Study on Identifying Safety Regulatory Issues for Domestic Gas-Cooled Reactors Based on the GIF VHTR SDC Methodology

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1. Introduction

As carbon neutrality implementation and energy transition accelerate, the Very High Temperature Reactor (VHTR) has emerged as a next-generation reactor concept with potential applications not only to electricity generation but also to high-temperature process heat supply and hydrogen production. It is designed to reduce the risks of core damage and radioactive material release during various accident condition by adopting the chemical stability of helium coolant, the large heat capacity of graphite moderators, TRISO fuel, and passive safety systems.

However, It spite of these safety characteristics, domestic regulatory framework for VHTR has not yet been established because the domestic nuclear safety regulatory framework has evolved primarily around light water reactors (LWRs), and regulatory requirements Therefore, it is necessary to examine the applicable scope and limitations of existing LWR-based regulatory requirements and to systematically derive VHTR-specific safety requirements.

The IAEA provides design safety requirements for nuclear power plants in SSR-2/1 (Rev.1), while the Generation IV International Forum (GIF) has developed and revised a separate Safety Design Criteria (SDC) framework reflecting the design characteristics of VHTRs. The GIF VHTR SDC maintains consistency with internationally accepted safety principles while incorporating VHTR-specific accident phenomena and safety functions, and thus can serve as a valid reference framework for developing domestic regulatory requirements for gas-cooled reactors.

The purpose of this study is to analyze the GIF VHTR and to identify key safety regulatory issues for incorporation into the domestic safety regulatory framework for gas-cooled reactors. Through this analysis, the study aims to derive safety regulatory issues that will support the future development of proposed regulatory requirements for HTGR/VHTR.

2. Scope and Methodology

2.1 Scope of the Study

• Analysis of domestic and international regulatory technology development trends for non-light water reactors (including gas-cooled reactors)
• Analysis of the safety design characteristics of the GIF VHTR
• Comparison of the structure and revisions of the GIF VHTR SDC relative to IAEA SSR-2/1
• Identification of regulatory issues associated with major VHTR safety phenomena
• Presentation of directions for developing domestic regulatory requirements for gas-cooled reactors

2.2 Methodology

This study was conducted primarily through literature review and comparative analysis of regulatory criteria. First, the domestic regulatory framework and international trends in non-LWR regulatory development were reviewed, and the requirement structures of IAEA SSR-2/1 and the GIF VHTR SDC were compared. Subsequently, in connection with the major design characteristics of VHTRs (e.g., fuel, coolant, moderator, passive safety systems, and high-temperature operating characteristics), safety phenomena that are difficult to address under LWR-centered regulatory criteria were identified, and corresponding regulatory review items and areas requiring supplementation were derived.

3. Domestic and International Trends in Regulatory Technology Development for Non-LWRs

3.1 International Trends in Regulatory Technology Development for Non-LWRs

VHTR/HTGR systems use helium gas as coolant and can operate at high temperatures of approximately 700°C (HTGR) to 950°C or higher (VHTR), which has attracted considerable interest not only for electricity generation but also for non-electric applications such as hydrogen production and industrial process heat supply. These characteristics require safety analysis frameworks and licensing approaches that differ from those applied to conventional light water reactors (LWRs).

The U.S. Nuclear Regulatory Commission (NRC) previously conducted pre-application safety evaluations for the Modular High Temperature Gas-Cooled Reactor (MHTGR) [1], and licensing reviews related to the Next

Generation Nuclear Plant (NGNP) in the early 2000s were performed under a deterministic regulatory framework based on design-basis-event-centered requirements in 10 CFR Part 50/52. Subsequently, in response to the emergence of advanced non-LWR technologies, the NRC has pursued a transition toward risk-informed, performance-based regulatory approaches. More recently, through pre-application processes, the NRC has continued technical engagement with developers such as X-energy and Kairos Power [2], while further refining related licensing guidance and regulatory frameworks.

In addition, international experience has been accumulated through China's HTR-PM demonstration and commercial operation, South Africa's development of basic licensing requirements for the PBMR, and Japan's HTTR operation, safety evaluation, and licensing experience. Furthermore, international regulatory cooperation bodies, including the OECD/NEA-led Multinational Design Evaluation Programme (MDEP), have facilitated the sharing of design review experience and discussions on regulatory issues for advanced reactors. These international developments provide a useful reference basis for the future development of domestic regulatory requirements for gas-cooled reactors.

3.2 Domestic Trends in Regulatory Technology Development for Non-LWRs

In Korea, regulatory technology development for non-LWR safety has been advanced in phases, led primarily by the Korea Institute of Nuclear Safety (KINS) [3]. Early efforts focused on foundational studies, including analyses of design and regulatory characteristics of high-temperature gas-cooled reactors and identification of general safety issues. Subsequently, the scope expanded to regulatory technology review for hydrogen-production-coupled HTGRs and other Generation IV reactor concepts. More recently, regulatory research on SMRs and planning activities for the development of regulatory foundation technologies for non-light water reactors have been initiated, and mid- to long-term research programs are currently underway.

3.3 Differences Between LWRs and VHTRs

Light water reactors (LWRs), which currently account for the majority of nuclear power generation, and Very High Temperature Reactors (VHTRs), which are attracting attention as next-generation reactor systems, differ substantially in terms of safety characteristics, efficiency, and application scope. LWRs are mature technologies optimized for stable electricity generation and generally rely on active safety systems for accident mitigation, including responses to events such as loss-of-coolant accidents. In contrast, VHTRs employ helium cooling and passive safety characteristics to substantially reduce severe accident risks, while enabling high-efficiency and multipurpose energy utilization through high-temperature operation.

Therefore, while both reactor types are similar in that they utilize nuclear heat as an energy source, they are clearly differentiated in terms of operating temperature, safety philosophy, and application range. The major differences between LWRs and VHTRs are summarized in Table I.

Category	LWR	VHTR
Generation classification	Generation II–III	Generation IV (Gen-IV)
Coolant	Light water (H_2O)	Helium (He)
Moderator	Light water (H_2O)	Graphite
Fuel form	UO_2 pellets + Zircaloy cladding	TRISO-coated particle fuel (pebble-bed / prismatic type)
Fuel enrichment	3–5 wt%	8–15 wt%
Coolant outlet temperature	Approximately 320°C	700–950°C
Operating pressure	15–16 MPa	Approximately 7 MPa

Table I. Comparison of LWRs and VHTRs

4. Analysis of Safety Characteristics and Safety Approach of the GIF VHTR System

4.1 GIF Safety Approach

To ensure the safety of advanced nuclear energy systems, the Generation IV International Forum (GIF) established the "Basis for Safety Approach" [4], which provides a common framework for Generation IV reactor design and safety assessment. This approach presents the principal safety principles, summarizes the basic approaches for design and evaluation, and includes the Integrated Safety Assessment Methodology (ISAM) as a methodology and set of tools for safety assessment. [5]

The GIF safety approach follows the defense-in-depth concept and plant state definitions in IAEA SSR-2/1, while modifying and supplementing them to reflect the characteristics of the VHTR system. The correspondence between the plant states considered in VHTR system design and the levels of defense in depth is summarized in Table II.

Defence in Depth Levels				
Level 1	Level 2	Level 3	Level 4	Level 5
Normal operation	Anticipated operational occurrences	Design basis accidents	Design extension conditions	Off-site emergency response

Plant states considered in design	

Table II. Defense in Depth Levels and Plant States for VHTR Systems

4.2 VHTR Safety Principles

The safety principles applicable to the design, construction, commissioning, operation, and decommissioning of VHTRs are generally similar to those applied to other Generation IV systems. However, compared with other systems, VHTRs exhibit several distinguishing features in terms of safety philosophy, as summarized below.

• Reliance on inherent safety characteristics
• Consideration of design-basis events in safety design (including external hazards and internal events)
• Application of defense in depth
•VHTR design objectives for normal operation, anticipated operational occurrences (AOOs), and design basis accidents (DBAs): maintenance of fuel integrity; reliable reactor shutdown when required; removal of decay heat to the ultimate heat sink; and confinement of radioactive materials
• Safety considerations for design extension conditions (DECs): consideration of common-cause failures; enhancement of system robustness through prevention of severe plant conditions and mitigation of consequences; and application of passive design features to mitigate event progression and secure operator response time

4.3 Major Safety Characteristics of the VHTR System

4.3.1 TRISO Fuel (Tri-structural Isotropic Coated Particle Fuel)

VHTRs use TRISO-coated particle fuel, in which each coating layer functions as a barrier for retaining fission products. This characteristic provides an important basis for maintaining fuel integrity under high-temperature conditions and contributes to reducing radioactive release risk even under accident conditions, including loss-of-cooling events. In particular, the TRISO fuel concept significantly reduces the likelihood of conventional core-melt-type accident progression.

4.3.2 Helium Coolant

Because helium is an inert gas, it does not chemically react with structural materials or fuel under normal reactor conditions. Unlike water-cooled reactors, it does not present the same hydrogen generation and explosion concerns associated with certain severe accident phenomena. In addition, helium remains in the gaseous phase, thereby avoiding coolant phase-change phenomena (e.g., boiling/condensation) and related thermal-hydraulic transients characteristic of light water reactors.

4.3.3 Graphite Moderator and Structures

Because the reactor core is composed largely of graphite, the system can absorb a substantial amount of heat. The high heat capacity of graphite provides thermal inertia that significantly slows the rate of core temperature rise during accident conditions. In addition, graphite can maintain structural integrity at very high temperatures within the design envelope, which contributes to preserving core geometry and supports stable heat removal performance during accident transients.

4.3.4 Passive Safety Systems and Decay Heat Removal

VHTRs are designed to remove reactor decay heat through convection, radiation, and conduction, without relying solely on offsite power or mechanically driven pumps. Accordingly, even under extreme conditions such as a station blackout, passive heat removal features can support continued core cooling and help the plant reach and maintain a stable safe state with limited operator intervention.

5. Analysis of VHTR Safety Regulatory Issues

5.1 Regulatory Issues by Major Safety Phenomena

In this study, major review issues were defined as reactivity control, water ingress, core heat removal, radioactive material confinement, and passive safety systems, taking into account the design characteristics and safety behavior of VHTRs. These constitute core elements for establishing VHTR regulatory requirements by supplementing the existing LWR-centered regulatory criteria.

5.1.1 Reactivity Control

In VHTRs, temperature feedback behavior associated with fuel and moderator characteristics is a key safety consideration, and it is necessary to suppress reactivity increases and ensure sufficient shutdown margin under both normal and abnormal conditions. In particular, regulatory review should address whether reactivity control capability is maintained under high-temperature conditions, changes in fuel and graphite characteristics, and design extension conditions (DECs), as well as the reliability of the control systems. In addition, because prismatic and pebble-bed cores may exhibit different reactivity behavior and event progression characteristics, reactor-type-specific considerations are required.

5.1.2 Water Ingress

In VHTRs, ingress of air (oxygen) and water (H_2O) can significantly affect fuel and structural materials (particularly graphite), the cooling system, and key safety functions. In particular, graphite oxidation may alter core geometry, reduce thermal resistance, and modify coolant flow paths. In addition, hydrogen generation and hydriding phenomena may contribute to

combustible atmospheres and accelerate corrosion of metallic components. Accordingly, regulatory requirements should address prevention, detection, isolation, and consequence evaluation for air/water ingress events.

5.1.3 Core Heat Removal

Because VHTRs operate at high temperatures (approximately 700–950°C) and remove heat using high-temperature gas coolant, the reliability of heat removal pathways under both normal and abnormal conditions is one of the most critical safety considerations. Key regulatory issues include decay heat removal capability, passive cooling performance, high-temperature degradation of fuel and structural materials (e.g., carbonization, oxidation, thermal deformation/creep), and the risk of oxidation or fuel damage during loss-of-pressure-boundary integrity and depressurization events. Although helium coolant does not present phase-change-related accident phenomena, demonstration of adequate heat removal by conduction and radiation under conditions such as circulator trip or loss of convective cooling is essential.

5.1.4 Radioactive Material Confinement

Coated fuel particles and the graphite matrix act as primary barriers to fission product release and limit the transport of most radionuclides during both normal operation and accident conditions. Additional barriers for preventing fission product release include the graphite matrix, the helium pressure boundary, and a ventilated low-pressure reactor building (or confinement structure).

Large-break depressurization is a representative design basis accident in which a portion of the circulating radionuclide inventory may be released to the environment. If the circulating inventory is sufficiently low, off-site releases at the site boundary can be maintained below regulatory limits, and post-accident ventilation isolation followed by filtered ventilation recovery should be achievable. In addition, fuel integrity should be demonstrated within time–temperature limits, while recognizing that prolonged transients—particularly for high-burnup fuel—may increase radionuclide release potential.

5.1.5 Passive Decay Heat Removal

In VHTRs, the passive decay heat removal system is a safety function that does not require an electrical power supply. Following reactor shutdown, decay heat is removed by passive mechanisms such as natural convection, heat conduction, and thermal radiation, thereby reducing reliance on external power or mechanically driven pumps. This is a key design feature for preventing fuel damage and limiting radioactive material release during accident conditions.

However, uncertainties in heat removal performance remain, including the possibility of insufficient core decay heat removal under unstable natural-circulation flow conditions and the potential for local overheating due to design limitations in piping and heat exchanger systems. Accordingly, regulatory requirements should include performance verification and uncertainty evaluation for passive decay heat removal systems.

5.2 Major Revisions in the GIF VHTR SDC Relative to IAEA SSR-2/1

The GIF VHTR SDC is a framework that retains the basic safety principles and structure of IAEA SSR-2/1 while adding, revising, and deleting selected requirements to reflect VHTR design characteristics and accident phenomena. This represents a shift from an LWR-centered severe-accident-response-oriented safety criteria framework toward a prevention-oriented design framework based on GIF safety and reliability goals. In this study, four major areas in which the GIF VHTR SDC departs from or supplements IAEA SSR-2/1 requirements were examined.

First, the VHTR design incorporates features intended to minimize the potential for core overheating and melting—such as low core power density, high heat capacity of ceramic structures, strong negative temperature coefficients of reactivity, and passive decay heat removal characteristics—although such conditions cannot be considered completely eliminated.

Second, water ingress can remove (“wash off”) radionuclides adsorbed on graphite and coated fuel surfaces, thereby increasing circulating activity. Therefore, rapid isolation and design measures to limit water ingress should be incorporated into the plant design.

Third, VHTRs rely on multiple physical barriers to limit radioactive material release, including TRISO-coated particle fuel, the graphite matrix, the coolant pressure boundary, and a low-pressure reactor building/confinement structure.

Fourth, when multiple modules are operated on a common site, common-cause accidents and radiological impacts associated with process coupling or shared systems should be minimized through design and regulatory provisions.

6. Conclusion

This study compares and analyzes the structural requirements and amendments of the GIF VHTR SDC

and IAEA SSR-2/1, identifying key safety regulatory issues for the domestic gas-cooled reactor framework based on the unique design characteristics of the VHTR.

The primary issues derived from this research include the design basis associated with the exclusion of core melt scenarios, reactivity control and multiple barrier isolation within functional confinements, the mitigation of moisture and air ingress accidents, the integrity verification of passive safety systems and multi-module safety, and safety requirements for integrated operations involving process heat and hydrogen production. These identified areas are difficult to address under the current light-water reactor (LWR)-centric regulatory system due to the inherent differences in reactor technology; therefore, they should be prioritized during the future refinement of domestic regulatory standards. While this paper focuses on issue identification through international standards, subsequent research will involve a detailed comparative analysis between the domestic regulatory framework and the GIF VHTR SDC.

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