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Demonstration-Based Integrity Assessment of Structural Materials in High-Temperature Reactors: Needs and Infrastructure

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1. Introduction

Advanced reactors are increasingly recognized as a key technology for achieving carbon neutrality and enabling large-scale hydrogen production. [1-4] Among them, High Temperature Reactors (HTRs), which provide thermal energy in the range of 700–950 °C, offer not only efficient electricity generation but also broad industrial applications, including hydrogen production, metal smelting, and chemical processing. Countries such as the United States, China, Japan, and France are accelerating the development of HTRs through national demonstration programs and public–private partnerships, while also actively advancing not only reactor design technologies but also regulatory frameworks and standardization.

A critical challenge for HTRs lies in securing structural materials that can sustain long-term operation under harsh conditions where high temperature, neutron irradiation, and corrosion act simultaneously. However, most of the currently applicable design codes were originally developed for light water reactors, and thus lack provisions addressing high-temperature, corrosive, and irradiation environments. This limitation hinders the systematic qualification of new materials and the assurance of their structural integrity.

Therefore, the demonstration and commercialization of HTRs require not merely the supplementation of existing light water reactor–based codes, but the establishment of dedicated design codes tailored to their unique operating conditions. To this end, long-term demonstration-oriented testing under representative service environments and the development of comprehensive databases must precede code formulation.

This study highlights the necessity of demonstration-based integrity assessment and discusses the role of hot-cell experimental infrastructure as a key enabler, as well as future directions for the development of dedicated design codes

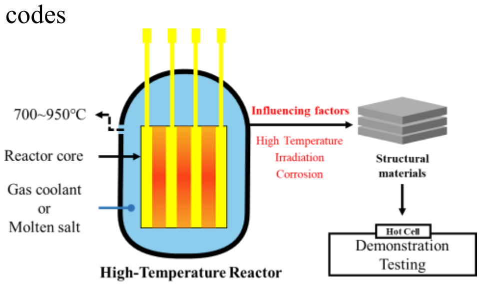

Fig 1. Conditions and Need for Demonstration Testing

2. Development Trends of High-Temperature Reactors

As global competition in Advanced reactor development intensifies, high-temperature reactors (HTGRs, MSRs, and others) emerge as core technologies for clean energy transition and industrial decarbonization. Countries are advancing reactor designs, validating critical components and materials, and moving steadily from demonstration toward commercialization.

2.1 International Trends

The United States has designated the development of next-generation nuclear reactors as a national strategy to achieve carbon neutrality and energy security. Through the Department of Energy's Advanced Reactor Demonstration Program (ARDP), projects such as X-energy's Xe-100, TerraPower's Natrium, and Kairos Power's Hermes are being advanced, representing exemplary cases of public–private partnership models [4]. Japan has resumed hydrogen production experiments utilizing the High-Temperature Engineering Test Reactor (HTTR). China has commenced operation of the world's first commercial high-temperature reactor power plant (HTR-PM) and has initiated the operation of TMSR-LF1. France, Russia, and Canada are likewise pursuing demonstration and commercialization efforts, with a primary focus on fuel qualification, materials assessment, and system optimization [5].

2.2 Domestic Trends

In Korea, nuclear research has expanded beyond its previous focus on sodium-cooled fast reactors (SFRs) to encompass high-temperature gas-cooled reactors (HTGRs), molten salt reactors (MSRs), and small modular reactors (SMRs). This shift has been institutionalized as a mid- to long-term strategy through the Korean Advanced Reactor Demonstration Program (K-ARDP), announced in 2024, which envisions not only demonstration plans for SMRs and MSRs but also the exploration of multipurpose applications such as industrial heat and hydrogen production [6]. Concurrently, ongoing efforts include the development of molten salt fuels and coolants, performance evaluations of high-temperature structural materials, and reactor design optimization. In addition, Korea is engaging in international collaborative projects to ensure alignment with global standards.

3. Current Status and Limitations of Regulatory Codes for High Temperature Reactors

Although the global development of high-temperature reactors (HTRs) is accelerating, their demonstration and commercialization fundamentally require the establishment of a robust regulatory framework. Given that HTRs operate under unique service conditions where high temperature, radiation irradiation, and corrosion act simultaneously, the conventional regulatory systems developed primarily for light water reactors (LWRs) are insufficient. Nevertheless, regulatory codes dedicated specifically to HTRs have yet to be established.

Internationally, various efforts are underway. In the United States, the ASME Boiler and Pressure Vessel Code BPVC Section III, Division 5 was established with HTR applications in mind, providing detailed provisions for the design and integrity assessment of high-temperature structural components [7]. Similarly, France's RCC-MRx, originally developed based on fast reactor design experience, includes requirements for high-temperature structures and can be partially applied to HTR design [8]. However, neither code comprehensively addresses specific reactor types such as HTGRs or MSRs. Japan, China, and Russia continue to rely largely on LWR-based regulations or internally developed guidelines, which remain inadequate for the unique operating conditions of HTRs.

The domestic situation in Korea is not substantially different. The Technical Standards for Reactor Facilities are strictly predicated on LWR operating conditions and are therefore not directly applicable to HTRs. Likewise, although the KEPIC-MNN code was nominally established for high-temperature reactor applications, it fails to reflect the combined service conditions of elevated temperature, irradiation, and corrosion that such reactors encounter in practice [9]. Consequently, no dedicated design code grounded in the operational environment of HTRs currently exists either domestically or internationally. This regulatory gap remains the most critical obstacle in the design, safety evaluation, licensing, and commercialization of next-generation reactors.

4. Necessity of Demonstration-Based Integrity Assessment for Structural Materials in High-Temperature Reactors

Structural materials in high-temperature reactors must withstand combined conditions that differ fundamentally from those of light water reactors, including exposure to temperatures above 700 °C, neutron irradiation, and corrosion associated with coolant environments. Consequently, these materials are required to simultaneously ensure high-temperature strength, long-term creep resistance, irradiation damage tolerance, and durability against oxidation and corrosion. Such requirements cannot be adequately validated through short-term experiments or simplified calculations alone; instead, demonstration-based long-term data under representative service conditions are indispensable for reliable design verification and safety assessment.

Currently, candidate structural materials for high-temperature reactors include Ni-based heat-resistant alloys (such as Alloy 617 and Hastelloy-X/N) and SiC composites. However, even these advanced materials lack sufficient long-term performance data under combined degradation environments, making systematic and extended demonstration testing essential for their qualification within dedicated design codes and for alignment with international standards.

Therefore, ensuring the integrity of structural materials for high-temperature reactors requires the accumulation of demonstration-based datasets and the establishment of comprehensive databases for the identified candidate materials. Such data will serve as the foundation for future design code development and safety evaluations and will constitute a strategic asset for the commercialization of high-temperature reactors and the enhancement of global competitiveness.

5. Infrastructure for Demonstration-Based Testing

To reliably evaluate the integrity of structural materials in high-temperature reactors, a wide range of demonstration tests and the supporting infrastructure are essential. Such testing includes basic property analyses to verify mechanical behavior under high-temperature conditions, post-irradiation examinations (PIE) to investigate degradation mechanisms induced by neutron exposure, high-temperature corrosion and oxidation tests to assess interactions with coolants and operating environments, and chemical and structural analyses to characterize microstructural changes and crack behavior.

In particular, the evaluation of irradiated specimens in post-irradiation examinations requires the use of hot cells equipped with radiation shielding and remote-handling capabilities. Hot cells enable the verification of long-term material behavior under conditions closely resembling actual reactor operation, providing highly reliable data that cannot be obtained through short-term experiments or simplified simulations. (Fig 2)

The accumulation of such demonstration-based data, including analyses performed within hot cells, constitutes a critical foundation for the development of dedicated design codes and the execution of safety assessments. Furthermore, these data are directly linked to the early commercialization of high-temperature reactors and the enhancement of technological competitiveness.

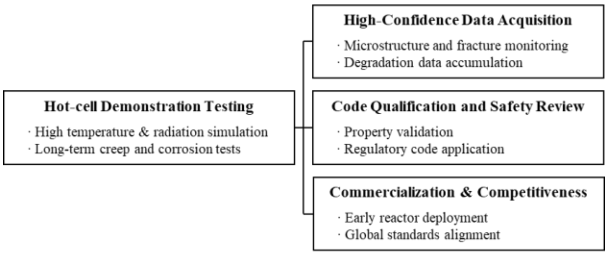

Fig 2. Implications of Hot-cell Demonstration Testing

6. Conclusion

This study pointed out that ensuring the long-term integrity of structural materials in high-temperature reactors cannot be sufficiently addressed within the framework of existing light water reactor–based design codes. To address this limitation, the characteristics required of structural materials under combined conditions of high temperature, irradiation, and corrosion were outlined, and the necessity of securing demonstration-based data for key candidate materials, such as Ni-based alloys and SiC composites, was emphasized. Furthermore, the scope and implementation items of demonstration testing were clarified, and the role of hot-cell infrastructure for post-irradiation examinations was discussed.

These discussions provide important insights into the direction of database construction required for the establishment of dedicated design codes for high-temperature reactors. Future tasks include the systematic execution of demonstration testing to generate robust datasets and their integration into international code development and standardization efforts. Through this process, it will be possible to substantiate the safety verification and early commercialization of high-temperature reactors, thereby strengthening the competitiveness of next-generation nuclear technologies.

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