrain the deployment of SMRs if applied in the same way. The report concluded that given the innovative design characteristics of SMRs, a new approach to regulatory frameworks was required.

The objective of this report is to describe the design and technology maturity necessary for the pre-licensing and licensing of SMR designs in several countries, while underlining the relationship between design phases and licensing processes in the surveyed countries and the main technology challenges facing the licensing of SMR designs. The surveys used to develop this report have a number of complementary areas with the SMRAG 2015 publication, and these are discussed in the relevant sections of this report.

Executive Summary

This report explores the expectations of design and technology maturity of small modular reactor (SMR) designs in relation to the regulatory pre-licensing and licensing processes. It is based on the results of two surveys of members from the CORDEL Working Group of World Nuclear Association, from nine countries across three regions (Asia, Europe and North America). The survey respondents covered a wide range of knowledge and experience from research and development to operation of nuclear power plants.

The report describes the different design phases and defines the various types of small modular reactor (SMR) considered in the survey, namely light water reactors (LWRs), high temperature gas-cooled reactors (HTGRs), fast neutron reactors (FNRs), molten salt reactors (MSRs) and heatpipe microreactors.

The results of the surveys and the subsequent discussions among World Nuclear Association members give an overall picture of the relationship between licensing processes and design phases, while also highlighting the key technology challenges associated with licensing SMRs.

The wide variety of licensing processes, number of steps and the diversity of overall national regulatory structures, previously highlighted in *Licensing and Project Development of New Nuclear Plants* [1], was immediately noticeable when evaluating the survey results.

Despite national differences in processes and number of steps, the design maturity required for a construction licence application is relatively well aligned in the countries represented by responses to the surveys. However, where they exist, pre-licensing processes vary greatly between countries and have different design maturity expectations for applicants in different countries.

The surveys identified a number of specific technology challenges for each SMR type, as well as generic challenges that need to be addressed by all SMR designs, *e.g.*, technology validation, multiple module considerations, development of supply chain and demonstration of manufacturability.

Some national regulators have already granted design certifications or construction licences to SMR demonstration units; however, most of the pre-licensing processes identified by responses to the surveys have not been used by the respective national regulators in relation to SMR designs. The perceived challenges to licensing a given type of SMR depends on a wide variety of criteria, including the regulatory experience with that reactor type.

Review and analysis of the responses to the surveys identified the following best practices and recommendations for SMR vendors, licence applicants, national regulators and governments:

- **SMR vendors'** completion of major research and development (R&D) activities, the associated design and technical decisions, and the demonstration of a clear programme of future technical development, are pre-requisites to commencing and/or completing pre-licensing activities, in the countries surveyed.
- Prior to undertaking pre-licensing or licensing activities in a country other than the SMR vendor's home country, it is important that a gap analysis against the requirements of the proposed host country be undertaken and appropriate approaches to resolving the identified gaps are developed.

- A systematic approach to recording all major design modifications, upgrades, safety decisions and the methodology or bases upon which decisions were made, is critical to build regulatory confidence in the design process.

- **Licence applicants'** active and early engagement with national regulators, in anticipation of expected licensing activities, is required to understand the technology readiness of the reactor designs and clarify the degree of technical and design maturity requirements for every phase of the pre-licensing and licensing processes.
- The safety case elements discussed in section 5.2.3 should be sufficiently developed and explained to the regulatory authorities through early engagement in order to minimize potential delays in regulatory reviews of the design.
- Continuous engagement and timely submission of design and safety documentation is important to build trust with national regulators and support the review process.

- **National regulators** undertaking SMR licensing activities, or planning to do so in the future, can benefit from engagement with other national regulators through bilateral and multinational agreements on design and safety reviews, sharing technical reviews, establishing common position statements on safety criteria, and identifying any other areas for collaboration making appropriate use of the reference SMR design review, where one exists.
- Engagement with international bodies such as the IAEA SMR Regulators' Forum and safety standards committees improves the ability to share common experience, develop international best practices, and to create, revise and harmonize safety standards and approaches to licensing.
- Informing potential applicants of any changes to the licensing frameworks and dedicating appropriate resources to support timely reviews, approval and licensing will be crucial to supporting the deployment of SMRs.

- **Governments** interested in the deployment of SMRs should undertake a detailed technology readiness assessment of the designs being considered prior to their entering the licensing process.

1 Introduction

Innovation in nuclear technologies is driving international collaboration to find reliable, cost-effective ways to license and deploy advanced technologies, including SMRs, efficiently and safely around the world. To ensure safe design and operation of this new generation of reactors, nuclear regulators are developing strategies to adapt their regulatory frameworks for licensing SMRs that respects both their independence and national sovereignty. The benefits to be realized from streamlining licensing efforts include improved safety, enhanced design efficiency, avoidance of unnecessary design complexities, regulatory efficiency, and lower costs.

This report provides the results and analysis of two surveys undertaken by members of CORDEL's Licensing and Permitting Task Force (LPTF) and Small Modular Reactor Task Force (SMRTF) of World Nuclear Association and builds on the conclusions from the previous reports, *Licensing and Project Development of New Nuclear Plants* [1] and *Facilitating International Licensing of Small Modular Reactors* [2].

The surveys aimed to provide an overview of existing regulatory frameworks, pre-licensing and licensing activities related to SMRs that are already under way, key licensing requirements expected for SMRs according to the maturity of the design, and an overview of the technology challenges that remain for generic SMR designs.

Review and analysis of the responses to the surveys aimed to map the required design maturity to the licensing steps in the surveyed countries, identifying key technology challenges for licensing of SMRs, and ascertaining the degree of readiness in regulatory frameworks for reviewing and licensing SMR designs.

It is expected that reactor vendors and prospective licence applicants would use the information in this report to get a better understanding of the licensing requirements and the differences in regulatory framework in each country they wish to undertake licensing. The report's findings could also be used by regulators to identify opportunities to work collaboratively with other regulators and further harmonize their approaches to licensing new reactor designs.

2 Definitions

2.1 Applicant

An 'applicant' is the organization or group of organizations generally comprising a reactor vendor, future plant operator or both, that apply to the regulatory bodies to undertake either pre-licensing or licensing activities.

For any given country the applicant for pre-licensing activities may be different to that for licensing activities.

2.2 Licensing and permitting

'Licensing' refers to the process undertaken by nuclear regulators that allow a construction and operating licence[1] to be granted.

'Permitting' is the process through which the applicant applies for specific permits *e.g.*, environmental permits that are required to allow the construction and operation of the nuclear power plant. While permits mainly relate to non-nuclear industrial requirements, for some countries permits can have both a nuclear and non-nuclear nature.

2.3 Small modular reactor

A 'small modular reactor' (SMR) is a nuclear reactor generally 300 MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times [2].

This broad definition includes many different types of reactor design, and it should not be assumed that a given design can be licensed under a particular regulatory framework.

This report is not intended to focus on any single SMR reactor design, but rather on the following five generic SMR designs:

Light water SMRs

Designed around the well-established pressurized water reactor (PWR) or boiling water reactor (BWR) concepts.

- Most designs use fuel enriched to less than 5% U-235.
- Some designs feature loop-type configurations typical of large LWRs; however, many others have integral designs, with the steam supply system inside the reactor pressure vessel.
- Ability to generate heat for industrial applications.
- Safety features through use of passive safety systems.

High temperature & very high temperature gas-cooled SMRs

- New fuels proposed with uranium enrichment up to 20% U-235.
- Typically moderated by graphite.
- Helium is usually the reactor coolant with temperatures up to about 1000°C.
- Ability to generate high temperature heat for industrial applications.
- Potential use of thorium-based fuels.

Fast neutron SMRs

- Fuels generally 15-20% enriched.
- Different coolant options (*e.g.*, sodium, lead, lead-bismuth).
- Ability to generate heat for industrial applications.
- More efficient fuel utilization but requires reprocessing.
- Longer refuelling intervals.

Molten salt SMRs

- Coolant is usually a molten mixture of lithium and beryllium fluoride at around 700°C and at relatively low pressure in comparison to LWR SMRs.
- Most designs use enriched uranium or thorium in different forms such as: fluoride fuel dissolved in the molten salt coolant or solid TRISO fuel elements.

[1] It should be noted that in some countries, *e.g.* the Russian Federation, the reactor itself is not subject to licensing by the regulator. The regulator issues a licence for a type of activity, *i.e.* design, siting, construction, operation and decommissioning of a specified number of nuclear power units.

- Usually moderated by graphite.
- Ability to generate heat for industrial applications.

Microreactors (particularly heatpipe reactors)

- Capacity ranging between 1 MWe and 30 MWe [3].
- Designed specifically for applications that require small amounts of highly reliable power.
- Use of fluid in sealed horizontal steel heatpipes to passively conduct heat from the hot fuel core to an external condenser.

2.4 Design phases

Reactor vendors, operators and regulators around the world use different terminology to define the level of maturity of a design at the different design stages, which can be a source of misunderstanding or confusion when licensing the same reactor in different countries, particularly in countries with well-established nuclear regulatory processes. It is therefore necessary to define an unambiguous qualitative measure of design progression that will ensure a shared categorization of the different design stages of a reactor. In this report the design stages are defined in terms of four separate phases [4]:

- Phase 1: Conceptual design.
- Phase 2: Plant-level engineering design.
- Phase 3: System-level engineering design.
- Phase 4: Component-level engineering design.

These phases are described below, where each phase is defined in terms of both its level of engineering design and the safety and environmental assessments that the design should be capable of underpinning.

The description of the phases is based on what is required for a first-of-a-kind (FOAK) reactor. For a n^{th}-of-a-kind (NOAK) reactor, the scope and level of detail required in each phase would be reduced depending on whether the NOAK reactor is being licensed or constructed in the same country as the FOAK reactor.

Phase 1: Conceptual design

This is the design phase in which the design options are selected, and enhanced, critical questions are asked, solutions developed, major risks are identified, and mitigation plans put in place.

The output from this phase is generally a document, or suite of documents, outlining the design and safety principles, the key decisions taken and the rationale for those decisions.

In general, the majority of the steps in this phase should be completed prior to any engagement with the regulatory authorities, although some pre-licensing activities allow for regulatory engagement during this phase.

Phase 2: Plant-level engineering design

During this phase all key systems, structures and components (SSCs), their requirements and key design parameters should be defined. This will generally include:

- Process flow diagrams of the systems.
- Preliminary instrumentation and control (I&C) architecture.
- Preliminary design drawings, *e.g.*, single line diagrams.
- Definition of plant layout (building design criteria including basic dimensions).
- Preliminary specifications for safety-classified systems.
- Safety design.
- First draft of 3D model.

The systems generally focused on in this phase include reactor core, reactor coolant system, safety systems (including auxiliary safety systems), I&C (preliminary architecture), electrical power supply, steam and power conversion systems, and civil works and structures.

The design at this stage should be sufficient to allow preliminary assessments of:

- Plant safety against regulatory requirements.
- Environmental impact.
- Security requirements.

The output from this phase will be a suite of documents defining the key design parameters of the safety related SSCs and safety features of the reactor design, alongside several preliminary assessments.

Phase 3: System-level engineering design

In this phase the definitions of the SSCs and their requirements and parameters are further refined, and all other plant systems are defined. During this phase the design team will grow significantly in size and capability, and the wider supply chain may be used to supplement some design capability or undertake design of SSCs under contract.

During this phase the following is normally produced:

- Piping and instrumentation diagrams of the systems.
- Plant and item list.
- I&C functional requirements; system architecture and drawings.
- Structure design criteria and dimensions.
- Preliminary specifications for safety-related components.
- Second draft of 3D model.

In addition to a more detailed description of the systems identified in Phase 2, additional systems of particular importance during this design phase are: reactor chemistry, radiological protection systems, and radioactive waste management systems.

Assessments undertaken at this phase require a greater underpinning of the design of the SSCs and their associated support systems. The design at this phase should be sufficient to allow the preliminary safety analysis report (PSAR) to be produced and the following assessments to be undertaken:

- Design basis and design extension conditions including deterministic analysis
- Probabilistic safety assessment (Level 1 and 2).
- Assessment and justification of any new materials proposed.
- Human factor engineering.
- Internal hazards: preliminary assessment.
- External hazards: definitions of required loads for building design.
- Operational principles and requirements.
- Decommissioning requirements.
- Environmental impact assessment[2].
- Security requirements.

It should be noted that this stage does not require the detailed component engineering design that is needed for the components to be manufactured, *i.e.* not all isometric drawings or detailed 3D models of components need to be developed at this point. The timing of the detailed design for manufacturing will be driven by the deployment schedule of the individual project.

Phase 4: Component-level engineering design

Very often for large-scale nuclear plants, the design process for the lower safety critical systems and non-safety systems, within the nuclear island, will take place during the construction phase. In the context of SMR deployment, this may be less feasible as a result of the modular nature of construction and more of these systems and components will need to be designed and manufactured earlier in the process.

It is during this phase that the final detailed engineering to allow manufacture of all SSCs for the entire plant is undertaken with the aim that design modifications are minimized once construction commences.

During this phase the following is normally produced or updated:

- Finalized detail design including manufacturing requirements and component specifications for all SSCs.
- Building layout specifications and drawings.
- Final 3D model.

The design at this phase should be sufficient to allow the final safety assessment report (FSAR) to be produced and assessments of the following to be undertaken:

- Design basis and design extension conditions, including deterministic analysis.
- Probabilistic safety assessment (Level 1 and 2)[3]
- Assessment and justification of any new materials proposed.
- Human factors engineering.
- Internal and external hazards.
- Operational principles and requirements.
- Decommissioning requirements.
- Environmental impact assessment.
- Security requirements.

An overview of the different phases of design maturity is provided in Figure 1.

[2] Environmental impact assessment may be produced and assessed separately to the safety analysis documentation.

[3] Some countries also required Level 3 probabilistic safety assessment.

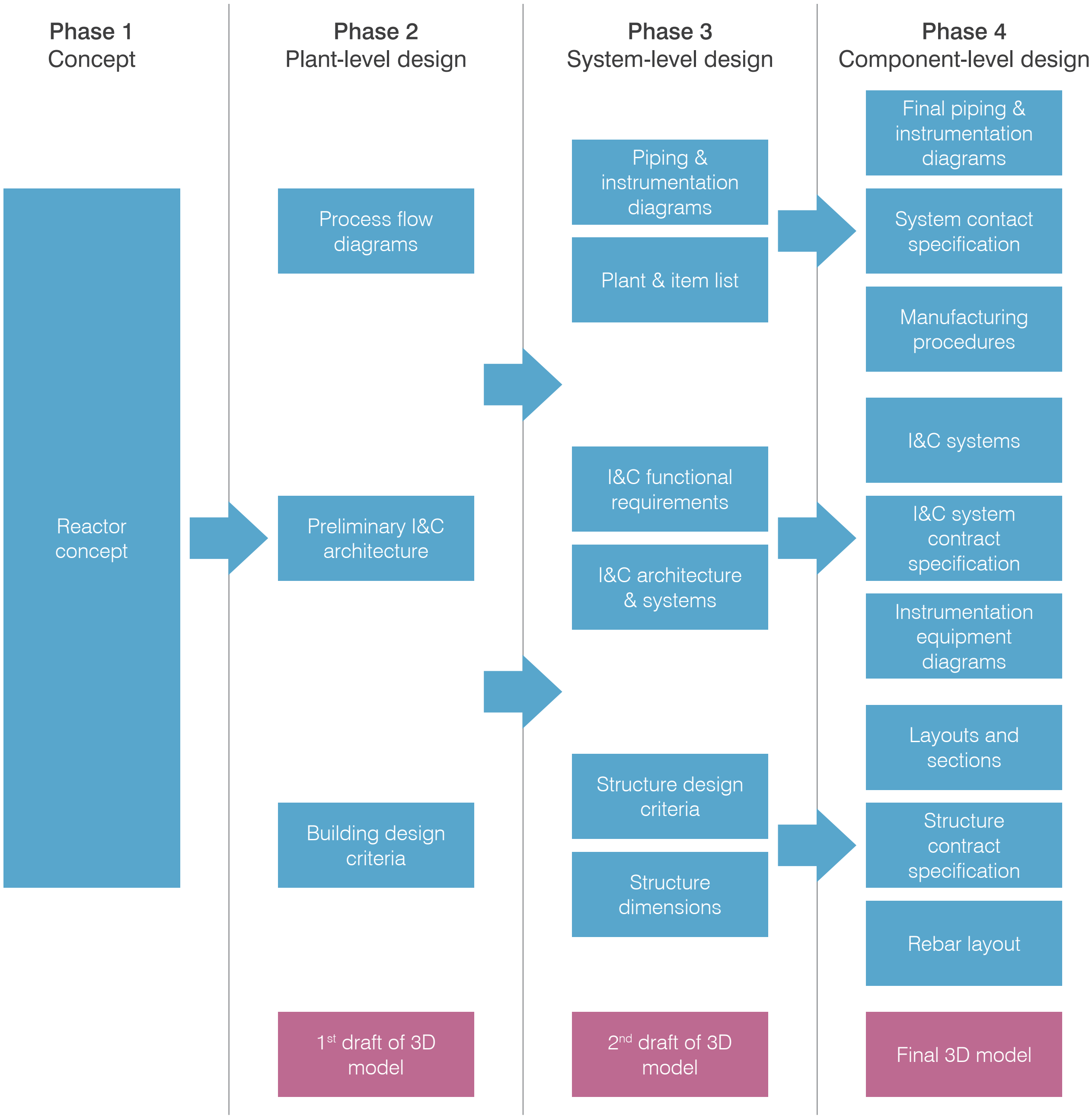


Figure 1. Schematic overview of the different phases of design maturity

3 Methodology

Members of the the Small Modular Reactor Task Force (SMRTF) and the Licensing & Permitting Task Force (LPTF) were invited to participate in two surveys.

The first survey (*Licensing Processes and SMR Activities*) was designed to collect data on countries' regulatory processes and current SMR activities. Survey responses provide for the mapping of the key licensing steps in each country against the design maturity steps outlined in section 2.4.

The second survey (*Technology Readiness*) is intended to collect data on the level of experience and challenges that generic SMR types pose to meeting current regulatory requirements in the surveyed countries.

3.1.1 Licensing framework and SMR activities survey

The information requested in this survey focused on the following five main areas:

- National regulatory organizations: description of the regulatory body (name, size, structure, funding model, regulatory text establishing its mandate, *etc.*); technical support organization (TSO); other organizations involved in the safety assessment/licensing process, *e.g.*, environmental protection agency, import/export control, ministries, *etc.*
- Current licensing practices: pre-licensing and licensing processes; existence of informal and formal pre-licensing and licensing processes/steps; reactor designs already licensed in the country (with particular attention to FOAK reactors) or having been through a pre-licensing process (or currently undergoing it).
- Past and ongoing licensing activities in relation to SMRs.
- Regulatory framework readiness for SMRs (respondents' perspective only[4]).
- Key documents, guidance, requirements, laws, codes and standards, *etc.*

3.1.2 Technology readiness survey

For each of the five SMR generic design types, respondents were asked to report their level of experience with pre-licensing and licensing activities associated with the SMR types (*i.e.*, significant experience, limited experience and no or very limited experience), as well as the level of challenges to be overcome for successful licensing of their SMR designs (*i.e.*, minor challenge; significant challenge; and major challenge). To capture challenges raised by SMR reactor types beyond LWR technologies, respondents were asked to use the following three categories:

- **Minor challenge**
  - o Either: SMR design utilizes proven and well-understood techniques, mechanisms, materials and components; some minor challenges associated with novel materials remain.
  - o Or: techniques or demonstration reactor already under construction or in operation within country; only minor challenges expected to result from operation of demonstration reactor.
- **Significant challenge**
  - o Either: SMR design utilizes well-understood processes but with significant changes to techniques, materials and/or components, or to plant layout and/or operability modes.
  - o Or: SMR is of a less understood nature within the country of licensing, with well-defined R&D still required to be undertaken by the applicant.

[4] Regulators have not provided direct input to this report.

- **Major challenge / large R&D programme**
  - o Either: SMR design is not well-understood in country of licensing, with major R&D to be undertaken.
  - o Or: SMR design utilizes some unproven techniques resulting in a large learning curve for all parties involved.

Each country received a template for each of the five SMR types (see Table 1). Respondents were to place the number representing their level of experience in the cell associated with the level of challenge they face to license their SMR designs.

As an example, a country with experience of pre-licensing LWRs, representing a minor challenge, would place a '1' in the cell of the 'Pre-licensing' column and 'Minor Challenge' row in the LWR table.

In addition, respondents were asked to describe the overall situation with respect to the feasibility of licensing the SMR design within their country in consideration of the technology (or other) challenges.

This second part of the survey aims to understand the level of 'comfort' with technology readiness of licensing any of the five SMR types in each of the respondents' respective countries.

Table 1. Technology readiness survey table

Level of Challenge	Pre-licensing	Licensing
Minor Challenge		
Significant Challenge		
Major Challenge		

1 = Significant experience

2 = Limited experience

3 = No or very limited experience

4 Survey results

This section presents the results of the *Licensing Processes and SMR Activities and the Technology Readiness* surveys. Table 2 presents a summary of respondent companies, their sector, country and region. France and the United Kingdom (UK) did not participate in the *Technology Readiness survey*.

Table 2. Survey contributors

Region	Country	Company	Sector
Asia	People's Republic of China (China)	Shanghai Nuclear Engineering Research & Design Institute (SNERDI)	R&D, engineering & construction
	Republic of Korea	Korea Electrical Power Corporation Engineering & Construction (KEPCO-E&C)	Engineering & construction
Europe	Russian Federation	Rosatom	R&D, engineering, construction & operation
	Belgium[5]	Tractebel	Engineering & consultancy
	United Kingdom (UK)	Jacobs Engineering	Engineering & consultancy
	Ukraine	NNEGC Energoatom	Power plant operation
	France	EDF	Design, construction & operation
North America	Canada	CANDU Owners Group	Power plant operation
	United states of America (USA)	NuScale	Design, construction & operation

4.1 Licensing framework and SMR activities

Respondents were asked to describe national regulatory organizations, current licensing practices, past and ongoing SMR-related licensing activities, their perspective on the regulatory framework readiness for SMRs and key documents.

4.1.1 National regulatory organizations

In all nine countries represented by the survey responses the relevant safety, security and environmental regulators are empowered by the state government to undertake the required licensing and permitting reviews in line with national regulations. Regulatory activities are undertaken in different ways, *e.g.*, in the USA, the regulatory activities are coordinated only through the US Nuclear Regulatory Commission (NRC). It is common in most countries to have separate nuclear safety and environmental regulators, *e.g.*, the Office for Nuclear Regulation (ONR) and the Environment Agency (EA) in the UK, although they may work in close collaboration throughout the assessment process. In most countries, regulatory authorities for nuclear security and safety regulation are within the same organization, but at times in separate departments with different protocols.

Funding for regulatory bodies varies. In some *e.g.*, in China, the regulatory authority is completely government funded. In other cases, funding is provided indirectly through fees from the nuclear industry. For example, in the USA, the NRC receives annual funding from Congress and then collects approximately 90% of this

[5] In Belgium there is a law excluding construction and operation of any new nuclear facility for industrial electricity production.

[6] While the Russian Federation has no formal pre-licensing process, the practice of analysis and evaluation of documents justifying the safety of Russian-designed SMRs is being introduced by the TSO, the Scientific and Engineering Centre for Nuclear and Radiation Safety (SEC NRS).

from fees it charges to the industry, which are subsequently paid back to the Department of the Treasury.

Regardless of funding sources, almost all nuclear regulatory bodies rely on or have access to the skills of scientific and technical support organizations (TSOs) to support regulatory activities. These TSOs may be organizations whose mandate is to support nuclear regulatory activities, typically government funded in countries where the government also funds the regulatory authorities. Otherwise, they are private companies with competencies or expertise in specific technical or safety areas that the regulator can call upon as required to inform regulatory decisions.

Engagement with the relevant regulatory authorities can take various forms and may initially be with a different entity to the regulator. For example, in the UK, the licence applicant must apply to the Department for Business, Energy and Industrial Strategy (BEIS) in order for it to instruct the safety regulator, the Office for Nuclear Regulation (ONR), to undertake the required assessment.

The regulatory authorities and supporting organizations from each of the surveyed countries are listed in Appendix 1, with further links to regulatory documentation and resources for each country listed in Appendices 2-10.

4.1.2 Current licensing practices

Pre-licensing

Generally, pre-licensing of designs or sites is seen by the nuclear industry as an effective means of enhancing the predictability of the duration and outcome of licensing processes. Pre-licensing allows for an important part of the licensing submission to be assessed by the time the licensing process for a particular nuclear power plant starts.

Respondents representing seven of the surveyed countries reported having a formal pre-licensing step for either reactor design review or site approval. China indicated no formal or informal pre-licensing activities. In the Russian Federation, a prospective reactor vendor or operator may engage the TSOs, independently of the regulatory authorities, to undertake a review of the reactor design against the safety requirements.

Pre-licensing applicants can either be a reactor vendor or designer, a prospective owner-operator organization or a combination of these. Amongst the countries surveyed (see Table 3), the pre-licensing activities are undertaken by the future operator in two (Belgium, France), the reactor vendor in two (Canada, Russia Federation[6]) and multiple options including a consortium in four (Republic of Korea, UK, Ukraine, USA).

In cases where early site approval may be granted, only the future operator can apply, even if the pre-licensing design review is undertaken by the reactor vendor. This situation is most prominent in the USA where reactor designers will apply to the NRC for design certification (pre-licensing) while utility companies will apply separately to the NRC for an early site permit.

Timescales for pre-licensing activities vary by country, but generally they are more a function of the scope of activities and complexity of the design review (see section 4.1.2). Due to the relatively new nature and flexibility of pre-licensing activities in some regulatory regimes, the required timescales are difficult to define accurately. In France and the USA, these timescales are agreed upon following initial discussions with the regulatory authorities.
For regulatory regimes with well-established pre-licensing activities, *e.g.*, the Republic of Korea and the UK, it can take two-to-five years from point of application of design review to its completion. Similar timescales can be expected for an early site permit. In Canada, the Canadian Nuclear Safety Commission (CNSC) established a formal pre-licensing process (Vendor Design Review) for review of new reactor designs, which is carried out in two phases, with an optional third phase as a follow-up on focused safety areas. Phase 1 constitutes an assessment of vendor processes and procedures against regulatory requirements and takes 12-18 months. Phase 2 is an assessment of potential barriers to licensing the design in Canada and takes approximately 24 months [5].

In most of the respondent countries, the pre-licensing activities are recommended by the country's regulatory authorities but are not mandatory. The pre-licensing design reviews serve to identify potential barriers to granting the new design the required construction and operating licences. The scope of pre-licensing activities may include regulator recommendations and identified gaps that require resolution prior to

Table 3. Summary of pre-licensing applicant types in surveyed countries

Pre-licensing Applicants	Respondents	Countries
Future operator	2	Belgium, France
Reactor vendor	2	Canada, Russian Federation[4]
Multiple options	4	Republic of Korea ,UK, Ukraine, USA

application for a construction licence or during commissioning of systems, structures and components (SSCs). The completion of the pre-licensing activities does not guarantee that a construction or operating licence will be granted.

Licensing

Licensing refers to the process through which approval to construct, commission and operate a nuclear power plant at a specific site is granted to the respective licensee. Licensing activities typically follow pre-licensing activities, but the two processes may occur in parallel, *e.g.*, the final stages of the generic design assessment (GDA) process in the UK can be completed in parallel with the application for a nuclear site licence.

The licensing process and number of steps vary significantly from country to country, ranging from a one-step process with several regulatory hold points through to multiple-step processes with specific site or commissioning licences required. Five of the responding countries report a multiple-step process (*i.e.*, more than two steps), two have a two-step process, one has a one-step process, and one has an option for either a two-step or one-step process.

Table 4 outlines the licensing steps in respondent countries.

Licensing process timelines may be affected by various uncertainties including but not limited to: insufficient communication between applicant and regulator; underestimation of effort required; technical readiness of applicant to demonstrate resolution of issues and gaps identified in pre-licensing activities; completeness of licence applications and/or state of design; issuance of new requirements or standards during the licensing or construction process; political changes; public acceptance (contested hearings, appeals against granting regulatory approvals or licences); delays in regulatory assessment of the applicant's safety case; and limited

Table 4. Licensing steps in surveyed countries

Country	Pre-licensing	Licensing			Regulatory Hold Points
Belgium	FANC opinion on design	Licence application and examination	Construction licence	Operating licence	Various hold points
Canada	Vendor Design Review (VDR)	Licence to prepare site	Construction licence	Operating licence	Muliple regulatory hold points
China	N/A	Construction permit (including site safety and environmental impact assessment)		Operating licence	
France	ASN opinion on design	Construction licence application	Construction licence (DAC)	Commissioning authorization	Various hold points
Republic of Korea	- Standard Design Approval (SDA) - Early Site Approval (ESA)	Construction permit		Operating licence	
Russian Federation	N/A	Site licence	Construction licence	Operating licence	
UK	Generic Design Assessment (GDA)	Nuclear site licence			- First Nuclear Concrete - First NI Construction - First fuel to site - Commissioning - Others as required
Ukraine	- SNRIU opinion on design - Feasibility study review	PSAR review & adoption into law	Construction & commissioning licence	Operating licence	- First delivery of nuclear fuel - First criticality - Commissioning - Experimental operation phase - Others as required
USA	- Pre-application readiness assessment - Standard Design Certification - Standard Design Approval - Early Site Permit (ESP)	Construction permit		Operating licence	- Inspections, tests, analyses and acceptance criteria (ITAAC)
		Combined construction and operating licence (COL)			

resources of the regulator to undertake multiple design reviews in parallel. Many countries also engage or consult with members of the public and other stakeholders at various stages of the environmental assessment and licensing processes, which can significantly affect timelines for informing or rendering regulatory decisions.

Some regulators publish indicative timelines, typically based on experience with previous and ongoing projects that help both the regulator and applicant schedule required activities and resources. Survey respondents reported expected timelines to achieve a construction licence or permit ranging from 12 months to six years from date of application, with a median period of three-to-five years.

4.1.3 Design phases related to licensing steps

Pre-licensing

Pre-licensing activities generally fall into two categories: design review and early site approval or permit.

In cases where site pre-approval is available, there is a broad consensus within the countries surveyed that the scope of review for an early site permit should contain: site boundaries; site characteristics (seismic, meteorologic, hydrologic, geologic, *etc.*); planned transport and access routes; impact on population of the area surrounding the site; proposed general layout of the facilities; maximum radiological and thermal effluents expected; type of cooling system to be used; radiological dose consequences of hypothetical accidents; and emergency plans. In some cases this will also include a public consultation on the use of the site for development of a nuclear power project.

While the scope of an early site permit may be relatively well-aligned within the surveyed countries, the scope of the pre-licensing design reviews are wide-ranging and in some cases multiple options exist within one country, *e.g.* design certification and standard design approval in the USA, with different advantages and drawbacks to each process, as well as different levels of design maturity required to have been achieved by the reactor vendor to undertake the process.

In some countries, notably France and Belgium, the pre-licensing activities can commence at an early stage in the design process, *i.e.*, during Phase 1 or Phase 2. While this can be of great benefit as it allows early feedback from the regulator on how to incorporate the safety requirements into the design at the earliest possible opportunity, the lack of information may raise issues from the regulator, leading to additional interaction between applicant and regulator before the licence application.

In some other countries, pre-licensing activities such as the design certification process in the USA and the generic design assessment (GDA) process in the UK require the design of the facility to be well-advanced, at least at Phase 2 upon commencement and generally Phase 3 upon completion of pre-licensing. The advantages of such processes are that any areas of the design captured within the pre-licensing activities will not be reassessed during the licence application; however, this requires a significant initial effort from the reactor vendor prior to the licence application.

Licensing

Licensing processes are largely comparable across respondent countries, with similar requirements on the design maturity in each country, *e.g.*, to submit an application for a construction licence, the design must be mature enough to support the development of the preliminary safety analysis report (PSAR). Experience from recent large-LWR licensing suggests that the minimum design maturity required to underpin the PSAR is the system-level design, *i.e.*, Phase 3.

In six of the nine respondent countries, approval of the PSAR along with meeting other regulatory requirements was a prerequisite for the granting of a construction licence. In the remaining three respondent counties, there is no specific construction licence, but instead the approval of the PSAR in conjunction with relevant regulatory hold points allows certain activities to take place, *e.g.*, in the UK, approval of the site-specific PSAR followed by a required regulatory hold point will allow first nuclear concrete to be poured, representing the first safety-critical construction element onsite.

Similarly, when a licence to operate is a regulatory requirement, there is a general consensus among contributors that a Phase 4-level design maturity is required, *i.e.*, component-level design documentation to underpin the final safety assessment report (FSAR). Acceptance of the FSAR along with satisfaction of other regulatory requirements, as defined through regulatory holds points, will allow the operator to load first fuel and commence commissioning and operating activities. In countries where a specific operating licence is not part of the process, the approval of the FSAR will form part of a specific regulatory hold point to allow commencement of commissioning and operating activities, *e.g.*, inspections, tests, analyses and acceptance criteria (ITAAC) in the USA.

4.1.4 Past and ongoing licensing activities in relation to SMRs

There are a large number of SMR designs being considered for deployment by various countries around the world. Several of these designs are going through pre-licensing or licensing activities, construction has commenced in some cases, and in a small number of cases there are operating SMRs. In most cases, the SMR reactor types undergoing pre-licensing or licensing activities within the surveyed countries are of a different reactor technology than what the regulators are familiar with or currently regulating.

At the time of the survey, six of the respondent countries were engaged in either pre-licensing or licensing activities for SMRs. China was undergoing construction of two different types of SMR (HTGR and LWR), and both the Russian Federation (RF) and China have SMRs in operation[7],[8]. France, the UK and Ukraine have no current formal licensing activities directly associated with SMRs. In Belgium, current regulatory activities concern the MYRRHA project, which is not specifically an SMR design to produce electricity or heat but rather a highly innovative research reactor; due to the innovative nature and limited technology maturity of some SMR designs, this case provides useful insights for the assessment of regulatory framework readiness for licensing novel reactor designs.

Most types of nuclear reactor currently in operation are water-cooled, specifically the light water reactor (LWR) type, *i.e.*, pressurized water reactors (PWRs) and boiling water reactors (BWRs). As a result, most regulators are more familiar with regulation and licensing of these reactor types. All respondent countries (see Table 5), have at least one water-

[7] See Russia connects floating plant to grid, World Nuclear News, (19 December 2019).

[8] In China, these are currently experimental or prototype reactors.

[9] Some of the information in Table 5 has been provided as a response to the survey, other information has been taken from publicly-available sources [6] [7].

Table 5. SMR regulatory activities and status in surveyed countries[9]

Country	SMR regulatory activities		Reactor types in operation within country
	Reactor type	Stage	
Belgium	1 FNR (MYRRHA Accelerator driven lead cooled research reactor)	Pre-licensing	PWR
Canada	2 HTGR (Micro Modular Reactor, Ultra Safe Nuclear; Xe-100, X-Energy) 1 MSR (IMSR, Terrestrial Energy) 1 FNR (ARC-100, ARC Nuclear Canada) 3 LWRs (SMR-160, Holtec; NuScale, NuScale Power; BWRX-300, GE Hitachi)	Pre-licensing	PHWR
China	1 FNR (China experimental fast reactor)	Operation	PWR, PHWR, FNR
	1 HTGR (HTR-PM)	Construction	
	1 LWR (ACP100)	Siet preparation - awaiting construction licence	
	Numerous floating LWRs	Early licensing	
France	1 LWR (Nuward project)	Preliminary discussions	PWR
Republic of Korea	1 LWR (SMART)	Pre-licensing (updated standard design approval)	PWR, PHWR
Russian Federation	2 LWRs (KLT-40S)	Operation	RBMK, PWR, FNR
	1 lead cooled FNR (BREST-OD-300)	Construction licence	
	1 LWR (RITM-200)	Early licensing for land-based units; RITM reactors for icebreakers in operation	
UK	No current activities		AGR, PWR
Ukraine	No current activities		PWR
USA	1 LWR (Nuscale, 50MWe version)	Design certification awarded	PWR, BWR
	4 LWRs (NuScale, 77 MWe version; mPower, BWXT; SMR-160, Holtec; BWRX-300, GE Hitachi)	Pre-licensing	
	3 MSRs (Xe-100, X-energy; KP-FHR, Kairos Power; IMSR, Terrestrial Energy)	Pre-licensing	
	1 heatpipe microreactor (eVinci, Westinghouse)	Pre-licensing	

cooled reactor, with seven of them predominantly using LWR technology, in some cases supplemented with heavy water reactors (Canada) or with RBMK reactors (Russian Federation). Among the respondents, only the UK uses a different reactor type as its predominant technology, *i.e.*, the advanced gas-cooled reactors (AGRs).

4.1.5 Regulatory frameworks' readiness to regulate SMRs

Regulatory frameworks around the world have different approaches to licensing, with some regimes (*e.g.* USA) being historically heavily prescriptive and rule-driven, while others are primarily goal-based or risk-informed (*e.g.* UK). Table 6 lists the prevalent regulatory regime of the country's regulatory framework reported by each respondent, as well as some initiatives that are currently under way or have been completed to support the licensing of SMRs.

As outlined in Table 6, four respondents reported having largely rule-driven frameworks, one respondent a goal-driven framework, and four a combination of both. Countries with regulatory frameworks that combine rule-driven and goal-driven regimes generally have added risk-informed elements to a rule-driven regime. Some of the countries with rule-based regulatory regimes also have the flexibility, and are actively seeking, to incorporate risk-informed decision-making processes into their reviews of innovative technologies such as SMRs.

Table 6. Regulatory frameworks and SMR initiatives

Country	Regulatory regime	SMR focused licensing initiatives	SMR licensing activities
Belgium	Combined - rule-based and risk-informed	Establishment of pre-licensing framework in 2009 / 2010	Pre-licensing: MYRRHA
Canada	Combined - rule-based and risk-informed	CNSC recently issued the following regulations: - REGDOC-2.5.2, Design of Reactor Facilities: Nuclear Power Plants - REGDOC-1.1.1, Site Evaluation and Site Preparation for New Reactor Facilities - REGDOC-1.1.2, Licence Application Guide: Licence to Construct a Nuclear Power Plant - REGDOC-1.1.3, Licence Application Guide: Licence to Operate a Nuclear Power Plant - REGDOC-1.1.5, Supplemental Information for Small Modular Reactor Proponents	Pre-licensing: several vendor design reviews in parallel
China	Rule-based	National Nuclear Safety Administration is currently organizing relevant institutions to conduct research and development.	- HTR-PM received construction licence - ACP-100 licensing review complete, awaiting construction licence - Early stages of Licensing for floating reactor designs
France	Combined - rule-based and risk-informed	None	None
Republic of Korea	Rule-based	- KINS report [8] - on the regulatory requirements for new innovative reactor licensing; > Draft licensing procedure and, > Regulatory requirements for innovative reactor systems - KINS conducted a policy study [9] to identify safety issues associated with the licensing of SMR; > Defining EPZ reflecting the safety characteristics of SMR > Reinforcing DiD levels 3 and 4 > Graded Approach based on risk-informed/performance-based regulation	- SDA for SMART reactor completed in 2012 - Updated SDA for SMART applied for in Dec 2019
Russian Federation	Combined - rule-based and risk-informed	None	- Initial stages of licensing for RITM-200. Site licence expected mid-2023; construction licence beginning of 2024; operating licence mid-2027. - Construction licence granted for lead cooled FNR (BREST-OD-300)
UK	Goal-based	Updated GDA process making it more flexible to help with the assessment of SMRs. This includes providing other options for the GDA outcome, in addition to the current option of issuing (or not) a 'Design Acceptance Confirmation' (DAC) and 'Statement of Design Acceptability' (SoDA) Report outlining the Office for Nuclear Regulation, Approach to regulating innovation	None
Ukraine	Rule-based	1. The Ukrainian Module Consortium has been established composed of a Ukrainian operator, SMR developer and the TSO (SSTC NRS). - The tasks of this consortium include analyzing the regulatory documents as they would apply to the SMr developers conceptual design. - A technical Report *Development of approaches to comparative analysis of the foreign and Ukrainian regulatory requirements for designing and nuclear facility safety justification (Rev.1)* has been developed - awaiting signature and adoption. - The comparative analysis will be the next step in this process 2. NuScale and the TSO (SSTC NRS) have signed a memorandum of understanding to start evaluation of regulatory and design gaps between USA and Ukrainian processes for the licensing, construction and operation of the SMR design.	None
USA	Rule-based	- *NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness* published in December 2016 (ML16356A670). - *Flexible Licensing Processes for Advanced Reactors - NRC developed guidance for its flexible regulatory review processes within the bounds of existing regulations* (ML17312B567) - Industry-Led Licensing Modernization Project - develop technology-inclusive, risk-informed, and performance based regulatory guidance for licensing non-LWRs - Advanced Reactor Content of Application Project (ARCAP) - build on the outcome of the Licensing Modernization Project. - The NRC issued SECY-20-0010 *Advanced Reactor Program Status* in January 2020 (ML1933A1A628). - Memorandum of Cooperation (MOC) for joint reviews of SMR's and AR's with Canadian Nuclear Safety Commission (CNSC)	- NuScale (50MWe) completed design certification (awaiting rule making) - Pre-application underway for 4 other LWR's (NuScale, 77 MWe version; mPower, BWXT; SMR-160, Holtec; BWRX-300, GE Hitachi) - Pre-application underway for 3 MSRs 3 MSRs (Xe-100, X-energy; KP-FHR, Kairos Power; IMSR, Terrestrial Energy) and 1 heatpipe microreactor (eVinci, Westinghouse) - COL applied for Aurora reactor

4.2 Technology readiness

Respondents were asked to report their level of experience with pre-licensing and licensing activities associated with the five generic SMR types in line with the criteria outlined in section 3.1.2 (*i.e.*, significant experience; limited experience; and no or very limited experience), as well as the level of challenges to be overcome for successful licensing of the SMR designs (*i.e.*, minor challenge; significant challenge; and major challenge).

France and the UK did not participate in this survey; however, both countries have significant experience in designing, building, operating and decommissioning different reactor types.

It should also be noted that China's responses cover only LWR and HTGR/VHTR SMRs and, as there is no formal pre-licensing process in China, the responses only capture the licensing process.

For each of the SMR types, this section describes the main areas where additional technology development is still required to support licensing requirements. Challenges that are generic to most SMR types are as follows:

- Technology validation (*i.e.*, equipment testing), primary coolant flow modelling/ demonstration, safety system operation, reactor and steam cycle testing, fuel manufacturing and testing.
- Implications of multiple modules, *e.g.*, how to introduce additional modules during operational activities, operational staffing requirements and how to control multiple modules from one control room.
- Supply chain and manufacturability, *e.g.*, creation of a new supply chain or developing the existing one; possible certifications required for manufacturing and testing.
- In-factory versus onsite testing, *e.g.*, what must be in place during in-factory testing, transport and delivery to site to maintain validity of testing undertaken in-factory.
- Passive safety system performance and demonstration of reliability (experiments with demonstration facilities and calculation tools to be developed and adapted).
- Achieving benefits of inherent improvements in safety *e.g.* reduction in emergency planning zone (EPZ) as a result of a lower radioactive inventory.

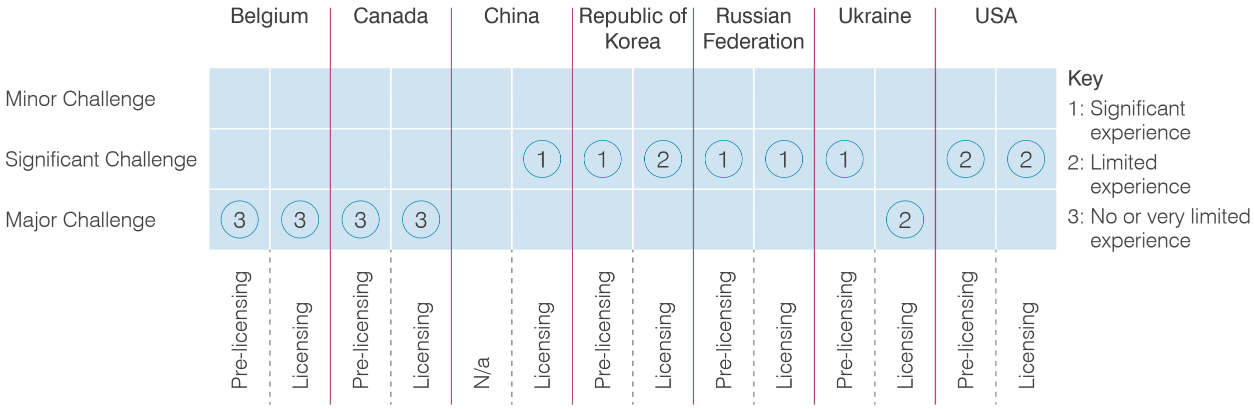
The following sections outline the technology-specific challenges to the SMR designs considered in the survey, the perceived status of technology development within each country, and the results of the comparison of each SMR to a generic large-scale LWR in order to assess the extent of the technology challenge in each of the surveyed countries.

This survey is not intended to be a full technology readiness assessment for each of the key safety areas. **It is recommended that any government interested in the licensing of SMRs undertakes a detailed technology readiness assessment of the designs being considered prior to entering the licensing process.** One example of such a study has recently been undertaken by the UK government [10].

4.2.1 LWR SMRs

SMR designs based on light water reactor (LWR) technology bear many similarities to large-scale LWRs in operation today. These types of SMR generally utilize well-understood technologies with smaller more integrated components and enhanced passive safety features in comparison to those in current large scale LWRs.

Figure 2. LWR SMR technology readiness by country



These SMR types have different design characteristics to large scale LWRs– such as passive cooling systems utilizing natural circulation and gravity driven injection, smaller plant and component sizes, and modular features leading to changes in initiating events, alternative production, assembly and testing requirements for components and the requirement for multi-module considerations. These differences resulted in some of the countries surveyed, notably the USA, indicating that both pre-licensing and obtaining a construction licence would be a significant challenge to meet current regulatory expectations, citing passive safety systems and operational aspects of the plant for first-of-a-kind (FOAK) designs as the main reason for this categorization.

Figure 2 represents the response from each of the survey contributors.

4.2.2 HTGR & VHTR SMRs

SMRs based on high and very high temperature gas-cooled reactor (HTGR & VHTR) technology are characterized by their use of a graphite moderator and gases such as helium as reactor coolants. These reactor types could reach temperatures of up to 1000°C and in general utilize new fuel types, some of which have higher enrichment than LWR fuel. These characteristics lead to additional technology-specific challenges to licensing such as:

- Post-operational fuel and moderator management.
- Fuel integrity (particularly the structural integrity under seismic loading for prismatic cores).
- Fission product release, *i.e.* creation of fission product 'dust' that is transported around the primary loop.
- Prevention of water ingress.

Research and development programs have existed in multiple countries investigating areas such as fuel production and performance, material properties, and spent fuel treatment and disposal. Several countries have previously operated demonstration units such as the Peach Bottom experimental reactor in the US and more recently the high temperature engineering test reactor (HTTR) in Japan and the HTR10 in China. These experimental activities have resulted in an improved understanding across multiple areas *e.g.* degradation mechanisms of graphite, production of TRISO fuel and identification of promising high temperature materials [11]. Further research and development is required in these areas, particularly in material mechanical testing and life modelling.

All the countries surveyed categorized the pre-licensing and construction licensing activities associated with HTGR & VHTR SMRs as either a significant or major challenge. A number of factors were cited by respondents in arriving at these categorizations, including: limited design experience; lack of construction codes; and unresolved questions concerning fuel development and safety analysis tools.

Figure 3 represents the response from each of the survey contributors. It is of note that China is currently building a twin 250 MWt pebble bed HTGR at the Shidaowan nuclear power plant with an expected coolant outlet temperature of 750°C [12].

4.2.3 FNR SMRs

Fast neutron reactors (FNRs) SMRs are characterized by their use of a fast neutron spectrum and generally feature the use of liquid metal coolants such as sodium or lead and have fuels with a greater concentration of fissile material, than that of large-scale LWRs, which allows for higher power densities to be achieved thus reducing the size of the core.

Figure 3. HTGR SMR technology readiness by country

	Belgium		Canada		China		Republic of Korea		Russian Federation		Ukraine		USA	
	Pre-licensing	Licensing	Pre-licensing	Licensing	N/a	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing
Minor Challenge														
Significant Challenge						1			2	2				
Major Challenge	3	3	3	3			3	3			3	3	3	3

Key
1: Significant experience
2: Limited experience
3: No or very limited experience

The Russian Federation has a long history of FNR development and has achieved commercial operation of large scale FNRs via its BN600 and BN800 reactors at Beloyarsk, with a larger BN1200 design in development. While these are not SMRs, the development of any fast neutron reactor designs increases technology awareness that can be subsequently applied to SMRs. However, technology-specific challenges to licensing remain that must be overcome to facilitate wider commercial deployment of FNR SMRs:

- Design development following lessons learned from previous experimental and demonstration reactors, *e.g.* computer codes, reactor systems such as chemistry control and reactor instrumentation, number of cooling loops and associated heat transfer efficiency.
- Management systems and material use associated with reactor coolants, *e.g.* avoiding water ingress with molten salt coolants, and managing the corrosive nature of lead.
- In service inspection of reactor vessel, reactor internals above and below the coolant level, and equipment required for leak monitoring.
- Fuel cycle – development, manufacture, and management of waste.

All of the countries surveyed identified the pre-licensing and construction licensing activities associated FNR SMRs as being either a significant or major challenge – see Figure 4. The technology challenges cited included: limited to no design, regulatory or operating experience of reactor technology; research and development required; fuel design and demonstration; and material development needed.

While the respondent for China did not provide a specific response in relation to FNRs, the China Experimental Fast Reactor (CEFR), a 20 MWe sodium cooled FNR, was connected to the grid in 2010 and the construction of two 600 MWe commercial demonstration reactors is under way at Xiapu.

Figure 4. FNR SMR technology readiness by country

	Belgium		Canada		People's Republic of China		Republic of Korea		Russian Federation		Ukraine		USA	
	Pre-licensing	Licensing	Pre-licensing	Licensing	N/a	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing
Minor Challenge														
Significant Challenge									2	2				
Major Challenge	3	3	3	3			3	3			3	3	3	3

Key
1: Significant experience
2: Limited experience
3: No or very limited experience

It is also of note that in the Republic of Korea, the design of a FNR demonstration plant has been completed, with further development and entry to licensing on hold since 2017.

4.2.4 MSR SMRs

Reactor designs based on molten salt reactor (MSR) technology mostly use a graphite moderator and a molten mixture of lithium and beryllium fluoride salts with dissolved enriched fuel (uranium or thorium fluorides). The coolant outlet temperatures of MSRs can reach at least 700°C and can be used to create steam for electricity production or heat for industrial applications.

MSR designs exhibit similar inherent safety features to other innovative SMR designs such as, strong negative temperature and void coefficients, and passive decay heat removal. MSRs with circulating fuel salt also have lower fissile inventories, no requirement to fabricate and handle solid fuel and have a homogeneous isotopic composition of fuel within the reactor. However, despite these features, the designs come with additional technology-specific challenges to licensing including:

- R&D challenges, *e.g.* material demonstration including resistance at high and low temperatures, metallurgical stability, resistance to irradiation, resistance to air oxidation and corrosion [13], waste management and online processing.
- Further research and design development required, e.g, computer codes, reactor systems such as chemistry control, irradiation of materials and impact of delayed neutrons [14].
- Management systems, including leakage of primary circuit, radiation exposure during maintenance and production of tritium.
- Fuel cycle – development and manufacture of fuel; online reprocessing of spent fuel; and liquid waste management.
- Safeguards – control of liquid fuel inventory.

While MSR technology has been researched in many countries for decades, the majority of the survey respondents agreed that licensing MSRs are a major challenge and that in general there was no or limited experience of design or operation of MSRs within their respective countries.

Figure 5. MSR SMR technology readiness by country

	Belgium		Canada		China		Republic of Korea		Russian Federation		Ukraine		USA	
	Pre-licensing	Licensing	Pre-licensing	Licensing	N/a	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing
Minor Challenge														
Significant Challenge														
Major Challenge	3	3	3	3			3	3	2	2	3	3	3	3

Key
1: Significant experience
2: Limited experience
3: No or very limited experience

Figure 6. Heatpipe microreactor technology readiness by country

	Belgium		Canada		People's Republic of China		Republic of Korea		Russian Federation		Ukraine		USA	
	Pre-licensing	Licensing	Pre-licensing	Licensing	N/a	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing	Pre-licensing	Licensing
Minor Challenge														
Significant Challenge														
Major Challenge	3	3	3	3			3	3	3	3	3	3	3	3

Key
1: Significant experience
2: Limited experience
3: No or very limited experience

Some recent designs contain the molten salt fuel mixture within fuel assemblies, which may remove some of the challenges associated with the impact of delayed neutrons, leakage of the primary circuit and management of the fuel inventory, however the other challenges to licensing such as, manufacture and post operational management of the fuel, production of tritium and radiation exposure during maintenance, remain.

Figure 5 represents the responses from each of the survey contributors.

4.2.5 Heatpipe microreactors

There are various designs of microreactor being considered, some of these based on variations on the types of reactor described in this report. The most advanced designs are of a heatpipe design. Heatpipe microreactors use a fluid in numerous sealed horizontal steel heatpipes to passively conduct heat from the hot fuel core (where the fluid vaporizes) to the external condenser (where the fluid releases latent heat of vaporization) with a heat exchanger. No pumps are needed to effect continuous isothermal vapour/liquid internal flow at less than atmospheric pressure.

The principle is well-established on a small scale, and like MSRs, heatpipe microreactors exhibit a large negative temperature reactivity coefficient; however similar additional technology-specific challenges to licensing also exist, namely:

- Further research and design development associated with scaling up, *e.g.*, flow dynamics, reactivity control, computer codes, thermohydraulic modelling.
- Management systems and materials, *e.g.* to demonstrate postulated lifetime.
- Fuel cycle – development, manufacture, and waste management.
- Scalability, *e.g.* maintaining a sufficiently small size to be easily transportable.
- Safeguards, *e.g.* maintenance of fuel inventory.

All countries surveyed identified the activities for pre-licensing and those to obtain a construction licence to be a major challenge (see Figure 6). All of the survey participants identified that their respective countries had limited to no experience of heatpipe microreactor technology.

5 Survey analysis

5.1 Regulatory organizations

The survey results reaffirm the findings in *Licensing and Project Development of New Nuclear Plants* [1], *i.e.* that there is a wide variety of regulatory organizations and structures between different countries.

The way in which these regulatory bodies are funded varies from country to country. This can range from being completely government-funded, to being fully or partially funded through collection of fees from the nuclear industry.

Almost all nuclear regulatory bodies rely on or have the capability to access the skills of scientific and technical support organizations (TSOs) in order to support their regulatory reviews and activities. TSOs are generally either well-defined organizations set up with the specific intention of supporting nuclear regulatory activities, or they can be private companies with competencies or expertise in specific technical or safety areas of interest that the regulator can call upon as required to inform its regulatory decisions.

The size of the regulatory authorities and the associated TSOs depends on both the scope of regulatory activities and the number of nuclear facilities within the regulators' respective jurisdictions or laws. For example, given the small number of nuclear facilities in Belgium, the regulatory authority and TSO have fewer resources in comparison with their counterpart in the USA, which has a larger fleet of nuclear facilities. In addition, the US NRC undertakes the full fuel cycle regulatory activities internally, resulting in a large nuclear regulatory body.

To support and discuss long-term objectives and safety concerns, regulatory bodies often share experiences under collaborative bilateral agreements and/or an international framework *e.g.*, collaboration with the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency (NEA), and the Western European Nuclear Regulators Association (WENRA).

5.2 Licensing processes

5.2.1 Pre-licensing

Pre-licensing frameworks do not exist in all of the countries represented by the surveys. Where they do exist, while being recommended by the country's regulatory authorities, they are generally not mandatory.

The survey observed that there are a wide range of pre-licensing processes in use by different regulators that vary in many ways, including:

- Applicant (vendor, operator or both).
- Breadth and depth of reviews.
- Expected level of design maturity required from entry to completion of the steps or phases established in the pre-licensing process.
- Outputs from the pre-licensing processes.

Despite this wide variety, where pre-licensing frameworks do exist, they have similar aims. These allow regulators to gain familiarity with the design, obtain early information on its main safety features, and inform the level of readiness of their workforce. Pre-licensing also allows applicants the opportunity to increase familiarity with the relevant regulations and requirements and to get some early feedback on how their designs meet a country's regulatory requirements, and identify areas where additional design information, evidence or research and development is needed.

Some respondents indicated that while the pre-licensing frameworks are not mandatory, if they were not to be used, it would likely take longer for the construction licence to be granted, particularly in cases where the direct licensing process has not been used for a number of decades or where the regulator has limited or no experience of new reactor types.

5.2.2 Licensing

The survey results confirm that the licensing frameworks in the countries represented are in line with the steps outlined in *Licensing and Project Development of New Nuclear Plants* [1], *i.e.* one-step, two-step or multi-step licensing.

However, despite the difference in the number of official stages within the licensing framework, in contrast to the varying multiple approaches observed for pre-licensing, the survey found that the licensing requirements and subsequent expected level of design maturity to achieve a construction licence are relatively well aligned among the countries represented by the surveys, *i.e.* achieving Phase 3 design maturity is a critical prerequisite for the construction licence in all countries.

Table 7 represents a general guide of the various pre-licensing and licensing steps in the countries surveyed against the design maturity phases as defined in section 2.4 of this report.

5.2.3 Minimum regulatory licensing requirements of SMRs

Depending on the country and regulatory framework, either the vendor and/or the potential licence applicant will be required to enter into an exchange process with the regulatory body, whether for pre-licensing or for licensing as discussed in section 4.1.2, and it is important for the licence applicant to anticipate the requests and expectations of the regulatory body.

While achieving a certain design phase and technology maturity are vital steps to supporting pre-licensing or licensing activities in a given country, there are other criteria such as those that would form the basis of the safety case, that are equally important to be addressed during Phases 1 and 2 to ensure a constructive dialogue with the relevant regulatory body.

The safety principles, concepts and technical requirements outlined in International Atomic Energy Agency (IAEA) Specific Safety Standards SSR-2/1 [15] are broadly applicable to all reactor designs and should be consulted by all reactor vendors as a starting point to understanding the regulatory expectations, and to demonstrate to the regulatory bodies how they are proposing to meet fundamental safety objectives. Furthermore, the IAEA has assessed the applicability of the design safety requirements to LWR and HTGR technologies [16].

Failure to demonstrate to the regulatory body compliance with, or suitable consideration of, these safety principles, concepts and technical requirements at an early stage in the licensing process may lead to uncertainty during the subsequent licensing activities and result in design modifications at a late stage in the design process, which can have a significant impact on later project phases.

Safety objectives

The safety objectives adopted for a new SMR design envisaged to be deployed in a specific country should be clearly established and justified. How these objectives

Table 7. Pre-licensing and licensing steps in relation to design maturity

	Phase 1: Concept	Phase 2: Plant-level design	Phase 3: System-level design	Phase 4: Component-level design
Belgium	Design options & provisions file (DOPF) preparation & examination		Licence application & examination	Confirmation of the construction and operation licence
Canada	Vendor design review (VDR)	Site evaluation Environmental impact assessment and licence to prepare site	Licence to construct	Licence to operate
China		Site evaluation and environmental impact assessment	Construction permit	Operating licence
France		Development of safety options dossier (DOS) and ASN opinion of safety options	Safety options assessment Construction licence application Construction licence (DAC-authorization decree)	Commissioning authorization
Republic of Korea		Early site approval (ESA) Standard design approval (SDA)	Construction permit	Operating licence
Russian Federation	While Russia has no Formal pre-licensing process, the practice of analysis and evaluation of materials justifying the safety of Russian design SMR nuclear power plants is being introduced by Russian technical support organization – SEC NRS		Site licence Construction licence	Operating licence
UK		Generic design assessment (GDA) Step 1: initiation	GDA Step 2: fundamental assessment GDA Step 3: detailed assessment Nuclear site licence	Regulatory hold points and inspections
Ukraine	Assessment by SNRIU of design and possibility of the design to complete licensing process	Feasibility study review	Design & PSAR review Construction & commissioning licence	Operating licence
USA	Pre-application review	Design certification Early site permit (ESP) Standard design approval (SDA)	Combined construction & operating licence	Regulatory hold points and inspections

[10] The size of the boxes used to represent the various licensing activities in Table 7 are not representative of the duration or scope required to complete the activity. The boxes represent the earliest start and finish point for each licensing activity relative to the design phase based on previous experience in each country. This is intended to provide SMR licence applicants with a general guide, and is not a comparative study of the licensing timescales between countries.

compare to the regulations, currently operating reactors, and previous relevant prototype reactors, should be explained and a development programme established and agreed with the regulators to demonstrate how any differences will be justified.

Consideration of experience feedback in the selection of safety options

When operating experience, including lessons learned from previous significant events, is available for certain technologies or concepts, the licence applicant should be able to explain: which lessons have been learned from operating experience and corrective actions implemented on previous reactors, and applied or considered within the proposed new design; which aspects may require deployment of innovative features or techniques; and what is proposed in these areas to improve the safety and the reliability of the new reactor concept or technology.

Requirement 9 (§4.16) of SSR-2/1 states: *"Where an unproven design or feature is introduced or where there is a departure from an established engineering practice, safety shall be demonstrated by means of appropriate supporting research programmes, performance tests with specific acceptance criteria or the examination of operating experience from other relevant applications. The new design or feature or new practice shall also be adequately tested to the extent practicable before being brought into service, and shall be monitored in service to verify that the behaviour of the plant is as expected."* [15]

Depending on the progress of the design development and the stage of regulatory engagement, even if some safety options are being considered but have not been adopted yet, the regulatory body should be informed; and later on, information should be provided regarding those options that were eventually adopted or discarded and how operational feedback influenced those decisions.

Identification and categorization of plant states

IAEA SSR-2/1 Requirement 13 states: *"Plant states shall be identified and shall be grouped into a limited number of categories primarily on the basis of their frequency of occurrence at the nuclear power plant."*

Requirement 16 (§5.5) states: *"Postulated initiating events shall be identified on the basis of engineering judgement and a combination of deterministic assessment and probabilistic assessment."* [15]

As expressed in section 4.2, not all reactor concepts benefit from the same level of operating experience; identifying and categorizing plant states is relatively more complicated for some than for others.

For new concepts or technologies at an early stage in the regulatory process, the licence applicant should be ready to provide the regulatory body with information justifying the adequacy of the programme deployed for establishing and categorizing plant states considered for the design. Wherever it is considered that the available operating experience or research programmes may not be sufficient to fully validate the methodology for identifying and categorizing plant states, the licence applicant should consolidate the approach as far as is reasonably practicable and agree with the regulatory authorities on a strategy for validating or amending the list and categorization of plant states during the plant operating lifetime (*e.g.*, during the course of periodic safety reviews) and implementing, as necessary, compensatory measures. During initial operation, the plant operator will monitor the plant closely and take immediate corrective actions in accordance with any relevant feedback and/or emerging issues.

The methods followed to identify a comprehensive set of postulated initiating events, establish the grouping and categorization of plant states, and the rules for conducting the deterministic safety analyses and definitions of the design basis and design extension conditions will form the basis on which the key safety principles – such as defence-in-depth, plant performance, separation of safety provisions for anticipated operational occurrences, safety systems for design basis accidents and safety features for the design extension conditions, including their supporting systems – are implemented. It therefore follows that early engagement with the regulatory authorities on these methods is fundamental to the development of an effective safety case and achieving constructive and meaningful dialogue with the regulators.

The approach used for consideration of severe accidents in the design and the principles adopted to identify and practically eliminate conditions which could lead to early or large radioactive releases should be expressed. For new concepts or technologies with limited or no operational experience, the programmes that have been, or are planned to be, implemented to demonstrate physical impossibility or to claim that conditions leading to such an early or large radioactive release would be extremely unlikely to arise with a high level of confidence, should be presented to the regulatory body.

Rules for the application of the single failure criterion, especially for passive safety systems or components, need to be clearly expressed. Rules for combinations of aggravating failures, for consideration of multiple failure events, for determining the initial conditions (different plant operating modes, with or without consideration of maintenance), and for conducting analyses (conservative, realistic, best-estimate), should be agreed and submitted to the regulatory body.

Any modifications to such rules could lead to having to consider new situations within the design. Implementing modifications to the rules could affect the architecture of systems and the layout of the plant. 'Adding-on' at a later stage rather than 'building-in' at an early stage would in most cases lead to an increase in the costs and complexity of the plant, cause delays and may even prove detrimental to safety.

Classification of items important to safety

The rules adopted for classifying structures, systems and components (SSCs) according to their significance to safety, the codes and standards applied for their design and the corresponding quality levels, as well as the principles followed for their qualification to accident conditions, should be established and presented to the regulatory body at an early stage.

For new concepts or technologies, manufacturability, constructability, reliability and maintainability, availability of relevant and qualified non-destructive examination techniques, and capacity for pre-service inspection and in-service monitoring, surveillance and inspection, should be considered before entering into discussion with the regulatory body. Strategies and programmes should be presented to the regulatory body explaining how these will be ensured.

Use of probabilistic studies

Especially for new reactor designs, the licence applicant should explain to the regulatory authorities how probabilistic studies have been conducted as a supplement to deterministic studies in order to assess the impact of various safety options in relation to the level of risk and how options have been selected to achieve a level of risk as low as reasonably achievable/practicable (ALARA/ALARP).

This will need to include detailed descriptions of the development, qualification, and the use of scientific computing tools and methodologies that have been used in the design and safety case development.

The targets adopted for the contribution of initiating events, internal and external hazards to the overall risk, and the impact of iterative steps of the design process on such contributions should be explained.

5.3 Regulatory framework – past and ongoing SMR regulatory activities

In most cases, the SMR reactor types undergoing pre-licensing or licensing activities within the surveyed countries are of a different reactor technology than what the regulators are familiar with or currently regulating.

While there are some national regulators that have already granted design certifications or construction licences to SMR demonstration units, most of the pre-licensing processes have not been used by the respective national regulators in relation to SMR designs. Moreover, many of the national regulators in the countries surveyed have updated, or are in the process of updating or adapting, their regulatory frameworks to provide more flexibility for the assessment of SMR designs,

These adaptions to regulatory frameworks are relatively new and in order to maximise learning between regulatory authorities and make appropriate use of the reference plant design, **it is recommended that national regulators that are already, or are planning to, undertake licensing activities for relevant SMR designs should engage internationally with other national regulators through bilateral and multinational agreements on design and safety reviews, to share technical reviews, establish common position statements on safety criteria, and identify any other areas for collaboration**. A potential framework under which such collaboration could occur has been proposed by *Lessons from transport for reactor design harmonization* [17].

5.4 Technology readiness

The results of the surveys indicated that LWR SMRs are generally at a higher degree of technology readiness and pose fewer challenges to current licensing processes in comparison to other SMR designs. This could be due to conventional LWR technology being well developed and most regulatory authorities being familiar with the technology, and therefore there is a relatively small learning curve for both designers and regulators. However, despite this relatively high degree of technology maturity, challenges to the licensing of LWR SMRs remain, particularly in the areas of approach to I&C architecture, demonstration of passive safety features, use of standard non-nuclear grade components and certain operational aspects.

The technology survey results indicated differing levels of perceived licensing challenges for HTGRs and FNRs. As would be expected, contributors from countries which currently have ongoing design or construction projects for HTGR or FNR designs, perceive the challenges to licensing to be lower than those from countries with limited or no such experience.

All contributors agreed that the largest challenges to licensing existed with MSR SMRs and heatpipe microreactors, for which it was generally agreed that both presented a major challenge to licensing. Contributors cited areas such as research and development, fuel cycle development and safeguards among the primary challenges to be overcome.

6 Conclusions and recommendations

This report presents the findings from two surveys undertaken by members of CORDEL's Licensing and Permitting Task Force (LPTF) and Small Modular Reactor Task Force (SMRTF). The survey respondents from nine countries across three regions (Asia, Europe and North America) covered a wide range of knowledge and experience from research and development to operation of nuclear power plants.

The first survey asked respondents to identify:

- National regulatory organizations and structures.
- Pre-licensing and licensing processes.
- Past and ongoing licensing activities in relation to SMRs.
- Regulatory framework readiness for SMRs (respondents' perspective only[11]).
- Key documents, guidance, requirements, laws, codes and standards, etc.

The results of the surveys and the subsequent discussions among members from the CORDEL Working Group of World Nuclear Association have described the relationship between licensing processes and design phases, highlighted some key safety case development considerations, outlined technology challenges associated with licensing SMRs, and identified on-going activities by regulatory authorities to facilitate the licensing of SMRs.

The wide variety of licensing processes, number of steps and the diversity of overall national regulatory structures, previously highlighted in *Licensing and Project Development of New Nuclear Plants* [1], was immediately noticeable when evaluating the survey results. License applicants should be prepared to tailor their licensing approach to account for these differences.

Where pre-licensing processes exist, they are recommended by national regulatory authorities and generally not mandatory. While pre-licensing processes exhibit similar aims, *e.g.* increasing familiarity with the design and decreasing the risks to its licensability, they vary widely in many ways, including:

- Applicant (vendor, operator, or both).
- Breadth and depth of reviews.
- Expected level of design maturity required for entry and completion to the processes.
- Outputs from the pre-licensing processes.

As a result of this variability, in some countries pre-licensing occurs early in the design maturity cycle over a relatively short period of time, whereas others require engagement at different design maturity phases and can last as long as the construction phase of the power station, *i.e.*, three-to-five years (see Table 7). As a general principle, a greater level of design maturity prior to engagement with the regulatory authorities will result in more predictable timescales and costs for pre-licensing and licensing activities.

While the number of licensing steps between each of the surveyed countries varies, there is a general alignment on the design phase required to achieve a construction licence within each licensing framework, *i.e.* Phase 3 design maturity.

Analysis of the survey results allowed the design phases to be mapped to each of the regulatory framework steps in the surveyed countries (see Table 7). This analysis also identified a number of key safety case

[11] It should be noted that regulators have not provided direct input to this report.

criteria that should be developed alongside the Phase 1 and Phase 2 design phases in order to ensure a constructive dialogue with the relevant regulatory body. The key criteria identified are:

- Safety objectives.
- Consideration of operational experience in the selection of safety options.
- Identification and categorization of plant states.
- Classification of items important to safety.
- Use of probabilistic studies.

A small number of countries have commenced operation of SMRs, while other national regulators are at different stages of licensing, in some cases multiple, SMRs. All SMRs currently operating or having achieved significant licensing milestones *e.g.* design certification in the USA, have utilised current regulatory frameworks and most of the pre-licensing processes identified by this survey have not been used by the respective national regulators in relation to SMR designs. SMRs currently undergoing licensing in the countries surveyed are generally of a reactor type that is different to the reactor technology that the relevant regulator is most familiar with.

Given the novelty of designs, the regulators undertaking the safety reviews will be going through a learning process; therefore, it is vital that the applicant maintains constant dialogue with the regulators and ensures timely submissions of documentation.

The perceived challenges to licensing a given type of SMR depends on a wide variety of criteria, including the regulatory experience with that reactor type. This highlights the need for national regulators to work together in areas where they can support each other's reviews and help to increase each other's knowledge about different reactor types. Some national regulators have identified the need to support each other and have formed formal relationships in order to do so, for example in the August 2019 cooperation agreement between the US NRC and the CNSC [18]. Such collaboration between regulators, accompanied by efforts to harmonize their approaches to licensing, would significantly improve the feasibility of deployment of large numbers of SMRs.

A country's regulatory framework is generally either rule-driven, goal-driven or a combination of both. In order to facilitate a large deployment of SMRs of all types, regulatory frameworks will have to undergo some adaptation to allow for new technologies. Some regulatory regimes have already taken steps towards adopting the graded approach into rule-driven regimes, *e.g.* the US NRC's efforts to incorporate risk-informed decision-making into the licensing of advanced reactors. In addition, some goal-driven regimes have amended their processes to allow for a greater amount of flexibility, *e.g.* the UK [19].

It is likely that the first full use of these adapted licensing processes will be in the licensing of SMR designs. It can therefore be reasonably assumed that there will be a learning curve for both regulators and reactor vendors as these approaches are applied systematically in making risk-informed decisions to address technology uncertainties and design provisions.

A number of generic areas relevant to all SMR designs were identified as key technology challenges to be resolved prior to engagement with the relevant regulatory bodies:

- Technology validation (*i.e.*, equipment testing), primary coolant flow modelling/demonstration, safety system operation, reactor and steam cycle testing, fuel manufacture and testing.
- Implications for plants consisting of multiple modules, *e.g.*, how to introduce additional modules during operational activities, and how to control multiple modules from one control room.
- Supply chain and manufacturability, *e.g.*, creation of a new supply chain or developing the existing one; possible certifications required for manufacturing and testing.
- In-factory versus onsite testing, *e.g.*, what must be in place during in-factory testing, transport and delivery to site to maintain validity of testing undertaken in factory.
- Passive safety system performance and demonstration of reliability (calculation tools to be developed and adapted).

Other specific challenges relating to each reactor type have also been identified and are detailed within section 4.2.

The results of the second survey indicated that LWR SMRs are generally at a higher degree of technology readiness in comparison to other SMR designs and pose fewer challenges to current licensing processes. The responses in relation to HTGR and FNR SMRs varied according to whether there was an active development programme within the that particular country. The most innovative technologies *i.e.*, MSR SMRs and heatpipe microreactors, presented the greatest challenge to licensing.

The following best practice and recommendations have been developed based on the results and analysis of the surveys presented within this report.

6.1 Identified best practices

- Prior to undertaking pre-licensing or licensing activities in a country other than the SMR vendor's home country, it is important that a gap analysis against the requirements of the proposed host country be undertaken and appropriate approaches to resolving the identified gaps are developed.
- SMR vendors having a systematic approach to recording all major design modifications, upgrades, safety decisions and the methodology or bases upon which decisions were made, is critical to build regulatory confidence in the design process.
- The safety case elements discussed in section 5.2.3 should be sufficiently developed by the SMR vendor and explained to the regulatory authorities through early engagement in order to minimize potential delays in regulatory reviews of the design.
- Continuous engagement by the license applicant and timely submission of design and safety documentation is important to build trust with national regulators and support the review process.
- National regulatory engagement with international bodies such as the IAEA SMR Regulators' Forum and safety standards committees improves the ability to share common experience, develop international best practices, and to create, revise and harmonize safety standards and approaches to licensing.
- Informing potential applicants of any changes to the licensing frameworks and dedicating appropriate regulatory resources to support timely reviews, approval and licensing will be crucial to supporting the deployment of SMRs.
- Governments interested in the deployment of SMRs should undertake a detailed technology readiness assessment of the designs being considered prior to their entering the licensing process.

6.2 Recommendations

- **SMR vendors'** completion of major research and development (R&D) activities, the associated design and technical decisions, and the demonstration of a clear programme of future technical development, are pre-requisites to commencing and/or completing pre-licensing activities, in the countries surveyed.
- **Licence applicants'** active and early engagement with national regulators, in anticipation of expected licensing activities, is required to understand the technology readiness of the reactor designs and clarify the degree of technical and design maturity requirements for every phase of the pre-licensing and licensing processes.
- **National regulators** undertaking SMR licensing activities, or planning to do so in the future, can benefit from engagement with other national regulators through bilateral and multinational agreements on design and safety reviews, sharing technical reviews, establishing common position statements on safety criteria, and identifying any other areas for collaboration making appropriate use of the reference SMR design review, where one exists.

References

[1] Licensing and Project Development of New Nuclear Plants, Licensing and Permitting Task Force, World Nuclear Association, January 2013, reprinted August 2015

[2] Facilitating International Licensing of Small Modular Reactors, Small Modular Reactors Ad-hoc Group, Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group, World Nuclear Association, August 2015

[3] Market and Technical Assessment of Micro Nuclear Reactors, 80775/REP/001/C, Nuvia, 31 March 2016

[4] Kristina Soderholm, Licensing Model Development for Small Modular Reactors (SMRs) – Focusing on the Finnish Regulatory Framework, Lappeenranta University of Technology, September 2013

[5] Pre-Licensing Vendor Design Review page on Canadian Nuclear Safety Commission website

[6] Small modular reactors page on Canadian Nuclear Safety Commission website

[7] Small Modular Reactors (LWR designs) page and Advanced Reactors Details page on US Nuclear Regulatory Commission website

[8] KINS/RR-740 "Development of the Regulatory Requirements for New Innovative Reactor Licensing," Feb (2010)

[9] KINS/GR-572, "Regulatory Review on SMR Licensing Direction in Regard with IAEA SMR Regulators Forum," 2015

[10] SMR Techno-Economic Assessment, Project 3: SMRs Emerging Technology, Assessment of Emerging SMR Technologies, Summary Report, For The Department of Energy and Climate Change, National Nuclear Laboratory, 15 March 2016

[11] NUREG/CR-6824. ANL-02/37. Materials behaviour in HTGR environments. Argonne National Laboratory.

[12] IAEA Status report 96- High temperature Gas Cooled Reactor – pebble-bed Modular (HTR-PM)

[13] Limitations of application of structural materials for generation IV reactors – MSR and VHTR, AIP Conference Proceedings 2047, 020009 (2018), Krejčí Miroslav, published online 28 November 2018

[14] Review of R&D of thorium molten-salt reactor, Kamei Takashi, 2013

[15] IAEA Safety Standards, Safety of Nuclear Power plants: Design, Specific Safety Requirements, No. SSR-2/1 (Rev. 1), International Atomic Energy Agency, 2016

[16] IAEA TECDOC-1936. Applicability of design safety requirements to small modular reactor technologies intended for near term deployment.

[17] Lessons from transport for reactor design harmonization, Cooperation in Reactor Design Evaluation and Licensing, World Nuclear Association, Dec 2020

[18] Memorandum of Cooperation on Advanced Reactor and Small Modular Reactor Technology Between the United States Nuclear Regulatory Commission and the Canadian Nuclear Safety Commission, 15 August 2019

[19] Office for Nuclear Regulation, Approach to regulating innovation, September 2020

Appendix 1 | National regulatory organizations

To simplify the various different funding models for each of the regulatory bodies and TSOs, the responses provided to the survey results have been summarized into three categories for use in this appendix;

- Government – government funded, no fee collection
- Government and nuclear industry – partly government funded and partly funded from direct or indirect collection of fees from industry
- Nuclear Industry – funded from direct or indirect collection of fees from industry

Country	Organization	Funding Model	Organizational Size (employees)[12]	Relevant Links
Belgium	Regulatory Authority - Federal Agency for Nuclear Control (FANC)	Nuclear Industry	160	www.fanc.fgov.be
	Technical Support Organization(s) (TSO) - Bel V	Nuclear Industry	65	www.belv.be
	Others - National Institute for Radioactive Waste and enriched fissile materials (NIRAS/ONDRAF) - Scientific Council - Regional Competent Authorities			
Canada	*Regulatory Authority* - Canadian Nuclear Safety Commission (CNSC)	Government and nuclear industry	886	www.nuclearsafety.gc.ca
	Technical Support Organization(s) (TSO) N/a			
	Others - Impact Assessment Agency of Canada (IAAC) - Atomic Energy of Canada Limited (AECL) - Nuclear Waste Management Organization (NWMO) - Canadian Standard Association Group (CSA Group) - Technical Standard and Safety Authority (TSSA)			
China	*Regulatory Authority* - National Nuclear Safety Administration, (NNSA)	Government	1000	http://nnsa.mee.gov.cn/english/
	Technical Support Organization(s) (TSO) - Nuclear and Radiation Safety Center (NSC)	Government and nuclear industry	600	http://www.chinansc.cn
	Others - National Energy Administration - State Administration of Science Technology and Industry for National Defense			
Ukraine	*Regulatory Authority* - State Nuclear Regulatory Inspectorate of Ukraine (SNRIU)	Government	250	http://www.snrc.gov.ua/
	Technical Support Organization(s) (TSO) - State Scientific and Technical Center for Nuclear and Radiation Safety (SSTC NRS)	Government and nuclear industry	250	https://www.sstc.ua/
	Others - Ministry of Energy of Ukraine - Ministry of Environmental Protection and Natural Resources of Ukraine - National Commission for State Regulation of Energy and Public Utilities of Ukraine - Other ministries as required			

[12] Organization sizes are approximate based on publicly available information at time of writing report.

Country	Organization	Funding Model	Organizational Size (employees)[12]	Relevant Links
Korea	*Regulatory Authority* - Nuclear Safety and Security Commission (NSSC)	Government and nuclear industry	155	https://www.nssc.go.kr/
	Technical Support Organization(s) (TSO) - Korea Institute of Nuclear Safety (KINS) - Korea Institute of Nuclear Non-proliferation and Control (KINAC)	Government and nuclear industry Government and nuclear industry	545 113	http://www.kins.re.kr/en/ https://www.kinac.re.kr/eng
	Others - Environmental Protection Agency - Import / Export Control - Other ministries as required			
United Kingdom	*Regulatory Authority* - Office for Nuclear Regulation (ONR)[13]	Nuclear industry	500	http://www.onr.org.uk
	Technical Support Organization(s) (TSO) - Multiple[14]			
	Others - Environment Agency (EA)			https://www.gov.uk/topic/environmental-management/nuclear-regulation
France	*Regulatory Authority* - Nuclear Safety Authority (ASN)	Nuclear industry	500	http://www.french-nuclear-safety.fr/ http://www.french-nuclear-safety.fr/ASN/About-ASN/The-ASN-organisation
	Technical Support Organization(s) (TSO) - Institute for Radiological Protection and Nuclear Safety (IRSN)	Nuclear industry	1750	https://www.irsn.fr/
	Others - National Radioactive Waste Management Agency (ANDRA) - Defence, Security and Economic Intelligence Department (HFDS)	Nuclear industry Nuclear industry		https://international.andra.fr/about-andra https://solidarites-sante.gouv.fr/ministere/defense-et-securite-hfds/
United States of America	*Regulatory Authority* - Nuclear Regulatory Commission (NRC) - Atomic Safety and Licensing Board (ASLB) - Advisory Committee on Reactor Safeguards (ACRS)	Nuclear industry	3200	https://www.nrc.gov/ https://www.nrc.gov/about-nrc/organization.html
	Technical Support Organization(s) (TSO) N/A			
	Others - Various organizations and government departments			

[13] For the purpose of the GDA, the ONR and EA have established a Joint Project Office (JPO) http://www.onr.org.uk/new-reactors/index.htm

[14] The ONR and EA do not have a set of fixed TSO's they instead appoint technical support providers as required through Technical Support Frameworks (TSF).

Country	Organization	Funding Model	Organizational Size (employees)[12]	Relevant Links
Russia	*Regulatory Authority* - Federal Environmental, Industrial and Nuclear Supervision Service (Rostechnadzor)	Government	1100	http://en.gosnadzor.gov.ru/
	Technical Support Organization(s) (TSO) - Scientific and Engineering Centre for Nuclear and Radiation Safety (SEC NRS) - JSC "VO Safety"	Government and nuclear industry Nuclear industry	350 >1000	https://www.secnrs.ru/en/about/ https://vosafety.ru/
	Others - Ministry of Environmental Protection and Natural Resources - Ministry of Health - Other relevant departments as necessary			

Appendix 2 | Belgium regulatory documentation and resources

Key documentation

Regulatory documentation

- *Eighth Meeting of the Contracting Parties to the Convention on Nuclear Safety, 2019, National Report including description of licensing process* – Link
- *A consolidated version of Belgian nuclear regulations is available on the FANC web site (only in Dutch and French)* – Link
- *Approach to Defence-in-Depth, radiological safety objectives and application of a graded approach to external hazards (April 2017)* – Link
- *Other Guidelines are on consideration of radiological consequences analysis, earthquake, flooding and aircraft risks* – Link

MYRRHA project

- *Role of the defence in depth within the pre-licensing* – Link
- *Insights on regulatory approach applied* – Link

Appendix 3 | Canadian regulatory documentation and resources

Key Regulatory documentation

- *Nuclear Safety and Control Act* - Acts - Canadian Nuclear Safety Commission
- *Regulatory framework* - The CNSC's Regulatory Framework Plan - Canadian Nuclear Safety Commission

Other regulatory links

- *Canadian Safety Standards* – Link
- *Technical Standards and Safety Authority* – Link
- *Nuclear Waste Management Organization* – Link
- *Atomic Energy of Canada Ltd* – Link
- *Impact Assessment Agency of Canada* – Link

Appendix 4 | China regulatory documentation and resources

Key Documentation

Laws

- *The Act of the People's Republic of China on Prevention and Control of Radioactive Pollution* – Link
- *The Act of the Peoples Republic of China on Nuclear Safety* – Link

Regulations

- *Regulations of the People's Republic of China on Safety Supervision and Management of Civil Nuclear Installations*
- *Regulations of the People's Republic of China on Nuclear Material Control*
- *Regulations (of the People's Republic of China) on Emergency Management of Nuclear*
- *Accidents at Nuclear Power Plants Regulations on the Safety and Protection of Radioisotopes and Radiation Devices*
- *Regulations on the Supervision and Management of Civil Nuclear Safety Equipment*
- *Regulations for the Safe Transportation of Radioactive Materials*
- *Regulations on the Safe Management of Radioactive Wastes*

Department Rules

- *Safety permit procedures for nuclear power plants, research reactors and nuclear fuel cycle facilities*
- *Safety Provisions on Quality Assurance of Nuclear Power Plants*
- *Provisions on the Safety of Nuclear Power Plants: Siting*
- *Provisions on the Safety of Nuclear Power Plants: Design*
- *Provisions on the Safety of Nuclear Power Plant Operation*
- *Provisions on the Safety of Research Reactor Design*
- *Provisions on the Safety of Research Reactor Operation*
- *Provisions on safety supervision and administration of radioactive waste*
- *Measures for the Licensing Management of Solid Radioactive Waste Storage and Disposal*
- *Rules for the Implementation of Regulations of the People's Republic of China on Nuclear Material Control*
- *Provisions on the Regulation for Imported Civil Nuclear Safety Equipment*

Appendix 5 | France regulatory documentation and resources

Key Documentation

Laws

- *Environment Code - Code de l'environnement* – Link
- *Decree No 63-1228 du 11 Dec 1963 on nuclear installations - Décret Procédure 2007-1557 du 2 novembre 2007* – Link
- *Order for Basic Nuclear Installations - Arrêté INB du 7 février 2012* – Link
- *Pressure vessel requirements - Arrêté ESPN du 12 décembre 2005 et 30 décembre 2015* – Link
- *Order on the surveillance of operation of principal primary and secondary circuits in PWRs - Arrêté du 10 novembre 1999 relatif à la surveillance de l'exploitation du circuit primaire principal et des circuits secondaires principaux des réacteurs nucléaires à eau sous pression* – Link

Other regulatory links

- *Regulatory process - Abrogation of Décret Procédure 2007-1557 du 2 novembre 2007 (codified in the Environment Code ; articles R593-1 to R593-75)* – Link
- *Licensing process* – Link
- *Commissioning and operation license - Article L.593-11 of Environment Code* – Link
- *Shutdown & Decommissioning - Articles 37 and 38 of Decree No 2007-1557 of 2 November 2007.* – Link
- *A Guide for New Designs - "Guide 22" for PWRs 2017* – Link

Appendix 6 | Republic of Korea regulatory documentation and resources

Key Documentation

- *Legal framework* – Link
- *Legislative framework* – Link
- *Nuclear Safety Act* – Link
- *Regulatory review process* – Link
- *KINS/RR-816, "Development of Safety Review Framework for Small and Medium Power Reactor," Nov. 2010*
- *KINS/RR-740, "Development of the Regulatory Requirements for New Innovative Reactor Licensing," Feb. 2010*
- *KINS/GR-572, "Regulatory Review on SMR Licensing Direction in Regard with IAEA SMR Regulators Forum," 2015*

Other

- *APR+ Summary* – Link
- *SMART Status report* – Link
- *Historical Overview of Nuclear Regulation in Korea* – Link

Appendix 7 | Russian regulatory documentation and resources

Key Documentation

- *Federal laws* – Link
- *Federal codes and regulations* – Link
- *Key Federal codes and regulations' document is NP-001-15 General provisions for safety assurance of nuclear power plants.*
- *Main mechanical code is PNAE G -7-002-86 Regulations for the strength analysis of equipment and pipelines of nuclear power installations*

Regulations

- *Radiation safety of the population - № 3-FZ dated 09.01.1996*
- *Environmental protection - № 7-FZ dated 10.01.2002*
- *Sanitary and epidemiological welfare of the population - № 52-FZ dated 30.03.1999*
- *Protection of the population and territories from natural and human induced emergencies - № 68-FZ dated 21.12.1994*
- *Fire safety - № 69-FZ dated 21.12.1994*
- *Water Act of the Russian Federation -№ 74-FZ dated 03.06.2006*
- *Ensuring the uniformity of measurements - № 102-FZ dated 26.06.2008*
- *Industrial safety of hazardous production facilities - № 116-FZ dated 21.07.1997*
- *Technical regulation on fire safety requirements - № 123-FZ dated 22.07.2008*
- *The use of atomic energy - № 170-FZ dated 21.11.1995*
- *About technical regulation - № 184-FZ dated 27.12.2002*
- *Building Code of the Russian Federation - № 190-FZ dated 29.12.2004*
- *Management of radioactive waste and on amendments to certain legislative acts of the Russian Federation - № 190-FZ dated 11.07.2011*
- *Technical regulation on the safety of buildings and structures - № 384-FZ dated 30.12.2009*

Appendix 8 | UK regulatory documentation and resources

Key Documentation

- *Licensing Nuclear Installations* – Link
- *Radioactive Substances Regulations (RSR)* – Link
- *Guidance on disposal of radioactive waste* – Link
- *Information on Generic Design Assessment (GDA)* – Link
- *Guidance on generic design for new nuclear build* – Link
- *"Applying for a nuclear site licence for new nuclear power stations - A step-by-step guide"* – Link

Appendix 9 | Ukraine regulatory documentation and resources

Key Documentation

Law

- *Law of Ukraine "On the Use of Nuclear Energy and Radiation Safety";*
- *Law of Ukraine "On the Licensing Activity in the field of Nuclear Power Utilization";*
- *Law of Ukraine "On Decision Making Procedures for Siting, Designing, Construction of Nuclear Installations and Radioactive Wastes Management Facilities of National Importance" No. 2861-IV dated 08 September 2005.*

Other

- *Development of approaches to comparative analysis of the foreign and Ukrainian regulatory requirements for designing and nuclear facility safety justification*
- *Safety requirements for site selection for nuclear power plant location (NP 306.2.144-2008), approved by the SNRIU Order No. 68 dated 07 April 2008 (registered by the Ministry of Justice of 28 May 2008, No. 467/15158);*
- *Law of Ukraine "On Human Protection against Impact of Ionizing Radiation" No. 15 dated 14 January 1998";*
- *Major sanitary rules for radiation protection of Ukraine (DSP 6.177-2005-09-02), approved by the Ministry of Healthcare Order of 02 February 2005 No. 54 (registered by the Ministry of Justice of 20 May 2005 No. 552/10832);*
- *Radiation Safety Standards of Ukraine (NRBU-97) (DHN 6.6.1.-6.5.001-98) approved by the Resolution of the Chief state sanitary physician of Ukraine of 01 December 1997 No.62.*
- *Law of Ukraine "On Physical Protection of Nuclear Installations, Nuclear Materials, Radioactive Wastes, other Ionizing Radiation Sources " dated 19 October 2000, No. 2064;*
- *SNRIU Order dated 28 January 2015 No. 12 "On approval of document list provided by the operating organization for granting the license for activity at the individual stages of nuclear installation life cycle";*
- *Resolution of the Cabinet of Ministers of Ukraine dated 06 December 2000 No. 1782 "On approval of licensing procedure of individual activities in the field of nuclear energy utilization";*
- *Conditions and procedures of granting the individual written permissions for activities and operations at the stages of commissioning, operating and decommissioning of nuclear installation (NP 306.2.090-2004), approved by the SNRIU Order dated 27 February 2004 No. 38 (registered by the Ministry of Justice of Ukraine of 17 March 2004 No. 331/8930);*
- *Procedure for state expert review on nuclear and radiation safety (NP 306.1.107-2005) approved by the SNRIU Order dated 21 February 2005 No. 21 (registered by the Ministry of Justice of Ukraine of 07 April 2005 No. 372/10652);*
- *Requirements for nuclear power plants safety assessment NP 306.2.162-2010 approved by the SNRIU Order dated 22 September 2010 No. 124, registered by the Ministry of Justice of Ukraine of 21 October 2010 No. 964/18259.*

Appendix 10 | USA regulatory documentation and resources

Key Documentation

- *Nuclear Power Plant Licensing Process - NUREG/BR-0298 Revision 2* – Link
- *NRC rule making process* – Link
- *Reactor Licensing process* – Link
- *SMR licensing* – Link
- *Advanced Reactors* – Link
- *NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness, December 2016, ML16356A670*
- *SECY-19-0117 "Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors," December 2019, ML18312A253*
- *DG-1353 "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors," April 2019, ML18312A242*
- *A Regulatory Review Roadmap for Non-Light Water Reactors, December 2017, ML17312B567*
- *Oklo Power Combined License Application, March 2020, ML20075A000*
- *SECY-20-0010 "Advanced Reactor Program Status", January 2020, ML1933A1A628*
- *NRO-REG-104 "Pre-application Readiness Assessment, ML14079A197*
- *NEI 18-06 "Guidelines for Development of a Regulatory Engagement Plan, Revision 0, June 2018*
- *NUREG-1350, Volume 31 "Information Digest 2019-2020, ML19242D331*
- *Issuance of Early Site Permit for Exelon Generation Company, LLC (ESP-001), March 15, 2007, ML070670140*
- *Issuance of Early Site Permit (ESP) for System Energy Resources, INC.- Grand Gulf ESP Site (ESP-002), April 5, 2007, ML070780457*
- *Issuance of Early Site Permit (ESP) for dominion Nuclear North Anna, LLC - North Anna ESP Site (ESP-003), November 27, 2007, ML073180440*
- *Issuance of Early Site Permit (ESP) for Southern Nuclear Operating Company-Vogtle Electric Generating Plant ESP Site (ESP-004), August 26, 2009, ML092290157*
- *Issuance of Early Site Permit (ESP) for SPSEG Power, LLC and PSEG Nuclear, LLC PSEG Site Early Site Permit (ESP-005), May 5, 2016, ML16084A798*

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There is significant interest in the role small modular reactors (SMRs) can play in the clean energy systems of the future. SMRs cover a wide range of technologies but have in common their potential to decarbonize electrical grids and other applications, such as district heating, process heat for industry, hydrogen and synthetic fuels production, as well as providing electricity to remote or off-grid areas.

To help support the process of bringing SMRs to market, *Design Maturity and Regulatory Expectations for SMRs* describes the relationship between licensing processes in a variety of countries and design phases of a reactor. The report highlights key safety case development considerations, technology challenges, and licensing activities.

The report emphasizes the importance of early engagement between SMR vendors and national regulators to clarify the degree of design maturity required to undergo the pre-licensing and licensing processes. In addition, the report recommends national regulators to collaborate through bilateral and multinational agreements on design and safety reviews, to share technical reviews, establish common positions on safety criteria, and make appropriate use of existing reference SMR design reviews to streamline SMR licensing processes.

This report has been jointly produced by the Small Modular Reactors Task Force and the Licensing and Permitting Task Force of World Nuclear Association's Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group.