2020年春の年会

原子力安全部会セッション

SMR 等革新炉の安全と安全規制について一今後の取組ー

Safety of Advanced and Innovative Nuclear Reactors and the Preparation of Regulatory Infrastructure
– future Initiatives –

（２）海外で検討が進んでいる革新炉の安全設計の特徴等について

（事例紹介：NuScale）

(2) Safety design features of innovative reactors - Case study: NuScale

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1. NuScale power plant

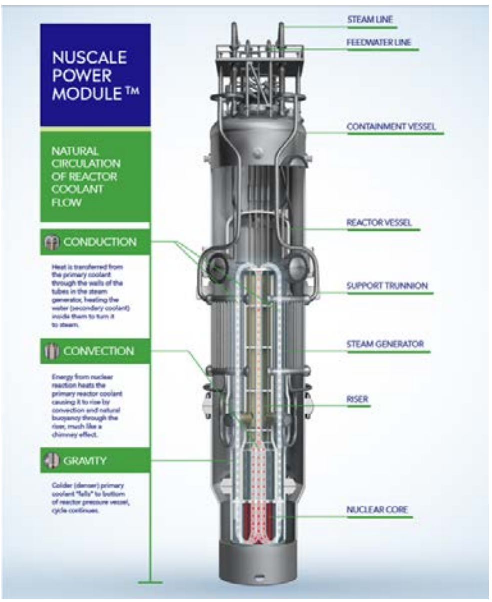
1-1. NuScale power plant current status

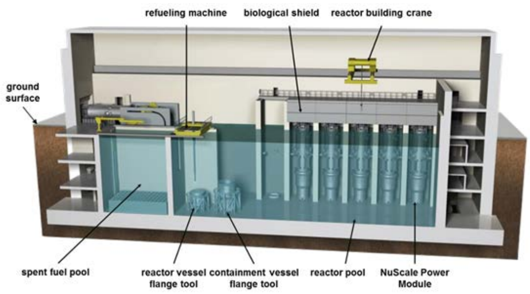
Drawing on 60 years’ experience with commercial application of PWR technology, the NuScale SMR is an evolutionary simple and innovative advancement. NuScale SMR design incorporates unique features that reduce complexity, improve safety and resilience, enhance operability, and reduce costs.

To date, licensing of the NuScale design within the U.S. has progressed to completion of Phase 4 of NRC review in Dec. 2019. NuScale is on track to meet the significant milestone of NRC design certification in January 2021.

1-2. NuScale general description

The NPM (NuScale Power Module) is the fundamental building block of NuScale SMR plant. It consists of a reactor core housed with other primary system components in an integral reactor pressure vessel (RPV) surrounded by a steel containment vessel, all of which is partially immersed in a large pool of water that also serves as the ultimate heat sink. As many as 12 NPMs can be co-located in the same pool for scalability. The major NuScale SMR design features and nominal parameters are provided in Figure 1.





Plant Parameter or Feature	Value
NuScale gross electrical output (MWe)	720
NPM gross electrical output (MWe)	60
NPM core thermal output (MWt)	200
Number of fuel assemblies in NPM	37
Fuel assembly lattice	17x17
Effective fuel length (m)	2.00
Average linear heat rate (kW/m)	10.25
Number of control rod assemblies in NPM	16
Design life (years)	60

Figure 1 : Major NuScale power plant design features

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2. Safety features

The NuScale design is the safest advanced light-water reactor. No other design has demonstrated the fully passive and fail-safe core cooling, assured ultimate heat sink cooling, and unlimited cool-down without operator action, electrical power, or water re-supply. The reactor building is a seismically robust (Seismic Category I) structure capable of withstanding natural and man-made events.

2-1. NuScale Defense-in-Depth approach

NuScale's Defense-in-Depth approach is compared to a conventional LWR in Table 1, organized by International Atomic Energy Agency (IAEA) defense-in-depth levels.

Table 1 : NuScale Defense-in-Depth approach

Defense-in-Depth Level	Conventional LWR	NuScale
1 – Prevent abnormal operation and failures	• ~20 safety-related systems • Historical set of design basis events • Active safety systems that require electrical power • Core damage frequency (CDF) ~1x10^{-5}	• Only 8 safety-related systems required for safe operation • Reduction in design basis events due to simplified design • Passive safety systems* • CDF < 1x10^{-7}*
2 – Control of abnormal operation and detection of failures	• Multiple active systems required to protect critical assets	• Simple, passive systems to protect assets*
3 – Control of accidents within the design basis	• Several design basis events lead to core damage	• No design basis events lead to core damage*
4 – Control of severe accident conditions	• Numerous active systems and operator actions requiring power.	• Passive systems requiring no power or operator action.
5 – Mitigation of consequences of significant radiological releases	• Large early releases • Emergency planning zone = 10 mi	• Small delayed releases* • Emergency planning zone << 10 mi*

IAEA DiD improvement recommendation (INSAG-12, Basic Safety Principles for Nuclear Power Plants)

2-2. Maximizing Simplicity

The use of innovative and simplifying features in NuScale design has a positive cascading effect on plant safety. Fundamental to NuScale's focus on simplicity is the incorporation of all major reactor coolant systems inside the reactor pressure vessel.

The innovative design of the NuScale ECCS requires no AC or DC electrical power to cope with design basis events. All valves are automatically aligned in their safe positions upon loss of power. By simplifying the reactor design and associated engineered safety features, it is easier to build in safety system diversity, redundancy, and independence. As a result, the plant's response to design basis and beyond design basis accidents (BDBA) is also simpler. The simplified response enables levels of automation not achievable in more complex designs.

Individual NPMs are designed to be independent from each other to the greatest extent possible to simplify and standardize NPM safety and auxiliary systems. NPM independence, from a safety perspective, ensures that upsets in one NPM do not propagate to others.

Table 2 provides a comparison of safety systems and components required to protect the reactor core for the NuScale Power Plant versus a typical PWR plant.

Table 2 : Safety systems and components required to protect the NuScale core in the US

Safety System or Component	Typical PWR	NuScale	Safety System or Component	Typical PWR	NuScale
Reactor Pressure Vessel	✓	✓	Condensate Storage Tank	✓	
Containment Vessel	✓	✓	Auxiliary Feedwater System	✓	
Reactor Coolant System	✓	✓	Emergency Service Water System	✓	
Decay Heat Removal System	✓	✓	Hydrogen Recombiner or Ignition System	✓	
Emergency Core Cooling System	✓	✓	Containment Spray System	✓	
Control Rod Drive System	✓	✓	Reactor Coolant Pumps	✓	
Containment Isolation System	✓	✓	Safety-Related Electrical Distribution System	✓	
Ultimate Heat Sink	✓	✓	Alternative Off-Site Power	✓	
Residual Heat Removal System	✓		Safety-Related Emergency Diesel Generators	✓	
Safety Injection System	✓		Safety-Related Class 1E Battery System	✓	
Refueling Water Storage Tank	✓		ATWS Mitigation System	✓	

2-3. Design basis accident

The NuScale SMR has its origins in the principle that advanced reactors can be made safer – safer to operate, safer for the public, and safer during and after accidents. From the elimination of primary coolant pumps to NuScale innovative passive emergency cooling system, NuScale design maximizes simplicity while providing defense-in-depth through redundancy, diversity, and independence of safety systems. NuScale risk-informed performance-based (RIPB) design leverages risk information in early design stages, simultaneously improving safety and reducing cost.

NuScale SMR design enhances plant safety through its deliberate design choices that eliminate or reduce the likelihood of potential accident initiators. As summarized in Table 3, six of eight traditional design basis accidents applicable to existing PWRs are eliminated or have reduced risks for NuScale NPMs.

Table 3 : Design basis accidents for NuScale

Design Basis Accident	**NuScale Response**
Steam system pipe break	Reduced consequences from lower fuel failure fraction
Feedwater system pipe break	No change
Reactor coolant pump shaft failure	Eliminated with natural circulation of primary coolant
Spectrum of control rod ejections	No change
Steam generator tube rupture	Reduced likelihood from tubes in compression (shell-side primary flow)
Large break LOCA	Eliminated by use of integral primary system configuration
Small break LOCA	Reduced consequences from no fuel heatup
Design basis fuel handling accidents	Reduced source term from half-height fuel assemblies and 15.2 m of water above spent fuel assemblies

2-4. DHRS and ECCS

The NPM are submerged in the reactor pool, which is part of the UHS. Passive heat removal to the UHS using DHRS and ECCS maintains core cooling without pool inventory makeup or operator action (Figure 2).

The decay heat removal system (DHRS) is used when the main steam isolation valves (MSIVs) and feedwater isolation valves (FWIVs) are closed. Once a DHRS passive condenser is in service, a closed natural circulation loop is established transferring core decay heat and sensible heat to the UHS. Emergency core cooling system (ECCS) valves open to establish natural circulation flow of reactor coolant between the reactor pressure vessel and the CNV. The CNV is immersed in the UHS, and transfers heat passively to the UHS.

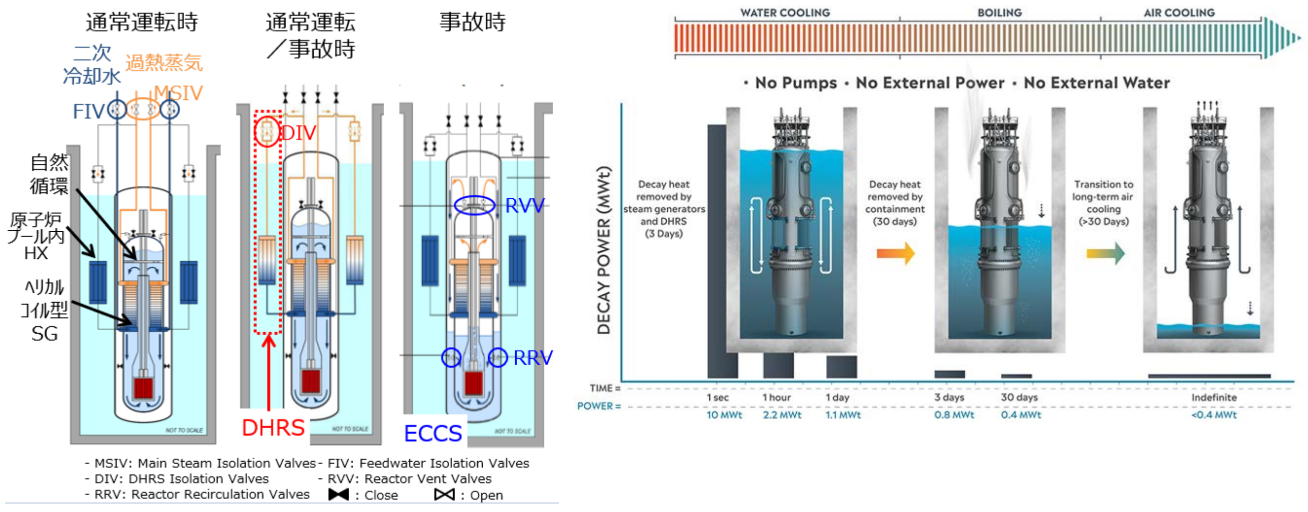

Figure 2 : DHRS and ECCS for NuScale

2-5. EPZ reduction

The NuScale-specific severe accident and source term analyses provide the technical basis for simplifying emergency planning and reducing the size of the NuScale plant emergency planning zone (EPZ) compared to traditional PWRs. Emergency planning is a fundamental part of NuScale defense-in-depth strategy with levels of defense that include accident prevention, accident mitigation, and protective actions. Based on this methodology and criteria as well as source term and radiological dose calculations, NuScale calculates that the EPZ can be reduced from the current 10-mile radius of most U.S. nuclear plants to the site boundary as shown in Figure 3. Reducing the EPZ size to the site boundary is only possible due to the incredible safety offered by NuScale design, which results in substantial reduction of societal risks to the public.

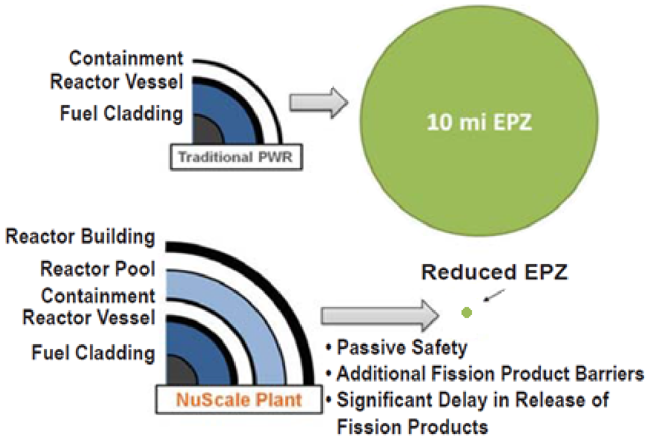

Figure 3 : NuScale EPZ

3. Regulatory Perspective

The NRC regulations include a process by which applicants can propose an alternative to existing requirements, known as exemptions. This process ensures that the alternative approach protects public health and safety. NuScale includes some exemption requests in its design certification application. These exemption requests are necessary to properly address the passive safety approach inherent in NuScale design. The design certification application provides the justification for the safety of each alternative sought by NuScale. The following seventeen (17) exemptions in Table 4 has been applied and approved by NRC.

Table 4 : List of exemptions in the US

No.	Regulation or Regulatory Guide	Description
1	10 CFR 50, Appendix A, GDC 17 & 18	Electric Power Systems
2	10 CFR 50, Appendix A, GDC 19	Control Systems
3	10 CFR 50, Appendix A, GDC 27	Combined Reactivity Control Systems
4	10 CFR 50, Appendix A, GDC 33	Reactor Coolant Makeup
5	10 CFR 50, Appendix A, GDC 40	Testing of Containment Heat Removal System
6	10 CFR 50, Appendix A, GDC 52	Containment Leakage Rate Testing
7	10 CFR 50, Appendix A, GDC 55, 56, &57	Containment Isolation
8	10 CFR 50.34(f)(2)(viii)	Post-Accident Sampling
9	10 CFR 50.34(f)(2)(xx)	Power Supplies for Pressurizer Relief Valves, Block
10	10 CFR 50.34(f)(2)(xiii)	Pressurizer Heater Power Supplies
11	10 CFR 50.34(f)(2)(xiv)(E)	Containment Evacuation System Isolation
12	10 CFR 50.46a and 10 CFR 50.34(f)(2)(vi)	Reactor Coolant System Venting
13	10 CFR 50.44	Combustible Gas Control
14	10 CFR 50.46	Fuel Rod Cladding Material
15	10 CFR 50, Appendix K	Emergency Core Cooling System Evaluation Model
16	10 CFR 50.54(m)	Control Room Staffing
17	10 CFR 50.62(c)(1)	Reduction of Risk from Anticipated Transients Without Scram

4. Summary

This paper introduced the features and passive safety of NuScale SMR, and the initiatives of regulatory and applicant in safety review for design certification of NuScale SMR in the United States.

The current Japanese new safety regulations are intended for restarting existing NPPs and are not intended for application to innovative reactors such as NuScale SMR. In addition, it is hardly reasonable to mechanically apply various SA measures newly introduced in the new safety regulations to innovative reactors such as SMR. If they do it, it is expected that the inherent benefits for the innovative reactors will be significantly impaired. In other words, new safety requirements and safety standards different from existing light water reactors should be considered and established for innovative reactors such as SMR. It should be understood that the US approach, that the applicant proposes alternatives to existing regulatory requirements that do not match the SMR and discusses with regulatory body, also illustrates one approach to such an attempt.

In other words, when considering safety requirements and safety standards suitable for an innovative reactor, the US approach is helpful, but need not be limited to it, and should be approached from a broader perspective and viewpoint. It is necessary to aim for the establishment of safety requirements and safety standards that higher safety can be achieved more rationally. Toward such a large goal, we would like to propose that gathering wisdom from industry, government and academia, a serious discussion on “What should be the safety requirements and safety standards for innovative reactors such as SMR?” should be started aggressively and quickly, first of all. We would also like to request sincerely that a new regulatory framework be applied to innovative reactors such as SMR are created based on the results of such discussions, and conclude this presentation.