Overview of Regulatory Considerations for Micro-Reactor Deployment in the U.S.A.

Jin Sun Choi, Jeong Ik Lee
Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Micro-reactors are emerging as an important technology for future energy production due to their ability to supply energy securely and safely. Micro-reactors can be utilized in a variety of applications, including off-grid areas, military applications, and space exploration. Thus, micro-reactors of various designs and technical characteristics are being developed around the world. The process of getting these reactors to the field requires specific regulatory guidance. In particular, clear regulation of the refueling, operational testing procedure at the factory, and the transport of these reactors to the site have to be in place.

In January 2024, the US Nuclear Regulatory Commission (NRC) published the document 'Microreactor Licensing and Deployment Considerations: Fuel Loading and Operational Testing at the Plant', which provides guidelines applicable to fuel loading and operational testing at the plant [1]. The document discusses regulatory actions that are essential for the deployment of microreactors.

According to a typical factory-constructed micro-reactor deployment model, factory fuel loading and operational testing is a critical step in ensuring the safety and reliability of a microreactor. This process ensures that all of the reactor's systems and components are operating as expected prior to the deployment and allows defects to be discovered and corrected early before the reactor reaches the site and begins operation. In addition, as shown in Fig. 1, factory testing can accelerate deployment by pre-assembling the reactor and preparing it for immediate operation. This approach can support technological innovation, improve reliability, and facilitate regulatory compliance, streamlining the process.

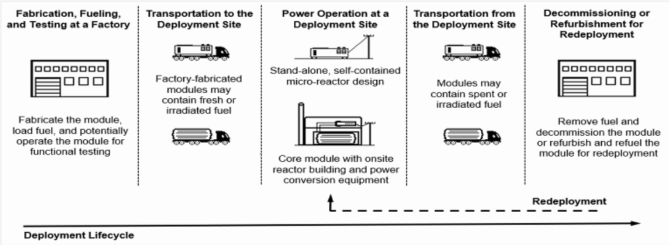

Fig 1. Generic factory-fabricated micro-reactor deployment model [1].

Based on the guidelines presented by the NRC, this paper reviews the major micro-reactor designs currently under development. It also compares and analyzes the potential issues expected to be faced in the application of these guidelines. From this analysis, the need for regulatory application adapted to the characteristics of each reactor is discussed.

2. Recent trends in Micro-Reactor Development

Recently developed micro-reactors have different design characteristics and are being developed for different purposes. As shown in Fig. 2, the USA Department of Defense (DOD) is collaborating with X-energy and BWXT to implement the Pele Project a part of the Advanced Reactor Demonstration Program (ARDP) for the development of transportable military micro-reactors [2].

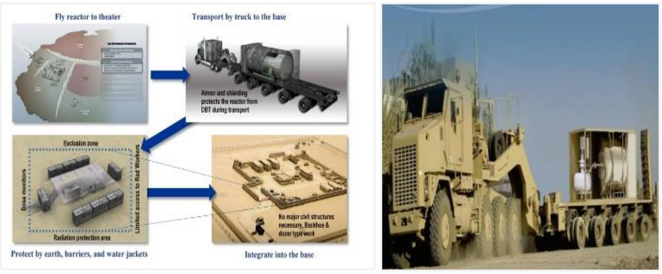

Fig 2. Pele Project as part of the ARDP [3].

The USA Department of Energy (DOE) has announced the major transportable micro-reactors currently under development and has summarized the characteristics of each reactor for comparison in Table 1. It is noted that initial operational testing and design approval for TRISO fuel are also planned in accordance with 10 CFR Parts 50[1] and 52[2] [4, 5].

Table 1. Characteristics of current MMR Technology [6–10].

	Reactor / Fuel	Output (MW_e)	Preclude Criticality[3]	Development Stage
X-energy (X-energy)	HTGR / TRISO	3-5	Yes	Design approval
BANR (BWXT)	HTGR / TRISO	1-5	Yes	Design completion
eVinci (Westinghouse)	Heat Pipe / TRISO	5	Yes	Pilot testing
Pylon (USNC)	HTGR / TRISO	1.2-1.9	Yes	Initial development stage
Kaleidos (Radiant)	HTGR / TRISO	1	Yes	Preparing for design review

In the USA, TRISO fuel significantly enhances safety by containing fission products at high temperatures. It is applicable to various reactor designs, such as High Temperature Gas-cooled Reactor (HTGR) and heat pipe reactors, due to its robust multi-layer containment structure. Micro-reactors, such as X-energy and BANR, are supported by the USA DOE and NRC, and extensive performance and safety verification testing ensure regulatory compliance.

---

[1] 10 CFR Part 50, General Design Criteria for Nuclear Power Plants

[2] 10 CFR Part 52, Licenses, Certifications, and Approvals for Nuclear Power Plants

[3] The NRC document "Regulatory Guide 3.71" and "Technical and Licensing Considerations for Micro-Reactors" published by Sandia National Laboratories (SNL) mention control rods, burnable absorbers, and passive safety systems (PSS) as features for criticality protection.

As shown in Fig. 3, TRISO in the BANR fuel uses an engineered multi-layer fission product barrier system to retain radioactive isotopes under both normal and accident conditions. The ability of the particle fuel to contain fission products within the particle itself provides 'functional containment', making it possible to provide safety without the need for large containment buildings. For the licensing approach recommended by the NRC, this is advantageous. As such, the particle is a critical component of the overall functional containment of the BANR HTGR design [11].

Fig 3. TRISO fuel particle model [12].

Economically, TRISO fuel can operate for extended periods without refueling, reducing operating costs. In addition, factory-based production enhances economy.

However, micro-reactors currently under development face difficulties in obtaining the license issued by the NRC, which hinders regulatory approval and operational testing. Therefore, to ensure commercial deployment and safety of micro-reactors, relatively relaxed regulations and clear guidelines for fuel loading and factory operational testing are needed.

3. Overview of USA NRC Guidelines

The NRC staff presented three regulatory options for fuel loading and operational testing to ensure the safe and efficient deployment of micro-reactors. These options include detailed regulatory guidance, application of non-power reactor regulations, and implementation of features to preclude criticality. The NRC staff is proposing near-term options within the existing regulatory framework before finalizing changes to the NRC's regulations. The main content of the NRC guidelines and a description of each option are presented in Table 2.

* Option A is the currently applied method and B is the NRC recommendation.

Table 2. Recommendations of fuel loading and operational testing at a factory [1].

Option		Description
1. Features to Preclude Criticality	a	A Factory loading fuel, reactor is considered operational
	b	A factory-fabricated module with features to preclude criticality is not in operation when loaded with fuel
2. Fuel Loading at a Factory	a	Fuel loading under a power reactor license (10 CFR Part 50 or 52 License)
	b	Fuel loading under a 10 CFR Part 70[4] (includes features to preclude criticality)
3. Operational Testing at a Factory	a	Operational testing under a power reactor license (10 CFR Part 50 or 52 License)
	b	Apply non-power reactor regulations

3.1 Regulatory approaches to preclude criticality

The NRC staff recommends an approach that incorporates criticality protection so that factory-built microreactors cannot sustain a nuclear chain reaction under any conditions. The Commission has considered fuel loading a part of reactor operation. However, staffs are considering an approach where modules with features to preclude criticality are not considered "operational" even when fuel is loaded, and operation begins when this feature is removed.

Under Option 1a, a reactor with fuel loaded at the plant is considered to be operational and requires an operating license under 10 CFR Part 50 or a combined license under 10 CFR Part 52. This approach maintains consistent licensing procedures without the need for new guidance, but could complicate compliance and require additional safety reviews and licensing if the reactor is considered "operational" during transport.

In contrast, Option 1b considers factory-fabricated modules with features to preclude criticality as not operational even with fuel loaded, allowing safe fuel loading and avoiding safety issues during transport. However, this approach requires additional guidelines including features to preclude criticality

3.2 Regulatory approaches to Fuel loading at a factory

The NRC staff is considering proposing a licensing approach for fuel loading at manufacturing facilities based on existing regulations. This includes an approach limited to fuel loading operations under a 10 CFR Part 50 operating license or a 10 CFR Part 52 combined license. In addition, an approach under 10 CFR Part 70 regulations covering the manufacturing and licensing of special nuclear material is being recommended.

Option 2a requires a 10 CFR Part 50 operating license or a 10 CFR Part 52 combined license, which requires compliance with complex and time-consuming regulations. In contrast, Option 2b allows fuel to be loaded under a 10 CFR Part 70 license, offering benefits such as reduced downtime, lower transportation costs and rapid deployment. However, it requires additional guidance on criticality and transport safety, fuel handling procedures and emergency procedures.

3.3 Regulatory approaches to Operational testing at a factory

The third option is recommendations for licensing approaches for conducting operational testing at manufacturing facilities based on current regulations. This includes approaches that are limited to operational testing under a 10 CFR part 50 operating license or 10 CFR part 52 combined license, and approaches that are limited to operational testing under a 10 CFR part 50 operating license based on non-power reactor regulations.

Option 3a requires a 10 CFR Part 50 operating license or a 10 CFR Part 52 combined license, which involves a lengthy licensing process for conducting operational tests at the facility. For example, Oklo Inc. formally applied to the NRC for a reactor license for its Aurora micro-reactor in March 2020, but the application was denied in January 2022 due to insufficient information [13].

---

[4] 10 CFR Part 70, Domestic Licensing of Special Nuclear Material

In contrast, Option 3b would apply non-power reactor regulations to allow fuel loading and operational testing, which would reduce the regulatory burden compared to existing regulations, improve safety, and reduce costs, thereby facilitating the commercialization of micro-reactors.

However, integrating these tests into the licensing process at the batch site can raise issues related to regulatory adaptation, documentation, site-specific conditions, coordination, and risk mitigation. The regulatory approaches and options above include important considerations for the safety of microreactor deployments. A comparative analysis is required to understand how these regulatory aspects apply to each reactor type and the following issues.

4. Regulatory options

The regulatory options presented by the NRC staff for the safe and efficient deployment of small reactors takes into account the unique characteristics of micro-reactor designs as in high level discussion. Each reactor characteristic should be considered for the challenges that may arise from applying the regulatory options and be supplemented with characteristic-specific guidance.

As shown in Fig. 4, the characteristics of the High-Temperature Gas-cooled Reactor (HTGR) and the Heat Pipe Reactor, shown in Table 1, were analyzed to derive the problems of the under-development micro-reactor. The BANR is based on the HTGR and the eVinci reactor is based on the Heat Pipe. These systems are analyzed by the ‘Regulatory engagement plan’ document.

Fig 4. BANR reactor, eVinci reactor design [14].

BANR's HTGR is a UN TRISO-fueled HTGR that uses a graphite block as a neutron moderator and structure, and helium gas as a coolant. The HTGR is designed to operate reliably at high temperatures of up to 1,000°C. For HTGRs, during the fuel loading process, TRISO particles are packed into the fuel elements and then filled with powder to increase their density. As shown in Figure 5, this process must be performed precisely in the factory and includes a pre-densification step[5] to increase the strength of the fuel elements. Consideration must be given to structural defects and fuel particle damage issues when loading the fuel [15].

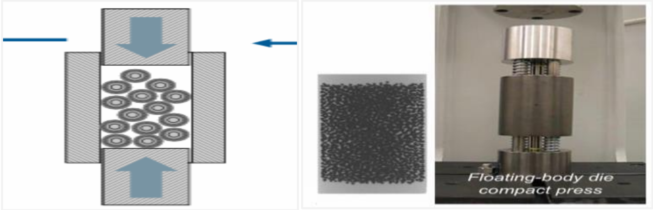

Fig 5. High-density compaction process [16]

However, during HTGR transport, multiple stresses can occur because the system is vulnerable to mechanical shock and vibration. Although helium is not flammable, these stress changes can cause mechanical failures or leaks, and potential ignition issues may need to be considered [17]. In addition, leaks or pressure changes in a system during transportation can cause radioactive particles to be deposited on components, including graphite blocks used as neutron moderators. This can lead to the accumulation of radioactive material in these graphite blocks, increasing radiation levels and the potential risks associated with handling.

However, these blocks can also adsorb radioactive fission products, a phenomenon known as plate-out. Over time, this can lead to a significant build-up of radioactive material on the graphite surface, which can cause problems with transport, handling and long-term maintenance [18]. The loading and transport of HTGR reactor fuel may therefore require regulatory measures to manage the risks.

The eVinci Heat Pipe reactor, on the other hand, uses UN TRISO fuel and has a passive cooling system utilizing Heat Pipe technology. This technology efficiently transfers heat through heat pipes and operates at temperatures up to around 800 °C. In the case of Heat Pipe Reactors, the fuel operates at relatively low pressure (less than 0.1 MPa), which can simplify fuel loading and testing at the plant compared to HTGRs.

However, during transport, additional regulations are required to maintain the structural stability of the heat pipes. In particular, transport protection is essential as heat pipes can be sensitive to external shocks.

Therefore, customized regulatory guidelines are required that take into account the characteristics of HTGRs and heat pipe reactors. For HTGRs, the precision of the fuel loading process and the importance of high-temperature testing should be emphasized, and protective devices are required to manage the accumulation of radioactive material during transport.

On the other hand, Heat Pipe Reactors have a relatively simple fuel loading process, but regulations need to focus on ensuring structural integrity during transport. It can be seen that it is essential to have regulations and guidelines tailored to the characteristics of micro-reactor.

5. Discussion / Summary

Applying regulatory guidance from the USA Nuclear Regulatory Commission (NRC), this study analyzed the characteristics of micro-reactors and the expected challenges in applying reactor type-specific regulations. HTGRs and heat pipe reactors have different regulatory requirements and challenges during fuel loading and operational testing based on their characteristics, which require reactor-specific regulations and guidance to mitigate.

It is important for the NRC's regulatory approach to develop improved guidance that considers key elements such as criticality protection, fuel loading, and operational testing. This is necessary to ensure the safety and reliability of MMRs and facilitate their rapid commercialization.

---

[5] BWXT, BANR UN TRISO fuel Qualification Plan (2023).

Further research and review is also needed to identify the optimal regulatory measures for each reactor's characteristics and assess their practical applicability.

In addition to these operational considerations, it is crucial to address the handling of Spent Nuclear Fuel (SNF) at the end of the MMRs' lifecycle. SNF can traditionally be unloaded directly from the reactor site and managed separately, where it can follow established safe transport and disposal procedures. A container that meets the transportation standards specified in 10 CFR Part 71[6] and the issuance of a transport license are required, along with compliance with the Environmental Impact Statement (EIS) procedures and regulations under the National Environmental Policy Act (NEPA).

However, depending on the reactor's design and operating plan, there is also a possibility that SNF could be transported with the reactor as a complete system to a disposal site. If the safety of this approach can be adequately ensured, regulatory frameworks and guidelines should be developed to facilitate this alternative method of transport. In this case, the NRC emphasizes the importance of thoroughly evaluating the environmental and radiological risks associated with transporting SNF together with the reactor. Regulatory requirements must be reviewed comprehensively to address these risks adequately. NUREG-2157 [7] evaluates the environmental impacts of the continued storage of SNF beyond the licensed life for operation of light water reactors (LWRs). However, the NRC must conduct case-by-case evaluations for the storage and transportation of fuel used in microreactors and other non-light water reactors, and, if necessary, develop specific regulations to address these cases [21].

Furthermore, the NRC highlights that transporting micro-reactors with their SNF might necessitate a more rigorous regulatory review compared to existing standards. While existing regulations such as 10 CFR Part 51[8] (Environmental protection), Part 20[9] (Protection against radiation), and Part 73[10] (Physical protection) provide a foundational framework for safety, the unique design and transportation methods of micro-reactors may require additional regulatory considerations. This includes assessing new risk factors that may arise during transport and applying supplementary regulations as needed.

These regulatory improvements are essential to ensuring that all safety and environmental impacts are properly managed when SNF is transported alongside reactors. Therefore, the NRC's regulatory framework will need to be thoroughly reviewed and potentially enhanced to ensure safety across all stages of micro-reactor deployment, including SNF transport.

In conclusion, adopting and adapting these regulatory improvements could significantly impact the successful commercialization of micro-reactors in South Korea. Developing a regulatory framework that is well-suited to the domestic situation, while also aligning with international standards, is crucial. The regulatory insights and enhancements proposed by the NRC can support this objective and play a pivotal role in ensuring safe and efficient deployment.

Continued research and international cooperation to develop optimal regulatory policies and assess their practical applicability could accelerate the commercialization of micro-reactors in the domestic and international markets.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.: RS-2024-00436693).

REFERENCES

[1] NRC, Micro-reactor licensing and deployment considerations: fuel loading and operational testing at a factory (2024).
[2] Jeff Waksman, Project Pele overview: Mobile nuclear power for future DOD needs (2022).
[3] Brett Tingley, The Military's Mobile Nuclear Reactor Prototype is set to begin taking shape (2021).
[4] Unites States Nuclear Regulatory Commission, 10CFR Part 50, Domestic licensing of production and utilization facilities(2023).
[5] Unites States Nuclear Regulatory Commission, 10CFR Part 52, Licenses, certifications, and approvals for nuclear power plant (2024).
[6] U.S Department of Defense, X-energy, Department of Defense expands X-energy contract for mobile microreactor prototype (2023).
[7] Travis A. Chapman, Microreactor Regulatory considerations (2024).
[8] Westinghouse Electric Company, eVinci Microreactor Design and development program (2023).
[9] Office of Nuclear energy, 3Microreactor experiments to watch starting in 2026 (2023).
[10] United States Nuclear Regulatory Commission, Kaleidos project overview (2022).
[11] Idaho National Laboratory, TRISO Fuel: Design, Manufacturing, and Performance (2019).
[12] BWXT, TRISO fuel the future of nuclear (2023).
[13] United States Nuclear Regulatory Commission, Combined license application documents for Aurora-Oklo Power Plant Application (2022).
[14] United States Nuclear Regulatory Commission, Next generation nuclear plant (2023).
[15] Idaho National Laboratory, TRISO Fuel Part I: Background, Fabrication, and Irradiation Performance (2021).
[16] United Stats Department of Energy Office of Nuclear Energy, Fuel Cycle Research and Development advanced fuels Campaign (2016).
[17] T-Ying Lin, Investigating Passive decay heat removal froma micro-HTGR during transportation (2024).
[18] United States Nuclear Regulatory Commission, High-Temperature Gas-Cooled Reactor NRC Research Plan (2023).
[19] Evans D. Kitcher, Initial evaluation of Microreactor Disposition Options (2020).
[20] United States Nuclear Regulatory Commission, Micro-reactor applications (2020).
[21] United States Nuclear Regulatory Commission, Generic environmental impact statement for continued storage of spent nuclear fuel (2014).

---

[6] 10 CFR Part 71, Packaging and transportation of radioactive material

[7] NUREG-2157, Generic environmental impact statement for continued storage of spent nuclear fuel

[8] 10 CFR Part 51, Environmental protection regulations for domestic licensing and related regulatory functions

[9] 10CFR Part 20, Standards for protection against radiation

[10] 10 CFR Part 73, Physical protection of plants and materials