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Design and technology development for small modular reactors – Safety expectations, prospects and impediments of their deployment

H. Hidayatullah, S. Susyadi, M. Hadid Subki*

Nuclear Power Technology Development Section, Division of Nuclear Power Department of Nuclear Energy, International Atomic Energy Agency (IAEA), Wagramerstrasse 5, PF 100, A-1400 Vienna, Austria

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A B S T R A C T

The IAEA has seen a significant increase in participation of Member States and their expertise in the IAEA program for small and medium-sized reactors (SMRs) technology development. There are high-level of interest in SMR development and deployment in technology holders and technology user's countries. The trend in development has been towards design certification of small modular reactors, which are defined as advanced SMRs that produce electric power up to 300 MW(e), designed to be built in factories and shipped to utilities for installation as demand arises. The current driving forces of SMR development are, among others: fulfilling the need for flexible power generation for a wider range of users and applications; replacing the aging fossil-fired units; enhancing safety performance through inherent and passive safety features; offering better economic affordability; suitability for cogeneration and non-electric applications, options for remote areas and hybrid energy systems of nuclear with renewable. The majority of the near-term deployment advanced SMRs is the integrated pressurized water reactors (iPWR). Several countries are pioneering in the development and application of transportable nuclear power plants (TNPP), including floating and marine-based SMRs. The innovative features of advanced SMRs that converge into safer, reliable and affordable plant have been discussed. Multiple module plant distinct concepts of operations, licensing process, legal and regulatory framework are the main issues for the SMRs deployment and are delineated. For newcomer countries, however, one of the challenges is how to reconcile the competitiveness issue between advanced SMR designs and potential energy alternatives including large reactors with proven technology. The paper focuses on some impediments in the deployment of such novel designs that need to be resolved through testing and qualification of components and equipment, Research and Development (R&D), training and international collaboration.
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1. Introduction

A secure supply of energy is fundamental for modern society good standard of living. Nuclear energy can provide an environmentally benign choice to meet the global energy demands in the 21st century. According to the IAEA Nuclear Technology Review (International Atomic Energy Agency, 2013a), significant growth in the use of nuclear power, between 35 and 100%, is anticipated by 2030, though the agency projections for 2030 are 7–8% lower than projections made in 2010. The advanced SMR are part of a new generation of nuclear power plant designs being developed to provide a flexible, cost-effective energy for various applications.

According to the classification adopted by the IAEA, small reactors are reactors with an equivalent electric power of up to 300 MWe and medium sized reactors are reactors with an equivalent electric power between 300 and 700 MWe (International Atomic Energy Agency, September 2012). All small modular reactors with output power per module less than 300 MWe are fitted well into the SMR class and are considered as a subclass of SMRs.

The advanced SMRs design offers several advantages over traditional large nuclear power plant (NPP) designs and may grow into an attractive technology once the designs become technologically proven. Advanced SMR designs can serve other purposes besides electricity generation, including industrial process heat applications such as water desalination, production of liquid transportation fuels and petrochemicals and hydrogen production. The advanced SMRs for power generation are expected to

* Corresponding author.
E-mail address: M.Subki@iaea.org (M.H. Subki).

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have greater simplicity in design, economy of mass production, and smaller footprint. Their designs also offer enhanced safety, security and proliferation resistance features. A major advantage of advanced SMR systems is that they adopt modularization, by which the structures, systems and components are shop-fabricated then shipped and assembled onsite, thus the construction time for SMRs can be substantially reduced. Although modularization construction technology is not new and already applied for the constructions of conventional large reactors, on-site stick-build method are still applied for large reactor construction because of their massive structures. Modularizations also offer the advantage of lower initial capital investment, scalability, and siting flexibility at locations unable to accommodate traditional large reactors.

Advanced SMRs will use different approaches from large reactors for achieving a high level of safety & reliability in their systems, structures, components, and that will be the result of a complex interaction between design, operation, material and human factor. Interest in SMRs continues to grow as an option for future power generation and energy security. However, the first phase of advanced SMR demonstration will have to produce superior operability and reliability to confirm it futures orders and popularity. To achieve the perceived benefits of advanced SMRs, developers, utilities and regulators must overcome many of the initial hurdles introduced by differences in the technologies, designs, and operational characteristics. These plants would have greater automation but will still rely on human interaction for supervision, system management, and operational decisions because operators are still regarded as the last line of defense if failures in automated protective measures occur.

2. Categorization of SMRs

Currently there are more than 45 SMR designs under development, only a few have received design certification, some are under construction as prototype plants, and the rest is under various stages of design development. Due to the large variety in SMRs technology, they can be categorized into the followings four categories (International Atomic Energy Agency, 2013b):

(i) Advanced SMRs, including modular reactors and integrated PWRs
(ii) Innovative SMRs, including small-sized Gen-IV reactors with a non water coolant/moderator
(iii) Converted or modified SMRs, including barge mounted floating NPP and seabed-moored submarine-like reactors
(iv) Conventional SMRs, those of Gen-II technologies and still being deployed.

The reactors considered in the scope of the present study are the category '(i)' advanced integral pressurized water small modular reactors (iPWR-SMR). A module is defined as a reactor and nuclear steam supply system. Each module is independent and can be shutdowned without affecting other modules, and installed later on in the multiple module plant. Further modules may share not only common secondary system, e.g. steam turbine, but also common essential equipment, e.g. diesel generators (International Atomic Energy Agency, 2013b). Modularization enables in-shop fabrication of reactor and containment components. Additional modules can be added as demand for energy increases by industrial or population growth in the area.

A transportable nuclear power plant (TNPP) is a factory manufactured, transportable and re-locatable nuclear power plant which, when fueled, could produce final energy products such as electricity and heat (International Atomic Energy Agency, 2013c). The examples of the currently under design and development TNPPs are KLT-40S, RITM-200, ABV-6M and Flexblue.

3. Innovative features of SMRs

There are many types of SMRs having a different configuration now under R&D, and passing through design certification in various countries. The water cooled SMRs designs available for near term

Table 1
Water-cooled SMRs designs available for near and mid-term deployment.

SMR designs	Type	Power output (MWe)	Designers	Status
CAREM-25	Integral PWR, natural circulation	27	CNEA, Argentina	One unit prototype under construction near Atucha-2 site
CNP-300	2 loop PWR	315	CNNC, China	Three units in operation, Two units under construction
ACP-100	Integral PWR	100	CNNC, China	Detailed design
CAP-150	Integral PWR	150	SNERDI, China	Conceptual design
Flexblue	Seabed-moored small modular reactor	160	DCNS, France	Conceptual design
AHWR300-LEU	Pressure tube	304	BARC, India	Detailed design
IMR	Integral modular PWR, natural circulation	335	MHI, Japan	Conceptual design
SMART	Integral PWR	100	KAERI, Korea	Standard Design Approval received in July 2012
ABV-6M	Integral PWR, natural circulation	8.6	OKBM Afrikantov, Russian Federation	Detailed design
VBER-300	Integral PWR	325	OKBM Afrikantov, Russian Federation	Detailed design
RITM-200	Integral PWR	50	OKBM Afrikantov, Russian Federation	Under construction
KLT-40S	Barge mounted - floating nuclear power plant	70	OKBM Afrikantov, Russian Federation	2 units in final stage of construction
VVER-300	Integral PWR	300	OKB Gidropress, Russian Federation	Detailed design
VK-300	BWR	250	RDIPE, Russian Federation	Conceptual design
UNITHERM	Very Small, Integral PWR, with Natural Circulation	2.5	RDIPE, Russian Federation	Conceptual design
SHELF	Seabed-moored small modular reactor	6	RDIPE, Russian Federation	Conceptual design
IRIS	Integral PWR	335	IRIS International Consortium, Italy	Conceptual design
mPower	Integral PWR (Twin-pack of 180 MWe)	360	B&W Generation mPower,USA	Detailed design
NuScale	Integral natural circulation PWR (12 modules of 50 MWe gross)	570 (nominal)	NuScale Power, USA	Detailed design
Westinghouse SMR	Integral PWR	225	Westinghouse Electric Corporation, USA	Detailed design
SMR-160	Integral PWR	160	Holtec Corporation, USA	Detailed design

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