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IAEA Extended Abstract Template

Technical Meeting on Advanced Technology Fuels: Progress on their
Design, Manufacturing, Experimentation, Irradiation, and Case Studies
for their Industrialization, Safety Evaluation, and Future Prospects

IAEA NFE TEAM
Vienna, 2025

PERFORMANCE ANALYSIS OF HRP IFA-790 EXPERIMENT REGADING MICROCELL PELLET IRRADIATION BEHAVIOR

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INTRODUCTION: The Korea Atomic Energy Research Institute is developing accident-tolerant fuel pellets based on the micro-cell pellet concept, i.e. micro-cell UO_2 pellets. These micro-cell pellets are composed of cell wall materials that form multiple layers within the UO_2 matrix. Metal micro-cell pellets use high-thermal-conductivity materials arranged in a continuous manner to enhance the thermal conductivity of the UO_2 pellet. This reduces the temperature of the nuclear fuel, decreases the movement of fission gases, and improves the operational margin. To verify the in-reactor characteristics of the micro-cell pellets, irradiation experiments were conducted at the Halden research reactor using the IFA790 rig. These tests were carried out by Thor Energy in Norway as part of the International Thorium Consortium. The test began in December 2015 and ended in February 2018, with an actual irradiation period of approximately 360 days and an average discharged burnup of 16.2 MWd/kgU. The in-pile performance of the micro-cell pellets was verified through power, nuclear fuel centerline temperature and rod internal pressure measurements. This study analyzed the results of the IFA790 experiment on the Cr metal micro-cell pellet developed by the Korea Atomic Energy Research Institute and performed a performance analysis of the in-pile experiment using the FRAPCON code.

1. HALDEN REACTOR PROJECT – IFA790 EXPERIMENT

The Korea Atomic Energy Research Institute manufactured two types of microcell UO_2 pellet for use in Halden tests. Depending on the additives used, the microcell pellets were classified as either ceramic or metal. In this context, 'additives' refers to the materials that constitute the walls of the microcells ('cell wall materials'). The microcell UO_2 pellets were manufactured using 4.5%-enriched UO_2 powder produced by the DC (dry conversion) method. Figure 1 shows the microstructure of the metal microcell UO_2 pellet containing chromium (Cr). This structure consists of Cr surrounding a cluster of small grains to form a single microcell. The microcell size is approximately 290 μm , and the high thermal conductivity of the chromium (Cr) connects the microcells continuously like thin walls, thereby improving the thermal conductivity of the pellet. The Cr additive content is 3.4 wt%, corresponding to 5 vol% of the entire pellet. The density of the manufactured pellet is 97% [1].

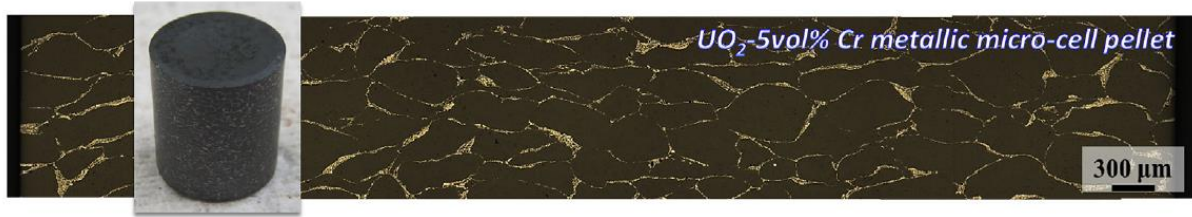


FIG. 1. OM image of Cr microcell UO₂ pellet

Figure 2 shows the power history of the fuel rods. The measured power output is displayed over time, showing only the period during which, the rods were irradiated. This period, known as the Effective Full Power Day (EFPD), lasts approximately 360 days. In terms of applied power, the reference fuel (black line) has the highest power output, followed by ceramic microcell pellet, then metal microcell pellet [2,3].

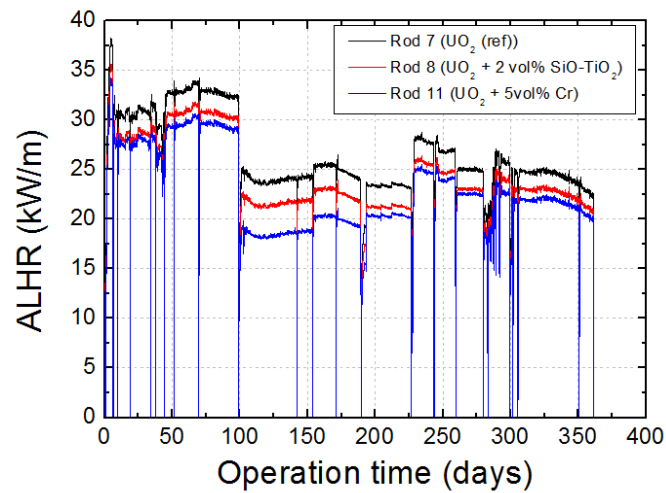


FIG. 2. Power history of rod 7, rod 8 and rod 11

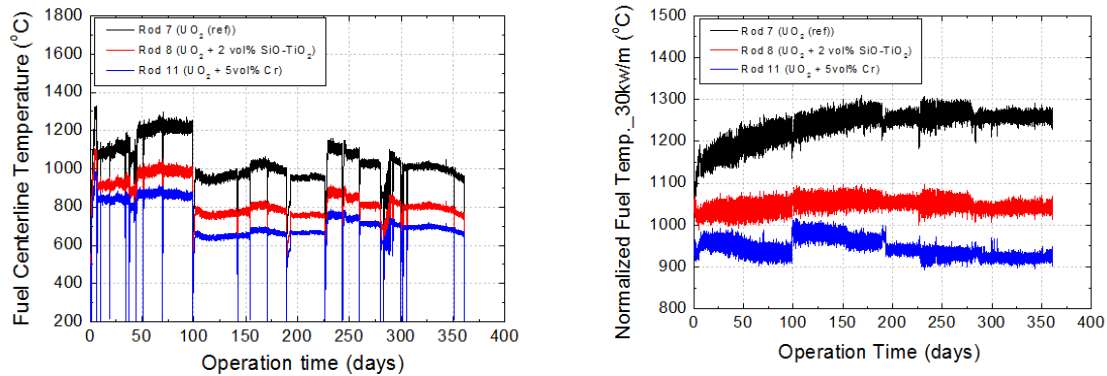


FIG. 3. Measured fuel centerline Temperature and normalized fuel temp of rod 7, rod 8 and rod 11

Figure 3 shows how the centre temperature changes over time for the reference UO₂ and KAERI's ATF pellets. Throughout the irradiation test, the temperature of the ATF pellets (Rods 8 and 11) were significantly lower than that of the reference fuel rod (Rod 7). This is thought to be due to the low applied power and the improved thermal conductivity characteristics. To quantify the effect of the improved thermal conductivity of the microcell pellets, the fuel centre temperatures were converted to the temperature at a constant power of 30 kW/m at the applied power. The normalisation temperature ($T_{\text{normalisation}}$) at 30 kW/m was calculated as shown in Fig. 3(right) [4]. The figure shows the normalised temperature changes according to irradiation time at an output of 30 kW/m. The pellet (Rod

11) containing 5% chromium showed a temperature approximately 20% lower than the UO_2 reference (Rod 7). Rod 8 (UO_2 -2 vol% SiO_2 - TiO_2) also showed a temperature approximately 10–15% lower. Rod 11 (metal microcell) exhibits a lower temperature thanks to the inclusion of chromium (Cr), a metal renowned for its high thermal conductivity. It was predicted that arranging Cr within a UO_2 cell structure would result in superior thermal conductivity compared to conventional UO_2 , leading to a lower core temperature, and this was indeed observed. Rod 8 (ceramic microcell) also exhibited a low temperature. A separate analysis of the PIE (post-irradiation examination) results is required to explain this phenomenon.

2. OPERFORMANCE ANALYSIS OF IFA 790 ROD 7(UO_2) AND ROD 11(CR-MICROCELL)

The performance analysis of HRP IFA-790 was conducted using the FRAPCON4.0P1 [5] to examine the irradiation behaviour of the test rods. This study analysed the performance of Rod 11. This rod was loaded with metal microcell pellet that were fabricated with added chromium (Cr). It was assumed that the reference UO_2 and the metal microcell pellet exhibited same irradiation behaviors (e.g. swell and densification) except for thermal conductivity. Based on the performance analysis result of Rod 7, the densification model was modified for the test. Having modified the Rod 7 densification model to match the actual test results, this model was then applied to analyse Rod 11.

2.1. Analysis of UO_2 reference irradiation behavior

As shown in Fig. 4 (left) (black line), the performance analysis results for the measured centre-line temperature and the reference fuel differed. This difference was particularly noticeable in the early stages of irradiation. Therefore, a correction calculation was performed on the model to account for the centre-line temperature of the fuel in these initial stages. Regarding gap thermal conductivity, a major factor affecting the centre-line temperature, it was determined that it is influenced by gap size and has a greater impact on the swelling and densification of nuclear fuel than on cladding material deformation during the initial stages of combustion. Consequently, the pellet densification model, which is impacted by pellet manufacturing characteristics, was modified. These model corrections produced a model similar to the measured data (orange line), which was then used to correct the UO_2 densification model. This model was also used in the rod 11 calculation. Figure 4 (right) shows the results of a direct comparison between the existing densification model and the densification model of the sintered pellet used in IFA790.

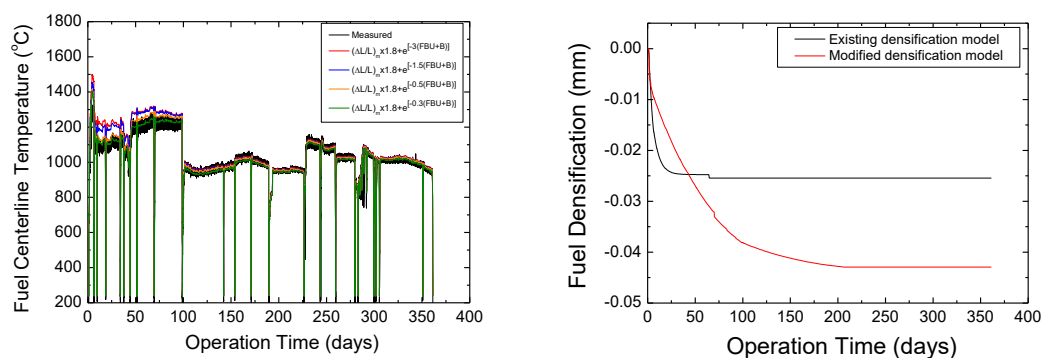


FIG. 4. Fuel centerline Temperature according to the modified densification models and comparison of densification model

2.2. Analysis of Rod 11(Cr-MICROCELL) irradiation behavior

A modified densification model was applied under the assumption that the accident-tolerant fuel (ATF) metallic microcell pellet exhibits the same densification behavior as the reference UO_2 pellet. Additionally, since the metallic microcell pellet contains a high thermal conductivity metal

mixed with UO_2 , the effective thermal conductivity of the composite must be newly considered. Therefore, for accurate temperature prediction of the metallic microcell pellet, a model capable of estimating the effective thermal conductivity of both UO_2 and the metal is required. To implement a microcell thermal conductivity model in FRAPCON, the model proposed by Yang [6], which simplifies the unit cell of the metallic microcell pellet as a rectangular parallelepiped and assumes radial heat transfer, was utilized. This model was applied to the metallic microcell pellet structure, and the effective volume fractions and directional thermal conductivities of the metal and UO_2 were calculated to determine the overall effective thermal conductivity in the composite UO_2 -metal structure. Figure 5 shows the changes in fuel centerline temperature based on both measured and simulated results for the two types of Cr-Microcell model during the burnup test. The measurements indicate that while power slightly increases over the burnup period, the change is minimal and remains relatively constant. In contrast, the simulation results show two distinct temperature regimes over the burnup period: the measured temperature is relatively higher during the early stage of burnup, then slightly decreases and stabilizes after approximately 50 days. However, after 230 days, the simulated temperature was higher than the measured temperature. This discrepancy was also observed in the simulation for Rod 7. The UO_2 pellet of Rod 7 and the metallic microcell pellet of Rod 11 were fabricated at different facilities, suggesting that variations in densification behavior could exist between them. Using a Cr-based metallic microcell pellet, the in-reactor test at low burnup demonstrated that the proposed thermal conductivity model provides reasonably accurate predictions. However, to more precisely evaluate the behavior, it is considered necessary to support the analysis with Post-Irradiation Examination (PIE) data concerning gap closure burnup and initial densification characteristics.

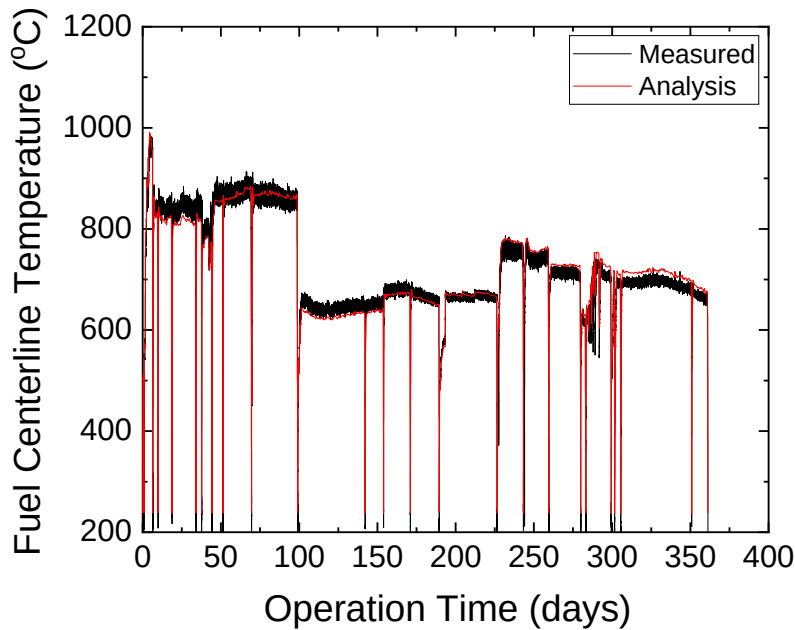


FIG. 5. Calculation result of Fuel centerline Temperature with the Cr-microcell thermal conductivity model

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2022- 00144002).

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