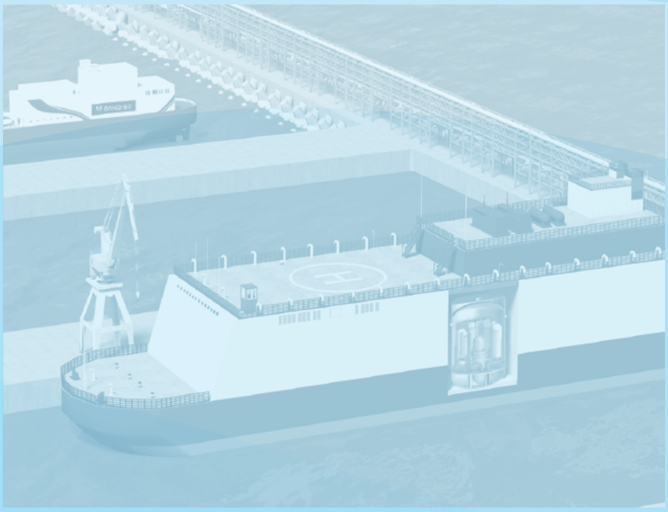
Small Modular Reactors for Marine-based Nuclear Power Plant

Technologies, Designs and Applications

A supplement to:

IAEA Advanced Reactors Information System (ARIS)



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Foreword

There has been growing interest in marine-based Small Modular Reactors (SMRs) as a solution to accelerate the transition towards net zero emissions using nuclear power – for applications in the regions for which land-based nuclear power installations would not be viable. Marine-based SMRs can be deployed as offshore barge-mounted floating power units as well as immersible power units. While marine-based nuclear power plants have been around since the mid-1960s, in naval facilities and nuclear icebreakers, the development of marine-based SMRs for various applications has been gaining momentum in recent years. Some marine-based SMR designs have reached advanced development stages. More countries are considering introducing marine-based SMRs to niche markets.

Marine-based SMRs have the potential to play an important role in providing cogeneration of electricity and heat to remote, off-grid communities where large reactors or land-based power plants are not practical. The smaller footprint and transportability of SMRs enable flexibility in siting and provide more deployment options. As some of the in-land SMR concepts, the marine-based SMRs can also be deployed to produce hydrogen to fabricate synthetic fuels for the transportation sector, and with their unique features to power offshore oil and gas extraction as well as for the remote islands – currently powered by diesel generators.

This booklet presents public information on several marine-based SMR designs and technologies that are in operation, under development for near term deployment as well as prospective designs for future deployment. The booklet aims to highlight design features, potential applications, and opportunities for the development and deployment of marine-based SMRs. The updated information presented in this booklet will serve as a valuable source of information for Member States interested in the development and deployment of marine-based SMRs.

"A key advantage of marine-based SMRs is that they can be built in a factory, assembled in a shipyard and then delivered to remote sites or exported to other countries and can be sited in remote, off-grid communities to enhance the access of such communities to clean electricity and heat."

– Mikhail Chudakov, Deputy Director General, Department of Nuclear Energy, IAEA

Opportunities for Marine-Based SMRs

Contributing to Net Zero Emissions

Decarbonization of the energy sector is closely related to net zero emissions as it is a global effort aimed at climate change mitigation and reducing anthropogenic greenhouse gas emissions. In addition to land-based large Nuclear Power Plants (NPPs) and SMRs, marine-based SMRs have the potential to replace fossil alternatives in remote regions, without any need to prepare for new inland NPP siting.

Reliable and Sustainable Power Supply

Nuclear power has the capability of being available twenty-four hours a day, seven days a week and secure national power supply. It applies to_land-based nuclear power plants, marine-based SMRs, which can be deployed as reliable, resilient, and sustainable part of the energy supply mix in specific applications and regions for which land-based NPPs would not be viable.

Deployable in Remote Areas with Mining

Marine-based SMRs can be readily deployed in remote areas currently powered by small fossil power plants, particularly diesel generators. They can be fabricated in factory, assembled in a shipyard and transported to remote islands, coastal areas and offshore oil and gas facilities, e.g. rigs.

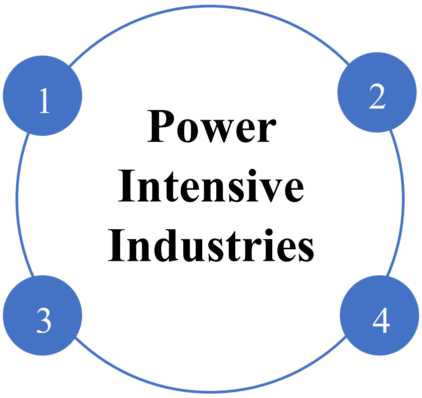
Nuclear-Renewable Hybrid Energy System

In the marine context, via integrating marine-based nuclear power and renewable resources (e.g., marine solar panels, offshore wind turbines), it could improve power grid stability considering the rising variable renewable capacity. The coupling of nuclear and renewable energy sources could serve electricity and cogeneration purposes.

Opportunities for Marine-Based SMRs

Offshore Oil and Gas Platforms

The power needs of offshore oil and gas platforms are on the scale of 1 MWe – 10 MWe. The existing power supply to them most commonly comes from diesel generators. Marine-based SMRs in floating nuclear power plants can provide reliable clean power supply bringing a strong impact to the sector's carbon emissions.



Shipbuilding and Commercial Ports

The shipbuilding industry is part of the supply chain in safe and secure delivery of marine-based nuclear power plants. The collaboration between reactor design organizations and shipbuilding companies is pivotal. The technological advancements open the option of exploring nuclear power for commercial ports.

Deep-sea Mining

A growing interest rises in deep-sea mining, a relatively nascent industry, to retrieve raw materials deposits (e.g. lithium, nickel, cobalt, rare earth elements) from the deep seabeds at depths of 1 000 meters and greater. Marine-based SMRs could provide safe, secure, and sustainable power to the deep-sea mining operations.

Desalination

The support for seawater desalination using nuclear energy has already accumulated over 200 reactor·years' operating experience worldwide. Marine-based SMRs' application is a viable option to meet the growing demand for potable water and provide hope to the areas with water shortages in coastal arid and semi-arid zones.

Current Status

Eight water cooled marine-based SMRs and one molten salt marine-based SMR are listed as marine-based SMRs in the 2022 IAEA SMR Booklet, which includes in total 83 SMR designs under development and deployment worldwide. Lately NuScale design started engaging in marine applications. The Pressurized Water Reactor (PWR) type KLT-40S, designed by JSC "Afrikantov OKBM" is already successfully deployed in the "Akademik Lomonosov", being the first floating NPP which started commercial operation in Pevek of Russian Federation in May 2020. Floating power units with the RITM-200 series reactors, designed by the JSC "Afrikantov OKBM", are expected to be commercially available for the medium and long terms. Other marine-based SMR designs are under different stages of development in countries in Asia-Pacific, North America, and Europe.

> "Member States' efforts in the development and deployment of marine-based SMRs reflect a rise of interest in enabling affordable use of nuclear energy extended to the coastal and offshore applications."
>
> *– Aline des Cloizeaux, Director, Nuclear Power Division, IAEA*

Asia-Pacific

In Pevek on the Chukotka peninsula close to the East Siberian Sea in Chaunskaya Bay, the "Akademik Lomonosov" Floating Nuclear Power Plant (FNPP) with two 35 MWe KLT-40S reactors was connected to the grid in December 2019 and started commercial operation in May 2020. It provides electricity, hot water for central heating to the region. It was designed to replace Chukotka's oldest coal fired Chaun thermal power plant which started operation some eighty years ago. The RITM-200M, derived from the latest Russian icebreaker projects, is adopted for the Optimized Floating Power Units, which are considered as the second generation of marine-based SMRs. Six RITM-200 reactors have already been successfully installed in icebreakers Arktika, Sibir and Ural. The State Atomic Energy Corporation "Rosatom" and industrial TSS Group plans to establish a joint venture "Energoflot" on a parity basis of at least 100 MWe and a service life of up to 60 years for foreign markets. The ABV-6E although in its finished final design, it has not yet been licensed. The VBER-300, a unique design completely relying on passive safety systems, is in the stage of completing its basic design documentation. The SHELF-M is targeted to start construction in 2025 and to be commissioned in 2030.

The basic design of the ACPR50S has been completed. It is currently under design optimization; various experiments were performed for design validation. Under basic design, the ACP100S is considered for the site near Yantai in Eastern China's Shandong province.

The BANDI-60 is under conceptual design with the plan for its construction to start in 2030.

Status of Marine-based SMR Designs

In operation:

- KLT-40S

At detailed design stage:

- ACPR50S
- RITM-200M
- ABV-6E
- VBER-300
- NuScale Power Module (Prodigy MPS)

At basic design stage:

- ACP100S
- SHELF-M

At conceptual design stage:

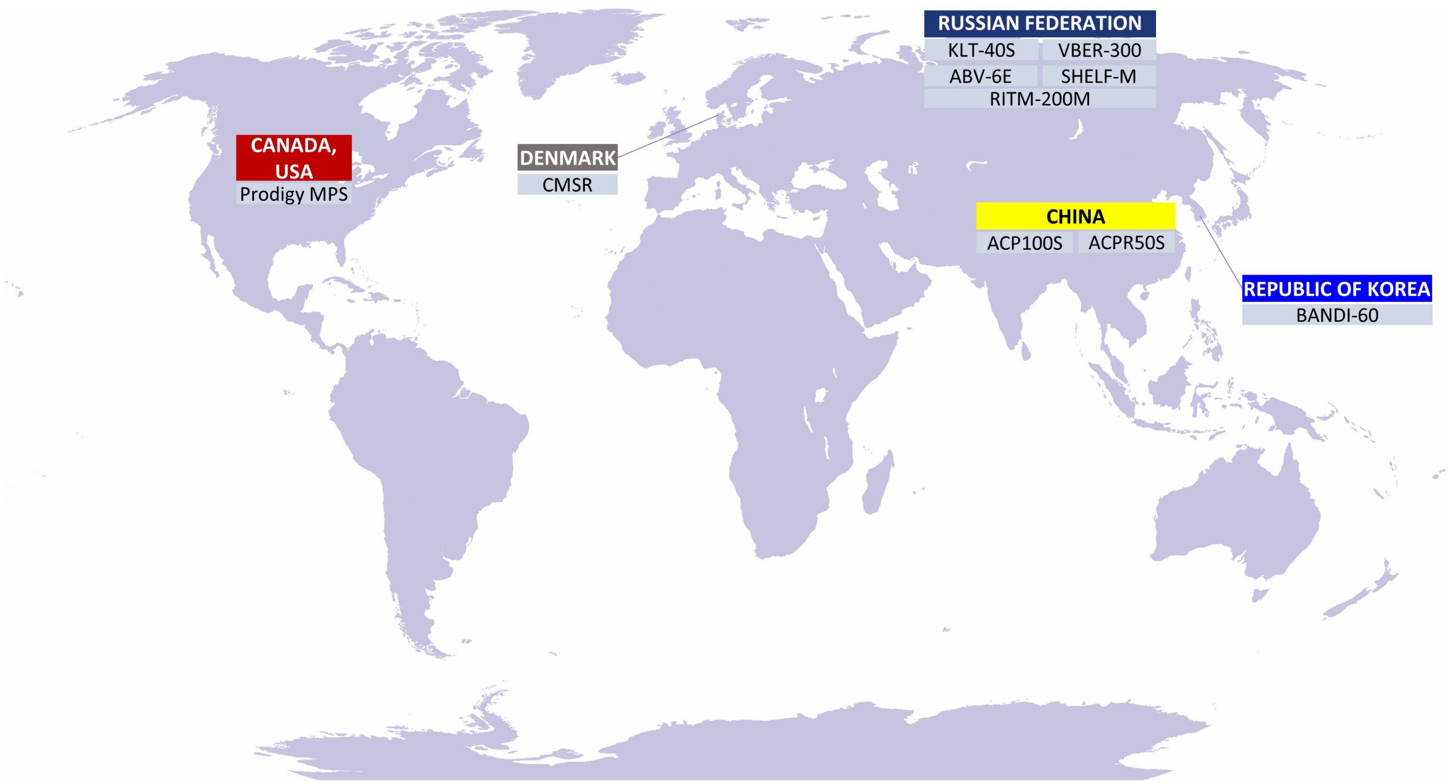
- BANDI-60
- CMSR

North America

The NuScale Power Module™ (NPM) is a small, light water-cooled PWR. The concept is scalable and can be built to accommodate a varying number of NPMs, thus meeting customer's energy demands. In August 2020 NuScale received standard design approval from the U.S. Nuclear Regulatory Commission (NRC). In November 2021, a Memorandum of Understanding (MOU) was signed by NuScale Power and Canada's Prodigy Clean Energy Ltd. and Kinectrics Incorporated to explore and inform the development of a regulatory framework to address licensing and deployment of a Prodigy Marine Power Station (MPS). NuScale would be able to integrate 1 – 12 NPMs for a total output of up to 924 MWe for the Prodigy MPS.

Europe

The Compact Molten Salt Reactor (CMSR), designed by Seaborg Technologies in Denmark, is an advanced, small, and modular molten salt reactor specific to using a liquid fluoride molten salt fuel and a liquid patented molten hydroxide moderator. It took the decision to change the fuel type for the first CMSR product line to Low-Enriched Uranium (LEU) due to the risks associated with developing a sufficient supply of High-Assay-Low-Enriched Uranium (HALEU) to meet Seaborg's timeline. It is currently under conceptual design, planning to complete the design in 2026 and to deliver the first CMSR power barge in 2028. In April 2023, Seaborg, KHNP, and Samsung Heavy Industries (SHI) announced consortium to develop CMSR based FNPP. In June 2023, Seaborg announced a collaboration with Korea Electric Power Corporation Nuclear Fuel and GS Engineering & Construction to investigate the feasibility of developing a LEU fuel salt production facility in the Republic of Korea.



GLOBAL SMR TECHNOLOGY DEVELOPMENT AND DEPLOYMENT

China, Denmark, Republic of Korea, Russian Federation, Canada and the USA are designing marine-based SMRs. Some other countries are pursuing and developing opportunities relative to the marine-based SMR technology development and deployment through the international cooperation.

Major Applications of Marine-Based SMRs

Marine-based SMRs can play a role in decarbonising industries in marine environment and niche markets for which land-based NPPs are not practical or economically viable.

Production of hydrogen, ammonia, synthetic fuels for maritime transport and transport fuels. The International Energy Agency predicts that by 2050 about half of the world's shipping fleets will be propelled by green ammonia. According to the US Department of Energy, one ammonia-fueled ocean vessel would require about 11,772 ton of clean hydrogen annually. Clean ammonia requires a lot of hydrogen. The shipping sector, facing competition from the broader fertilizer sector for ammonia, is exploring all available supply options.

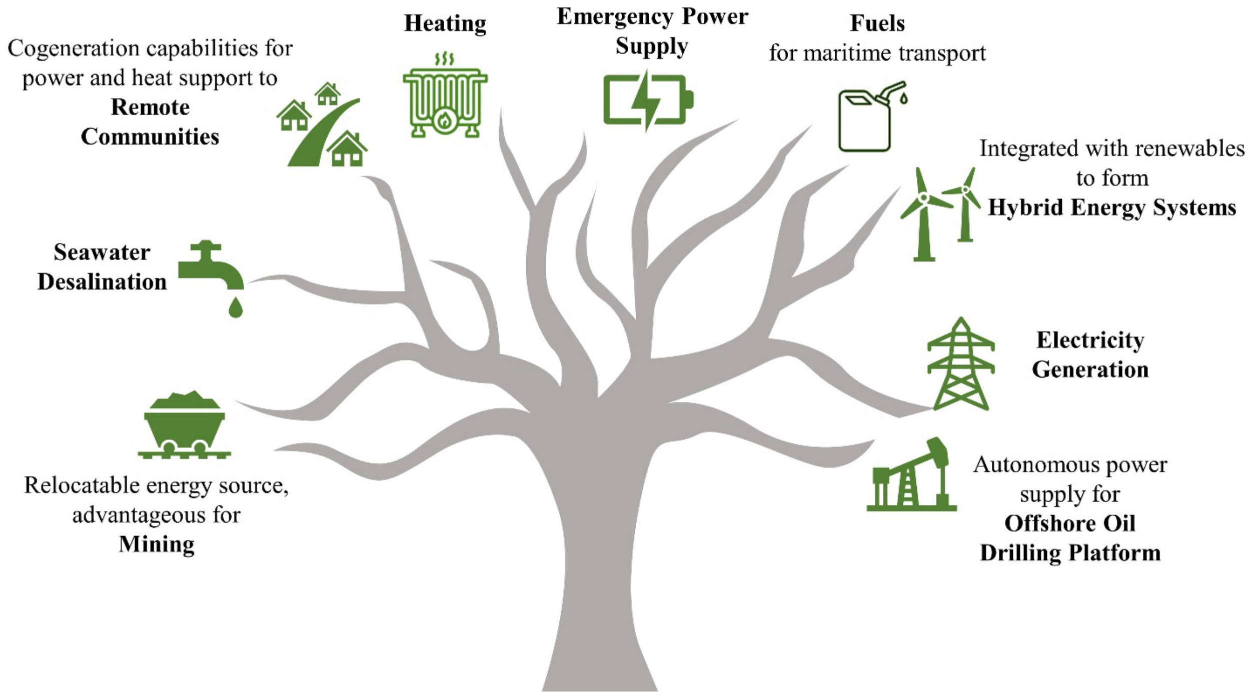
Hybrid energy systems. The volume that can be used and the marine ship's overall weight carrying capacity are constraints on the penetration of renewables. Due to the constraints of renewable energy in marine ships, it is necessary to combine renewable energy with other energy sources to meet baseload energy demands and eliminate the intermittent nature of renewable energy. SMRs, including microreactors, can be included into hybrid energy systems to produce power with essentially zero carbon emissions.

Powering off-shore platforms. For offshore installations and facilities located in distant or offshore locations, marine-based SMRs can lessen reliance on diesel generators or power connections from the coast by supplying a reliable and independent power source.

Remote communities. In remote communities where access to traditional power grids is limited or not available, these reactors can be used as reliable source of electricity and heat. These communities often rely on diesel generators, which are expensive and not environmentally friendly.

Seawater desalination. Desalination requires a significant amount of energy to convert seawater into freshwater. Marine-based SMRs can provide a stable and continuous power source for desalination, particularly in coastal areas with fresh water scarcity.

Vessel propulsion. Marine vessel propulsion by clean nuclear energy would accelerate the decarbonization of a sector struggling with heavy fossil fuel use and associated carbon emissions. In order to achieve net zero emissions by or near to 2050, the shipping sector recently agreed on new targets for greenhouse gas emission reduction through the International Maritime Organization.



MAJOR APPLICATIONS OF MARINE-BASED SMRS

Technical Aspects

General Considerations

Marine-based SMRs and land-based SMRs share similarities in many technical aspects, for example, the use of passive safety systems, and mitigation or prevention of human errors. They need to be small enough to fit into the confined reactor compartment of the barge. The sketch on this page illustrates the dimensions of the "Akademik Lomonosov" where two KLT-40S SMRs generating 35 MWe each are installed.

Specific Considerations for Marine-Based SMRs

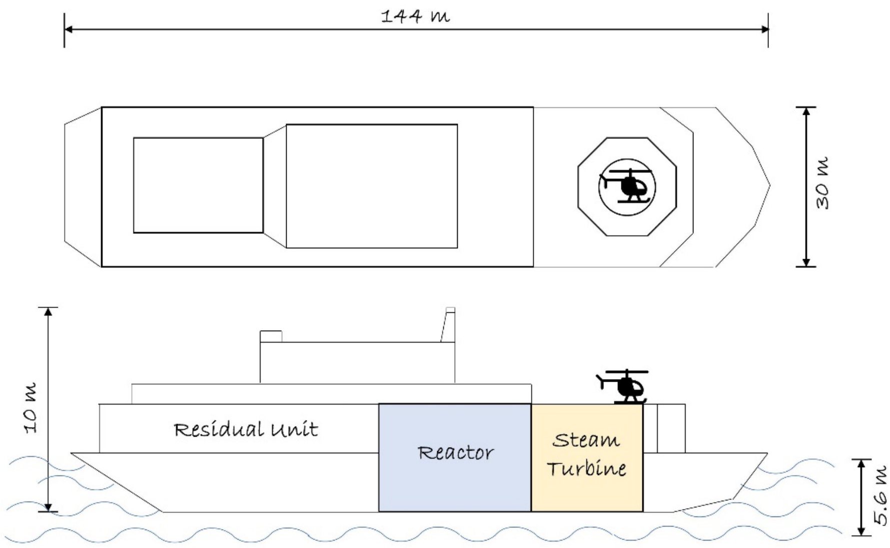
Design Simplifications. In order to decrease complexity and thus reduce manufacturing and maintenance cost, marine-based SMRs designs usually eliminate large piping, and reduce penetrating components. The design simplifications in consideration open up the prospect of assembly-line manufacturing of pre-fabricated module.

Safety Features. A mix of active and passive safety features enhance the safety of the reactor respectively in the cases of loss of power supply in an accident scenario. PWR type marine-based SMRs are designed with proven safety systems, including the emergency shutdown system.

Fuel Options. Nuclear fuel in marine-based SMRs is usually at higher uranium enrichment comparing to that in traditional land-based commercial reactors. For PWR type marine-based SMRs, some adopt LEU fuels (e.g. ACP100S, BANDI-60) while some others head for HALEU fuels (e.g. KLT-40S, ABV-6E, RITM-200M). For non-PWR type marine-based SMRs, LEU and HALEU may respectively be considered for short-term and long-term targets. Currently Russian Federation is the only viable commercial supplier of HALEU. However, other countries are also seeking the capabilities of providing HALEU for SMRs.

Long Refuelling Cycle. The refueling cycle needs to be commensurate with the deployment scheme and high load factor aim. Therefore, in all designs, it is usually no shorter than 24 months and can even be close to 144 months. For PWR type reactors, a single batch fuel loading is adopted, which means all fuel assemblies are discharged at the end of the refuelling cycle. For Molten Salt Reactor type reactor, there is no refuelling for 12 years. In Russian Federation consideration is given to non-refuelling on site option. It is based on four FNPPs party: three are operated on site, one is put into operation to substitute the one to be transported to centralized service facility for maintenance and refuelling.

Spent Fuel and Waste Management. The back-end fuel cycle option for spent fuel depends on the plant owner's policy and requirements. It may be taken back by the supplier state for storage, or final disposal, or reprocessing.



LAYOUT AND SIZE OF "AKADEMIK LOMONOSOV" FLOATING NPP

Low activity operational wastes will be temporarily stored in the barge and then transported to radioactive waste management facilities in the host country for storage/disposal.

External Hazards. External hazards including natural and man-made hazards, such as tsunami, aircraft crash, and underwater earthquake, need to be taken into consideration for the development of marine-based SMRs.

Maritime Conditions. In contrast to the land-based conditions, marine-based SMRs need to adapt to the effects of ocean waves and swells on passive fluid systems' thermalhydraulic performance and control rod mechanical performance, such as insertion when the reactor is tilted.

Radiation Protection. Owing to at least four barriers in the barge containing marine-based SMRs – nuclear fuel, reactor pressure vessel, reactor compartment, and barge hull, release of radioactivity is effectively prohibited against exposure to the crew member though they are in close proximity to the reactor compartment and the environment – ocean.

Operational Performances. The operational power range of a marine-based SMR is design specific, such as 10% – 100% for KLT-40S, 20% – 100% for ACPR50S.

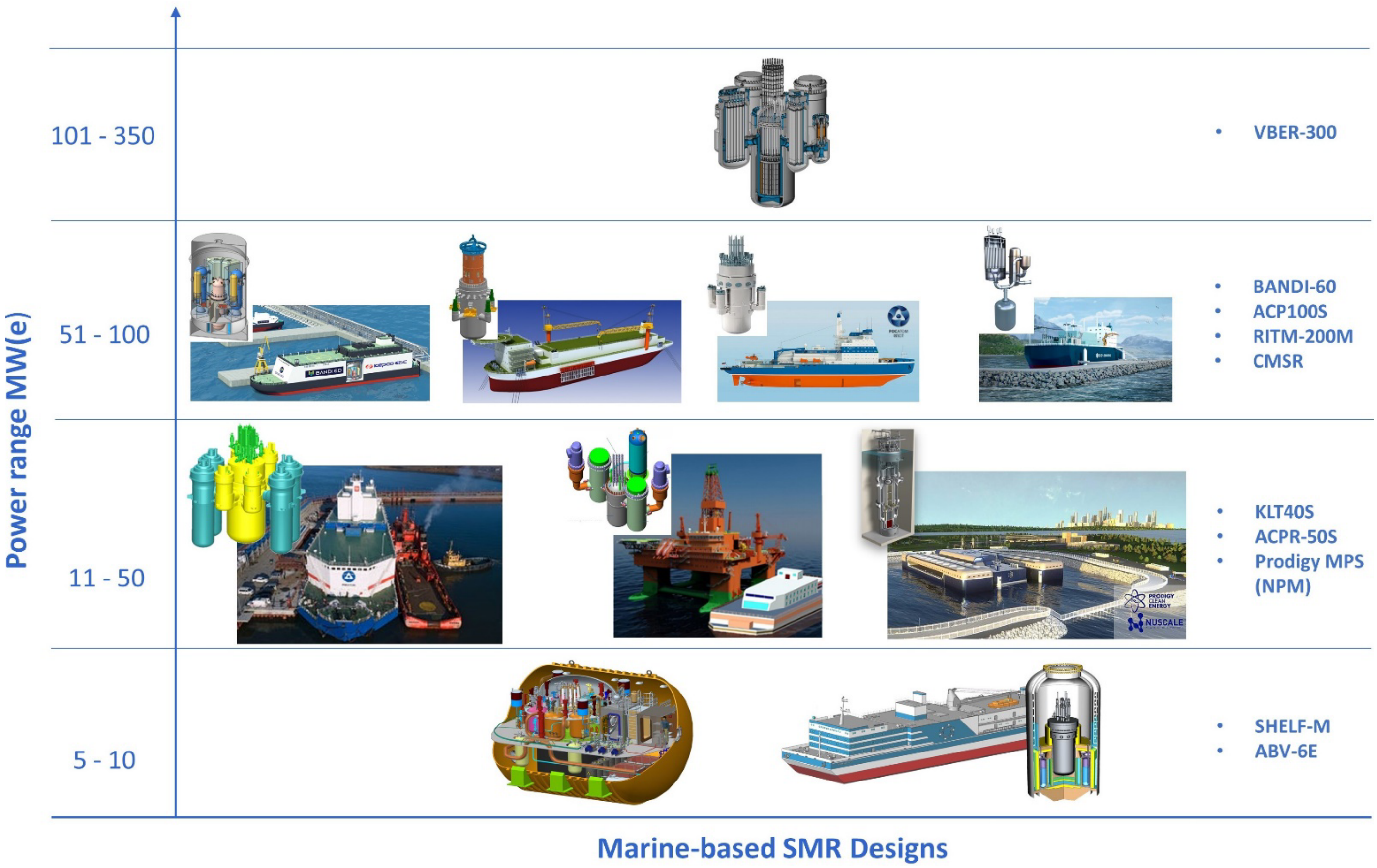
Emergency Power. In case of emergency, emergency power source such as diesel generator or batteries on organic fuel will be put into use for power supply to the barge.

Power Range

The existing marine-based SMR designs cover a wide range of power.

In some cases, two or even more reactors are deployed in the barge which adds up to the output power level according to the end user's needs.

In the case of "Akademik Lomonosov", two 35 MWe KLT-40S reactors supply more than enough electricity and heat for Pevek, where the population is around 4000.



POWER RANGE OF MARINE-BASED SMR DESIGNS

Main Technical Parameters of Ten Designs

MR Design	Design Organisation	Country	P_{th}, MWt	P_{el}, MWe	Fuel Type / Assembly Array	Fuel Enrichment, %	Refuelling Cycle, month	RPV height/diame m
LT-40S	JSC “Afrikantov OKBM”	Russian Federation	150	35	UO_2 in silumin matrix	18.6	30 – 36	4.8 / 2.0
CPR50S	CGN	China	200	50	UO_2 / 17 × 17 square	< 5	30	7.2 / 2.2
CP100S	CNNC/NPIC	China	385	125	UO_2 / 17 × 17 square	< 4.95	24	10 / 3.35
ANDI-60	KEPCO E&C	Republic of Korea	200	60	UO_2 / 17 × 17 square	4.95	48 – 60	11.2 / 2.8
ıScale ower odule	NuScale Power	USA	250	77	UO_2 / 17 × 17 square	≤ 4.95	18	17.7 / 2.7
3V-6E	JSC “Afrikantov OKBM”	Russian Federation	38	6 – 9	UO_2 / hexagonal	< 20	120 – 144	6 / 2.4
TM- 0M	JSC “Afrikantov OKBM”	Russian Federation	175	53	UO_2 in silumin matrix	< 20	Up to 120	8.6 / 3.45
3ER-300	JSC “Afrikantov OKBM”	Russian Federation	917	325	UO_2 / hexagonal	4.95	72	9.3 / 3.9
HELF-M	NIKIET	Russian Federation	35.2	Up to 10	UO_2 cermet / hexagonal	Up to 19.7	96	4 / 2.6
MSR	Seaborg Technologies	Denmark	250	100	Liquid fluoride molten salt / fuel tubes in 60° triangular tube pitch pattern	LEU	144	5.5 / 2.5

International and National Cooperation

For the safe, secure and efficient delivery of marine-based SMRs, close cooperation is pivotal among key stakeholders, including design organizations, shipbuilders, industrial supply chains, regulators, and so forth. It is observed that the cooperation exists both on a national level and on an international level.

Russian Federation and China

IMAGE COURTESY OF ROSATOM

Construction began in August 2022, at a Chinese shipyard at Nantong in Jiangsu province, north of Shanghai in eastern China, of a barge that will later be fitted with two RITM-200M reactors for the first of the four floating NPPs for the Cape Naglounyn project which will power the mining development at Baimskaya in the Russian Arctic. Each FNPP can supply 103 MWe. As the mining requires 300 MWe, three FNPPs are needed, with a fourth to be installed as backup for refuelling and maintenance. By the end of 2023, the hull will be towed to Russia for installation of two RITM-200M reactors, auxiliary equipment, control room and accommodation areas.

Denmark and Republic of Korea

IMAGE COURTESY OF KHNP

In April 2022, Samsung Heavy Industries (SHI) and Seaborg signed an MOU to manufacture and deploy turnkey power plants on power barges combining SHI's shipbuilding expertise and Seaborg's CMSR. In January 2023, SHI announced that it had completed the CMSR power barge conceptual design and obtained Approval in Principle from American Bureau of Shipping. In April 2023, Seaborg, KHNP and SHI established a consortium to develop FNPPs featuring Seaborg's CMSR technology. The consortium's first project is expected to be a 200 MWe power barge.

United States of America and Canada

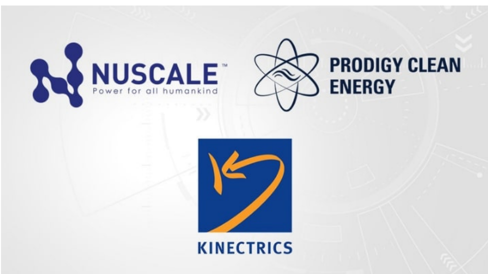


IMAGE COURTESY OF PRODIGY/NUSCALE/KINECTRICS

In November 2021, Amecica' NuScale and Canada's Prodigy and Kinectrics signed an MOU to explore and inform the development of a regulatory framework to address licensing and deployment of a Prodigy MPS. They plan to produce technical specifications and a regulatory considerations document on the MPS that will be used to engage regulators and potential customers. They will work together to evaluate commercial deployment opportunities where the MPS could be deployed either as the sole power source, coupled with renewables, or used to generate clean fuels (e.g. hydrogen and ammonia) economically and at commercial scale.

Japan and United Kingdom

IMAGE COURTESY OF CORE POWER

Thirteen Japanese companies, led by Onomichi Dockyard and Imabari Shipbuilding, have invested around $80m in a project of the UK-based start-up Core Power to build floating nuclear power plant. The project aims at adopting reactors which offer several advantages over conventional reactors – smaller, more efficient, and potentially less expensive to build. The Japanese companies taking part in the project have subscribed to a third-party allocation of new shares by Core Power.

United States of America and United Kingdom

IMAGE COURTESY OF U.S. DOE

In August 2022, the U.S. DOE granted research funds through its Nuclear Energy University Programme (NEUP) to Core Power, MIT Energy Initiative and INL for a three-year study on the development of offshore floating nuclear power generation in the U.S. With the funding, collaborative research into the economic and environmental benefits of floating advanced nuclear power generation is expected. The collaborating also allows to take a look at various aspects of building, operating, maintaining, and decommissioning such facilities.

United States of America

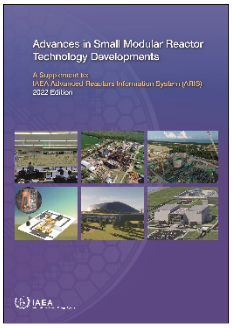
IMAGE COURTESY OF CROWLEY

Nuclear power leader BWX Technologies, Inc. teams up with global shipping and energy supply chain leader Crowley, through an MOU, signed in September 2023, for a ship concept that has the potential to generate alternative, zero-carbon emission energy for defense and disaster needs by including a microreactor on board. The two parties will jointly pursue and develop opportunities relative to the design, engineering and development of new shallow-draft hull ships that will supply small-scale nuclear energy to shoreside locations.

Republic of Korea

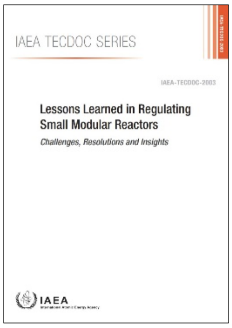
IMAGE COURTESY OF KAERI

In February 2023, nine organisations in Republic of Korea have signed an MOU to cooperate on the development and demonstration of ships and offshore systems powered with SMRs. The partners will also develop marine systems and the production of hydrogen using molten salt reactors (MSRs). Shipping companies H-Line Shipping, Hyundai Merchant Marine (HMM), Janggeum Merchant Marine (Sinokor) and Wooyang Merchant Marine, plus the Korea Atomic Energy Research Institute (KAERI), Korea Register of Shipping and the Korea Ship & Offshore Plant Research Institute (KRISO) participate in the cooperation.



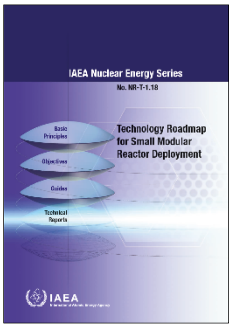
Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2022 Edition

This booklet is reporting the advances in design and technology developments of SMRs of all the major technology lines. It covers land-based and marine-based water-cooled reactors, high temperature gas-cooled reactors, liquid metal-cooled fast neutron spectrum reactors, molten salt reactors, and microreactors, a sub-category of SMR, that generate electrical power up to 10 MWe. The booklet provides some insights on the economic challenges in deployment of SMRs, a summary on enabling design features to facilitate SMRs' decommissioning and a summary on experimental testing for design verification and validation. The brief design description of SMRs is provided by the responsible institute or organization and is reproduced, with permission, in this booklet.



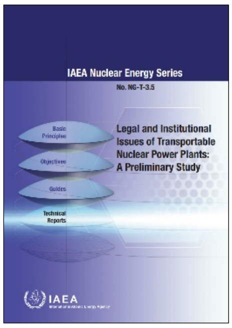
Lessons Learned in Regulating Small Modular Reactors, Challenges, Resolutions and Insights, IAEA-TECDOC-2003, 2022

documents existing experience gained by regulatory bodies on the regulation of SMRs, including licensing and compliance assurance, with particular focus on challenges encountered, their resolutions, and insights to future issues. It also identifies key regulatory challenges and lessons learned that have emerged in regulatory decision making related to SMRs in Member States. This publication also presents the early challenges and lessons learned by regulatory bodies in preparation for review of an application for an SMR licence. The document also provides some forward-looking insights on how regulatory bodies expect to address the challenges in the near future. It is expected that the TECDOC will help enhance the effectiveness of regulating SMRs deployed in the short and medium term.



Technology Roadmap for Small Modular Reactor Deployment, IAEA Nuclear Energy Series, No. NR-T-1.18, 2021

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



Legal and Institutional Issues of Transportable Nuclear Power Plants: A Preliminary Study, No. NG-T-3.5, 2013

studies the legal and institutional issues, including those concerning ownership and contract, for the deployment of TNPPs, reveals challenges that might be faced in their deployment considering several technological options and deployment scenarios, and outlines pathways for resolution of the identified issues and challenges in the short and long terms. It addressed to senior legal, regulatory, and technical officers in Member States planning to embark on a nuclear power programme or to expand an existing one by considering the introduction of a TNPP. The present report focuses essentially on the different legal and institutional issues that would specifically apply to TNPPs.

For additional information, or to order a book, please visit www.iaea.org.

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