A Study on Regulation Standard for SMRs

by

Tae Seok Kang

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Ontario Tech University

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Abstract

The current thinking in the nuclear energy industry is favoring by small-scale Small Modular Reactors (SMRs) with improved safety and multiple applications compared to conventional large-size nuclear power plants. The demand for SMR is increasing in places where existing large-scale nuclear power plants are not applicable, such as developing countries with distributed power generation areas, small power grid capacity, heating demand in remote areas, and seawater desalination.

Currently, cooperative research between Generation IV Information Forum (GIF) member countries is actively underway. SMRs are being evaluated as a major development direction for the nuclear energy industry. However, SMRs reactor facilities have not yet been deployed in commercial operation, and research and development is ongoing.

External leakage of radioactive material from accidents can pose a very serious risk to workers and the public. Therefore, nuclear facilities must meet the regulatory standards of the regulatory body, from construction to operation and accident management.

However, it is inappropriate to consider the characteristics of SMRs and then apply the current regulatory standards to SMRs. In this report, a literature review method was used to characterize SMRs. The main technical standards were examined to determine which items were found to be inadequate for SMRs based on the characteristics of the SMRs. As a result, four characteristics were derived. Then, an alternative to the regulatory criteria for siting and operation was derived. Improvements in operations and siting related regulatory requirements are recommended.

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LIST OF ABBREVIATIONS AND SYMBOLS

ARIS	Advanced Reactors Information System
BDBA	Beyond Design Basis Accident
CDF	Core Damage Frequency
CFR	Code of Federal Regulations
CPS	Current Policy Scenario
DBA	Design Basis Accident
GDC	General Design Criteria
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
IEA	International Energy Agency
IEs	Initiating Events
LBE	Lead-Bismuth Eutectic
LBLOCA	Large Break Loss of Coolant Accident
LERF	Large Early Release Frequency
LFR	Lead-cooled Fast Reactor
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MHTGR	Modular high-temperature gas-cooled reactor
MSFR	Molten Salt Fast Reactor
MSR	Molten Salt Reactor
NNL	National Nuclear Laboratory
NPS	New Policy Scenario
PAZ	Precautionary Action Zone
PRA	Probabilistic Risk Assessment
PRISM	Power Reactor Innovative Small Module
RCCS	Reactor Cavity Cooling System

SBO	Station Black-Out
SCWR	Super Critical Water-cooled Reactor
SFR	Sodium-cooled Fast Reactor
SIAP	Senior Industry Advisory Panel
SMRs	Small Modular Reactors
UPZ	Urgent Protective action planning Zone
VHTR	Very High Temperature Gas-cooled Reactor
WNA	World Nuclear Association

Chapter 1. Introduction

As a low-carbon energy source, nuclear energy has been regarded as a sustainable clean energy source capable of addressing global warming. However, since the Fukushima Dai-Ichii accident [1], the nuclear energy industry crisis has arrived. The safety issue of nuclear power plants has risen, and nuclear power plant accidents, which were considered to be unavoidable accidents, has amplified distrust of nuclear energy and caused the public to lose confidence in nuclear energy. Some countries that have nuclear energy have discussed shut-down and phase-out of nuclear power plants, and the trend of expanding the development of renewable energy has been accelerated [2].

The Fukushima Dai-ichi accident taught that severe accidents once considered highly improbable are something that can happen. As a result, the development direction of future nuclear power plants will be strengthened not only to prevent accidents but also to mitigate potential accidents. Therefore, it is considered that the concept of a fully passive safety system design of nuclear power plants is no longer an option but a necessity. Also, fully passive safety systems alone are no longer considered sufficient.

Due to the atmosphere of the nuclear power generation industry, the necessity and demand of Small Modular Reactors (SMRs) is increasing in part due to advantages such as improvement of stability and reduction of construction cost compared with conventional large nuclear power plants. Demand for SMRs is growing in applications where it is impossible or difficult to apply the existing large-scale nuclear power plant, such as, power and heating demand in remote areas (low energy requirement), developing countries with small power grid capacity, and special applications such as desalination. As a result, the proportion of SMRs is expected to rise in the near future nuclear industry market. According to a report of the National Nuclear Laboratory (NNL) 'Small Modular Reactors (SMR) Feasibility Study'[3], specific projections for SMR capacity do not exist, however comparison between the analyses conducted for USA, Russia, and China and the top-down projections for these nations yields that by 2035 an averaged figure for SMR take-up of around 20% of the existing nuclear power plants compared to the total potential nuclear market in those nations.

ʹThe Technology Roadmap Updateʹ, released in 2014 in the Generation IV International Forum (GIF), defined and planned the R&D required to achieve the four goals and enable the deployment of Gen IV nuclear energy systems from 2030 [4]. Figure 1 shows the four generations of reactor designs.

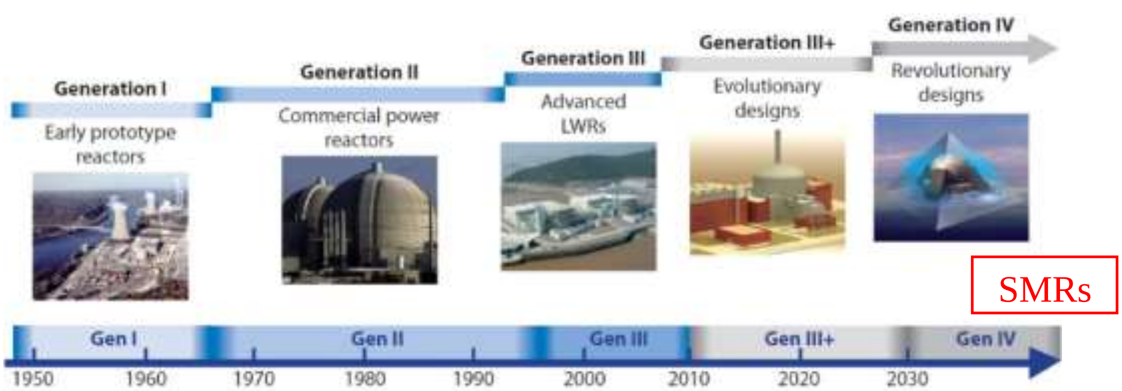

Figure 1. The four generations of reactor designs [4].

The SMR technology, although based on Generation I principles is expected to be largely Generation IV designs. Understanding principles of SMRs is essential to establishing regulatory standards for SMRs with new technologies and designs. The design and construction characteristics of SMRs differentiated from existing large nuclear power plants allow some of the following features:

(1) Fully passive safety systems: system operation by gravity, natural circulation, or gas compression power;

(2) Underground construction of containment buildings;

(3) Improvement of equipment production and transportability: Design and manufacture of nuclear reactor internalization and integration;

(4) Differentiation of siting: remote area, mining area, or small-scale electricity demand place (small and medium city).

These characteristics enable SMRs to be compared to existing nuclear power plants to improve stability, reduce construction time, and reduce initial investment costs. In addition, flexibility in power capacity due to the modular construction makes it possible to respond quickly to changes in economic conditions and demand.

SMRs are very small in physical scale compared to existing nuclear power plants, and electric power is also proportionally small. Although there are now a variety of new technology-based reactor types currently under development, SMRs designs are not yet licensed and have not commenced commercial operation. In addition, it is a module format that connects multiple SMRs to set the output changing the nature of the risk. Due to the physical size and the new design, the scale and occurrence of accidents are very different from those of existing large nuclear power plants. Therefore, it is not appropriate to license and regulate SMRs by applying regulatory guidelines of existing large nuclear power plants. And, it seems that the need for new regulatory guidelines is crucial to the licensing and regulation of SMRs.

As such, the demand for SMRs is expected to increase due to the need for small-size, multi-purpose nuclear power plants and the need to improve the safety of nuclear facilities in the future. However, since SMRs differ from large nuclear power plants, which are currently in operation, with different nuclear fuel, engineered safety features, and/or design characteristics, it is necessary to establish a new regulatory direction or modify existing regulations. For this reason, this report explores the characteristics of SMRs and suggests appropriate regulatory guidelines for SMRs through literature review of existing regulatory guidelines for nuclear power plants. As part of the work, a review and investigation shall be completed of current safety standard and regulatory guides and the characteristics of SMRs. Then, the results of the literature review, the presentation of regulatory standards for siting and operation will be examined.

Chapter 2. Literature review

This chapter describes the literature review of trends in the global nuclear energy market, the definition of SMRs and their differentiation, in terms of purpose and characteristics from existing nuclear power plants.

2.1 Nuclear energy policy in the world

At present, countries that are planning to utilize nuclear energy are showing a variety of trends such as shutdown, maintenance, and expansion of nuclear power plants in accordance with the status of energy availability and energy policies. According to the World Energy Outlook 2018 of the International Energy Agency (IEA) [5], Germany and Belgium have decided to abolish nuclear power, while France, Sweden, Switzerland, Japan, and South Korea are planning to gradually reduce the proportion of nuclear power. At the same time, about 20 countries, including China, India, Russia, the UAE, and Saudi Arabia, are seeking to expand nuclear power. IEA estimates that the capacity of nuclear installations worldwide is expected to increase. The projected scenarios for facility capacity are divided into three categories: New Policy Scenario (NPS), Current Policy Scenario (CPS), and Sustainable Development Scenario (SDS). In all scenarios, nuclear capacity is expected to increase [5]. Table 1 shows the current status of nuclear power policy in countries operating nuclear power plants [6].

Table 1. Nuclear Policy Status of Nuclear Power Operated Nations [6].

Country	Policy and Status
United States of America	Increase of early closing power plant due to economic decline, and Federal and state-level nuclear support policy in progress. US nuclear power was 98.4 GWe, accounting for 20% of the total electric generation.
France	By 2035, nuclear power will be reduced from 75% (58 reactors in total, 63.2GWe total generating capacity) to 50%.
China	Nuclear power plants are increasing, and new nuclear power plants are under construction. The world's largest nuclear plant capacity will be acquired by 2030. Targeted nuclear power generation capacity of 58 GWe and new construction power generation capacity of 30 GWe by 2020. 48 reactors are operated (45.5 GWe).
Japan	In the Fifth Energy Basic Plan, nuclear power plants are referred to as important base load power sources. In 2030, the target ratio of nuclear power is 20 ~ 22%. 37 reactors are operated (35.9 GWe)
Russia	By 2030, plans to build 11 new reactors. Currently, six new reactors are under construction. A total of 36 reactors (28.4 GWe) are operated.
Korea	Construction of new nuclear power plants and prohibition of continued operation in accordance with energy conversion policy. 25 reactors in operation. (23.8 GWe)
Canada	By 2033, Darlington and Bruce continued to operate the nuclear power plant through refurbishment. 19 units are in operation and the total power generation is 13.6 GWe.
Ukraine	Nuclear power will remain at 50% by 2035. 15 reactors are operated (13.6 GWe)
Germany	All nuclear power plants will be phased out by 2022. It currently operates 7 nuclear reactors (total generating capacity of 9.5 GWe).
England	Six new nuclear project plans. Currently, Hinkley Point C nuclear power plant is under construction. A total of 15 reactors are in operation (total generation capacity 8.9 GWe).
Sweden	Targeting 100% renewable energy by 2040. Ten new construction permits are allowed on existing nuclear sites. 8 nuclear power plants are in operation and supplying about 41.5% of electricity (generation capacity 8.6 GWe).
Spain	A total of seven reactors will be shut down between 2025 and 2035. 7 nuclear reactors are in operation. It supplies about 21% of the total electricity demand (7.1 GWe total generating capacity).
India	Plans to build 21 new nuclear power plants by 2031. A total of 22 reactors are in operation. (Generation capacity 6.3 GWe)
Belgium	Seven reactors will be phased out from 2022 to 2025. 7 nuclear reactors are in operation. Total generating capacity 6 GWe.

Czech Republic	Construction of new nuclear power plant is under way. The proportion of nuclear power plants in 2040 is forecast at 46 ~ 58%. 6 reactors in operation. About 38% of total power (4 GWe).
Taiwan	Government promotes nuclear power phase-out. 4 reactors in operation. Approximately 15% of the total generating capacity (5.1 GWe).
Swiss	Decision to shut down all nuclear power plants by 2034. 5 nuclear power plants are in operation. (3.5 GWe)
Finland	Construction of new nuclear power plant is under way. Plan for continuous use of nuclear power. 4 reactors in operation. About 30% of the total power (2.8 GWe total generating capacity).
Bulgaria	The new nuclear power Belene project, which was withdrawn in 2012, is being resumed. Kozloduy Power Plants 5 and 6 (VVER-1000) were operated to produce 33% of the total power (total generation capacity 1.9 GWe).
Hungary	New nuclear power plants are being planned with a goal of 54% of nuclear power by 2030. 4 reactors supply approximately 50% of the total power (total generation capacity 1.9 GWe)
Brazil	Construction of Angra Unit 3 is suspended, and the government plans to complete the project using private investment. 2 reactors are in operation (1.9 GWe)
South Africa	By 2030, it plans to build a new nuclear power plant with a capacity of 9,600 MW, but recently withdrew. 2 reactors at Koeberg's nuclear power plant are in operation (1.9 GWe), providing 5% of the total power.
Slovakia	Two new reactors are under construction. The proportion of nuclear power plants in 2025 is forecast at 61%. 4 reactors are in operation (1.8 GWe)
Argentina	Research reactor under construction. Nuclear power will account for 9% by 2025. 1 reactor is in operation (0.4 GWe)
Mexico	In September 2015, the Vice Minister of Energy announced the possibility of constructing two nuclear reactors at the existing site. 5 reactors are in operation (1.6 GWe)
Pakistan	Plans to expand nuclear capacity to 8.8 GWe by 2035. 5 reactors are in operation (1.3 GWe).
Romania	Cernavoda 3,4unit under construction. 2 reactors are in operation (1.3 GWe).
Iran	Expanded capacity to 12,000MW by 2025. 1 reactor is in operation (0.9 GWe)
Slovenian	No plans to expand nuclear power. 1 reactor is in operation (0.7 GWe)
Netherlands	Currently, there is no plan to construct new nuclear power plants. 1 reactor is in operation (0.5 GWe)
Armenia	Nuclear power plant construction plan for replacement of old nuclear power plant. 1 reactor is in operation (0.4 GWe)

The capacity increase is the lowest in the CPS, and the expected increase in capacity is the highest in the SDS.

- In the baseline scenario, the NPS, global nuclear capacity increased from 412 GW in 2017 to 464 GW in 2030 and 518 GW in 2040, with an annual average capacity growth rate of 1% by 2040;
- In the CPS, 459GW is expected in 2030 and 298GW in 2040, with an increase of 0.8%;
- In the SDS scenario, 542 GW in 2030 and 678 GW in 2040 are expected, with an increase of 2.2%.

As of 2019, 450 reactors were in operation in 30 countries around the world, with a total installed capacity of 399.7 GWe. Figure 2 shows the number of reactors operating in each region.

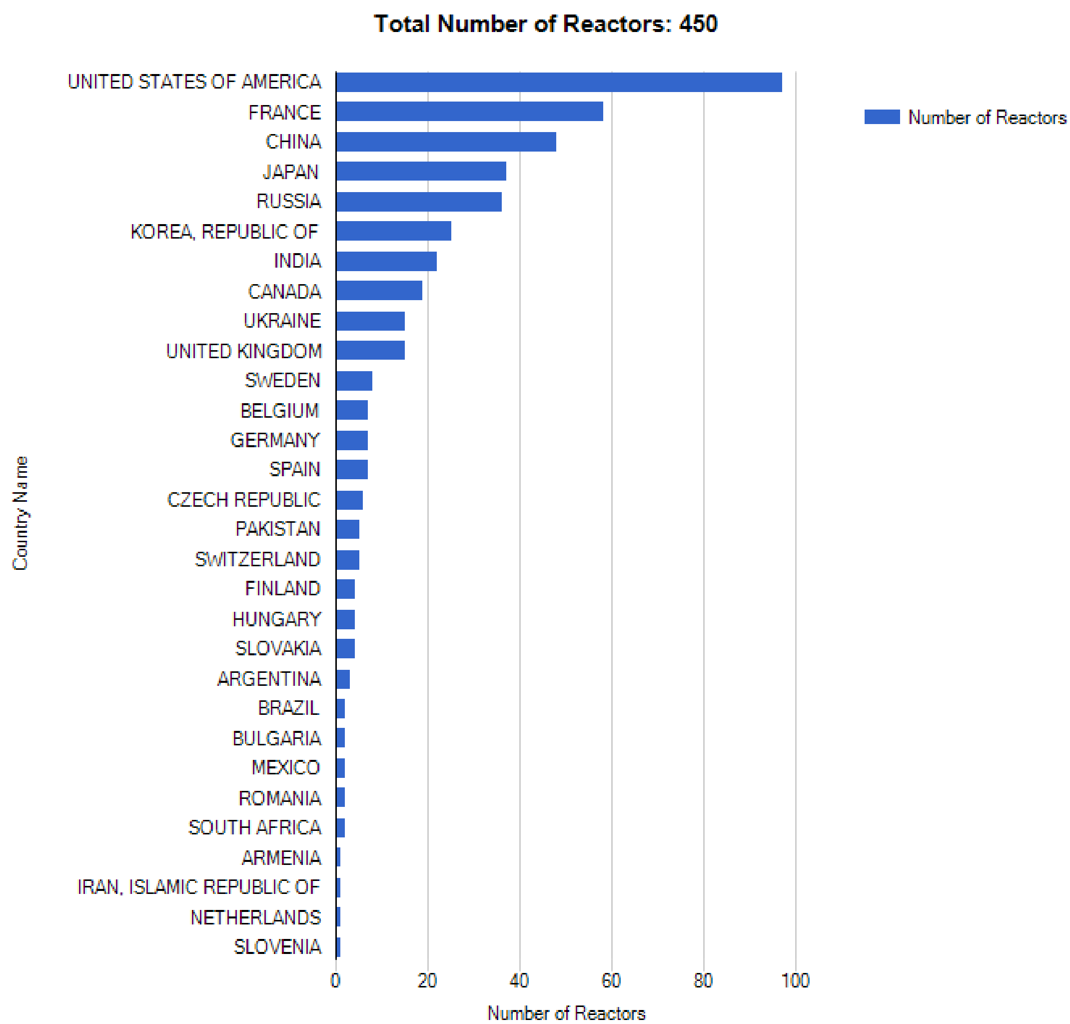

Figure 2. Operation reactors of all around the world in 2019 [7].

Table 2 shows the number of reactors in operation and power generation capacity in each country [7]. In addition, 57 reactors were under construction around the world, with a total capacity of about 58 GWe.

Table 2. Number of reactors and capacity of Nuclear Power Operated Nations [7].

Country	Number of Reactors	Total Net Electrical Capacity [GW]
UNITED STATES OF AMERICA	97	98.4
FRANCE	58	63.1
CHINA	48	45.5
JAPAN	37	35.9
RUSSIA	36	28.4
KOREA, REPUBLIC OF	25	23.8
INDIA	22	6.3
CANADA	19	13.6
UKRAINE	15	13.1
UNITED KINGDOM	15	8.9
SWEDEN	8	8.6
BELGIUM	7	5.9
GERMANY	7	9.5
SPAIN	7	7.1
CZECH REPUBLIC	6	3.9
PAKISTAN	5	1.3
SWITZERLAND	5	3.3
FINLAND	4	2.8
HUNGARY	4	1.9
SLOVAKIA	4	1.8
ARGENTINA	3	1.6
BRAZIL	2	1.9
BULGARIA	2	2.0
MEXICO	2	1.6
ROMANIA	2	1.3
SOUTH AFRICA	2	1.9
ARMENIA	1	0.4
IRAN, ISLAMIC REPUBLIC OF	1	0.9
NETHERLANDS	1	0.5
SLOVENIA	1	0.7
Total	450	399.7

2.2 SMRs

2.2.1 Characteristics and advantages of SMRs

The 2015 World Nuclear Association report described the characteristics and advantages of SMRs. These are classified into three categories as shown below: size characteristic, safety improvement, and cost efficiency [8].

(1) Size characteristic:

- Small size (less than 300 MWe) and modularity; SMRs could almost be completely built in a controlled factory setting and installed module by module, improving the level of construction quality and efficiency.

- Modularity of fabrication (in-factory); which can also facilitate implementation of higher quality standards.

(2) Safety improvement:

- Passive safety features; can be lend them to countries with smaller grids and less experience of nuclear power. (No case yet)

- Small power and compact architecture; less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation.

- Lower power; reduction of the source term as well as smaller radioactive inventory in a reactor (smaller reactors).

- Underground or underwater location of the reactor; more protection from natural (e.g. seismic or tsunami according to the location) or man-made (e.g. aircraft impact) hazards.

(3) Cost efficiency:

- Construction efficiency; can lead to easier financing compared to that for larger plants.

- Economies of series production; for a specific SMR design will reduce costs further.

- The modular design and small size lends itself to having multiple units on the same site.

- Lower requirement for access to cooling water – therefore suitable for remote regions and for specific applications such as mining or desalination.

- Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.

2.2.2 Goals of SMRs

SMRs are currently being researched for commercial applications. SMRs are motivated by a variety of goals including improved safety, sustainability, efficiency, and cost. Eight technology goals have been defined for Generation IV reactors in four broad areas: sustainability, economics, safety and reliability, and proliferation resistance, and physical protection. The GIF defines the goals of the SMRs as follows [9];

(1) Sustainability; focus on fuel utilization and waste management. Sustainability requires the conservation of resources, protection of the environment, preservation of the ability of future generations to meet their own needs, and the avoidance of placing unjustified burdens upon them. The two sustainability goals encompass the interrelated needs of improved waste management, minimal environmental impacts, effective fuel utilization, and development of

new energy products that can expand the benefits of nuclear energy beyond electrical generation.

- Goal 1: Generate energy sustainably and promote long-term availability of nuclear fuel.
- Goal 2: Minimise nuclear waste and reduce the long term stewardship burden.

(2) Safety and reliability; focus on safe and reliable operation, improved accident management and minimization of consequences, investment protection, and essentially eliminating the technical need for off-site emergency response. Safety and reliability are essential priorities in the development and operation of nuclear energy systems. Generation IV systems have goals to achieve high levels of safety and reliability through further improvements. The three safety and reliability goals continue the past trend and seek simplified designs that are safe and further reduce the potential for severe accidents and minimize their consequences. The achievement of these ambitious goals cannot rely only upon technical improvements, but will also require systematic consideration of human performance as a major contributor to the plant availability, reliability, inspectability, and maintainability.

- Goal 3: Excel in safety and reliability.
- Goal 4: Have a very low likelihood and degree of reactor core damage.
- Goal 5: Eliminate the need for offsite emergency response.

Table 3 shows the expected Core Damage Frequency (CDF) of several SMRs [10]. Some SMRs are not CDF capable or not considered, and SMRs such as AHWR-300, IRIS, NuScale, mPower, KLT-40S, 4S and SVBR-100 have a Core Damage Frequency of 10^{-8}.

Table 3. Core Damage Frequencies of various types of SMRs [10].

SMRs	Core Damage Frequency
WATER COOLED SMALL MODULAR REACTORS (LAND BASED)	
CAREM (CNEA, Argentina)	$<10^{-7}$
ACP100 (CNNC, China)	$<10^{-6}$
CAP150 (SNERDI/SNPTC, China)	$<10^{-7}$
CAP200 (SNERDI/SNPTC, China)	$<10^{-6}$
AHWR-300 (BARC, India)	$<10^{-8}$
IRIS (IRIS International Consortium)	$<10^{-8}$
DMS (Hitachi-GE Nuclear Energy, Japan)	$<5.0\times10^{-8}$
IMR (Mitsubishi Heavy Industries, Japan)	$<2.9\times10^{-7}$
SMART (KAERI, Republic of Korea)	$<2.0\times10^{-7}$(internal events)
UNITHERM (NIKIET, Russian Federation)	$<10^{-6}$
KARAT-45 (NIKIET, Russian Federation)	$<10^{-6}$
KARAT-100 (NIKIET, Russian Federation)	$<10^{-6}$
ELENA (Kurchatov Institute, Russian Federation)	-
RUTA-70 (NIKIET, Russian Federation)	PSA is not completed, assessment < 10-6
NuScale (NuScale Power Inc., United States of America)	$<10^{-8}$(internal events)
mPower (BWX Technologies, Inc., United States of America)	$<10^{-8}$
Westinghouse SMR (Westinghouse Electric Company, LLC., United States of America)	$<5.0\times10^{-8}$
SMR-160 (Holtec International, United States of America)	$<10^{-6}$
WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)	
ACPR50S (CGN, China)	$<10^{-6}$
Flexblue (DCNS, France)	$<10^{-7}$
KLT-40S (OKBM Afrikantov, Russian Federation)	$<5\times10^{-8}$
RITM-200 (OKBM Afrikantov, Russian Federation)	$<9\times10^{-7}$
VBER-300 (OKBM Afrikantov, Russian Federation)	$<10^{-6}$
ABV-6E (OKBM Afrikantov, Russian Federation)	$<10^{-6}$
SHELF (NIKIET, Russian Federation)	-
HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS	
HTR-PM (Tsinghua University, China)	Core damage frequency not applicable to HTGRs. No off-site shelter or evacuation plan needed.
GTHTR300 (Japan Atomic Energy Agency, Japan)	$<10^{-8}$
GT-MHR (OKBM Afrikantov, Russian Federation)	Core damage frequency not applicable to HTGRs. BDBA frequency < 1E-5 /year. Frequency of ultimate release at BDBA < 1 E-7 /year
MHR-T reactor/Hydrogen production complex (OKBM Afrikantov, Russian Federation)	Core damage frequency not applicable to HTGRs. BDBA frequency <1E-5/year. Frequency of ultimate release at BDBA <1E-7 /year.
MHR-100 (OKBM Afrikantov, Russian Federation)	Core damage frequency not applicable to HTGRs. BDBA frequency <1E-5/year. Frequency of ultimate release at BDBA <1E-7 /year.
PBMR-400 (Pebble Bed Modular Reactor SOC Ltd., South Africa)	Core damage frequency not applicable to HTGRs. No off-site shelter or evacuation.
HTMR-100 SMR (Steenkampskraal Thorium Limited (STL), South Africa	Slight damage with water ingress event with design base frequency.< 1E-4 /year
SC-HTGR (AREVA NP, USA)	-
Xe-100 (X-energy, United States of America)	No core melt possible
FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS	
LEADIR-PS (Northern Nuclear Industries Incorporated, Canada)	-
4S (Toshiba Corporation, Japan)	$<1.7\times10^{-8}$
BREST-OD-300 (NIKIET, Russian Federation)	-
SVBR-100 (JSC AKME Engineering, Russian Federation)	$<10^{-8}$
G4M (Gen4 Energy Inc., United States of America)	-
EM^2 (General Atomics, United States of America)	-
MOLTEN SALT SMALL MODULAR REACTORS	
Integral Molten Salt Reactor (Terrestrial Energy, Canada)	Not applicable
MSTW (Seaborg Technologies, Denmark)	
ThorCon (Martingale, International Consortium)	-
FUJI (International Thorium Molten-Salt Forum, Japan)	Core meltdown is impossible
Stable Salt Reactor (Moltex Energy, United Kingdom)	$<10^{-6}$
SmAHTR (Oak Ridge National Laboratory, United States of America)	
Liquid Fluoride Thorium Reactor (Flibe Energy, United States of America)	Not applicable
Mk1 PB-FHR (UC Berkeley, United States)	-

(3) Economics; focus on competitive life cycle and energy production costs and financial risk. Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems. While it is anticipated that Generation IV nuclear energy systems will primarily produce electricity, they will also help meet anticipated future needs for a broader range of energy products beyond electricity. For example, hydrogen, process heat, district heating, and potable water will likely be needed to keep up with increasing worldwide demands and long-term changes in energy use. Generation IV systems have goals to ensure that they are economically attractive while meeting changing energy needs.

- Goal 6: Have a life cycle cost advantage over other energy sources.
- Goal 7: Have a level of financial risk comparable to other energy projects.

(4) Proliferation resistance and physical protection; focuses on controlling and securing nuclear material and nuclear facilities. Proliferation resistance and physical protection are also essential priorities in the expanding role of nuclear energy systems. This goal applies to all inventories of nuclear materials in the system involved in enrichment, conversion, fabrication, power production, recycling, and waste disposal. In addition, existing nuclear plants are highly secure and designed to withstand external events such as earthquakes, floods, tornadoes, plane crashes, and fires. Their many protective features considerably reduce the impact of external or internal threats through the redundancy, diversity, and independence of the safety systems. This goal points out the need to increase public confidence in the security of nuclear energy facilities against

terrorist attacks. Advanced systems need to be designed from the start with improved physical protection against acts of terrorism, to a level commensurate with the protection of other critical systems and infrastructure.

- Goal 8: Be a very unattractive route for diversion or theft of weapon-usable materials, and provide increased physical protection against acts of terrorism.

The goal of SMRs are summarized as follows;

- Generate energy sustainably and promote long-term availability of nuclear fuel.
- Minimise nuclear waste and reduce the long term stewardship burden.
- Excel in safety and reliability.
- Have a very low likelihood and degree of reactor core damage.
- Eliminate the need for offsite emergency response.
- Have a life cycle cost advantage over other energy sources.
- Have a level of financial risk comparable to other energy projects.
- Be a very unattractive route for diversion or theft of weapon-usable materials, and provide increased physical protection against acts of terrorism.

2.2.3 Six representative types of SMRs

To achieve the goals of SMRs, GIF selected six new concept reactors [11]:

(1) Gas-cooled Fast Reactor (GFR); The GFR system is a high-temperature helium-cooled fast-spectrum reactor with a closed fuel cycle. It combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimization, with those of high-temperature systems. The GFR cooled by helium is proposed as a longer-term alternative to sodium-cooled fast reactors. The helium coolant is a single-phase coolant that is

chemically inert, which does not dissociate or become activated, is transparent and while the coolant void coefficient is still positive, it is small and dominated by Doppler feedback. The reactor core has a relatively high power density, offering the advantages of improved inspection and simplified coolant handling. The high core outlet temperature above 750 °C, typically 800-850 °C is an added value to the closed fuel cycle.

(2) Lead-cooled Fast Reactor (LFR); The LFRs feature a fast neutron spectrum, high temperature operation, and cooling by either molten lead or Lead-Bismuth Eutectic (LBE), both of which support low-pressure operation, have very good thermodynamic properties, and are relatively inert with regard to interaction with air or water. An important feature of the LFR is the enhanced safety that results from the choice of a relatively inert coolant. Also, it would have multiple applications including production of electricity, hydrogen, and process heat. The LFR is an advanced Gen IV reactor type that offers significant advantages in achieving the goals set by GIF. Among the 6 reactor types considered to be promising by the GIF, the LFR may well offer the best combination of characteristics and advantages.

(3) Sodium-cooled Fast Reactor (SFR); The SFR uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction and operation at low pressure. The SFR can reduce the radiotoxicity and heat load which facilitates waste disposal and geologic isolation, and enhanced utilization of uranium resources through efficient management of fissile materials and multi-recycle.

(4) Molten Salt Reactor (MSR); The MSR is a reactor type that uses molten salt as the primary cooling system. Molten salts have low vapour pressure and high stability, lower reactivity than liquid sodium, and high thermal efficiency. Because the MSR does not use fuel assemblies, it has features of simplified reactor structure and uniform combustion rate, and can be reprocessed while the reactor is operating.

(5) Very High Temperature Gas-cooled Reactor (VHTR); The VHTR is primarily dedicated to the cogeneration of electricity and hydrogen, the latter being extracted from water by using thermo-chemical, electro-chemical or hybrid processes. The VHTR has potential for inherent safety, high thermal efficiency, process heat application capability, low operation and maintenance costs, and modular construction.

(6) Super Critical Water-cooled Reactor (SCWR); The SCWRs are high temperature, high-pressure, light-water-cooled reactors that operate above the thermodynamic critical point of water (374 °C, 22.1 MPa). The SCWRs can increase in thermal efficiency, remove reactor coolant pumps and steam separators and dryers, reduce containment and steam turbine size. These general features offer the potential of lower capital costs for a given electric power of the plant and of better fuel utilization, and thus a clear economic advantage. However, at this stage, this type of SMRs has not been developed yet.

Table 4 shows the six representative types of SMRs [12].

Table 4. Characteristics according to typical design type of SMRs [12].

	Neutron spectrum (fast/thermal)	Coolant	Temperature (°C)	Pressure	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180, 300-1200, 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - advanced high-temperature reactors	thermal	fluoride salts, chloride based	750-1000		UO_2, particles in prism	open	1000-1500	electricity & hydrogen
Sodium-cooled fast reactors	fast	sodium	500-550	low	U-238 & MOX	closed	50-150, 600-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal), closed (fast)	300-700	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2, particles in prism	open	250-300	electricity & hydrogen

Table 5 shows the summary of main design features and status of SMRs from the 2018 Report of the IAEA Advanced Reactors Information System (ARIS) [13].

Table 5. Summary of main design features and status of SMRs [13].

Design	Output MW(e)	Type	Designers	Country	Status
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Basic Design
CAP200	150/200	PWR	CGNPC	China	Conceptual Design
DHR400	(District Heating)	LWR(pool type)	CNNC	China	Basic Design
IRIS	335	PWR	IRIS Consortium	Multiple Countries	Conceptual Design
DMS	300	BWR	Hitachi GE	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	100	PWR	KAERI	Republic of Korea	Certified Design
ELENA	68 kW(e)	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
KARAT-45/100	45/100	BWR	NIKIET	Russian Federation	Conceptual Design
RITM-200	50 × 2	PWR	OKBM Afrikantov	Russian Federation	Under Development
RUTA-70	70 MW(t)	PWR	NIKIET	Russian Federation	Conceptual Design
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
UK-SMR	443	PWR	Rolls-Royce and Partners	United Kingdom	Mature Concept
mPower	195 × 2	PWR	BWX Technologies	USA	Under Development
NuScale	50 × 12	PWR	NuScale Power	USA	Under Development
SMR-160	160	PWR	Holtec International	USA	Preliminary Design
W-SMR	225	PWR	Westinghouse	USA	Conceptual Design
ACPR50S	60	PWR	CGNPC	China	Preliminary Design
ABV-6E	6~9	Floating PWR	OKBM Afrikantov	Russian Federation	Final design
KLT-40S	70	Floating PWR	OKBM Afrikantov	Russian Federation	Under construction
RITM-200M	50 × 2	Floating PWR	OKBM Afrikantov	Russian Federation	Under Development
SHELF	6.4	Immersed NPP	NIKIET	Russian Federation	Detailed Design
VBER-300	325	Floating PWR	OKBM Afrikantov	Russian Federation	Licensing Stage
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
GTHTR300	300	HTGR	JAEA	Japan	Basic Design
GT-MHR	285	HTGR	OKBM Afrikantov	Russian Federation	Preliminary Design
MHR-T	205.5x4	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
SC-HTGR	272	HTGR	AREVA	USA	Conceptual Design
Xe-100	35	HTGR	X-energy LLC	USA	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
SVBR-100	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	Small Lead Cooled	LeadCold	Sweden	Conceptual Design
EM2	265	GMFR	General Atomics	USA	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	USA	Conceptual Design
WLFR	450	LFR	Westinghouse	USA	Conceptual Design
IMSR	190	MSR	Terrestrial Energy	Canada	Basic Design
CMSR	100-115	MSR	Seaborg Technologies	Denmark	Conceptual Design
CA Waste Burner	20	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	Martingale	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor	37.5×8	MSR	Moltex Energy	United Kingdom	Conceptual Design
Stable Salt Reactor	300~900	MSR	Moltex Energy	United Kingdom	Pre-Conceptual Design
LFTR	250	MSR	Flibe Energy	USA	Conceptual Design
Mk1 PB-FHR	100	MSR	University of California, Berkeley	USA	Pre-Conceptual Design
MCSFR	50	MSR	Elysium Industries	USA and Canada	Conceptual Design
eVinci	0.2~15	Small Heat Pipe	Westinghouse	USA	Under Development

Figure 3 shows a histogram of the SMRs listed in Table 5 over a range of power generation capacities. The largest number of reactors with an output below 50 MWe was 14. The number of reactors with outputs of 50 to 100 MWe was 12, and the number of reactors with high outputs above 250 MWe accounted for 16.

2.3 Review of characteristic of SMRs

Due to the characteristics of SMRs, regulatory guidelines applied to existing large nuclear power plants may have to be revised or reset. To establish the appropriate regulatory guidelines for SMRs, it is necessary to correctly understand the characteristics of SMRs. For this purpose, the characteristics of SMRs are classified and explored into four categories: fully passive safety system; multi-unit modular reactor; underground construction of containment buildings; design of nuclear reactor internalization and integration. The exploration of the characteristics of SMRs in this Chapter includes design, manufacturing, and construction. Table 6 shows whether some SMRs are applicable to the four categories described above.

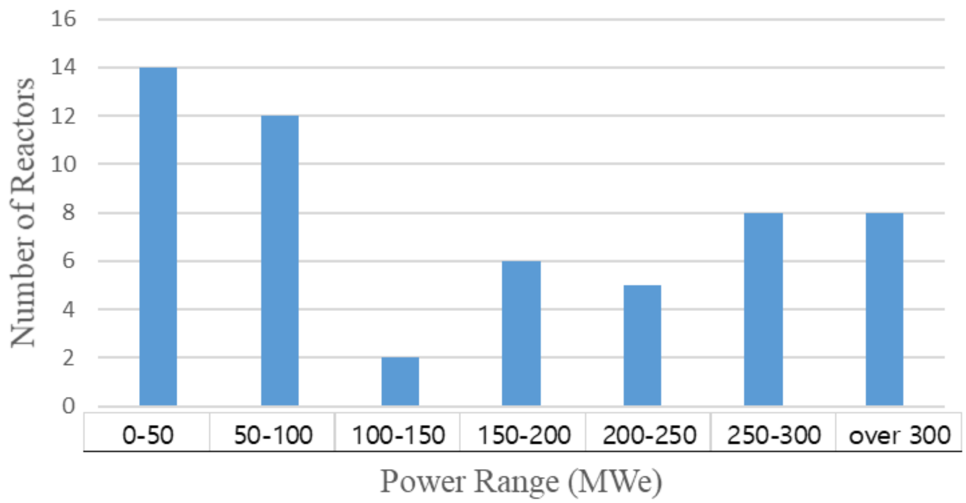

Figure 3. Summary of SMRs design based on power range [13].

Table 6. Evaluation of some SMRs in four categories.

Reactor design	Fully passive safety system	Multi-unit modular reactor	Underground construction	Internalization and integration
CAREM	Yes	Yes	No	Yes
IRIS	Yes	Yes	No	Yes
SMART	No	Yes	No	Yes
mPower	No	Yes	Yes	Yes
NuScale	Yes	Yes	Yes	Yes
KLT-40S	No	Yes	No	Yes
HTR-PM	No	Yes	No	No
4S	No	Yes	No	No

2.3.1 Fully Passive Safety System

SMRs, represented by Generation IV reactors, have significantly lower accident consequences than conventional large reactors due to their size and unique design characteristics. This is because the Engineered Safety Features of the SMRs are designed to achieve safety objectives using a complete passive concept.

The integrated reactors of Light Water Reactor (LWR) type SMRs, such as NuScale, which is expected to be commercially available soon [14], are designed so that the Large Break Loss of Coolant Accident (LBLOCA) does not fundamentally occur. In addition, the reactor coolant, which has a lower density due to the heat from the fuel, transfers heat to the steam generator and increases in density and spontaneously circulates. Cooling by natural convection of the reactor coolant is designed to eliminate the need for a separate device for forced flow. In the case of other LWR-type SMRs, the reactor coolant pump is designed as a canned-pump type to prevent leakage of the reactor coolant. Furthermore, the reactor is designed to be immersed in a large reactor pool. The reactor pool fulfills the role of a refueling water storage tank, and is considered as a final heat removal source. For example, NuScale has a reservoir capable of storing 30.3 million Liter (8 million gallons) of cooling water, which acts as a final heat removal source to cool the reactor core in a natural circulation manner during normal and emergency cooling operations. Therefore, even in Station Black-Out (SBO) situations, it is designed to enable safe shut-down and self cooling of the core without the action of an operator [15]. Figure 4 shows the NuScale reactor. The left side of the figure shows the schematic of the integrated reactor. The right side shows the expected natural circulation flow paths.

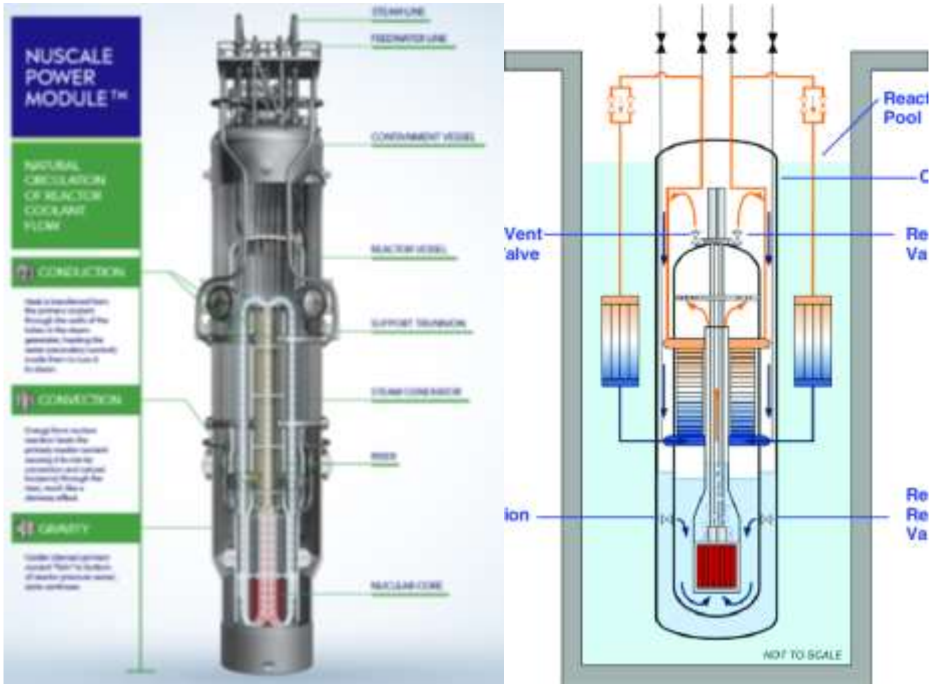

Figure 4. NuScale Small Modular Reactor [15].

Assuming that all safety engineered features failed due to the occurrence of severe accidents, the mission time of the reactor pool (the ultimate heat sink for the removal of decay heat) was calculated:

45 MWe (160 MWth) fuel power : 3.15 MWe decay power

The time to boil 30.3 million liters = 53,866 minutes

The time required to boil 30.3 million liters of water is about 897 hour (37.4 day). This time is considered to be enough time to refill the pool.

In the case of the Very High Temperature Reactor (VHTR) with a fully passive safety system, the VHTR transfers the residual heat from the nuclear fuel to the reactor vessel in case of an accident, and then to the Reactor Cavity Cooling System (RCCS) as the passive safety device as shown in Figure 5. Then, the heated, lighter air inside the device is discharged to the outside through the upper "natural circulation riser", the chimney.

The natural circulation process in which the cold air in the outside is sucked into the space where the heated air escapes, and is again heated and discharged is repeated. As the inside of the containment vessel is cooled with air, even if the vessel is broken, the air can cool the reactor better. It is designed to cool the reactor with natural phenomena such as thermal conduction and radiative cooling of the reactor. VHTRs are also designed to eliminate the need for separate cooling units used in existing reactors. VHTRs are less likely to leak radioactive material and cool down naturally with air. Also, the explosion does not occur at the origin. Figure 5 shows an example of a recent VHTR design submitted to the Senior Industry Advisory Panel (SIAP) [16].

In the case of Molten Salt Reactors (MSRs), Since the graphite used as a moderator has a good thermal conductivity, if the reactor fails and the chain reaction stops, the remaining

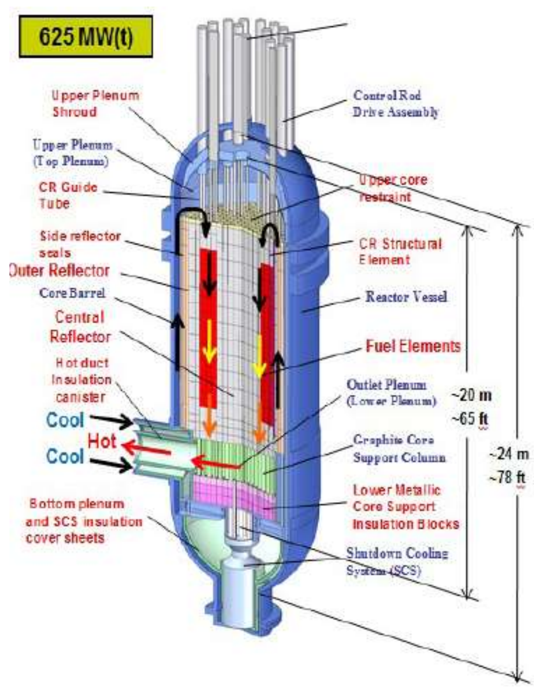

Figure 5. Examples of recent VHTR designs by SIAP (SC-HTGR) [16].

heat is easily conducted out of the reactor. It is designed to prevent leakage of radioactive material by cooling the reactor vessel automatically without any external power source or operator action.

2.3.2 Multi-Unit Modular Reactor

With a fully passive safety system design, one of the most distinctive features of SMRs is a modular design, construction, and operation. Multi-unit modular reactor design is the concept of constructing and deploying a nuclear power plant using standardized reactor modules defined by modularity. The modularity refers to a module at the reactor level, not a module at the part level. The modularity of SMRs means "Plug and Play" level of modularization with minimal work on the construction site of the plant. This is characterized in that the generation capacity can be set by determining the number of modules according to the demanded power amount of the power generation company. Furthermore, in the case of an area where power demand is gradually increasing, it is possible to increase the generation capacity by adding modules within the same site already constructed. The US Department of Energy (DOE) defines the modularity of SMRs as follows [17]:

> The term “modular” in the context of SMRs refers to the ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use. Even though current large nuclear power plants incorporate factory-fabricated components (or modules) into their designs, a substantial amount of field work is still required to assemble components into an operational power plant. SMRs are envisioned to require limited on-site preparation and substantially reduce the lengthy construction times that are

typical of the larger units. SMRs provide simplicity of design, enhanced safety features, the economics and quality afforded by factory production, and more flexibility (financing, siting, sizing, and end-use applications) compared to larger nuclear power plants. Additional modules can be added incrementally as demand for energy increases.

If additional reactor modules are installed in an already built or operating SMRs nuclear facility, this has the advantage of reducing expenses such as site survey, securing ownership, construction of transmission and distribution network, *etc*. at the initial stage of construction because it uses pre-secured site. Also, unlike conventional large power plants that have to shut down all the power plants for maintenance, modular reactors maximize facility utilization by stopping individual modular reactors that require maintenance and sequential maintenance. As can be seen in Table 6, SMRs of modular design are currently IRIS, SMART, mPower, NuScale, KLT-40S, HTR-PM and 4S. Figure 6 shows the installation of three NuScale SMRs as an example of a multi-unit modular nuclear power plant [18].

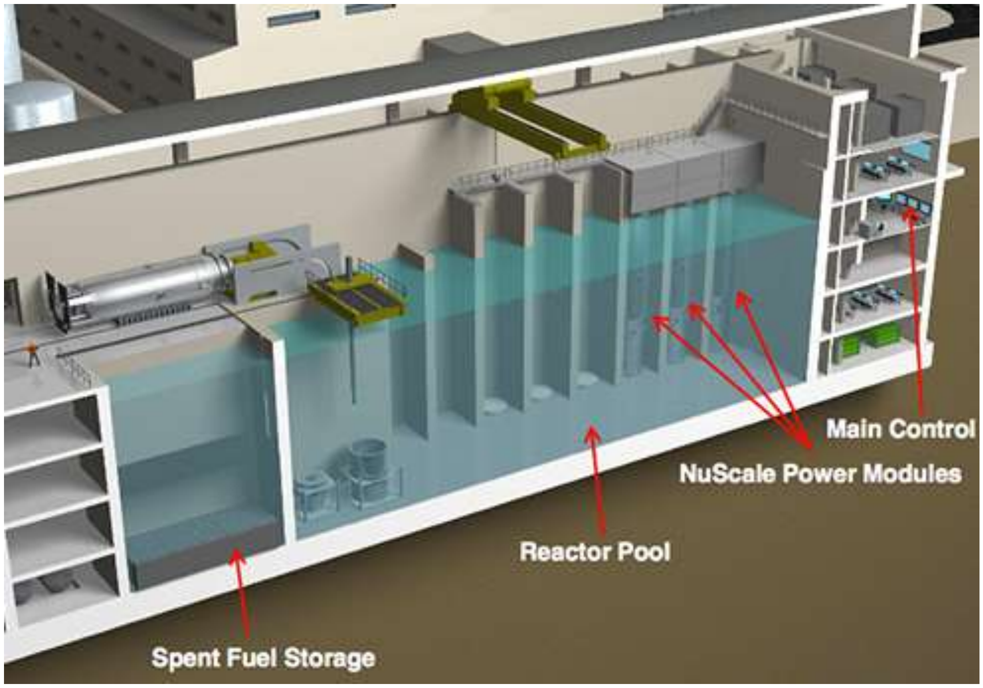

Figure 6. An example of a Multi-unit modular nuclear power plant layout [18].

2.3.3 Underground construction of containment buildings

The size and thickness of containment buildings in existing large nuclear power plants are determined by taking into account the maximum pressure and temperature caused by the release of all pressurized water from the primary cooling system to the steam in the event of a severe accident such as a Loss-of-Coolant-Accident (LOCA). The function of the containment building is to prevent external leakage of radioactive material during design basis accidents and to maintain safety. It also protects internal facilities not only during severe accidents but also during accidents such as earthquakes, aircraft crashes, and terrorist attacks.

If nuclear power plants are constructed underground, the characteristics of SMRs such as passive safety features, small integral reactor, and underground construction, are prominent compared to existing nuclear power plants. According to report by Pinto [19], construction of existing large nuclear power plants underground is expected to increase construction costs by more than 30% compared to building on the ground due to scale problems. However, in the case of SMRs, which have advantages such as reduced costs due to the small size of the nuclear power plant and reduced construction costs due to the modularization of the reactor, it is clear that this rise in construction costs will be significantly reduced.

If the nuclear power plant is underground, the ground can replace the role of the containment building, and safety can be greatly increased. The possibility of external leakage of radioactive material, which can be caused by internal high-temperature high pressure due to a severe accident or unexpected external load, will be greatly reduced. As a result, it is possible to achieve a high level of containment effect and to improve the safety of the nuclear power plant.

In addition, the restrictions on the construction sites of nuclear power plants can be drastically reduced. The multiple barriers for the internal sealing of radioactive materials make the construction of nuclear power plants very restrictive in siting, design and licensing of nuclear power plants. For example, it is expected that the regulations on the impacts of the people around the nuclear power plant and the surrounding environment, meteorological, and hydrological impact assessment can be greatly simplified. The existing large-scale nuclear power plants were constructed to avoid population centers, but the underground construction of nuclear facilities made it possible to build the SMRs nuclear facilities near the city. In addition, the earthquake, meteorological and hydrological characteristics of the region where nuclear power plants are to be constructed are very important factors for site selection of nuclear power plants.

However, the underground construction of nuclear facilities allows them to be very free from factors that threaten the safety of nuclear power plants, disasters such as earthquakes, tornadoes or aircraft crashes.

Secondly, it is expected to improve the seismic safety of nuclear power plants. According to Earthquake engineering of large underground structures, the general view is that underground structures are much less severely affected by strong seismic motion than surface structures [20]. In the case of ground structures, when the mass of structure is large or the ground stiffness is relatively small compared to the structure, when the earthquake occurs, the inertial force of the structure greatly affects the seismic response of the ground structure. However, in the case of underground structures due to earthquake effects, the surrounding medium is almost the same behavior as the surrounding ground rather than different behaviours. As a result, the underground structure shows an improvement in seismic safety because it does not show a large amplification phenomenon in the seismic response as compared with the ground structure [21].

Finally, the most significant advantage of underground nuclear power plants is that nuclear power plants can be constructed and operated at close proximity to the power demand reducing transmission related costs. These benefits are another key to the flexibility of site selection for SMRs.

On the other hand, what can be considered as a disadvantage of underground nuclear power plants is expected to be a decrease in accessibility. However, the minimum accessibility to mitigate accidents in the event of an accident is expected to be designed with due consideration, and it seems that this will not be a problem. As shown in Table 6, current reactor designs for undergrounding nuclear facilities are estimated to be mPower

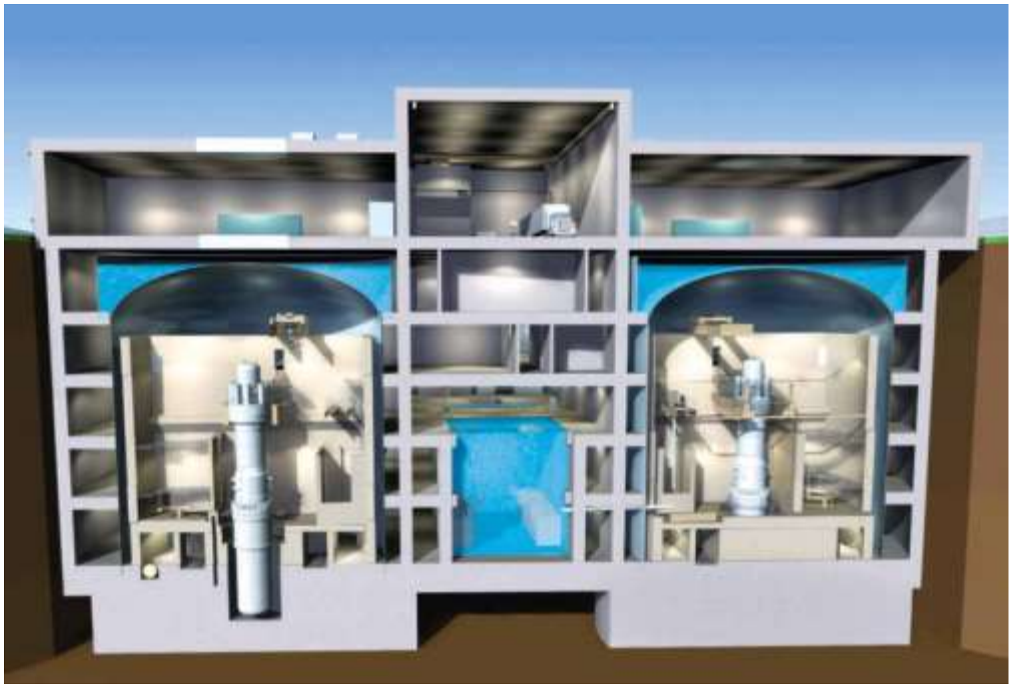

Figure 7. Conceptual drawing of an underground containment structure (B&W mPower) [22].

and NuScale only. Figure 7 shows a conceptual drawing of an underground containment structure housing two B&W mPower reactor modules [22].

2.3.4 Design of nuclear reactor internalization and integration

As has been shown, the most important design feature of SMRs is that they are designed to be located inside the reactor to pursue an integral reactor. Conventional large-scale nuclear power plants consisted of core apparatuses or systems such as steam generators, control rod drives, and reactor coolant pumps connected or attached to the reactor independently by pipelines. In the case of a coolant pump, which is essential for the coolant flow of existing large nuclear power plants, the design of SMRs is designed to apply passive principles such as natural convection or gravity, or to attach pipes directly to the reactor vessel to avoid piping. Also, the steam generator is designed to be located inside the reactor vessel, and it is designed not to require piping from the reactor to the steam generator. Therefore, it is believed that the absence of such large-scale piping of the existing nuclear power plant causing LOCA in case of an accident greatly increased the safety of the reactor.

Chapter 3. Methodology

The purpose of this report is to define the key changes necessary in nuclear regulatory standards to address issues raised by SMRs. To capture all changes necessary would be an exhaustive task and in some cases premature. It is better instead to concentrate on regulations that can help with the initial design process to improve the concepts before they become finalized.

To achieve this goal, a 5 step process is followed as shown in Figure 8. The first step consists of reviewing the current status of all SMRs. The second step is to review current regulations. The third step is to develop a set of criteria to adequately judge the current regulations. The fourth step is to perform the assessment and identify gaps and the fifth step is to recommend changes to key regulations. Figure 8 shows a flowchart for deriving appropriate regulatory standards for SMRs through literature review.

Figure 8. Flow chart for literature review for establishing regulatory standards for SMRs.

To this end, a literature review was performed regarding SMR features as discussed in Chapter 2. First, the characteristics of the design aspects and the literature related to research and development are reviewed and investigated to characterize the SMRs. The SMRs features are devided into 4 categories that are significantly different from current plants: implementation of passive safety features; modularity; underground construction; and system integration. The literature review will consider these categories in comparison to the reactor types and identify the relevant features that need to be considered. A review of the literature on the design characteristics of SMRs was conducted using reports issued by the World Nuclear Association (WNA) [23], information published by the manufacturer, and R & D results and forecast reports issued by the Generation IV Information Forum (GIF).

For step 2, in order to establish the regulatory standards, several sources are considered. The USNRC's regulatory standards (listed in Table 7), and the safety series report of the IAEA (listed in Table 9) were reviewed as foundational as they are the source documents most other countries base their standards and regulations on. Additional review of Canadian standards and regulations and research papers were also reviewed. In this review, a line by line assessment is considered too comprehensive and has the potential to get buried in detail. In essence, the review was to identify the crucial key concerns such as Control, Cool, and Contain that are fundamental to nuclear plant design. Note that as the number of standards to be reviewed is large, this step will also consider the key documents that need to be assessed for the final phase in an effort to have a reasonable scope.

Table 7 USNRC 10 CFR part for the regulation

Part	Title
Part 20	Standards for protection against radiation
Part 50	Domestic licensing of production and utilization facilities
Part 51	Environmental protection regulations for domestic licensing and related regulatory functions
Part 52	Licenses, certifications, and approvals for nuclear power plants
Part 73	Physical protection of plants and materials
Part 100	Reactor site criteria

Table 8. Configuration of Regulatory Guide.

No.	Title
1	Power Reactors
2	Research and Test Reactors
3	Fuels and Materials Facilities
4	Environmental and Siting
5	Materials and Plant Protection
6	Products
7	Transportation
8	Occupational Health
9	Antitrust and Financial Review
10	General

Table 9. List of safety standard of IAEA [24].

Categories	Title	
Safety Fundamentals	SF-1	Fundamental Safety Principles
General Safety Requirements	GSR Part 1	Governmental, Legal and Regulatory Framework for Safety
	GSR Part 2	Leadership and Management for Safety
	GSR Part 3	Radiation Protection and Safety of Radiation Sources
	GSR Part 4	Safety Assessment for Facilities and Activities
	GSR Part 5	Predisposal Management of Radioactive Waste (2009)
	GSR Part 6	Decommissioning and Termination of Activities
	GSR Part 7	Emergency Preparedness and Response
Specific Safety Requirements	SSR-1	Site Evaluation for Nuclear Installations
	SSR-2/1	Safety of Nuclear Power Plants: Design
	SSR-2/2	Safety of Nuclear Power Plants: Commissioning and Operation
	SSR-3	Safety of Research Reactors
	SSR-4	Safety of Nuclear Fuel Cycle Facilities
	SSR-5	Disposal of Radioactive Waste (2011)
	SSR-6	Regulations for the Safety Transport of Radioactive Material

For the USNRC, the main guidelines for the regulation of nuclear facilities are listed in the following table.

In addition, the regulatory guide provides guidance on licensing nuclear facilities, combining interpretations and opinions when the USNRC makes specific regulations in accordance with the guidelines. The composition of the Regulatory Guide is shown in the following table. Regulatory guides are issued in the following 10 broad divisions:

Each guide is identified by a number composed of the regulatory guide designator, followed by a division number, a period, and a sequential guide number.

Upon completion of the first two steps, a view of SMR concepts and current regulatory approaches can be considered. Criteria is established that links fundamental guidance to the reactor designs. These criteria will be set such that failure to achieve them would render one of the SMR design features unsuccessful. Then for step 4, the current regulations can be reviewed again to see if they contain the specific requirements established in the criteria phase and further if sufficient detail is available in the current standards and regulations. Then a judgement on whether or not the reviewed regulatory standards matched the characteristics of the SMRs can be achieved. The results of the literature review are used to establish the regulatory standards that should be applied to SMRs.

The first step is the exploration phase of the characteristics and development status of SMRs and the significant differences between existing large-scale nuclear power plants and SMRs, as described in Chapter 2 of this report. The second and third stage is discussed in Chapter 4. The fourth and fifth stages shall be discussed in Chapter 5.

Chapter 4. Review of current safety regulatory standards

The principles for the safety of nuclear power plants can be found in the safety series published by the IAEA and in Title 10 of the Code of Federal Regulations (CFR), which are covered by the USNRC as listed in Table 7 and 8 (See previous chapter). While other codes and standards will be considered, these two are fundamental to this work. The set of Safety Standards of the IAEA includes a unified Safety Fundamentals (SF1), a General Safety Requirements (GSR) in seven parts applicable to all facilities and activities with a graded approach, complemented by a set of six facilities and activities Specific Safety Requirements (SSRs). The Safety Requirements are implemented through a set of general and specific safety guides. Table 9 listed the standards according to the hierarchy of the IAEA safety series [24].

Section 4.1 will discuss IAEA documents while section 4.2 will discuss USNRC documents, and Section 4.3 will discuss siting. Section 4.4 will discuss operations. Section 4.5 is a summary, and Section 4.6 will identify key criteria.

4.1 Basic Safety Principles for Nuclear Power Plants

First, the IAEA INSAG-3 (1988) systematically presented the safety goals of nuclear power plants and the various principles of safety to achieve them [25]. It was revised to INSAG-12 (1999) in 1999 [26]. INSAG-3 / INSAG-12 presents basic safety principles systematically by dividing them into operational responsibilities, defense in depth strategies, and general technical principles.

4.1.1 Operational Responsibility

Operational Responsibility emphasizes three aspects: Safety Culture, Operational Organization Responsibility, and Regulation and Independence Verification.

(1) Safety culture: An established safety culture governs the behaviour and interactions of individuals and organizations engaged in nuclear-related activities. This is important to ensure the plant has the proper mindset when problems occur. Safety culture strengthens the defense in depth.

(2) Operational Organization Responsibility: The ultimate responsibility for a nuclear plant safety rests with the operating organization. It cannot be diluted by separate activities or responsibilities of designers, equipment suppliers, constructors, or regulators. This aspect requires the owner of the plant to be responsible and ensure all workers on site, including contractors and sub-contractors, conduct work in a safe manner.

(3) Regulation and Independence Verification: The Government establishes a legal framework for the nuclear industry and establishes an independent regulatory organization that will enforce nuclear power licensing and regulation. The responsibility of the regulatory organization is clearly separated from that of other organizations, ensuring that the regulator is independent of the safety responsible body and protected from undue pressure. As part of this aspect, it is necessary for the regulator to have certain expertise with respect to the safe operation of the plant as design. Note that no information is provided to a specific design regardless of size or type.

4.1.2 Defense-in-Depth Strategy

The Defense-in-Depth strategy is one of the most important principle of the technical aspect for nuclear safety. To compensate for possible human errors and mechanical failures, the concept of defense in depth with multi-level protection, including continuous barriers (Multiple Barrier) to prevent environmental leakage of radioactive materials, is implemented. This concept includes measures to protect the barriers by preventing damage to the power plants and the barriers themselves and to protect the public and the environment from disasters even if the barriers are not fully effective. Figure 9 shows the concept of defense-in-depth.

The intent shown in Figure 9 is to ensure the fission products or radioactive material is retained in the fuel and does not reach the surrounding environment. The fuel is designed to keep the material in solid form. This represents the first barrier. The second barrier is the cladding. The material is chosen such that it stops gases from easily escaping. The third barrier material is the pressure boundary of the coolant system. The fourth barrier is

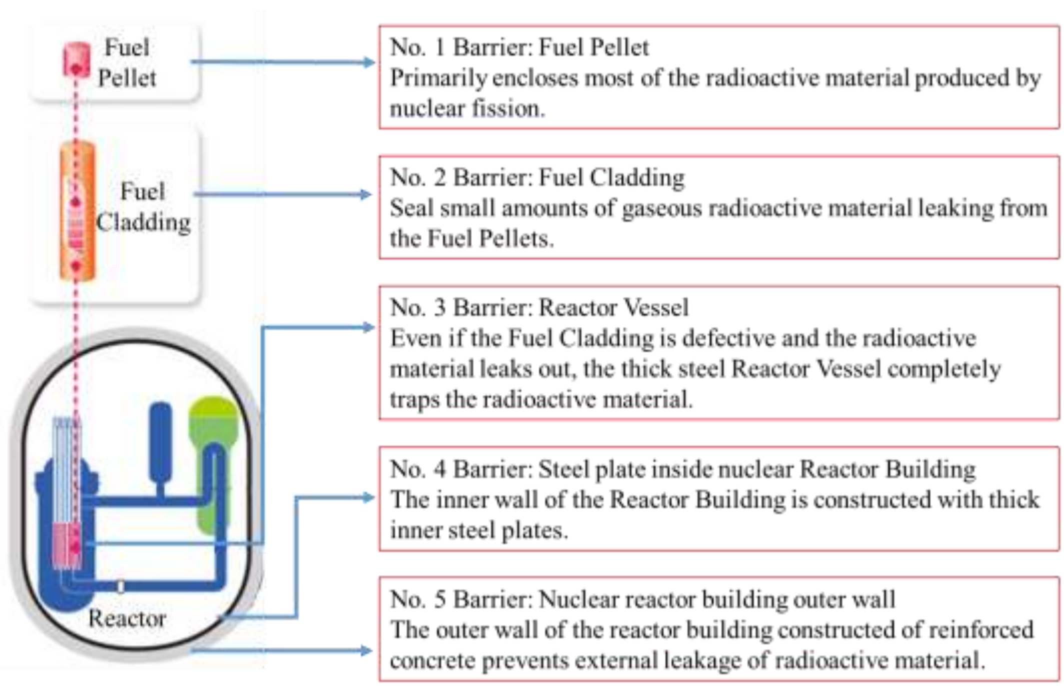

Figure 9. Concept of Defense-in-Depth of nuclear power plant.

a steel plate on the inner side of the containment building. The final barrier is reinforced concrete.

The strategy for defence-in-depth is twofold: first, to prevent accidents and second, if prevention fails, to limit the potential consequences of an accident and to prevent its evolution to more serious conditions. Defence-in-Depth is generally structured in five levels. The objectives of each level of protection and the essential means of achieving them in existing plants are shown in Table 10.

Table 10. Levels of Defence-in-Depth in existing plants [26].

Levels	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

(1) Accident Prevention: The first priority is to ensure safety, *i.e.* prevention of accidents (especially accidents that can cause severe core damage).

(2) Accident Mitigation: On-site and off-site mitigation measures are in place to significantly reduce the effects of radiation leakage in the event of a severe accident.

Note that no information is provided to a specific design.

4.1.3 General Technical Principles and Specific Principles

The safety objectives and the fundamental principles provide a conceptual framework for the specific safety principles. The specific principles are presented as follows:

(1) Siting: The selection of an appropriate site is an important process since local circumstances can affect safety. The choice of site takes into account the results of investigations of local factors that could adversely affect the safety of the plant. Local factors include natural factors and human made hazards. Natural factors to be considered include geological and seismological characteristics and the potential for hydrological and meteorological disturbances. Human made hazards include those arising from chemical installations, the release of toxic and flammable gases, and aircraft impact.

(2) Design: The design of a nuclear power plant ensures that the components, systems and structures of the plant have the appropriate characteristics, specifications and material composition, and are combined and laid out in such a way as to meet the general plant performance specifications. Most aspects of safety design are achieving nuclear plant safety objectives by achieving reactor power control, fuel cooling, and the confinement of radioactive materials by appropriate physical obstructions. To this end, normal operation and anticipated operational occurrences are controlled so that plant and system variables remain within their operating ranges. In addition, in a solid fuel reactor, almost all the radioactive materials are confined in fuel pellets sealed within an impervious barrier, usually metallic fuel cladding. Nuclear safety is ensured for these

reactors if the radioactive materials are kept inside the fuel and within other barriers provided by the design.

(3) Manufacturing and Construction: The operating organization and the regulatory organization carry out construction of a nuclear power plant only after appropriate evaluation of the major safety issues have been satisfactorily resolved. At approximately the stage when preliminary design has been completed a safety analysis is performed. This overall analysis is reviewed with the regulatory authorities to ensure that regulatory requirements have been met or will be met, and the plant will be safe for operation. The plant manufacturers and constructors discharge their responsibilities for the provision of equipment and construction of high quality by using well proven and established techniques and procedures supported by quality assurance practices. The manufacturer establishes procedures for the control of processes and documents; identification and control of materials and components; setting of inspection and test schedules; maintenance of records, hold points and corrective procedures for deviations; the whole being subject to a hierarchy of quality assurance practices.

(4) Commissioning: The commissioning programme is established and followed to demonstrate that the entire plant, especially items critical to safety and radiation protection, have been constructed and function according to the design intent, and to ensure that weaknesses are detected and corrected. To ensure that the design intent has been met, the commissioning programme includes checks of safety equipment and its functional characteristics, and of provisions for

radiation protection. Where complete tests of components and systems under realistic conditions cannot be made, tests are performed in combination under conditions as close as possible to realistic. Procedures for normal plant and systems operation and for functional tests to be performed during the operating phase are validated as part of the commissioning programme. During the commissioning programme, the as-built operating characteristics of safety and process systems are determined and documented. Operating points are adjusted to conform to design values and to safety analyses. Training procedures and limiting conditions for operation are modified to reflect accurately the operating characteristics of the systems as built.

(5) Operation: The operating organization exerts full responsibility for the safe operation of a nuclear power plant and, safety review procedures are maintained by the operating organization to provide a continuing surveillance and audit of plant operational safety. The operating organization is responsible for providing all equipment, staff, procedures and management practices necessary for safe operation, including the fostering of an environment in which safety is seen as a vital factor and a matter of personal accountability for all staff. Operation of the plant is conducted by authorized personnel, according to strict administrative controls and observing procedural discipline. The plant manager ensures that all elements for safe plant operation are in place, including an adequate number of qualified and experienced personnel. Safety review procedures are maintained by the operating organization to provide a continuing surveillance and audit of plant operational safety and to support the plant manager in the overall safety

responsibilities. A set of operational limits and conditions is defined to identify safe boundaries for plant operation. Minimum requirements are also set for the availability of staff and equipment.

(6) Accident management: The results of an analysis of the response of the plant to potential accidents beyond the design basis are used in preparing guidance on an accident management strategy. Accident management includes constructive measures of operational personnel in the event of a severe accident, to prevent the accident from occurring and to mitigate its effects, including measures to protect the confinement function and to limit the release of radioactive material. The capability for accident mitigation has always been important in nuclear plant design. The use of confinement structures and containment systems is evidence of this objective.

(7) Decommissioning: Consideration is given in design and plant operations to facilitating eventual decommissioning and waste management. After the end of operations and the removal of spent fuel from the plant, radiation hazards are managed so as to protect the health of workers and the public during plant decommissioning. A plant that is shut down remains an operating plant until its decommissioning and is subject to the normal control processes and procedures to ensure safety. In particular, the principles that govern a plant in a shutdown state apply.

(8) Emergency preparedness: The emergency plans define the actions that would be taken in the event of a severe accident to re-establish control of the plant, to protect staff and the public, and to provide the necessary information speedily

to the regulatory organization and other authorities. Emergency planning and preparedness comprise activities necessary to ensure that, in the event of an accident, all actions necessary for the protection of the public and the plant staff could be carried out, and that decision making in the use of these services would be disciplined. Emergency planning zones defined around the plant provide a basic geographical framework for decision making on implementing protective measures as part of a graded response. These measures include as required early notification, sheltering and evacuation, radio-protective prophylaxis and supply of protective equipment, radiation monitoring, control of ingress and egress, decontamination, medical care, provision of food and water, control of agricultural products, and dissemination of information.

While significant the guidance is given to process for design in a nuclear power plant, there are no restrictions or guidance related to the size or type of nuclear power plant.

4.2 USNRC 10 CFR

In case of USNRC 10 CFR, four of the most cited parts related to nuclear power plant safety are:

(1) Part 20: Standards for Protection against Radiation;

   A. Establish standards for protection against ionizing radiation resulting from activities conducted under licenses issued by the Nuclear Regulatory Commission;

   B. Set requirements for total dose to individuals and controls the recieipt, possession, use, transfer, and disposal of licensed material by any licensee so that those dose levels are not exceeded.

(2) Part 50: Domestic Licensing of Production and Utilization Facilities;

A. As a requirement for obtaining an operating license or construction permit, to provide for the licensing of production and utilization facilities;

B. Appendix A to Part 50: establishes necessary design, fabrication, construction, testing, and performance requirements for structures, systems, and components important to safety;

C. Appendix B to Part 50: Quality assurance requirements for the design, construction, and operation of all structures, systems, and components included in a production or utilization facility.

(3) Part 52: Licenses, Certifications, and Approvals for Nuclear Power Plants;

A. Requirements for early site permits, standard design certifications, combined licenses, standard design approvals, and manufacturing licenses for nuclear power facilities licensed.

(4) Part 100: Reactor Site Criteria;

A. requirements for reactor site criteria based on population zones, and seismic activity.

Appendix A 'General Design Criteria for Nuclear Power Plants' of 10 CFR 50 divides the General Design Criteria (GDC) of nuclear power plants into six areas in terms of Overall Requirements, Protection by Multiple Fission Product Barriers, Protection and Reactivity Control Systems, Fluid Systems, Reactor Containment, Fuel and Radioactivity Control, and presents a total of 64 items [27].

Note that there is no information in the USNRC regulation related to the specific reactor type or size.

4.3 Siting

4.3.1 IAEA SSR-1 Site Evaluation for Nuclear Installations

The IAEA safety series provides procedures for meeting each criterion, but does not include specific details of the methods and techniques. In the case of IAEA, the general and specific standards for the siting of nuclear power plants are explained as follows [28].

(1) General criteria;

  A. Selecting proposed sites and assessing their suitability for the construction of a nuclear power plant;

  B. Determining safety requirements related to a site;

  C. Evaluating the acceptability of a nuclear power plant.

(2) Specific criteria;

  A. Effect of the region on the site on the plant;

  B. Effect of the plant on the region;

  C. Population considerations.

In addition, sub-section 3.1.12 of the Code of Practice on Safety in Nuclear Power Plant Siting (IAEA Safety Series No. 50-C-S) [28] states that:

> "For each proposed site the potential radiological impact on people in the region during operational states and accident conditions, including those which could lead to emergency situations, shall be evaluated with due consideration of the relevant factors including population distribution, people's diets, use of land and water, and the radiological impact of other radioactive releases in the region"

For areas within 10 km radius of the site, the population distribution is analyzed at 10-year intervals from the reactor operation year to the end of its life. The concentric circles of 2, 4, 6, 8, and 10 km of the reactor radius are divided into 16 orientations, and the resident population and the floating population status of each zone are analyzed. In this way, the IAEA also identifies the assessment of population distribution as an important factor. And, this criterion suggests the resident population and the floating population and the population density limitation [29].

4.3.2 USNRC

The USNRC applies the following criteria for site selection of nuclear power plants in 10 CFR 100.11 "Determination of exclusion area, low population zone, and population center distance" [30]. It is regulated based on the distance standard according to the amount of leaked radiation and the population density around the nuclear power generation facility in case of external leakage accident.

> (a) As an aid in evaluating a proposed site, an applicant should assume a fission product release; from the core, the expected demonstrable leak rate from the containment and the meteorological conditions pertinent to the site to derive an exclusion area, a low population zone and population centre distance. For the purpose of this analysis, which shall set forth the basis for the numerical values used, the applicant should determine the following:
>
> (1) An exclusion area of such size that an individual located at any point on its boundary for two hours immediately following onset of the postulated fission product release would not receive a total radiation dose to the whole

body in excess of 25 rem[2] or a total radiation dose in excess of 300 rem[2] to the thyroid from iodine exposure.

(2) A low population zone of such size that an individual located at any point on its outer boundary who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage) would not receive a total radiation dose to the whole body in excess of 25 rem or a total radiation dose in excess of 300 rem to the thyroid from iodine exposure.

(3) A population centre distance of at least one and one-third times the distance from the reactor to the outer boundary of the low population zone. In applying this guide, the boundary of the population center shall be determined upon consideration of population distribution. Political boundaries are not controlling in the application of this guide. Where very large cities are involved, a greater distance may be necessary because of total integrated population dose consideration.

4.4 Operation

Regulatory standards for operators of existing large nuclear power plants can be found in the US NRC's 10 CFR 50.54 (m) [31]. Table 11 shows the minimum requirements per shift for on-site staffing of nuclear power units.

Table 11. Minimum Requirements Per Shift for On-Site Staffing of Nuclear Power Units by Operators and Senior Operators Licensed Under 10 CFR Part 55 [31].

Number of nuclear power units operating[2]	Position	One Unit	Two units		Three units	
		One control room	One control room	Two control rooms	Two control rooms	Three control rooms
None	Senior Operator	1	1	1	1	1
	Operator	1	2	2	3	3
One	Senior Operator	2	2	2	2	2
	Operator	2	3	3	4	4
Two	Senior Operator		2	3	[3]3	3
	Operator		3	4	[3]5	5
Three	Senior Operator				3	4
	Operator				5	6

These technical standards do not include consideration of specific reactor design methods or the size of nuclear facilities.

4.5 Summary of key regulation requirements

In order to construct and operate a nuclear power plant, a nuclear power licensee must prove that a nuclear power plant can be constructed and operated without any risk to the health, safety and environment of the operator and the public. To this end, regulatory bodies such as the IAEA and USNRC should establish technical standards for safety requirements and review whether nuclear power plants are constructed and operated properly in accordance with these safety requirements. The technical criteria related to the construction and operation of nuclear power plants discussed in 4.1 to 4.2 are summarized as follows.

(1) The three basic safety functions of a nuclear power plant are classified into reactor reactivity control, nuclear fuel cooling and containment of radioactive material.

(2) These safety functions are accomplished through the installation of nuclear reactor protection systems and engineering safety equipment in accordance with the concept of defense in depth.

(3) To achieve the basic safety functions of nuclear power plants, specific technical standards for construction and operation classified into eight categories should be observed.

   A. Siting
   B. Design
   C. Manufacturing and Construction
   D. Commissioning
   E. Operation
   F. Accident management
   G. Decommissioning
   H. Emergency preparedness

The current regulation and standards well discuss the above item but do not address specifics related to any reactor type of design. As such, SMR vendors are expected to make their own interpretations. While such interpretation can lead to a good design, it may not be optimal since the actual criteria are really based upon fissile load and residual heat load. Hence guidance in addressing heat load and fissile load more accurately for small reactor cores is beneficial.

Considering the characteristics of the SMRs derived from Chapter 2 through the literature review, it is considered that siting and operation is not well covered in the current regulations. Therefore, literature reviews on regulatory standards for siting and operation specified in the USNRC and IAEA were conducted in 4.3 and 4.4. Further, the ability to take advantage of passive safety system is not clear in the current standards.

4.6 Establishment of criteria for SMRs regulation

SMR differs from the current operating nuclear power plant in terms of design and operation characteristics such as nuclear fuel and safety systems. The criteria for the establishment of regulatory standards for SMRs stem from these differences, which necessitates a new direction for appropriate regulation. Therefore, in this report, when the technical standards for the regulation of nuclear power plants are applied to SMRs, the criterion that the graded approach is necessary or necessary to change is the gap between the characteristics of the SMRs and the existing regulatory standards. The characteristics of SMRs derived from literature review are as follows.

(1) Fully passive safety system

(2) Multi-unit modular reactor

(3) Underground construction of containment buildings

(4) Design of nuclear reactor internalization and integration

Based on this, Chapter 5 describes the establishment of new regulatory standards for siting and operation among the existing regulatory standards for nuclear power plants. For the assessment of regulatory standards related to siting, the following criteria are considered to be the key elements for review:

(1) Appropriate Emergency Planning Zone: Due to the low fissile load and the use of significant passive safety features in SMR designs, the size of the emergency planning zone can be significantly reduced or even eliminated for off site considerations. i.e. reduced to the exclusion zone.

(2) Appropriate Exclusive Zone: Due to the low fissile load and the use of significant passive safety features in SMR designs, the size of the exclusion zone can be reduced. However, a minimum exclusion zone is still required for SMRs as a function of the size of the fissile load.

(3) Local Factors: The following local factors are more relevant for SMRs and need to be well correlated in the regulatory standards:

    A. Environmental Factors: climate and population

    B. Socio-Economic Factors: local economy

    C. Technical Efficiency Factors: climate and population

For the assessment of regulatory standards related to operations, the following criteria are considered to be the key elements for review:

(1) Due to the very small (less than more 10-3) CDF and LERF compared to conventional nuclear power plants, fewer staff are needed for accidents and mitigation.

(2) Due to the small size of the total facility, and modular reactor design, fewer operator in MCR and patrol personnel in the field are required during normal operation.

(3) Modular format allows monitoring of multiple units in one MCR, requiring fewer staff.

Chapter 5. Establishment of Regulatory Standards for SMRs

From the results shown in Chapter 4, some of the regulatory standards will cover the majority of the needs for SMRs. The regulations for most safety concerns are generic. Hence it is clearly possible to create a conceptual design based upon the existing regulatory standards.

The two areas that are considered key are the regulations related to adoption of passive safety and principles of siting. The current regulations for passive safety are not complete as they address the current plants with a significant dependency on active systems. As such, there are likely improvements in the current regulations for either simplicity or clarity that may be beneficial for adopting for SMR applications.

Siting of a nuclear power plant is the other key area where it is expected that can expect the potential for significant improvements in the regulations. The concept of siting and the key principles that affect siting are not expected to significantly change yet the specific criteria for each of those principles may change due to smaller fissile core loads and lower heat loads, hence less impact on the environment.

Section 5.1 will discuss the safety related regulations from the perspective of passive safety. The specific gaps and the nature of those gaps will be identified. Section 5.2 will discuss the siting regulations from the perspective of the needs of the SMR. This will include a discussion on where changes in the regulations may be required with specifics on the criteria. Finally, section 5.3 will recommend the changes that should be done to improve the quality of standards to address SMR related issues.

5.1 Operation

SMRs have characteristics such as simplicity, small capacity, improved operating performance, unique safety function, passive design characteristics, and increased safety compared to existing nuclear power plants. These features allow SMRs to function without operator intervention in normal operating conditions, accidents and post-accident conditions. Thus, the operation of SMRs is generally more automatic and requires less operator intervention compared to existing nuclear power plants. Because of the design simplicity and more automated operating conditions of these SMRs, when a Design Basis Accident (DBA) or a Beyond Design Basis Accident (BDBA) occurs, the actions of the operator required to achieve a safe shutdown of the reactor and to establish a stabilized state of the plant will be reduced. The action of the operator will be passive observation and confirmation that confirms the state of the safety shutdown of the reactor or the state of the containment seal. For small nuclear facilities, the sites can be monitored and maintained by fewer operators. Therefore, the number of operators of SMRs can be expected to decrease compared to existing large nuclear power plants due to the reduction in complexity of their work. For this reason, given the characteristics of SMRs, regulatory standards for requirements related to operators of existing nuclear power plants are not appropriate.

In addition, SMR type nuclear power plants will use modular-type reactor arrangements and operation. Since it is necessary to monitor and control multiple reactors in the centralized main control room, it is not appropriate to apply the operator number of SMRs according to the number of reactors as was shown in Table 9 (page 34). The current regulations have a gap in their requirements to account for the benefit of passive safety features with respect to their operating modes.

To determine the proper operation and the number of operators, it is necessary to understand and apply the unique design of the SMRs and the characteristics according to the differences between the existing nuclear power plants. To this end, the use of Risk-Informed analysis and Probabilistic Risk Assessment (PRA) for SMRs are expected. However, since the SMRs are still in the conceptual design phase or under development, there is still insufficient information on the design and operation of nuclear reactors and reactor facilities. In addition, inherent SMR reactor characteristics, which are fundamentally different from existing large nuclear power plants, have the problem that the criteria for risk measurement such as Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) for SMRs reactors are not applicable or difficult to demonstrate as the design intent is to eliminate CDF and LERF. It is difficult to produce a complete PRA at this early stage of the research and development and application of SMRs reactors as the new passive safety features do not have operation experiences. Therefore, after commercialization of SMRs in the future, PRA information should be supplemented based on operational experience. Nevertheless, it is considered that PRA should be applied to siting and operation of SMRs.

To apply PRA to SMRs, the selection of (IEs) and the preparation of accident scenarios should be preceded. Table 12 shows the Initiating Events Group of the SMRs presented in the Advanced SMR PRA Framework Technical Exchange Meeting [32]. The potential IEs were grouped into 36 IEs for SMRs, and Power Reactor Innovative Small Module

(PRISM) identified for the 21 IEs and 8 IEs for the Modular high-temperature gas-cooled reactor (MHTGR).

Table 12. Identification of Initiating Events for aSMRs [32].

IE Group	aSMR	PRISM	MHTGR
Transients	8	9	5
RCPB / ICPB breaches	5	4	1
Chemical reactions (GCR)	0		
IS-LOCA (GCR)	1		
Special initiators (support system failures)	6	2	1
Structural faults	0		
Internal flooding or fire events	2		
External hazards	2	3	1
Direct releases (GCR)	1		
Startup / low power operations	2		
Shutdown and refueling	2	3	
Spent / used fuel handling and storage	2		
Dry cask storage (LMR)	2		
Radioactive waste systems	3		
Nonradioactive waste systems	0		
	36	**21**	**8**

At Power IEs

2 Identification of IEs for aSMRs

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The main form of initiating events are transients which is common for all type of nuclear power plants. The next most common are pressure boundary breaks, support system failures, extended hazards, and shut-down refuelling issues. As the number of IEs is very small in comparison to a large nuclear power plant (>100), this suggests the PRA results could be very low.

In summary, due to the characteristics of SMRs mentioned in Chapter 2, the frequency and probability of core damage and the probability of radiation leakage of SMRs are expected to be very low compared to existing nuclear power plants. As was shown in Table 3 (page 14), the CDF of some SMRs designs is 'Not applicable' or 'Not possible'. In addition, the CDF of SMRs such as IRIS, NuScale, mPower, 4S, SVBR-100, *etc.* was evaluated as 10^{-8}. Therefore, it is inappropriate to determine the number of operators of SMRs based on existing regulatory standards. The number of operators of SMRs is considered to be suitable to evaluate the risk of SMRs nuclear power plants to be applied. It is considered appropriate to establish the criteria for determining the number of operators of SMRs according to the calculation result after calculating the frequency of core damage, the frequency of radiation leakage, and the probability of radiation leakage per module or the total amount of power determined by the module.

5.2 Siting

As one of the conditions for the siting of traditional nuclear power plants, there was a need for large-scale transmission networks for the transmission of generated electricity, roads, railways, and ports for the transport of machinery and equipment for the construction and operation of nuclear power plants. However, as can be seen from the fundamental characteristics of the SMRs described in Chapter 2, SMRs require only minimal facilities to transport the modules produced by the factory due to their small mass and size. Less transmission lines are needed to supply the generated electricity to nearby electricity consumers. Therefore, it is considered inappropriate to apply the standard of siting of traditional nuclear power plants.

In case of SMRs, according to the characteristics of the SMRs discussed in Chapter 2, the characteristics of the locations where SMRs are expected to be constructed are as follows [33].

SMRs may be located on sites that differ from where traditional nuclear power plants have been built. For example, SMRs may be established:

- on small grids where power generation needs are usually less than 300 megawatt electric (MWe) per facility

- at edge-of-grid or off-grid locations where power needs are small – in the range of 2 to 30 MWe

For example, the location of the construction of SMRs expected in Canada is shown Figure 10 [34]. Figure 10 identifies oil sands, high-temperature steam for heavy industry, replacing conventional coal-fired power, and remote communities and mines as suitable locations for SMRs.

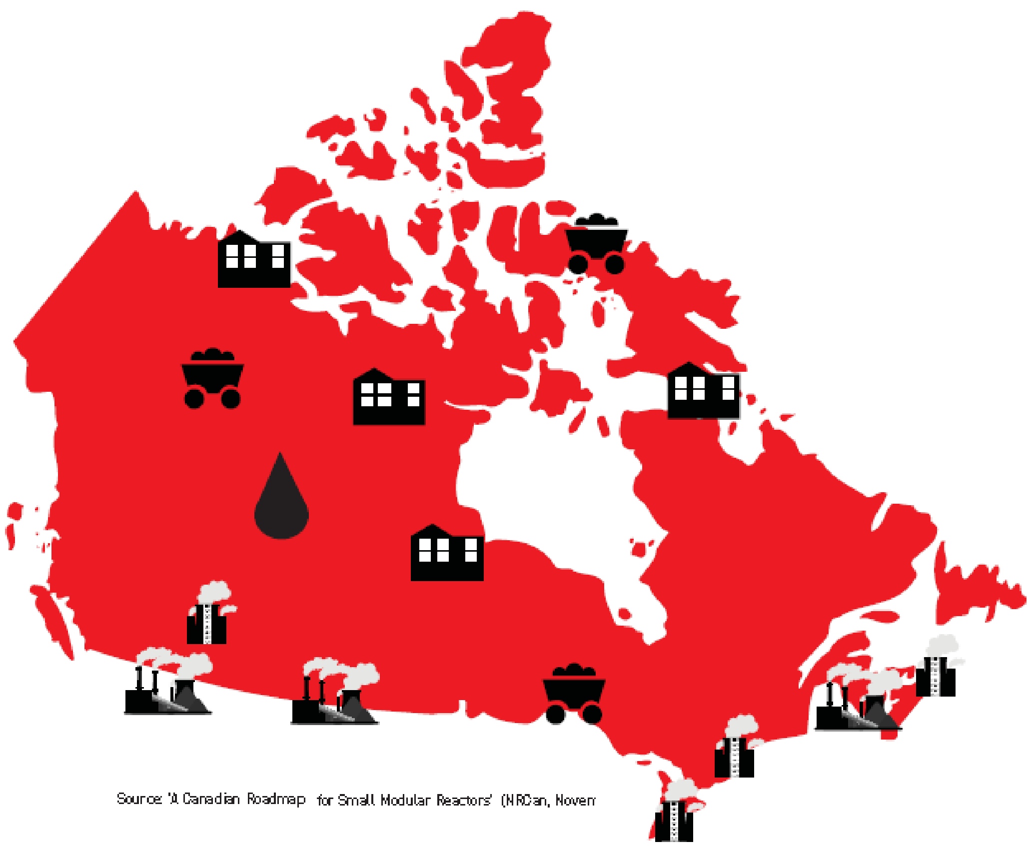

Figure 10. Areas where demand for SMRs is expected in Canada (NRCan) [34].

Both smaller in size and in energy output, SMRs are considered ideal for deployment both on-grid and off-grid in remote locations such as mine sites or the oil sands, as well as willing communities in northern Canada reliant on diesel-fuelled generators for electricity. In addition, these technologies can also be utilized in other industrial applications such as production of hydrogen, local area heating, or other industrial heat applications [35]. Thus, in Canada, the applicability and availability of SMRs are much more likely to be realized than in other countries because of accumulated technology and geographical conditions that fit well with the siting conditions of SMRs [36].

Recent studies on the site selection of SMRs have also raised the need for site selection that reflects the characteristics of SMRs. Harvel [37] conducted an assessment of site selection for SMRs for remote communities and mines in Canada using site evaluation methods for nuclear power plants in various ways. Given the nature of SMRs, it is inappropriate to select sites that are both traditional and more modern and quantitative. The site selection method for the production of electricity and the enhancement of community safety, which is the fundamental goal of existing large nuclear power plants, is not suitable to be applied to site selection of SMRs because of the difference in the fundamental objectives with SMRs having various purposes, efficiency and flexibility. This evaluation is in good agreement with the difference from the existing nuclear power plant due to the characteristics of SMRs mentioned in Chapter 2. This paper suggests that the impact of SMRs, mines or communities, and the additional facilities needed to support these mines and communities should be included in the assessment to assess the siting, so that the impact of the site selection process will be more accurate.

In short, the criteria for site selection of SMRs should be differentiated from those of existing nuclear power plants. Firstly, the Emergency Planning Zones (EPZ) are not considered due to the nature of the nearly fully passive engineered safety features of SMRs and the underground construction of containment buildings. If an EPZ is required, then an appropriate minimum setting is preferred. The consequences of an emergency scenario are not likely to be significant off site due to the low fissile load.

The criteria of the EPZ for the nuclear power plants of each country are as follows: In the United States, 10 miles are set as the radiation exposure pathway EPZ, and 50 miles as the food ingestion exposure pathway EPZ. In Japan, the EPZ is calculated and set the amount of potential radioactive material leakage from the theoretical accident through the nuclear safety analysis and establishes an 8-10 km evacuation zone for the nuclear power plant. The United Kingdom does not specify an EPZ scope. The UK selects reference accidents that may occur at each nuclear facility. After that, the EPZ is set up by conducting accident analysis on these reference accidents (Typically 1 to 3 km)

Table 13 shows the emergency planning area by category of nuclear facilities, as described in the IAEA Safety Guide No. GS-G-2.1, APPENDIX II: AREA AND ZONE SIZES [38]. SMR nuclear power plants would be included in 'Reactors 100 ~ 1000 MW (th)' of Category I facility category. The emergency planning area of the item will be applied to Precautionary Action Zone (PAZ) within 3 km and Urgent Protective action planning Zone (UPZ) within 30 km. Yet these values are much higher than necessary for a SMRs and an underground SMRs likely does not require a zone beyond the site.

Table 13. Suggested Emergency Zones and Area sizes (IAEA) [38].

Facilities	Precautionary action zone (PAZ) radius[b,c]	Urgent protective action planning zone (UPZ) radius[d]
Threat category I facilities		
Reactors >1000 MW(th)	3–5 km	5–30 km[e]
Reactors 100–1000 MW(th)	0.5–3 km	5–30 km[e]
A/D_2 from Appendix III is $\geq 10^5$ [f]	3–5 km	5–30 km[e]
A/D_2 from Appendix III is $\geq 10^4$–10^5 [f]	0.5–3 km	5–30 km[e]
Threat category II facilities		
Reactors 10–100 MW(th)	None	0.5–5 km
Reactors 2–10 MW(th)	None	0.5 km
A/D_2 from Appendix III is $\geq 10^3$–10^4 [f]	None	0.5–5 km
A/D_2 from Appendix III is $\geq 10^2$–10^3 [f]	None	0.5 km
Fissionable mass is possible within 500 m of site boundary[g]	None	0.5–1 km

Furthermore, according to the WNA report on the EPZ, the EPZ for SMRs should be limited to within 300 m, since small reactors are considered to replace fossil fuel power plants in many situations [39]. Conventional large-scale nuclear power plants were built away from population centres. However, the characteristics and purpose of SMRs are small power supply, district heating, and desalination water supply for low population and remote areas where large scale transmission networks are impossible. Therefore, the limitation criteria related to the population around the nuclear power plant, which has been an important factor in siting in the existing regulatory standards, are not significant. Although it is necessary to prepare basic data and characterization of the population distribution around the site for the site selection of the SMRs, it is inappropriate to apply it to the criteria of the siting of the SMRs. Secondly, the criterion for siting of SMRs should be considered as the most important factor of radiation dose after accident. In the

SMRs where containment buildings are constructed underground, the frequency and magnitude of radiation accident occurrences are very different from those of existing nuclear power plants, so, the existing siting restriction zone must be changed. The detailed numerical values should be determined through the accident analysis calculated considering the design details of the SMRs to be applied to nuclear power plant construction, radiation protection characteristics, and characteristics of the engineered safety features. There is clearly an individual characteristic according to the reactor-type of SMRs such as light-water reactor, heavy-water reactor, or High-Temperature Gas-cooled Reactor (HTGR) or Sodium-cooled Fast Reactor (SFR). Therefore, it is considered that the appropriate bounding source term should be set according to the reactor-type in the detailed accident analysis. The Exclusive Zone provides the minimum separation distance for the safe protection of SMRs facilities, so it is appropriate to maintain the existing standards.

In conclusion, due to the characteristics of SMRs such as small capacity, low power density, low severe accident probability, slow accident progression, small radioactive accident per module, SMRs can extremely limit the radiation leakage to the outside even in the event of a severe accident, and the progress of the accident is also very limited. Therefore, it is considered that the EPZ other than the Exclusive Zone is not considered or the minimum setting should be applied. And, in the case of setting the siting limit zone, the design of the specific SMRs to be applied and the evaluation of the leakage radiation dose at the accident should be considered as the main factors of the site selection. Finally, in assessing site selection for SMRs, the impact of SMRs on the surrounding area, mine or community, and any additional facilities needed to support them should be included in the assessment.

5.3 Recommended Changes to Regulatory Standards

Many of the regulations that currently exist already address many of the needs of an SMR plant. Hence, the creation of a unique set of regulations to address SMRs is not a recommended pathway. While a unique set would be clearer to understand, the workload to essentially copy several standards would still be significant and it may be perceived as producing a lesser standard. Instead, most of the current standards could either be used as is or have slight modifications to accommodate the unique requirements of SMRs.

That said, for SMR technology to progress, this work suggests that two areas of regulations should be updated fairly early in the process to allow for the regulations to be incorporated into SMR design.

The first set of regulations that should be updated/modified are those associated with the adoption of passive safety systems. The SMRs will use a significant amount of simplification and passive features. The current regulations do not encourage this as defense in depth requires multiple barriers and usually considers both active and passive barriers. To include the same number of active and passive barriers in smaller designs does not necessarily improve the design or make it safer as the additional barrier does not necessarily cause a significant improvement in the benefit. Hence, a clear understanding of the nature of the risk is important so that designers can concentrate on the passive features and minimize or eliminate the use of unnecessary systems. These regulations are of a higher priority as they directly influence the design phase which the SMR vendors currently are working.

Due to the low probability failure and the reduction in the number of tasks for the operators, a reduction in the number of operators can occur even for multi-unit control rooms. Establishing a better relationship of PRA to control room operator requirements is therefore a recommended change to the regulatory standards.

The second set of regulations that should be updated/modified are those associated with siting. Essentially, due to the SMR small size, many sites that would be unacceptable to a large nuclear power plant are now options available to SMRs. Yet this is largely due to the consequence of size. One of the main advantages of SMRs is to build them in lots and as such the site needs to consider expansion of additional units. This may result in a site that initially is acceptable but over time is not acceptable as the number of units increases. Guidance on how to balance size and the site is necessary for the SMR designs to be finalized and for the true impact on the site to be considered.

Chapter 6. Concluding Remarks

Demand for SMRs is expected to increase globally to provide stable and economical power to regions such as the need to replace aging thermal power plants, remote areas without power grids, and developing countries with difficulties in attracting large nuclear power plants. Research and development of innovative design SMRs in Canada, the United States, and other countries is entering the visualization phase. However, there are few standards for licensing and regulating SMRs that are differentiated from existing large-scale nuclear power plants. For the development of SMRs regulatory technology, this report explored the characteristics of SMRs design, manufacture and construction as follows.

(1) Fully passive safety system: Improved safety by applying inherent design characteristics and fully passive concept of engineered safety features

(2) Multi-unit modular reactor: It is possible to set power generation capacity by determining the number of modules according to power demand.

(3) Underground construction of containment buildings: The possibility of external leakage of radioactive materials is very rare and achieves a high level of containment.

(4) Design of nuclear reactor internalization and integration: Design of main devices to be located inside the reactor to pursue an integral reactor.

In addition, the guidelines for the siting of SMRs and the number of operators of SMRs facilities, which are deemed inappropriate to apply the existing large nuclear power plant regulatory standards, are as follows.

(1) Siting

A. It is considered that the EPZ other than the Exclusive Zone is not considered or the minimum setting should be applied.

B. In the case of setting the siting limit zone, the design of the specific SMRs to be applied and the evaluation of the leakage radiation dose at the accident should be considered as the main factors of the site selection.

C. The impact of SMRs on the surrounding area, mine or community, and any additional facilities needed to support them should be included in the assessment.

(2) Operation

A. Based on the results of the PRA per module or the total number of modules for the determined amount of power, the criteria for determining the number of operators of SMRs should be established and applied.

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