Development of a Thermal Conductivity Model for Irradiated High-Gadolinia (U,Gd)O_2

Hyeongju Bae [a], Ho Jin Ryu [a,*]
[a] Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daehak-ro 291, Yuseong-gu, Daejeon, 34141, Korea
[*] *Corresponding author: hojinryu@kaist.ac.kr*

***Keywords:** Thermal conductivity, (U,Gd)O_2, Burnable absorber, Fuel performance code*

1. Introduction

Small modular reactor (SMR) focus on low-boron and boron-free concepts. Gadolinium-based materials are burnable absorber (BA) candidates with large neutron absorption cross-sections of ^{155}Gd and ^{157}Gd for this concept. (U,Gd)O_2 fuel fabricated by mixing Gd_2O_3 into UO_2 can be a option among them and long-cycle reactivity control requires high Gd_2O_3 additions of 8–20 wt.%. However, increasing the Gd_2O_3 content can degrade the thermal conductivity of UO_2 [2], and no measured conductivity exists for irradiated high-gadolinia fuel. The Modified NFI model implemented in FRAPCON considers the gadolinia effect as a single independent additive thermal resistance (1.1599·gad) based on low-content (<10 wt.%) measurements [7]. When evaluated at zero burnup against 58 out-of-pile unirradiated measurements (0–20 wt.% Gd_2O_3), the Modified NFI baseline systematically underpredicts by about 8%, whereas the modified Hirai [1,2] correlation recently extended to high gadolinia contents reproduces the same data within 2.2%, as shown in Fig. 1.

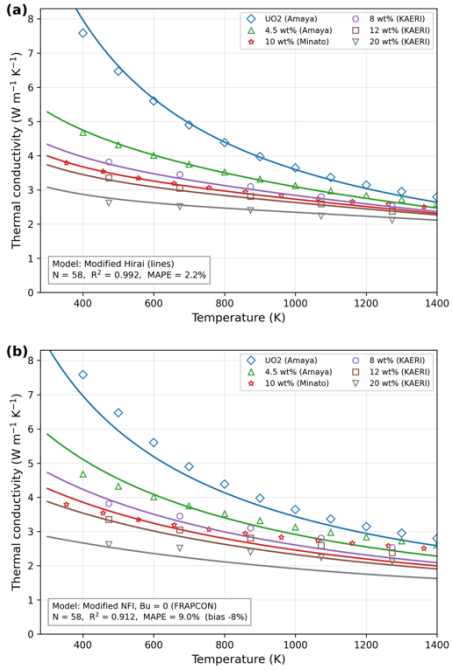


Fig. 1. Comparison of (a) the modified Hirai correlation and (b) the Modified NFI baseline (Bu = 0) with 58 out-of-pile unirradiated measurements (0–20 wt% Gd_2O_3).

In this study, an irradiated (U,Gd)O_2 thermal conductivity model is studied by combining the modified Hirai unirradiated basis with additive irradiation-resistance effects explicitly separated into a permanent irradiation-defect component (dissolved fission products and precipitates) and a recoverable component (annealable point defects).

2. Model Development and Results

2.1 Model formulation

Phonon thermal resistivities of independent scattering mechanisms are additive by the Matthiessen rule, since point-defect, and precipitate/pore scattering exhibit distinct phonon-frequency dependences. The model is therefore written as

$$k = [W_{Hirai}(T,y) + W_{irr,perm} + W_{irr,rec}]^{-1} + k_{el},$$
$$W_{Hirai} = x/(K_0 \arctan x),\quad K_0 = (2.35\times10^{-2}+2.55\times10^{-4}T)^{-1},$$
$$x = 3.365\, e^{-7.856\times10^{-4}T}(y\cdot K_0)^{1/2},$$
$$W_{irr,perm} = c_1 Bu,\quad W_{irr,rec} = g_0 h(T),\quad k_{el} = 3.57\times10^{-12}T^3$$

where y is the gadolinium cation fraction in $(U_{1-y}Gd_y)O_2$ (converted from the Gd_2O_3 weight content), Bu is the burnup (GWd/tU), h(T) is a sigmoid describing thermal recovery of point defects, and k_{el} is the high-temperature electronic conduction contribution. The recoverable term $W_{irr,rec}$ is active in the as-irradiated state and vanishes upon annealing.

2.2 Calibration data and parameter estimation

Out-of-pile conductivity measurements of irradiated UO_2 and (U,Gd)O_2 pellets (0–10 wt% Gd_2O_3, 33–61 GWd/tU, as-irradiated and recovered states, T ≤ 1400 K) were compiled from Amaya et al., Minato et al., and Staicu et al. [3–5]. Comparison of candidate functional forms converged to a linear burnup dependence for the permanent term, while the defect term showed burnup saturation, leaving a temperature-only h(T). The coefficients c_1 and g_0 were each calibrated with a 95% relative uncertainty near ±10%. Comparison with the soluble-fission-product coefficient of SIMFUEL measurements [6] attributes the permanent term predominantly to dissolved fission products, with a minor contribution from precipitates. Fig. 2 shows the double-difference test $D = [W_{irr,Gd} - W_{0,Gd}] - [W_{irr,UO2} - W_{0,UO2}]$: the irradiation increments are Gd-independent

for the permanent, recoverable terms, justifying shared coefficients between UO_2 and $(U,Gd)O_2$.

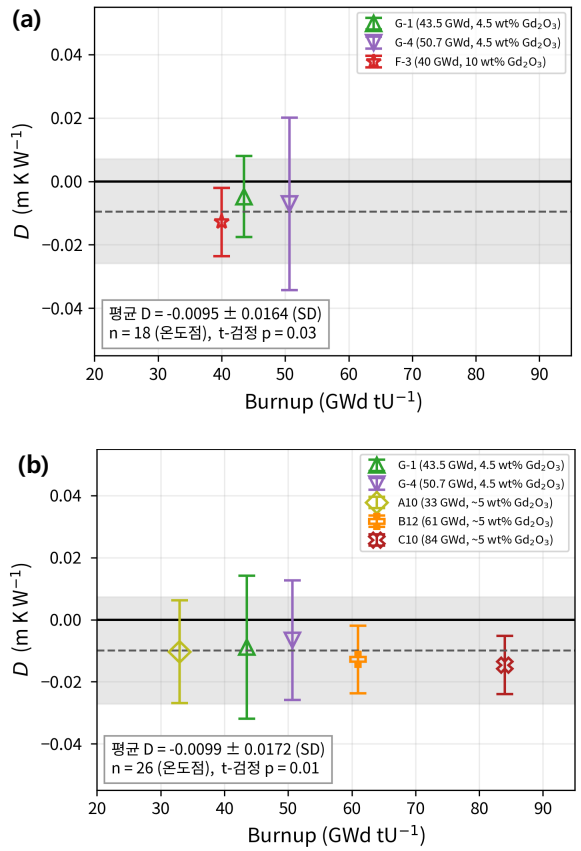


Fig. 2. Double-difference test against burnup-matched UO_2: (a) permanent, (b) recoverable terms.

2.4 Model validation

Fig. 3 presents the predicted-versus-measured parity for all 62 irradiated data points in both states. The model reproduces the data with R^2 = 0.90, RMSE = 0.16 $Wm^{-1}K^{-1}$, MAPE = 4.0%, and zero mean bias; state-wise errors are 4.3% (as-irradiated) and 3.6% (recovered).

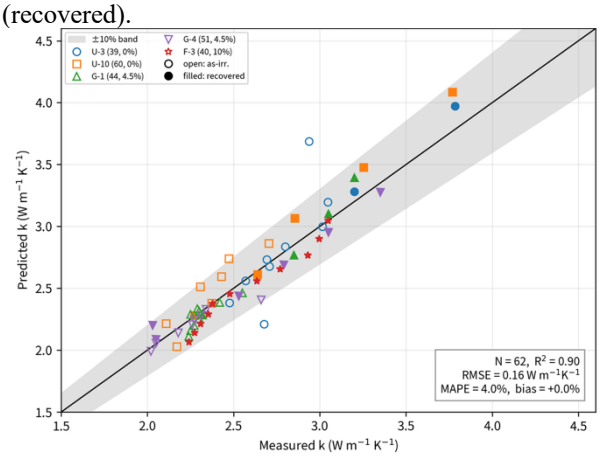


Fig. 3. Parity plot of the thermal conductivity model for irradiated High-Gadolinia model for the 62 irradiated measurements.

3. Conclusions

A thermal conductivity model for irradiated high-gadolinia $(U,Gd)O_2$ fuel was studied by combining the modified Hirai unirradiated basis with statistically selected and attributed permanent and recoverable irradiation-resistance terms. The model was calibrated on irradiated measurements up to 0–10 wt% Gd_2O_3 and 61 GWd/tU, reproduces the 62 points within 4% on average (R^2 = 0.90, RMSE = 0.16 W $m^{-1}K^{-1}$) with 95% of points inside the ±10% band. The model can be directly implemented in fuel performance codes for boron-free reactor design, and further extensions such as the high-burnup structure (HBS) regime are possible.

REFERENCES

[1] M. Hirai and S. Ishimoto, "Thermal Diffusivities and Thermal Conductivities of UO2–Gd2O3," J. Nucl. Sci. Technol., 28(11), 995 (1991).
[2] J. H. Lee, et al., "Effect of High Gd2O3 Content on the Thermal Conductivity of UO2–Gd2O3 Fuels," Nucl. Eng. Technol., 104261 (2026).
[3] M. Amaya, et al., "Thermal Conductivities of Irradiated UO2 and (U,Gd)O2 Pellets," J. Nucl. Mater., 300, 57 (2002).
[4] K. Minato, et al., "Thermal Conductivities of Irradiated UO2 and (U,Gd)O2," J. Nucl. Mater., 288, 57 (2001).
[5] D. Staicu, et al., "Effect of Burn-up on the Thermal Conductivity of Uranium Dioxide up to 100 GWd/tHM," J. Nucl. Mater., 453 (2014).
[6] S. Ishimoto, et al., "Effects of Soluble Fission Products on Thermal Conductivities of Nuclear Fuel Pellets," J. Nucl. Sci. Technol., 31(8), 796 (1994).
[7] K. Ohira and N. Itagaki, "Thermal Conductivity Measurements of High Burnup UO2 Pellet and a Benchmark Calculation of Fuel Center Temperature," Proc. ANS Int. Topical Mtg. on LWR Fuel Performance, Portland, USA (1997).

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science and ICT (MSIT) of the Republic of Korea (RS-2024-00420956, RS-2025-02353161), Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (RS-2025-02633904).