Small modular reactors

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Chapter outline

5.1 SMRs: Why?

There is a clear surge of interest in modular low-power reactors in the world. In recent years, a number of developments in this area—both new and updated archival projects—have been presented. Moreover, in some countries the pace of development of small reactors was ahead of the introduction of their full-sized counterparts. Compact nuclear facilities themselves are not new to the nuclear industry, but numerous practical steps toward their commercial implementation in various regions of the world have become a fresh trend.

According to the classification of the International Atomic Energy Agency (IAEA), small reactors usually include an electric capacity of up to 300 MW. From a formal point of view, a number of power plants operating in the world fall under

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this category. From this definition follows an unexpected fact—low-power reactors account for more than 30% of the total number of power reactors in the world. In the past, this power level was considered typical for designs of previous generations, such as the first series of British gas-cooled reactors; the first boiling water reactor (BWR), pressurized water reactor (PWR), water-water energetic reactor (VVER), and pressurized heavy-water reactor (PHWR); and other models. Today, about 50 projects of promising low-power reactors are at various stages of development, and some projects will be implemented in the near future. Currently, four small modular reactors (SMRs) are in advanced stages of construction in Argentina, China, and Russia, and several countries with nuclear power plants (NPPs) and countries embarking on nuclear power development are conducting research and development (R&D) on SMRs.

However, the meaning that is customarily used in the concept of "small reactors" is not limited exclusively to power. Now we are talking about purely commercial and modular designs, which are distinguished by the special layout of the main equipment and the method of its manufacture and delivery, which allows us to offer the customer a wide power range of the station, recruited from a different number of blocks [1].

Such SMRs should be competitive in terms of construction costs and electricity generation costs, as well as meet the requirements for the nonproliferation of nuclear weapons.

Reactor plants that meet these conditions are just beginning to be implemented. At the same time, there are up to 50 constructions that can become the basis for the creation of commercial SMR. The largest volume of R&D in this area have been in the United States and Russia, followed by France and the United Kingdom, as well as Germany and Japan. However, most recently, new players have been moving to the forefront in this niche, primarily China and South Korea, while Germany, Japan, and the United Kingdom have seen some stagnation in the practical implementation of SMR technology [2].

Although there's a variety of concepts of low-power modular reactors created in the world, they have several common features due to the requirements imposed on them. First, the SMRs are of a modular execution. For example, for most such structures with pressurized water, an integrated concept of the reactor installation is typical, in which the reactor core, steam generator, pressurizer, and a number of other types of equipment are assembled in a single package—called a monoblock—manufactured in factory conditions and delivered in finished form to the site. There are a few exceptions with the classical layout of stationary reactor plants (RP), but even in these cases, solutions are applied that ensure the greatest compactness and modularity of the steam generating plant.

All conceptual projects of nuclear power plants on the basis of SMR differ depending on location. Projects of land-based stationary SMR provide for the placement of RP below ground level. A number of concepts involve the deployment of RP on mobile platforms or stationary on the seabed.

The overwhelming part of SMR projects provides for various power distribution schemes for the generation of heat and electricity, as well as desalination. A number of designs are capable of generating superheated steam or high temperature heat (approximately 750–950°C) required in chemical industry and metallurgy, as well as for hydrogen production.

Most SMRs, when compared with large reactors, are low maintenance. In particular, SMR projects involve a longer interval between fuel overloads (from 2 to 10 years versus 12 to 24 months for large power units) or fuel laying in general for the entire life cycle. This requires periodic (about once every 10 years) replacement of the compact reactor module. A number of designs do not allow the usual periodic reloading of a part of the fuel assembly but rather only a one-time replacement of all fuel or constant automated updating during the operation of the RP.

A number of technical solutions aimed at compliance with nonproliferation standards are similar in many SMRs projects. For example, some concepts of small fast neutron reactors do not include a reactor blanket suitable for producing weapons-grade materials, and uranium enrichment in most fast SMRs is limited to 15% to 20%.

At the same time, passive safety principles are the most widespread in the SMR. The possibility of their use is expanded due, as a rule, to the lower energy intensity of small reactors. Due to this, the stability of nuclear power plants with SMR to complete de-energization is higher on average, to the extent that in the event of an accident a number of SMRs models allow a complete lack of power supply for a long time. For large reactors, this period is measured at best in days.

Most SMRs with a close prospect of implementation (10–15 years) belong to the following types of tank reactor: PWR (VVER), fast neutron reactors, or high-temperature projects. Channel reactors, including heavy-water SMRs or small BWRs, have not been developed, although there are some such developments. For example, from heavy-water reactors, the advanced heavy-water reactor (AHWR) reactor currently under construction in India is approaching the niche under consideration. In terms of power (about 285 MW), it corresponds to small reactors, but it is not modular in the full sense and uses a very exotic fuel—thorium—in different versions of the mixture with other fissile materials. This discrepancy is understandable; this design is created not so much for the purpose of promotion in open international markets, although an export version is expected. It is regarded as one of the links in India’s three-stage nuclear program, which involves the use of the richest reserves of thorium in the country and the closure of the nuclear fuel cycle.

In addition, SMRs are options suitable for remote regions with less-developed infrastructure and offer the possibility of creating synergistic hybrid energy systems combining nuclear and alternative energy sources, including renewable sources.

5.2 SMR technology

5.2.1 IAEA activities

Today, the IAEA is actively working to expand international cooperation and coordination in the design, development, and commissioning of small and medium power reactors or SMRs (also called SMPRs)—one of the most promising new technologies in nuclear power.

At the same time, great progress has been made in the development of SMPRs/SMRs: some of the reactors will be assembled from systems and components of factory assembly, which will reduce the construction time and make them more flexible and less expensive than traditional nuclear power plants. Today all over the world, there are about 50 SMPRs/SMRs concepts at different stages of development, and the IAEA is forming a technical working group (TWG) that will set the direction of the Agency's activities in the field of SMPRs/SMRs and will become a platform for the exchange of information and knowledge among member countries.

Interest in SMPRs/SMRs are increasing worldwide. SMPRs/SMRs are able to meet the needs of a wide range of consumers and are becoming a low-carbon replacement for aging fossil-fired power plants. They also have improved safety specifications and are suitable for nonelectrical applications such as cooling, heating, and desalination. Many TWG member countries that use, expand, and introduce nuclear power or are considering the possibility of its creation show great interest in the creation and implementation of SMPRs/SMRs.

It is expected that the industrial exploitation of the first three modern SMPRs/SMRs will begin in the 2020s in Argentina, China, and the Russian Federation. The development of SMPRs/SMRs is well under way in a number of other countries.

The TWG includes about 20 IAEA member countries and international organizations. This is part of the expanding range of services that the IAEA provides to member countries in connection with this new nuclear power technology [3]. These include:

- SMPR/SMR computer simulation program for the education and training of nuclear specialists;
- Methodology and associated IT tools for training in the assessment of reactor technology of various types of SMPRs/SMRs;
- Forum of regulatory authorities for SMPRs/SMRs.

Established in 2015, this forum allows for discussions between member countries and other stakeholders to share knowledge and experience in the field of SMPRs/SMRs. It contributes to increased safety by identifying and solving problems that may arise during the examination of the SMPRs/SMRs by regulatory authorities and by facilitating competent and informed decision-making by those bodies.

In response to requests from member countries in Europe, the IAEA is implementing a project to build regional capacity to make informed decisions on SMPRs/SMRs, including a technical assessment of the SMPR/SMR market for commissioning in the near future. This project is designed to help meet growing European demand for flexible sources of electricity that do not lead to the formation of greenhouse gases.

The rapid commissioning of SMPRs/SMRs poses a number of challenges, including the need to create a solid regulatory framework, new codes and standards, a reliable supply chain, and human resources. Although SMPRs/SMRs require less initial investment per unit, the cost of the electricity produced by them will probably be higher than in high-capacity reactors. Their competitiveness should be assessed considering alternatives and ensured by the effect of scale. Their competitiveness must be assessed by reference to the alternatives and to account for economies of scale. Detailed technical data on SMPRs/SMRs under construction and design can be found in the IAEA Information System for Advanced Reactors.

Assessing the prospects, it can be expected that the first industrial park SMPRs/SMRs will be put into operation in 2025–30.

5.2.2 Placing SMRs

Nuclear power plants of low power (NPPLP) have retained their relevance for more than half a century. They not only have their own market niche, but in a number of cases they are called upon to become almost irreplaceable sources of energy supply.

Types of NPPLP are subdivided into mobile and stationary, ground, underground, and floating. Their close relatives are the “nuclear engines”: from those widely used in civilian, naval, and space vehicles; to experimental armored vehicles and railway locomotives that have not outgrown the experimental design stage. Both directions are based on the useful features of a nuclear energy source: compactness, duration of work on a small amount of fuel, and high power density. Also, the experience of operating atomic engines is helpful in creating small NPPs.

The higher the installed capacity of the power unit, the more economical the production of a unit of electricity is in kilowatt-hours. Naturally, within reasonable limits, the upper limit is set by difficulties in the manufacture and transportation of equipment, the presence or capacity of transmission lines, and the redundancy criteria for generating capacity (the reserve in the power system must cover the disconnection of the most powerful power plant).

In most cases, an NPPLP based in a remote, sparsely populated area, of course, will lose at the cost price of electricity to a large power unit (the construction of which is unprofitable, as the generated energy will not find a consumer). However, it will benefit from a traditional source of energy based on organic fuel; according to optimistic calculations, electricity will be 30% cheaper.

Geography of application of NPPLP imposes specific requirements. The NPPLP or its large functional units should allow convenient and safe transportation over long distances. They must be manufactured at the factory practically on a “turnkey” basis, with a minimum amount of construction and installation work on site. The NPPLP must have high reliability, safety, minimum requirements for management and maintenance at the site of use, and requires the longest period of work between fuel overloads. Moreover, carrying out this overload is expedient in the factory. Nuclear and radiation materials should be localized inside the NPPLP, without the possibility of unauthorized access to them and their release into the environment. Moreover, according to the requirements of the IAEA, the level of enrichment of nuclear fuel should be below the “weapons-grade” level of 20%. Returning to the plant for fuel overloads and maintenance, the NPPLP must take away all radioactive waste and use nuclear fuel inside, leaving behind a clean area of the “green lawn” class.

5.2.2.1 Mobile installations

Tracks and wheels

From the 1960s to the 1980s, designers did not attempt to put a small NPP on tracks or wheels. All projects of ground self-propelled NPP had unrecoverable problems that did not give them a chance for widespread implementation.

First, it is impossible to provide high-quality protection against reactor radiation due to its heavy weight and limited transport capacity, as well as the inability to provide necessary radiation safety.

Second, severe restrictions on the size of the reactor and the compactness of the core forced researchers to use highly enriched nuclear fuel of “weapon” quality, which went against international norms on the nonproliferation of nuclear weapons.

Third, it was difficult to ensure the protection of ground self-propelled land-based NPPLP from both road accidents and terrorists.

Railway

What is beyond the power of wheeled or tracked chassis is able to use the train echelon. The “railway” version provides the best radiation protection and ease of operation; as the fuel is produced, only one “reactor” car is replaced and sent to the plant. In addition, this option is able to provide consumers with both electric and thermal energy in a wide range of parameters—from industrial to municipal.

The disadvantage of such an NPPLP is that remote areas of application of stations often do not have a railway connection with the location of the manufacturers.

5.2.2.2 Permanent placement

Recently there were NPPLP projects designed for permanent placement. They are also almost completely mounted in “turnkey” basis at the factory, delivered to the place of work, and installed permanently. A single load of nuclear fuel should be enough for the entire life cycle: 25–30 years. The remaining criteria are reliability, safety, inaccessibility to outsiders, nonproliferation of nuclear materials, minimum management and maintenance, etc., which are similar to those for stationary nuclear power plants. At the end of the life cycle, such NPPLPs are dismantled and, together with the accumulated radioactive waste and used fuel, taken to the factory—either permanently or for “recharging.”

Such stations can be used in municipal services as district CHP plants oriented toward heating and hot water supply. However, these types of NPPLPs still require significant construction work at the installation site and do not meet the criterion of mobility.

Floating NPPs

The NPPLP project, which is already embodied in the metal, is a floating nuclear power plant (FNPP). Floating NPP meets the entire spectrum of requirements for NPPLP. Floating power unit (FPU) is a large-tonnage marine non-self-propelled vessel (length 144 m, width 30 m, displacement 21.5 thousand tons) capable of carrying full-fledged radiation protection. Towing is carried out on the water. All radiation and nuclear materials are localized inside the FPU. A set of four reactor cores provides a long period of operation between factory repairs. Production, also almost completely factory-made, is on a place of installation mooring only hydraulic structures, and coastal devices for reception and transfer of the electric power and hot water (if necessary) are built. Design life is three periods of 12 years, separated by 1-year intervals for maintenance and fuel reloading in the factory.

A series of several FNPPs will allow them to “shuffle” in such a way that consumers in the places of their installation do not lose power supply during the entire service life.

Underground NPPs

The advantages of underground NPPs are that they are better protected from unwanted external influences, are more resistant to seismic cataclysms, and more convenient in the event of an accident localization and for decommissioning.

Their main disadvantages are the high cost of construction and the limitation on the capacity of the power unit due to its size limitations. In this version, in case of failure of forced cooling systems, it is very difficult to implement a convective cooling system, which is one of the modern requirements for NPP safety.

However, it is possible to save on earthworks during the creation of an underground nuclear power plant if there is a spent iron ore mine in the area of its intended location, which can serve as the basis for the location of reactors, because used reactors can be used as marine NPPLPs, the operation of which is well developed.

5.2.3 Significant benefits

One of the main advantages of NPPLP is that it allows you to reliably provide electricity for the extraction of mineral deposits located in undeveloped areas to the north. Small amount of consumed fuel, speed and ease of movement, minimum labor costs for deployment and commissioning, transfer of maintenance operations from the site to specialized factory workshops, the ability to use a minimum of personnel working on a rotational basis—all this makes NPPLP an almost indispensable source of energy in this area.

It is very important that the volume and cost of capital construction in the area of NPPLP placement are minimized: all high-tech, expensive, and time-consuming operations are transferred to specially adapted factory workshops and performed by specialized personnel of the necessary qualification. As a result, the production time of the NPPLP is significantly reduced, as well as an extremely simplified solution of the issues of storage of radioactive waste, qualified maintenance of the plant, and its decommissioning after the development of a technical resource.

5.3 Integral PWR concepts

It is not possible to consider all versions of IAEA-registered SMRs projects; therefore, in this work we will focus on light water modular reactors.

Light water modular reactors use ordinary water as a moderator and coolant. They have the lowest technological risk among all SMRs, which is similar to most of the currently operating power reactors. They mainly use fuel with enrichment by U-235 to 5%, with a fuel overload interval of not more than 6 years. Moreover, for this type of reactor, regulatory obstacles are likely to be minimal among all small reactors. Consider the main design features of these reactors with specific examples [4].

5.3.1 Description of some iPWR examples

5.3.1.1 NuScale

The "NuScale" project was developed jointly by the Idaho National Engineering Laboratory and the University of Oregon (United States). In 2007, "NuScale Power Inc." was established to commercialize the project. The project has been developed since 2000. As this is a modular reactor, 12 such modules were installed on the site as standard (Table 5.1).

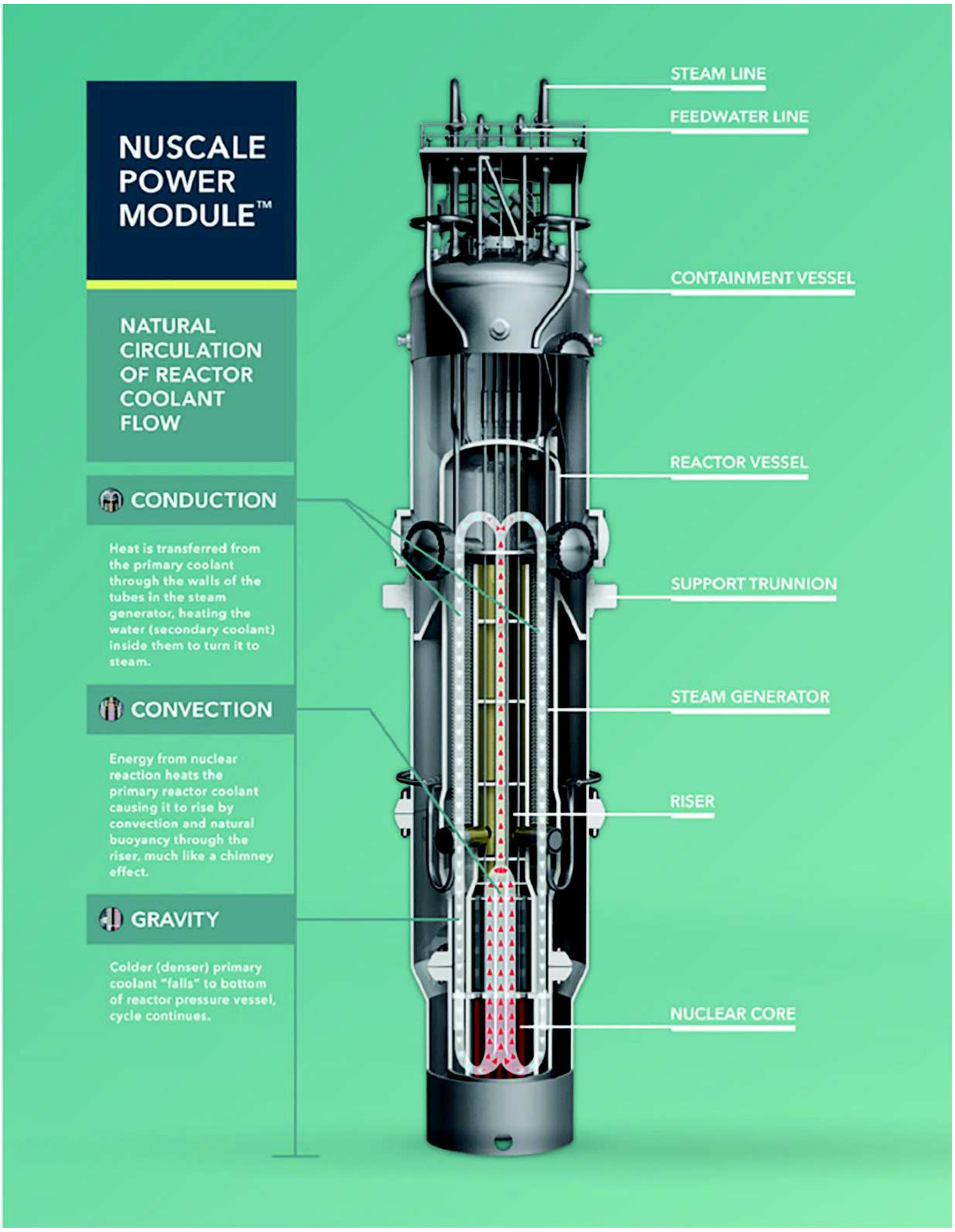
The reactor core, steam generators, and pressurizer are located within the same vessel; there are no circulation pumps. The case diameter is 2.9 m and height 17.4 m. The heat carrier, heating up in the reactor core, moves upward, giving off heat in the steam generator, and returning through the descending channels. Thus, the reactor operates using natural circulation (Fig. 5.1).

The reactor core is recruited from fuel assemblies called NuFuel-HTP2. In fact, this type of fuel assembly is similar in design to fuel assembly for PWR units. Fuel overload is planned to be carried out every 24 months.

The main distinguishing feature from similar projects is that the reactor vessel is additionally placed in a thick-walled metal vessel made of stainless steel. The entire design is in the pool, completely immersed in water. The residual heat removal system consists of two independent passive systems.

Table 5.1 Major technical parameters [5].

№	Parameter	Value
1	Technology developer, country of origin	NuScale Power, LLC, United States
2	Reactor type	Integral PWR
3	Coolant/moderator	Light water/light water
4	Thermal/electrical capacity, MW(t)/MW(e)	160/50
5	System pressure (MPa)	12.8
6	Core inlet/exit temperatures (°C)	258/314
7	Fuel type/assembly array	UO_2 pellet/17 × 17 square
8	Number of fuel assemblies	37
9	Fuel enrichment (%)	<4.95
10	Fuel burnup (GWd/ton)	>30
11	Fuel cycle (months)	24
12	Design life (years)	60



Heat is transferred from the primary coolant through the walls of the tubes in the steam generator, heating the water (secondary coolant) inside them to turn it to steam.

Energy from nuclear reaction heats the primary reactor coolant causing it to rise by convection and natural buoyancy through the riser, much like a chimney effect.

Colder (denser) primary coolant "falls" to bottom of reactor pressure vessel, cycle continues.

Fig. 5.1 NuScale project.

At the end of 2016, the company applied for a license to a US regulator. This is the first application for a license for an SMR in the United States. This fact means that, at this stage, the project is ready almost completely and has the opportunity to become a real commercial product.

5.3.1.2 CAREM-25

CAREM-25 is a PWR-type reactor with an integral arrangement, the construction of which began in 2014 near the Atucha NPP. It deserves special mention due to the fact that this is Argentine technology, and 70% of all equipment and materials are planned

Table 5.2 Major technical parameters [5].

№	Parameter	Value
1	Technology developer, country of origin	CNEA, Argentina
2	Reactor type	Integral PWR
3	Coolant/moderator	Light water/light water
4	Thermal/electrical capacity, MW(t)/MW(e)	100/~30
5	System pressure (MPa)	12.25
6	Core inlet/exit temperatures (°C)	284/326
7	Fuel type/assembly array	UO_2 pellet/hexagonal
8	Number of fuel assemblies	61
9	Fuel enrichment (%)	3.1
10	Fuel burnup (GWd/ton)	24
11	Fuel cycle (months)	14
12	Design life (years)	40

to be purchased from local manufacturers. The project was developed as an energy source for electricity supply in regions with low consumption. It can also be used for desalination (Table 5.2; Fig. 5.2).

The reactor core, control rod drives, and 12 straight-tube vertical steam generators (with steam overheating) are located in one vessel, according to all canons of modularity. In the primary loop of the reactor, natural circulation is used. The reactor vessel has a diameter of 3.2 m and a height of 11 m. The active area is recruited from 61 hexagon fuel assemblies.

CAREM-25 contains passive and active security systems. The project stipulates that, in case of a severe accident, the reactor core remains intact for 36 h without operator action and without external power supply. The expected frequency of core damage (FCD) will be no more than 10^7 reactor/year.

Stopping the fission chain reaction is performed using two independent systems: the control rods and injection of boron in the water. Under normal operating conditions, boron is not used. Removal of afterpower is carried out by a passive system PRHRS. It works on the principle of technological capacitor (isolation condenser). PRHRS capacitors are located in the pool at the top of the containment.

The project also provides for a passive emergency system for pouring water EIS into reactor core. If the pressure in the case drops below the setpoint of 1.5 MPa, the safety diaphragm breaks and the borated water from the EIS tank is poured into the case. In a simple way, this is the hydraulic capacities of the emergency core cooling system (ECCS).

5.3.1.3 SMART

SMART is a light water pressurized reactor with a thermal capacity of 330 MW. Its electric power is 100 MW(el.). In another version, it produces 90 MW(el.) and 40 thousand tons of desalinated water per day, which is considered sufficient for a city with a population of 100 thousand people (Table 5.3; Fig. 5.3).

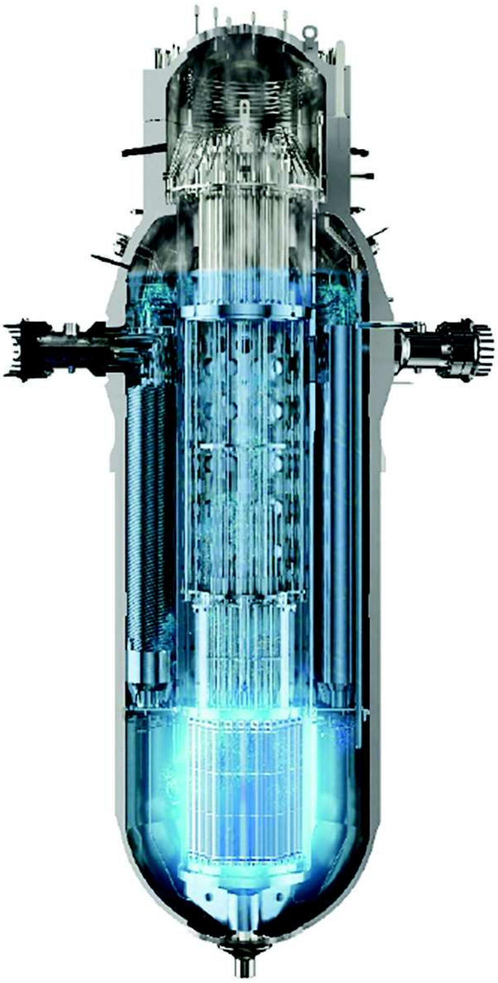


Fig. 5.2 CAREM-25 project.

Table 5.3 Major technical parameters [5].

№	Parameter	Value
1	Technology developer, country of origin	Korea Atomic Energy Research Institute (KAERI), Republic of Korea
2	Reactor type	Integral PWR
3	Coolant/moderator	Light water/light water
4	Thermal/electrical capacity, MW(t)/MW(e)	330/100
5	System pressure (MPa)	15
6	Core inlet/exit temperatures (°C)	296/323
7	Fuel type/assembly array	UO_2 pellet/17 × 17 square
8	Number of fuel assemblies	57
9	Fuel enrichment (%)	<5
10	Fuel burnup (GWd/ton)	<60
11	Fuel cycle (months)	36
12	Design life (years)	60

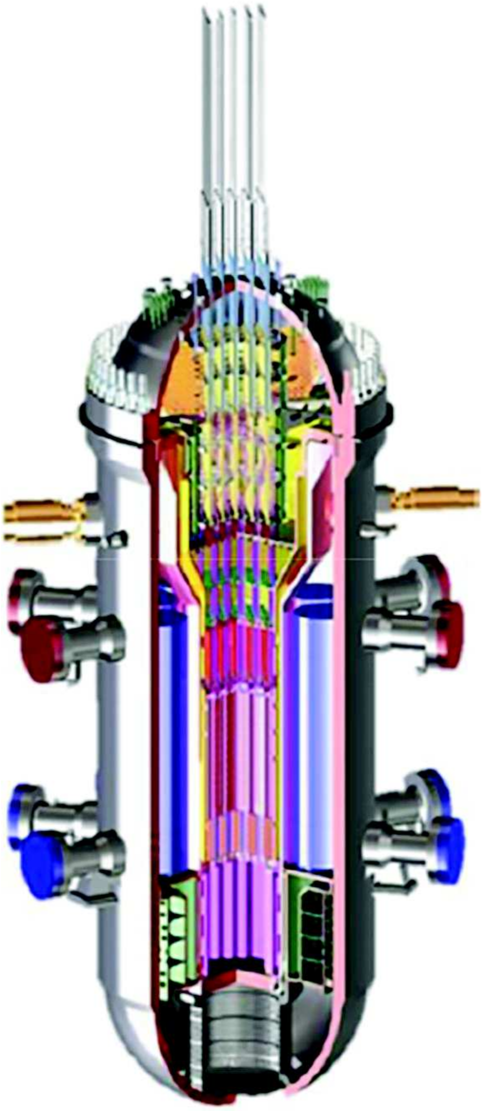


Fig. 5.3 SMART project [5].

The enrichment of uranium in SMART is typical for large PWRs, that is, no more than 5%. The reactor core is reloaded every 3 years. There are various approaches to the overload scheme. One of the options assumes that about half of the fuel assemblies will be removed during an overload. Reactor core is recruited from 264 square fuel assemblies with dimensions of 17 × 17 cm.

Control of reactivity in the course of the campaign is done by the control rods and boric acid. The fuel rods are provided with a burnable absorber. Removal of afterpower is carried out by a passive system PRHRS. It is designed to cool the reactor to 200°C for 36 h.

The project envisages eight once-through steam generators with helically coiled heat exchange tubes, in which superheated steam is produced. Transfer of the heat carrier is provided by four hermetic main circulation pumps.

5.3.1.4 ACP100

The advanced reactor system ACP100 developed by CNNC has a thermal capacity of 385 MW and an electric power of approximately 125 MW. It has an integral arrangement, but its content has evolved (Table 5.4).

Table 5.4 Major technical parameters [5].

№	Parameter	Value
1	Technology developer, country of origin	CNNC (NPIC/CNPE), People's Republic of China
2	Reactor type	Integral PWR
3	Coolant/moderator	Light water/light water
4	Thermal/electrical capacity, MW(t)/MW(e)	385/125
5	System pressure (MPa)	15
6	Core inlet/exit temperatures (°C)	286.5/319.5
7	Fuel type/assembly array	UO_2/17 × 17 square pitch arrangement
8	Number of fuel assemblies	57
9	Fuel enrichment (%)	<4.95
10	Fuel burnup (GWd/ton)	<52
11	Fuel cycle (months)	24
12	Design life (years)	60

In the initial construction of the design, the reactor core and 16 direct-flow steam generators were placed inside a single vessel; however, the reactor plant had an external pressurizer, external control systems, and four vertical pumps connected to the case with short nozzles. The recently developed version of the reactor (under the designation ACP100+) differs by internal electromagnetic control rods drives, internal pressurizer, horizontal external circulation pumps built directly into the reactor vessel, and a number of other features. The interval between fuel overloads is 2 years (Fig. 5.4).

The ACPR100 reactor developed by CGN has a thermal power of 450 MW and an electric power of 140 MW. It also has an integrated layout: the vessel combines the reactor core, pressurizer, and 16 direct-flow steam generators with spiral pipes. Eight vertical pumps of the primary circuit are attached to the outside of the vessel by short pipelines on the principle of "pipe in pipe."

The steam-generating unit with a height of 17 m is placed in a steel containment with a height of 22 m and a diameter of about 10 m, in which reduced pressure is maintained to reduce heat loss. The containment shell is completely submerged in a mine located below ground level. The reactor core has 69 fuel assemblies. The interval between overloads is 2.5 years.

5.3.1.5 IRIS

The IRIS project uses decades-proven approaches on the basis of which hundreds of tank-type water reactors were designed and built. But at the same time, the concept of IRIS introduced several innovative approaches (Table 5.5; Fig. 5.5).

This project, first of all, characterizes simplicity while caring for improving the safety, reliability, and efficiency of the structure. To ensure safety, an approach called "safety-by-design" (security through design solutions) is used. The modularity principle helps to improve economic performance.

Fig. 5.4 ACP100 project [5].

Table 5.5 Major technical parameters [5].

№	Parameter	Value
1	Technology developer, country of origin	IRIS
2	Reactor type	Integral PWR
3	Coolant/moderator	Light water/light water
4	Thermal/electrical capacity, MW(t)/MW(e)	1000/335
5	System pressure (MPa)	15.5
6	Core inlet/exit temperatures (°C)	292/330
7	Fuel type/assembly array	UO_2/MOX/17 × 17 square
8	Number of fuel assemblies	89
9	Fuel enrichment (%)	4.95
10	Fuel burnup (GWd/ton)	65
11	Fuel cycle (months)	48
12	Design life (years)	60

The number of personnel employed on the IRIS unit will be reduced to the required minimum. The construction period of such blocks will not exceed 3 years. Developers pay a lot of attention to the future decommissioning of IRIS; now, optimization calculations are conducted to reduce the dose burden on people who will be involved in reactor decommissioning work as much as possible.

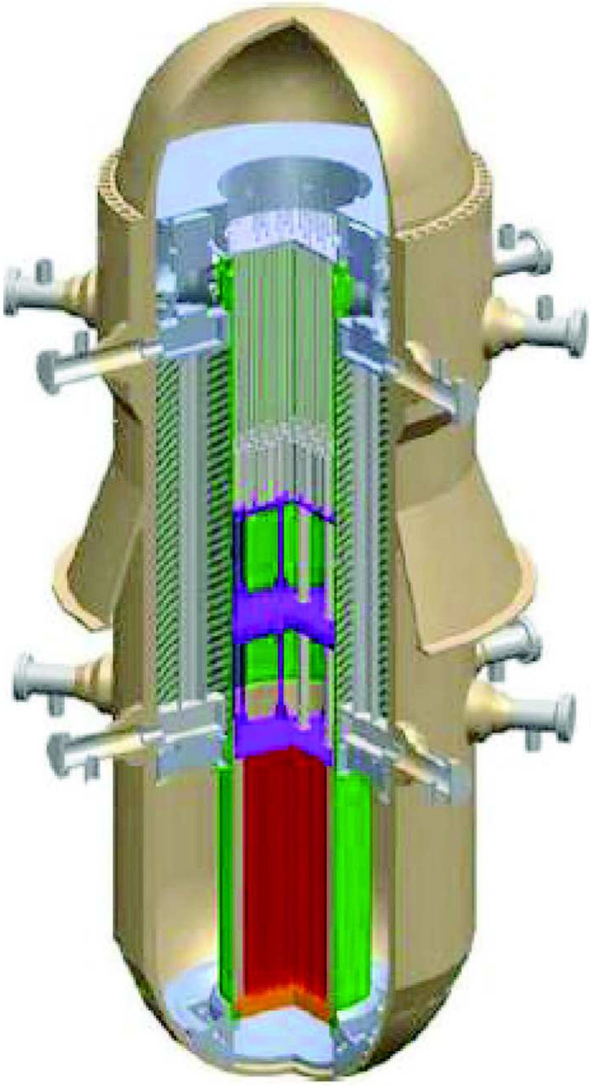


Fig. 5.5 IRIS project [5].

In the IRIS reactor, an integrated layout is used, in which all the main components of the primary circuit will be inside a single vessel including the reactor core with control rods drives, eight steam generators with eight main circulation pumps, and a volume compensator.

The larger volume-to-power ratio chosen for the IRIS volume compensator allows performance improvement of the reactor installation in transients, which is especially important for safety. Main circulation pumps installed inside the common vessel will not require any maintenance during operation. The absence of channels for control rods in the reactor lid eliminates the repetition of accidents such as Davis-Bess.

New design of steam generators will eliminate the corrosion that occurs under tensile stress (tensile stress corrosion). Measures have been taken to protect the vessel against the flux of fast neutrons; the vessel remains cold, and there will be practically no increase in the radioactive background beyond its borders. The size of the shell will naturally increase, but the dimensions of the containment of the block with the IRIS reactor will sharply decrease.

IRIS fuel cassettes are based on fuel assembly designs used in Westinghouse light water reactors. The initial 48-month fuel cycle is assumed.

The integrated reactor layout allows us to abandon large-diameter pipelines, which, in turn, reduces the threat of loss-of-coolant accidents (LOCA). Finally, a high vessel has a positive effect on the processes of natural circulation and provides a greater supply of water inside the system, necessary for cooling the reactor core in the event of an accident.

5.3.1.6 RITM-200

RITM-200 is a water-water nuclear reactor developed at the Afrikantov OKBM designed for installation on icebreakers and advanced floating nuclear power plants (manufacturer is ZiO-Podolsk) (Table 5.6; Fig. 5.6).

RITM-200 is made according to a dual circuit. A distinctive feature of the reactor are four steam generators integrated into the core body. Traditionally, steam generators are made in a separate housing connected to the core housing by primary coolant pipelines. The integrated layout reduces the material consumption and dimensions of the installation, reduces the risk of leaks from the primary reactor loop, and facilitates installation and dismantling of the installation. The four main circulation pumps are located around the reactor vessel. The reactor will have a thermal capacity of 175 MW, providing power on the shaft of the propulsion system of 30 MW (in the transport version) or 55 MW of electric (in the energy version). To comply with the principle of nonproliferation, uranium enrichment is limited to 20%. Fuel reload is every 7 years.

Steam production (248 t/h) is carried out according to a two-circuit scheme, which has been traditionally used in nuclear energy by transferring heat from the water of the primary circuit to the steam of the secondary circuit in a steam generator.

Table 5.6 Major technical parameters [5].

№	Parameter	Value
1	Technology developer, country of origin	Afrikantov OKBM, Russian Federation
2	Reactor type	Integral PWR
3	Coolant/moderator	Light water/light water
4	Thermal/electrical capacity, MW(t)/MW(e)	175/50
5	System pressure (MPa)	15.7
6	Core inlet/exit temperatures (°C)	277/313
7	Fuel type/assembly array	UO_2 pellet/hexagonal
8	Number of fuel assemblies	199
9	Fuel enrichment (%)	<20
10	Fuel burnup (GWd/ton)	65
11	Fuel cycle (months)	–
12	Design life (years)	60

Fig. 5.6 RITM-200 project [5].

Reducing neutron fluence on the vessel allows us to increase the radiation resource of the steam generator vessel and reduce the temperature during hydraulic tests.

Security systems operate on an active and passive principle. Security of reactor RITM-200 is based on the following principles:

- high heat storage capacity
- natural circulation of primary coolant sufficient for cooling of the reactor
- the minimum length of the pipelines of the primary circuit
- use of flow limiters in small branch pipes
- a large volume of the primary coolant in the reactor vessel increases the time reserve before the core dries in accidents with loss of primary coolant

5.4 Safety strategy

Despite the rather high requirements for safety at modern nuclear power plants, these requirements are increasing annually. The small linear dimensions of the NPPLP reactors and the small stored energy make it possible to use other approaches and design solutions for the main systems, in contrast to those acceptable for high power reactors. The deterministic level of safety of their operation requires significantly less engineering security systems. It is provided not by the action of safety or localizing systems, but by eliminating their occurrence, as such, based on the rational use of the laws of nature, including negative feedbacks in reactor physics.

All modern developed projects NPPLP provides increased security of operation. Some of them additionally provide for long-term work without reloading the fuel, which will contribute to increased protection against the spread of fissile materials, the adoption of adequate measures, and guarantees nonproliferation in the scenario of global large-scale development of nuclear energy. These projects combine the advantages of many proven technologies: fuel, coolant, and converters of energy, which allow you to work reliable and safely in any geological and climatic conditions. Briefly consider the security systems used in modern NPPLP project.

5.4.1 Residual heat removal system

One of the solutions used today in NPPLP projects is the organization of the removal of residual energy release through steam generators and heat exchangers, recessed into the water basin (tank). Due to the residual energy release in steam generators, steam is generated, which goes to the heat exchanger in the tank, where it condenses. In turn, the condensate is returned to the steam generator through the feedwater line.

This solution is used in the passive emergency heat removal system (EHRS) of emergency reactor core cooling in the IRIS project, the passive removal system (PRHR) of residual heat removal in the SMART project; and the decay heat removal system (DHRS) of the “NuScale” project [6].

Instead of or together with heat removal through the steam generator, in some projects of the NPPLP, an approach using a technological condenser, similar to those that can be seen in BWR projects, has been applied. The condenser heat exchanger is located in the water tank and is connected to the reactor vessel. Inside the reactor vessel in the reactor core, steam is generated due to the residual heat, which goes through the pipeline in the upper part or case cover. The steam enters the condenser-heat exchanger, condenses, and returns to the reactor vessel.

Cooling of the reactor core in this case takes place by natural circulation of steam, and condensate is returned to the reactor core by gravity. As in the previous solution with a steam generator, there are valves in the line to actuate the line. The solution with the condenser is applied in the CAREM25 and “NuScale” projects [7].

5.4.2 High-pressure injection system

High-pressure injection systems in NPPLP projects are, as a rule, disposable systems that provide injection of a certain volume of water with boric acid into a reactor. Water is stored in a tank, where it is under pressure created by nitrogen or other inert gas.

From the bottom of the tank, a pipeline departs to the reactor vessel. The pipeline has a shut-off valve that opens when the pressure in the housing drops below the pressure in the tank.

The purpose of such systems is to provide a single injection of water to compensate for its loss in the reactor vessel during LOCA accidents. As a rule, high-pressure injection systems should work out in the period before the start of active water supply systems in the reactor vessel.

The modification of this solution is used by “Westinghouse” in the IRIS and “Westinghouse SMR” projects. In these projects, a tank with a supply of water with a solution of boric acid is installed above the reactor vessel. The upper part of the tank is connected to the reactor with a pipeline with an open valve in normal operation. From the bottom of the tank, the pipeline leaves with a closed valve. In an emergency situation, the valve in the lower pipeline opens and water with boric acid is drained into the reactor vessel by gravity, providing cooling of the core and the introduction of negative reactivity.

In contrast to the “Westinghouse” projects, in the SMART project (South Korea), water with boric acid from the storage tank is injected into the reactor vessel by means of a high-pressure electric pump.

RCIC systems (core cooling systems in isolation) can be found in NPPLP projects, characteristic of the BWR. In such systems, steam from the core triggers a small turbine that drives the pump and, with the help of the pump, water is pumped from the battery tank at high pressure.

Such systems were installed on the reactors of the Japanese NPP “Fukushima Daiichi” with the exception of the first one, which used a technological condenser. Systems operate in cases when the reactor is isolated from the turbine during an emergency [7].

5.4.3 Low-pressure injection system

Active and passive low-pressure injection systems are widely used in modern and prospective high-power reactor designs. Thus, in the APR-1400 and ATMEA-1, an active injection system with a low-pressure pump from a pool (tank) located inside the containment is implemented. It is supposed to be used in case of large accidents of the LOCA type, when the pressure in the reactor vessel is low, and the loss of coolant is large. The system should be switched on after the high-pressure injection system has been activated.

In the passive version, which can be seen in an economic simplified boiling-water reactor (ESBWR; GDCS system), water enters the reactor from a tank located at a higher level under the action of gravity. However, the efficiency of the system can be reduced in cases where a sufficiently large amount of steam is generated in the reactor core.

In the Argentinean ASMM CAREM25 project, the EIS system has implemented low-pressure water injection from a pressure tank. The tank contains a supply of water with boric acid and is connected to the reactor vessel. The task of the system is to prevent core drainage during accidents of the LOCA type.

Under normal operating conditions, the tank is insulated from the rupture disk. In the event of an LOCA accident, when the pressure in the reactor vessel decreases to 1.5 MPa, the membrane breaks and the water supply to the reactor vessel from the tank begins.

The “NuScale” project implemented the following solution with the use of valves: in the event of an accident, steam from the reactor vessel is vented to the containment vessel through open vent valves in the upper part of the reactor vessel. Steam is cooled on the inner surface of the containment vessel. The containment vessel itself is located in the water basin, where the heat from the cooled steam is transferred. Inside the container, cooled condensate accumulates in the lower part.

Recirculation valves are installed at a certain point at the bottom of the containment vessel. After the water level (condensate) in the container reaches the level of the recirculation valves, they open and the water returns to the reactor. Thus, the “NuScale” project implemented natural circulation in severe accidents between the reactor vessel and the containment vessel [7].

5.4.4 Containments

The temperature and pressure inside the container must be maintained within the limits specified by the project. Pressure compensation in the CAREM25 project use the pressure suppression pool. Steam from the reactor is sent to a bubbler where it condenses.

In the SMART project, the pressure inside the containment vessel is compensated using a sprinkler system. Sources of water for the system can be both inside and outside the container.

In the previous two cases, it was about concrete containers. “NuScale” and “Westinghouse SMR” projects practice a different approach—the reactor plant is placed in a metal containment vessel, relatively far from the external concrete structures. The space between the metal container and concrete structures can be filled with water, which provides heat removal from the metal container.

The mPower project uses a solution for cooling metal containment, which is close to the solution from the AP-1000 project. In this solution, the metal container is passively cooled either by an air flow or by a sprinkler system. In the mPower project, they selected a water-cooling option [7].

5.4.5 Systems that mitigate the consequences of accidents

In many NPPLP projects—in particular, SMART, IRIS, and mPower—the same approach is adopted as in the AP-1000, namely, retention of corium in the reactor vessel is made by external cooling of the reactor vessel with water. This strategy is known as an in-vessel retention (IVR) strategy, i.e., cooling inside the vessel.

The practical implementation of the IVR approach is obvious. The reactor shaft is filled with water so that the lower part of the reactor is always below the water level. The IVR strategy must be supplemented with measures to cool the containment—a constant presence of water in the mine should be ensured, which ensures reliable cooling of the corium and no damage to the reactor vessel.

An alternative approach is to use a melt trap, but it is more typical for high-power reactor designs. Of the promising projects, there is a trap in ATMEA-1. A trap variant called “BiMac” is used in the ESBWR project.

To prevent hydrogen explosions during severe accidents with the melting of the reactor core, many NPPLP projects provide for passive catalytic hydrogen recombiners—in particular, in the SMART, mPower, IRIS, and CAREM25 projects.

In the IRIS project, the hydrogen control system is connected to a nitrogen supply system in the containment to displace oxygen.

Also, in most of the NPPLP projects, a system of ventilation of the containment with filters is provided, which allows detainment of a significant part of radioactive substances when they are discharged into the atmosphere [7].

5.4.6 The summary of the safety strategy of the SMRs

The designers of advanced SMRs implement safety design options with the maximum use of the inherent and passive safety features (also called "by-design" safety features) possible for a given technology line and for a given size of the plant.

On their own, the "by-design" safety features used in SMRs are not size dependent in most cases and could be applied to reactors of larger capacity. However, SMRs offer broader possibilities to incorporate such features with a higher efficacy. As noted, smaller reactor size contributes to a more effective implementation of the inherent and passive safety design features because of:

- Larger surface-to-volume ratio, which facilitates easier decay heat removal, especially with a single-phase coolant.
- Reduced core power density, facilitating easy use of many passive safety features and systems.
- Lower potential hazard that generically results from lower source term owing to a lower fuel inventory, lower nonnuclear energy stored in the reactor, and lower integral decay heat rate.

All of the presented SMR designs aim to meet the current national regulations and generally meet the international safety norms, such as that formulated in the IAEA Safety Standard NS-R-I, regarding implementation of the defense-in-depth strategy, and provision of the redundant and diverse active and passive safety systems.

The core damage frequencies (CDFs) indicated by the designers of advanced SMRs are within the range from 10^{-5} to 10^{-8} per annum, i.e., are comparable to or lower than the ones indicated for the state-of-the-art large-capacity water-cooled reactors. The upper boundary (10^{-5}) mainly results from the risks associated with nonconventional deployment (e.g., floating power plants) [8].

5.5 Conclusions: SMR, an opportunity to be confirmed

5.5.1 Harmonization

The nuclear industry as a whole, and SMR in particular, is characterized by a high degree of international cooperation, and the discussion of the harmonization of nuclear regulatory standards is reaching a new level. Let us consider why such harmonization is needed, how the convergence of regulatory approaches may look in practice, and at what stage this work is at now.

A pioneer of harmonization standards regulation has been the company Areva. In fact, the prototype of Multinational Design Evaluation Programme (MDEP) was created in 2005 precisely to enable regulators in France, Finland, and the United States to exchange technical data during the certification of the EPR reactor developed by the French group. It is no secret that security requirements vary in different countries, which determines the nature of work with national regulators.

The MDEP program, which is currently being implemented under the auspices of the NEA/OECD, brings together regulators. Since 2005, the circle of its members has expanded to include Canada, China, Japan, South Africa, South Korea, Russia, and the United Kingdom in the meetings of the MDEP and the IAEA.

The goal of the program is to bring together codes, standards, and security tasks. It is assumed that at the next stage, considering past experience, similar work will be carried out on new types of reactors, including generation IV. In essence, MDEP is a platform where national regulators share technical data, regulations, and standard practices to avoid duplication of work.

The industry has merged into the Cooperation in Reactor Design Evaluation and Licensing group (CORDEL), which cooperates in evaluating reactor projects and licensing. This working group exists on the basis of the World Nuclear Association (WNA); its goal is to stimulate dialogue between the industry and regulators to bring together safety standards around the world. In particular, the group analyzes the benefits of creating internationally recognized standards in relation to reactors of generations III and III +.

The ideal sought by CORDEL is the creation of a regulatory environment throughout the world in which globally recognized standardized reactor designs could be widely implemented without significant changes, except for those dictated by the specifics of the site.

CORDEL has formulated the benefits of project standardization. First, it will lead to increased security. After all, the general database on reliability will consider the entire experience of operating the reactor fleet at all stages of the life cycle of the facility during the design. The projects of the new stations will also consider the latest technologies; each new station will be cheaper than the previous one built on the same project. The repetition of techniques and methods of construction will have a positive impact on its quality.

Second, the global fleet of standardized reactors assumes the potential to increase operational efficiency, improve availability factor and installed capacity utilization factor, and improve maintenance performance. A positive operating experience will be extended immediately to all stations of the park, which will make it possible to strengthen safety on an ongoing basis. Customer service will be able to easily navigate between the stations and clearly focus on their tasks.

Moreover, if a fleet of reactors of a company is part of a wider network of reactor units—national or international—this provides additional benefits in the form of exchange of experience, internal benchmarking, and identification of best practices for the purpose of their replication.

Of course, CORDEL also sees risks. In the scenario of global implementation of a limited number of standardized projects, detected design flaws will affect the entire fleet of reactors of a specific design. But when scaling up (creating a larger number of reactors of the same type), a compensating effect will arise; the probability of early detection of a project flaw will be much higher due to the rapid accumulation of experience and exchange of knowledge during the examination of projects, tests, and operation.

Of course, identifying a significant common flaw will create serious economic problems for the operator. For example, retrofitting (addition) a large number of reactors at the same time can lead to a shortage of electricity due to shutdown. The industry will not be able to produce the required number of components simultaneously. However, this issue is no longer related to security, WNA analysts say. And they propose comparing the small probability of this risk with the large economic benefits from standardization.

For regulators, the benefits are as follows. The convergence and harmonization of national standards will contribute to their international cooperation. Regulators will be able to share the methods and data obtained during the examination of projects, which will allow them to increase their effectiveness. The transfer of data on all regulatory issues, including practices, will contribute to the development of civilian nuclear energy in developing countries where regulatory regimes are not yet well established. However, such cooperation will become possible only after achieving a high degree of convergence of standards and norms at the international level.

An area in which close cooperation based on harmonized regulatory requirements is urgently needed is quality control in construction and in the production of components. Against the background of a large number of contractors and subcontractors from all parts of the world involved in the construction of new NPPs, the cooperation of regulators on this issue is important for the management of production supervision.

The harmonization process can improve regulation as such: regulators will understand why foreign partners have chosen a particular solution. Together, regulators will be able to choose the most reasonable and convincing solutions.

Last but not least, harmonization of safety standards will have a positive effect on public confidence in regulatory decisions.

The convergence and harmonization of national standards will allow for greater international regulation and cooperation. Regulatory design assessments that are central to national licensing processes will become more effective [9].

5.5.2 Licensing of new technologies

The trend toward harmonization of regulatory standards is observed against the background of a new task facing regulators—the licensing of innovative reactor technologies. A case in point is Canada, where in recent years fertile ground has been created for licensing SMRs of various designs [10].

In this regard, a number of problems appear before the regulator. SMRs are completely different in terms of technology. It is argued that these reactors will provide a high level of safety, but to achieve this goal, the project encompassed many innovations. These innovations have already become widespread in other industries but are not at all mandatory for reactors—for example, increased automation.

The integration of new innovations, such as new types of coolant like molten salt, sodium, gas, and the widespread use of passive safety elements, creates significant problems in the modeling and implementation of safety justifications. The definition of “small modular” is actually just a general designation for the type of reactors. Each project has its own characteristics: one may be based on a remotely controlled reactor with a minimum of personnel, whereas another is a transported power unit.

By and large, SMRs is a park of different reactors that requires increased attention from regulators when issuing licenses for building prototypes, because this technology will be used again and again [11].

5.5.3 *Public trust*

Another key issue of concern to both regulators and the industry is increasing public acceptance. Public trust is vital for the sustainable development of nuclear power.

A high degree of trust is achievable under three conditions:

- availability of responsible industry with reliable internal regulation;
- strong and independent regulator;
- public awareness.

Any initiatives to build new blocks fall under the public eye. After the accident at “Fukushima Daiichi NPP”, more attention is paid not to the construction of new units but to the reconstruction of existing facilities, decommissioning, and waste management, and now there is also an interest in SMRs. Issues of prevention and elimination of severe accidents and emergency situations are also in the foreground.

Against this background, the transparency of regulation is not just big words and propaganda slogans. The Commission regularly holds public hearings and meetings where members of the public, indigenous peoples, environmentalists, industry associations, trade unions, and academics can contribute to the EIA assessment and influence licensing decisions.

In the United Arab Emirates, where the first nuclear power plant in the history of the country is being built, the population shows great interest in information about the benefits and risks of using atomic energy, and what regulators are doing to protect society. Therefore, one of the fundamental principles of the Federal Authority for Nuclear Regulation (FANR) is transparency.

The organization pays a great deal of attention to informing all government departments, because “they have a great influence on society”; FANR has already concluded many memorandums of understanding with various national organizations responsible for customs, defense, security, environmental protection, and health care. All this is done with one goal—to convince people that the main task of FANR is to ensure their safety [9].

References

[1] A.A. Sarkisov (Ed.), Low-Power Nuclear Power Plants—A New Line in the Development of Power Systems, In: vol. 2, Academ-Print, Moscow, 2015. ISBN 978-5-906324-04-7, 387 pp [in Russian].

[2] V. Kuznetsov, A. Lokhov, Current Status, Technical Feasibility and Economics of Small Nuclear Reactors, Nuclear Energy Agency Organisation of Economic Cooperation and Development, Paris, 2011.

[3] J. Augutis, et al., Small Reactors Without On-Site Refuelling: Neutronic Characteristics, Emergency Planning and Development Scenarios, IAEA-TECDOC-1652, 2010.

[4] Small Nuclear Power Reactors, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

[5] IAEA, Advances in Small Modular Reactor Technology Developments, (2018).

[6] D.T. Ingersoll, Passive safety features for small modular reactors, In: 43 Session on the International Seminars on Planetary Emergencies—The Role of Science in the Third Millennium, Oak Ridge National Laboratory, United States, 2010.

[7] M. Alamgir, et al., Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from the Fukushima Daiichi Accident, IAEA-TECDOC-1785, 2016.

[8] OECD NEA, Current Status, Technical Feasibility and Economics of Small Nuclear Reactors, (2011).

[9] Standard Utopia, http://atomicexpert.com/page1926263.html/.

[10] M.V. Ramana, L.B. Hopkins, A. Glaser, Licensing small modular reactors, Energy 61 (2013) 555–564.

[11] Small Modular Reactors/Siting and Licensing in Washington State, Prepared for: Washington State Energy Facility Site Evaluation Council, Golder Associates, January 2016.