Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Fission Gas Adsorbents in PWR Fuel Rod Plenum for Mitigation of High-Burnup Rod Internal Pressure: Experimental Feasibility Study and Fuel Performance Simulation

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***Keywords : High-burnup fuel, Fission gas adsorbent, Fission gas release, Rod internal Pressure**

1. Introduction

Fission gas release (FGR) and the resulting increase in rod internal pressure constitute major safety concerns for high-burnup Pressurized Water Reactor (PWR) fuel rods (≈75 MWd/kgU) pursued under LEU+ fuel deployment strategies. Previous studies indicate that, at such burnup levels, fuel rod internal pressure can approach the reactor coolant operating pressure (~15.5 MPa), thereby challenging fuel safety during steady-state, accidents, and extended dry storage. [1, 2] Conventional mitigation strategies, such as increasing plenum volume or introducing central voids in fuel pellets, can partially alleviate excessive pressurization; however, their applicability is inherently constrained by existing reactor and fuel design envelopes. As an alternative approach, this study proposes the incorporation of a fission gas adsorbent [3, 4] within the plenum region of a fuel rod and evaluates its preliminary feasibility under representative thermal and pressure conditions.

Specifically, since the fuel rod plenum can reach temperatures exceeding 610 K during operation, the adsorbent must maintain its structural integrity and gas-capturing performance under such harsh thermal environments. Therefore, this study first characterizes the high-temperature adsorption behavior of candidate materials and subsequently integrates these findings into a fuel performance code to assess the net benefit of adsorbent deployment.

2. Experimental & Result

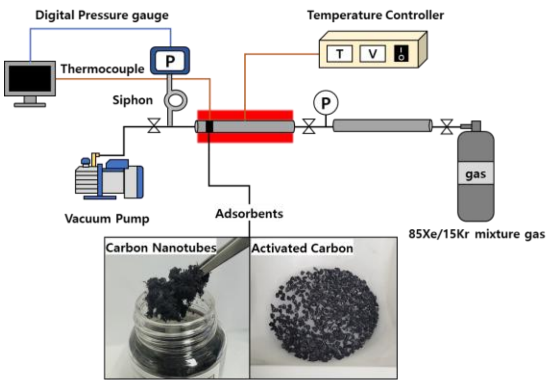


Fig. 1. Schematic illustration of the adsorption apparatus

The apparatus consists of two main sections: a pressure part and an adsorption part. The pressure part introduces a controlled Xe/Kr gas charge into the adsorption section. The adsorption part is heated to high-burnup PWR plenum-representative temperature (340–370 °C). During each experiment, temperature and pressure are logged every second as shown in Fig 1. Adsorption capacity is quantified by comparing the stabilized pressures obtained with and without the adsorbent. An 85% Xe / 15% Kr gas mixture was used to simulate representative fission gas composition. As candidate adsorbents, activated carbon (NUCON NUSORB®) and carbon nanotubes were examined to evaluate both mass-specific and volumetric adsorption performance at elevated temperatures.

2.1 High-Temperature Adsorption Experiments

Adsorption experiments were conducted at 24–360 °C using an 85% Xe / 15% Kr gas mixture with an initial inventory of ~10 mmol gas per test. The adsorption capacity at high temperature was determined from the net pressure difference between the reference case (without adsorbent) and the test case (with adsorbent), accounting for the reduced free volume introduced by the adsorbent.

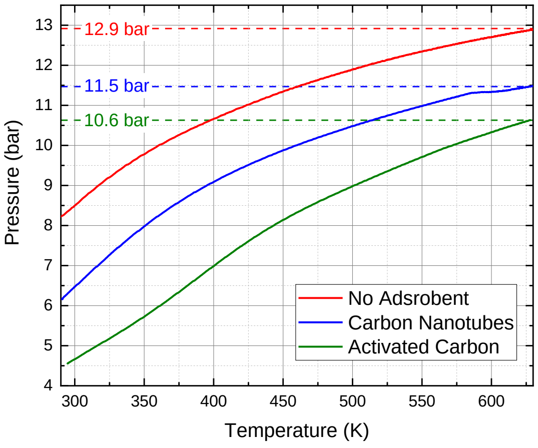


Fig. 2. Pressure-Temperature (P-T) curves for Xe/Kr gas with a fixed initial inventory of ~10 mmol gas

Activated carbon exhibited a gas uptake of ~1.7 mmol at 360 °C, corresponding to approximately 7.5% of the projected high-burnup FGR inventory (~22.4 mmol).

Although carbon nanotubes showed higher mass-specific uptake, their substantially larger specific volume (approximately 4.2 times that of activated carbon) resulted in inferior volumetric adsorption performance. Consequently, the stabilized pressure measured in the carbon nanotube case was higher than that of the activated carbon case, as shown in Fig. 2.

2.2 Heating-Cooling Cycle Experiment

To evaluate adsorption stability under repeated thermal transients, heating–cooling cycle experiments were performed for four consecutive cycles. In each cycle, the system was heated over 360 °C and subsequently cooled to room temperature using an initial gas inventory of approximately 5 mmol.

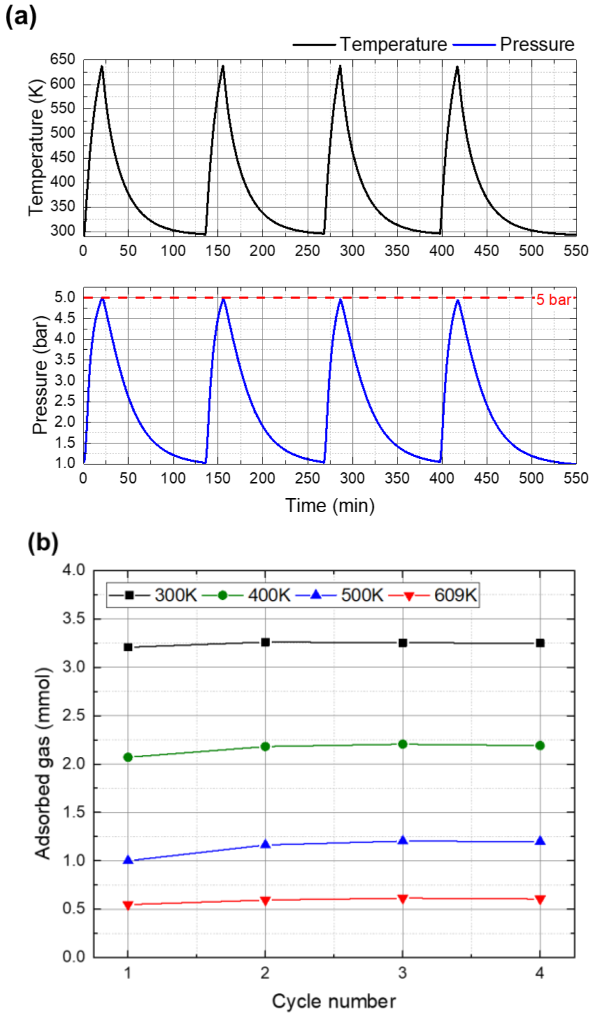


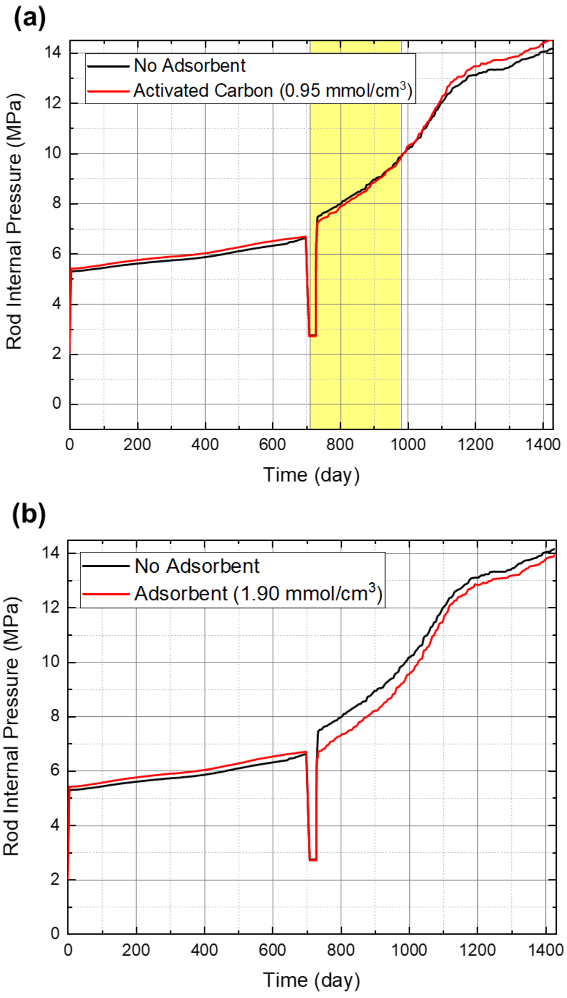
Fig. 3. (a) time-Temperature/Pressure diagram for Xe/Kr gas with activated carbon (b) Amount of adsorbed gas at specific temperature across cycles

Despite repeated thermal exposure, no progressive increase in stabilized pressure was observed over successive cycles in Fig. 3 (a). The pressure response during each heating stage remained reproducible, indicating that no significant degradation or irreversible loss of adsorption capacity occurred within the tested temperature range.

This behavior is further supported by Fig. 3(b), which shows that the amount of adsorbed gas at representative temperatures (300 K, 400 K, 500 K, and 609 K) remains nearly constant across consecutive thermal cycles. The absence of any systematic decrease in adsorbed gas amount confirms that adsorption performance is preserved without thermal degradation. This cyclic stability suggests that carbon-based adsorbents can maintain structural and adsorption functionality under plenum-representative thermal histories.

2.3 Implementation into GIFT Fuel Performance Code

The experimentally derived adsorption characteristics were subsequently implemented in the LWR fuel performance analysis code GIFT to assess their impact on fuel rod internal pressure evolution.



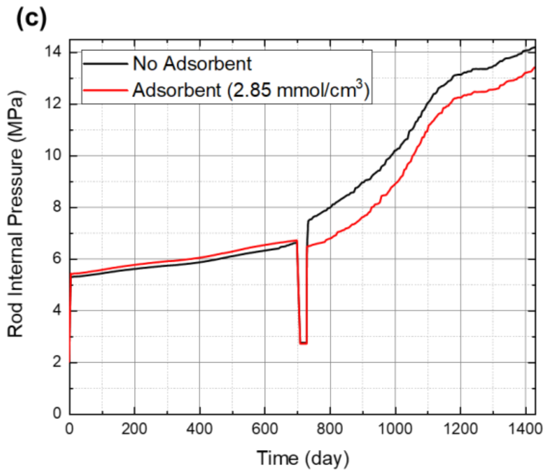


Fig. 4. compares the predicted RIP histories for three cases with increasing volumetric adsorption density: (a) measured activated carbon performance (0.95 mmol/cm^3), (b) 1.90 mmol/cm^3 (+100% improvement), and (c) 2.85 mmol/cm^3 (+200% improvement), while maintaining a constant adsorbent volume

The simulation results, as shown in Fig. 4 (a), demonstrate that adsorbent deployment introduces a competitive effect between fission gas capture and the reduction of available void volume. In the early stages of high-burnup operation, the pressure is effectively mitigated; however, as the fission gas release exceeds the cumulative adsorption capacity, the volume penalty (approx. 1.81cm3 in this study) can lead to a higher RIP compared to the reference case.

In contrast, the 1.90 mmol/cm^3 and 2.85 mmol/cm^3 cases (Fig.4 (b) and (c)) exhibit progressively greater pressure mitigation, indicating that volumetric adsorption density is the governing parameter for achieving net rod internal pressure reduction.

To identify the specific design envelope for effective mitigation, a parametric sensitivity analysis was conducted as shown in Fig. 5. This contour map illustrates the predicted end-of-life (EOL) rod internal pressure by varying the adsorbent volume and its adsorption density, evaluated at the projected EOL plenum temperature of 614.15 K.

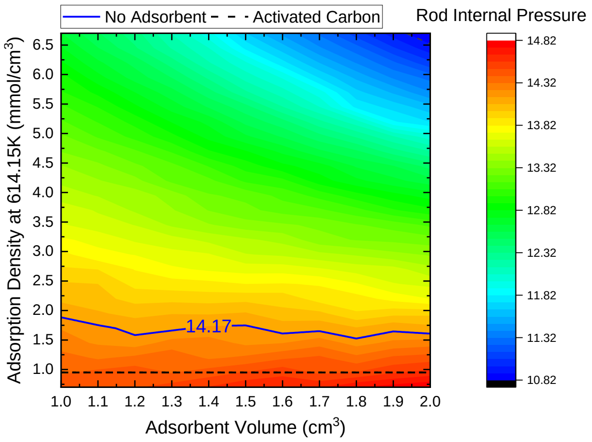


Fig. 5. Contour map of predicted EOL rod internal pressure as a function of adsorbent volume and adsorption density at 614.15 K

The results reveal a clear performance threshold for practical application; specifically, an adsorption density exceeding approximately 1.95 mmol/cm^3 is required to achieve a net reduction in pressure by overcoming the associated void-volume penalty. This threshold significantly surpasses the measured performance of current activated carbon (0.95 mmol/cm^3 at 614.15 K), explaining its limited impact in the reference case. By identifying these quantitative requirements, the contour map provides a strategic design envelope for selecting future candidates with higher volumetric efficiency, such as MOFs or high bulk density graphene-based materials, to ensure the feasibility of in-rod deployment.

3. Conclusions

This study investigated the feasibility of using fission gas adsorbents to mitigate the increased rod internal pressure (RIP) in high-burnup PWR fuel.

High-temperature adsorption experiments confirmed that activated carbon and other candidates can capture Xe/Kr even at temperatures exceeding 610 K, though the capacity is reduced compared to low-temperature conditions.

Integration with the GIFT code demonstrated that while in-rod adsorption can initially reduce internal pressure, the reduction in free void volume becomes a dominant factor as fission gas release exceeds the adsorbent's capacity. For effective RIP mitigation in high-burnup rods, the adsorbent must exceed a specific performance threshold (e.g., 1.95 mmol/cm^3 at 614.15 K) to compensate for the volume loss.

Future research will expand the experimental matrix to include additional candidates with higher volumetric efficiency, such as graphene nanoplatelets and MOFs, and conduct high-pressure tests using He-added gas mixtures to further refine the deployment criteria under realistic reactor conditions.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Climate, Energy & Environment(MCEE) of the Republic of Korea (No. RS-2025-02633904, Center for Advanced Nuclear Fuel Innovation).

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