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Nuclear and Thermal Sensitivity Analysis of a Double-Layer Thermal Medium Capsule in Neutron Irradiation Tests

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1. Introduction

The development of Generation-IV reactors and other advanced reactor designs has driven extensive research on various reactor materials. Before commercialization, these materials must undergo rigorous validation to ensure their integrity and safety.

Neutron irradiation tests play a crucial role in evaluating whether various nuclear materials, both currently in use and under development, can withstand extreme environmental conditions. These tests help to analyze microstructural changes, mechanical property degradation, and radiation damage mechanisms caused by neutron irradiation, thereby predicting long-term stability. Additionally, they are essential for assessing material performance under specific operating conditions and verifying whether the materials can fulfill their intended functions in a reactor environment.

To conduct systematic neutron irradiation tests, it is necessary to determine the appropriate test temperature, irradiation dose, and exposure period, as well as to check the safety of the experiment. For this purpose, nuclear and thermal evaluation are essential. These evaluations ensure the reliability of neutron irradiation tests and contribute to the precise interpretation of experimental data.

The increasing demand for materials that remain stable under high-temperature conditions has led to the development of neutron irradiation tests specifically designed for such materials. In this context, a capsule with a double-layer thermal medium has been developed.

In this study, nuclear and thermal evaluation conducted to the capsule with double-layer thermal medium. Monte Carlo-based particle transport calculations were performed to determine the neutron and gamma heating within the capsule, and an analytical method was applied to calculate the temperature distribution under given boundary conditions. Additionally, the effect of gap size on the specimen temperature was analyzed.

2. Model Descriptions

This study assumes the neutron irradiation test by loading the capsule with double-layer thermal medium into the irradiation hole located at the central region of the core in the HANARO. Monte Carlo-based particle transport calculations were performed using the MCNP6.2[1] code, based on an equilibrium core with a reactor power of 30 MW. Temperature distribution within the capsule were calculated using the one-dimensional GENGTC[2] code.

Within the capsule, the alloy specimen has a rectangular shape with dimensions of 1.0 × 1.0 × 11.4 cm^3, 1.0 × 1.5 × 11.4 cm^3, and mass of 88.8 g, 133.38 g, respectively.

Figure 1 presents a schematic diagram of a one-dimensional node divided along the centerline of the specimen within the capsule.

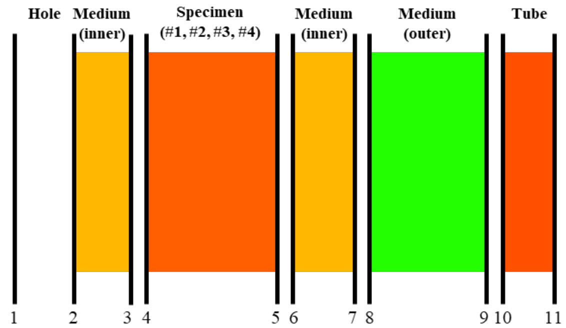

Fig. 1. One-dimensional materials arrangment from the center of the capsule with corresponding numbers

The temperature of materials in each node are calculated as follows,

$$T_i = T_0 + \frac{q'''}{4k}\left(R_o^2 - R_i^2\right) + \frac{Q}{2\pi k}\ln\left(\frac{R_o}{R_i}\right) - \frac{q'''}{2k}R_i^2\ln\left(\frac{R_o}{R_i}\right),$$

- R_i : *inner radius*
- R_o : *outer radius*
- q''' : *heat ratio of the ring*
- Q : *heat flow from the inner point*
- k : *heat conductivity coefficient*.

In this calculations, the effect of material property variations on temperature change was not considered.

3. Nuclear and Thermal Evaluation as Gap Size

Figure 2 shows the neutron flux in unit lethargy along with the neutron energy as HANARO operation cycle. The control rod height at the BOC(Beginning Of Cycle), MOC(Middle Of Cycle) and EOC(End Of Cycle) was assumed to be 350 mm, 450 mm, and 550 mm respectively. The neutron spectrum remained relatively constant across different operating cycles for the specimens.

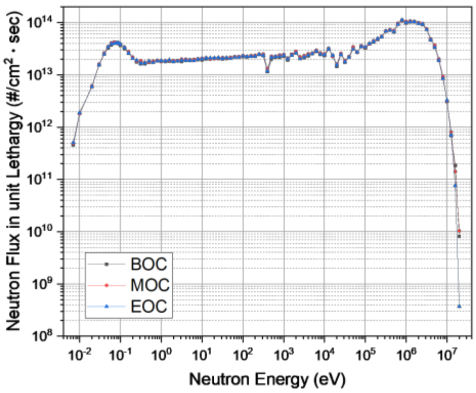

Fig. 2. Neutron flux per unit lethargy as a function of neutron energy over the HANARO operation cycle

Figure 3 presents the total neutron flux distribution according to the height of the control rod for the four specimens loaded in the capsule. The specimens were positioned at 0˚, 90˚, 180˚, and 270˚.

Due to structural characteristics of the HANARO core, specimen #4(270˚) exhibited the highest neutron flux. Additionally, the neutron flux increased with control rod height up to 450 mm before decreasing.

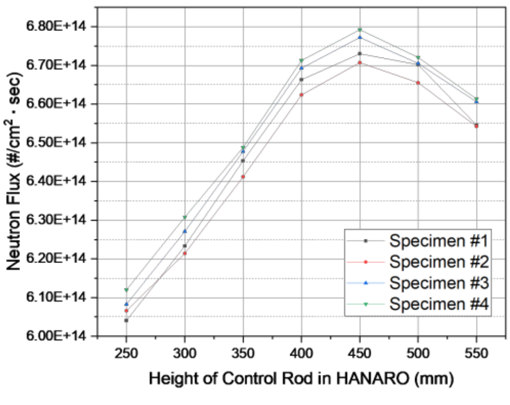

Fig. 3. Total neutron flux variation for four specimens as a function of control rod height

Subsequently, the effect of specimen temperature on gap size within the capsule was analyzed. The gaps considered were: 1) Specimen - Inner thermal medium, 2) Inner thermal medium - Outer thermal medium, 3) Outer thermal medium - External tube.

Table 1 presents the specimen temperature variation with gap size.

Table 1. Specimen temperature variation with gap size

Gap	Gap Size (cm)	Specimen Temp. (℃)
1)	0.005 ~ 0.015	965 ~ 960
2)	0.015 ~ 0.025	908 ~ 1000
3)	0.020 ~ 0.030	835 ~ 978

Among the three of gaps, the outer thermal medium - external tube gap exhibited the most significant impact on specimen temperature. A change of 0.01 cm in this gap size resulted in a temperature difference of 143℃.

4. Conclusions

This study focused on the sensitivity analysis of thermal calculations related to gap size in a capsule with a double-layer thermal medium for the HANARO irradiation test. The analysis revealed that temperature distribution within the capsule is significantly affected by gap sizes, particularly the gap between the outer thermal medium and the external tube. Smaller gaps in this region led to substantial increases in specimen temperature, emphasizing the importance of precise gap control for thermal management during neutron irradiation.

Additionally, neutron flux distribution was influenced by the specimen position and control rod height, with notable variations between specimens placed at different angular positions within the capsule. These findings underscore the importance of optimizing gap sizes to enhance thermal performance and maintain material integrity during irradiation tests. This study provides valuable insights for designing future irradiation capsules and improving the accuracy of thermal evaluations in reactor experiments.

ACKNOWLEDGEMENT

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