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Technology Roadmap for Small Modular Reactor Deployment

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TECHNOLOGY ROADMAP FOR SMALL MODULAR REACTOR DEPLOYMENT

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TECHNOLOGY ROADMAP FOR SMALL MODULAR REACTOR DEPLOYMENT

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

Technology roadmaps have proven to be very useful management tools for identifying, evaluating and promoting the development of complex technological projects. More importantly, the development and use of a technology roadmap can accelerate development of the technology while avoiding unforeseen barriers to the product's deployment. Technology roadmaps promote enhanced collaboration and knowledge sharing, and help to ensure that efforts (by technology developers, industry, users and regulatory bodies) are focused on a common objective. Additionally, for Member States, technology roadmaps can support science and technology policy decisions, investments across government and industry in terms of loan guarantees and incentives, industry led initiatives and human resource development.

This publication is intended to provide Member States with a set of generic roadmaps that can be used in the deployment of small modular reactors (SMRs). These roadmaps are based on the latest inputs from Member States currently pursuing this technology. The publication places emphasis on the activities of owners/operating organizations, who drive the demand and requirements for reactor designs; designers, who develop the technologies; and regulators, who establish and maintain the regulatory requirements that owners/operating organizations are obliged to meet. It also provides a methodology for developing a technology roadmap for reactors with longer development horizons, and provides information on emerging opportunities and challenges for this relatively new nuclear technology.

Before deploying nuclear power technology, Member States need relevant reference and guidance documents to develop the necessary infrastructure. Although the focus of this publication is on roadmaps, a discussion related to infrastructure is included with reference to the appropriate guidance documents. This publication assumes that Member States either have the needed infrastructure or are working to develop the infrastructure necessary to support a peaceful nuclear power programme. The technology roadmaps laid out in this publication were developed with the support of experts from several Member States in four meetings convened by the IAEA over the course of three years.

The IAEA wishes to acknowledge the assistance provided by the contributors and reviewers listed at the end of the publication, especially C.L. Painter (United States of America), who developed the initial draft on SMR technology roadmaps. The IAEA officers responsible for this publication were M.H. Subki, S. Monti and F. Reitsma of the Division of Nuclear Power.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

In September 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development [1] with 17 Sustainable Development Goals (SDGs). Goals 7, 9 and 13 are entitled Affordable and Clean Energy; Industry, Innovation and Infrastructure; and Climate Action, respectively. In December 2015, during the 21st annual session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), held in Paris, 195 countries agreed on a historic and first-ever legally binding global climate agreement establishing an action plan to limit global warming to well below 2°C [2]. To achieve these goals, a worldwide change in the way energy is both produced and consumed is required. Moreover, a wide range of low carbon energy technologies will be needed to support this transition, including a variety of renewable energy technologies, energy efficiency measures, advanced vehicles, carbon capture and storage, and nuclear energy. The Paris Agreement offers an incentive for nuclear power development because every signatory has to update its Nationally Determined Contribution every five years.

According to the IAEA's Power Reactor Information System (PRIS), as of July 2021 there were 443 nuclear power reactors in operation in 32 IAEA Member States, contributing 393 241 MW(e) total net installed capacity. Furthermore, 51 nuclear power reactors were under various stages of construction in 19 Member States which will in due course contribute 53 905 MW(e) total net installed capacity. These power reactors can trace their lineage back to small prototype or demonstration reactors. The earlier generation designs generally ranged from less than 100 MW(e) to as large as 300 MW(e), and a small number of these facilities continue to be safely operated today. These designs were part of many efforts around the world to experiment with different cooling technologies, fuel types and operating configurations. Although not designed at the time for modular fabrication or construction, these early plants shared many of the same considerations for modern day small modular reactor (SMR)[1] technologies in that vision and careful planning were needed to develop and successfully deploy them. Preferential technologies that emerged from these early commercial efforts are based on the following:

- The expected effort required to obtain technology maturity for use in commercial facilities;
- The ability to resolve technical uncertainties in a timely manner (e.g. material degradation challenges, chemistry);
- Political considerations such as nationalization of supply chains where possible, preferences for reactor brands, access to technology user groups to share and learn from operating experience.

Water cooled reactors (WCRs) were the dominant technology to emerge, although considerable efforts in other coolant technologies continued over the decades, recognizing that significant advantages could be gained in operating performance if outstanding technological issues could be resolved.

Over time, economies of scale, based on maximizing megawatts against operating and maintenance (O&M) costs, drove nuclear power reactor technology developers to produce ever larger designs, leading to designs today with power levels of up to 1700 MW(e). An interest in reducing plant O&M costs while improving safety performance led to the development of passive safety features that are adopted in today's advanced evolutionary reactor designs (also known as Generation III and III+ reactors). However, these advanced reactor designs are now pushing the technological envelope and little can be done to make them more efficient.

The development of innovative reactor designs and technologies (also known as Generation IV reactors), to establish a step change in efficiency as well as in safety performance over existing water

[1] The IAEA uses the SMR abbreviation to refer to small and medium sized reactors or small modular reactors. This publication uses SMR only to refer to small modular reactors.

cooled technologies, continues. New fuels, reactor configurations and materials push thermal efficiency higher while reducing the number of systems necessary to run the plant safely.

However, the market for large capacity power plants is limited to countries with a grid capacity capable of accepting them. The grid demand of such a country should also be growing to the extent that plants of this capacity would be necessary (e.g. replacement of old plants or addition of new generation plants). At the same time, recognizing the need for political support for nuclear power, a utility and its stakeholders should select a technology that they know with certainty can be constructed and operated more cost effectively, safely and efficiently than existing plants.

Of the more than 50 new plants currently under construction in 19 countries, all are based on water cooled technologies, except two nuclear power reactors. One is in China, a high temperature gas cooled reactor, and one is in India, a sodium cooled fast reactor. Most of the power reactors under construction are in countries with well developed grids. However, after 2010, countries embarking on nuclear power programmes, including Bangladesh, Belarus, Turkey and United Arab Emirates, started construction projects for large nuclear power reactors with advanced technology. In addition to the issues of reliability and cost competitiveness, there is also the issue of political risk, with nuclear projects becoming topics of political and/or public controversy, and consequently lengthening licensing procedures, the risk of governments imposing nuclear phase out, etc.

Limitations of grid capacity[2] and slow growth in power demand are leading factors in exploring whether smaller, more incremental, nuclear power technologies can be used either instead of new large nuclear power plants, or to supplement existing installed capacity. In addition, with the growing use of intermittent renewable capacity such as solar, wind, small hydroelectric and tidal generation, there are advantages to introducing small baseload nuclear plants with enhanced load following capabilities to stabilize the supply to the grid. A large number of nuclear technology developers have recognized this gap in the market and are responding with smaller reactor facility concepts that promise to meet the long term needs of power utilities and their stakeholders. In some cases, developers are going a step further and are looking to address yet another market niche for smaller sources of reliable power supply in remote places, such as a mine where the only source of reliable power comes from local off-grid combustion generation (e.g. diesel sets).

The key to the success of these new technologies is the ability to demonstrate stronger economic efficiency, given that smaller reactors equate to a loss of economies of scale. This means that:

- Users will no longer accept delays in construction and commissioning, which lead to increased long term costs to be absorbed by a project. This is resulting in the use of more predictable manufacturing and construction approaches, such as modular engineering and construction, which come from the shipbuilding and aerospace industries.
- Users require modern technological measures to reduce O&M costs and to improve the overall plant capacity factor while at the same time demonstrating to their stakeholders an improvement in safety performance necessary to ensure public acceptance of a nuclear project.

These new reactor concepts are known in the marketplace as SMRs in an attempt to differentiate them from larger nuclear power plants. They are generally understood to be smaller than 300 MW(e) per reactor in output. However, despite being built and operated using different approaches, the IAEA considers these concepts to be smaller nuclear power plants that should still address the requirements specified in the IAEA safety standards and guides.

The market for smaller nuclear facilities has the potential to be an order of magnitude larger than for current full scale nuclear power plants, given that most small countries either have small grids or are developing mixed generation grids. However, much of the infrastructure essential for larger plants is still needed for these smaller types of facilities, albeit scaled commensurate with risk. These include the

[2] Assuming a country is seeking to avoid costly grid expansion to accommodate new generation capacity.

regulatory regime; operator capacity to oversee safe conduct of its activities; emergency planning; and security and safeguards.

The IAEA has pursued a number of initiatives to support the development and deployment of SMRs, recognizing their potential as options for enhancing energy supply security in countries expanding their nuclear programmes or embarking on such programmes. The driving forces in the development of such reactors are the following:

— Meeting the need for flexible power generation for a wider range of users and applications.
— Replacing existing ageing fossil fuel fired power plants or enhancing a grid which contains more intermittent renewables. This may be feasible technically but a challenge from the perspective of the economics involved.
— Enhancing safety performance through inherent and passive safety features.
— Offering better financial affordability.
— Ensuring suitability for non-electric applications.
— Providing options for remote regions with less established electricity grid infrastructures.
— Offering possibilities for synergetic energy systems that combine nuclear and alternative energy sources.

1.2. OBJECTIVE

Given the increasing interest of Member States in the near term deployment of SMRs, the objective of this publication is to present several model technology roadmaps to Member States which can be adapted to their specific projects. These roadmaps are based on the best ideas generated during a series of international meetings on this topic. For nuclear newcomer countries, these roadmaps assume that a Member State has already developed, or is at least well along the way in developing, the infrastructure necessary to operate a nuclear power programme.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

The scope of the technology roadmap described in this report is the deployment of SMRs of all major types for electricity production and non-electric applications, and their integration with other energy resources. The emphasis here is on the activities of owners/operating organizations, who drive the demand and requirements for reactor designs; designers, who develop the technologies; and regulators, who establish and maintain the regulatory requirements that need to be met by owners/operating organizations. This report also provides a methodology for developing a technology roadmap for reactors with longer development horizons, and provides information on emerging opportunities and challenges for this relatively new technology.

1.4. STRUCTURE

This publication is divided into seven main sections. Section 1 presents the background, objective, scope and structure of the technology roadmap for SMR deployment. Section 2 provides the current status of SMR deployment, presents a brief discussion of the term ‘modular’ and how it is used. The importance of infrastructure development, non-proliferation and safeguards to support any nuclear power programme is also discussed. Finally, a summary of the various types of technology roadmap and their importance is presented. Section 3 discusses prospects and impediments related to the deployment of SMR technology,

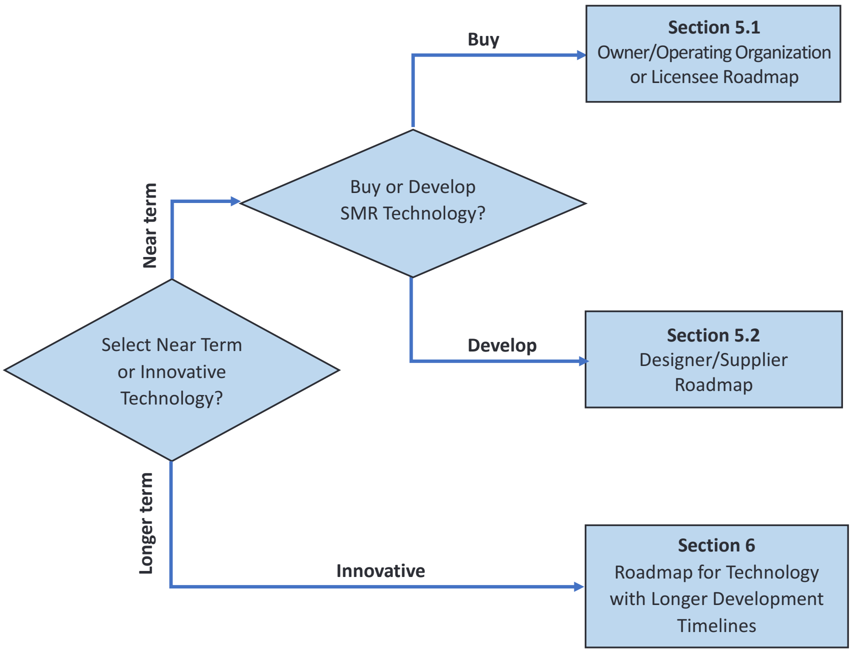

FIG. 1. Basic flowchart of SMR technology roadmaps in the publication.

and indicators that Member States can use to make an initial assessment of their readiness to adopt the technology. Section 4 provides a summary of the various stakeholders that are likely to be involved in SMR development and deployment, as well as a short discussion and comparison of the various types of regulatory framework. Section 5 presents an overview of near term deployable SMRs and identifies examples of roadmaps that can be either followed or adopted with adjustments to suit the specific needs of Member States. A designer/vendor based roadmap, as well as an owner or licensee based roadmap, is presented, the major differences being the complexity of effort and time taken. The type of technology roadmap used in this section is similar to a project planning roadmap and is applicable to more mature reactor designs that possess a higher state of technology readiness. Section 6 proposes a methodology for creating a technology roadmap for reactor concepts and designs that are associated with a lower state of technology readiness and require a substantially larger investment in research, development and demonstration. Section 7 concludes with a set of recommendations.

The Annex provides a review of both the technology and the associated approaches taken by several manufacturers currently developing SMRs.

Figure 1 shows a basic flowchart of SMR technology roadmaps in this publication and is a schematic representation of its key sections. The structure and content of this publication reflect the discussions and key messages that emerged from technical meetings as well as from additional input incorporated during the drafting and review process.

2. SMALL MODULAR REACTORS AND THE TECHNOLOGY ROADMAP

This section describes the current status of SMR deployment, and provides a brief discussion of the term ‘modular’ and how it is used. It also highlights the aspects of infrastructure development, non-proliferation and safeguards that are not included in the roadmap, but that are essential to support any nuclear power programme. Finally, a summary of the various types of technology roadmap and their importance is presented.

2.1. CURRENT STATUS OF DEPLOYMENT

SMRs are designed to be manufactured as needed, with their modules tested in the manufacturing facilities before being shipped to utilities for installation. These approaches aim to reduce lengthy construction times while simultaneously increasing quality, thereby minimizing the financing costs associated with today’s large construction projects. Some SMR design concepts are intended to be deployed in multiple module configurations within a single power plant. Several countries are also pioneering the development of transportable nuclear power plants, including marine based floating and seabed based SMRs. In December 2019, the Akademik Lomonosov floating nuclear power plant was connected to the electricity grid in Pevek, Russian Federation and started commercial operation on 22 May 2020. Several other SMR designs, and the associated technology, are expected by 2030 and later.

A large number of SMR designs that cater to different end uses and power producing capacities are being developed around the world. The list of these SMRs is changing continually as new companies are set up and concepts are developed, and also as companies restructure or abandon, or combine efforts to establish credibility with potential customers in different Member States. The Annex discusses three SMR deployments that were under way in 2020. Perhaps the most important goal of SMR technology is to significantly reduce the scheduling risk associated with nuclear reactor construction and its associated cost of debt.

In this publication, SMRs are categorized into three distinct groups:

(1) SMRs recently connected to the grid and currently under construction. For the most part these are designs with significant government backing and are being built as prototypical facilities or as first of a kind (FOAK) demonstration and commercial facilities. These SMRs are discussed in the Annex.

(2) SMRs likely to be deployed in the next ten years following completion of design, testing and R&D activities. These designs have well advanced development programmes and significant government or private sector support. They are likely to use more traditional technological methods (hence a shorter development timeline) with evolutionary changes, but may not have the increased efficiencies of more advanced technologies.

(3) SMRs likely to be deployed within 20 years. These designs are currently establishing R&D programmes to test new approaches and materials and may need to generate significant testing and even operating experience in areas such as safety performance of fuels, corrosion tolerance, ageing mechanisms and component reliability.

Some developers of advanced SMR technologies have proposed novel solutions to bypass some of the time consuming test programmes, especially those dealing with materials development. For example, these could include defining shorter lifetimes of some components and equipment where long term operating experience does not currently exist. This could shorten the time to deployment, but may also carry additional regulatory and licensing risks. Some Member States allow licensing through a prototype plant where aspects of design and operation are confirmed stepwise for a first plant. This may reduce development time.

Currently, there are more than 70 SMR designs under development for different applications. As mentioned above, the Russian Federation's Akademik Lomonosov was connected to the grid in 2019 and started commercial operation in May 2020. In 2003, the Russian Federation's nuclear regulator, Rostechnadzor, issued the first construction licence for the Akademik Lomonosov, which is a floating power unit (FPU) with two KLT-40S reactor modules capable of generating 70 MW(e) of shore deployable power, with each reactor module rated at 35 MW(e). No reactor power is used for the propulsion system of the vessel. Construction of the first domestic design of this FPU began in 2007 and was completed in the beginning of 2018. The application for the plant operating licence was then submitted to Rostechnadzor. After initial completion and testing in St. Petersburg, the FPU was towed to Murmansk, where nuclear fuel was loaded and final tests conducted, before finally being towed and deployed in Prevek. The developer is also considering a modified version of the FPU for export outside the Russian Federation, based on the RITM-200M design and possibly adapting a simplified and innovative refuelling approach consisting of FPU replacement.

By mid-2020, two SMRs were in advanced stages of construction: the Argentine CAREM (a small-scale prototype of a future larger commercial design) and the Chinese HTR-PM (an industrial demonstration plant).

The Central Argentina de Elementos Modulares (CAREM) reactor is a prototype small, integral type pressurized LWR with a rated electrical power of 27 MW(e). It is being built to develop the operating experience necessary to support a future larger version that will be rated at between 150 and 300 MW(e). All the traditional primary coolant system components have been incorporated inside the reactor vessel (i.e. integral to the reactor vessel). Site excavation work for the CAREM reactor was completed in August 2012 and plant construction has begun, with a variety of contractors being employed to manufacture the various components. The project's target startup date for commissioning and first fuel loading is the second half of 2023. The regulator has established a staged licensing approach suitable for this prototype aimed at demonstrating specific safety milestones before proceeding to the next phase of project work.

China started its R&D programme on high temperature gas cooled reactors (HTGRs) in the 1970s. In 1992, the Chinese Government approved construction of a small test HTGR (HTR-10); in January 2003, the reactor reached full power (10 MW(th)). Since that time, Tsinghua University's Institute of Nuclear and New Energy Technology (INET) has used the HTR-10 to conduct various experiments, collect engineering data and verify crucial inherent safety features. In 2001, China launched its High Temperature Gas Cooled Reactor–Pebble Bed Module (HTR-PM) reactor development project. HTR-PM will be a commercial demonstration plant for electricity production, with two reactor units driving a single 200 MW(e) power turbine. Compared with the HTR-10, the components for HTR-PM have been scaled up, although the design bases are similar. Construction of this reactor began in December 2012. Despite a comprehensive test programme, the construction of this demonstration reactor is also being used to test and develop operating experience of new and major components in the design such as the helium circulators and steam generators, as well as manufacturing and quality assurance practices for those components. The demonstration plant is expected to start commercial operation in 2021. Other domestic and international projects are also being considered using the same reactor units, albeit as scaled up versions (a six unit design is under development) of the demonstration design, such as in the Middle East. More information on some of the other design and development activities in Member States is given in Section 2.3.1.

2.2. MODULAR DESIGN AND CONSTRUCTION: TERMINOLOGY

Modularization is considered a key part of the concept of an SMR. It generally refers to techniques borrowed from other mature industries such as shipbuilding and aerospace. These techniques merge improvements, claimed by those industries, in quality and efficiency, as derived from serial factory manufacturing, attempts at standardization of components to the extent practicable, as well as more simplified on-site installation of pre-assembled modules.

Until there is evidence of a sufficient number of SMR orders, a full module manufacturing environment (e.g. factory) is not likely to exist for the following reasons:

— Such a facility requires a major capital investment that can only be recovered over time from the fleet to be deployed.
— Manufacturing practices for a specific design need to be field-proven and accepted by the participating users and regulatory bodies before they can be used for mass production.
— Operating experience is gained from the first series of the reactor design.
— Configuration stability has to be reached for each module (i.e. level of sufficient standardization[3]).

As a result, the first few SMRs are likely to be deployed as on-site construction facilities with perhaps the testing of prototypical small volume module manufacturing lines to acquire manufacturing experience. This is proving to be the case for SMRs being built as of 2020, as described in the Annex. This means that the economies of serial production will not be realized until the 'nth of a kind' (NOAK) case, if a number of orders exist to justify the factory manufacturing approach. To attract the first few utilities to adopt the technologies, they would need an incentive in lieu of the NOAK economies being promised by the manufacturer.

The term 'modular' is used in this publication to describe activities related to the design, construction and arrangement of power modules inside a power plant. In general, products designed and constructed using modular techniques benefit from economies of series production, factory fabrication and shorter assembly and construction schedules. It is important to recognize that a module will vary from one reactor design to the next. In some designs, such as an integrated LWR, a module may consist of an entire reactor assembly, including all primary systems and associated instrumentation. Others may use more traditional but integrated components designed to be easily assembled in the field such as an instrumentation and control (I&C) system module that can be tested and partially commissioned in factory or major civil structure modules.

When used in reference to a design activity, the term 'modular design' is often related to an approach whereby the design of a component, assembly or structure is subdivided into modules that can be more easily assembled and may be replaced over time to facilitate ease of maintenance.

In reference to construction, 'modular construction' refers to a technique in which modules are constructed on-site or off-site and shipped to their final destination where they are assembled in a building. For large buildings (e.g. the reactor building), such construction techniques necessitate large lift and rigging capabilities, sometimes the building of temporary structures, and increased transportation costs (e.g. large trailer trucks and barges). However, the advantage is that the modules can be fabricated in parallel with early site excavations and preparation work, reducing the overall construction time (and, as a result, a reduction in the long term finance costs associated with borrowed capital[4]) [3]. Clearly, modular construction lends itself well to building a series of units with the same design.

Factory built modules (as opposed to stick-built construction in the field) refer to modules that are built in a factory. These modules typically have been designed to be all inclusive with regard to mechanical, electrical and instrumentation features, and can be assembled in a more controlled plant environment, by fully trained labour, using the same materials, codes and standards for each subsequent module. In

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[3] In any mass production industry of complex equipment, the definition of standardized will normally vary due to regular improvements made, as lessons are learned in the production of the equipment.

[4] A typical large nuclear power plant construction project may take four to eight years to complete, with overnight capital costs ranging from US $2000 to US $5000 per installed kW(e) [3]. Depending on the actual length of the construction schedule and interest rates charged, the long term financing costs associated with such a large capital intensive project can be significant.

addition, these modules are designed and built to be less complex to handle and transport — often being designed to use portable skids. Moreover, labour costs are generally lower since the workforce does not have to be transient and relocated each time a plant is constructed. Additionally, a stable labour force is often easier to train and qualify, and produces higher quality and less expensive products due to the improved learning curve and ease of implementing continuous quality improvements. Lower labour costs can also be achieved as a result of shorter project timelines because of serial fabrication techniques and more efficient use of materials.

Some SMR designers, as part of their effort to enable modularization, have integrated the various components of a reactor coolant system (e.g. core, pressurizer, steam generator and pumps) into a single reactor pressure vessel (RPV). By integrating these primary components into the RPV, large diameter piping can be eliminated, which in turn will eliminate the possibility of a large break loss of coolant accident (LBLOCA) — a major design basis accident for large traditional WCRs.

Multi-module reactor plants describe reactor plant designs that have more than one reactor module located within the same plant, with the understanding that there could be several multi-module plants built at a particular site. It is important to differentiate this from the more traditional multi-unit site approach employing large nuclear reactors, where a nuclear site can have more than one unit, with each unit having one large reactor housed inside. There are several advantages to this approach:

- Lower initial capital investment;
- Ability to add additional modules as the demand for power grows;
- Higher plant availability since not all modules will need to be off-line for refuelling at the same time.

Regardless of this terminology, it is imperative that certain reactor safety design standards be adopted. One of the primary references is IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [4]. With regard to technical design considerations, there are several key requirements that must be met[5]:

- Requirement 4: Fundamental safety functions;
- Requirement 5: Radiation protection in design;
- Requirement 6: Design for a nuclear power plant;
- Requirement 7: Application of defence in depth;
- Requirement 8: Interfaces of safety with security and safeguards;
- Requirement 9: Proven engineering practices;
- Requirement 10: Safety assessment;
- Requirement 11: Provision for construction;
- Requirement 12: Features to facilitate radioactive waste management and decommissioning.

2.3. NUCLEAR POWER INFRASTRUCTURE

Launching a new nuclear power programme is a major undertaking that requires careful planning, preparation, public interaction and investment of time and resources. The infrastructure that is required to support the successful introduction or expansion of nuclear power covers a wide range of issues, including:

- Physical facilities for the delivery of electricity;
- Site and supporting facilities for handling radioactive waste;

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[5] The scope of SSR-2/1 (Rev. 1) [4] states: "It is expected that this publication will be used primarily for land based stationary nuclear power plants with water cooled reactors designed for electricity generation or for other heat production applications (such as district heating or desalination). This publication may also be applied, with judgement, to other reactor types, to determine the requirements that have to be considered in developing the design."

— Legal and regulatory framework;
— Financial resources necessary to implement the required activities;
— Trained human resources.

Owing to the variety of complex and interrelated issues, developing a nuclear power programme can take 10–15 years until commissioning of the first plant. It also requires a proponent (e.g. a utility), as well as a Member State government, which should consider planning for the long term. Thus, Member States should set at least a 100 year timeframe for their programme. This planning should take into account long lead issues such as:

— Essential physical infrastructure (e.g. grid capacity, transportation, education facilities);
— Regulatory capacity, capability and framework (nuclear and complementary conventional frameworks such as occupational health and safety, environmental protection, etc.);
— Waste management (conventional and radiological);
— Long term land use controls and planning.

2.3.1. SMR deployment in a country with an existing nuclear power programme

Significant advances have been made in the design and technology development of SMRs, a newer generation of reactors designed to generate up to 300 MW(e). SMRs aim for the economies of serial production with a short construction schedule. The systems and components of SMRs can be factory fabricated to be transportable as modules to the sites when needed. SMRs offer flexible power generation for a wider range of users and applications, including replacing ageing fossil power plants. With a potential reduced emergency planning zone (EPZ) size and less cooling water requirements, SMRs could be deployed at locations inaccessible for large nuclear power plants.

Three industrial demonstration SMRs are in an advanced stage of deployment, as mentioned earlier: Akademik Lomonosov in the Russian Federation; CAREM in Argentina; and the HTR-PM in China. These SMRs are scheduled to begin commercial operation between 2020 and 2023. More commercial fleets of SMRs are expected to start operation in 2025–2035.

The Republic of Korea has approved the standard design of SMART, a 100 MW(e) integral PWR design to produce electricity and power seawater desalination. Saudi Arabia and the Republic of Korea have completed the pre-project engineering of SMART to prepare for the eventual construction of two units in Saudi Arabia. China has also designed the ACP100, a 100 MW(e) land based SMR that completed the IAEA's Generic Reactor Safety Review (GRSR) in April 2016. GRSR is a service provided on request for Member States by the IAEA. China has recently identified offshore energy supply as a priority for resources exploration, island development and to support the development of marine economies.

In addition to the two KLT-40S modules in operation in the Akademik Lomonosov FPU, the manufacturing of the systems and components of the RITM-200, with a rated power of 50 MW(e) and intended as an icebreaker, has been completed. Future FPUs will be based on the RITM-200M design; land based deployment is also under consideration. The Russian Federation is also forming an international consortium to develop the SVBR-100, a lead–bismuth eutectic cooled SMR with a fast neutron spectrum to generate 100 MW(e).

In the United States of America, three water cooled SMR designs and technologies currently under development and licensing are the 60 MW(e) NuScale Power Module, SMR-160 (from Holtech) and BWRX-300. Also reported were the considerable activities conducted earlier on the 195 MW(e) mPower and the 225 MW(e) Westinghouse SMR.

With regard to non-water-cooled reactors, specifically the most advanced designs, the only ones for which pre-application activities with the US Nuclear Regulatory Commission (NRC) have been undertaken are the Xe-100 modular high temperature gas cooled reactor, the Kairos Power Fluoride Salt Cooled, High Temperature Reactor (KP-FHR), the Integral Molten Salt Reactor (IMSR), and the Westinghouse eVinci micro reactor.

A significant milestone has been reached in the development of NuScale, an integral PWR with a reactor building that houses 12 modules. Each module has a rated output of 60 MW(e), yielding a total capacity of 720 MW(e). NuScale completed the four year design certification review process with the NRC in September 2020 by the issuance of a standard design approval. Issuance of this approval signifies completion of the NRC staff's technical review of the NuScale SMR design. The first commercial NuScale power plant will be built at the Idaho National Laboratory with a target date for commercial operation of 2029. Other developments include the Tennessee Valley Authority, which obtained an early site permit for the utility's Clinch River site to potentially build and operate SMRs.

In November 2018, Canada issued A Call to Action: A Canadian Roadmap for Small Modular Reactors, a report prepared by the Canadian SMR Roadmap Steering Committee [5]. The Roadmap seeks to answer the question: 'What's next?' The result of a ten month effort, representatives from industry, governments, utilities and enabling partners came together to chart a vision for the next wave of nuclear innovation. This vision was informed by expert analysis as well as dialogue across the country, including initial engagement with northern and indigenous communities and organizations. What emerged is a collective vision statement for bringing this innovative technology to fruition in Canada: "Small Modular Reactors as a source of safe, clean, affordable energy, opening opportunities for a resilient, low carbon future and capturing benefits for Canada and Canadians."

In addition to the Canadian Roadmap on SMRs, the Canadian Nuclear Safety Commission (CNSC) runs a Pre-Licensing Vendor Design Review (VDR) as an optional service when requested by a vendor. The objective of a review is to verify, at a high level, the acceptability of a nuclear power plant design with respect to Canadian nuclear regulatory requirements and expectations, as well as Canadian codes and standards. These reviews also identify fundamental barriers to licensing a new design in Canada and ensure that a path exists to resolve any design issues identified in the review. However, this review does not certify a reactor design.

Table 1 presents an overview of vendors which have established service agreements with the CNSC for pre-licensing engagements using the VDR process for their new reactor designs. The duration of each review is estimated, based on the vendor's proposed schedule. A Phase 1 review typically takes 12–18 months and a Phase 2 review takes 24 months.

During the regular session of the IAEA General Conference in Vienna in September 2019, the French Alternative Energies and Atomic Energy Commission (CEA), Electricité de France (EDF), Naval Group and TechnicAtome unveiled NUWARD™, their jointly developed SMR project. This is a PWR based solution to meet the growing world demand for decarbonized, safe and competitive electricity generation of 340 MW(e) from two independent reactor modules to offer flexible operation. NUWARD™ will benefit from up to date technologies acquired over more than 50 years of experience in France in PWR design, development, construction and more than 2000 reactor-years of French PWR operating experience. Developed as a Generation III+ SMR, NUWARD™ is an integral PWR that features a shortened reactor pressure vessel (RPV), and the nuclear steam supply system (NSSS) installed in a steel containment, submerged in the underground water wall, allowing for enhanced in-factory manufacturing.

In the United Kingdom, the Department for Business, Energy and Industrial Strategy (BEIS) has announced national policies for the advanced nuclear technologies. Three initiatives were launched in December 2017, at the same time that BEIS closed the information gathering SMR competition:

(a) The Advanced Modular Reactor (AMR) Programme. This is an R&D programme to support AMR vendors. The aim is to study the feasibility of around eight new types of reactors and their commercial role; and to provide development grants to a small number of promising projects.
(b) Funding for the Office for Nuclear Regulation (ONR) and Environment Agency (EA). Up to £12 million was allocated for the nuclear regulators to build the regulatory capability and capacity needed to assess, licence and issue a permit for new designs. The aim of this funding is to allow ONR and EA to build the capability of advanced nuclear technologies and to ensure that regulatory tools have the flexibility needed to respond to the challenges offered by new reactor designs.

TABLE 1. VDR SERVICE AGREEMENTS IN FORCE BETWEEN THE VENDOR AND THE CNSC *(as of November 2020)*

No.	Name of design	Cooling type	Capacity (MW(e))	Status
1	IMSR	Integral molten salt reactor	200	Phase 2 in progress
2	MMR-5 and MMR-10	High temperature gas	5–10	Phase 1 completed (12/2016)
3	SEALER	Molten lead	3	Phase 1 started, on hold
4	ARC-100	Liquid sodium	100	Phase 1 complete
5	Moltex Energy Stable Salt Reactor	Molten salt	300	Phase 1 in progress
6	SMR-160	PWR	160	Phase 1 in progress
7	NuScale	iPWR	60	Phase 2 in progress
8	U-Battery	High temperature gas	4	Phase 1 started
9	BWRX-300	BWR	300	Phase 2 in progress
10	Xe-100	High temperature gas	75	Phase 2 in progress
11	eVinci Micro-Reactors	Solid core heat pipe	25	Phase 2 started
12	StarCore Module	High temperature gas	10	Series Phase 1 and 2

(c) The Expert Financing Working Group was created to advise on how SMR projects could raise investments in the United Kingdom.

Still under development are initiatives to support the development of advanced manufacturing techniques and capability building in the United Kingdom supply chain as part of the Nuclear Sector Deal.

In line with this national policy, the United Kingdom Small Modular Reactor (UK-SMR) design has been developed to deliver a market driven, affordable, low carbon, energy generation capability. The design is based on the optimized and enhanced use of proven technologies that present a class leading safety outlook and attractive market offering with minimum regulatory risk. A three loop, close coupled PWR provides a power output of 443 MW(e) from 1276 MW(th) using industry standard UO_2 fuel. Rapid, certain and repeatable build is enhanced through site layout optimization and by maximizing modular build, standardization and commoditization. The designer has projected the earliest start of construction to be 2030 for FOAK commercial operation in 2035.

2.3.2. SMR deployment in a country without an existing nuclear power programme: The IAEA's Milestones approach

The IAEA has developed an approach setting out the infrastructure needed for a nuclear power programme: Milestones in the Development of a National Infrastructure for Nuclear Power [6]. This Milestones approach, shown in Fig. 2, was developed to provide Member States with 'guideposts' to

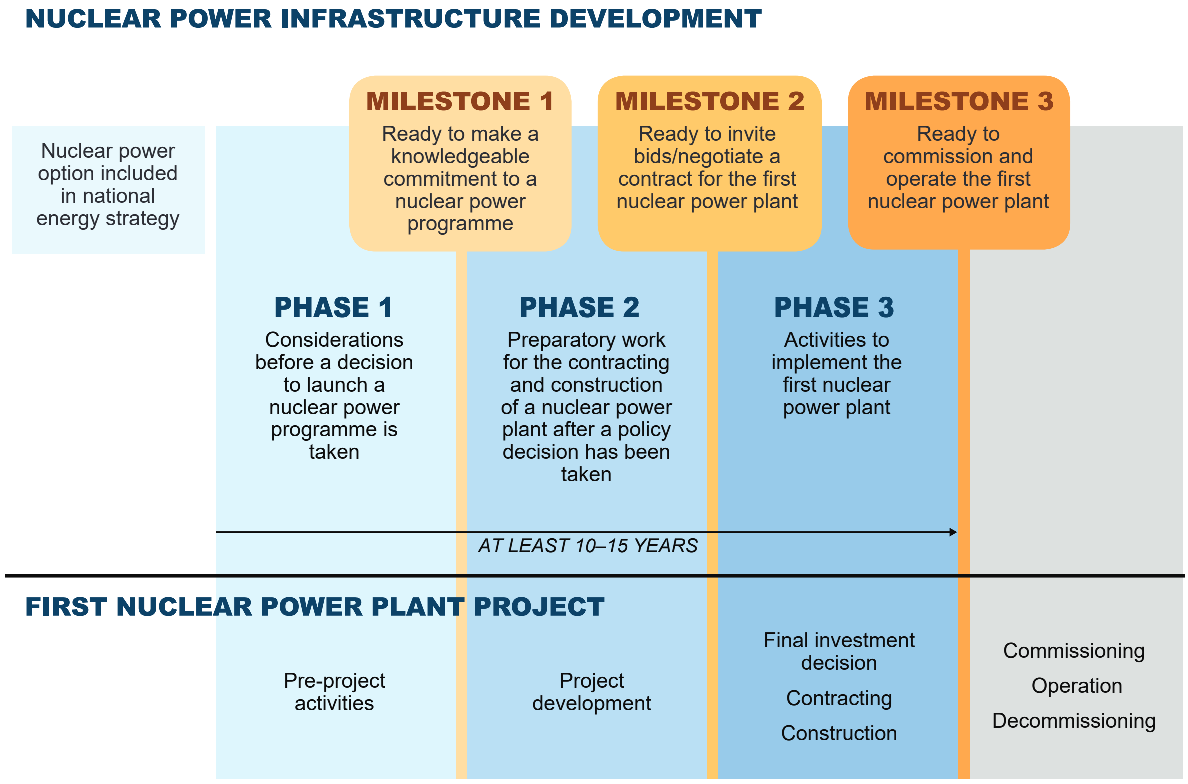

FIG. 2. Milestones for infrastructure development to support a nuclear power programme (reproduced from Ref. [6]).

demonstrate their progress during the planning stages, and to show national and international stakeholders their commitment to nuclear safety and the control of nuclear material. In this regard, the infrastructure for a nuclear power programme includes the elements necessary for the safe, responsible and sustainable use of nuclear technology.

Even countries with a large nuclear fleet should assess the impact that the deployment of an SMR fleet would have on the existing nuclear infrastructure. Special attention should be paid to the procurement of new fuel types and their compatibility with existing strategies for the interim and long term disposal of nuclear fuel and the resultant intermediate level waste. Depending on the SMR technology of choice, significant and costly upgrades might be required to existing infrastructure, which have to be carefully accounted for in the life cycle plan.

In Section 2.3.1, it is assumed that SMR deployment will take place in a country which already possesses the *infrastructure* necessary to support the deployment of nuclear power technology (including SMR technology). This infrastructure will include not only a so-called *hard* infrastructure (such as an adequate electrical grid) but also a *soft* infrastructure (such as a regulatory framework, policies on radioactive waste management, human resources policies, etc.). If key components of this infrastructure are not in place when a country first contemplates deploying SMR technology for electricity generation, it will be necessary to develop them in advance of such deployment.

The IAEA recommends a systematic approach to preparing the infrastructure for nuclear facility deployment which is relatively high level — and thus generally applicable across technologies ranging from *traditional* large reactors of various types through research reactors to SMRs: the IAEA’s Milestones approach. In this approach, activities needed to prepare the infrastructure for nuclear power are split into three phases, with the duration of each phase dependent on the degree of commitment and resources allocated in the country. The term *infrastructure milestone* is used to identify the point at which the activities required in that phase of development have been successfully completed. Each therefore corresponds to the completion of a set of activities with no implications on the speed at which it is reached. Figure 2 shows the details.

The three phases in developing the infrastructure necessary to support a nuclear power programme are as follows:

- Phase 1: Considerations before a decision to launch a nuclear power programme is taken;
- Phase 2: Preparatory work for the contracting and construction of a nuclear power plant after a policy decision has been taken;
- Phase 3: Activities to implement the first nuclear power plant.

The completion of each phase is marked by a specific milestone at which the progress of the development effort can be assessed, and a decision can be made to move on to the next phase. These milestones are the following:

- Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme;
- Milestone 2: Ready to invite bids/negotiate a contract for the first nuclear power plant;
- Milestone 3: Ready to commission and operate the first nuclear power plant.

In accordance with this approach, one of the key steps in establishing a new nuclear power programme, or in planning an expansion of an existing nuclear power plant fleet, is to commission a feasibility study. Such a study assesses all aspects of energy demand in a country or geographical area to place the nuclear project in proper context. In this regard, the IAEA has issued a publication entitled Preparation of a Feasibility Study for New Nuclear Power Projects [7].

It is possible that the point at which the decision is made to pursue SMR deployment falls somewhere along the timeline shown in Fig. 2. For example, the inclusion of nuclear energy in the national energy strategy may have been followed by a number of pre-project activities (e.g. development of a pre-feasibility study), which would mean that some activities that are required to achieve, for example, Milestone 1 have already been carried out.

It is important to note that the three phases and three milestones refer to developing the national infrastructure to support a nuclear power programme. The programme includes one or more nuclear power plants, possible related projects, such as uranium exploration and fuel fabrication, and the supporting infrastructure. As the programme develops, many activities will be undertaken to implement the first nuclear power plant project; it is important that the distinction is clear. Projects are temporary undertakings to develop and construct nuclear power plants. The infrastructure provides the processes and capabilities to implement project activities and the subsequent operation of the nuclear power plant safely, securely and sustainably.

In the development of the nuclear infrastructure, three key organizations are involved: the government, the owner/operating organization of the nuclear power plant and the regulatory body[6]. Each has a specific role to play, with responsibilities changing as the programme advances. The owner/operating organization may be State owned or private, be part of a domestic or international utility or be another commercial entity. The regulatory body should by Phase 2 be effectively independent in its regulatory decision making. It will not be entirely separate from other governmental bodies, but in general should have sufficient authority, staffing and financial resources to be able to make independent regulatory decisions free from undue influences, such as pressures associated with changing political circumstances or economic conditions, or pressures from government departments or other organizations.

In the remainder of this section, it is assumed that the government will create a mechanism (which may involve high level and working level committees) to coordinate the work of these and other

[6] There may be more than one regulatory body. For example, there may be one for nuclear safety and another for nuclear security. Thus, statements in this publication about the regulatory body should generally be read as the regulatory body or bodies.

TABLE 2. INFRASTRUCTURE ISSUES [6]

The 19 infrastructure issues	
National Position	Stakeholder Involvement
Nuclear Safety	Site and Supporting Facilities
Management	Environmental Protection
Funding and Financing	Emergency Planning
Legal Framework	Nuclear Security
Safeguards	Nuclear Fuel Cycle
Regulatory Framework	Radioactive Waste Management
Radiation Protection	Industrial Involvement
Electrical Grid	Procurement
Human Resource Development	

organizations involved in infrastructure development. In this publication, this mechanism is called the nuclear energy programme implementing organization (NEPIO). It should be noted that this designation is used for illustrative purposes only. The country may organize the activity in a manner most appropriate to its own customs and needs.

Table 2 shows the 19 infrastructure issues that need to be considered for each milestone [6]. The order does not indicate relative importance. Each issue is important and requires careful consideration. Different organizations will need to consider which issues relate most to them and to plan their work and resources accordingly. The three key organizations — the government, the owner/operating organization and the regulatory body — need to ensure awareness of all issues.

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme

At the beginning of Phase 1, it is assumed that a country has determined that it needs additional energy and has considered nuclear power as a possible option to meet some of these needs. During Phase 1, the country will analyse all issues that would be involved in introducing nuclear power, so that at the end of Phase 1, it is in a position to make a knowledgeable decision on whether or not to introduce nuclear power.

In Phase 1, it is essential that the country acquires a comprehensive understanding of the obligations and commitments involved, and what would be required to fulfil them, before any decision on implementation is taken. It is important that the country has a clear understanding of its energy needs and the potential role of nuclear power within its long term energy and economic development plans.

A country considering nuclear power probably already has an infrastructure in place for nuclear security, radiation safety and emergency preparedness to cover existing facilities and activities. Building on the existing infrastructure and associated experience will assist the country in establishing the necessary infrastructure for a nuclear power programme.

In Phase 1, the NEPIO should ensure overall coordination and the engagement of all key parties, compile the information and studies necessary for a knowledgeable policy decision on whether to proceed with nuclear power, and, at the end of Phase 1, provide a comprehensive report that should recommend a positive national decision, and that defines and justifies a national strategy for nuclear power. Any pre-feasibility study conducted during Phase 1 can be a significant input to the report, although it is important that the report fully addresses all 19 infrastructure issues described in Table 2.

Milestone 2: Ready to invite bids/negotiate a contract for the first nuclear power plant

Following the policy decision to proceed with the development of a nuclear power programme, substantive work is needed to achieve the necessary level of technical and institutional competence. This phase requires a significant, continuing commitment from the government, and the responsibility should be clearly assigned to an appropriate governmental ministry. It is also important that the work of all organizations continues to be well coordinated and driven through the NEPIO. The key functions of the NEPIO include the following:

- Maintaining momentum and providing a continuing forum for communication and cooperation among organizations (e.g. the owner/operating organization, the grid operator, the regulatory body, relevant government agencies, legislators, other decision makers);
- Ensuring that the roles of the key organizations (i.e. the government, regulatory body and owner/operating organization) are well defined and understood by all stakeholders;
- Ensuring that the key organizations develop in line with the project schedule;
- Ensuring that the rationale for the national decision to introduce nuclear power is well understood by all stakeholders;
- Ensuring that the contracting approach and technical specifications remain consistent with the country's nuclear power development strategy.

During Phase 2, the country will carry out the work required to prepare for the contracting, financing and construction of a nuclear power plant. It should develop the necessary infrastructure (covering all 19 infrastructure issues) to the point of complete readiness to invite bids/negotiate a commercial contract between the owner[7] and the supplier. An effectively independent regulatory body should be developed to a level at which it can fulfil all of its authorization and inspection duties.

The owner/operating organization has a key role to ensure that by the end of Phase 2, it has developed the competence to manage a nuclear power project, meet regulatory requirements and be a knowledgeable customer in Phase 3. The owner/operating organization should also have, by the end of Phase 2, clear plans to develop or acquire the capability to safely operate the plant during Phase 3.

Milestone 3: Ready to commission and operate the first nuclear power plant

For countries using a competitive bidding process, Phase 3 starts with the tendering and subsequent negotiation of the contract for the design, construction and commissioning of the nuclear power plant. For other countries, Phase 3 starts directly with the negotiation of the contract. Much of the work on infrastructure development will be well advanced by the beginning of Phase 3, but the largest capital expenditure for the nuclear power plant will occur during Phase 3. Depending on the specific agreements between the owner/operating organization and the contractor(s), the contract may involve different phases of work (e.g. detailed design and construction) with different price agreements (e.g. fixed price or cost plus). After agreement on the contract, the final investment decision by investors may wait for final project costs and schedule agreements and other financial arrangements. Whatever the detailed contract arrangements are, the final investment decision is a pivotal step.

The initial work will be to develop the site specific design, produce the preliminary safety analysis report and complete all of the required licensing and planning approvals. At this stage, the project costs and schedule can be finalized. Subsequent work will then include all procurement and construction activities, under appropriate management arrangements, and will involve regulatory oversight and approvals throughout the phase.

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[7] The reference here to just the owner, rather than the owner/operating organization, reflects the possibility that a country may prefer a sole supplier or strategic partner to offer operating services as part of its proposals. In such cases, the operating organization would only be established at the beginning of Phase 3 with the conclusion of the contract negotiations.

Milestone 3 is reached when the entire infrastructure is in place to start the stages of nuclear power plant commissioning that involve nuclear testing. Some verification and non-nuclear testing of equipment and systems will start during Phase 3.

By successfully completing Phase 3, the country will have established a nuclear power programme to realize the benefits of energy security and economic development envisioned in the initial policy decision. At the end of Phase 3, the owner/operating organization should be fully capable of, and licensed for, commissioning and operating the nuclear power plant. If the owner/operating organization has been newly created, or is new to nuclear power, this will have required significant development and training for all staff and a demonstration that the owner/operating organization can manage the project throughout the lifetime of the nuclear power plant.

The regulatory body will have been in operation for some time, having developed safety regulations, reviewed contract specifications, licensed construction of the plant and carried out inspections during construction. It should now be clearly seen as a competent, effectively independent regulatory body to provide continuing oversight of all facilities and activities and enforce continuing compliance with all regulatory requirements.

The competence of both the owner/operating organization and the regulatory body may be ensured through expertise and support from experienced foreign organizations, including the nuclear power plant supplier. Consideration should be given to the need to ensure competence throughout the lifetime of the nuclear power plant.

While achieving Milestone 3 is a major accomplishment, it should be remembered that it is only the beginning of a lasting commitment to the safe, secure, peaceful and sustainable application of nuclear power.

2.4. NON-PROLIFERATION AND SAFEGUARDS

As stated earlier in this publication, an SMR is essentially a smaller version of a nuclear power plant, but may be different in terms of fuel, fuel handling and waste handling, all of which need to be considered from safeguards and non-proliferation perspectives. From the point of view of IAEA safeguards, a nuclear power reactor is considered an item facility. This means that the nuclear material at the facility is confined in identifiable fuel assemblies for WCR type SMRs, the integrity of which normally remains unaltered during its residence at the facility [8]. Additional safeguards and physical protection requirements that are specific to the design and development process will be discussed throughout this publication.

Information and guidance for designers and operators of nuclear reactor facilities are also available as part of the concept of safeguards by design, the process of including the consideration of international safeguards throughout all phases of a nuclear facility project [9].

2.5. TECHNOLOGY ROADMAP AS A CONCEPT

Technology roadmaps are planning tools that were originally created by the Motorola Company in the 1970s to coordinate the development of their products and their supporting technologies. Technology roadmaps are part of a methodology that guarantees the alignment of investments in technology and the development of new capabilities. A proven management tool, technology roadmaps are used for identifying, evaluating, communicating and promoting the development of complex technology projects. Additionally, for Member States, technology roadmaps can inform the science and technology policy and aid in making investment decisions across government and industry in terms of loan guarantees and incentives, industry lead initiatives and human resource development.

More importantly, the creation and use of a technology roadmap can accelerate technology development while ensuring the best chance of bridging the ‘point of pitfall’ or, as is known in the electronics industry, the ‘valley of death’. As described in Ref. [10], there are two distinct barriers to

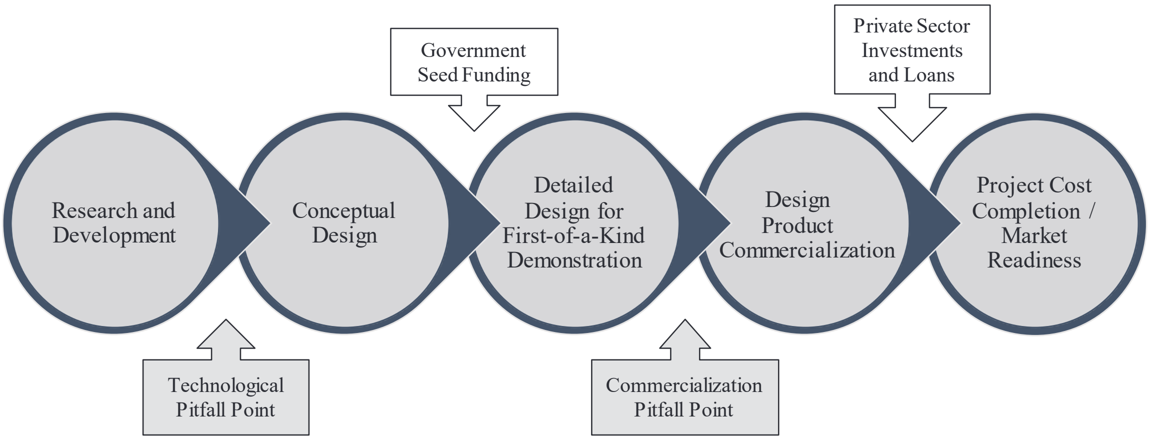

FIG. 3. Process of product design development and the two distinct points of pitfall.

the adoption of new energy technologies which impede the innovation life cycle: (1) the technological point of pitfall; and (2) the commercialization point of pitfall. Figure 3 describes the process of product design development and these two distinct points of pitfalls. The first major challenge with regard to energy innovation is a technological one. The question to be asked here is whether R&D has satisfactorily addressed all technology gaps to enable the construction of a reliable prototype or the performance of an important proof of concept test. Failure at this stage in the innovation life cycle results in the concept falling into a technological point of pitfall. This point sits between the R&D phase and the prototype/proof of concept phase in the innovation life cycle as researchers seek further capital to develop and prove their basic concept.

The second major challenge in energy innovation is commercialization. The question to be asked here is whether the technology is reliable, accepted by the regulator and cost competitive against its alternatives. If the new technology fails at this stage, it falls into the commercialization point of pitfall. This occurs later in a technology's development and represents the point at which entrepreneurs seek capital to fund a FOAK commercial scale project and/or manufacturing facility.

Finally, technology roadmaps promote enhanced collaboration and sharing of knowledge and help to ensure that efforts by all involved parties (technology developers, industry, users and regulatory bodies) are focused on a common objective.

There are various types of technology roadmaps [11] and each serves an intended purpose. In this publication, two specific types are utilized: the project planning technology roadmap and the technology gaps roadmap.

The project planning technology roadmap is used to align the different project activities for the various project participants while identifying project milestones and performance indicators (i.e. how do we know that the milestone has been reached?). This type of roadmap is best suited for projects that have either overcome the technological point of pitfall or there is absolute confidence that they will avoid it.

The technology gaps roadmap is more common and is used to identify and tie together the various technologies that should be fully developed so that a product can be demonstrated. This tool is better suited for efforts that involve more significant technology gaps and typically require more R&D effort.

As a point of reference, several nuclear technology roadmaps have been prepared by various organizations. In 2002, the United States Department of Energy (DOE) and Generation IV International Forum (GIF) jointly published A Technology Roadmap for Generation IV Nuclear Energy Systems [12], updated by the OECD and GIF in 2014 [13]. In 2010, the DOE issued the Nuclear Energy Research and Development Roadmap: Report to Congress [14]. Most recently, in 2015, a collaborative effort between the International Energy Agency (IEA), the OECD Nuclear Energy Agency (OECD/NEA) and their Member Countries resulted in a publication entitled Technology Roadmap, Nuclear Energy [15]. However, those reports were much broader in terms of reactors, fuel cycles and safeguards programmes. This publication focuses on the issues specific to the development and deployment of SMRs.

3. PROSPECTS, IMPEDIMENTS AND DEPLOYMENT INDICATORS

This section focuses on the likely prospects of SMR technology, the challenges related to deployment, and indicators that Member States can use to make an initial assessment of their readiness to adopt the technology. The word *likely* is used deliberately to describe the prospects of this emerging technology since several years of operational experience will need to be assessed on the FOAK plants before the prospects can be fully realized.

3.1. PROSPECTS

In discussions with Member State representatives, the IAEA determined that prospects for SMR technology were promising, and that there is a great deal of interest in this technology, particularly from developing countries with smaller grid capacities.

3.1.1. Enhanced safety, energy security and carbon free power

Most SMR designs share a common set of design objectives which, in part, aim to enhance plant safety and overall robustness while improving economic performance in order to remain competitive with other sources of power generation. For example, these new designs aim, where possible, to eliminate vulnerabilities, incorporate lessons learned from almost 60 years of reactor operations, significantly reduce the likelihood of an accident, greatly increase the time during which operators can act to cope with an unlikely event, and mitigate the consequences in the event of an accident.

In discussions with Member States, it was apparent that there is a widespread expectation that this new technology should present lower risks than traditional large reactors, due to smaller source terms, elimination of more challenging design basis accidents and a greater reliance on passive safety systems. Reduced risk is considered to be very important in obtaining public acceptance to proceed with projects. For example, passive safety systems rely on passive forces such as gravity, natural circulation, evaporation and condensation. The ability to incorporate passive safety systems to remove core decay heat and containment heat/pressure eliminates the need for external power, which in turn can result in a lower likelihood of core damage during a reactor plant accident. However, the designer will need to work with the future licensee to ensure that sufficient analyses and R&D activities have been completed to validate such conclusions, so that safety and security claims can be substantiated during licensing. During construction and startup, a more comprehensive set of inspections and tests may need to be carried out to ensure that the FOAK plant performs as designed. These activities may be reflected in the licensing approach for the facility.

The cost of nuclear fuel is a relatively small contribution to the overall levelized cost of electricity produced by a nuclear power plant. A few years of uranium supply can easily be stockpiled due to its massive energy content. This is a key factor that positions nuclear power as an energy source that enhances energy security. When compared with historical natural gas prices, uranium fuel prices have been relatively stable over the last 30 years. SMR technology with a fast neutron spectrum could be an attractive alternative for developed countries seeking to reduce plutonium stockpiles.

With the United Nations predicting that the world's population will grow to 8.7 billion by 2035, the demand for energy may also be likely to increase over this same period. Annual editions of the World Energy Outlook issued by the IEA make clear the increasing importance of nuclear power in meeting energy needs while achieving security of supply and minimizing CO_2 emissions. This implies that SMR technology is a potential option for countries to consider when planning their future energy mix.

3.1.2. Smaller grids, remote locations, integration with renewables and replacement of ageing fossil fuelled plants

As a rule of thumb, a new nuclear reactor, or any other single generating unit in an electrical system, should not represent more than 10% of the overall installed capacity of an existing grid [16]. There are two reasons for this: (1) to ensure that a single reactor trip does not cause unacceptable grid system voltage and frequency fluctuations that would prevent the grid from supplying power to the tripped unit; and (2) to ensure that the grid is sufficiently stable to continue to provide a reliable supply of electricity. This rule of thumb is being challenged in some Member States through widespread deployment of intermittent renewable generation sources. Adopting SMR technologies could extend the market for nuclear energy by providing stability to a grid in strategic locations as well as power to remote locations or to countries with existing smaller electrical grid systems where larger nuclear plants would not be suitable. In some cases, smaller technologies could be a reliable supply in areas where there is an absence of an electricity grid but a strong need for consistent power supply.

In many parts of the world smaller and older fossil fuelled power plants need to be phased out due to their age and as part of the growing effort to combat CO_2 emissions. These sites often already have the grid interconnections and transmission infrastructure necessary to accommodate a new power plant. Moreover, future growth projections reflect the need for incremental additions to generating capacity and, as a result, SMR technology is seen as a suitable candidate since more modules can be added at future dates.

3.1.3. Easier to site and smaller emergency planning zones

SMRs may open up more sites for consideration for two main reasons. The first is that a smaller source term, in principle, can be used to make an argument for a smaller EPZ, and as a result these plants might be located closer to population centres. The second reason is that the smaller plant components that need to be shipped to a site may eliminate the need to build the more robust transportation and site infrastructure that is often necessary for building larger plants. This second reason may also lead to overall reduced siting costs; however, the siting costs on a per MW installed basis will need to be demonstrated.

Another advantage of a relatively small source term is the possibility of locating an SMR closer to industrial activities to provide process heat for non-energy applications (e.g. wood and paper products, desalinization, biomass).

The quality of probabilistic safety assessment (PSA) techniques adopted as the main tool for performing risk informed analyses has been continuously improving over the past two decades. The maturity and regulatory acceptance of the techniques involved in the risk informed approach offers the possibility of extending these techniques in evaluating the last level of the defence in depth (DiD) philosophy — off-site emergency planning and zones. SMR vendors are currently working with regulatory bodies to demonstrate the ability to reduce the size of the required EPZs, which will also allow more flexibility in future siting if the technology can be better accepted by the local public. National regulatory frameworks should recognize different sizes of nuclear power plant, not just locations. In this way, it becomes clear that there are more locations available in principle for SMRs than for a large nuclear power plant.

3.1.4. Capacity factors and incremental additions of generating capacity

Several SMR concepts are based on multi-module designs which would allow a utility to perform maintenance and refuelling on one module while other modules continue to operate and produce power. The capacity factor of a power plant is defined as the ratio of its actual output over a period of time to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time. Therefore, the ability to have several modules continuing operation during outage periods should ensure increased overall capacity factors, assuming the outage time for each SMR module is reduced with respect to large reactor units. Increased capacity factors lead to a reduced levelized cost of electricity, and the ability to perform rotational outages will improve the use of staff resources and skill retention.

Another key advantage of the multi-module design is that additional modules can be added to a power plant as the demand for more electricity increases at only marginal additional cost (i.e. the cost of more modules). This ability to add incremental generating capacity while at the same time producing power and collecting revenue improves long term financing costs by reducing the cost of debt.

3.1.5. Dispatchable integration with non-dispatchable renewables and the future grid

The increasing market penetration of renewables, especially wind power, has dramatically changed the market price of electricity and the challenges associated with managing a highly reliable electrical grid. Large deployments of wind and solar generating capacity are resulting in power fluctuations on the grid that can result in hundreds of megawatts of electricity being added or subtracted within minutes. Weekly and seasonal fluctuations can amount to gigawatts of additional electricity being either requested, or eliminated, by traditional baseload (dispatchable) fossil and nuclear power plant operators.

Nuclear power reactors, in particular SMRs, can respond to changing load demands as requested by the grid operator. However, it is not necessarily economical to operate large, capital intensive nuclear power plants in a load following mode since the levelized cost of electricity is directly related to a plant's capacity factor.

Most modern nuclear reactors can respond rapidly (i.e. within minutes) to variations in the grid caused by changing wind conditions (i.e. when the wind dramatically picks up during a storm), since these plants represent dispatchable power plants. In this case, steam to the turbine can be reduced rapidly with little effect on the reactor core, thereby unloading the turbine and reducing generator output to the grid by dumping steam directly to the condenser through a steam bypass valve.

To accommodate slower changes (e.g. daily variations caused by solar generating capacity), reactor power can simply be reduced. However, for a large reactor plant this means operating the steam turbine at less than optimal efficiency conditions whereas in a small multi-modular reactor plant, which incorporates several smaller steam turbines, the overall loss in plant efficiency is reduced.

To accommodate seasonal variations (i.e. fluctuations over longer periods), reductions in baseload power can be achieved more effectively, and perhaps economically, in multi-module designs by simply taking one or more modules off-line. Maintenance and refuelling efforts can be planned and conducted during these seasonal variations.

Modern societies need a reliable and robust electrical grid to serve as the backbone for the electrical power system. The technologies that make up the grid are seeing unprecedented technological change, and the future grid is likely to look and be managed much differently than today. Smart grids of the future may favour more decentralized electricity generation stations and will certainly have a larger percentage of non-dispatchable renewable energy systems, where supply and demand are balanced at the local level, thereby restricting the use of traditional large baseload power plants.

3.1.6. Non-electrical applications and water usage

Depending on the reactor's operating temperature, all nuclear power reactors can be used not only for electricity production but also for co-generation, providing process heat for other non-electrical applications. Co-generation of electricity, and energy for non-electrical applications improves overall plant thermal efficiencies, thereby reducing waste heat, which is often a loss to the environment in terms of thermal pollution. Large reactors are in some cases considered more economical for non-electrical applications and more suitable for large industrial parks due to the larger amount of waste heat generated. However, if the waste heat from SMRs could be more effectively used to support non-electrical applications, an improvement in plant economics could be achieved.

Low temperature non-electrical applications, such as desalination systems, district heating and even conventional electrolysis to support hydrogen gas production can make use of waste heat produced by traditional LWRs and/or new water cooled SMRs. However, advanced reactor technologies operating at higher temperature outputs allow for a larger number of possible non-electrical applications to be considered. For example, the heat from an HTGR could be used to support hydrogen production using high temperature steam electrolysis or other thermochemical processing, or could be applied to a variety of petrochemical applications, including ammonia and methanol synthesis, bitumen extraction from oil sands, coal gasification, or hydrocracking of heavy crude oil.

Finally, the development of SMRs could allow for a tri-generation mode of operation, where electricity is generated efficiently, high quality heat is used to produce hydrogen gas for future transportation needs, and the remaining lower quality heat is used to produce fresh, clean drinking water from sea water.

3.1.7. Public acceptance, localization and decommissioning

In several cases, Member States felt that SMRs with enhanced passive safety systems and smaller source terms would be more widely accepted by the public when compared with larger multi-gigawatt plants. Moreover, the potential to localize some aspects of the construction work and building of non-safety-related components offers the prospect of domestic job creation, which also helps with public acceptance in locations where jobs are an important factor.

Since SMRs are smaller, Member States also felt that once the fuel was removed from a reactor, module removal of the reactor vessel and (in some cases the containment) would be relatively straightforward. The decommissioning of an SMR appears technically easier for full factory assembled reactors as they can be transported back to the factory in an assembled form. The dismantling and recycling of components of a decommissioned nuclear power plant at a centralized factory is expected to be cheaper, compared with the on-site activity, in particular due to the economies of scale associated with the centralized factory.

3.1.8. Economics and reduced debt financing

Although many aspects of SMR economic analysis are the same as for the large nuclear power plants currently deployed, some specific economic aspects of advanced SMRs were highlighted by Member States. As previously discussed, the idea that incremental generating capacity could be added with only moderate additional financial investment is attractive for many Member States. Because SMRs can be built one module at a time, SMRs offer financing flexibility, which reduces exposure to financial risk. In addition, owners/operating organizations could have the opportunity to deploy SMRs at existing power plant sites as coal and oil plants are retired, further reducing the costs associated with site infrastructure and transmission. Other topics highlighted were quality and schedule improvements associated with factory manufacturing, the economy of multiples, and inherent savings in long term operations due to multiple units located at the same site and shorter construction schedules that may significantly reduce long term financing costs. In the specific case of HTGRs, the possibility of co-generation, and supplying high temperature heat to support industrial processes, was highlighted as an advantage.

Perhaps the most important aspect of SMRs is that their design simplification and approach to modular factory fabrication promise to create more certainty in the overall site construction schedule, which in turn will reduce the long term debt burden associated with financing. Even though current large nuclear power plants incorporate factory fabricated components (or modules) into their designs, a substantial amount of field work is still required to assemble components into an operational power plant. The complexities associated with large site construction projects have introduced more schedule risk which manifests itself as long term financing cost. Some SMRs may require limited on-site preparation and substantially reduce the lengthy construction times that are typical of the larger units. Moreover, SMR designs will allow builders to take advantage of economies of mass production where series production techniques offer major opportunities for design improvements and better methods of manufacture to be identified and incorporated, progressively reducing costs, quality problems and schedule risks.

A recent economic and market assessment study performed by the OECD/NEA concluded that if all the competitive advantages of SMRs are realized, they are expected to have lower absolute and specific construction costs (per kW(e)) than large reactors, while variable costs (O&M and fuel costs) are expected to be higher. Additionally, it was concluded that the optimal share of SMRs in the energy mix minimizes the total cost of electricity produced by the system, varying from 16% to 33% of the total installed nuclear capacity, depending on the penetration level of variable renewables [17].

3.2. ISSUES AND IMPEDIMENTS

While there are a number of advantages associated with SMR technology, there are also substantial impediments relating to economics, licensing, utilization, public acceptance and R&D for advanced technologies.

3.2.1. Economics and early adopter of first of a kind technology

While numerous studies have been published on the economics related to SMRs, the economic case has yet to be proven. The only way the economics for an SMR will be fully understood is by building the first demonstration plants, working through all of the associated startup problems and successfully operating the reference plant for several years. Unfortunately, as with much of nuclear reactor technology, few owners/operating organizations are keen to be the first to take on this risk, and typically the first of a kind requires government support. The good news is that, based on discussions with Member States, interest in this technology is considerable and many would like to purchase and build NOAK reactor plants.

With regard to early adopters of FOAK technology, there has been a long history of government involvement. Governments often provide financial support to universities, laboratories and industries to pursue R&D in support of new technology. This financial support helps to generate new knowledge and develop the necessary human capital so that new trained resources are available to the industry. Additionally, government has the responsibility to ensure that efficient and robust regulations are in place to ensure public safety and health.

In order for the first SMRs to be built and fully demonstrated, it is envisioned that some form of government support and/or incentives will be needed to reduce the financial risk of investing in facilities and people that are needed to develop, fabricate, test and qualify FOAK components, systems and structures. Creating a supply chain with the requisite technical skill sets and quality systems will be a challenge and will require an indication from the power markets that it is needed. Once the supply chain is established, disruptions in factory orders are often detrimental, resulting in the layoff of critically skilled labour and the sell-off of key pieces of equipment. Once abandoned, it can be very expensive to reassemble a product line. As a result, the more a reactor designer can incorporate standard commercial items, or rely on existing nuclear suppliers, the less of a challenge this issue will be to manage. This may mean creating a well organized supply chain of nuclear qualified suppliers/vendors.

Finally, long drawn out construction schedules and corresponding long term debt costs have been the challenges and problems in several large nuclear power plant projects. The FOAK SMRs may also be faced with longer construction timelines than initially planned. Ensuring that new projects are carefully planned and that all elements of the project are fully integrated are essential to reduce the risk of project failure.

3.2.2. Licensing issues and the need for harmonization

SMR technology is evolving rapidly. However, the regulatory guides and processes to assess this emerging technology are lagging and, in some cases, are not yet available. In the future, robust, technology neutral regulatory review methodologies would be beneficial to minimize the time needed to adopt and commercialize new nuclear reactor technologies.

Regulators and developers will therefore need to work hand in hand to facilitate the design and development of these FOAK reactors and ensure that the path to construction and operation is safe and as streamlined and as cost effective as possible. In discussions with Member States, the area of regulatory development and licensing was seen as the most significant challenge to SMR deployment. In 2015, as a result of meetings facilitated by the IAEA, several Member States agreed to establish the Small Modular Reactor Regulators' Forum[8], with the IAEA serving as the secretariat. The purpose of the forum is to identify, understand and address key regulatory challenges that may emerge in future SMR regulatory discussions. This will help enhance safety, introduce efficiency in licensing, and enable regulators to inform changes, if necessary, to their requirements and regulatory practices.

The forum developed a two year pilot project plan and established three working groups. Each group has been assigned an important regulatory issue related to SMR deployment: EPZ sizing; application of the graded approach; and DiD. The working groups have been tasked with gathering information on how each member of the forum is approaching the issue, to look for commonalities and good practices, and to propose next steps for regulators and the IAEA.

The forum produced a report in 2017 on the pilot effort that includes the results of the working groups, overall conclusions about the project and a recommendation on whether or not the forum should continue. The forum is continuing, being involved in three new working groups addressing licensing issues; design and safety analysis; and manufacturing, commissioning and operations. Interim reports were published in 2020.

In addition to these important regulatory issues, SMR developers need to carefully work through the technical details associated with developing the safety basis for the operation of multi-module units while assessing both common cause and multi-module failure scenarios. The heavy reliance on passive safety systems in some designs may lead regulatory authorities to challenge the developers on concepts related to achieving an adequate level of redundancy and diversity without providing a strict definition of what level is required.

It should be noted that the World Nuclear Association's Cooperation on Reactor Design and Licensing (CORDEL) group has established an SMR task force. This task force has explored SMR licensing and published a report in 2015 entitled Facilitating International Licensing of Small Modular Reactors [18].

3.2.3. Fuel burnup

For the smaller LWR cores, which have higher neutron leakage factors than larger core designs, the fuel burnup achievable, given current fuel designs and clad materials, will be lower. This means that from a resource utilization standpoint these new reactors will not be as efficient as the large LWRs with better overall neutron economies. As a result, the amount of spent fuel produced per unit of electricity generated

[8] More information can be found at https://www.iaea.org/topics/small-modular-reactors/smr-regulators-forum

and provided to the electrical grid will be slightly larger in volume than a typical large LWR with its higher fuel burnup. This may be compensated for by increasing the enrichment of the fuel. Moreover, advanced SMRs based on other reactor technologies (e.g. gas cooled, metal cooled, salt cooled) may mitigate this shortcoming.

3.2.4. Public acceptance

As with any nuclear reactor technology, the public continues to have concerns about reactor safety, nuclear waste disposal, nuclear proliferation and nuclear security. Support for nuclear power is generally correlated with the level of knowledge of, and experience with, nuclear energy. Increasingly, people around the world are becoming more concerned with issues related to climate change and are more aware of the potential contribution that nuclear energy can make to combating climate change. In particular, according to the Intergovernmental Panel on Climate Change (IPCC), in order to limit the average global temperature increase to 1.5°C, global energy production and use need to be fully decarbonized by around 2050, with rapid reductions in emissions starting immediately [19]. Consequently, the only way to do this is by integrating an appropriate mix of technologies, including both renewables and nuclear.

3.2.5. Continued R&D

When Member States were asked what areas of research would be most beneficial to SMR technology development in the educational system and in universities, the following responses were received:

— Developing new multi-module probabilistic safety assessment methodologies;
— Developing new and innovating I&C for diagnostics;
— Developing new technologies to increase the automation of controls and safety methodologies that are needed to obtain regulatory acceptance;
— Developing new risk metrics for quantifying low risk designs;
— Developing fuels and materials for extended refuelling cycles.

3.2.6. Infrastructure considerations of SMRs in the context of the IAEA's Milestones approach

Considering the increasing interest of Member States in the near term deployment of SMRs, it is necessary to understand whether additional guidance on the required nuclear power infrastructure for such reactors is needed. Recognizing that SMRs contain specific features distinct from commercially available power reactors, the IAEA convened two meetings, in 2014 and 2017. The purpose of these meetings was to assess if the conditions in IAEA Nuclear Energy Series No. NG-T-3.2 (Rev. 1) [20] (also called the evaluation methodology) for the evaluation of the status of national nuclear infrastructure development remain applicable or if they need to be modified for SMRs. The topics were discussed in other meetings on nuclear power infrastructure development where the specificities of SMRs were covered. The meetings concluded that in terms of infrastructure at the national level, the same 19 areas as described in the IAEA's publication Milestones in the Development of a National Infrastructure for Nuclear Power [6] need to be addressed. The IAEA evaluation methodology is also applicable for the evaluation of the infrastructure for SMR deployment. The following paragraphs discuss the rationale of the applicability of the IAEA's Milestones approach for SMRs.

A nuclear power plant with an SMR is still categorized as a nuclear installation. The operation of an SMR nuclear power plant involves the use of radioactive material. In this regard, the Convention on Nuclear Safety, the Vienna Convention on Civil Liability for Nuclear Damage and the Protocol to amend it, and the Treaty on the Non-Proliferation of Nuclear Weapons are applicable. Public support and proper stakeholder engagement are needed. Site and non-site feasibility studies need to be conducted, as well as preparation of the electricity grid infrastructure. A NEPIO will be created as a coordination mechanism in the development of nuclear power infrastructure. The State should also determine contractual and ownership models. Required nuclear law should be prepared prior to the deployment of a nuclear power plant, irrespective of the plant's size. An independent and reliable national nuclear regulatory body should be established for licensing and regulatory oversight. The construction of a nuclear power plant is a national responsibility that requires a long term commitment of about 100 years.

One of the primary lessons learned from the new nuclear construction is how to minimize project risk. For countries embarking on a nuclear programme with an urgent need to deploy nuclear power technology, a proven design with operating reference plant(s) will be deployed. Regulatory cooperation will be established between exporting countries and host countries with regard to design and licensing. The nuclear power project should make sense economically for developing economies. These countries need viable, risk informed contracting models. In addition to qualified design/technology developers or vendors, an experienced architect–engineer or builder is required to ensure project success. The new regulatory body and nuclear electrical utility in a country embarking on a nuclear power programme are advised to hire subject matter experts or advisory firms with nuclear power plant experience and engage them early in the process. As an IAEA Member State, the country can also be invited to various peer review and advisory services. The leadership of the country should keep abreast with the progress of recent new builds and implement lessons learned from other power plants in operation or to be built.

The meetings produced the assessment of the 19 elements relevant to SMR deployment by considering the technology specificities that may affect infrastructure development, as presented in Table 3.

TABLE 3. SPECIFIC ASPECTS OF SMRs TO BE CONSIDERED IN THE 19 INFRASTRUCTURE ELEMENTS

No.	Infrastructure element	Specific aspects or potential impacts of SMRs
1	National Position	The same as that of commercial large reactors; SMRs may facilitate decision making due to the low power, lower radiological risk and the lower upfront capital cost for newcomers with a small electricity grid.
2	Nuclear Safety	Enhanced levels of safety through the incorporation of lessons learned from major safety events in the SMR design under development should facilitate faster acceptance by the energy policy maker and stakeholder.
3	Management	Recognize the important role of R&D organizations to address novel technologies; standardization of reactor modules may result in enhanced sharing of management experience and better management efficiency.
4	Funding and Financing	Easier to finance due to a lower upfront capital cost; less interest during construction; phased financing; private sector interest; and potential for minimized investment risk.
5	Legal Framework	Some marine based SMRs may require a non-nuclear legislative framework to address inter-regional transport of modules and maritime aspects.
6	Safeguards	Some SMRs have higher enrichment within the LEU level for long fuel cycles, or new plant layout arrangements including underground construction; these may need novel approaches to implement safeguards.
7	Regulatory Framework	Depending on the licensing readiness level of the design features and technologies, challenges may arise in the establishment of a regulatory framework (regulations, guidance, training and research, operating experience feedback).

TABLE 3. SPECIFIC ASPECTS OF SMRs TO BE CONSIDERED IN THE 19 INFRASTRUCTURE ELEMENTS (cont.)

No.	Infrastructure element	Specific aspects or potential impacts of SMRs
8	Radiation Protection	In principle, the same as that of commercial large reactors; some impacts may arise depending on the emergency planning zone size and site selection.
9	Electrical Grid	SMRs can be deployed on smaller grids that require less reserve capacity and be less dependent on off-site power for safety functions.
10	Human Resource Development	A built-in factory setting and the use of modular construction technology can reduce the peak construction workforce and shorten the construction period; may also avoid large workforce fluctuations for refuelling operations.
11	Stakeholder Involvement	Need to evaluate whether SMRs may develop a conducive environment for the introduction of a nuclear power programme; the role of vendor countries to support embarking countries for the new SMR project should be studied.
12	Site and Supporting Facilities	The smaller footprint of SMRs can expand the availability of acceptable sites, lower water usage and lower transmission requirements.
13	Environmental Protection	Allows for geographically distributed power production, but may require additional environmental assessments.
14	Emergency Planning	Can result in simplified emergency planning and a smaller evacuation zone.
15	Nuclear Security	Intrinsic design features, such as additional barriers, may provide security advantages and limit vulnerabilities for sabotage.
16	Nuclear Fuel Cycle	Dependent on enrichment and type of fuel cycle. No impact on most SMRs with a refuelling interval of 12–36 months with an enrichment lower than 5%; some SMRs have long fuel cycles of up to 30 years, thus requiring higher enrichment within the LEU scale; some designs adopt an innovative fuel cycle.
17	Radioactive Waste Management	Radioactive waste management may be different for some non-water-cooled SMRs; need to evaluate whether the existing infrastructure is applicable, or adjustment/new solutions will be needed for new radioactive waste streams.
18	Industrial Involvement	Design simplification in SMRs reduces safety grade components, enables more diversity in the supply chain, including increased local industrial participation; on the other hand, standardization could facilitate deployment, yet invite less local industrial involvement.
19	Procurement	Potential for a simplified supply chain due to the smaller components and enhanced standardization, but not proven; need to ensure that suppliers can provide a novel system, equipment and services specific for SMRs.

3.2.7. Operation and maintenance of novel technology

There are misperceptions that nuclear power plants cannot perform load following and that they can only generate steady baseload power, thus generating an income stream for the utility, based on a low and controlled fuel cost that is not subject to rapid market fluctuations or interruptions in supply. Most nuclear power plants around the world have in the past operated in this way (and many still do today). Depending on the design and markets, the introduction of load following may reduce fuel utilization efficiency, increase the maintenance cost or reduce the lifetime of the plant due to thermal cycling.

However, in several markets, nuclear power plants have already successfully performed flexible operations for many years: primary and secondary frequency control, and load following. Many plants exhibit good safety characteristics and performance during load following operations, since this was part of the original design requirements, or the analyses and design or operational adjustments (sometimes also operator licence amendments) made it possible when this became a requirement. The need for load following operations will continue and grow with the development and increased deployment of intermittent, non-dispatchable energies. As future energy systems, SMRs will be required to operate in a flexible mode with a high degree of manoeuvrability. The advanced SMR designs are expected to have a better load following capability than the conventional large nuclear power plants due to their size (small core), a large number of rod control cluster assemblies (RCCAs), typical lower power densities (larger operating margins), soluble-boron-free reactivity controls, simpler robust designs and a new digital I&C. SMRs have intrinsic advantages to address modern load following requirements, the primary one being that the load following capability should be incorporated in the design or as a built-in feature. It will also be a safety and licensing requirement from the outset. The inclusion of load following capability as an integral part of the standard design and operational procedures are expected to lead to reduced vulnerability to operational disturbances and transients, and a simplified and robust plant to take full advantage of the intrinsic features (small core, increased margins, passive means, accidents eliminated by design, and a new digital I&C).

In the case where water cooled SMRs with an integral PWR configuration perform load following operations, special care should be taken, since in general the fuel utilization efficiency will decline and the maintenance costs will rise. This is counteracted to some extent by designs without soluble boron where control rods are used for long term reactivity control (and thus also short term reactivity variations due to load following). Some SMRs that operate with natural circulation enable load following without excessive internal metal fatigue since the nature of density driven flow is such that as the heat generation from the core is throttled, the reactor coolant temperature profile changes, but the mean coolant temperature remains substantially constant.

SMRs can also be considered to supply electricity to off the grid areas. In this case, they will be required to supply variable loads at all times instead of baseload power as part of a larger distribution network.

3.3. INDICATORS OF SMR DEPLOYMENT

In addition to increasing energy production through the deployment of large nuclear power plants, countries may choose to utilize SMRs in their energy and economic development strategies. The IAEA has conducted a study that provides Member States with a methodology to evaluate indicators for deploying SMRs in a national energy portfolio by analysing the key factors. It describes the specific attributes of SMRs and evaluates their deployment potential from the viewpoints of energy demand, finance and economics, infrastructure, climate change, and energy security in an energy portfolio [21]. Case studies were used to illustrate the types of conditions that are potentially favourable for use of an SMR. The study identified 18 indicators that provide a broad survey of a country's potential to adopt SMR technology. It also proposed a methodology to assist Member States in utilizing indicators to make an initial assessment of their readiness for adopting SMR technology and helped to inform them as to whether SMRs are a technology that can meet their energy needs.

The assessment is likely to be different, depending on whether the country is trying to assess its readiness level for adopting SMR technology or deploying large nuclear reactors. The reasons for countries to embark on a nuclear power programme will be reflected in their unique national energy policies. Those policies will ultimately dictate what solution is right for their specific situation. For example, some important questions that need to be asked initially include the following:

— Is the country trying to cope with an increasing demand for electricity, or develop energy solutions in remote areas?
— What are the characteristics and size of the existing grid?
— Do the energy policies state that decarbonizing the production of not only electricity but also heat is a strategic objective?
— What are the climatic, geographical and geological characteristics of the country?

Depending on the answers to these questions, an assessment of deployment indicators might conclude that a country is not ready, or well suited, for deploying large nuclear reactors. However, the results might indicate possible benefits in deploying SMRs.

3.3.1. Categories and indicators for SMR deployment

There are 18 indicators that provide a broad survey of a country's potential to adopt SMR technology. The indicators fall into six main categories (three each):

(1) National energy demand;
(2) SMR energy demand;
(3) Financial/economic sufficiency;
(4) Physical infrastructure sufficiency;
(5) Climate change motivation;
(6) Energy security motivation.

These indicators are shown in Table 4.

Data on the indicators are available from the World Bank, the OECD, the United States Energy Information Administration (EIA), the World Economic Forum (WEF), IAEA, OECD/NEA, the University of Melbourne in Victoria, Australia (for climate classification), UNFCCC, United Nations Department of Economic and Social Affairs (UN DESA), and the IEA.

3.3.2. Overview of the methodology

A method — based on indicators — to assess a country's readiness for adopting SMR technology and to help determine whether or not an SMR may be a good option for meeting future energy needs is based on a straightforward scoring of each indicator using the decile system. Except for a few select indicators described in detail in the study, those indicators achieving the most favourable score are awarded a score of 10, with the least receiving a score of 1. The indicators are weighted equally for cumulative scoring and ranking. Therefore, with 18 indicators, the theoretical maximum achievable score is 180. Realistically, a country would have a minimum score of 100 before considering adopting SMR technology, with most of the score obtained on the basis of SMR or size specific indicators.

However, there are several conditions that should also be met before a country considers deploying SMR technology. First, the IAEA has issued guidelines on the size of nuclear power plants relative to the total grid size [16]. Under these guidelines, the size of an SMR, like any other generating unit, should be less than 10% of the total grid capacity. However, in the absence of a grid, SMRs of a certain design may

TABLE 4. KEY CATEGORIES AND INDICATORS FOR SMR DEPLOYMENT

National energy demand	SMR energy demand	Financial/ economic sufficiency	Physical infrastructure sufficiency	Climate change motivation	Energy security motivation
Growth of economic activity	Dispersed energy in rural regions	Ability to support new investments	Electricity grid capacity	Reduce CO_2 emissions per capita	Reduce energy imports
Growth rate of primary energy consumption	Co-generation of electricity and process heat	Openness to international trade	Infrastructure conditions	Reduced fossil fuel-energy consumption	Use of domestic uranium resources
Per capita energy consumption	Energy intensive industries	Fitness for investment	Land availability	Achieve NDC[a] carbon reduction goals	Balance intermittent renewables

[a] Nationally Determined Contribution.

be the only solution. For example, in many locations near the Arctic Circle small communities rely heavily on expensive imported fossil fuels. Several Member States are currently exploring both the technical and economic aspects associated with deploying microreactors — sometimes referred to as nuclear batteries. This class of reactor could be considered a special subset of SMRs and they are being developed as megawatt sized reactors which have power levels similar to research reactors. Considerations relative to the size of the grid might be less important if the country is looking at microreactor generation (i.e. less than 10 MW(e)) to provide power and heat to isolated regions.

In addition to the electrical grid capacity, a country should have sufficient economic and financial resources to invest in nuclear energy technologies. Countries with low levels of overall economic activity are unlikely to have the demand and financial resources necessary for deploying either large nuclear power plants or SMRs.

4. STAKEHOLDERS AND REGULATORY FRAMEWORKS

This section presents a brief summary of important stakeholders who need to be considered when developing a nuclear power project and their role in the deployment of SMR technology. It also contains an overview of regulatory frameworks.

4.1. STAKEHOLDERS

Due to concerns related to safety and proliferation, nuclear technology has always had a significant number of interested parties. The term stakeholder is used in a broad sense to mean a person or group having an interest in the performance of an organization. Stakeholders are often interested parties in the sense that their views need to be considered.

4.1.1. Designer/supplier

The designer/supplier is the organization that is primarily responsible for developing the basic and detailed design associated with a nuclear reactor plant, as well as maintaining design codes and methods and having specialized knowledge of all the systems and components important to safety. In some cases, the designer may hold the reactor's design certification and will maintain supporting calculations and specifications for a facility and its systems, structures and components (SSCs). The supplier has to demonstrate the ability to build the reactor plant that it has designed on time and within budget.

The role of the designer/supplier is important in emphasizing the design features that differentiate SMRs from a traditional large nuclear plant, and in which situations these might be an attractive option for owners/operating organizations and/or governments. The designer/supplier is also responsible for making sure that those features are fully taken into account within the design basis and safety case to facilitate the certification and licensing of the modules. For example, if the module is going to be used for the provision of district heating, the design basis and safety case need to consider how and if that feature will affect the delivery of any fundamental safety functions. Otherwise, the perceived advantages of SMR technology will only be achieved through costly design modifications.

In some cases, the designer may be involved in a build–own–operate scheme, which is a form of project financing where an organization receives a contract from a utility or government body to finance, design, construct and operate a nuclear power plant. Another similar form of project financing is a build–own–operate–transfer model, which involves the future transfer of ownership, and a period of staff capacity development and negotiations on return on investment.

4.1.2. Owner/operating organization

The owner/operating organization (e.g. State electricity company, private electric utility, independent power producer) and its contractors undertake the siting, construction, commissioning and/or operation of a nuclear facility. It is typical for the applicant of a licence to construct and/or operate a nuclear power plant and to be responsible for ensuring that the design submitted to the regulatory body meets all applicable safety requirements. This organization is sometimes referred to as the *licensee*, since it is the body that eventually receives the licence to operate a nuclear plant and is primarily responsible for establishing a formal system to ensure proper maintenance of a plant's design basis throughout the lifetime of the plant.

4.1.3. Technical support organization

The technical support organization (TSO) provides in-depth assistance to support nuclear power plant licensing, siting, design, construction, operations and/or decommissioning activities. The TSO can be internal or external to a nuclear organization. It can support the owner/operating organization or the regulatory body, but typically does not support both due to possible conflicts of interest.

Almost every reactor plant operating organization is a member of the World Association of Nuclear Operators (WANO). This body helps its members achieve the highest practicable levels of operational safety by facilitating access to the nuclear operating experience from around the world. Its focus is on nuclear safety around the world and it is considered an important TSO.

4.1.4. Investors

In the final analysis, the investor is often the most important stakeholder in a nuclear power project. This group can be representative of private or public organizations. In theory, the investor's primary objective is the preservation of its original investment followed by a steady income and future capital appreciation. Nuclear projects are capital intensive and historically have exposed investors to significant schedule risks, which in turn amount to long term cost escalations and investor disappointment. Perhaps one of the most significant aspects of SMR technology is the promise of shorter construction periods and lower upfront capital investment.

4.1.5. Regulatory bodies

A regulatory body[9] is an authority, or a system of authorities, designated by the government of a State as having the legal authority for developing the safety principles and criteria, establishing the regulations and conducting the regulatory process, including issuing authorizations, and thereby regulating nuclear, radiation, radioactive waste and related transport safety. The regulatory body has the authority to grant permits, licences and certifications as they pertain to siting, design, construction, commissioning, operation or decommissioning of nuclear installations. Another very important responsibility of this regulatory body is to licence reactor plant control room operators and set the minimum requirements for staffing the plant's security force.

Since SMR technology includes a wide range of reactor technologies and designs, it is important that regulators are well prepared to assess the safety and security of advanced technologies, such as very high temperature reactors and molten salt reactors. Both the regulator and the environmental agency also need to take into account the implications of using different fuel cycles and fuels other than low enriched uranium. Depending on the choice of SMR technology, having a regulator ready to assess the safety and security implications of various reactor technologies could be an indicator of the level of readiness of a country to embark on the deployment of a fleet of SMRs.

4.1.6. Government

Ultimately, the decision to embark on the deployment of SMRs for either newcomer countries or those with already established nuclear programmes will be driven by the energy policies set by the national government. These policies provide the basis for the decisions made by the infrastructure planning organizations when they receive applications for strategic national infrastructure.

The government has a role in facilitating the deployment of SMR technology by clearly specifying in national policies what it is hoping to achieve from this deployment. Whether this is the decarbonization of electricity or heat production, guaranteeing the power supply in remote areas, or promoting macroeconomic growth by developing a local industry to manufacture components and support SMR operations, the country objectives need to be clear from the outset.

A stable government framework with clear policy objectives is an important element in encouraging investors to finance the construction of SMRs. The government also has the responsibility of ensuring that the necessary infrastructure is created to support a nuclear power reactor. As discussed in Section 2.3.2, the IAEA has developed the Milestones approach to assist Member States in developing the national infrastructure for nuclear power, which is explained in Ref. [6].

Other important roles for the government are to create:

- Policies that recognize nuclear power as a dispatchable, low carbon energy source;
- Programmes that support education and training opportunities;
- Institutions that ensure that nuclear material is safeguarded and nuclear waste is safely managed.

4.1.7. Public

The public is an essential stakeholder in many countries and public acceptance of nuclear power continues to be one of the most important elements in establishing a credible nuclear power programme. It is a good practice for the owner/operating organization to develop a thoughtful and strategic communication plan that is coordinated at both the local and national levels to ensure that only correct,

[9] There may be more than one regulatory body, e.g. one for nuclear safety and another for nuclear security.

factual and transparent information is released. Focusing the plan on the role that nuclear power can play with respect to energy security, affordability, job creation, air quality and mitigation of climate change would be appropriate.

Gaining support from local academic and scientific institutions can also be important to counter inaccurate and often incorrect technical information that is propagated. Many safety attributes associated with SMR technology could be discussed in public forums, media releases and web based information systems. Such attributes could include, for example, small source terms, greater reliance of passive safety systems, extended coping periods when there is no operator action and subsequent mitigation of beyond design basis accidents when compared with traditional large nuclear power plants.

4.1.8. Other stakeholders

Other stakeholders include, but may not be limited to, local and regional governments, trade groups, community groups, interested private companies and environmental groups. These stakeholders may have specific concerns and agendas that may need to be acknowledged and addressed.

4.2. REGULATORY FRAMEWORKS

The two main international organizations working in the area of nuclear safety and security are the IAEA and the OECD/NEA. Under Article III.A6 of its statute [22], the IAEA is required:

> "To establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property (including such standards for labour conditions), and to provide for the application of these standards to its own operations as well as to the operations making use of materials, services, equipment, facilities, and information made available by the Agency or at its request or under its control or supervision; and to provide for the application of these standards, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of atomic energy".

The OECD/NEA, an intergovernmental body within the framework of the OECD [23], assists:

> "its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development."

At the regional level, some regulators have gathered into associations to share good practices. For example, many European regulators attempt to harmonize their national nuclear regulations through the Western European Nuclear Regulators Association (WENRA). At the international level, the basis for a nuclear power plant regulatory framework is embodied in two internationally accepted and binding agreements:

— Convention on Nuclear Safety (CNS). The CNS was adopted in Vienna on 17 June 1994. It was drawn up during a series of expert level meetings between 1992 and 1994 and was the result of considerable work by governments, national nuclear safety authorities and the IAEA Secretariat. Its aim is to legally commit participating States operating land based nuclear power plants to maintain a high level of safety by setting international benchmarks to which States are expected to adhere.

To a large extent, the obligations of the Parties are based on the principles contained in IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [24]. These obligations cover for instance, siting, design, construction, operation, the availability of adequate financial and human resources, the assessment and verification of safety, quality assurance and emergency preparedness.

— Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention. Established under the auspices of the IAEA (1996) on Civil Liability for Nuclear Damage, the Paris Convention provides for compensation for injury to, or loss of life of any person, and for damage to, or loss of any property, caused by a nuclear accident in a nuclear installation or during the transport of nuclear substances to and from installations. It does not cover damage to the nuclear installation itself.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from the harmful effects of ionizing radiation. Some important publications, in addition to the Fundamental Safety Principles [24] referred to above, include:

— SSR-2/1 (Rev. 1) [4].
— IAEA Safety Standards Series Nos GSR Part 1 (Rev. 1), Governmental, Legal and Regulatory Framework for Safety [25], and GS-G-1.1, Organization and Staffing of the Regulatory Body for Nuclear Facilities [26]. The former deals with a general organization, while the latter gives more detailed advice.
— IAEA Safety Standards Series No. NS-R-3, Site Evaluation for Nuclear Installations [27].
— IAEA Safety Standards Series No. SSR-2/2 (Rev. 1), Safety of Nuclear Power Plants: Commissioning and Operation [28].

In parallel with the IAEA's recommendations to assess the site characteristics and basic safety features of the reactor's design, the construction, the pre-operational test programme and the operations, most countries have developed their own licensing processes. The IAEA distinguishes between two major licensing approaches: (1) prescriptive based; and (2) goal setting (or performance based).

The prescriptive based approach (which is the most common), as defined in Ref. [29], is based largely on a deterministic safety assessment. In this approach, the overall reactor design, critical safety systems and selected components and materials are judged based on their ability to meet a set of pre-defined principles and requirements. Under this approach, the regulator needs to develop (or to adopt) a wide range of codes and standards facilitating its technical judgement. From a licensing point of view, this approach is efficient because the codes and the standards are almost tailored to the specific reactor design and the country of construction. In theory, the advantage of such an approach is that it establishes a set of prescriptive requirements that are readily accessible by the reactor designer, engineering contractors and plant operators. However, the disadvantage of such an approach is that it can often create challenges for technologies that are not as well understood.

The goal setting (or performance based) approach is typical of countries that base their nuclear programme on open market principles (rather than a country development strategy promoting the domestic industry); Canada and the United Kingdom are examples. While the US licensing approach is sometimes considered a prescriptive based approach, it also contains elements of goal setting. The goal setting approach relies more extensively on risk informed regulation in combination with the principles of as low as reasonably achievable (ALARA) and as low as reasonably possible (ALARP).

The goal setting approach is based on generic safety assessment principles that allow for the evaluation of any technology, provided that the design has been sufficiently developed and the safety, security and environmental claims have been properly substantiated. However, the disadvantage is that it is perceived to be more ambiguous and uncertain by applicants since specific guidance is not provided. The onus is therefore on the applicant to demonstrate not only that the design is safe, but also that any further investment in increasing the safety of the design would be grossly disproportionate.

The SMR Regulators’ Forum [30] was created as a pilot project in March 2015 to identify, understand and address key regulatory challenges that may emerge in future SMR regulatory discussions. The members are regulators and TSOs with experience related to SMR licensing. The current members are Canada, China, Finland, France, Republic of Korea, Russian Federation, Saudi Arabia, United Kingdom and United States of America. The initial pilot project resulted in reports on (i) examination of existing practices and strategies for understanding how flexible (i.e. risk informed) EPZs are in Member States; (ii) discussions on the applicability of DiD principles to SMRs; and (iii) the examination of existing practices employed by regulators for the application of the graded approach and the influence that SMRs have on these practices. In early 2020, interim reports were also made available on (i) key regulatory interventions during an SMR life cycle; (ii) manufacturability, supply chain management and commissioning of SMRs; and (iii) multi-unit/multi-module aspects specific to SMRs. The IAEA serves as the directorate of the forum.

The licensing of SMRs not only needs to take the smaller size of the reactors into account, but also the different design approaches and alternative non-water-cooled technologies. For a long time in the United States of America, the NRC has acknowledged the need for different requirements for non-water-cooled technologies. This has led to the release of Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors [31]. The proposed general design criteria already reflect due consideration of the specific safety characteristics of these technologies.

5. TECHNOLOGY ROADMAP FOR NEAR TERM DEPLOYABLE SMR TECHNOLOGY

This section provides notional roadmaps that should be considered and either adopted as is or modified, as necessary, to suit the specific needs of an organization based on their specific goals, requirements and circumstances. Currently, there are more than 70 SMR designs under development for different applications. They are scheduled to start operation between 2030 and 2050. The first SMR plant, a floating power unit, was launched for commercial operation in May 2020 in the Russian Federation. Two other industrial demonstration SMRs are in an advanced stage of construction in Argentina and China. Dozens of other SMR designs are being prepared for near term deployment in the mid-2020s. When deployment challenges and issues are resolved, the first commercial fleet of SMRs is expected to be in operation in the time frame of 2025–2035 [32].

As opposed to developing a more comprehensive and integrated roadmap to address the entire life cycle, the approach taken in this publication is to split the roadmap into three different sections that connect the three primary stakeholders back to a timeline for the development and deployment of an SMR project in a Member State. They are:

(a) *Owner or operating organization*. This stakeholder drives the demand for a technological solution that has to address:
  - User requirements[10] that also encompass and address regulatory requirements;
  - Timelines for deployment;
  - Long term product support needs.

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[10] User requirements are typically established by user groups composed of both experienced and less experienced operating organizations with a common interest in communicating with vendors to derive common solutions that benefit everyone.

This stakeholder is ultimately responsible/accountable for both economic and safety performance for activities that it will conduct using the SMR technology. This stakeholder may be a private interest or a government backed business entity.

(b) *Designer/vendor of the SMR technology.* This stakeholder works with the owner or future licensee to develop technological solutions that address the user's requirements. This means that the developer should establish a communication framework with the user and regulatory bodies to understand what the requirements mean and how they are being addressed within the user's required timelines.

(c) *Regulatory bodies.* This stakeholder enables the safe conduct of licensed activities by establishing a clear regulatory framework of requirements and ensuring that proposals put forth by an operating organization (who will be a licensee) are meeting them. The regulator is mandated to also ensure that the licensees perform activities in compliance with their licence, thereby keeping risks reasonably low. The stakeholder needs to understand how requirements apply in a licensee's application. This requires significant early engagement with the owner/licensee and possibly with the developer of the technology to understand any challenges involved in interpreting and applying requirements.

The first part of the roadmap is meant for the owner/operating organization or licensee, while part two is meant for the designer/vendor of near term evolutionary reactor technology. An attempt has been made to discuss the critical interactions between the owner/operating organization and the designer/vendor. In the case of a country interested in SMR technology, it is assumed that the necessary nuclear infrastructure has already been developed. Historically, newcomer countries adopting nuclear technology have entered into some form of a collaborative/learning mode during detailed design activities, or later at the owner/licensee stage if the reactor has already been fully designed and is operational.

Both of the roadmaps presented focus on the pursuit of a reactor technology which is based on more proven technology and which features a relatively high state of technology readiness. There are numerous references in the literature that explain methodologies for assessing the technology readiness of complex engineering systems. A systematic approach to technology development based on technology readiness levels should be sufficient to assess the readiness level of various technology elements and, if needed, guide an organization in the development of a technology maturation plan.

The term *proven technology,* as used in this publication, is consistent with IAEA Nuclear Energy Series No. NP-T-1.10[11] [33], which provides the following definition: "The level of experience through operation of a certain component or a certain nuclear power plant design for a certain length of time demonstrating the capabilities of those technologies."

The use and application of proven technologies in complex systems are often seen as an important technical criterion for consideration in assessing various reactor technologies and helps ensure a plant's safe and reliable operation over the long term and its future economic performance. It is common to refer to SSCs, design and analysis codes and methods, materials and manufacturing processes, and plant environment conditions that are identical (or similar) to those that have been applied successfully in existing nuclear power plants and/or engineering development programmes (i.e. demonstrations) with a high state of technology readiness or are based on more proven or mature technology.

For an SMR to be based on proven technology, for example in some Member States with a nuclear industry capability, it is not necessary for there to be a reference plant already available. Nor should the term proven technology be construed to mean water cooled technology. Gas cooled, sodium cooled, lead cooled and molten salt cooled reactor technologies have been in existence since the 1960s.

[11] A new IAEA publication is being prepared which will supersede this reference.

5.1. GENERIC ROADMAP FOR THE OWNER/OPERATING ORGANIZATION

The focus of this section is to provide a template *project plan* for use by an owner/operating organization or licensee of an SMR. The objective of this plan is to identify major project activities and milestones. Estimated durations for each of the major activities are provided for illustrative purposes and should be modified as necessary according to specific use, particular circumstances and user knowledge. The duration of this roadmap is clearly shorter than the one to develop a reactor, as described in the previous section. Most notably, the duration of the second activity is significantly reduced, since the reactor development, design and testing activities are assumed to have been completed. Engineering development, design and testing activities typically involve uncertain risks in terms of cost and schedule. Therefore, by eliminating these activities there will be more certainty in the overall project schedule and cost.

In general, the following criteria need to be met before this roadmap is implemented:

— National level nuclear infrastructure has been established, which includes an independent and competent governmental regulatory body and well defined processes for reviewing and accepting reactor licensing documentation.
— The owner or licensee, often referred to as the owner/operating organization (e.g. electric utility company), has assembled a team of qualified technical staff that have experience in planning and managing complex projects, reactor engineering and safety, power plant operations, health physics, quality assurance, procurement, and regulatory processes.
— The technology to be selected is assumed to be well developed, based on proven technologies and has a sufficiently established component supplier base. Preferably, operational data from a reference plant (if any) would be helpful in selecting the technology.

Figure 4 depicts a roadmap template for the owner/licensee of a near term deployable SMR or a project plan for buying an SMR. This plan is divided into eight major activities that are set within the overall structure identified by the IAEA's Milestones approach. This approach identified three major phases. Phase 1 focused on the considerations related to a nuclear power programme before a formal decision was made to launch it. Phase 2 involved the preparatory work necessary to begin contracting and construction activities, while Phase 3 dealt with the activities associated with the full implementation of a nuclear power project (i.e. contract award, siting and construction).

5.1.1. Task 1: Project creation

The first steps in creating any new project are as follows: (1) identifying the objective and source of funding; (2) deciding on an effective and competent leadership team; and (3) assembling a project team. In general, the need for a new nuclear power project would already be well established and documented in some form of utility integrated resource plan or a national level energy scenario and feasibility study indicating that nuclear power is a necessary part of the overall long term energy mix.

The project charter is formulated at the beginning, envisaging the scope, cost and time constraints of the whole project. The project charter document typically contains objectives and reasons for undertaking the project. It identifies the main stakeholders and early risks attached with the project. It is also used as a baseline throughout the project life cycle.

An effective and competent leadership team will possess outstanding communication skills and understand both the technology and regulatory environments. This team will need to be able to develop and empower senior staff, quickly understand project details and make both technical and financial decisions, work well under pressure, and promote a culture of transparency, respect for others and integrity. An ability to work with the initial project team to fully develop a strategic plan for the organization is of utmost importance. A project team will need to be hired and organized based on the situation and

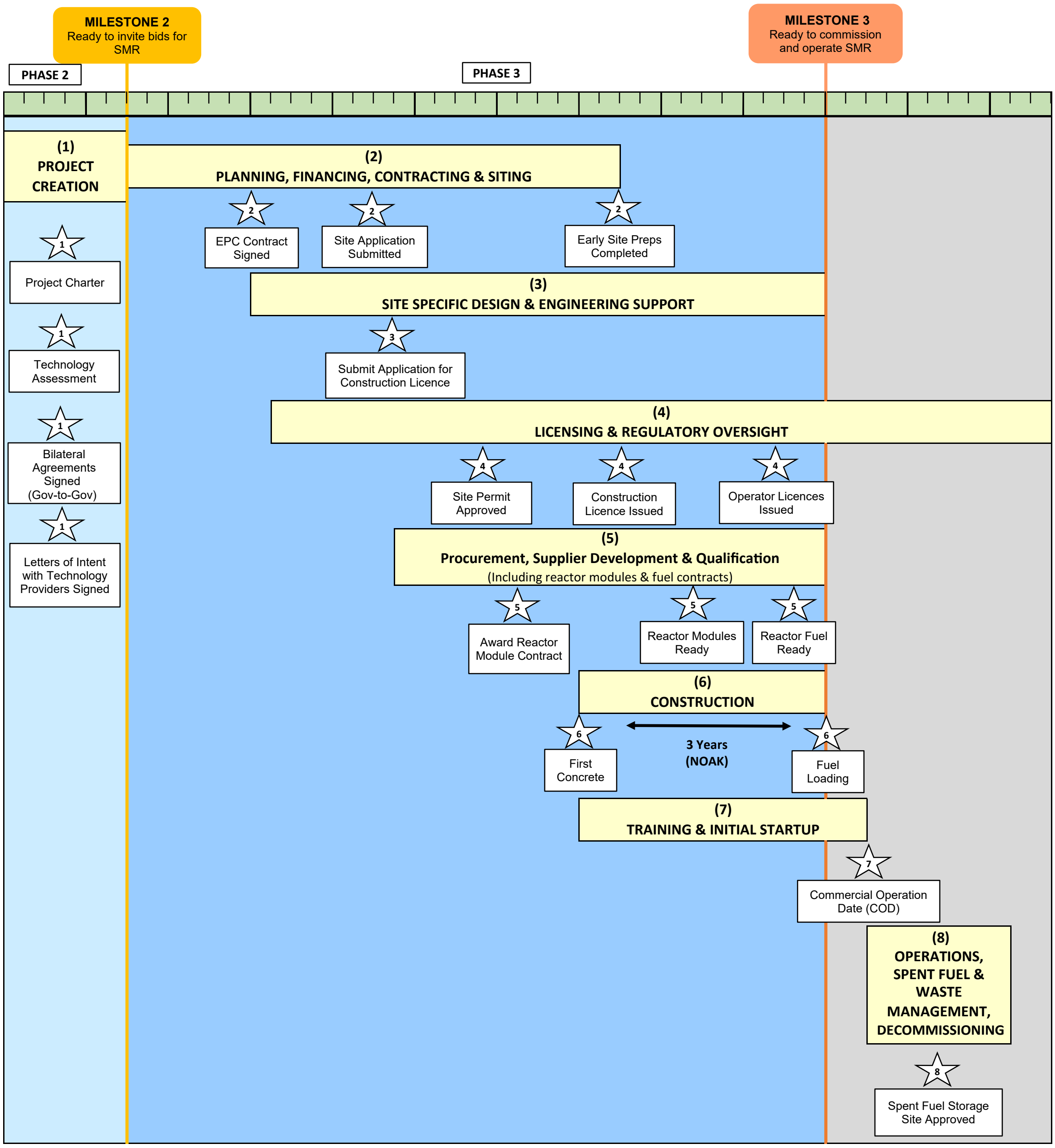

FIG. 4. Roadmap for an owner/licensee of a near term deployable SMR.

resources available. The IAEA publication Workforce Planning for New Nuclear Power Programmes may be helpful in developing a project team [34].

As a first step it is common to assess and select a reactor technology using a reactor technology assessment, a decision making process designed to determine the most appropriate nuclear power plant technology to fulfil both future energy requirements and national level policy objectives. The IAEA recommends a methodology for assessing various reactor designs [33][12]. The assessment, if performed correctly, will facilitate a better understanding of siting characteristics, grid considerations, reactor

[12] A new IAEA publication is being prepared which will supersede this report.

performance and safety, fresh fuel supply, fuel burnup, spent fuel storage, proliferation considerations, ownership involvement, technology transfer and construction and operating costs. Over the course of the project, there may be further assessments based on different levels of technical detail. For example, a simplified first cut may be needed to downsize a large list of potential candidates for consideration to a much shorter list where a more detailed assessment can be made.

Before most countries will consider exporting their nuclear technology, it is necessary to establish some form of bilateral agreement for civil nuclear trade. Several of these agreements might be needed as a precursor to the reactor technology assessment so as to allow the transfer of technical information on reactors to be used in supporting the reactor assessment. These agreements will require support by the ministry of foreign affairs and can take several years to conclude.

It is common practice to also sign a letter of intent outlining an agreement between the owner or licensee and a reactor designer to cooperate in evaluating a particular technology in terms of better understanding the reactor's safety features, results from PSAs, siting requirements, technology readiness and supplier chain capabilities. In some cases, a bilateral agreement between countries will first be needed and in some cases the bilateral agreement will serve the purpose of the letter of intent.

Project planning for a new nuclear power plant consists of a long term development strategy that includes a series of activities related to the study, acquisition, design, construction, commissioning and operation of the plant. It also includes an understanding of the fuel cycle activities required for the provision of fresh fuel and the disposal of spent fuel and waste, together with the development of the necessary regulatory and supporting infrastructures and services. Thus, nuclear power plant project planning becomes a major undertaking, involving a wide variety of activities and a range of organizations, both public and private, requiring abundant human and material resources and a substantial effort at the national, and sometimes even at the international, level.

The goal of this activity is to prepare the project plan, identifying all the necessary activities, schedules and costs. Within each major activity are a multitude of minor activities. Since more details are often known for near term activities, project planning is a continuing effort that requires assessment and updates. A responsibility assignment matrix is a useful tool to ensure that working groups within the NEPIO understand the specific activities that they are responsible for completing. Routine coordination meetings are essential to ensure proper communication and coordination of the work across organizational boundaries and with external organizations.

Project planning requires the organization to clearly understand the country's needs in terms of local and regional energy requirements and transmission capacity, historical power plant siting studies, local resources available to manage waste heat (i.e. access to the sea, river or lake water), the national position on adopting nuclear power, status of nuclear regulatory processes, and the assessment of available technologies to understand which will be the best fit to satisfy a particular set of requirements.

In parallel with the effort to create an overall project plan, it is necessary to develop the organization's quality assurance (QA) manual. QA practices are an essential part of good management and need to be applied to all activities affecting the quality of items, processes and services important to safety. Implementation of a QA programme involves understanding and acceptance at all levels of the organization (i.e. top level managers, engineers, skilled labour, contracting staff), as well as those individuals responsible for verification and assessment of the effectiveness of the programme — it is not the sole domain of any single group. However, it is the primary responsibility of management teams to ensure that the programme is designed to function efficiently and to establish and cultivate principles that integrate QA practices with daily work activities.

As outlined in the IAEA's Milestones approach, during the development of a country's nuclear infrastructure several prospective reactor sites need to have been evaluated. The deployment of SMR technologies can potentially offer more potential sites and/or change the outcomes of the previous site studies if the original studies were performed with the goal of siting a larger power reactor. A site evaluation report with SMR specific attributes can be prepared. In reviewing the list of possible sites, the following attributes need to be considered more carefully:

— As a result of the smaller electrical power output, the existing transmission infrastructure may not necessarily need to be upgraded.
— With a smaller source term, SMRs may be located closer to population centres.
— Possessing a smaller thermal power output, SMRs will require less water resources to manage waste heat.
— As a result of the smaller size of components, the existing transportation infrastructure (i.e. roadways, barges and rail) required to support construction activities may not need to be upgraded.
— An SMR's smaller overall footprint means that design features that can increase physical security could be implemented, reducing the number of security personnel on-site.

Task 1: Progress indicators — Project creation
• Project charter approved • Government to government bilateral agreements signed • Letters of intent with technology providers signed • Technology assessment completed • Potential reactor re-evaluated in the light of specific SMR features

5.1.2. Task 2: Planning, financing, contracting and siting

Early engagement with regulators, reactor designers, industry suppliers, local governments and social organizations is key to moving a project forward and preventing delays. Such engagement with all relevant stakeholders can assist the continuing project planning effort as more information is identified. In particular, early engagement with the regulatory bodies and local/regional governments is essential to ensure that all obligations are well understood.

In order to accelerate the eventual contracting process between a prospective owner or licensee and a reactor designer, it is best (and in some cases most effective) to develop a user requirements document which serves as a procurement specification for the owner/operating organization that will ultimately be responsible for preparing the bid invitation specification for any new reactor. The user requirements document can be used as a guide to facilitate the evaluation of cost, establish timelines/milestones, and identify key acceptance testing activities. It is also a good idea to perform a regulatory gap analysis once the specific technology has been identified to detect roadblocks in obtaining final acceptance. Once the gaps have been recognized, strategies (and often funding) are necessary to develop solutions for effectively closing each gap.

As a result of lower overnight capital costs, it is anticipated that financing for SMRs will be less challenging than for larger reactor projects. However, it is still very important to establish a solid financing scheme, since ultimately the cost of electricity paid by the customer will be directly affected by construction costs, schedules and financing. Schemes like public–private partnerships, build–own–operate, build–own–operate–transfer and their variations define the ultimate ownership of a project, but are not necessarily financing schemes. In parts of the world, equity and debt are the basic elements of capital finance. Equity raises capital by selling shares of ownership in a venture, as opposed to debt which is composed of borrowed money. For large, capital intensive, high risk projects, it is becoming more common for governments to either completely finance the project or provide guaranteed low interest rate loans.

At the national level, it is important to promote the State's support for a nuclear power programme. For example, in the United States of America, new nuclear power plants are being built with loan guarantees and tax credits which enable industry to build a track record of successful projects, which in turn will attract private investment in future projects. Another mechanism is seen in Finland, where large industrial companies are willing to join together to fund the cost of a new reactor in return for receiving electricity at cost. Finally, in the Russian Federation, Rosatom provides direct financing to countries wanting to pursue nuclear power programmes under a build–own–operate agreement.

With regard to the overall economics of a nuclear reactor, the levelized cost of electricity (LCOE) is commonly expressed in terms of energy (US \$/kW·h). This value represents the total life cycle costs of producing a kW·h of power plus the desired return on investment. This parameter can be calculated as shown in Eq. (1).

$$L\quad OE = \frac{\begin{array}{c}\text{[Capital Costs (overnight capital costs + financing costs) +}\\ \text{Operating Costs (including fuel purchases + spent fuel storage + waste management) +}\\ \text{Decommissioning Costs + Return on Investment]}\end{array}}{\text{[Rated Capacity}\quad \text{MW(e))} \times 1000 \left(\dfrac{\text{kW}}{\text{MW}}\right) \times \text{Capacity Factor (\%)} \times 8760 \text{ (h per year)]}} \tag{1}$$

Upon examination of this equation, it is clear that higher financing costs resulting from long construction schedules and low plant capacity factors will drive up the cost of electricity. Moreover, the long term operating costs need to include the cost of storage and ultimately disposal of spent nuclear fuel. As a result, fuel burnup becomes an important parameter to consider in the reactor technology assessment. Higher fuel burnup could reduce fuel costs. It is also expected to reduce spent fuel storage costs, although not by a large margin.

An often overlooked aspect of capital cost is the added grid infrastructure necessary to connect the new power plant to the grid — the electrical highway through which all electricity traffic passes as it moves energy from the supplier (generation) to the customer (load). Being able to replace an ageing fossil plant and existing infrastructure with an SMR will reduce the upfront capital costs associated with the project.

For a typical utility it will be easier to finance an SMR based modular project with incremental deployment than one large reactor. Locatelli et al. [35] concluded that SMRs will be attractive in scenarios where utilities have limited financial resources and can add modules as needed, based on a demand to exploit self-financing options. When compared with large power reactors, there are two distinguishing financing attributes associated with SMRs. The first is the promise of shorter construction schedules which will reduce costs associated with long term debt financing. For example, consider a company having to borrow US \$5 billion for 30 years at a 5% interest rate. During the first five years of construction, no finance payments have been made, since there is no income being generated. The total cost of this loan will be approximately US \$9.6 billion. A one year delay in construction will add approximately US \$500 million to this cost. Shorter and more controlled construction schedules will greatly reduce the overall plant finance costs. The second aspect is that some emerging SMR designs are multi-module plants. This type of design may allow (depending on regulatory acceptance) several modules to be installed and operated, with others being installed at a later date. The early start of several modules will allow the generation of revenue. As described by Boldon et al. [36], the ability to create a cash flow from operations and start repaying debt will significantly reduce the overall financing costs. Significantly reduced financing costs can make a high capital cost nuclear project economically viable.

Selecting reliable engineering firms and suppliers is probably the most important decision in implementing a safe and economic nuclear power plant project. Case studies of complex projects indicate that it is not only the demonstration of a product, but also the demonstration of a project team and the experience of the organization backing it. A newly formed consortium which has never executed a certain type of contract, domestically or for export, will have to undergo a learning process and may have startup problems. Typically, there are several contracts that should be carefully coordinated to ensure a successful project. One approach commonly taken is to award a single engineering, procurement and construction contract to fully implement the project with minimal intervention from the owner or licensee. Contract negotiations can be time consuming and require significant resources to ensure that what is being proposed is consistent with the owner or licensee’s specification (or user requirements document) and that scheduling between contractors is properly coordinated.

During contract negotiations related to plant construction, it is important to also be working on long term contracts to support future nuclear fuel supply. While some organizations hold the view that fuel and power plants should be separate business and profit centres, others see the fuel, particularly the first core, as an integral part of the plant. However, reload fuel will have to be supplied for the entire plant life and spent fuel will have to be managed. Therefore, the owner/operating organization will eventually deal with different companies or organizational units for these fuel related matters.

With regard to siting, public acceptance is arguably one of the most fundamental prerequisites. If a site for a new nuclear plant is accepted, it is also likely that the wider national or regional need for a new nuclear plant has been accepted. It is essential to develop trust and local support within a community that is considering a nuclear power plant. Another challenge is often found in the public's understanding of nuclear energy and the fears associated with it. Engagement with the public at an early stage is essential to promote the benefits that the project will bring and also to address misconceptions relating to nuclear energy that the public is likely to hold. Transparency in planning and early education of the local public is often a key to gaining public trust. In this regard, regular media briefings, open public hearings and engaging members of parliament could help to build a positive public perception.

Local academics who understand the safety characteristics associated with advances in safety systems might be the best source of public information. Support of nuclear engineering programmes at local universities which can in turn participate in public education and outreach activities might be a worthwhile investment.

Historically, a population living close to a reactor could impact public acceptance; local communities with existing nuclear power plants are often accepting of both the benefits and the risks. Good, higher paying jobs with education and training benefits are often a benefit of siting a nuclear plant in a nearby locality.

One important aspect related to siting is giving proper consideration to emergency planning and response. The owner/operating organization/licensee needs to ensure that proper arrangements are made for emergency preparedness and response in the event of a reactor plant accident to mitigate consequences for human life and health, and the environment. The IAEA defines emergency zones as the precautionary action zone and/or the urgent protective action planning zone. Traditionally, regulators have specified site boundary distances, using an enveloping analysis of reactor accidents based on large WCRs, an understanding of leakage pathways and worst case meteorological conditions. The IAEA provides suggestions for emergency zones [37] based on facility categories and precautionary action zones, urgent protective action planning zones, and longer term protective action planning zones. However, determining the size of an appropriate EPZ based on a technical analysis alone may need to be balanced with public acceptance towards site selection.

SMR technologies present opportunities to reconsider the traditional basis for establishing the size of an EPZ, given their often lower operating power, related source terms and expectations of enhanced safety inherent in many SMR designs. As discussed in Section 3.1.3, the quality of PSA techniques has greatly improved over the past two decades and as a result these techniques offer an opportunity to establish SMR site-specific EPZ dimensions. Negotiating an appropriate and acceptable regulatory limit for determining when and what emergency actions should be taken may be the most difficult aspect of such an analysis, given that the combination of deterministic and risk based techniques for quantifying the maximum dose levels at a particular location are well established.

One possible methodology for establishing the technical basis for SMR appropriate EPZs has been proposed recently by the Nuclear Energy Institute (NEI) [38]. The methodology addresses the use of design specific PSA, while accounting for the uncertainties involved in establishing an appropriate EPZ and the need to address the effects of modularity and co-location of reactors. A summary of their methodology is provided:

- Step 1: Select appropriate accident scenarios.
- Step 2: Determine appropriate source terms for the selected accident scenarios (source term in this context refers to fission product release to the environment as a function of time).

— Step 3: Calculate the dose consequences for selected accident scenarios at the proposed site boundary for which emergency planning actions will need to be coordinated, given bounding metrological data for the site.
— Step 4: Compare the dose consequences for selected accident scenarios with the established and acceptable regulatory limit to ensure that the projected doses do not exceed this limit.

From a safety standpoint, there are critical issues that need to be given careful consideration during the siting evaluation. These issues are sufficiently important for the IAEA to have issued NS-R-3 [27]. The general factors to be included in a site evaluation are as follows:

— Earthquakes;
— Flooding;
— Meteorological events;
— Geotechnical hazards;
— Ambient radioactivity;
— Hydrology and oceanography;
— Aquatic and terrestrial ecology;
— Atmospheric, surface water and groundwater dispersion of radioactive material;
— Population densities and distribution;
— External human induced events;
— Uses of land and water in the region;
— Reactor power level and type of plant cooling to be used;
— Radiation dose consequences for hypothetical worst case accidents;
— Plans for coping with emergencies.

From an engineering and construction standpoint, the key issues are as follows:

— Proximity to the electrical grid and load centres;
— Site access via roads, railways and waterways to allow transport of heavy construction equipment, reactor components, materials and supplies;
— Access to an adequate supply of cooling water for normal operation and long term shutdown decay heat removal;
— Access to human resources that are either skilled or in a region where skills can be more easily developed as a result of existing education systems.

In many places around the world, water is becoming a critically important resource. Water is also necessary to cool nuclear power plants. Among cooling technologies, once-through systems consume about 1% of the water they utilize, while wet cooling tower systems consume about 2%, or twice as much. However, despite their water usage, nuclear power plants have been successfully located in desert environments. For example, the Palo Verde power plant, located in Arizona (United States of America), was designed to use treated sewage wastewater from a nearby city for cooling and produces more electricity than any other US power plant.

5.1.2.1. SMR attributes: Siting

The primary objective of the site evaluation is to develop the materials needed to prepare an application for regulatory review to allow the owner/operating organization to obtain a site permit. The site permit indicates acceptance by the regulatory body of the proposed site. Once the permit is obtained, non-safety-related site preparations can typically begin. These activities might include improvements to roads and other transportation infrastructures, construction of non-safety-related buildings (e.g. administrative, housing and maintenance) to support future site construction, additions and/or modifications to existing ports, and transmission lines to the plant.

Some attributes associated with many SMR designs currently being pursued around the world may alter reactor site considerations when compared with traditional larger WCRs. Examples include the following:

— Potentially lower site infrastructure development costs (i.e. roads, rails and port upgrades to support heavy equipment);
— Potential use of the existing grid infrastructure, thus requiring less investment for transmission and grid upgrades;
— Smaller cores and associated source terms for SMRs;
— Higher safety margins with a reduced magnitude and probability of potential accident sequences;
— Slower accident progressions that allow more time to implement mitigative actions;
— Possibility to be located closer to electricity demand centres, thereby reducing transmission costs.

Task 2: Progress indicators — Planning, financing, contracting and siting
• Engineering, procurement and construction contract signed • Site permit approved • Early site preparations completed

5.1.3. Task 3: Site specific design and engineering support

The extent of standardization is limited. Nuclear power plants of a given design for different locations will not be identical in every respect since site specific attributes will dictate the final design. However, the NSSS, which includes the plant's safety systems, can be standardized. The site specific design will require good coordination between the owner/operating organization and the design authority. Examples of site specific design issues are the following:

— Arrangement of auxiliary buildings, cooling systems and dry spent fuel storage, given the physical features of site boundaries;
— Coastal, riverside or desert locations;
— Use of once-through or recirculating cooling systems;
— Local seismic considerations;
— Design of conventional parts (turbine generator) and balance of plant;
— National requirements or market pressure to localize component procurement, which would mean using national codes and standards, and possibly modifying the design.

During the construction phase, the focus needs to shift to safeguards related equipment installation and testing to support monitoring and material control and accountability (MC&A); developing the safeguards programme, as well as corresponding training plans; and preparing a safeguards readiness plan to ensure that the programme, equipment and people are ready to implement safeguards and the plant is in full compliance with both national regulations and international obligations.

In this phase, the facility operator completes a design information questionnaire for the IAEA which contains a detailed physical description of the facility and its material flow. The questionnaire forms the basis for the practical implementation of IAEA safeguards at the facility and is closely controlled by the IAEA. When all negotiations are concluded, the IAEA creates a Facility Attachment which describes the IAEA's safeguards arrangements for that particular facility.

5.1.3.1. *SMR attributes: Site specific design and engineering support*

While the process is the same for both large and small reactors, aspects specific to SMRs may present some new opportunities, for example:

- — Below-grade siting in general provides a security advantage against human intrusion although security response can be an issue;
- — Below-grade siting provides a confinement structure to protect against airplane impacts;
- — Engineering support is reduced per module but may be complex for multi-unit nuclear power plants.

Task 3: Progress indicators — Site specific design and engineering support
• Reactor modules ready to ship • Fuel assemblies ready to ship

5.1.4. Task 4: Licensing and regulatory oversight

The framework that a nuclear regulatory authority will adopt in design and safety reviews is the key to the licensing of SMRs, as is the case for any reactor design. Effective licensing in part depends on the technology readiness or maturity level of the SMR design. Novel and unproven design features may pose a challenge to licensing, as in the case of advanced WCRs with passive safety features. The nuclear regulatory authority, as the licensing body, has to be able to license and regulate SMR designs to ensure that all safety, environmental, regulatory and policy issues are addressed and resolved. SMR designers claim enhanced safety characteristics that require technically qualified regulators to assess, certify and license them.

Licensing risks are a combination of the adequacy of the safety documentation provided by the licensee and the preparedness of the regulators to review the reactor technology. Both parties share the risk. There is also a need to reinforce IAEA safety principles. Thus, Principle 1: Responsibility for safety of SF-1 [24] states: “The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks.”

As a result, it is the owner/operating organization that is licensed by the regulatory authority to safely operate a nuclear plant within the established and accepted safety parameters.

5.1.4.1. *Emergency preparedness and response*

For SMRs, a performance based emergency preparedness and response (EPR) framework and risk based EPZ size methodology for multi-unit designs need to be carefully considered. EPR is one of the layers of the DiD strategy in deploying a nuclear power plant. Emergency planning is also one of the 19 infrastructure issues that need to be considered under the IAEA’s Milestones approach (see Section 2.3.2). While SMR designs adopt advanced engineered safety features that further minimize the probability of radiation release from the plant, experience from past accidents at plants has demonstrated the importance of EPR as the fifth layer of DiD for the protection of plant personnel, emergency workers and the public. Since SMRs may be deployed to sites located near the intended users, arrangements are needed to ensure that practical and effective mitigative actions are implemented in the case of an event. Based on the potentially enhanced safety performance from inherent and passive safety features of SMRs, the source term released into the environment in the event of an accident would be much smaller than it would be for large power reactors (LWRs). The quantity and hazard of radioactive material would accordingly be much lower, leading to less serious consequences for the surrounding area and safety of the public.

Consequently, there is a need to consider using a graded approach as a basis for adopting off-site EPR arrangements commensurate with these SMR features. Based on the requirements set forth in international safety standards, current off-site emergency arrangements, including the EPZ, are required for LWRs, since their hazard assessment ranks them as emergency preparedness Category I facilities. Hazard assessment for a new SMR should be carried out (based on the potential consequences of postulated events, including those of a low probability) to determine the appropriate emergency preparedness category for them and consequently derive the EPR arrangements to be implemented, including the appropriate size of the EPZ.

Emergency preparedness is based on the projected off-site radiation dose in the event of a severe nuclear accident. The current emergency preparedness framework in the United States of America is based on the LWRs that make up the country's operating nuclear fleet, and establishes two EPZs around a plant: a ten mile (16 km) zone, within which action might need to be taken to provide protection from airborne radiation; and a 50 mile (80 km) zone in which food and water would need to be monitored for contamination.

Currently, the NRC is finalizing new Emergency Preparedness Rulemaking with regard to water cooled SMRs and other advanced and new technologies in reactor plant designs. It adopts a consequence oriented, performance based and technology inclusive approach. The size of the EPZ is determined according to dose assessments made from plume exposure pathway evaluations that take into account the time dependent and isotopic characteristics of potential releases.

Task 4: Progress indicators — Licensing and regulatory oversight
• Obtain site permit approval • Obtain construction licence • Obtain operating licence

5.1.5. Task 5: Procurement, supplier development and qualification

At present, there are over 400 operational nuclear power plants, with 50 more under construction worldwide. Operating experience has shown that inadequate control of the procurement process can adversely affect the safety of these plants and has caused costs to increase for operating utilities. Therefore, procurement has to be managed effectively to ensure the availability of design and safety functions over the lifetime of the nuclear power plants. From the viewpoint of nuclear safety, this means managing the plant configuration so that sufficient safety margins are maintained.

There is only one floating SMR plant in operation, while two SMR designs from land based and HTGR categories are at an advanced stage of construction as demonstration plants. Furthermore, common procurement processes and strategies specific for SMRs have either not yet been identified or are unavailable. Nevertheless, the more than 50 construction projects, mostly new build nuclear power plants with a capacity of more than 700 MW(e), are evidence that common procurement processes and strategies have been implemented to ensure the availability of a sustainable market and information over the lifetime of new nuclear power plants.

Unlike large reactors that aim to achieve economies of scale, SMRs are deliberately designed to be small in power and possess specific design, safety and deployment features that seek the economies of serial or multiple manufacturing, taking into account lessons learned from earlier production programmes. Procurement processes for the acquisition of key equipment during different phases of an SMR deployment project life cycle may be slightly different from that of a large nuclear power plant project owing to the specific fabrication and transportation techniques of various SMR modules. Preparation of specifications, and ensuring that a delivered module adheres strictly to these specifications, is a task that requires special attention. The SSCs of SMRs are intended to be manufactured as modules in a factory setting and then shipped to the site for installation. This facilitates a small, incremental addition of power to the electrical grid. Most of the SMRs adopt FOAK SSCs; it means that a novel approach for managing the procurement activities may be needed. To maintain the economic and financial viability of SMRs, just like conventional large nuclear power plants, procurement activities are required and need to be managed carefully. The electricity generating cost of SMRs depends to a large extent on the procurement. The costs of materials, spare parts, inventory, staffing and processes required to support procurement all add to the facility operating charges [39].

For multi-unit (or multi-module) nuclear power plants with SMRs, procurement may become complex. Sustainability of the supply chain is a prerequisite and this depends on the continuous order or demand. During the pre-project phase, procurement may be less, due to modularization adopted in SMRs. As it is part of an engineering, procurement and construction package, procurement is an important factor in maintaining the economic competitiveness of SMRs. Fewer subcontractors and vendors may be required in the case of multi-module SMR plants than in multi-unit large reactor plants.

However, the electricity market is changing, even in Member States with operating nuclear power plants or those constructing new plants. Demand could decrease, for example, due to cheap natural gas. This issue alone has suspended deployment projects in countries with nuclear power. In these circumstances, nuclear suppliers can go out of business or withdraw from the nuclear business because they are no longer able to supply materials. In turn, the utilities will face difficulty identifying and procuring replacement components and parts that satisfy the original design and quality requirements.

Dozens of SMR designs are being prepared for near term deployment and are expected to come on-line in the next 10–15 years. Complexity can be caused by the fact that SMRs have novel SSCs that are not used in conventional large nuclear power plants and by the untested nature of the electricity market for SMRs despite many optimistic energy scenarios. In addition to these challenges, utilities adopting SMRs should anticipate that a robust supply chain may not be available for their plant equipment over extended plant lifetimes. SMR utilities or operating organizations have to take proactive steps to understand national and international procurement markets, analyse critical plant SSCs that are either of a low purchasing volume or have limited suppliers, and take appropriate measures to ensure that required items can be made available. In the near future, cooperation among utilities operating SMRs is recommended; this has been proven useful for currently operating nuclear power plants.

Finally, engineering procurement and the supply chain have a major impact on nuclear safety. Utilities that will operate SMRs should consider adopting graded approaches to focus efforts on critical systems and components and ensure that the supply chain will never adversely affect the safe operation of a plant.

Task 5: Progress indicators — Procurement, supplier development and qualification
• Award contract for reactor module(s) • Reactor module ready for shipment • Reactor fuel ready for shipment

5.1.6. Task 6: Construction

According to IAEA PRIS, as of December 2020, there were worldwide 52 nuclear power reactors under construction in 19 Member States, including two nuclear power plants with SMRs in Argentina and China, respectively. The Russian Federation started commercial operation of the Akademik Lomonosov barge mounted floating nuclear power plant on 22 May 2020.

In general, expectations are growing concerning the schedule, cost and quality of the construction of new nuclear power plants. Significant advancements in techniques and methods in constructing nuclear power plants have been made, as described by the IAEA [40]:

— Integrated project planning and management;
— Implementation and verification of design control, validated by a continuous review of the project schedule;
— Deployment planning;
— Information and data management of design, schedule, cost, procurement, personnel and job status information;
— Site construction infrastructure and layout for construction.

Incorporating lessons learned from the past and ongoing construction projects, methods, techniques, tools and applications are continuously improved and developed for complex multidisciplinary construction projects. The development is driven mainly by the requirement to attain optimized construction schedules while satisfying stringent regulatory requirements on nuclear safety.

Another critical parameter to the nuclear power plant construction project is the overall plant cost. If the construction schedule can be shortened or optimized, both the financing and the labour costs involved in construction will usually be lower.

Nuclear power plant construction techniques are independent of NSSS technology, whether it is a direct cycle, loop type, compact PWR type or an integral PWR type, such as that implemented in many water cooled SMR designs. While different NSSS technologies may have specific equipment or systems that could need special installation instructions, the fundamental construction techniques remain the same, regardless of the NSSS technology.

5.1.6.1. Application of modularization technology for SMR construction

Although modularization technology has been applied to current new builds of advanced WCRs, emphasis is given to SMRs. Modularization is intended to significantly shorten the construction schedule. Among other advantages, with modularization modules may be fabricated in a controlled environment in a factory on the plant site. Multiple modules, or multi-unit SMR plants, can be fabricated in factories while civil work is progressing on the site in preparation for receiving the modules. On the site, only a sequential assembly of the modularized assemblies is required. This reduces on-site congestion, improves accessibility for personnel and materials, and can improve the construction schedule. It can also significantly reduce the staff needed for the site work at an NPP. Other important attributes and advantages of modularization include capability for mass production of modules for several units, with the associated benefit of reducing production time and labour requirements. Therefore, the primary benefit of modularization is that it shortens schedules by enabling parallel construction activities and reducing construction time of some systems and equipment, since testing may be conducted at the factory.

There are, however, challenges and disadvantages of modularization. The use of this method generates several requirements on the project schedule. The engineering design of long lead items and components will need to be finalized prior to module procurement. The quality of the modules off-site and on-site has to be certified for successful implementation of modularization. The schedule for component procurement will also be affected: materials required for modules will have to be ordered earlier than was necessary for conventional stick-build construction. The use of multiple module vendors will also require strict coordination to ensure proper delivery times. Finally, modularization will need a detailed plan for how to arrange and schedule connections between adjoining modules.

Modularization for SMRs may also introduce further challenges to project schedules, including the following:

— Design schedules may increase because of additional upfront work;
— In some cases, the size and weight of large modules require that they be delivered by barge to the site;
— Late delivery of modules can cause schedule delays and setbacks;
— Damage to modules during shipment to the site can cause project delays.

Task 6: Progress indicators — Construction
• Pouring of first concrete • Fuel loading

5.1.7. Task 7: Training and initial startup

At present, there are only three SMR designs from different categories operational or at an advanced stage of construction as prototype and demonstration plants, i.e. a land based integral PWR SMR, a floating barge mounted nuclear power plant with two small modules, and a high temperature gas cooled SMR. Each category has a specific training programme and initial startup procedure not yet disclosed publicly. In addition, for near term deployable water cooled SMRs, at least six of the available designs use natural circulation for their primary cooling circuit (i.e. no reactor coolant pump in the NSSS). While this feature increases the level of safety, a loss of flow event is practically eliminated, but a natural circulation system may be susceptible to flow instability during low pressure startup. Each reactor design has developed a startup procedure that satisfies both the design and safety requirements.

WANO has been working with other organizations, such as the Institute of Nuclear Power Operations (INPO), the IAEA and the Japan Nuclear Safety Institute (JANSI) to determine what other corporate peer reviews can be judged as being equivalent to WANO reviews. At present, they have agreed that they meet equivalency only with INPO in the United States of America. They have also looked at the IAEA's Operational Safety Review Team (OSART) process and have ruled that this is not fully equivalent.

One of WANO's recommendations after the accident at the Fukushima nuclear power plant was that a pre-start-up peer review be conducted at each new nuclear power plant before the initial criticality of the reactor. This recommendation also appears in the WANO Compass report as one of the four focus area initiatives. Together with the IAEA, WANO has identified a need to engage on a number of levels a little earlier than do the WANO pre-start-up reviews, which are typically one to two months before fuel loading and before first criticality at the latest.

Task 7: Progress indicators — Training and initial startup
• Submit readiness review package • Commercial operation date achieved

5.1.8. Task 8: Operations, spent fuel/waste management and decommissioning

SMRs are intended to be a part of the nuclear generation that can be operated both in baseload and load follow modes. Economic reasons and less complexity of operation have made the baseload mode of operation preferable for nuclear power plants. Recently, there has been an increasing need for nuclear power plants to operate in *flexible* modes, i.e. load following, frequency control, or abrupt changes to output upon request from grid operators. When the share of nuclear energy in the mix of national electricity supply increases and/or the total supply of electricity exceeds demand during off-peak cycles, SMRs are expected to have a load following capability similar to what is available currently in many countries, achieved by adjusting the output of other sources of electricity such as hydro and thermal plants. Many SMRs are based on integral PWR designs, each design having a specific operation and maintenance procedure.

Water cooled SMRs with integral PWR arrangement can be configured to load follow; however, the fuel utilization efficiency will decline and maintenance costs will increase. The fact that some SMRs operate in natural circulation that facilitate the ability to load follow without excessive internal metal fatigue is in one way another advantage of the gravity driven design. The nature of density driven flow is such that as the heat generation from the core is restricted, the reactor coolant temperature profile changes but the mean coolant temperature remains more or less constant.

SMRs can also be considered to supply electricity to *off-grid* areas. In this case, they will be required to supply variable loads at all times instead of baseload power as part of a larger distribution network. The capability of nuclear power plants in general, and SMRs in particular, to integrate with renewable sources, which would require load following, is an important issue.

The fundamental strategic spent fuel management options facing countries with small or newly established nuclear power programmes can be categorized as follows [41]:

- National storage and disposal (early or late);
- Reprocessing abroad, recycling and waste disposal nationally;
- Reprocessing, recycling and waste disposal abroad;
- National storage, disposal in a shared disposal facility;
- Fuel leasing;
- Retention of spent fuel as a valuable commodity.

5.1.8.1. Safeguards considerations

During the operations and waste management phase, safeguard efforts will shift to day to day physical protection and MC&A compliance and reporting, as well as supporting routine IAEA inspections. Particular emphasis may be placed on waste related materials, depending on the reactor technology selected and the fuel type.

In particular, during this phase, any physical or software related changes and/or modifications to safeguards equipment will need to be carefully coordinated with the IAEA. Depending on the extent of the modifications, the IAEA will perform inspections to confirm that no modification was made that would allow unreported activities to take place.

Typical IAEA inspection activities include, but are not limited to:

- Examination of records;
- Inventory and material transaction verifications;
- Verification of the performance and calibration of instruments and equipment;
- Servicing of IAEA safeguards equipment installed at the facility;
- Independent measurements and sampling for destructive analysis.

Task 8: Progress indicators — Operations, spent fuel/waste management and decommissioning
• Dry spent fuel storage site approved or fuel take-back operations begin

5.2. GENERIC ROADMAP FOR THE DESIGNER/SUPPLIER

The focus of this section is to provide a generic *project plan* that might be followed by a nuclear power plant designer. The objective of this planning tool is to identify major project activities and milestones. Based on input provided by Member States, the duration for such an effort can vary between 6 and 16 years, depending on the adoption of new technologies and the availability of engineering data.

A reactor designer intending to embark on the design of an SMR should ideally focus its initial resources by following a streamlined process that answers the following questions:

— What are the technology user's requirements and priorities?
— What technology (coolant and neutron spectrum) is to be developed and why?
— What are the applications of this new reactor technology?
— What are the distinctive features, relative to existing large nuclear reactors, and why will these be attractive to the marketplace?

Answering these questions will require engaging electrical utilities and governments to better understand their specific needs and nuclear related policies. Once they have been answered, other criteria relative to the technical capacity of the organization should be considered. The list below represents a minimum set of criteria that should be met before using this particular roadmap:

— The designer is in possession of design procedures, standards, codes and methods that have generally been acknowledged and/or endorsed by the associated established entities, and has the necessary testing programme to support the licensing process.
— The designer has access to material properties and irradiation data, at the relevant operating temperatures and conditions, for the chosen fuels and materials.
— The designer either has, or is able to develop, partnerships with companies that understand the necessary fabrication methods and inspection methodologies for nuclear related technologies.
— The designer has access to proven primary and secondary chemistry control guidelines to mitigate excess corrosion and degradation associated with the plant specific materials.
— The designer has experience in reactor design, engineering, safety, operations, quality, planning and procurement, and regulatory processes.
— An independent and competent governmental regulatory body is in place and has well established processes for reviewing and accepting reactor safety documentation.

Even when the criteria above have been satisfied, it is recognized that evolution in plant safety systems, incorporation of passive safety systems, adoption of advanced I&C technologies, adoption of automation technologies, developments in advanced materials, and advances in safety methodology may influence new designs. As a result, sufficient time should be added to the various tasks to support engineering development activities, testing and validation efforts, supplier development, and pre-licensing reviews and discussions. Figure 5 is a roadmap template for the designer/vendor to support the development of a near term deployable SMR. The discussion that follows will attempt to highlight aspects of SMRs related to the major activities that have been identified.

5.2.1. Task 1: Project creation, conceptual design, funding and economic studies

5.2.1.1. Project creation

The two main drivers for developing a new reactor design have been, and will continue to be, the need to enhance both safety and economics. Other drivers that encourage new reactor designs are advances in fuels and materials, and advances in simulation and modelling; as well as the need to improve fuel utilization, reduce waste generation and handling, and meet more stringent standards for safety and proliferation resistance. Of particular interest today, and certainly a potential driver of nuclear technology development, are the rapid changes being made to the more traditional electric utility model, as carbon intensive fuels are being replaced with intermittent renewable energy resources and smart grid technologies are beginning to emerge.

The first few steps in creating any new project are: (1) identifying the objective and a source of funding; (2) deciding on an effective and competent leadership team; and (3) assembling a project

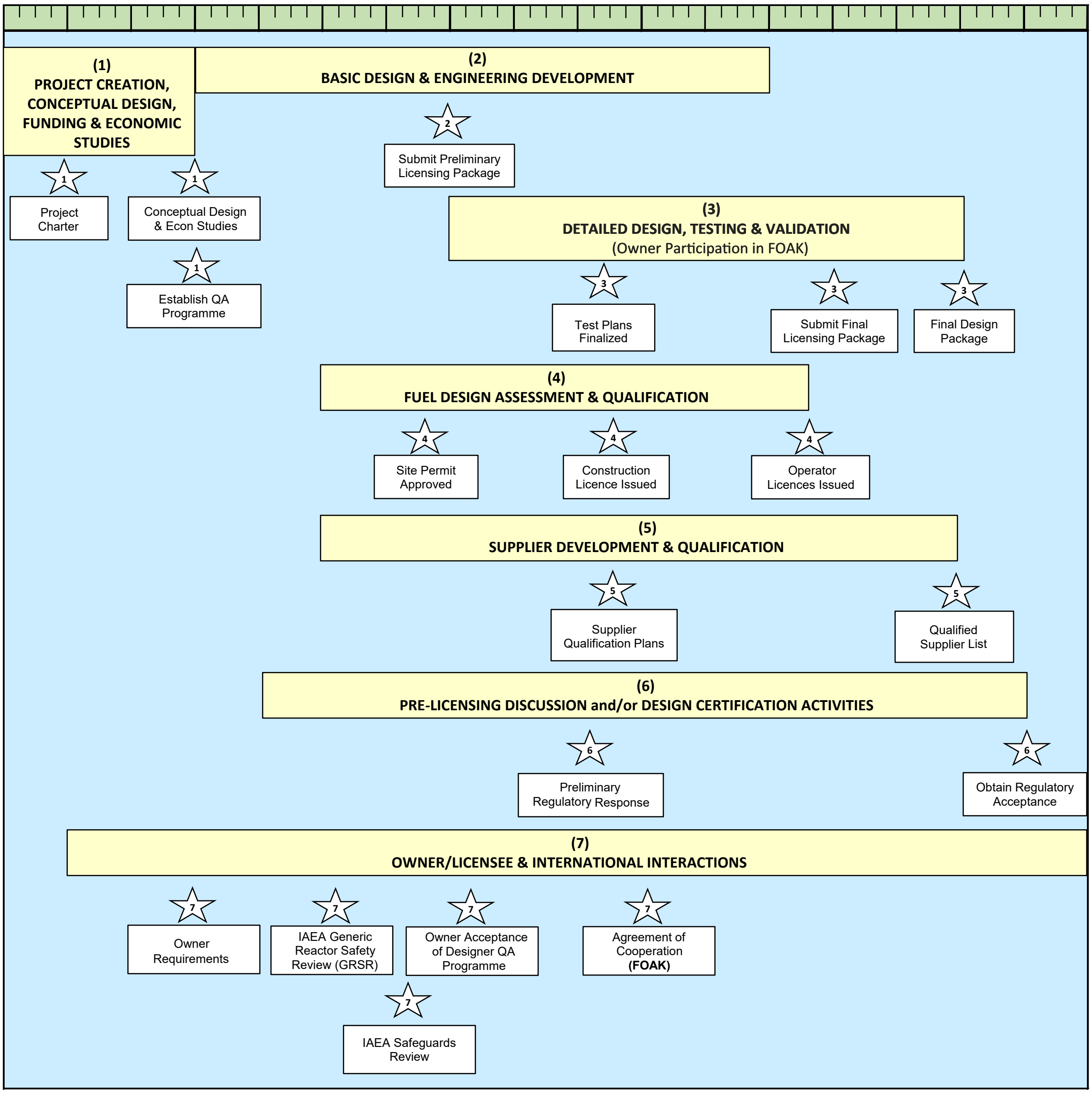

FIG. 5. Roadmap for the designer/vendor for a near term deployable SMR.

team. An effective and competent leadership team will possess outstanding communication skills and an understanding of both the technology and regulatory environments. This team will need to be able to develop and empower senior staff, quickly understand project details, make both technical and financial decisions, work well under pressure, promote a culture of transparency, and have respect for others and integrity. An ability to work with the initial project team to fully develop a strategic plan is of utmost importance. A project team will need to be hired and organized, based on resource availability and the particular situation.

5.2.1.2. Conceptual design

An initial design concept for the selected technology is likely already to have been conceived by team members who have been working on developing such ideas in learning centres or development organizations. At this stage, it is desirable to issue a conceptual design study to provide a basis for selecting a particular concept to demonstrate that various ideas have been fully explored. The study should provide an overview of the concept and its benefits, as well as key results from trade studies and outcomes associated with the analysis of alternatives. It should also give priority to the safety philosophy, which is based on how the three main safety functions (control of reactivity, long term core cooling and confinement of radioactivity) will be ensured. Major differences between the SMR concept and large power reactors need to be identified. These include the delivery of safety functions using passive systems, or fewer safety classified systems due to a reduction in the number of initiating events by design (e.g. an LBLOCA is not possible in many integral reactor designs).

Several other tools that can be used at this stage include the application of multi-attribute utility theory to help select the best ideas and concepts and technology readiness level (TRL) assessments to provide a snapshot of technology maturity for comparison purposes. The modular approach (design and construction) should be duly introduced in the conceptual stage in order to be effective in the deployment phase.

The use of TRL assessments can help an organization to better understand the current status of the technology at the system and component levels. However, the following should be taken into account when using such assessments:

- TRLs are time specific, explaining the risk level if the technology element is introduced into an operating plant at the time of assessment.
- TRLs are context specific and are highly dependent on operating conditions and environment.
- A TRL score is a useful measure of technical development, but it does not mitigate any risk in itself. It is the development plan that drives technical risk reduction.

Some preliminary research, advanced engineering and development may be conducted at government research centres and/or universities, domestically or through international cooperation, in support of a design concept. In such cases, it is important to ensure that these organizations fully understand the necessary QA expectations with regard to collecting and reporting data and results. Thinking through a graded and phased approach to applying QA during developmental activities is time well spent. Developing strategic partnerships with other organizations that are well along in the development of desirable new technology should be given careful consideration.

Upon completion of the conceptual design, consideration should be given to writing an analysis of regulatory requirements to identify existing regulatory gaps for the particular concept. Engaging both an organization operating a nuclear power plant and the regulatory authority to review and receive feedback regarding the overall concept, and regulatory gap analysis is highly advisable at this point. Early engagement with regulatory authorities will lead to a much smoother and more rapid design process. Engagement with international groups working on the harmonization of licensing requirements for SMRs can also be beneficial. This will facilitate the international deployment of the technology and will increase the chances of building a strong business case for utilities, considering the inclusion of this technology in their operating fleets.

To ensure the sustainable development of nuclear energy, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was set up in 2000, based on a resolution of the IAEA General Conference (GC(44)/RES/21). Over the years, INPRO has developed a methodology [42] to help Member States assess the sustainability of an innovative nuclear (energy) system (INS), as provided in Table 5. The methodology can be used to:

- Screen evolutionary or advanced reactor and fuel cycle technologies to evaluate whether they are compatible with the objective of ensuring that nuclear energy is available to contribute to meeting the energy needs in the 21st century in a sustainable manner;
- Compare different INSs, or components thereof, to find a preferred or optimum system, consistent with the needs of an IAEA Member State;

TABLE 5. METHODOLOGY TO ASSIST IAEA MEMBER STATES IN ASSESSING THE SUSTAINABILITY OF AN INS [42]

Category	Example documents
1. Project creation	— Project charter — Organizational chart with defined roles and responsibilities — Work breakdown structure and high level milestones for the initial phases of the project — Early financial plans — Communications plan — Market review and/or utility requirements
2. Conceptual design	— Preliminary plant and systems description document — Preliminary modelling and simulation studies — Preliminary fuel cycle studies
3. Preliminary studies	— Conceptual design report — Preliminary technology readiness assessment — Regulatory gap analysis — Assessment of front end and back end fuel cycle development needs — Initial screening of R&D needs and engineering development efforts — Initial sustainability assessment

— Identify the research, development and demonstration required to improve the performance of existing components of an INS or to develop new components.

Task 1: Progress indicators — Project creation
• Issue project charter • Complete conceptual design and economic studies • Issue a QA programme

5.2.2. Task 2: Basic design and engineering development

One critical aspect for any reactor design is to fully develop a DiD strategy which can be used to guide the preliminary design process. The concept of DiD is centred on multiple levels of protection, including successive physical barriers, to prevent the release of radioactive material to the environment in the event of an accident. This concept has been developed and refined by the nuclear safety community over many years and is widely accepted by most regulatory authorities around the world. A sound DiD strategy is necessary to:

— Compensate for potential human and component failures;
— Maintain the effectiveness of the physical barriers by averting damage to the plant and to the barriers themselves;
— Protect the public and the environment from harm in the event that these barriers are not fully effective.

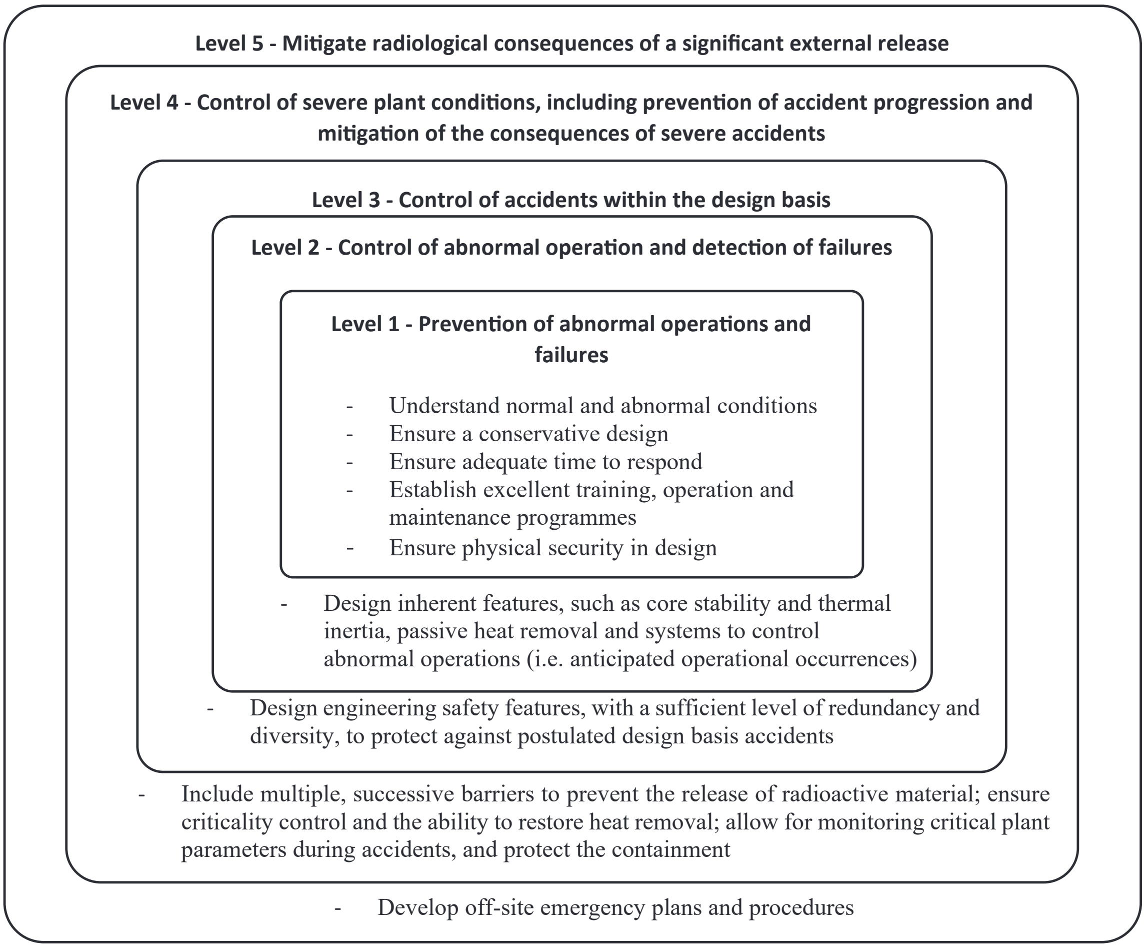

FIG. 6. The architecture of DiD.

During the basic design effort, emphasis needs to be placed on developing a well thought out DiD strategy in parallel with the development of the various technical aspects associated with the major plant SSCs. In 1996, the IAEA International Nuclear Safety Advisory Group (now the International Nuclear Safety Group) issued INSAG-10, Defence in Depth in Nuclear Safety [43], which was updated in 1999 as INSAG-12 [44]. These publications present the history of DiD in the nuclear industry — including how it is currently applied — and list the modifications advisable for the application of DiD to the next generation of reactors.

The DiD concept comprises five levels and may vary from one country to another, or be influenced by a particular plant design. However, the main principles are common to most designs. Figure 6 depicts the concept, which is consistent with INSAG's guidance and described in IAEA-TECDOC-1791 [45].

5.2.2.1. Basic design

The main objectives of the basic design effort are to:

— Complete detailed planning to identify all safety, regulatory and design requirements;
— Identify major plant systems and components;
— Develop the necessary plans (e.g. the quality plan, system engineering plan);
— Identify design codes and standards and determine any gaps;
— Identify any major engineering development efforts that are required;

— Assess plant failures leading to an initial estimate of core damage frequency;
— Begin early discussions with the regulatory authorities to understand their licensing expectations.

The most important aspect at this stage is to have a complete understanding of the general design criteria, and/or safety requirements, which are sometimes codified by a regulatory body and can be based on international standards. In this regard, the IAEA has developed a series of publications on safety standards comprising Safety Fundamentals, Safety Requirements and Safety Guides. These publications are based on an international consensus on what constitutes a high level of safety for protecting people and the environment from the harmful effects of ionizing radiation.

In order to streamline the licensing process, particularly for regulators, and using a goal setting approach, it is important to incorporate safety into the design at this stage, rather than adding it later. To this end, the following actions are important during the basic design effort:

— Break down the three main safety functions into plant level safety functions and low level safety functions;
— Identify nuclear safety, functional and qualification requirements for the SSCs delivering those safety functions.

During this phase of the project, the plant designer should not only consider design aspects specific to plant construction, safety and performance, but also safeguards and decommissioning. Decommissioning costs can add significant life cycle costs to a nuclear power plant depending on decisions taken early in the design phase.

Additionally, the design team should consider the need to accommodate future upgrades necessitated by regulatory requirements, technology advancements, changes in the supply chain and identification of material related issues.

When using existing codes and standards, the design organization should fully evaluate the basis for the models implemented in the code and ensure that they are suitable for the intended analysis. This is even more important when developing advanced non-water-cooled reactor technology. During a detailed analysis of codes, standards and methods, developers of this technology may find gaps, requiring engagement with other organizations to help develop and gain acceptance of new codes, standards and methods. Identifying these gaps during the basic design will minimize delays during the detailed design and reduce an eventual schedule risk during licensing.

Depending on the technology of choice, computer codes might have to be used in applications that are beyond what they have been qualified for. Should this be the case, it will be necessary to prepare a thorough validation plan, together with a software QA document, setting the objectives that need to be met for the code to be accepted by the regulatory authorities in applications related to nuclear safety. This document would be a possible place to certify the validity of the code for its intended purpose.

Preparing an initial Level 1 PSA will significantly improve the designer's understanding of the various plant failure modes, while leading to an initial estimate of core damage frequencies. Understanding the failure modes will encourage an assessment of alternative design approaches to either eliminate a certain failure mode or significantly reduce its probability of occurrence. A properly prepared Level 1 PSA provides significant insights into design weaknesses and ways to prevent core damage.

The basic design is normally complete once a design package is finished and a basic design review is concluded. The purpose of the basic design review is to ensure that the organization is ready to advance to the next stage — detailed design. The basic design may be subdivided into a number of related SSCs. The goals of this review are the following:

— Ensure that all design requirements are identified;
— Ensure that nuclear safety functions have been identified, together with the way they will be delivered;
— Review future work plans to ensure that the approach will have a high probability of fully meeting all the requirements;

— Understand the plan to gain regulatory acceptance;
— Agree on the final design that is to be developed.

With regard to the plan to gain regulatory acceptance for an SMR, it is important to understand the regulatory situations that inspectors will face. These are fundamentally different from what is seen in a large nuclear reactor design, and include:

— Is it a multi-module plant design, where a power plant contains more than one operating reactor module, which is different from a multi-unit site with two or more large units, each contained within its own structure?
— Should the risk of each module on-site be assessed separately while accounting for shared systems from a positive perspective, or does a multi-reactor plant have the potential to create more challenging accident sequences?
— Which systems are interconnected, taking into account that in some licensing regimes safety features delivering a safety function need to be dedicated solely to the delivery of that safety function for the reactor that they are protecting?
— What is the right backup equipment philosophy for a plant with multiple reactors, following the lessons learned from the accident at the Fukushima nuclear power plant?

The vendor/designer should consider at this stage how these questions could be answered and, in particular, what advantages SMR technology offers when compared with large nuclear plants in areas such as risk, source terms or scalability of radiological consequences with the number of modules.

5.2.2.2. SMR attributes: Basic design

There are attributes associated with many SMR design concepts currently being investigated around the world that in theory may reduce the amount of work associated with the basic design effort. These include, for example, the following:

— Simplification of design basis events, fault trees and preparation of a Level 1 PSA;
— Limited reliance on active safety systems which require redundancy;
— Greater reliance on passive safety systems;
— Smaller source term for eventual accident evaluation;
— Ability to incorporate physical protection and safeguards measures by design;
— Ability to simplify decommissioning steps and reduce associated future costs.

5.2.2.3. Safeguards considerations

The preliminary design stage is the first opportunity in the development of a new SMR for a discussion related to proliferation concerns. Ideally, national policies ensure that all stakeholders are aware of the importance of safeguarding nuclear technology and special nuclear material in order to meet international norms. Moreover, the design management team should have a working knowledge of the State’s comprehensive safeguards agreement and any additional protocols that have been agreed on, as well as national laws and regulations related to safeguards. Early communication of design details in terms of safeguards to the IAEA is beneficial for the long term success of a new SMR design.

The preliminary design stage allows developers to innovate with respect to the safeguards by design approach. This is a process where international safeguards design considerations are included throughout all phases of a nuclear facility life cycle, from the initial conceptual design to facility construction and to operations, including design modifications and decommissioning. Incorporating safeguards into the design of the plant will save resources and time in the long term and ensure a more acceptable design for export. Safeguards by design falls into two categories: (1) aspects of the design which provide for ease of inspections; and (2) aspects of the design which inherently prevent diversion activities.

Designers should consider the following areas with regard to the nuclear power plant layout: flow of nuclear material and its physical and chemical form; material balance areas (MBAs); accountancy of nuclear material; identification techniques; measurement methods; implementation of containment and/or surveillance devices to monitor each plausible diversion pathway; fuel receiving and storage areas; inclusion of passive sensors (i.e. cameras and radiation detectors) to monitor nuclear material; ease of access to MBAs for inspectors; access to key equipment by inspectors; the refuelling method (i.e. continuous or periodic); and continuous versus interrupted operation of the reactor. To understand safeguards needs, it is necessary to first analyse the possible diversion paths, and also to fully understand requirements in the State's comprehensive safeguards agreement. References [46–52] provide information for designers/developers.

A *safeguardability analysis* tool is provided in appendix C of Ref. [48] which can help in developing a structured approach to understanding and identifying potential safeguards issues early in the design process. Ultimately, the goal of the safeguards professional assisting in plant design is to simplify the efforts of plant operators in ensuring that international safeguard requirements are being met at minimum cost.

5.2.2.4. Decommissioning considerations

The OECD/NEA, together with the IAEA, issued a publication which provides insights into designing new nuclear power plants based on lessons learned from recent decommissioning efforts [53]. This is especially important in countries that request a funded decommissioning plan to be in place before a site licence can be obtained.

5.2.2.5. Engineering development and testing

There is an expectation that only a limited R&D effort is needed to support the design effort. At the same time, SMR technology, even if non-disruptive, in principle has the potential to implement several innovative solutions based on the evolution of current or proven technology. As a result, engineering development efforts to support eventual design certification and/or regulatory acceptance might still be significant. For example, thermohydraulic testing to acquire empirical data for correlations, materials testing to support code development, and development of new manufacturing processes and inspection methods to support advanced manufacturing techniques may be needed to support design validation efforts. Without these, it is unlikely that a vendor will be able to put together a safety case that will satisfy regulatory requirements. The identification of testing programmes that describe separate effects testing and/or integrated tests to ultimately support design validation activities may be necessary. Similarly, the identification of the associated work scope and cost of these efforts is an important outcome of this particular phase of the project. Access to testing facilities and appropriate laboratories may be needed during this phase. It is also possible that special testing facilities may have to be built and funded. With most early energy technology development efforts, there has historically been public support provided to industry in the form of grants or in-kind contributions from national laboratories to acquire the needed validation data.

Given the fact that many SMR concepts being pursued are based on integral concepts that assemble a number of components within a small space, the designer may want to put in place an engineering programme with the purpose of understanding how FOAK components are going to be manufactured, integrated, tested and inspected. This programme will also provide the basis for the design of a future manufacturing and assembly plant. Additionally, early engagement with suppliers will help to better understand how best to develop future procurement specifications for parts and components and eliminate the tendency to design systems and components that cannot be easily manufactured or inspected. Early supplier engagement may also reduce final plant costs since manufacturers often understand better than designers how to optimize manufacturing, assembly and inspection steps to reduce labour costs.

Components designed, fabricated and tested in accordance with nationally and internationally accepted standards will have a longer and more useful service life and, for many applications, will ensure the protection of human life and property. The design team needs to engage national and, in some cases, international codes and standards organizations to identify gaps based on a particular design/technology and then work with the right organizations to facilitate revisions and/or the development of new and necessary codes and standards. Government organizations can often facilitate the development of new standards and provide expertise and testing to satisfy the revision of codes and establishment of new ones.

Newcomer countries interested in joining the reactor designer at this stage, even if only in an on-the-job training mode, may take advantage of an early education on SMR technology which would be an invaluable experience if the technology is selected for eventual construction. For example, Saudi Arabia and the Republic of Korea have made progress in a collaboration for a SMART design. The Republic of Korea's Ministry of Science and ICT (MSIT) and Saudi Arabia's King Abdullah City for Atomic and Renewable Energy (KACARE) have signed a revised pre-project engineering contract to establish a joint entity for the commercialization and construction of SMART in Saudi Arabia. Historically, agreements referred to as a Design Participation Programme involving International Technical Associates have been established between vendors and supporting/participating organizations in support of such efforts. However, due to strict export control rules on nuclear related information and the sensitive dual use nature of nuclear technology itself, when foreign entities are involved, governmental agreements are needed to authorize such joint activities. The transfer of reactor technology and software for peaceful purposes between States is governed by Nuclear Suppliers Group (NSG) guidelines [54] and national laws. The guidelines ensure that trade in nuclear technology does not contribute to the proliferation of nuclear weapons or other nuclear explosive devices.

Task 2: Progress indicators — Basic design completed
• Submit preliminary licensing package

A typical design package would consist of the following documents, as shown in Table 6.

5.2.3. Task 3: Detailed design, testing and validation

Once a clear interest is expressed by a potential customer, or a specific governmental programme has been established to support the continued development and deployment of an SMR, the designer will embark on a more detailed design effort (although not yet at the level of creating blueprints certified for construction). Several key objectives of the detailed design task are the following:

- Be prepared to answer all licensing and regulatory questions related to the design of the reactor as either part of the design certification process or in support of a reactor site licence;
- Predict the cost of the plant with a high level of confidence;
- Obtain a complete set of design validation data with the exception of data that might be acquired during initial cold testing, hot testing and startup testing.

In order to answer all future licensing and regulatory questions, it is necessary to develop a rigorous set of technical documents to support a reactor design's safety case which covers the safety of the plant and its future operations. This documentation serves as written confirmation that all relevant standards have been met and the plant's safe operating conditions are clearly defined. The UK Office for Nuclear Regulation describes the safety case as not being a one-off series of documents prepared to obtain a

TABLE 6. A TYPICAL DESIGN PACKAGE FOR BASIC DESIGN, ENGINEERING DEVELOPMENT AND TESTING

Category	Example documents
1. Plant design and overview	— General description of the plant and safety systems — Principal design parameters — Identification of design basis events — Identification of nuclear safety functions and their operating mode — Summary of requirements analysis (to include design principles, general design criteria, safety goals, performance requirements and regulatory requirements, both domestic and international) — Preliminary study of fuel cycle and identification of waste streams and disposal paths — Preliminary results of economic studies and cost targets
2. Project planning and systems engineering	— Project management plan to include schedules, milestones and budget — Quality assurance plan — Systems engineering plan — Human factors engineering plan — Human–system interface goals — Methodology for classification of SSCs — Design/technology validation and testing plan — Cyber security plan — limited distribution — Regulatory acceptance plan
3. Codes, methodologies and preliminary studies	— Listing of design codes and methodologies — Fuel and material selection; performance and properties handbook to support the detailed design — Core/fuel design criteria and analysis methodology — Results of preliminary dynamic simulation studies — Results of preliminary engineering studies — Probabilistic safety assessment (Level 1 PSA) — Quantification of source term for accident evaluation — Preliminary assessment of the EPZ and its size — Results of initial hazards identification and screening; transients, accidents and external events
4. Development needs, concept papers preliminary commitments and ITAAC	— Identification of computer codes that need to be developed — Description of engineering development work packages — Concept for reactor and turbine control — Concept of control room and operations staffing — Concept of physical plant security — limited distribution — Preliminary listing of design commitments and inspections, tests, analyses and acceptance criteria (ITAAC)
5. Safeguards	— Results of analysis for applicability of safeguards

nuclear site licence but rather a living framework which underpins all safety related decisions made by the licensee. Explicitly defining the safety function of all important SSCs and mitigation strategies for their possible failure modes is key to future successful engagement with a licensee and/or regulator.

In order to achieve a detailed design suitable both to formally start a licensing process and to further develop the business case and relationships with potential customers and interested countries, the design team will begin the demanding and complex design activities (e.g. neutronic, thermohydraulic, mechanical and structural, and prediction of material behaviour and performance under irradiation conditions) needed to understand and predict the behaviour of a dynamic and highly integrated NSSS. The team may need to adopt suitable nuclear design codes and methods for their particular design, perform calculations in accordance with acceptable industry standards (e.g. boiler and pressure vessel codes), produce a series of design drawing packages, and prepare a series of procurement specifications. All of this work is performed in accordance with an approved QA programme to ensure both the quality of the work and the accuracy of the results. There are a number of international nuclear QA standards that can be adopted (see, for example, Ref. [55]).

For new SMR designs, designers should consider incorporating traditional material surveillance methods (e.g. locating material coupons throughout the reactor vessel and in-service inspections) with consideration of risk informed guidance to reduce long term inspection requirements and the associated costs. In addition, new predictive on-line monitoring technologies have been developed and are now available for monitoring the behaviour of balance of plant (e.g. turbines) components to predict maintenance activities.

In terms of a multi-module reactor concept, designers will need to develop and eventually obtain regulatory approval of new methodologies for assessing common cause failure modes and shared systems that can lead to accidents occurring in a reactor module as well as other modules. Such technical assessments will likely reveal opportunities to prevent such accidents.

During the detailed design task, substantial resources will be needed to support experimentation, engineering testing and validation activities. Identifying the appropriate testing facilities and laboratories will be important in effectively controlling costs. In some cases, dedicated experimental/testing facilities may need to be built to carry out tests. Historically, there have been strong international collaborative efforts to support such activities. With regard to the adoption of enhanced passive safety features, there is a need to ensure, through various types of well designed integral effect tests, the ability to validate best estimate safety analysis codes that are unique to these systems.

In parallel with the design effort, a verification and validation plan should be prepared which is focused on improving the TRL of innovative safety related SSCs. The results of these efforts will help to demonstrate the validity of the innovations adopted for a specific design as well as to prepare for the eventual licensing process. This aspect of the detailed design task should be considered a high risk activity, depending on the level of innovation that is to be included in the SMR design. At the end of the detailed design task, the team should be able to assemble the set of documentation that would be required for certification and/or licensing reviews by a competent regulatory authority. Independent design reviews should be conducted throughout the detailed design effort.

Examples of important activities that need to be undertaken during the detailed design include, but are not limited to, the following:

- Description of the generic site envelope and the site characteristics that have been assumed as the basis for the safety analysis.
- Refinement of the general plant layout.
- Detailed system descriptions, including safety functions.
- Preparation of component procurement specifications; early engagement with suppliers can facilitate this work and reduce long term construction and redesign costs.
- Identification of normal plant operating modes and abnormal plant conditions.
- Refinement of design basis events and accident source terms, as necessary; and both understanding and documentation of the margins associated with events and source terms.
- Refinement of the DiD strategy.
- Detailed analysis of reactor core behaviour and the NSSS under normal, abnormal or transient, and accident conditions.
- Detailed analysis of component and piping stresses.
- Appropriate consideration during design to: operability, testability, maintainability, reliability, supportability, exportability and sustainability.
- Detailed description of fuel performance and relevant safety limits.

— Detailed description of chemistry control methods and approaches to monitor materials degradation and ageing.
— Detailed analysis of emergency core cooling systems.
— Detailed fault tree analysis to identify all initiating events, clarify necessary safety functions, and develop prevention and mitigation strategies which will all help to inform the finalization and clear articulation of a DiD strategy.
— Comprehensive Level 1, 2, and 3 PSAs assuming a generic site envelope and, if applicable, taking into consideration the multi-module nature of a plant's design, common cause failures through shared systems and escalation of consequences if accidents occur in other modules.
— Description of the processes being adopted to ensure that risks are reduced to ALARP levels (particularly important for licensing in goal setting regulatory regimes).
— Detailed description of the resulting radioactive waste and its management.
— Detailed description of physical security and safeguards measures with the identification of vital areas of the plant and protective measures.
— Detailed description of decommissioning steps.

Configuration management (CM), one element of a robust QA programme, is a systems engineering process for establishing and maintaining consistency of a product's performance, functionality and physical attributes with its required design specifications throughout its operating life. Modern digital CM tools can be used to ensure that a system performs as intended, and is documented in sufficient detail to support its projected life cycle. These tools also facilitate orderly management of system information and system changes for such beneficial purposes as to revise capability; improve performance, reliability or maintainability; extend life; reduce cost; reduce risk and liability; or correct defects. Investment in a high quality CM tool and the human resources needed for its implementation will pay great dividends in the long run. The lack of CM, or its ineffectual implementation, can lead to expensive cost overruns. In a worst case scenario, it can lead to project failure.

CM, as part of the design process, is an area where much can be learned from studying other industries. For example, both the nuclear and aviation industries operate within highly regulated regimes, and share an overall goal of excellence in safety and reliability. The aviation industry has greatly enhanced safety in the last decades and a major contributor to this has been international standardization and harmonization of the design approval and CM procedures. Throughout the life of an aircraft design, the original designer is always involved in the response to events and safety relevant findings. For serious events, the aviation authority of the State of design may issue an airworthiness directive, which will be based on solutions proposed by the original designer. This airworthiness directive requires other national authorities to implement remedial measures to their regulated entities, making sure that changes are applied consistently over the entire fleet of aircraft of the same design. Several lessons can be learned from this industry's system of redesign and regulation, including:

— Achievement of an international, political agreement on the acceptance of basic safety requirements;
— Iterative design change management and maintenance of design licensing throughout the lifetime of a design;
— Execution of the design authority role by manufacturers;
— Maintenance of the responsibility of national regulators within an internationally agreed framework.

Taken together, the broad lesson is that consistent regulation, clear delegation of design responsibility, and a system that allows design information to be efficiently shared and updated is critical to the success of complex, safety intensive designs. Synchronizing licensing requirements should ensure that a design qualified as safe in one country does not have to be substantially modified to meet licensing requirements elsewhere, therefore reducing time and costs while at the same time improving safety.

Design commitments to ongoing and future ITAAC procedures are critically important. For example, there were more than 800 ITAAC commitments made by the designer of the AP-1000 reactor[13]. In the United States of America, the NRC is expected to verify that all ITAAC commitments have been satisfactorily completed before they authorize fuel to be loaded. However, there is currently an industry effort under way to change this interpretation so that interim plant operations can be granted to allow some aspects of plant testing to occur during startup operations. With the goal of building SMRs in a factory setting, it is desirable to perform as many inspections and perhaps some testing in the factory where the reactor module is manufactured as this is a controlled environment and will decrease the overall construction timeline.

5.2.3.1. SMR attributes: Detailed design

While the design process is similar for both large and small reactors, aspects specific to SMRs may simplify the effort considerably:

— Simplifications in the development of detailed fault trees, and preparation of Level 1 and 2 PSAs;
— Reduced effort preparing detailed descriptions of safety systems and associated design work due to a greater reliance on passive features;
— Reduced number of piping and structural analyses due to simplification of the number of systems;
— Reduced effort preparing detailed piping and identification drawings due to simplifications in design;
— Reduced decommissioning steps and associated costs due to simplifications in design;
— Reduced long term costs associated with both physical security and safeguards related activities due to design features.

Codes and standards to support design qualification of a FOAK SMR design may require new developments. Due to the cost associated with creating and validating such documents, government funding is sometimes needed, with acceptance by both the designer and regulatory body as the final objective. For example, during the design of SMART, the Korea Atomic Energy Research Institute (KAERI) developed its own methodical approach to support design qualification. This included the development of a design and assessment methodology, a safety validation effort and a performance validation effort. Based on validation tests of both safety and performance using scaled, non-fuelled systems, the methodology was verified and validated for the core, thermohydraulic, safety analysis and human–machine interface system. The documented results were used to support regulatory acceptance of their design.

It is important to involve the next generation of nuclear scientists and engineers early on with any new type of technology so that they can become familiar with it. A large portion of research can be done at a very reasonable cost with the help of university students.

This is of particular interest in the materials science and corrosion control areas for new technology. A second area of potential university work is in the area of nuclear reactor code development and simulation. The development of a simulator in parallel with the detailed design effort can accelerate the design effort and help to identify and eliminate unforeseen plant operational problems. Universities, in partnership with simulator development companies, are particularly well suited for this work as they contain both the theoretical expertise and the technological capacity to produce user-friendly simulators. Furthermore, universities develop needed human resources and can perform scaled engineering tests to gather data to support design activities as well as fundamental and engineering testing to validate predictive computer codes.

However, due to the smaller and more compact nature of many of the envisioned SMR concepts, careful consideration will need to be given to factory based assembly steps and inspections. Performing

[13] Understanding ITAAC requirements and commitments is important to prevent an iterative design process that could cause delays in design certification.

final inspection on an assembled reactor module may be challenging if the buyer and/or regulatory agency desire to view components and/or fasteners that are internal to the assembled reactor module. Early and clear communication with the appropriate stakeholders regarding final acceptance inspections and tests will be needed to minimize rework steps and delays. Designing modules for ease of inspections and testing should be given careful consideration.

5.2.3.2. Safeguards considerations

In this second phase related to design certification and early site approval, safeguards documentation in support of the design application and the proposed location of the reactor in relationship to other nearby facilities are important considerations. In general, as part of the documentation presented to the regulatory authority and the IAEA, the designer will prepare details and technical data that identify the nuclear material present, a schematic flow of the material throughout the plant (including MBAs, storage and inventory locations), handling methods, diversion pathways, MC&A programmes, as well as measurement methods, physical protection of nuclear material and reactor parameters. Ultimately, the designer should demonstrate that the reactor plant design fully meets both national and international safeguards requirements. It is important that the designer understands where IAEA safeguards related equipment will be installed.

During this phase it is important to develop an overall concept regarding nuclear MC&A at the national level with regard to the supply chain associated with possible fuel enrichment, fuel fabrication and reactor sites. This ensures that there will be proper accountability of nuclear material at all times within the supply chain and at the facility. Additionally, the team should develop a coherent vision for both fuel cycle and waste management. In this phase there is an opportunity for continued cooperation with the IAEA on the most cost efficient and effective safeguards methods.

One additional detail to consider is reactor location. The design team should conduct a cost–benefit analysis of having the reactor isolated in a remote region. While an isolated location is a good deterrent against security breaches of the facility, it is difficult for inspectors to reach, and could also mean higher capital costs. The idea of *centralization and co-location of fuel cycle facilities* presented by INPRO suggests that central sites provide greater national control over material and technology and that co-located facilities reduce security risks related to the transportation and storage of material.

Ultimately, the designer should demonstrate that the reactor plant design fully meets both national and international safeguards requirements. It is important for the designer to reach an understanding with the IAEA on where IAEA safeguards related equipment will be installed. Good practices concerning safeguards and safety related oversight should be considered during all phases of the detailed design.

Task 3: Progress indicators — Final design package
• Finalize test plans • Submit final licensing package • Prepare final design package

A typical design package would consist of the documents shown in Table 7.

TABLE 7. A TYPICAL DESIGN PACKAGE FOR DETAILED DESIGN, TESTING AND VALIDATION

Category	Example documents
1. Plant design	— Plant layout and system description documents — Component description documents and procurement specifications — Identification of normal plant operating modes and abnormal plant conditions — Final listing of design basis events — Detailed description of specified acceptable fuel design limits — Detailed plant piping and identification drawings — Simulator specification — Preliminary study of the fuel cycle and identification of waste streams and disposal paths — Final economic studies and cost targets
2. Codes, methodologies and analyses	— Detailed analysis of reactor core behaviour under normal, abnormal and accident conditions — Results of piping 3-D CAD model and stress analysis — Results of engineering studies — Verification and validation results for new design codes, methods and major components — Probabilistic safety assessment (Levels 1 and 2) — Final assessment of the EPZ and its size — Final safety analysis report
3. Fuel performance, material degradation and corrosion studies	— Results of fuel performance studies and test programmes — Results of material performance studies and test programmes — Corrosion control studies, strategies and test results
4. Inspections, tests and analyses	— Listing of outstanding inspections, tests and analyses — Cold, hot and startup test plans
5. Safeguards	— Physical security and safeguards assessments

5.2.4. Task 4: Fuel design assessment and qualification

Perhaps more than any other technical aspect of a reactor's development, it is the selection of the nuclear fuel and fuel design that will determine whether or not an SMR can truly be considered to be near term deployable. Historically, fuel development, qualification and licensing programmes have taken several decades to complete and require specialized manufacturing, irradiation and testing facilities. The time needed to obtain adequate fuel burnup and clad dose is often limited to a test reactor's flux level. Because of the financial risks associated with poorly performing, or defective, nuclear fuel, even small changes in well established fuel designs often require formal qualification efforts and regulatory acceptance.

For near term deployable reactor technology, one would expect that the technical basis for the selected fuel and fuel design would be similar to previously licensed fuels, or fuels that have already had a long history of related development. As a result, any required fuel qualification effort can be accomplished in a much more reasonable time period (i.e. less than decades) and will focus more on confirmatory testing and/or perhaps data gathering to assess the performance of a new configuration. For example, water cooled SMR designs currently being considered around the world will simply adopt current fuel designs but in shorter configurations. Therefore, testing programmes will be more focused on structural, mechanical and thermohydraulic confirmatory testing and perhaps obtaining critical heat flux data, given that the flow regimes associated with natural circulation may be outside traditional large water cooled reactor experience and existing databases. One benefit is that many of these tests can be completed as non-fuelled tests.

An assessment of the current technical basis for a chosen fuel and fuel design would be appropriate for any new SMR design. Such an assessment would ideally focus on the differing operating conditions and specific changes in design that would be needed to accommodate a new reactor design. A technical evaluation of each difference would then be needed to identify what, if any, additional qualifications or data gathering would be needed, with the ultimate goal of ensuring that a sufficient technical basis exists for future regulatory acceptance. The fuel design assessment report would ideally lead to the issuance of a fuel qualification plan, which in turn would lead to a fuel qualification effort. The approved fuel qualification data would be summarized in a qualification report which, taken together with the original assessment report, would serve as the technical basis for the fuel design. In most cases, the reactor designer/developer would need to engage a fuel manufacturing company to accomplish such an effort.

Task 4: Progress indicators — Fuel design assessment and qualification
• Issue fuel design assessment • Issue fuel qualification plan • Fuel qualification report

5.2.4.1. SMR attributes: Fuel design assessment and qualification

In this case, there were no specific SMR aspects that make this effort any different from similar efforts undertaken in support of traditional large reactors.

5.2.5. Task 5: Supplier development and qualification

First modules/plants are likely to be built using existing infrastructure. New infrastructure will follow if the demand is sufficient. Supply chain development, vendor qualification and component manufacturability are aspects that have to be addressed.

The construction of SMRs should be looked at as an assembly on-site rather than a construction. The more construction that takes place within a closed and regulated environment as opposed to on-site, the better. However, a large buy-in from manufacturers is needed to make this a reality. This approach to construction coupled with new manufacturing techniques decreases significantly the construction time of SMRs. Developers should also consider involving the manufacturer in the design process at an early stage. This will allow the manufacturer to give feedback on what is possible and, if necessary, upgrade a plant to comply with nuclear standards.

ITAAC needs to be applied for factory built reactor modules. These are connected to accepted standards. In the United States of America, the activities are being supported by industry through the Nuclear Energy Institute and there is a major effort under way to develop standardized ITAAC. There are new opportunities to perform in-factory ITAAC for certain inspection and testing activities. The design process should take the modular methods of construction into account and allow for easy transport and assembly of modularized pieces on-site.

Building a factory for manufacturing components for SMR is challenging. Approaches to licensing such a factory need to be defined. Therefore, how the designer, builder and nuclear regulatory authority are going to address the issues is essential in SMR deployment.

Nuclear indemnification is where the government concludes an agreement with a nuclear reactor plant operating organization to reimburse the operating organization for losses arising from having to compensate individuals for nuclear damage not covered by a liability insurance contract. For an operating organization to be indemnified, certain obligations have to be fulfilled in terms of standards of operation, maintenance and quality. Depending on the safety significance of the equipment or component, these standards are passed down to the sub-suppliers which have to comply with them.

5.2.5.1. SMR attributes: Supplier development and qualification

While the supplier development and qualification process is the same for both large and small reactors, aspects specific to SMRs may present some new opportunities. There may be more vendors capable of fabricating components for an SMR due to the size of the components. However, for manufacturing safety related components new vendors may be required who would have to greatly enhance their QA and staff qualification programmes.

Task 5: Progress indicators — Supplier development and qualification
• Issue and complete supplier qualification plans • Prepare qualified suppliers list

5.2.6. Task 6: Pre-licensing discussion and/or design certification activities

There are several options that have been selected in various countries for the pre-licensing of SMRs:

— Option 1: Issue a licence for each reactor site;
— Option 2: Issue a licence for each reactor module;
— Option 3: Issue a certificate for the design of each module.

A design certificate for a reactor indicates that the design meets all relevant safety requirements and, once selected by an owner/operating organization for use on an approved site, will be accepted by the regulatory body. In the United States of America, the NRC encourages reactor designers and licence applicants to engage in pre-application discussions with the NRC to help identify potential certification or licensing issues that the designers may wish to address before submitting design certification or combined licensing applications.

An example, albeit of a very reduced scope and limited depth, of a design review having an international effect, independent of a national project, is the IAEA safety review services, such as the GRSR. Upon application by a Member State, a team of IAEA experts reviews a reactor design against the IAEA's safety standards and issues a report stating whether or not compliance has been achieved. This is not comparable to a full scope design review as performed by a national regulator, especially as the IAEA review does not consider national safety requirements and does not have any binding effect on any national licensing procedure.

Task 6: Progress indicators — Pre-licensing and/or design certification activities
• Obtain preliminary regulatory response • Obtain design certification (as applicable)

5.2.7. Task 7: Owner/licensee and international interactions

Several SMR designs have passed through design licensing and/or design certification. The experience gained highlights the importance of pre-licensing activities between (1) designer and owner; (2) designer and nuclear regulatory authority; and (3) owner/licensee and regulatory authority in identifying issues that may raise concerns during licensing. Pre-licensing activities can also lead to the issuance of technical reports that can be reviewed by those concerned. These activities will help facilitate the actual regulatory review process. Through proper pre-licensing engagement, the nuclear regulatory authority will acquire better design familiarity with innovative features introduced in the SMR design. This will also increase efficiency with regard to the design certification review.

Task 7: Progress indicators — Owner/licensee and international interactions
• Obtain owner requirements • Obtain IAEA Generic Reactor Safety Review (GRSR) • Obtain owner acceptance of QA programme • Obtain any necessary agreements of cooperation • Obtain IAEA safeguards review

5.2.8. Documentation

Developing any new nuclear reactor plant design requires the preparation and independent review and approval of many documents. Figure 7 provides an overview of the various types of documentation that are helpful to manage such an effort and record the results of various design, safety and security efforts.

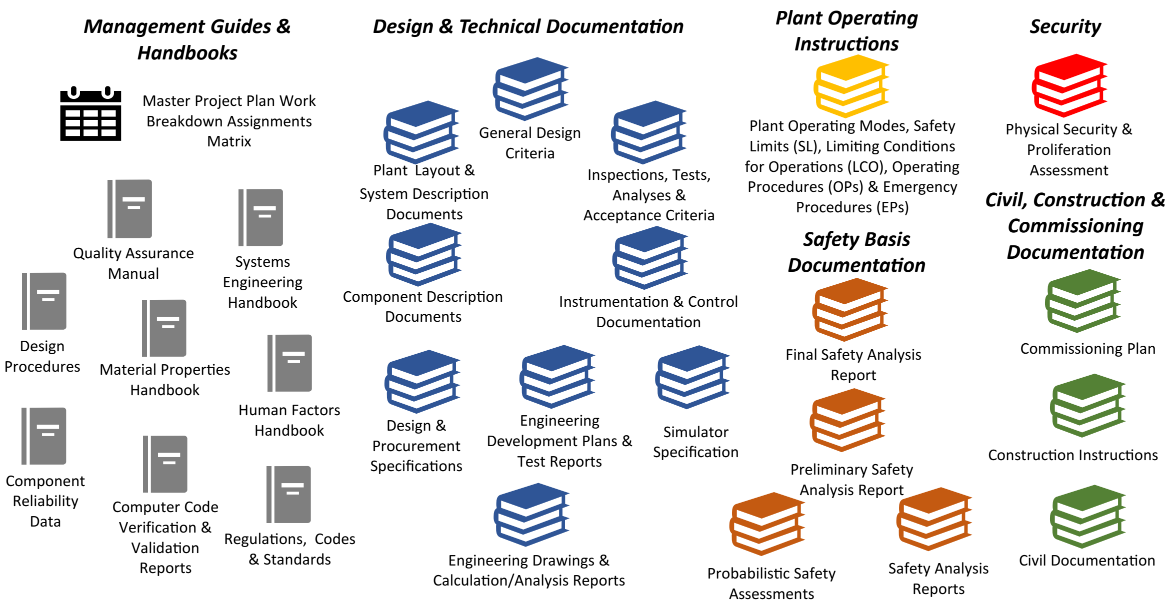

FIG. 7. Types of documentation for reactor plant projects.

5.2.9. Minimization of project risks

One of the greatest financial issues for nuclear power plant projects is schedule uncertainty. The ability to keep a project on schedule is very important and, given the duration of a typical nuclear project, changes in management, staffing, and regulatory requirements create additional scheduling challenges. The following techniques can help to reduce project delays:

- Hire technically competent staff and understand the project's technical and financial goals; clearly communicate these goals to staff.
- Develop a detailed project plan to understand critical path activities and uncover possible future delays; communicate the plan to staff and get their support.
- Focus engineering development efforts on technology solutions that will shorten critical path activities and/or reduce expensive components or construction techniques; communicate the goals to staff.
- Perform a monthly progress review of all activities and update/evaluate the critical path; communicate the status to staff.
- Maintain a well organized interface review and control among design, fabrication and construction.
- Know the organization's strengths and weaknesses; hire expertise where appropriate.
- Adopt internationally recognized design codes and standards and standard off the shelf components whenever possible.
- Partner with companies that add value.
- Invest in QA and systems engineering training for all project staff.
- Invest in training supply chain participants in QA procedures, quality control methods and regulatory expectations.
- Ensure early and effective communications with key stakeholders throughout the project's development.

5.3. GENERIC APPROACH FOR REGULATORY BODIES

Regulatory bodies are mandated by a Member State to perform three primary functions:

(1) Regulators assist in establishing a legal interpretation of such terms as *reasonable risk* or *safety* in the context of specific activities that present hazards to health, safety, security and environmental protection within a Member State's overall legal framework. Although the science of potential harm from hazards is generally consistent from country to country, individual Member States, through their law making processes, decide to what extent potential for harm is acceptable in the face of potentially significant benefits to society. Regulatory bodies, such as a nuclear regulator, may contribute to the scientific investigations but have to act to reflect the results of these investigations in the regulatory framework through regulations, requirements and guidance. When establishing regulatory framework tools, the regulatory body needs to consult often with key stakeholders to ensure that these tools will keep risks reasonable without constraining licensed activities by competent licensees. It is not the responsibility of the regulator to help a licensee be economically viable. The licensee is responsible for this while meeting regulatory requirements; however, the regulator should not place an undue regulatory burden on a licensee, and this is a consideration in setting requirements in a regulatory framework.

(2) Regulators help an applicant for a licence understand the requirements and acceptable ways to meet them. If there are no requirements available, regulators have a duty to provide a framework by which an applicant can conduct a safety demonstration until such time as sufficient experience has been generated to address the gap in requirements. One example of this is permitting the incorporation of quality assured R&D activities into a safety case in lieu of codes and standards that do not yet exist.

(3) Regulators facilitate the safe conduct of licensed activities by ensuring that the licensee carries out activities in compliance with the licence, thereby keeping risks reasonably low and at a level that is generally acceptable to the Member State. A regulator needs to facilitate the understanding of how requirements apply in a licensee's specific application. One example of an enabling approach is to permit controlled early engagement with the owner/licensee and possibly with the developer of the technology, to understand where challenges may exist in interpreting and applying requirements.

There are a number of IAEA publications that establish fundamental attributes and guidelines for a Member State to establish and maintain a strong regulator with a healthy safety culture.

For countries considering the potential deployment of SMRs, these fundamental attributes and guidelines remain the same and SMR technologies do not represent any shortcuts to establishing a competent, effective and trusted regulatory body. For example, if a regulatory body in the country of origin has reviewed a design against its regulatory framework for application in a project and/or has certified the design, this does not relieve the regulator in another deployment country from confirming that the design meets its own national requirements. It is possible for the receiving regulator to review information used in the country of origin's process, but it should be able to understand the rationale for the country of origin's decisions, recognizing that the laws in that country and the rules on the application of codes and standards can be substantially different.

A number of international regulator forums exist to facilitate discussions between regulators who are preparing for new build projects. They generally include a mix of experienced regulators and Member States embarking on a nuclear power programme and seeking to develop a capacity for new builds. One key example is the OECD/NEA Working Group on the Regulation of New Reactors (WGRNR). Although not all forums explicitly address SMRs, they do provide significant information about experience related to the licensing of new build projects, including the use of FOAK technologies. Other resources exist for countries embarking on a nuclear power programme, for example, the IAEA which facilitates discussions between Member States to develop regulatory competencies. Many of the lessons learned and experiences documented are generic enough that they will also apply to SMR projects. It is expected that these forums will either be expanded or new ones created by regulators as SMR projects reflect on their lessons learned to the world for consideration.

In the following sections, additional considerations are discussed for regulators preparing for either pre-licensing or licensing of activities involving many of the new technological concepts being introduced with SMRs.

5.3.1. Establishing a versatile and clear regulatory framework

A versatile regulatory framework establishes requirements and guidance that can be applied broadly, regardless of technology type. Not only does each requirement have to be clearly linked to fundamental safety principles but also appropriate guidance has to be available on how the requirement can be met under different circumstances. Generally, two approaches can be used to accomplish this:

— Performance based regulatory frameworks avoid prescribing methodologies to meet requirements, but rather set objectives that a licensee has to demonstrate it has achieved using quality assured and credible methodologies. Safety assessment guides may be published by the regulator in order to communicate review criteria to the regulated community. Although very flexible, there is less regulatory certainty for the proponent because there is a risk that the regulator may judge the approaches to be inadequately supported late in the technology development process. The proponent will need to support the credibility of the supporting information by documenting where uncertainties exist and how they are being identified. The United Kingdom and Canadian regulatory approaches generally follow this methodology, but also recognize that more prescriptively written codes and standards will be used to inform and support a safety case.

— In the case of more prescriptive regulatory regimes (generally for regulatory environments with large nuclear power plant fleets where consistency in regulatory decision making is critical), regulators may develop technology specific guidance documents to help facilitate:
  - Interpretation of requirements for specific applications;
  - An understanding of how and where the graded approach (or use of safety focused insights) could be applied.

Although less flexible and responsive to changing technological approaches, there is more regulatory certainty for the proponent because the regulator has more clearly established acceptance criteria and, in some cases, acceptable approaches to be followed to meet them. The regulatory approaches in the Republic of Korea and the United States of America generally follow this methodology, but also recognize that in special cases early discussions with the regulator can be used to obtain sufficient feedback to inform and support a safety case.

Both approaches, or combinations thereof, can be used to establish versatile regulatory approaches but there will always be a need to balance the need for flexibility in technological innovation with the need for regulatory certainty.

5.3.1.1. New licensees versus experienced licensees and expected roles of a regulatory framework

In the development of a regulatory framework that considers the use of SMRs with new technological or operational approaches, the articulation of requirements and guidance in the regulatory framework is expected to consider the needs of two key types of industry stakeholders. These stakeholder needs compete with one another and are a source of significant tension for the regulator.

(a) New licensees

New companies choosing to build and operate smaller reactors do not have the benefit of regulatory experience in the deployment country. In some cases, they may have experience from other countries with different regulatory approaches and frameworks. The regulator needs to help these companies understand the rationale behind requirements and how to use regulatory framework tools. This is generally accomplished with an increased level of detail in regulatory documents in areas such as guidance. This additional information can assist as follows:

— Support pre-licensing discussions and facilitate more effective submissions in licence applications.
— Identify and correct any misconceptions or misinterpretations of regulatory language which may be different from the company's international experience. For example, the definition of *important to safety* typically varies between countries dependent on past practice and safety classification approaches used.

(b) Experienced licensees

Companies with significant nuclear power experience in the deployment country generally have extensive experience with the regulatory framework and often request that the regulator remove all unnecessary guidance and information from regulatory documents. However, for new technologies such as SMRs, these companies often seek additional information about what the regulator will accept in a specific technical area (for example, acceptable methodologies to demonstrate the correct use of a graded approach in, say, the application of single failure criteria). In this connection, the regulator should carefully consider the following:

— Impacts on potential new licensees (which need more detail);
— Whether providing this guidance can unnecessarily constrain an applicant's need for flexibility to address requirements using different approaches.

5.3.2. Capacity and capabilities to assess competencies of future licensees

Whether an existing owner/operating organization of a nuclear power facility or a potential new owner/operating organization of an SMR facility, the entity which will become the licensee responsible for either overseeing construction or for operation of the facility or actually performing these activities needs to be evaluated and verified by the regulatory body as being competent to perform those activities. This judgement is a prerequisite to the issuance of a licence or authorization to perform licensed activities and is a follow-up in the regulator's compliance activities against the licence.

The use of new technologies such as SMRs introduces additional considerations in judging whether a future licensee is competent to perform licensed activities. Examples of considerations are discussed below and all reflect the need for *intelligent customer* attributes that the future licensee should reflect in its management system processes. These considerations may require a regulator to develop enhanced regulatory guidance, skill sets and the capacity to assess a future licensee's programmes, essential competencies and abilities to conduct activities:

— *Modularity and procurement processes.* A procurement process for a module will need to reflect that manufactured modules are more complex than individual components. A future licensee needs to have processes in place to ensure that latent flaws are not introduced to modules when they operate in the integrated plant. Setting procurement requirements, performing supply chain (i.e. vendor) inspections and performing delivery receipt and acceptance inspections requires a coordinated, multidisciplinary approach including, for example, civil engineering, I&C, mechanical components, human factors and skills in management system audits. In some cases, where the manufacturer performs certain early module commissioning activities at the factory, the procurement process of the licensee has to agree with the commissioning approach used and how it will impact commissioning activities at the site once the module is installed and placed into service. The regulatory body may have to develop new inspection practices to address how the licensee organization is prepared for these activities.
— *Modular construction.* This may involve oversight of construction activities not conducted at the deployment site. Regulatory requirements will need to provide clarity on what legally constitutes *construction* versus *manufacturing*. This legal definition may vary between Member States. The regulator's assessment and inspection processes need to be in place to confirm that the licensee is addressing both activities in their management system, including transitions between them where goods and services are incorporated into a safety case. The regulator has to be aware of differences in QA practices (i.e. standards) between the two areas to be able to confirm that the licensee has correctly justified which types of verification practices (i.e. inspections) are to be used under different conditions. Again, the aim of these processes needs to be ensuring that latent flaws are not introduced to the plant SSCs.
— *Configuration management.* Modularity in engineering and construction requires a future licensee to extend its CM control processes beyond the site because design changes, particularly those related to manufacturing methods, may occur at the factory of origin. The licensee has to be aware of the impacts of any changes on its site specific safety case. The regulator therefore has to implement the strategy and corresponding capabilities to confirm that the licensee's configuration is being managed effectively in consideration of changes made off-site.
— *Knowledge management*. Use of novel features, such as passive and inherent safety approaches, will play a major role in the safety case of a future facility. The regulator needs to have capabilities in place to determine if the licensee has sufficient knowledge about these features to support the credibility of its safety case in front of the regulator. This is particularly important where novel

features are being implemented in the absence of sufficient codes and standards (for example, in a prototypical or demonstration reactor facility). Here, the R&D information may be the only information supporting the credible performance of these features until operating experience has been acquired. The regulator needs to have processes in place to evaluate how the licensee has established both the credibility and quality of the information that is supporting the safety case, including documenting influences of uncertainties and decisions made to address uncertainties.

5.3.2.1. Existing owner/operating organization of a nuclear power facility — considerations introduced by SMRs

In countries with mature nuclear power programmes, an entity may already have a licence to operate a more traditional facility and may have established a track record for competent and safe operation of the facility over a long period of time. Although the above considerations factor into a regulator's treatment of that licensee should a new SMR facility be proposed, the following considerations are important in interactions between the regulator and the licensee which is considering deployment of an SMR[14]:

— Knowledge of the operation of the existing nuclear power facility does not necessarily translate to expertise in operating a new technology. The regulator needs to confirm that the licensee has plans and processes in place to build technical competencies to understand the new technologies being considered. Operating approaches and even terminologies may be subtly different; the regulator may need to provide additional guidance to reinforce a licensee's programme for developing technical competency. These programmes generally need to be developed to support the licensee's potential role in a technology evaluation and selection process.
— Competency in operation does not mean the licensee has competencies in place to procure goods and services and oversee construction and commissioning of a new facility. It is important that an existing licensee quickly recognizes what it does not know and how it plans to address these knowledge gaps in its management system. The regulator needs to have the capability to evaluate the licensee's organization to confirm it understands which programmes and competencies need to be in place to support the licensing process and ensure that activities are being conducted in accordance with a licence. This includes the licensee's intelligent customer approach to the procurement of goods and services.
— R&D is being used in lieu of established operating experience (OPEX). Many established utilities have strong OPEX programmes that feed back into their opening programmes, but because they are dealing with proven technologies, they may have smaller programmes in place to evaluate any R&D used to support their safety case. New technologies generally have limited or no OPEX or a licensee needs to determine whether a vendors' OPEX references are in fact relevant to their design. Where technologies are more novel, the results of R&D will play a significantly greater role in supporting the safety case of a facility and therefore the licensee needs to have the skills to evaluate the quality and sufficiency of the R&D results. The regulator will need processes that evaluate the licensee's scientific and engineering capabilities to work with the R&D information, which may require more specialized skills in areas such as nuclear physics or thermohydraulics. This regulator capability requires specialized skills in evaluating R&D programmes to be able to ask the right questions to the licensee.

[14] Or any reactor technology that differs from what it is currently operating.

5.3.2.2. *New and inexperienced owner/operating organization of a new nuclear power facility — considerations introduced by SMRs*

In countries introducing new nuclear power programmes, both the regulator and the potential licensee have minimal to no track record for competent and safe operation of this type of facility. In such a case, international tools exist for both the regulator and the licensee to develop key skills.

(a) For industry

— WANO provides mechanisms to assist new operating organizations in developing competencies and peer review processes to measure performance. The principles for safe and competent operation are no different for SMRs.
— Technology owners' groups allow for experienced and new operating organizations to exchange information and support each other. For new SMRs, however, these groups may be either small or may not exist.
— Vendor countries often introduce assistance programmes for new operating organizations to establish the necessary competencies to operate the technologies they are exporting. However, the new operating organization should recognize differences in the legal framework of its country versus the vendor country and should establish a 'trust but verify' relationship with the vendor country who is in a commercial contract with the new operating organization.

(b) For regulators

— Regional (i.e. Asian, European) and international (IAEA, OECD/NEA) regulatory forums are available to help new regulators develop the necessary competencies to address new technologies in licensing and compliance.
— Technology regulator groups exist for regulators to share OPEX related to ongoing regulatory issues for specific technologies. Examples can be found for large nuclear power plants in the OECD/NEA's Multi-National Design Evaluation Program, where regulators cooperate to understand design specific regulatory issues. However, no such forum has yet been established for SMRs.

The following considerations are important in interactions between the new regulator and the new licensee which is considering deployment of an SMR[15].

— The regulatory framework may be untested. Whether adopting processes from other countries or building a regulatory framework from scratch, pre-licensing and licensing timelines need to provide additional time to test and interpret the regulatory framework. If this time is not taken into account, latent issues will emerge later in the licensing process and possibly delay operation of the plant. Regulators should consider the use of international consultants with extensive experience to mentor the regulators in the use of the framework and develop lessons learned early.
— Both parties have minimal experience and may need to temporarily leverage the expertise of others until experience has been gained. The regulator needs to ensure that the licensee has plans and processes in place to build technical competencies to understand the new technologies being considered. Again, this may require initial mentoring by experienced regulators.
— The regulator will need to provide significant guidance to enable a licensee to establish a programme for developing technical competency. This programme generally needs to be developed to support the licensee's potential role in a technology evaluation and selection process.

[15] Or any reactor technology that differs from what it is currently operating.

- The regulator will need to provide detailed guidelines to help the licensee establish management system programmes and processes such as competencies to procure goods and services and oversee the construction and commissioning of a new facility.
- The regulator should have the capability to evaluate the licensee's organization to confirm that it understands which programmes and competencies need to be in place to support the licensing process and ensure that activities are being conducted in accordance with a licence. This includes the licensee's intelligent customer approach to procurement of goods and services. Organizations such as the IAEA and OECD/NEA facilitate a Member State regulator's participation in inspection activities in experienced countries. This is particularly important for the procurement of complex modules.
- R&D is being used in lieu of established OPEX. New technologies generally have limited or no OPEX, or a licensee needs to determine whether a vendors' OPEX references are in fact relevant to their design. Where technologies are more novel, the results of R&D will play a significantly greater role in supporting the safety case of a facility, and therefore the licensee needs to have the skills to evaluate the quality and sufficiency of the R&D results. The regulator will need both capabilities, capacities and processes to evaluate the licensee's scientific and engineering capabilities to work with the R&D information, which may require more specialized skills in areas such as nuclear physics or thermohydraulics. This regulator capability requires specialized skills in evaluating R&D programmes to be able to ask the right questions of the licensee.

5.3.3. Receptiveness and capabilities to adopt and cope with new technological approaches

Some new technological approaches have the potential to improve safety performance and therefore present overall benefits to society. Others might have a neutral, or unknown, impact on a safety case being primarily designed for economical performance. A regulator needs to have the capability and capacity to accomplish the following:

(a) Develop an understanding of the safety implications of a proposed approach. This may require:
    - Regulatory research;
    - Revisiting the origins of specific requirements to understand the fundamental safety principles being addressed.

(b) Challenge the proponent of the proposed approach to demonstrate it:
    - Can prove a neutral or (preferably) positive benefit;
    - Is understanding and addresses uncertainties in safety claims.

(c) Address unique cases not addressed in the regulatory framework. It should have processes in place to both understand the implications of a specific case and make decisions that can be used later in licensing and compliance decision making.

One key function of a regulator, necessary to accomplish the points listed above, is receptiveness to early engagement with reactor designers. This introduces two key challenges that need to be addressed early on to maintain the regulator's credibility as an independent decision making body:

(a) Cost recovery may not be possible, given that an application for a licence has not yet been submitted. This means that processes need to be put in place to fund these engagement activities from sources that keep the regulator independent of the body with which they are engaging.

(b) Any discussions or decisions must be made in a controlled and transparent fashion and can never legally impact the decision making capability of the regulator.

6. DEVELOPING REACTOR TECHNOLOGY WITH LONGER DEVELOPMENT TIMELINES

6.1. RELEVANT TECHNICAL AREAS AND SUPPORT FOR R&D

This section provides an example of an *integration planning technology roadmap* for use by an R&D organization with a focus on developing the next innovative reactor technology. IAEA-TECDOC-936[16] [56] provides the following definition:

> "An innovative design is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and a prototype or demonstration plant are probably required."

The development of innovative reactor technology will require longer development timelines, with efforts focused on identifying and resolving technology gaps. The objective of this section is to present a systematic methodology to define a set of prioritized *work packages*, and identify government and international collaborative efforts that will assist in the development of new reactor technologies.

Developing a strategy for publicly funded energy research is a difficult and often controversial task in many countries. The task involves codifying the full range of research options so that they can be considered against numerous cross-cutting criteria. The resulting priorities are greatly dependent on the consensus opinion regarding how research can influence the risks, opportunities and objectives. Additionally, the prioritized schedule of research should be traded against the available funding. In addition, it would be desirable if the development of the research strategy could provide a mechanism for a wide range of stakeholders (including research providers) to contribute to the prioritization process. Figure 8 shows relevant technical areas and development of R&D support.

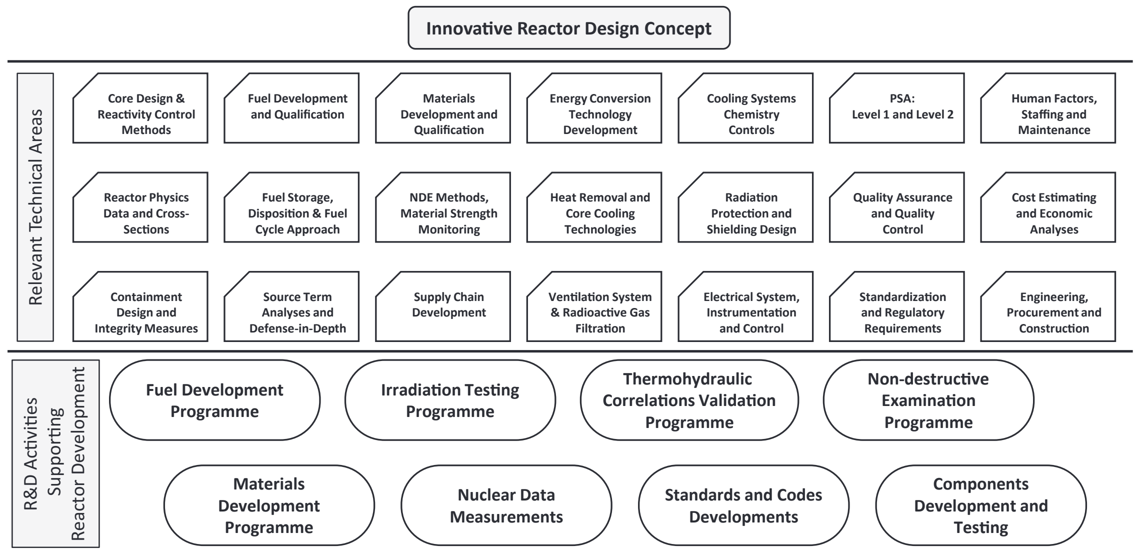

FIG. 8. Relevant technical areas and development of R&D support.

[16] A new IAEA publication is being prepared which will supersede this reference.

6.1.1. Technology readiness assessments and identifying technology gaps

The US Department of Energy's Office of Environmental Management issued a Technology Readiness Assessment (TRA) that provides a Technology Maturation Plan (TMP) Process Implementation Guide that explains the following [57]:

> "A TRA is a systematic, metric-based assessment of how far technology development has proceeded ... It is not a pass/fail exercise and is not intended to provide a value judgment of the technology developers or the technology development program. … A TRA can:
>
> — Identify the gaps in testing, demonstration and knowledge of a technology's current readiness level and the information and steps needed to reach the readiness level required for successful inclusion in the project;
> — Identify at-risk technologies that need increased management attention or additional resources for technology development; and
> — Increase the transparency of management decisions by identifying key technologies that have been demonstrated at certain levels of maturity or by highlighting immature or unproven technologies that might result in increased project risk."
>
> "A TRA provides a snapshot in time of the maturity of technologies and their readiness for insertion into the project design and execution schedule."
>
> "A TRA evaluates technology maturity using the Technology Readiness Level (TRL) scale that was pioneered by the NASA [National Aeronautics and Space Administration] in the 1980s."

6.1.2. Technology development and demonstration plans

Internationally, GIF considers the following reactor types to be innovative reactors:

(a) Sodium cooled fast reactor (SFR);
(b) Lead cooled fast reactor (LFR);
(c) Gas cooled fast reactor (GFR);
(d) Very high temperature reactor (VHTR);
(e) Supercritical water cooled reactor (SCWR);
(f) Molten salt reactor (MSR).

The GIF goals for these reactors are summarized below:

- *Sustainability*
  - Meet clean air objectives and provide long term availability of systems and effective fuel utilization for worldwide energy production;
  - Will minimize and manage nuclear waste and notably reduce the long term stewardship burden.
- *Economics*
  - Have a clear life cycle cost advantage over other energy sources;
  - Have a level of financial risk comparable to other energy projects.
- *Safety and reliability*
  - Excel in safety and reliability;
  - Have a low likelihood and degree of reactor core damage;
  - Eliminate the need for off-site emergency response.
- *Proliferation resistance and physical protection*
  - Provide increased physical protection against acts of sabotage and theft of weapons usable material.

In general, innovative reactors promise to further expand on the efficiency gains and sustainability achieved in currently available evolutionary reactors, in particular through higher operating temperatures and closing the fuel cycle. However, it should be clear that all of the above mentioned ultimate goals may not be reached and that some reactor systems only have a limited scope to excel in specific goals.

Furthermore there are trade-offs, e.g. fuel reprocessing is required, innovative fuels and materials have to be first developed and then qualified, which may involve decades. Innovative reactors also present other challenges such as technical and licensing uncertainties (which are big drivers of construction cost) associated with large departures from current technologies, methods, materials, etc. While one of the innovative reactors, the SCWR, seems to be the natural evolution in the lineage of large commercial WCRs, it still faces several technical challenges related to its high operating temperature and pressure (approximately double that of current designs).

Almost all of the innovative designs still require significant R&D and industrial demonstration through the construction and operation of an experimental plant (e.g. GFR), a demonstration plant (e.g. LFR) or a prototype (e.g. SFR) which are currently only at a preconceptual design phase. Their construction is planned within the next decade. Some concepts also require significant changes to regulations.

6.1.2.1. Fast reactors

These systems, operated in a fully closed fuel cycle, have the potential to significantly increase the sustainability of nuclear power, i.e. they can extract 60–70 times more energy from uranium than existing thermal reactors, contribute to reducing the plutonium stockpile, and minimize the heat load, volume and required isolation time for high level radioactive waste. They will also have higher efficiency and the innovative concepts promise to have enhanced safety characteristics with respect to evolutionary reactors (a feature not yet proven). Another advantage of liquid metal cooled fast reactors (FRs) is that they operate at very low pressure.

Due to their particular physics, FRs are very flexible and can be designed as *breeders*, *burners* or *general purpose* reactors. When designed as a breeder, FRs produce more fuel than they consume. As burners they are specifically designed to minimize the volume, heat load and the lifetime of the most hazardous nuclear waste, thus dramatically reducing the requirements of the geological repository. In both cases, in order to be effective, the technology requires a closed fuel cycle, including fuel reprocessing. General purpose FRs have higher fuel burnup, a longer fuel cycle, and/or higher coolant temperatures. They are particularly suitable for producing electricity with higher efficiency or for non-electrical applications (e.g. hydrogen production). Some projects do not require reprocessing in the country of deployment.

Due to their flexibility, FRs can be adapted to different national nuclear policies and needs. If the goal is natural uranium preservation (e.g. in countries expected to operate a large fleet of nuclear power plants), FRs can be operated as breeders. If the goal is to minimize plutonium stockpiles and/or reduce the number and requirements of geological repositories, FRs can be operated as burners. Even from a strategic viewpoint, the motivation for developing an FR programme can be significantly different in different countries. For instance, Japan is developing an FR programme due to a lack of traditional energy resources. The Russian Federation has enough fossil fuel resources but is fully engaged in FR development and deployment for future strategic goals (including export) and to maintain technological leadership.

The main challenge of any FR is to significantly reduce the capital cost that currently is 30–50% higher than the project cost of the NOAK of an evolutionary reactor. Competitiveness also depends on the uranium price. Operation and maintenance are more challenging than that for WCRs.

6.1.2.2. Sodium cooled fast reactors

The most mature FR technology, the SFR, has more than 400 reactor-years of experience acquired through the design, construction and operation of experimental, prototype, demonstration and commercial units operating in a number of countries, including China, France, Germany, India, Japan, the Russian Federation, the United Kingdom and the United States of America.

In terms of innovative SFR designs and plans, the Russian Federation is developing an advanced large size SFR, BN-1200. Japan is developing the 1500 MW(e) JSFR. The Republic of Korea is carrying out a broad R&D programme in support of its 600 MW(e) SFR. France was, until recently, developing the 600 MW(e) SFR prototype called ASTRID, but suspended its development in 2019. All these industrial prototypes are under conceptual design and their construction is expected to start in the next decade. As a consequence, the FOAK will not be in operation in the next 20 years and a commercial fleet SFR can reasonably only be deployed after 2040.

6.1.2.3. Lead cooled fast reactors

Lead (and lead-bismuth eutectic (LBE)) cooled fast reactors can be significantly safer compared with SFRs thanks to the high boiling temperature of heavy liquid metals. Since lead and lead-bismuth do not react with air and water, LFR designs can be greatly simplified and, as a consequence, have the potential to offer a significant reduction in the capital cost. However, the major drawback is the corrosion/erosion of the coolant. The selection of suitable materials for the core is still a challenge. The Russian Federation has some experience with LBE cooled reactors for submarines, and has completed the design of BREST-300, a 300 MW(e) lead cooled FR prototype, aiming for a construction start date of 2025. Another design is the SVBR-100, a 100 MW(e) prototype FR cooled with LBE alloy. Belgium is designing a 100 MW(th) fast neutron spectrum subcritical irradiation facility, MYRRHA. Europe is developing a 100 MW(e) LFR demonstrator, ALFRED. Demonstration units are expected to be built in the next decade, with the start of operation on the 2030 horizon. Using feedback from the operation of demonstration plants and subsequent prototypes, commercial deployment is expected after 2040.

6.1.2.4. Gas cooled fast reactors

A GFR is a high temperature, helium cooled fast neutron spectrum reactor with a closed fuel cycle. It aims to combine the advantages of VHTR (high temperatures) and FRs (long term sustainability of uranium resources and waste minimization). The level of technology development is not very mature and major technology challenges need to be overcome, especially in areas such as safety (decay heat removal), high temperature materials, power conversion systems (direct gas turbines/Brayton cycle) and fuel development. Since there is no OPEX on GFRs, an experimental reactor is needed to prove the technology. The experimental reactor then has to be followed by a demonstration plant and a prototype. A few concepts of an experimental reactor are at a very early stage of development and currently the level of research activities is rather low. Commercial offerings of GFRs are expected later than other FRs.

6.1.2.5. Very high temperature reactor

VHTRs rate high on technology viability with ~50 years of OPEX, some of which is with full scale plants. They are primarily dedicated to the co-generation of electricity and high temperature process heat. The original target of an outlet temperature of 1000°C (for hydrogen production) has been lowered to the current target (up to 850°C), where no new material development or qualification is required.

The enhanced safety characteristics have been demonstrated with severe accidents practically excluded (no core meltdown or massive fission product release is possible even in extreme conditions). Designers therefore claim that there is no need for an evacuation zone. Economic viability needs to be shown with the modern modular concepts (the old demonstration plants were not economical). One challenge is that designers need to convince licensing authorities that many expensive active safety systems common in today's operating reactors are not needed; otherwise, VHTRs may not be economically competitive. The acceptance of this philosophy has largely been achieved in the current licensing process of the commercial demonstration plant HTR-PM (high temperature gas cooled reactor pebble bed module) finalizing construction in China. Therefore, this is an important development step. However, achieving the operating temperature of 1000ºC or more for a VHTR would require additional fuel testing and materials development.

The first HTR-PM is scheduled to perform startup commissioning and operation in 2021. It will demonstrate the operability of a multi-module unit (two reactors driving a single power turbine) which will be used in future nuclear power plants. When the HTR-PM is successful, the technology may be available as an international commercial offering in the 2025–2030 time frame. Memoranda of understanding for possible future exports of HTRs have been signed with Saudi Arabia, South Africa, Jordan and Indonesia).

6.1.2.6. Supercritical water cooled reactor

The SCWR is an innovative WCR design which uses most systems from existing WCRs at a higher temperature and pressure. The advantage is an efficiency significantly higher than evolutionary WCRs; the main challenge is related to its complicated reactor core thermohydraulics, which needs R&D and qualification. Several concepts are being developed in China, Canada, Europe, Japan and the Russian Federation. Their designs have been reviewed and their viability has been confirmed. China has the best possibility of deploying an SCWR commercial plant in the future. Taking into consideration that no experimental or demonstration reactor of the SCWR type has been constructed/operated, it will take at least 20 years to start the construction of the first SCWR plant.

6.1.2.7. Molten salt reactor

The MSR is distinguished by its fuel which is dissolved in molten salt, although some designs use solid fuel and molten salt as a coolant. It is attractive in terms of efficiency (higher temperatures), safety (low pressure and fuel in a molten state), sustainability (through a closed fuel cycle with on-line reprocessing, if chosen) and waste reduction. The technology was partly developed and demonstrated in the Molten Salt Reactor Experiment in the United States of America (1965–1969). However, its technical feasibility still needs to be evaluated, especially the long term performance of structural materials in molten salt. Some SMR designers circumvent these potential lifetime issues by using innovative equipment replacements.

Other challenges are the acceptance of its safety case in licensing and also some proliferation concerns. Even if some of the proliferation aspects (e.g. on-line reprocessing) could be resolved technically, politically it may be deployed only in countries which allow reprocessing. Some start-up companies already offer specific MSRs in the market, but no large scale commercial deployment is foreseen before 2030, although demonstration reactors may be operational during this timeframe (a molten salt test reactor is currently being developed in China).

6.1.2.8. Challenges to advance reactor technologies — commercial, licensing and political framework

Technology considerations cannot be seen in isolation from commercial, regulatory and political issues. A few of these issues are highlighted here to support the discussion above.

Large commercial reactor vendors have made significant investments in the current advanced evolutionary reactors (Generation III and III+) that are already in operation, under construction or are currently being offered commercially. These investments not only include the design costs, but also substantial qualification, testing and licensing efforts. Unless the decision is driven by strategic factors, it is clear that these costs need to be recovered from the market before new funds and effort will be devoted to bringing a large number of SMRs or even innovative (Generation IV) designs to the market.

In addition to R&D projects from traditional national organizations and vendors, a considerable number of smaller startup companies are developing concepts and actively seeking development funding.

While large, advanced WCRs are almost always suited for a country's baseload electricity generation, the interest in — and the eventual deployment of — innovative designs is greatly dependent on a country's policy drivers and its technical and infrastructure capabilities. Innovative reactors, including FRs, HTRs and SMRs, may slowly be introduced to niche markets, such as actinide burning (e.g. from PWR spent fuel or plutonium stockpiles), hydrogen production and industrial process heat, and to provide electricity and heat to remote and off-grid locations.

Limited experience is available for the licensing of non-WCRs by current independent regulatory or licensing authorities. Information in this respect is also limited at the IAEA, where safety requirements and guidelines were to a large extent developed mainly for WCRs. Activities have been started on the applicability of current safety standards to advanced reactors. For example, the NRC has started a process to include advanced non-water-cooled technologies (specifically SFRs and HTGRs) in its general design requirements, while China has licensed the HTR-PM, except for the operating licence. Some of these Member State efforts on safety requirements for SMRs, SFRs and VHTRs are being supported by the IAEA.

The current fleet of reactors, including the currently available evolutionary designs, was initially developed with government support and then enhanced over the last 60 years. Other technologies that in the past have reached some level of maturity (HTGRs and SFRs) have also benefited from this model. The development and commercialization of new innovative nuclear power plants will also need some form of government support, either direct or indirect. In deregulated markets the opportunities for these innovative technologies to come to market are extremely limited. It is noteworthy that current projects and those in the last 20 years that have made substantial progress towards this goal have almost exclusively been funded by the government.

6.1.2.9. Micro modular reactors

In the past five years a new development trend has emerged in the field of microreactors that seek to generate power of up to 10 MW(e). Generally included as a subcategory of SMRs, this advanced technology is under development notably in Canada, China, the Russian Federation, the United States of America and several Member States in Europe. Microreactors have some unique characteristics. To a greater degree than other SMRs, they can be more fully fabricated in a factory setting, transported more easily to sites and connected to the end user of electricity and heat. These reactors may be self-regulating, based on inherent and passive safety systems and thus achieve a high level of control and safety with minimal operator actions. They are also not limited to a specific type of moderator, coolant or neutron energy range, and exhibit widely different characteristics. For example, coolants may include helium, lead, air, water, liquid metal and heat pipes. Microreactors are also often loaded for the lifetime of the reactor. For deployment to become a reality, these very small power plants should also have proper security and positive proliferation resistant characteristics.

Microreactors are typically targeted to serve future niche electricity and district heat markets in remote sites (arctic or island communities), mining operations, industries and fisheries, to provide backup power (also for data centres), to serve oil platforms or to be used in maritime shipping. These markets were served by diesel power plants for decades. Compared with SMRs that address energy demand by adding incremental capacity with moderate financial commitment by utilities, microreactors are more focused in these niche markets and will typically compete in a market currently served by diesel generators. Some experts see microreactors as the entry pathway for SMR deployment, especially since the business case may initially be more favourable for them as no other off-grid solutions currently exist and diesel generators are expensive to operate and polluting. This view is also strengthened by the actions taken by vendors and designers in Canada, where five of the 12 pre-licensing vendor design reviews currently reported are by microreactor vendors.

In 2019, a site application was submitted by Global First Power for a single SMR, using Ultra Safe Nuclear Corporation's Micro Modular Reactor (MMR) technology, at the Chalk River Laboratories site in Renfrew County, Ontario[17]. The MMR would produce approximately 15 MW(th) process heat to generate

[17] Micro Modular Reactor Project at Chalk River; https://iaac-aeic.gc.ca/050/evaluations/proj/80182

electrical power and/or heat, over an operating life span of 20 years. The environmental assessment process started in July 2019.

6.1.3. Non-electrical applications of SMRs

There has been growing interest in nuclear co-generation in many countries over the past several years, driven by the integration of advanced nuclear reactor technologies. Among these technologies, SMR designs are gaining more attention in co-generation applications. They are considered an attractive option to enhance energy supply security in newcomer countries that have small grids and less developed infrastructure, and in mature nuclear power countries for remote areas or specific purposes. SMR nuclear co-generation technologies could be key for future freshwater production and energy security worldwide. More recently, several hybrid energy systems (e.g. nuclear and renewable energy configurations) have been under investigation for non-electrical applications, including desalination and hydrogen production.

Furthermore, nuclear co-generation has a key role to play in accordance with the Paris Agreement, adopted in 2015 by the Conference of the Parties to the UNFCCC. The Paris Agreement offers an incentive for nuclear power development because of the recurring five year cycle of plans that must be submitted by signatories for climate action, known as Nationally Determined Contributions. In addition to the CO_2 emission reduction that comes from replacing conventional fossil based energy systems with nuclear power plants, co-generation applications of nuclear energy lead to lower specific emissions, where less emissions per unit of produced products are achieved. This is further enhanced with the utilization of the waste heat of the nuclear reactor. Nuclear co-generation also results in better operating efficiency, better energy utilization, and better grid flexibility, along with being more benign to the environment. Advancement in the technologies towards the recovery and reuse of waste heat for non-electrical applications has increased the potential of nuclear co-generation projects.

Nuclear co-generation for process heat applications can be used in seawater desalination, district heating and cooling in residential and commercial buildings, industrial process heat supply, and fuel synthesis. In fact, several Member States have been using nuclear co-generation for district heating and desalination applications. Practical OPEX in nuclear district heating and seawater desalination has reached a total of ~750 operation-years (as of 2012) from 74 nuclear reactors. The main challenges to the deployment of nuclear co-generation are demonstrating the economic viability and commercialization potential, along with the required licensing of a co-generation plant. The IAEA assists Member States in the demonstration of non-electrical applications of nuclear energy, including nuclear desalination, hydrogen production, district heating, and other industrial applications. Figure 9 shows a summary of SMR designs for non-electrical applications according to their system temperature.

6.1.4. Integration of renewable energy sources with nuclear power

Climate change concerns combined with issues related to the price volatility of energy and the intermittency of renewable resources are reasons for integrating SMRs with renewable energy sources for the production of electricity as well as for non-electrical applications. This configuration represents itself as an optimal case that embraces the advantages of renewables and the stability of nuclear energy. In combination with renewable energy sources, an SMR as a flexible baseload supply has the potential to produce positive synergism among these clean energy options. Flexibility here refers to the ease of use for co-generation of electricity and heat, and easier siting and installation of additional modules when demand increases. This synergy could promote energy supply security to meet the needs of the population and fulfil a number of criteria of energy supply security, i.e. enhancing the diversity of technology and fuel sources, staging environmentally benign resources and technologies, protection against supply disruptions and price volatility, establishment of economic sustainability of supply, and the support of fuel import reduction.

SMRs can also play a stabilizing role in a grid with a large share of renewable sources and contribute to reducing the cost of a low carbon energy supply. They may be combined with solar, wind, tidal, hydro and geothermal power for electricity and non-electrical products such as heat production with the objective of

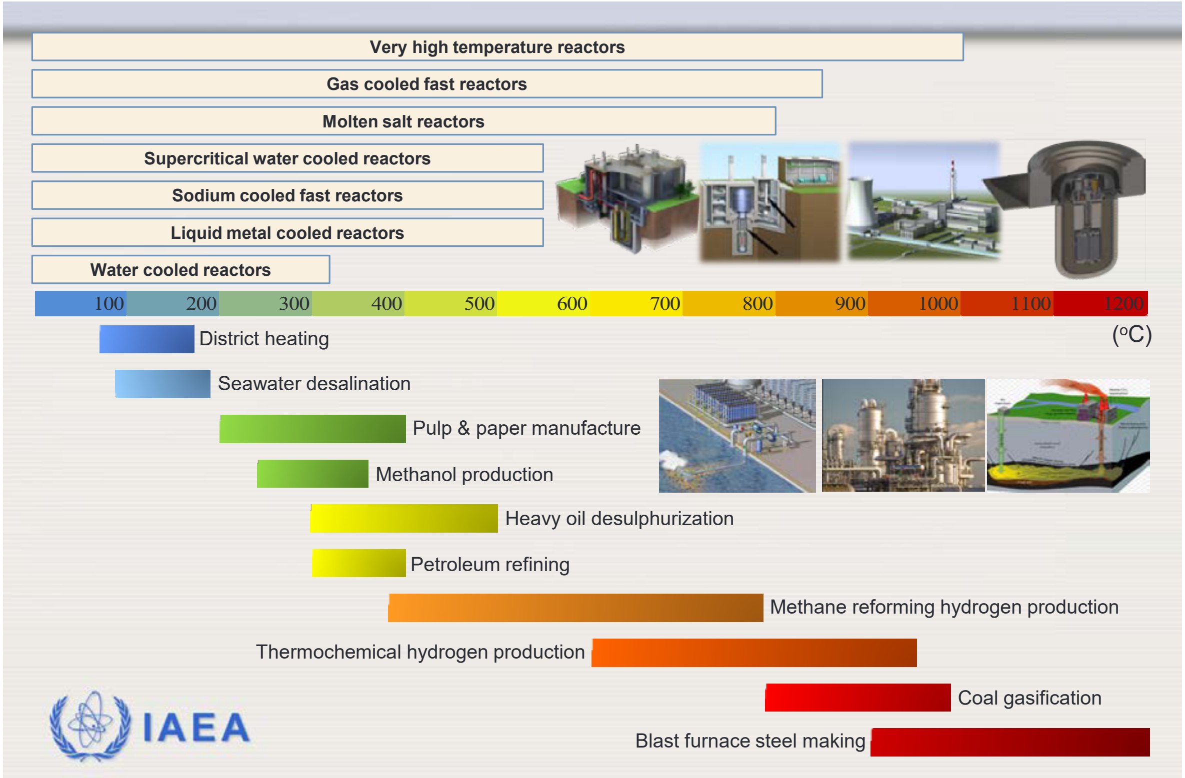

FIG. 9. SMR designs for non-electrical applications according to system temperature.

enhancing energy supply security and balancing supply and demand in Middle Eastern countries with arid environments. Or they can be used in a floating power unit to power northern climates. There are various prerequisites for the development of this kind of hybrid system such as the deployment of a high capacity transmission super grid and storage that would support the large penetration of renewables along with the stable supply of SMRs. These are necessary for handling the intermittency of renewables and guaranteeing the storage of a significant energy baseload. Figure 10 shows a hybrid system of wind power and an HTGR connected to a coal gasification plant.

The synergies between nuclear and renewable energy could be a solution to an energy challenge. The hybrid energy systems are those systems having multiple energy inputs (nuclear and renewables) and multiple products (electricity, fuels, chemicals, and possibly others). The current energy grid employs diverse energy resources to meet demands for thermal energy and electricity. However, these resources are very loosely coupled in most of the present modes of implementation; each production source connects to the grid individually, and their relative input is managed on the large scale grid as a whole. A truly hybrid system would be tightly coupled, requiring an individual subsystem to be operated in an integrated fashion to respond appropriately to a grid level transient. The hybrid system is a new approach to an energy system which could lead to better utilization of resources. Hence it would offer a more attractive alternate energy solution.

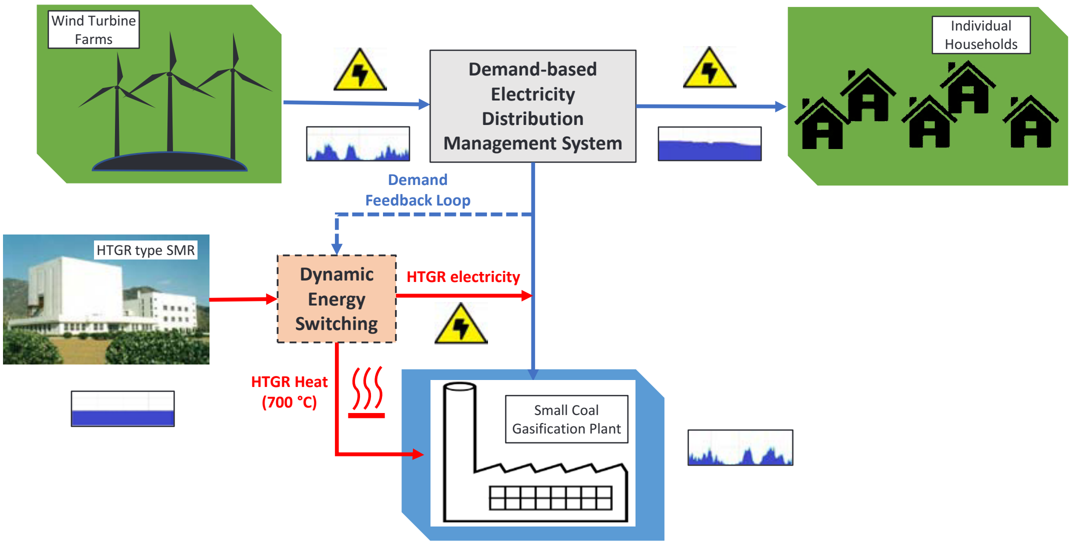

FIG. 10. Hybrid system of wind power and HTGR connected to a coal gasification plant.

7. SUMMARY AND CONCLUSIONS

Given the increasing interest of Member States in the near term deployment of SMRs, this publication presents several model technology roadmaps that States can adapt for their specific projects. For nuclear newcomer countries, these roadmaps assume that a Member State has already developed, or is at least well along the way to developing, the infrastructure necessary to carry out a nuclear power programme.

The concept of modularization is a key feature of SMRs. It generally refers to techniques adopted from other mature industries, such as automotive, shipbuilding and aerospace. These techniques merge quality and efficiency improvements claimed by those industries derived from serial factory manufacturing, standardization of components to the extent practicable, as well as more simplified on-site installations of pre-assembled modules. Modularization technology has also been extensively applied in the construction of large commercial nuclear power plants from the mid-1990s.

Technology roadmaps have proven to be very useful management tools for identifying, evaluating and promoting the development of complex technology projects. More importantly, the development and use of a technology roadmap can accelerate the development of the technology while avoiding unforeseen barriers to product deployment. Technology roadmaps promote enhanced collaboration and sharing of knowledge and help to ensure that efforts (technology developers, industry, users and regulatory bodies) are focused on a common objective. Additionally, for Member States, technology roadmaps can inform science and technology policy decisions and investments across government and industry in terms of loan guarantees and incentives, industry lead initiatives and human resource development.

For the project planning technology roadmap for an owner or licensee, the plan is divided into eight major activities that are set within the overall structure, identified by the IAEA's Milestones approach that was developed to assist countries considering or planning their first nuclear power plant. The Milestones approach identifies three major phases. Phase 1 focuses on the considerations related to a nuclear power programme before a formal decision was made to launch it. Phase 2 focuses on the preparatory work necessary to begin contracting and construction activities, while Phase 3 focuses on the activities associated with fully implementing a nuclear power project (i.e. contract award, siting and construction).

The project planning roadmap for a reactor plant designer/supplier stipulates that reactor designers intending to embark on the design of an SMR have to go through a concise process that addresses the following issues: technology user's requirements and priorities; technology (coolant and neutron spectrum) to be developed; the applications for this new reactor technology; and the distinctive features, relative to existing large nuclear reactors, and why these will be attractive to the marketplace. Addressing these issues will require the engagement of electrical utilities and governments to better understand their specific needs and nuclear related policies.

On the project planning roadmap for regulatory bodies, a versatile regulatory framework establishes requirements and guidance that can be applied broadly, regardless of technology types being considered. Each requirement should be clearly tied back to fundamental safety principles but also provide sufficient guidance to understand how the requirement can be judged to be met under different circumstances. Since SMR technology includes a wide range of reactor technologies and designs, it is important that regulators be well prepared to assess the safety and security of advanced technologies, including very high temperature reactors and MSRs. Both the regulator and the environmental agency also need to consider the implications of using different fuel cycles and fuel technology other than those currently being used. Depending on the choice of SMR technology, having a regulator ready to assess the safety and security implications of various reactor technologies could be an indicator of the level of readiness of a country to embark on the deployment of a fleet of SMRs.

The development of innovative reactor technology will require longer development timelines, with efforts focused on identifying and resolving technology gaps. This publication presents a systematic methodology to define a set of prioritized work packages, and identifies government and international collaborative efforts that will assist in the development of new reactor technologies.

SMR technologies are also gaining more attention for co-generation applications. They are considered an attractive option to enhance energy supply security in newcomer countries with small grids and a less developed infrastructure, and in mature nuclear power countries for remote areas or specific purposes. SMR nuclear co-generation technologies are expected to play important roles for future freshwater production, industrial process heat, hydrogen production and energy security worldwide. More recently, several hybrid energy systems (e.g. nuclear and renewable energy configurations) have been under investigation for non-electrical applications, including desalination and hydrogen production.

Climate change concerns combined with issues related to the price volatility of energy and the intermittency of renewable resources have provided an incentive to consider integrating SMRs with renewable energy sources for the production of electricity as well as for non-electrical applications. As such, this can be considered an optimal case that combines the advantages of renewables with the stability of nuclear energy. As a hybrid with renewable energy sources, SMRs as a flexible baseload supply have the potential to lead to a positive synergism among these clean energy options. The synergy aims to promote energy supply security to meet the needs of the population and ensure the security of energy supply.

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Annex

REVIEW OF SMR DESIGNS IN OPERATION OR UNDER CONSTRUCTION

This Annex provides a summary of the three SMRs that are currently in operation or under construction around the world with an emphasis on design and safety features; approach to licensing; financing; roadmap; and lessons learned. The three designs are presented alphabetically according to the country of origin (Sections A–1 to A–3). Section A–4 provides a global SMR deployment map and an example of a deployment schedule.

A–1. INTEGRAL LIGHT WATER REACTOR (CAREM) (ARGENTINA)

In 1984, Argentina's Comisión Nacional de Energía Atómica (CNEA), in collaboration with leading nuclear companies in Argentina, officially launched the Central Argentina de Elementos Modulares (CAREM) project. CAREM was one of the first concepts to fully integrate the pressurizer, control rod drive mechanisms (CRDM), and 12 mini-helical, once-through steam generators (SGs) inside the reactor pressure vessel (RPV). Because of its innovative integration of major PWR components into a single unit, this particular concept has been referred to as an integral pressurized water reactor (iPWR) and is now the basis for several designs around the world. A 27 MW(e) prototype plant is currently under construction to validate the innovative technologies, prove the licensing approach and study reliability issues. CNEA envisions that the prototype will be followed by construction of a larger version, providing an electrical power output of between 100 and 200 MW(e).

A–1.1. Design overview and key safety features

The key plant parameters associated with the CAREM prototype are summarized in Table A–1. The location of the SGs above the reactor core, combined with the relatively long RPV, promotes a natural circulation driving force that creates a coolant flow in the primary circuit. The integral design eliminates the chance of a large break loss of coolant accident (LBLOCA) by removing primary circuit pipework from the design. A LOCA condition could lead to a severe accident in older plant designs, requiring significant redundant safety systems to mitigate the related consequences. The use of natural circulation and passive cooling systems for decay heat removal eliminates severe accidents related to a station blackout condition.

Because the pressurizer is located at the top of the RPV, the pressurizer, core outlet and dome temperatures are all near the saturation temperature. Under all operating conditions, this has proved to be sufficient to guarantee the required stability performance of the reactor coolant system. The control system has been designed to keep the reactor pressure at an operating point during different transients, even in the case of power ramps. The negative reactivity feedback coefficients, the plant's relatively large water inventory and the self-pressurization features make this possible with minimal control rod motion.

Water within the secondary circuit flows upwards inside the SG tubes, while the primary coolant water circulates in a counter-current flow downwards through the helical once-through SG tubes. The size of the coolant nozzles entering the RPV is limited to 12 coaxial cross-tubes within each nozzle so as to separate hydraulic connections for feedwater inlets and steam outlets through vertical SGs. This design also serves to eliminate the probability of an LBLOCA. The secondary system piping is similar to those of PWRs. To provide pressurized feedwater to the inlet of the 12 SGs through hydraulic connections within the steam nozzles, electrically driven feedwater pumps are employed.

TABLE A–1. MAJOR TECHNICAL PARAMETERS OF CAREM

Parameter	Value
Thermal capacity (MW(th))/electrical capacity (MW(e))	100/~30
System pressure (MPa)	12.25
Coolant inlet/outlet temperature (°C)	284/326
Coolant/moderator	Light water
Primary circulation	Natural circulation
Main reactivity control	CRDM only
Coolant flow rate at rated power (kg/s)	410
RPV height/diameter (m)	11/3.2
Power conversion process	Indirect Rankine cycle
Fuel type/assembly array	UO_2 pellet/hexagonal
Number of fuel assemblies	61
Active fuel length/core diameter (m)	1.4/1.2
Fuel enrichment (%)	3.1 (prototype)
Fuel cycle (months)/burnup (GW·d/t)	14/24 (prototype)
Number of safety trains	2
Emergency safety systems	Passive
Residual heat removal systems	Passive
Modules per plant	1
Estimated construction schedule (months)	~36
Seismic design (g)	0.25
Design life (years)	40
Design status	Under construction (as prototype)

The defence in depth (DiD) concept employed in the CAREM design is consistent with the proposal from the Western European Nuclear Regulators Association (WENRA) and includes clarification on multiple failure events; severe accidents; independence between levels; the use of the scram system in some DiD Level 2 events; and containment in all the protection levels. The safety systems consist of two reactor protection systems; two independent safe shutdown systems (scram and boron injection); a passive residual heat removal system; safety valves; a low pressure injection system; a depressurization system; and a containment of the pressure suppression type.

Many intrinsic characteristics contribute to the preclusion of typical LWR initiating events, such as LBLOCAs, loss of flow accidents, boron dilution and control rod ejection. The safety systems are duplicated to fulfil the redundancy criteria, and the shutdown system is diversified to fulfil regulatory requirements. CAREM safety systems incorporate passive features so that neither AC power nor operator action is required to mitigate any postulated events during the specified 36 h grace period. The core decay heat removal system can ensure safe core temperatures in the case of loss of heat sink or station blackout during the 36 h grace period, assuming redundancy failure. Severe accident prevention measures for periods that exceed this grace period allow the use of simple systems supported by the fire extinguishing system or external pumps and containment protection. To mitigate the consequences of a beyond design basis accident, provisions have been included in the design to control hydrogen gas (passive autocatalytic recombiners) and for cooling the lower head of the RPV for in-vessel corium retention.

A–1.2. Approach to licensing and regulatory acceptance

As in many countries with nuclear power reactors, the Argentine regulatory body has established regulatory standards relating to radiation and nuclear safety, physical protection and the control and use of nuclear material, licensing and inspection of nuclear facilities, international safeguards, and transportation of nuclear material in all aspects regarding nuclear, radiation safety and physical protection. These standards are performance based and, instead of being a prescriptive, deterministic based approach to regulation, they are focused on defining compliance with safety and security goals. Explaining how these goals are achieved is the responsibility of the reactor plant licensee who is also responsible for the design, construction, commissioning, operation and decommissioning of the reactor plant. The licensee is expected to demonstrate to the regulator that the technical means employed fully meet the safety and security goals as stated in the standards.

The licensing process for the construction of CAREM, a prototype, was approved by the Argentine regulatory body (Autoridad Regulatoria Nuclear (ARN)) in 2010. The process is based on a staged approach: siting and construction, fuel loading, subcritical testing, first criticality, zero power tests, power testing, and full power testing [A–1]. In addition, each stage requires specific approval by ARN, which is given based on the review of specific technical details. A preliminary safety analysis report and quality assurance (QA) manual have been submitted to ARN for review. In September 2013, based on a review of the documentation, ARN authorized the start of the first stage of construction (Stage 1 approval), which is primarily associated with non-nuclear auxiliary buildings. In December 2014, ARN gave authorization to start construction of safety related buildings and containment structures (Stage 2 approval).

A Level 3 probabilistic safety assessment has been prepared to provide insights into the relative importance of accident prevention and mitigation measures expressed in terms of adverse consequences to public health and the contamination of land, air, water and food provisions. In addition, it provides insights into the relative effectiveness of aspects of accident management related to emergency response planning and emergency planning zones.

Operation of the prototype, under a provisional licence, will allow valuable engineering data to be gathered and OPEX to be gained. The engineering data will support design validation efforts and the OPEX will provide insights into potential reliability issues, as well as allowing validation of plant operating procedures and emergency procedures.

In Argentina, the use of land is under the jurisdiction of the provinces according to the national constitution. The non-radiological environmental impact assessment (EIA) is under the jurisdiction of the provinces and a provincial permit is needed for industrial facilities. To receive this permit, the application authority of Provincia de Buenos Aires (OPDS) requires an EIA to be prepared and signed by registered professionals. The Universidad Tecnológica Nacional, Facultad Regional Avellaneda (UTN-FRA), conducted an EIA for the CAREM reactor prototype. The EIA was presented to the authorities in 2012, and in October 2013 the OPDS issued the Certificado de Aptitud Ambiental through resolution 233.

A–1.3. Fuel cycle and waste management

Argentina has made no decision with regard to an open or closed fuel cycle policy. Since CAREM uses enriched fuel, enrichment services are required as part of the front end of the fuel cycle to support the reactor. Irradiated fuel will be typical of other spent LWR fuel and will eventually need to be dealt with according to Argentina's disposal and/or reprocessing policies. In the near and medium term, the irradiated fuel will be stored in the reactor plant's spent fuel pool and can eventually be moved into dry storage canisters. Due to the relatively low fuel burnup there will be a larger quantity of spent fuel with lower decay heat to manage per unit of electricity generated.

Argentina's national laws require the creation of a trust fund to support nuclear power plant decommissioning and management of medium and high activity radioactive waste. The trust funds are required to be set up by the generators of nuclear electricity. CNEA is responsible for enforcing the radioactive waste management law and has created a fund for the final disposal and management of radioactive waste. With regard to the final disposal of high level radioactive waste, during the 1980s CNEA began a feasibility study for the construction of a deep geological repository in stable granite formations which were located in low seismic regions with scarce hydraulic conductivity. However, as a consequence of low public acceptance, studies were suspended for the desired location and it was not possible to locate other favourable regions in the rest of the country. Today, activities dealing with the treatment of high level waste are focused on research and economic feasibility studies related to the transmutation of radionuclides to reduce the radiotoxicity associated with high level waste and to shorten the very long isolation times associated with irradiated fuel.

A–1.4. Relationship to feasibility studies and energy scenarios

As discussed previously, one of the key steps towards establishing a new nuclear power programme, or in planning an expansion of an existing fleet, is to commission a feasibility study. The study assesses all aspects of the energy demand in a country or geographical area in order to place the nuclear project in its proper context. In accordance with guidance found in Ref. [A–2], a project specific feasibility study should be undertaken to focus on new information and risks that may not have been included by the nuclear energy programme implementing organization (NEPIO) in its pre-feasibility study which provided direct input into the national energy strategy. The IAEA has created a series of analytical tools and methodologies to aid the development of a feasibility study [A–3].

Laws have been passed in Argentina with the aim of decreasing the use of fossil fuels and encouraging rational use of energy. These laws propose a series of objectives and mechanisms of promotion, and recognize the importance of using every energy source in the integration of the national energy mix. The main goal of Argentina's national energy policy is to diversify the matrix of power generation technologies, to include a greater percentage of carbon free nuclear power, hydropower and renewable energies.

While the CAREM project was first sanctioned by legislation in 1999, it was not until 2009 that the legislation was enacted to design and commission a prototype reactor. The aim is to demonstrate its technical and economic viability as a possible future means of diversifying Argentina's carbon-free energy mix.

Additionally, the project's stated objective is to recover and develop nuclear expertise and to create infrastructure and the suppliers needed with the aim of developing large complex nuclear projects after years of not having actively pursued such projects.

A–1.5. Financing and economics

In 2005, CNEA estimated the cost of the CAREM project to be ~US $105 million (61% materials and hardware and 29% design and engineering services), and it expects to recoup the initial investment in engineering development within the first 15 years by selling future units. As of May 2015, CNEA refined the prototype's cost estimate to be about US $430 million for infrastructure development, licensing, construction and commissioning. Given the current emphasis on building the CAREM prototype, CNEA has provided less information about the cost and economics of commercializing larger modules. However, the target for a 200 MW(e) nuclear power plant is to have an overnight cost of US $5500/kW(e) and, according to CNEA, studies have shown the feasibility of meeting this goal. The target for levelized cost of electricity is 9.5 cents/kW·h.

A–1.6. CAREM technology roadmap

The licensing process to support construction of the CAREM prototype was established in 2010 and site construction began in September 2014. The first criticality is currently scheduled for 2023. Based on the experience developed with this prototype reactor, commercial modules will be designed with power levels of up to 200 MW(e) and will rely on natural circulation core flow. The construction of the first CAREM commercial unit at Formosa Province is under consideration. Siting and optimal size studies have been performed. There are plans to develop higher power modules of up to 300 MW(e) using forced circulation to achieve the flow rate needed to operate at full power.

1984	The CAREM concept was one of the first of the new generation reactor designs. CNEA officially launched the CAREM project
2001–2002	The design was evaluated at a GIF meeting and selected in the near term development group
2006	The Argentina Nuclear Reactivation Plan listed the CAREM project among the priorities for national nuclear development
2009	CNEA submitted its preliminary safety analysis report for CAREM to the ARN. An announcement was made that Formosa Province in Argentina was selected to host CAREM
2011	The startup of a high pressure and high temperature loop for testing the innovative hydraulic control rod drive mechanism (CAPEM)
2011	Site excavation work began and discussion on contracts and agreements between stakeholders began
2012	Civil engineering works began
2014	Formal start of construction on 8 February
2023	First criticality

A–1.7. Major impediments, outstanding issues and lessons learned

The preparation of licensing documentation and the development/approval of pertinent qualification tests are important and complex tasks. Additionally, the development of an organization with appropriate human resources to support the design and construction of a new nuclear power plant requires significant effort and management oversight. Resources to support the development and qualification of suppliers should be started early and given high priority. Hence, in summary, important factors in the deployment of CAREM are the following:

- Adequate licensing documentation;
- Human resource development;
- Qualified suppliers.

A–2. HTR-PM GAS COOLED REACTOR (CHINA)

China started its R&D programme on high temperature gas cooled reactors (HTGRs) in the 1970s. In 1992, the Chinese Government approved the construction of a small high temperature gas cooled test reactor (HTR-10) and in January 2003 the reactor reached full power (10 MW(th)) operation. Since that time, Tsinghua University's Institute of Nuclear and New Energy Technology (INET) has used the HTR-10 to conduct experiments and verify crucial inherent safety features associated with modular HTRs, including:

- Loss of off-site power without any countermeasures;
- Main helium blower shutdown without any countermeasures;
- Withdrawal of control rod without any countermeasures.

China's next step in HTGR development began in 2001 when the High Temperature Gas Cooled Reactor–Pebble Bed Module (HTR-PM) project was launched. In 2006, the project became part of the top 16 priority projects for the Chinese Science and Technology Plan for the period 2006–2020. The HTR-PM will be a commercial demonstration plant for electricity production. Compared with the HTR-10, the components for the HTR-PM have been scaled up, although the design bases are similar. The construction of this reactor commenced in December 2012 in China's Shandong Province. The first HTR-PM is scheduled for startup commissioning and operation in 2021.

A–2.1. Design overview and key safety features

The key plant features of the HTR-PM are summarized in Table A–2. The primary circuit consists of the RPV, the SG pressure vessel and the hot gas duct vessel connecting the two in a side by side arrangement. The 250 MW(th) core comprises a bed of 6 cm diameter fuel elements enclosed by a ceramic cylindrical shell which acts as a reflector, heat insulator and neutron shield. Coolant channels are designed within this shell. A control rod system and a small absorber sphere system provide two independent control systems of reactivity.

The HTR-PM uses an indirect Rankine cycle. The main helium blower, designed as a vertical structure, is installed at the top of the SG inside the SG pressure vessel. Helium flows upwards through the coolant channels before returning down over the pebble bed of fuel and passing to the SG. The SG is a vertical, counter-flow, once through generator with a helium–water interface producing superheated steam.

In the HTR-PM demonstration plant two reactor modules (each with their own SG) are connected to a single turbine generator set. This configuration will allow the developer to fully demonstrate the feasibility of connecting multiple modules to a single turbine. Future commercial deployment of the HTR-PM is likely to connect as many as six modules together to a single turbine.

The HTR-PM utilizes the Tri-structural Isotropic (TRISO) coated microsphere fuel particles that were originally conceived in the United Kingdom as part of the DRAGON project. They are formed into billiard sized spherical fuel elements (i.e. pebbles). The various layers of the TRISO fuel element include a porous carbon buffer layer and two dense pyrolytic carbon layers, separated by a silicon carbide layer. The use of pebble fuel elements allows continuous fuel loading and discharge. The fuel elements are dropped into the reactor core from a central fuel loading tube and are discharged through a fuel extraction

TABLE A–2. MAJOR TECHNICAL FEATURES OF THE HTR-PM

Feature	Value
Thermal capacity (MW(th))/electrical capacity (MW(e))	500 (2 × 250)/210
System pressure (MPa)	7.0
Coolant inlet/outlet temperature (°C)	250/750
Coolant/moderator	Helium/graphite
Primary circulation	Forced circulation
Coolant flow rate at rated power (kg/s)	96
Main reactivity control	Control rod insertion
RPV height/diameter (m)	25/5.7 (inner)
Power conversion process	Indirect Rankine cycle
Core type/diameter/height (m)	Pebble bed core/3.0/11.0
Fuel type	Pebble bed with spherical coated particle fuel
Fuel sphere diameter (cm)	6.0
Number of fuel spheres	420 000 (in each reactor module)
Fuel enrichment (%)	8.5
Fuel cycle (months)/burnup (GW·d/t)	n.a.*/90 On-line refuelling, average fuel pebble remains in the core for ~35 months
Number of safety trains	n.a.*
Emergency safety systems	Control rod insertion; circulator trip; isolation of secondary circuit; drain of steam generator in the case of steam generator tube break
Residual heat removal systems	Passive
Modules per plant	Up to possibly six reactor/SG modules feeding a single turbine generator set
Estimated construction schedule (months)	59 months for the first unit
Seismic design (g)	0.2
Design life (years)	40
Design status	Under construction (prototype)

* n.a.: not applicable.

pipe at the core bottom. Subsequently, the discharged fuel elements pass a burnup measurement facility one by one and, depending on their fuel burnup, they are either discharged and transported into the spent fuel storage tank or reinserted into the reactor to pass through the core again. On average, fuel spheres are circulated 15 times through the reactor.

The HTR-PM design utilizes inherent safety features and passive core cooling systems. The relatively low power density, excellent demonstrated fuel performance and a balanced system design ensure that the fundamental safety functions are maintained.

A large negative temperature coefficient is ensured under all operating and accident conditions. The three layer coatings on each fuel kernel act as the first barrier against release of radioactive fission products. Tests have shown the fuel elements to be capable of retaining fission products when subjected to temperatures of up to 1620°C. This temperature is not expected under any plausible accident scenario. The second and third barriers to release are the primary pressure boundary and the reactor building. These barriers provide defence in depth.

Under accident conditions, the primary helium circulator is stopped. Due to the low power density and the large heat capacity of the graphite reflector structure, the decay heat in the fuel elements can dissipate to the outside of the RPV by means of heat conduction and radiation within the core's internal structure without leading to fuel temperatures which exceed the thermal design limits of the fuel. These factors combine to eliminate the possibility of a core melt accident and associated releases of radioactivity into the environment. Consequently, there is no need for emergency core cooling system(s) in the design. The safety margins during both normal operation and accident conditions are large (several hundred degrees in temperature).

Due to the passive nature of the safety systems, if accidents occur, a limited number of reactor protection actions will be initiated by the reactor protection system to trip the reactor and helium circulator and isolate the primary and secondary systems. Little or no operation intervention is required.

Another feature of the HTR-PM design is the long time period of accident progression due to the large heat capacity of fuel elements and graphite structures within the RPV. As a result, it takes days for the fuel elements to reach the maximum temperature if coolant is completely lost.

A–2.2. Approach to licensing and regulatory acceptance

The National Nuclear Safety Administration (NNSA) under the China Atomic Energy Authority (CAEA) was set up in 1984 and is the licensing and regulatory body which also maintains international agreements regarding safety. NNSA is responsible for the licensing of 11 nuclear reactors and other facilities, their safety inspections and reviews, operational regulations, licensing transport of nuclear material, waste management and radiation protection, including sources and naturally occurring radioactive material.

The licensing authority was engaged early in the HTR-PM project. Important licensing criteria, codes, standards, safety goals and key anticipated licensing issues were documented, reviewed and accepted by the licensing authority before the formal start of licensing. The preliminary safety analysis report for the HTR-PM was accepted by the licensing authorities during 2008–2009 and the first concrete was poured in December 2012. The final safety analysis report assessment is expected in time for the first operation in 2021.

A–2.3. Fuel cycle and waste management

Currently, the HTR-PM design uses low enriched uranium (8.5%) as its fuel within the spherical (TRISO) ceramic coated particle fuel elements. In general, each of these contains coated fuel kernels of 200 µm UO_2, UC_2 or UCO but, in theory, the kernels could contain plutonium (if a MOX recycle option was selected). For HTR-PM, each coated fuel kernel has a diameter of 0.92 mm. Each spherical fuel element has a diameter of 60 mm, which includes a 5 mm thick fuel free region. The HTR-PM is also capable of using the thorium–uranium fuel cycle, if required in future, which is an attractive option for China due to its large thorium reserves.

The HTR-PM demonstration plant will use a once through fuel cycle. During reactor operation, the fuel elements go through the reactor in a multi-pass mode before reaching a specified discharge burnup and being discharged into storage tanks. The spent fuel will be stored on-site for a certain period before being moved to a centralized storage facility in the future. Final long term waste disposal and packaging certification for pebble fuel elements have not yet been demonstrated.

A–2.4. Relationship to feasibility study and energy scenarios

The HTR-PM project forms part of China's plans for continued growth in its nuclear power generation. China has a rapidly growing economy and associated growth in its energy demand. It also faces shortages in electricity, coal and oil supplies as well as environmental pressures relating to atmospheric pollution and climate change. This has contributed to China's commitment to expand its domestic nuclear power generation — a State Council published action plan has stated that it plans to increase its nuclear generation capacity from 19 GW(e) to 58 GW(e) by 2020.

The HTR-PM technology in particular is being developed as a power source for co-generation and process heat applications, location in arid regions that are more constrained in terms of water supply, and producing hydrogen as a fuel in the future.

A–2.5. Financing and economics

The first HTR-PM demonstration plant is fully funded by the Chinese Government. However, the focus of this government supported demonstration plant is to prove that a cost overrun during the construction period will be avoided and that the predicted smooth operation and performance will be maintained. Hence, this demonstration plant is intended to show that follow-on HTR-PM plants can be competitive in terms of cost as compared with conventional LWR plants without any government support.

A–2.6. HTR-PM technology roadmap

2001	Launch of commercial HTR-PM project
2004	Standard design of HTR-PM started
2006	HTR-PM demonstration power plant approved as one of the National Science and Technology major projects
2006	Huaneng Shandong Shidaowan Nuclear Power Co. Ltd, the owner of the HTR-PM, established by the China Huaneng Group, the China Nuclear Engineering Group Co. and Tsinghua University
2006–2008	Basic design of the HTR-PM completed
2009	Assessment of the HTR-PM preliminary safety analysis report completed
2012	First pouring of concrete of HTR-PM
2013	Fuel plant construction started

2014	Qualification irradiation tests of fuel elements completed
2015	Civil work of reactor building finished
2016	RPV and core barrel, etc., delivered, installation of main components ongoing
2017	Fuel plant achieved expected production capacity
Q4/2020	Startup commissioning test of primary circuit
2021	Commercial/demonstration operation

A–3. BARGE MOUNTED LWR (KLT-40S) (RUSSIAN FEDERATION)

The KLT-40S is a PWR developed for a barge mounted nuclear power plant and provides 35 MW(e) per module (Table A–3). The design is based on the commercial KLT-40 marine propulsion plant and is an advanced version of the reactor, which historically provided power to icebreakers under more severe conditions when compared with stationary nuclear power plants. The floating nuclear power plant is being manufactured in shipyards and can be delivered to customers as fully assembled, tested and ready for operation. This approach eliminates the need to build special transportation links and preparatory infrastructure, which are required for land based nuclear plants. Ideal locations are in protected coastal areas where robust environmental siting studies and evaluations of external hazards (e.g. tsunamis and hurricanes) have been completed. To ensure adequate cooling, the floating power unit (FPU) must be moored in 12–15 m of water with a footprint of almost 30 000 m². Underwater cables will be needed to connect the plant to the local grid. Large scale maintenance activities can be performed in the Russian Federation using the existing infrastructure and highly skilled labour. Refuelling can be done on-site using specially configured refuelling ships.

Construction of a prototype FPU was completed in the shipyard of the JSC Baltiysky Zavod in St. Petersburg in 2017. The prototype was moored in Pevek, the northernmost town in the Chukotka region of the Russian Federation, and full operation started in December 2019.

A–3.1. Design overview and key safety features

The major components, RPV, pressurizer, SGs and reactor coolant pumps, are connected with very short piping runs to mitigate the possibility of an LBLOCA. The reactor utilizes a four loop system with forced and natural circulation, a pressurized primary circuit with canned motor pumps and leaktight bellow type valves, a once through coiled SG, and passive decay removal systems.

The steam lines, while exiting from the SGs, are routed through containment to a set of steam admission valves, and finally into the turbine building for electricity conversion. Co-generation equipment can be modified to the medium–low temperature heat process concept if one or multiple separation heat exchangers are positioned between the primary and secondary loops. The KLT type configuration is comparable with that of a VBER-300 reactor design; the difference is that each reactor coolant pump is directly connected to the RPV. This design configuration allows the coolant to flow under pressure from the reactor coolant pumps, down the sides of the RPV, and from the bottom of the RPV up through the reactor core and then into the SGs.

The emergency protection CRDM is an electromechanical type actuator consisting of a rack mechanism with a spring, asynchronous motor and an electromagnet. During a plant malfunction, loss of

TABLE A–3. MAJOR TECHNICAL FEATURES OF THE KLT-40S

Parameter	Value
Thermal capacity (MW(th))/electrical capacity (MW(e))	150/30
System pressure (MPa)	12.7
Coolant inlet/outlet temperature (°C)	280/316
Coolant/moderator	Light water
Primary circulation	Forced circulation
Main reactivity control	Control rods only
Coolant flow rate at rated power (kg/s)	—*
RPV height/diameter (m)	4.8/2.0
Power conversion process	Indirect Rankine cycle
Fuel type/assembly array	UO_2 pellet/hexagonal
Number of fuel assemblies	121
Active fuel length (m)/core diameter (m)	1.2/
Fuel enrichment (%)	18.6
Fuel cycle (months)/burnup (GW·d/t)	30–36/45.4
Number of safety trains	2
Emergency safety systems	Active and passive
Residual heat removal systems	Passive; requires seawater
Modules per plant	2
Estimated construction schedule (months)	48
Seismic design	9 point on the MSK scale
Design life (years)	40
Design status	In operation since December 2019

* —: Data not available.

site power, or as a result of an operator action, the neutron absorbing control rods are rapidly inserted into the core to safely shut down the reactor.

The KLT-40S is designed with proven safety solutions such as a compact structure of the SG unit with short nozzles connecting the main equipment, small diameter primary circuit pipelines, and proven reactor emergency shutdown actuators based on different operation principles. The emergency heat removal systems are connected to the primary and secondary circuits. This eliminates weak design points based on the experience of prototype operation, and use of available experimental data, certified computer codes and established calculation methodologies.

Both passive and active systems are used to ensure safety. Safety systems are physically separated and independent. During normal operation, active core cooling is achieved through the SG heat exchangers with decay heat removal accomplished through the condenser, which in turn is cooled by ambient sea or lake water. In the event of a shutdown, passive cooling trains with onboard water tanks and built-in heat exchangers ensure reliable cooling for up to 24 hours. Actuation of the system is performed by special devices with a passive actuation — hydraulically operated pneumatic valves. In the event of a longer shutdown, decay heat is removed through two active and independent cooling trains that make use of the primary circuit purification system's heat exchanger which is thermally coupled with a third independent circuit exchanging heat energy with ambient sea or lake water.

The KLT-40S safety systems installed on FPUs are distinctive from those applied to land based installations in the security of water areas surrounding the FPU, anti-flooding features and anti-collision protection.

A–3.2. Approach to licensing and regulatory acceptance

In 2002, an EIA associated with the proposed moorage site in Pevek was approved by the Russian Federation's Ministry of Natural Resources. In 2003, the first KLT-40S FPU received a construction licence from Rostechnadzor — the Russian Federation's nuclear regulator. In July 2019, the Akademik Lomonosov FPU, which is operated by two KLT-40S reactor modules, received an operating licence from Rostechnadzor.

A–3.3. Fuel cycle and waste management

The fuel makes use of improvements in nuclear fuel and in the fuel cycles of nuclear, icebreaker reactors, spent fuel reprocessing and an increase in fuel burnup through the development and use of a dispersion based fuel.

One of the advantages foreseen by the FPU based ATES-MM under construction is long term autonomous operation in remote regions with a decentralized power supply. The design requires refuelling after every three–four years of operation. In order to maintain a high capacity factor, refuelling is performed 13 days after reactor shutdown, when the levels of residual heat released from spent fuel assemblies are still high.

The fresh and spent fuel storage is either located in the central pontoon between the reactor plant or in a dedicated pool. In all the FPU configurations, spent nuclear fuel is stored in a special pool for at least three years and then removed from the floating plant by a special ship. Shipping casks with spent fuel are handled by a bridge crane designed to transfer the casks between the floating station and the special spent fuel transport ship. Solid and liquid radioactive wastes (radwaste) produced at the plant are also removed by casks together with the spent fuel.

The development and production of a new type of cermet fuel for use in the KLT-40S reactors began in 2009. That same year, Mashinostroitelny Zavod (MSZ) successfully tested steel casks for the storage and transport of KLT-40S fuel.

A–3.4. Financing and economics

The resources for the development of the KLT-40S FPU are provided in the 1998 federal programme on the 'development of nuclear engineering in the Russian Federation in 1998–2005 and with an outlook to 2010'. In 2002, a new programme, 'Energy-Effective Economy of the Russian Federation in 2002–2005 and with an Outlook to 2010' confirmed federal support for its continued development.

As mentioned earlier, the target market of the floating plant is users in remote and difficult to reach sites and locations (e.g. permafrost regions), where construction of large nuclear plants is not feasible (or would be very expensive). Taking into account operating and fuel costs, the per kW·h costs for the FPU plant in such regions are estimated to be significantly lower than for fossil alternatives despite the higher capital costs.

It is expected that KLT-40S FPUs will have the following economic advantages:

- FPUs can be serially manufactured in shipyards and delivered to a customer fully assembled and ready for operation.
- FPUs are based on a proven design; the layout of the reactor system is compact and modular.
- Less capital is needed to prepare an FPU's docking area as compared with a land based nuclear power plant.
- Shorter construction periods (anticipated to be four years), reduced long term financing costs.
- Reduced operating costs due to fewer on-site employees.
- Simplicity of the decommissioning process.

The delivery of an FPU assembled in a controlled factory environment, fully tested and delivered as a turnkey power plant might prove to be a cost effective option. Deployment of such an FPU would only require interconnection with the bulk power grid through simplified switchyard connections bridging the FPU with existing local grids. The sites eligible for such applications could already be industrially developed. Furthermore, they might have power ratings for local grid interconnection nodes that do not require grid upgrades, as the FPU based stations generally do not represent a large baseload generator (compared with large nuclear power plants).

According to original cost estimates by OKBM (Experimental Design Bureau of Mechanical Engineering), overnight capital investments are estimated to be between US $3500 and US $4000/kW(e) and the levelized cost of electricity is projected to be around US $0.05 /kW·h. The calculations are based on the 40 year plant service life and a four year construction timeline.

A–3.5. KLT-40 technology roadmap

1998	The first project to build a floating nuclear power plant was established
2002	The EIA was approved by the Ministry of Natural Resources of the Russian Federation
2006	After several delays the project was revived by Minatom (Ministry of Nuclear Energy of the Russian Federation)
2012	Pevek was selected as the site for the installation of the nuclear power plants. JSC Baltiysky Zavod undertook charge of construction, installation, testing and commissioning the first FPU
2017	Completion of construction and testing of the FPU at the Baltic shipyard

2018	Dockside trials, fuelling, completion of final tests with the reactor core, attainment of reactor first criticality
Mid-2019	Transport of the FPU to the town of Pevek
2019	Connected to the grid on 19 December in Pevek
2020	Fully commissioned on 22 May

A–4. SMR DEPLOYMENT MAP AND ESTIMATED DEPLOYMENT SCHEDULE

Figure A–1 shows a global map of SMR technology developers to illustrate not only the many designs being pursued, but also the involvement of many Member States, some not traditionally involved as vendor States for the current fleet of nuclear power plants. The map is by no means complete, but is based on interactions with Member States and designers with the IAEA in the area of technology development. Many other SMR designs are also under development.

Figure A–2 gives examples of SMR deployment timelines. For the first three SMR designs (in operation and at an advanced stage of construction), the commissioning and operational time frames are based on actual project schedules.

Turning to the next three examples, the construction of the ACP 100 is to begin in 2021, aiming for startup commissioning by 2027. The US Nuclear Regulatory Commission (NRC) issued the Final Safety Evaluation Report in August 2020 for NuScale. Afterwards, a standard design approval was issued in September by NuScale SMR. This represents approval of the NuScale SMR design, aiming for deployment by 2029. Others, including RITM-200 (a reactor design already deployed on six ice breakers), may have a reference plant or similar design for deployment by 2028.

BWRX-300, another example, is based on the mature technology of large advanced BWRs that have design certification. MMR is an example of a microreactor that is active in terms of pre-licensing in Canada and already has a site licence application and environmental assessment under consideration. These may be deployed in the late 2020s.

The Xe-100 and IMSR are examples of non-water-cooled SMR designs with a relatively mature technology basis and in pre-licensing discussions with a regulator, which may result in deployment before 2030. Finally, three water cooled SMR designs, SMART, UK SMR and NUWARD™, are given as examples with plans announced for deployment around or after 2030.

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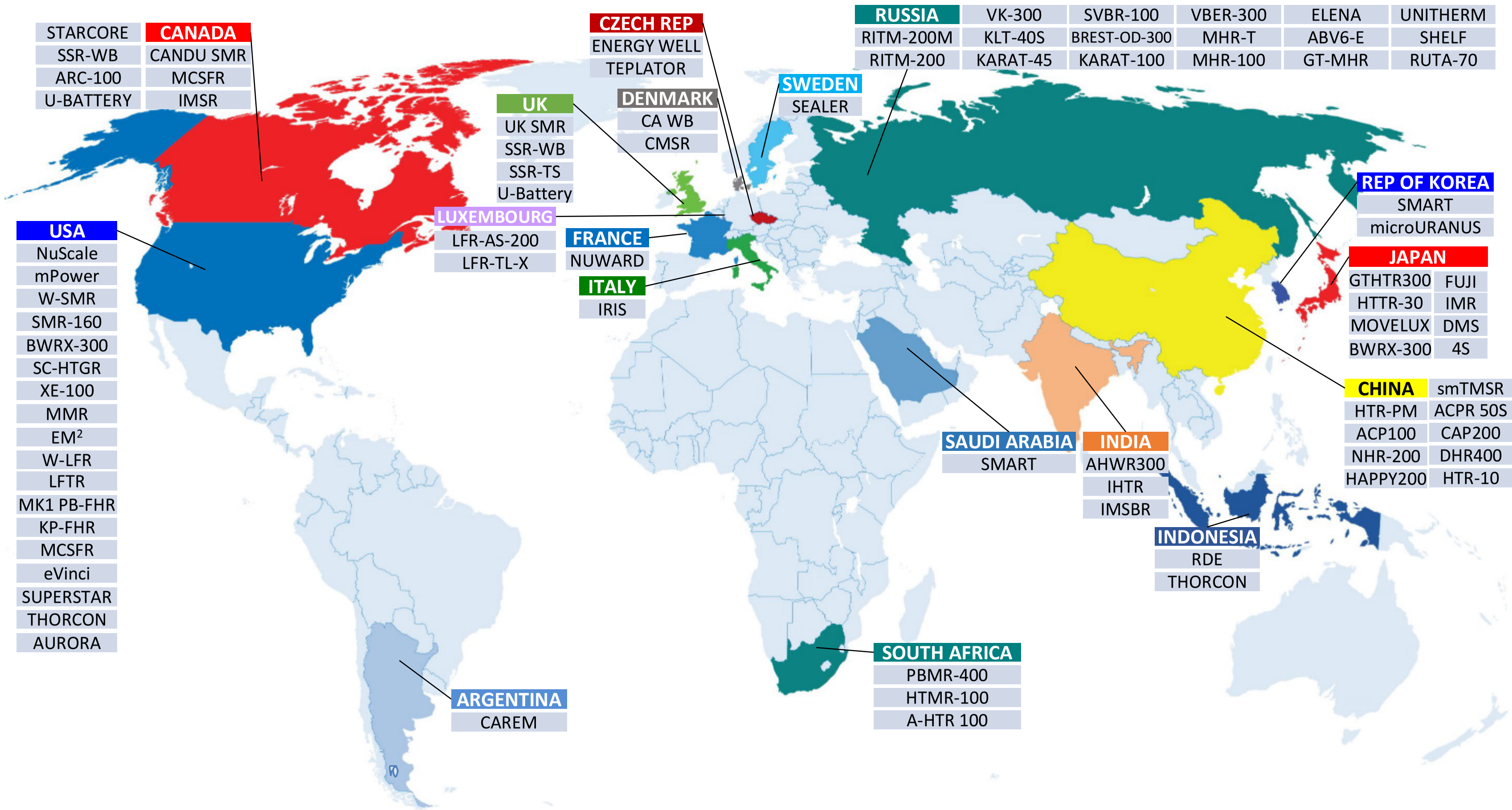

FIG. A–1. Global map of SMR technology development.

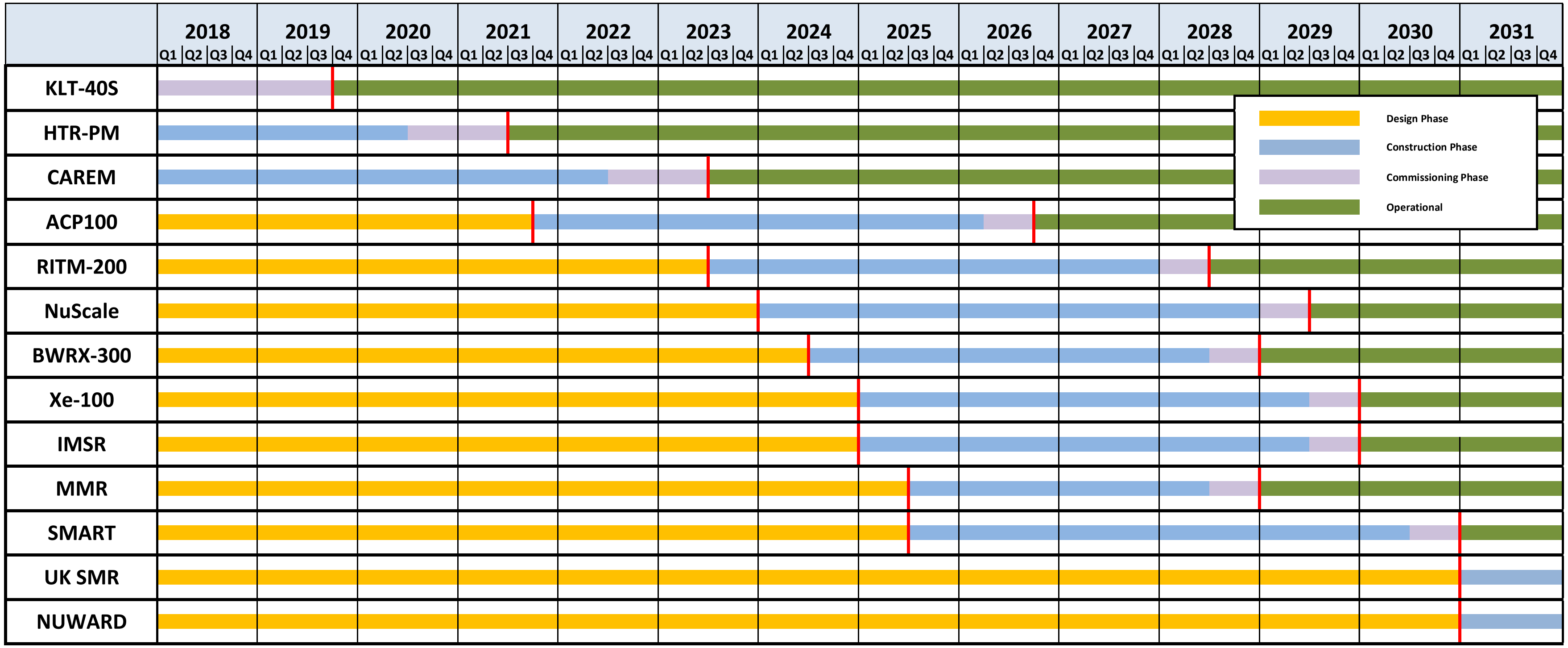

FIG. A–2. *Timeline of deployment of SMR designs to 2030.*

ABBREVIATIONS

CAREM	Central Argentina de Elementos Modulares
CM	configuration management
CRDM	control rod drive mechanism
DiD	defence in depth
EIA	environmental impact assessment
EPR	emergency preparedness and response
EPZ	emergency planning zone
FOAK	first of a kind
FPU	floating power unit
FR	fast reactor
GFR	gas cooled fast reactor
GIF	Generation IV International Forum
GRSR	Generic Reactor Safety Review
HTGR	high temperature gas cooled reactor
HTR-PM	High Temperature Gas Cooled Reactor–Pebble Bed Module
I&C	instrumentation and control
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	innovative nuclear (energy) system
ITAAC	inspections, tests, analyses and acceptance criteria
LBLOCA	large break loss of coolant accident
LEU	low enriched uranium
LFR	lead cooled fast reactor
LWR	light water reactor
MBA	material balance area
MC&A	material control and accountability
MMR	Micro Modular Reactor
MSR	molten salt reactor
NEPIO	nuclear energy programme implementing organization
NOAK	nth of a kind
NRC	US Nuclear Regulatory Commission
NSSS	nuclear steam supply system
OPEX	operating experience
PRIS	Power Reactor Information System
PSA	probabilistic safety assessment
PWR	pressurized water reactor
QA	quality assurance
RPV	reactor pressure vessel
SCWR	supercritical water cooled reactor
SFR	sodium cooled fast reactor
SG	steam generator
SMR	small modular reactor
SSCs	systems, structures and components
TRL	technology readiness level
TSO	technical support organization
VDR	Vendor Design Review
VHTR	very high temperature reactor
WCR	water cooled reactor

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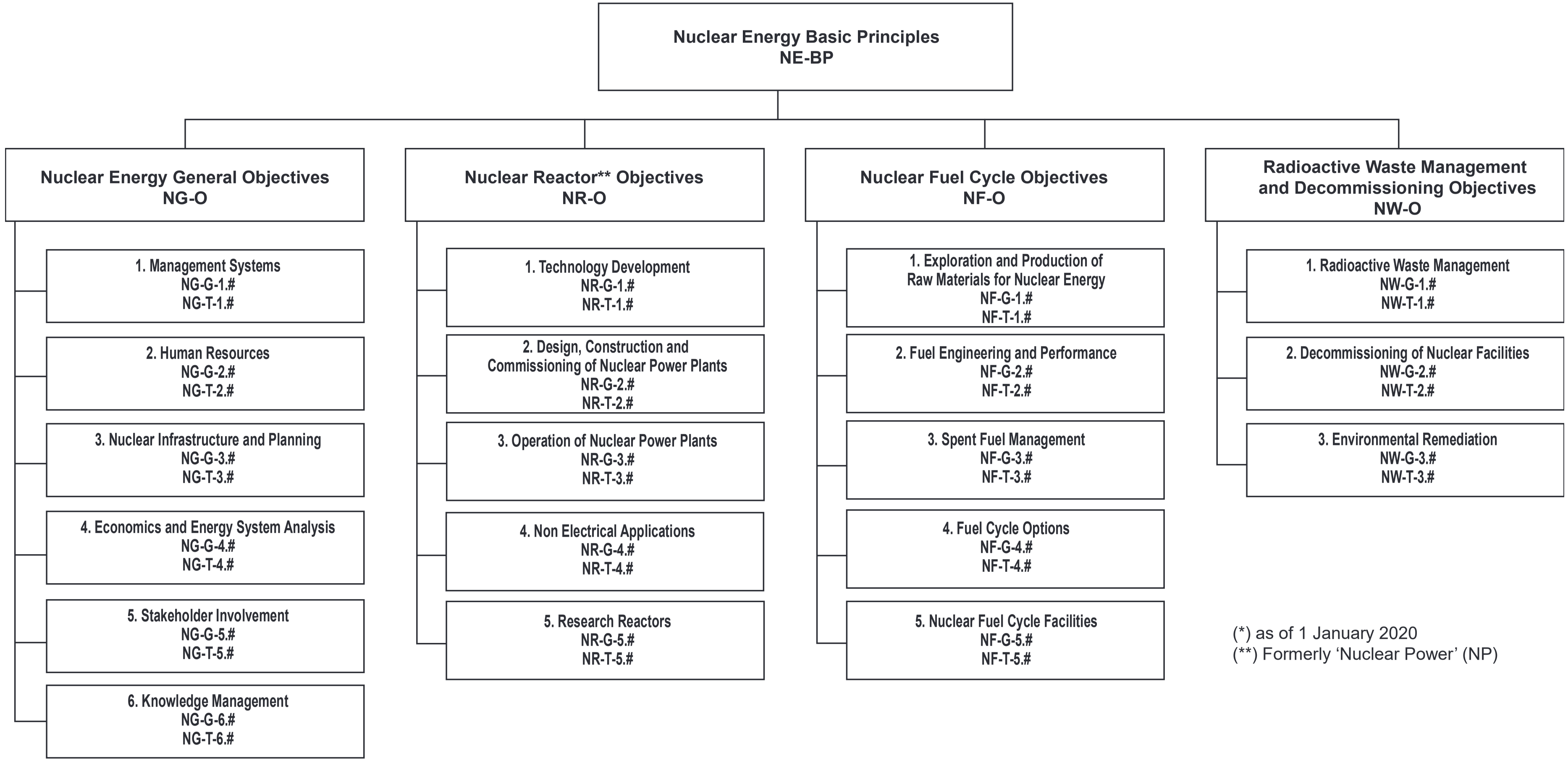

(*) as of 1 January 2020
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Key

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