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Characterization of Radial Power Distribution for In-Reactor Testing of Fuel Rods in HANARO

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1. Introduction

Recently, in Korea, a development of various light water nuclear fuels such as accident tolerant fuel, iSMR fuel, and high burnup fuel through increased U-235 enrichment is required. In order to commercialize these nuclear fuels, their performance and safety should be verified through in-reactor tests. In particular, since tests can be conducted using HANARO, the unique research reactor in Korea, tests for centrally-shielded burnable absorber (CSBA) pellets and accident tolerant fuels currently under development by academic and research institutes are being conducted[1]. The tests of the rods for iSMR burnable absorbers and control rod pellets are also being prepared[2]. However, these tests focus on observing changes in the physical properties of materials according to burnup accumulation. Since the characteristics of the reactor where the test is performed can affect the power distribution and mechanical behavior of the test fuel rods, it is important to understand these characteristics. This is the basic data for the HANARO test evaluation to be used as the licensing data. Therefore, the differences with the environment in commercial nuclear power plants must be clearly described. In this paper, in order to evaluate the reactor characteristics in HANARO, the radial power distribution was evaluated based on nuclear analysis of standard nuclear fuel rods. The test characteristics is identified and the mechanical evaluation method is suggested for an accurate evaluation.

2. Methods

2.1 HANARO test example

To analyze the test characteristics, the actual 92nd cycle operation history of HANARO was used. This is because the 92nd cycle operation of HANARO was stably performed at full power (30 MW) without reactor power change from January 27 to February 24, 2014 with an optimal operation history. During the HANARO operation, various tests were performed in the other flux traps. It was assumed that UO_2 standard fuel rods test with an enrichment of 4.5wt% is performed in the OR4 irradiation hole. The test rig consists of upper and lower clusters, and each cluster is equipped with three fuel rods. In this test, it was assumed that the Hf shroud was installed to control average power level of the test rods between 40 and 50 kW/m. Although this is higher than the peak power in the commercial nuclear power plant, the accelerated depletion test was considered because the coolant temperature of HANARO is low and thus the nuclear fuel temperature is low, too.

2.2 Evaluation methods

In order to simulate the test in HANARO, MCNP[3] and ORIGEN[4]-based analysis system is used as shown in Fig. 1. Since the reactivity of HANARO core is controlled only with the control absorber rods, the effect of the control rods to the nuclear values is relatively large, so the core calculation is performed according to the movement of the control absorber rods. HANARO Fuel Management System (HANAFMS), which manages the nuclear fuel and the core, calculates the core states for each 50 mm movement of the control absorber rods. Since the HANARO fuel is not of interest in this evaluation, the HANARO fuel information (burnup) is obtained from HANAFMS. The 3-D geometric structure of the irradiated material is modeled through MCNP, and the neutron transport analysis is performed. The depletion or activation over test duration is calculated through the ORIGEN code. Since MCNP can only calculate the steady state, the calculation of each step is sequentially evaluated through the predictor-corrector method. The MCNP-ORIGEN analysis system took about 3 days to evaluate one cycle of HANARO operation.

This evaluation assumed a total of 8 cycles of testing. The analysis model was assumed that dummies were loaded in other irradiation holes and only utilized the operating history of 92nd cycle, it is expected that there will be some differences in reality, but it would be better to exclude other influences. Fig. 2 shows the MCNP model of the rig and fuel rod used in the analysis. In order to evaluate the radial power distribution and the inventory of each nuclide, the fuel rod was divided into a total of 20 regions. In general, since the outer region has a higher selectivity in the case of light water reactor fuel, the outer region was configured more finely. In this test, the expansion of the fuel pellet was not considered.

The diameter of the fuel pellet was assumed to be in contact with the inner surface of the cladding. The calculation results of each region satisfied the fractional standard deviation within 2%.

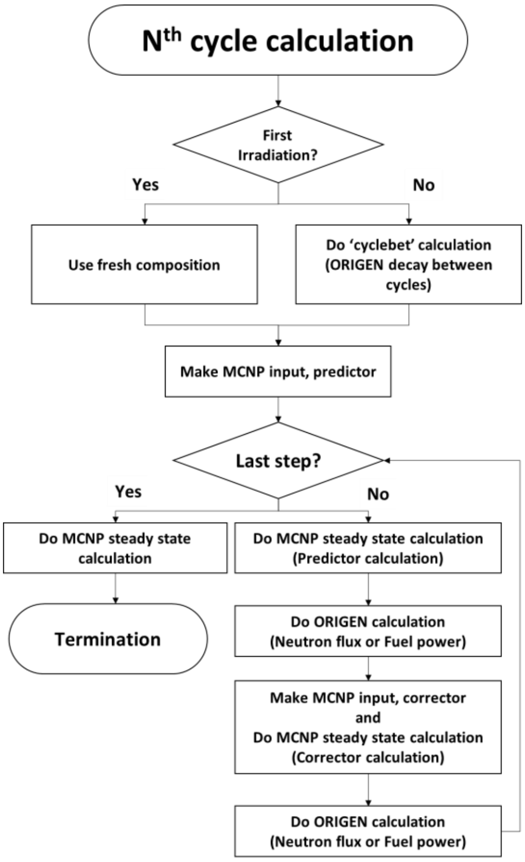

Fig. 1. Flow chart of sequential depletion evaluation for irradiated material by MCNP and ORIGEN codes

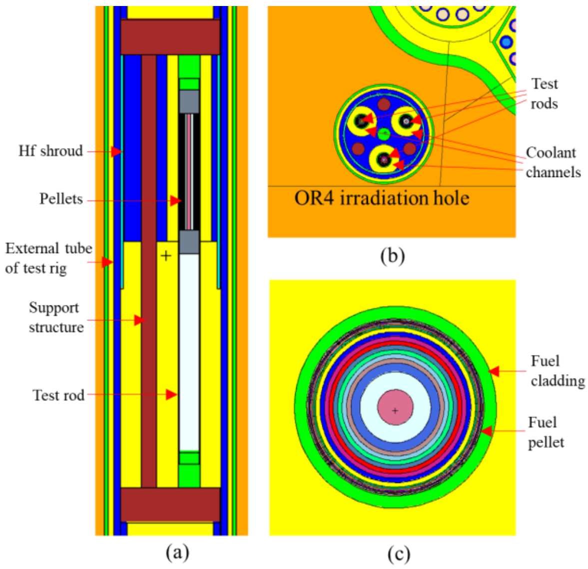

Fig. 2. MCNP model: (a) axial view of cluster, (b) horizontal view of test rig, and (c) divided radial region in a rod

3. Results and Discussions

3.1 Burnup of test rods

Fig. 3 is a graph showing the average burnup of each fuel rod according to the test duration. The average burnup was approximately 18,000 MWD/tU during a total of 226.86 EFPD. The burnup increase trend was different in the upper and lower clusters. In the case of the upper cluster, it changed from low power at the beginning of the cycle to high power at the end of the cycle. In the case of the lower cluster, it changed from high power at the beginning of the cycle to low power. This is because the neutron flux distribution changed when the control absorber rods inserted at the beginning of the cycle was withdrawn. In addition, the power difference occurred even within the same cluster because the OR4 irradiation hole is located in the reflector area outside the core, which has a large neutron flux gradient. Therefore, in order to accurately evaluate the HANARO test, the geometric structure should be simulated more clearly. When HANARO is operated normally, approximately 6 to 7 cycles are operated per year. In this test, high burnup was shown by the result of acceleration of the rod power. If the same design is applied, burnup can be achieved within three years to make burned fuel rod approximately 30,000 MWD/tU.

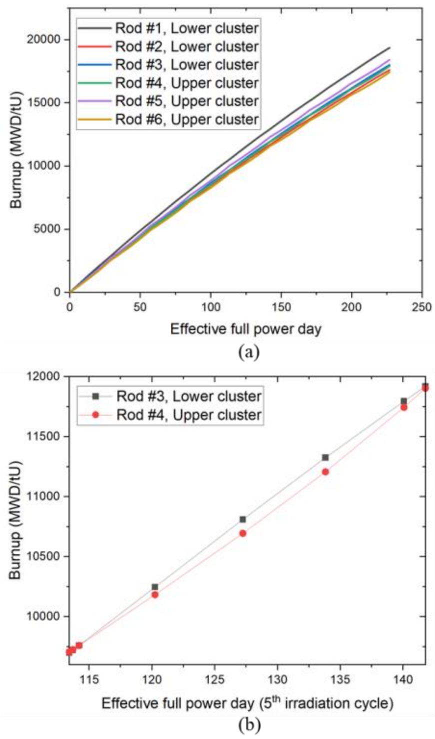

Fig. 3. Burnup increase of test rods by test duration: (a) burnup increase of each rod up to 8th irradiation cycles and (b) burnup increase comparison between lower and upper rods at 5th irradiation cycle

3.2 Radial power distribution and Pu-239 inventory

Table I is a graph showing the radial power distribution according to the irradiation period of the test rod #1. The power at the outer region of fuel pellet was relatively higher as the burnup increase compared to the early stage of burnup. Fig. 4 shows the radial inventory distribution change of Pu-239. The nuclear fuel test at HANARO mainly uses the OR irradiation hole because it has a high thermal neutron flux. However, the irradiation hole is located in the heavy water reflector area and is far from the HANARO nuclear fuel, so the neutron spectrum is different from that of the commercial nuclear power plant. It is similar to the HBWR, a heavy water-based research reactor, but the thermal neutron flux in HANARO is somewhat higher than that of HBWR. Therefore, due to this effect, the power at the outer pellet is relatively higher than that of the commercial nuclear power plant and the HBWR. The high power at the outer pellet causes the nuclear fuel temperature distribution to be different. In other words, if the power at the outer pellet is relatively high at the same nuclear fuel power, the central temperature of the nuclear fuel is lower. FRAPCON[5] has a built-in library of the commercial nuclear power plant and HBWR, and assuming the same power, the core temperature of the nuclear fuel showed a difference of about 20℃ at the beginning of depletion. Therefore, it is expected to be lower temperature than that when testing at HANARO, and the difference should be clearly confirmed.

Table I: Radial power distribution change of Rod #1

Radial region		Normalized power distribution at the beginning of cycle							
r_i	r_o	Cycle #1	Cycle #2	Cycle #3	Cycle #4	Cycle #5	Cycle #6	Cycle #7	Cycle #8
0	0.2	0.929	0.936	0.925	0.940	0.959	0.964	0.949	0.941
0.2	0.4	0.947	0.955	0.943	0.956	0.956	0.970	0.961	0.940
0.4	0.5	0.983	0.960	0.957	0.973	0.970	0.972	0.976	0.966
0.5	0.55	0.979	0.967	0.957	0.984	0.968	0.972	0.982	0.984
0.55	0.6	0.972	0.967	0.973	0.971	0.979	0.973	0.969	0.986
0.6	0.65	0.986	0.973	0.977	0.981	0.995	0.969	0.971	0.982
0.65	0.7	0.985	0.987	0.988	0.994	0.999	0.974	0.978	0.991
0.7	0.75	1.001	0.996	0.998	1.005	0.987	0.980	0.984	0.998
0.75	0.8	1.004	1.008	1.007	1.001	0.994	0.991	0.998	0.989
0.8	0.85	1.016	1.018	1.020	1.008	1.005	1.006	1.002	1.002
0.85	0.9	1.029	1.032	1.037	1.017	1.020	1.011	1.014	1.017
0.9	0.9125	1.039	1.038	1.050	1.026	1.031	1.033	1.022	1.033
0.9125	0.925	1.028	1.047	1.058	1.036	1.030	1.040	1.039	1.032
0.925	0.9375	1.054	1.055	1.063	1.044	1.032	1.046	1.037	1.042
0.9375	0.95	1.052	1.065	1.063	1.041	1.044	1.050	1.042	1.045
0.95	0.96	1.058	1.074	1.077	1.046	1.053	1.076	1.067	1.062
0.96	0.97	1.057	1.074	1.077	1.059	1.062	1.078	1.081	1.072
0.97	0.98	1.067	1.087	1.080	1.072	1.072	1.091	1.084	1.090
0.98	0.99	1.079	1.085	1.094	1.087	1.102	1.116	1.125	1.124
0.99	1	1.101	1.110	1.135	1.154	1.170	1.198	1.237	1.245
r_i: normalized inner surface of radial region, r_o: normalized inner surface of radial region									

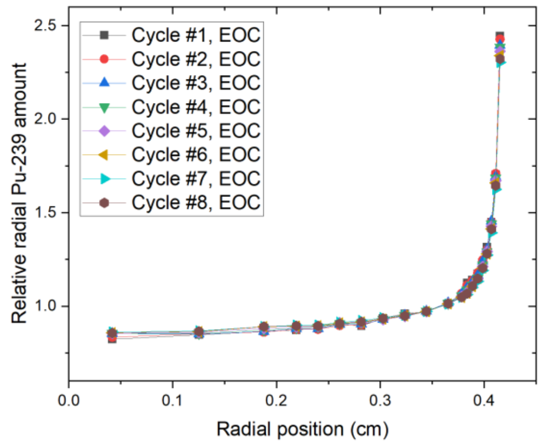

Fig. 4. Radial Pu-239 distribution change of Rod #1

3.3 Effective cross section

Fig. 5 shows the comparison results of the effective cross sections according to the test duration. It can be seen that there are differences depending on the radial position and burnup of the pellet. Plutonium generated by the neutron absorption reaction of U-238 is the main factor that increases the power outside the pellet. The FRAPCON uses the TUBRNP model[6] to evaluate this effect. However, TUBRNP uses the effective cross section of nuclear fuel as a constant library, so it is not realistic. In particular, in the case of the HANARO test, since the behavior at a local location is identified, an optimal evaluation can be performed rather than a conservative evaluation. In addition, since the HANARO irradiated material is likely to change every cycle and the behavior of the control absorber rod is also different. The same core model cannot be used, so the evaluation according to the corresponding changes must be performed every cycle. Therefore, the FRAPCON-based calculation cannot be utilized for HANARO fuel testing. It is appropriate to perform a performance evaluation along with MCNP and ORIGEN-based system.

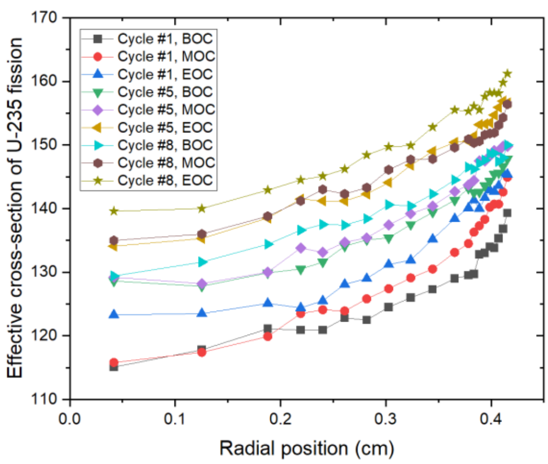

Fig. 5. Effective cross-section change of Rod #1

4. Conclusions

In order to evaluate the nuclear fuel test in HANARO, a simulation was performed. It was assumed that the actual operating history is used for the evaluation for the test of six fuel rods in OR4 irradiation hole. As a result of the evaluation, the burnup increase rate according to EFPD was calculated, and the characteristics of the fuel rods by location were evaluated. In addition, the radial power distribution was calculated, and the inventory of Pu-239 was also evaluated. The effective cross section of the nuclear fuel by radial location and burnup was calculated, and as a result, it was determined that the existing FRAPCON code would not be able to perform accurate calculations. In the future, for accurate calculations, a performance analysis module for nuclear fuel will be added and verified. If the calculation system is verified, it is expected that precise evaluations can be applied not only to research reactors but also to commercial nuclear power plants.

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