Technology Options for a Country's First Nuclear Power Plant

Several Member States of the Agency are considering introducing nuclear power to their energy mix for the first time. Although various technology options are available to these countries, selecting the most suitable nuclear reactor design requires not only a careful understanding of existing designs but also in-depth knowledge of country-specific needs, conditions and other considerations. To make an informed decision, the key characteristics of a particular nuclear project must be clearly understood and specified from the outset and balanced, comprehensive and up to date information about reactor designs, concepts and fuel cycle options must be made available and evaluated. This document details important considerations to be taken into account when selecting a reactor design for a country's first nuclear power plant (NPP) and provides information on technology options available to newcomer countries, listing potential designs and describing their key characteristics.

A. Some considerations when selecting the first nuclear power plant

Some elements are of key importance when narrowing down potential nuclear reactor designs to be selected. These include the size and stability of the national electricity grid, the seismicity of the selected site, the availability of water resources for ultimate cooling and the accessibility to waterways or other appropriate transportation routes for the transportation of large components or modules. Therefore, it is important for prospective NPP owners to examine these elements in some detail in order to clearly establish the boundary conditions in the technology assessment process.

The desired level of technological maturity or innovation in the new NPP design is another decision which has to be made early. Structures, systems and components (SSCs), and design and analysis methods and techniques which involve characteristics, materials, manufacturing processes, working conditions and plant environment conditions that are identical or similar to those that have been operated or applied successfully in existing NPPs, preferably over a span of several years, are referred to as 'proven technology'. Each country needs to balance the benefits and the challenges associated with the selection of a design of a specific level of technological maturity. Some countries may prefer to use the deployment of a new nuclear power programme as an opportunity to develop national capabilities in several key areas associated with these advanced reactor designs. This is usually done through comprehensive technology transfer arrangements with the supplier, where a newcomer country may initially pursue a 'turnkey approach' (following the lead of the supplier country) but would increasingly take on larger and more significant roles in future nuclear projects. Each country needs to strategically evaluate the technological maturity risk they are willing to assume and weigh it against the potential gains in national capabilities associated with innovation and technology transfer.

The level of completion of a design and its licensability in the new hosting country are also important considerations. Choosing a nuclear reactor design that is finalized and frozen, particularly one that has undergone licensing review in other countries, can minimize project uncertainties. While some modifications may be needed due to local regulatory requirements or due to the special characteristics of a site, a complete design helps to ensure that the project will be within budget and schedule.

On some occasions, striking a balance between the use of a large, inexpensive local labour force applying traditional construction techniques on site and the use of advanced construction techniques that may require the procurement of module fabrication facilities (i.e. a 'modular approach') or sophisticated machinery is also important. A cost–benefit analysis would enable a country to assess whether the increase in construction time when using traditional construction techniques will be offset by the increase in cost associated with the use of more advanced construction techniques.

Performance-specific considerations of a given design, such as operability, manoeuvrability, inspectability, maintainability, availability factor and reliability, are of course also of paramount importance and careful evaluations of each one of those characteristics should be carried out.

Furthermore, it may be of interest to examine the technology options that are being selected in other countries in the same region, since establishing productive regional partnerships would enable efficiencies in areas such as operating experience, spare parts inventories, enrichment and fuel fabrication services, waste and spent fuel management facilities, etc. Similar efficiencies could be achieved by selecting a widely used reactor design and by participating in the 'owners' group' for that design. It is generally recommended that newcomer countries consider both types of partnerships, in particular with more experienced countries or operators. As an additional benefit, these may increase negotiating strength when dealing with suppliers.

Last but not least, other key factors in choosing a nuclear reactor design include fuel procurement and spent fuel and waste management. With regard to fuel, the availability of several competitive suppliers for the various raw materials and services needed to produce the nuclear fuel required for a given reactor design, such as the procurement of the fissionable raw material, enrichment services, and fuel fabrication, should also be considered. As for spent fuel and waste management, long term plans are needed.

B. Classifications of reactor designs

There are various categorizations for nuclear reactor designs. For example, advanced NPP designs are defined as those designs of current interest for which improvements over their predecessors and/or existing designs are expected (Ref. IV-1). Depending on the number of modifications implemented, advanced reactor designs can be divided into 'evolutionary' and 'innovative' (Figure IV-1). An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining the essentials of the proven design to minimize technological and investment risks. The development of an evolutionary design requires, at most, engineering and confirmatory testing. An innovative design is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial research and development (R&D) efforts, feasibility tests, and a prototype and/or demonstration plant are probably required prior to the commercial deployment of this type of design.

An alternative classification was developed by the Generation IV International Forum (Ref. IV-2), which divided nuclear reactor designs into four generations. The first generation consisted of the early prototype reactors of the 1950s and 60s. The second generation is largely made up of the commercial NPPs built since the 1970s which are still operating today. The Generation III reactors were developed in the 1990s and include a number of evolutionary designs that offer improved safety and economics. Following the increased interest in nuclear power seen in the first decade of the 21st century, additional improvements are being incorporated into Generation III designs, resulting in several concepts that are actively being developed and being seriously considered for near term deployment in various countries. Beyond 2030, it is anticipated that new reactor designs will address key issues such as closing the fuel cycle or enhanced proliferation resistance at the same time as competitive economics, safety and performance. This generation of designs, Generation IV, consists of innovative concepts where substantial R&D is still needed. However, it should be noted that there is no precise and generally accepted definition of each generation.

In addition, nuclear reactors have traditionally been classified depending on their neutron spectrum, or depending on the coolant they use to extract the fission energy from the core. According to the first criterion, reactors can be described as 'thermal' when they use low energy neutrons and as 'fast' when they use much higher energy neutrons that are not slowed down by a moderator. According to the latter criterion, reactors can be classified as water cooled reactors (WCRs), gas cooled reactors (GCRs), liquid metal cooled reactors (LMRs) and molten salt cooled reactors (MSRs). Furthermore, the WCR category can be subdivided into boiling water reactors (BWRs) — where the core is at relatively low pressure and the coolant is allowed to boil — and pressurized water reactors (PWRs) — where the core is at high pressure and the coolant remains a liquid. The WCR category can also be subdivided into light water reactors (LWRs) and heavy water reactors (HWRs) that use deuterium water. While most HWRs belong to the PWR type and are also referred to as pressurized heavy water reactors (PHWRs), some advanced designs use the BWR concept. Several advanced designs are referred to as 'integral designs', that is, designs in which the whole reactor primary circuit (including, for instance, the pressurizer, coolant pumps, and steam generators/heat exchangers, as applicable) is enclosed in the reactor vessel. Finally, depending on the size of the plant, nuclear reactors can be classified as 'small' (with an output of less than 300 MW(e)), 'medium' (between 300 and 700 MW(e)) and 'large' (more than 700 MW(e)). In general, although innovative reactor designs do not always fit this norm, we can say that most WCRs and GCRs are thermal reactors, while most fast reactors are cooled by liquid metals.

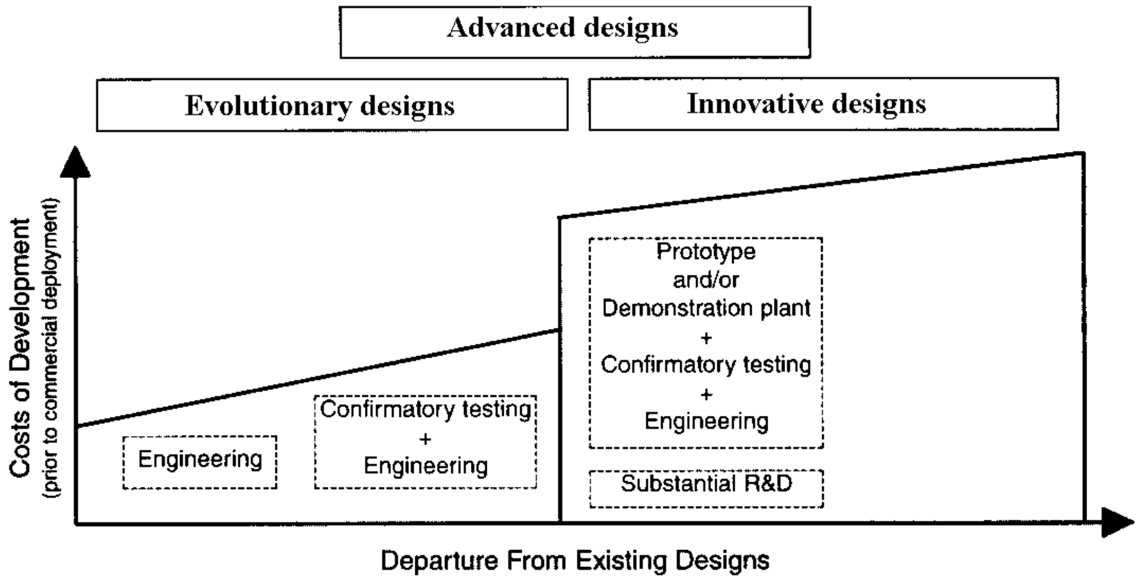

FIG. IV-1. Classification of advanced reactor designs.

Various organizations, including design organizations, utilities, universities, national laboratories and research institutes, are involved in the development of advanced NPPs featuring evolutionary and innovative reactor designs. Since evolutionary designs are the most likely candidates to serve as the basis for a first NPP in most countries, the remainder of the document will examine only these.

C. Trends in evolutionary reactor designs

Evolutionary reactor designs focus on improving the economics and the performance of existing designs while at the same time meeting even more demanding nuclear safety requirements. Although efforts have also been made to optimize the use of fissionable materials and minimize the production of spent fuel and nuclear waste, the full closing of the nuclear fuel cycle is to be expected only once NPPs based on innovative reactor designs are brought into operation.

The following trends in the design of evolutionary reactors can be observed:

Firstly, there is a trend towards reducing the overall capital cost of a new NPP by reducing and simplifying plant systems and components; developing standardized designs that need to be validated and licensed only once; using advanced construction technologies and management practices that shorten the construction schedule and improve the quality or by incorporating modularity in the design, which enables factory pre-fabrication of both structural and system modules. Most evolutionary designs also include design features that allow for plant lifetimes of 60 years and longer. Taking advantage of economies of scale by designing larger reactors (capital costs are amortized faster due to higher electricity production) can also help reduce overall capital costs. On the other hand, in recent years a parallel trend emphasizing the affordability of NPPs has arisen, resulting in the development of small or medium size reactors that can be built in a phased manner up to the total desired power according to the owner's financial means. These smaller designs may also be ideal for newcomer countries with small electricity grids and limited financial resources.

The second trend is towards lowering operating costs through the optimization of the fuel cycle. Savings result from increased plant availability, more effective use of fissionable resources and minimization of waste and spent fuel quantities and management costs. Efforts have also been made to attain higher thermal efficiencies by using advanced turbines and sophisticated thermodynamic cycles, as well as expanded non-electrical applications.

The third trend is towards improved performance, by various means, including the use of smart components that monitor their own performance and warn operators about incipient failures; in-service testing and maintenance; relying on probabilistic risk assessment methods and databases that allow designers to focus design efforts on the systems and components with higher risk of failure; or using digital instrumentation and control (I&C), as well as improved human–machine interfaces that significantly reduce human errors. Better knowledge of underlying phenomena and better technology mean that the margins needed to accommodate unknowns can be reduced in new designs. Furthermore, since these designs are expected to operate under higher demands, they also use improved corrosion resistant materials.

Lastly, another key design improvement is the use of passive safety systems that rely on gravity and natural convection, as well as temperature and pressure differentials, enabling these systems to function without electrical power and/or actuation by electrically powered I&C systems. Furthermore, many evolutionary designs have been developed based on 'user requirements', that is, the lessons learned from the operation of the existing fleet of NPPs.

D. Evolutionary designs and their key characteristics

A publication providing technical guidance and a design-neutral systematic approach to evaluate the technical merits of the various NPP technologies available on the market, based on each country's needs and requirements, is being developed by the Agency. In addition, Member States can obtain up to date information about advanced reactor designs and concepts — from evolutionary WCR designs for near term deployment to innovative reactor concepts still under development — through the Agency's web-based Advanced Reactors Information System (ARIS)[1].

Table IV-1 summarizes all evolutionary reactor designs for which information has been made available to the Agency through the development of ARIS, through the Agency's relevant technical working groups and from the open literature. The designs are arranged in descending order of electrical output. A brief summary of some key features of each one of these designs can be found after Table IV-1.

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[1] See Reference IV-4.

Table IV-1: Reactor designs available for near- and mid-term deployment

NAME	TYPE	DESIGNER	POWER [MW(e)]	STATUS[2]
ABWR-II	BWR	GE Hitachi	1700	Basic design
APWR	PWR	MHI	1540–1700	Detailed design
EPR	PWR	AREVA	1600+	Under construction
ESBWR	BWR	GE Hitachi	1550	Detailed design
ABWR	BWR	GE Hitachi, Toshiba	1350–1500	In operation
APR-1400	PWR	KHNP	1400	Under construction
KERENA	BWR	AREVA+E.ON	1250+	Basic design
ACR-1000	PHWR	AECL	1200	Detailed design
WWER-1200	PWR	Gidropress	1200	Under construction
ATMEA1	PWR	ATMEA	1100	Basic design
WWER-1000	PWR	Gidropress	1000	In operation
AP1000	PWR	Westinghouse	1000	Under construction
BN-800	SFR[3]	Rosenergoatom	880	Under construction
mPower	Integral PWR	B&W	180 – 360	Conceptual design
EC6	PHWR	Candu Energy Inc.	740	Detailed design
ACR-1000	PHWR	Candu Energy Inc.	1200	Basic design complete
Indian PHWR-220	PHWR	NPCIL	220	In operation
Indian PHWR-700	PHWR	NPCIL	700	Under construction
Indian PHWR-540	PHWR	NPCIL	540	In operation
PFBR	SFR	IGCAR/BHAVINI	500	Under construction
IMR	Integral PWR	MHI	350	Conceptual design
IRIS	Integral PWR	International Consortium	100–335	Basic design
SMART	Integral PWR	KAERI	330 MW(t)/100 MW(e)	Detailed design
AHWR300-LEU	Boiling HWR	BARC	300	Basic design
CAREM-25	Integral PWR	CNEA	27	Under construction
NuScale	Integral PWR	NuScale	45 - 540	Basic design
KLT-40S	Floating PWR	OKBM	35	Under construction
SVBR-100	Lead-Bismuth FR	AKME Engineering	100	Detailed design
4S	SFR	Toshiba	10	Conceptual design
ACP-100	PWR	CNNC	100	Detailed design

[2] Status descriptions can be found in *Terms for describing new, advanced nuclear power plants* (IAEA-TECDOC-936, Vienna, April 1997) (Ref. IV-1).

[3] Sodium cooled fast reactor.

ACP-600	PWR	CNNC	600	Detailed design
ACP-1000	PWR	CNNC	1000	Detailed design
ACPR-1000	PWR	CGNPC	1150	Detailed design

The designs listed in Table IV-1 are briefly described hereafter, in alphabetical order. The advanced boiling water reactor (**ABWR**), available from two competing vendors (GE-Hitachi and Toshiba), combines BWR design features from Europe, Japan and the USA. Developed in direct response to the Electric Power Research Institute's (EPRI's) *Utility Requirements Document* (Ref. IV-5), the ABWR is licensed in Japan, the USA[4], and it is the first evolutionary reactor design to operate commercially. Currently four ABWRs are in operation in Japan (Kashiwazaki-Kariwa 6 & 7, Hamaoka-5 and Shika-2), and two are under construction there.[5] Several more are planned in both Japan and the USA. Therefore, this design has a proven capital, operation and maintenance cost structure. Taking advantage of existing prefabricated construction experience and applying it to a modularized design, the ABWR was designed with a shorter construction schedule in mind. Although existing ABWRs have a capacity of 1370 MW(e), future ABWRs are expected to reach 1500 MW(e) due to an existing reactor core margin for uprates. The ABWR has fully digital I&C and has adopted reactor internal pumps that eliminate the need for large external recirculation coolant loops and make it possible to maintain core coverage during a postulated loss of coolant accident (LOCA). Significant efforts have also been made in the design of the ABWR to improve its safety systems and reduce the core damage frequency to very low values. Features have been included to mitigate severe accidents and to reduce the off-site consequences of accidents, and its containment vessel is made of reinforced concrete with an internal steel liner.

The **ABWR-II**, developed by GE-Hitachi, is a further enhancement of the ABWR. It offers a larger power output of up to 1700 MW(e), due to a larger core (with 1.5 times larger fuel bundles) and the control rods arranged in a K-lattice (as opposed to the conventional N-lattice). This new core design may also provide increased flexibility in terms of higher burnup, use of mixed oxide (MOX) fuel and higher conversion rate configurations. The ABWR-II also includes a modified emergency core cooling system and a combination of active and passive heat removal systems designed for improved economics, performance and safety.

The **ACP100**, a multipurpose small module reactor developed by the China National Nuclear Corporation (CNNC), is a 100 MW(e) advanced pressurized water reactor with small integrated modules. Its 2-6 modules can be built at the same time and a single module of the ACP100 can supply 310MWt of Reactor thermal power, a maximum heat production of 1000GJ/h, a maximum steam production of 420t/h and a maximum seawater desalination production of 120000t/d.

The **ACP600** is a 600 MW(e) two-loop advanced PWR developed by CNNC. The reactor core contains 121 fuel assemblies, with decreased core linear power density supplying higher thermal margin. Passive safety systems are employed in addition to active safety systems, enhancing the response capability in the case of a station black out accident.

The **ACP1000,** also developed by CNNC, is an 1100 MW(e) three-loop advanced PWR. The reactor core of this advanced light water reactor is composed of 177 advanced fuel assemblies, increasing power while ensuring a sufficient thermal safety margin. Both active and passive safety systems were adopted in the ACP1000 design to perform functions such as emergency core cooling, core residual heat removal, melt core retaining and cooling, and containment heat removal. It also contains enhanced protection for external hazards. It also offers an extended plant design lifetime (60 years) and refueling cycle (18 months) for an improved economic competitiveness.

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[4] In addition, it is licensed in Taiwan, China.

[5] Two ABWRs are also under construction in Taiwan, China.

The **ACPR1000** is an advanced Chinese 1000 MW(e) PWR nuclear reactor developed by CGNPC. This 3-loop PWR, with a generator output of around 1150 MW(e), focuses on safety performance while maintaining consideration for economic efficiency. Enhanced safety features include an extra heat removal system to remove the heat out of the containment through containment spray and to realize in-vessel retention (IVR) of core damage under severe accident by external reactor vessel cooling (ERVC).

The advanced CANDU reactor-1000 (**ACR-1000**), developed in Canada, is a 1200 MW(e) pressure tube reactor that retains many essential features of a typical CANDU plant design, including a core with a horizontal fuel channel, a low temperature heavy water moderator, a water filled reactor vault, two independent safety shutdown systems, a highly automated control system, on-power fuelling and a reactor building that is accessible for on-power maintenance and testing. Key differences incorporated into the ACR-1000 are the use of low enriched uranium fuel (as opposed to natural uranium), the use of light water instead of heavy water as the reactor coolant, and a lower moderator volume to fuel ratio. The phase 2 pre-licensing review by the Canadian Nuclear Safety Commission has been completed.

The Indian advanced heavy water reactor (**AHWR**) is a 300 MW(e), vertical pressure tube-type, heavy water moderated, boiling light water cooled reactor. It has been designed to achieve large-scale use of thorium for the generation of commercial nuclear power. It will produce most of its power from thorium, with no external input of uranium-233 in the equilibrium cycle. The reactor incorporates a number of passive safety features and is associated with a closed fuel cycle with the objective of reducing its environmental impact. In addition, several features have been incorporated that are likely to reduce its capital and operating costs.

The Westinghouse advanced passive PWR (**AP1000**) is a two-loop 1100 MW(e) PWR, scaled up from the AP600 design already certified in the USA, which was originally compliant with EPRI's *Utility Requirements Document* (Ref. IV-5). In the AP1000, designers have made an effort to simplify all systems and to reduce the number of systems and components for easier construction, operation and maintenance. Like other evolutionary concepts, the AP1000 uses prefabrication and modular construction with the objective of reducing construction schedule uncertainties. One of the signature characteristics of the AP1000 is the use of passive safety systems which require no outside electricity or operator action for 72 hours. On the other hand, the plant design utilizes proven technology and capitalizes on more than 40 years of PWR operating experience. The AP1000 also incorporates features designed to mitigate severe accidents, such as in-vessel retention of core debris following a core melt event, and no reactor vessel penetrations below the top of the core level. Two AP1000 projects (four units in total) are currently under construction in China (Haiyang and Sanmen) and substantial construction and operating experience is expected to be gained from these. In the USA, final certification by the US Nuclear Regulatory Commission (USNRC) for the amended AP1000 design is expected, and three engineering, procurement and construction contracts for the Vogtle, Summer and Levy sites were signed.

The advanced power reactor 1400 (**APR1400**), with a rated power of 1400 MW(e), is the largest two-loop PWR currently available. It was developed in the Republic of Korea, based on accumulated experience from the design and operation of the 1000 MW(e) OPR 1000 and from EPRI's *Utility Requirements Document* (Ref. IV-5). The APR1400 incorporates a number of changes in response to operators' needs for enhanced safety, performance and economics and to address new licensing requirements such as the mitigation of severe accidents. It has a very characteristic configuration, with two large steam generators and four reactor coolant pumps in a 'two hot legs and four cold legs' arrangement. The APR1400 also features fully digital I&C, and a main control room designed with full consideration of human performance capabilities (or, as these are generally referred to, 'human factors'). Incorporating safety systems with both active and passive characteristics, the APR1400 has also been designed to take advantage of modularization and prefabrication construction techniques designed to make the construction budget and schedule more predictable. Four APR1400 units are currently under construction in the Republic of Korea at Shin-Kori 3 & 4 and Shin-Ulchin 1 & 2 and are expected to enter commercial operation in 2013–14 and 2015–2016, respectively. The APR1400 has also been selected for the first four units that will be built in the United Arab Emirates.

The advanced pressurized water reactor (**APWR**) is a four-loop PWR developed jointly by a group of Japanese utilities, Mitsubishi Heavy Industries (MHI) and Westinghouse that relies on a combination of active and passive safety systems. The high capacity APWR, with 1500 MW(e) (1700 MW(e) in Europe and the US), takes advantage of economies of scale and uses high performance steam generators and low pressure turbines with very large last stage blades. The APWR allows operation with long fuel cycles and increased flexibility such as the use of low enriched fuel in order to reduce uranium requirements and the use of MOX cores and high burnup fuels. A neutron reflector is used with the objective of improving the neutron economy and the long term reliability of the reactor vessel. The container includes a steel liner intended to prevent leakage, surrounded by the concrete structure that provides structural protection. As in other evolutionary designs, the construction of the APWR also takes advantage of modularization and advanced design, simulation and management computer programmes.

ATMEA1, developed by Japan and France, brings together technology that is already incorporated into AREVA's EPR (see below) and MHI's APWR (described above). A three-loop PWR that relies primarily on active safety systems, it incorporates severe accident mitigation features. ATMEA1 will be able to operate using a full core of MOX fuel.

The 880 MW(e) **BN-800** sodium cooled fast reactor design is the logical development of the BN-600 reactor design. BN-600, the world's only commercial fast breeder reactor in operation, has been operating since 1980 at the Beloyarsk NPP site in Russia. The experience gained during the BN-600 reactor operation has led to new design features in the BN-800 reactor, as well as to enhanced safety characteristics. Of these, the most important are the adoption of one turbine; steam instead of sodium reheating; the introduction of a special decay heat removal system that dissipates the heat through 'sodium–air' heat exchangers connected to the secondary circuit; the adoption of a core catcher for collecting core debris in the case of core melting and of a special sodium cavity located above the core to reduce the sodium void reactivity effect; and the inclusion of an additional passive shutdown system with hydraulically suspended absorber rods.

CAREM-25 (in Spanish, 'Central Argentina de Elementos Modulares') is an Argentine nuclear reactor based on an indirect cycle with some distinctive and characteristic features that greatly simplify its design. These include an integrated primary cooling system, a self-pressurized primary system and safety systems relying on passive features. The first step of this project is the construction of a 27MW(e) (CAREM-25) prototype at the Atucha nuclear site.

The Canadian enhanced CANDU 6 (**EC6**) is a 740 MW(e) pressure tube reactor designed by Candu Energy. The EC6 design incorporates the principles and characteristics of the CANDU 6 design, such as natural uranium fuel; two independent safety shutdown systems; a separate low-temperature, low-pressure moderator (that provides an inherently passive heat sink by permitting heat to be removed from the reactor core under abnormal conditions); a reactor vault filled with cool light water that surrounds the reactor core and provides a further passive heat sink; on-power refuelling; and a modular, horizontal fuel channel. The EC6 design includes a more robust containment (e.g. thicker walls, steel liner), enhanced severe accident management, the addition of an emergency heat removal system as a safety system, wider LOCA margins and a plant life of 60 years with one life extension of critical equipment such as fuel channels and feeders at midlife. The Canadian Nuclear Safety Commission (CNSC) is currently conducting the design review of the EC6.

The European pressurized water reactor (**EPR**) is the result of a joint development effort by Framatome and Siemens, and is now being made available by AREVA. It is a 1600+ MW(e) four-loop PWR design. In the EPR, the designers have chosen to use active safety systems and to increase redundancy in power sources and water inventories to smooth any potential transients. The EPR also has a double concrete containment and a core catcher for the mitigation of severe accidents. Its core is designed to operate with both UO_2 and MOX fuel, and reduced uranium consumption is expected. The EPR has been designed to operate under load following conditions, at between 20% and 100% of rated generator power. It includes fully digital I&C systems. EPR reactors are currently under construction in China, Finland and France.

GE Hitachi Nuclear Energy's economic simplified boiling water reactor (**ESBWR**) is a 1500 MW(e) reactor design based on the earlier 670 MW(e) simplified boiling water reactor (SBWR) design. Like the earlier SBWR design, the ESBWR design incorporates innovative features designed to further simplify an inherently simple direct cycle reactor. The ESBWR completely relies on passive safety systems for both normal and off-normal operating conditions, such as natural circulation, isolation condensers or gravity driven cooling systems. The core of the ESBWR is shorter and the overall vessel height is larger than in a conventional BWR, in an effort to maximize natural circulation and avoid the use of recirculation pumps or their associated piping. The USNRC issued an advanced safety evaluation report with no open items for the ESBWR in August 2010, and final design certification is expected shortly.

The integrated modular water reactor (**IMR**) developed by MHI is a medium sized power reactor with a reference output of 350 MW(e) and an integral primary system reactor with potential deployment after 2020. It employs a hybrid heat transport system, which is a natural circulation system under bubbly flow conditions for primary heat transportation, and no penetrations in the primary cooling system thanks to an in-vessel control rod drive mechanism. These design features enable the elimination of the emergency core cooling system. Because of its modular characteristics, the IMR is not only suitable for large NPPs consisting of several modules but also for small plants, especially when the capacity of the grid is small. The IMR is also capable of providing district heating, seawater desalination and process steam production.

India has developed its own pressurized heavy water reactor (**IPHWR**) design that consists of 220 MW(e), 540 MW(e) and 700 MW(e) units. India currently operates fifteen 220 MW(e) units and two 540 MW(e) units. Construction of three 700 MW(e) units is under way. The IPHWR was developed on the basis of experience gained in operating earlier units and from national R&D efforts. The important features introduced in these units include two diverse and fast acting shutdown systems, double containment of the reactor building, a water filled calandria vault, an integral calandria end shield assembly, and a calandria tube filled and purged with carbon dioxide to monitor pressure tube leaks by monitoring the dew point of carbon dioxide. These units also include a valveless primary heat transport system and a unitary control room concept, as well as advanced I&C systems.

The **international reactor innovative and secure, IRIS**, is a modular light water reactor with an integral primary system configuration designed by an international group comprising 20 organizations from nine countries. It features a simplified compact design in which the primary vessel houses steam generators, pressurizer and pumps, a novel safety approach, and an optimized refuelling cycle with intervals of at least four years. Due to the integral configuration of the IRIS, a variety of accidents are by design either eliminated or their consequences and/or probability of occurring can be greatly reduced.

The **KERENA** is an evolutionary boiling water reactor based on the experience gained from the proven engineering of current generation BWR plants supplemented by an innovative approach. The current final basic design of KERENA is part of a strategic partnership between AREVA NP and the German utility E.ON Kernkraft. In KERENA, safety systems have been simplified by introducing passive safety systems and most nuclear safety functions are performed by active systems with a passive system as a backup. The core height has been reduced to promote natural circulation, and the eight reactor water recirculation pumps are so-called 'wet-motor pumps', in which the electric pump motor is situated inside the reactor coolant pressure boundary.

The **KLT-40S** is a PWR based on the commercial KLT-40 marine propulsion plant and it is an advanced variant of the reactor plants that power nuclear icebreakers. The construction of a small floating nuclear cogeneration plant with two KLT-40S reactors is currently under way in the Russian Federation. The KLT-40S is a modular design in which the reactor, the steam generators and the main circulation pumps are connected by short nozzles (without long pipelines). It is a four-loop system which features forced and natural circulation of the primary coolant, with a once-through coiled steam generator, an external gas pressurizer system and passive safety systems.

A **NuScale** plant consists of 1 to 12 independent modules, each capable of producing a net electrical output of 45 MW(e). Each module includes a pressurized light water reactor operated under natural circulation primary flow conditions. Each reactor is housed within its own high pressure containment vessel which is submerged underwater in a stainless steel lined concrete pool. In early 2008, NuScale

Power notified the USNRC of its intention to begin pre-application discussions aimed at submitting an application for the design certification of a twelve-module NuScale power plant. The reactor is now at the pre-application stage of design certification in the US.

The **mPower** is a scalable and modular system in which the core and steam generators are contained within a single vessel. It is a modular reactor designed to match customer demand in 180 MW(e) increments. Its features include an integral nuclear system design, passive safety systems, a 4.5-year operating cycle between refuellings, 5% enriched fuel, secure underground containment, and a spent fuel pool with capacity to last for the lifetime of the plant. A scaled prototype of mPower using electric heating instead of nuclear heating is currently under construction in the USA to verify the reactor's design and safety performance. The reactor is now at the pre-application stage of design certification in the US.

The prototype fast breeder reactor **(PFBR)** is a 500 MW(e), sodium cooled, pool type reactor with two primary and two secondary loops featuring four steam generators per loop. The reactor is under construction at Kalpakkam, India. The primary objective of the PFBR is to demonstrate the techno-economic viability of fast breeder reactors on an industrial scale. The reactor's power output level was chosen so as to enable the adoption of a standard turbine as used in fossil power stations, to have a standardized design in reactor components resulting in further reduction of capital cost and construction time and to ensure compatibility with regional electricity grids. The reactor assembly houses the cold and hot pool components apart from the main vessel, the safety vessel and the top shield. The main cold pool components are the core catcher, the core support structure and the grid plate. The main hot pool components are the control plug and its internals, the inner vessel and the intermediate heat exchangers.

SMART, developed by the Korea Atomic Energy Research Institute (KAERI), is a 330 MW(th)/100 MW(e) integral PWR with inherent safety features including an integral configuration of the reactor coolant system, an improved natural circulation capability, a passive residual heat removal system and an advanced LOCA mitigation system. SMART has a low power density core that results in a thermal margin of more than 15% to accommodate any design basis transients with regard to the critical heat flux. SMART has been conceived as a multipurpose energy source that can also be used for non-electric applications such as seawater desalination, district heating or other industrial applications.

The **WWER-1000** is a Russian pressurized WCR that incorporates active and passive safety systems and has been adapted to Western standards based on the substantial design and operating experience accumulated in the Russian Federation over the last 50 years. It is currently under construction in India and the Islamic Republic of Iran. The **WWER-1200** is a scaled up version of the WWER-1000. Like its predecessor, it is a four-loop design with horizontal steam generators which have a track record of providing the longest operating life. The WWER-1200 also includes active and passive safety systems, double containment and severe accident mitigation systems, such as a core catcher.

The SVBR-100 is a Russian innovative small modular fast reactor with lead–bismuth eutectic alloy (LBC) as the coolant and a power output of 100 MW(e). The Russian Federation has planned to construct several SVBR-100 units. In the country, lead–bismuth cooled reactor technology has been used in eight different nuclear submarines. The experience gained from these reactors included: ensuring the corrosion resistance of structural materials, controlling the LBC quality and the mass transfer processes in the reactor circuit, and multiple LBC freezing and unfreezing in the reactor facility. The small reactor is in detailed design and will have a fuel cycle of 7–8 years with 16.3% enrichment. The SVBR-100 has a 60-year design life.

The Japanese **4S** reactor (super-safe, small and simple) is a small sodium cooled reactor without on-site refuelling in which the core has a lifetime of approximately 30 years. The 4S offers two outputs of 30 MW(th) and 135 MW(th), respectively selected on the basis of an analysis of energy demand. Although it has a fast neutron spectrum, the 4S is not a breeder reactor since blanket fuel (usually consisting of depleted uranium located around the core to absorb leakage neutrons from the core to achieve breeding of fissile materials) is not part of its basic design. The reactor power can be controlled by the water/steam system without affecting the operation of the core directly. The capacity for power self-adjustment makes the reactor suitable for a load following operation mode. The reactor is of the pool type and it is also an integral design since all the primary components are installed inside the reactor vessel.

E. Conclusion

As seen in the previous sections of this document, various technology options for near- and mid-term use are available to countries considering starting a new nuclear power programme and every nuclear reactor design has its own key characteristics and benefits. The selection of the most suitable design requires an objective assessment of both the technical and economic benefits of each design, as well as of the associated technologies and related fuel cycle, all of which must be evaluated against the conditions and the needs of each country. Agency support is available to guide Member States in the process of evaluating these different technology options. Moreover, the Agency has developed a range of tools, such as the ARIS database, to provide Member States with balanced, comprehensive and up to date information regarding advanced reactor designs and concepts and to facilitate informed decision making.

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