# As-run Analysis of HANARO Irradiation Test for CSBA-loaded Pellets and KAERI ATF

Seongwoo Yang*, Junesic Park, Yoon-Taeg Shin, Ye-Eun Na, Dong-Joo Kim
*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beongil, Yuseong-gu, Daejeon, 34057*
**Corresponding author: swyang@kaeri.re.kr*

***Keywords :** HANARO, CSBA, KAERI ATF, burnup, radial power distribution*

## 1. Introduction

Korean academic and research groups are developing innovative concepts of nuclear fuel. Centrally-shielded burnable absorber (CSBA) located in the center of a fuel pellet can suppress the initial excess reactivity of a reactor[1]. It is expected to be utilized especially in commercial nuclear power plant and i-SMR for low-boric acid and boric acid-free operation. KAERI is developing microcell pellets to improve thermal conductivity and cladding tubes coated with Cr or Cr/Al to prevent hydrogen production by oxidation as an accident-tolerant fuel (ATF) for application to commercial nuclear power plants[2, 3]. Accordingly, a HANARO test was planned to verify the in-reactor performance of CSBA-loaded $UO_2$ pellets and KAERI ATF[4]. The test was beginning on May 14, 2024.

The main focus of the HANARO test is to investigate various performances according to the burnup of the target nuclear fuel. Since the HANARO test cannot measure the in-reactor performance of nuclear fuel in real time, the performance must be observed through post-irradiation examinations. Therefore, the behavior of test fuel during the HANARO operation has no choice but to depend on computational evaluation. The test fuel is expected to show different behavior with the conventional homogeneous $UO_2$ pellets due to the innovative concept of installing burnable absorbers inside the fuel pellet. In addition, the HANARO operation cycle is relatively short, and the irradiated material in the other flux traps, power history, and control rod operation history of each irradiation are different for each operation cycle. This paper presents evaluation results considering the irradiation history of HANARO for CSBA-loaded pellets and KAERI ATF. In particular, we investigated the difference with conventional materials for its performance analysis.

## 2. HANARO test

### *2.1 Test fuel*

The HANARO test was conducted on a total of eight test rods targeting CSBA-loaded pellets and KAERI ATF. The test rig consisted of upper and lower clusters, each of which was installed with four test rods. The test fuels (Rod #1, #2, #3, #4) of lower cluster are shown in table I. The same fuels (Rod #5, #6, #7, #8) were considered for the upper cluster. Two CSBA pellets with different densities and two KAERI ATF test rods containing erbium and gadolinium were selected. The upper and lower clusters were composed of the same material. Their performances at different burnups will be observed through post-irradiation examinations after the HANARO test.

Table I: Test pellets in the rods of lower cluster

| Test material | CSBA-loaded pellets | | KAERI ATF | |
|---|---|---|---|---|
| Test rod | Rod #1 | Rod #2 | Rod #3 | Rod #4 |
| Pellet #1 | Low density CSBA in $UO_2$ | High density CSBA in $UO_2$ | $UO_2$ + 2wt%$Er_2O_3$ | $UO_2$ + 8wt%$Gd_2O_3$ |
| Pellet #2 | Low density CSBA in $UO_2$ | High density CSBA in $UO_2$ | $UO_2$ (reference) | $UO_2$ (reference) |
| Pellet #3 | Low density CSBA in $UO_2$ | High density CSBA in $UO_2$ | Mo microcell $UO_2$ | Mo microcell $UO_2$ |
| Pellet #4 | Low density CSBA in $UO_2$ | High density CSBA in $UO_2$ | Mo microcell $UO_2$ | Mo microcell $UO_2$ |
| Pellet #5 | Low density CSBA in $UO_2$ | High density CSBA in $UO_2$ | Mo microcell $UO_2$ + 2wt%$Er_2O_3$ | Mo microcell $UO_2$ + 8wt%$Gd_2O_3$ |
| Pellet #6 | Low density CSBA in $UO_2$ | High density CSBA in $UO_2$ | Mo microcell $UO_2$ + 2wt%$Er_2O_3$ | Mo microcell $UO_2$ + 8wt%$Gd_2O_3$ |
| Cladding | Zircaloy-4 | | Cr or Cr/Al coated Zircaloy-4 | |

### *2.2 HANARO operation history*

The test was started from the $109^{th}$ cycle of HANARO. Table II shows the power history of HANARO operations conducted until February 2025. The target full power of HANARO is 30 MW, but recently, the reactor power has been operated at 27 MW for stable operation of the cold neutron source system. As shown in $110^{th}$ cycle operation history of table II, the reactor power is changing due to various causes. In addition, the reactor operation period is just about 2 weeks, which is very different from the operating characteristics of a commercial nuclear power plant that is operated continuously for about 18 months. Accordingly, it is expected that the conservative performance of the test fuel can be observed by post-irradiation examinations due to frequent decreases and increases of the linear power. Since the method for core reactivity control of HANARO only depends on the control rod, the rod worth is very large. As shown in table II, the control rod operation history is different for each operation cycle, so the control rod operation history of the corresponding operation cycle should be considered in the evaluation. Therefore, it is necessary to utilize the relevant information to make an accurate evaluation.

Table II: HANARO irradiation test history

| HANARO cycle | Operation day | Reactor power (MW) | CAR position* (mm) |
|---|---|---|---|
| 109-1 | 2024.05.14. ~ 2024.05.28. | 27 | 295 ~ 520 |
| 109-2 | 2024.06.04. ~ 2024.05.28. | 25 | 373 ~ 610 |
| 110-1 | 2024.08.20. ~ 2024.08.29. | 13 | 224 ~ 345 |
| | 2024.08.29. ~ 2024.09.06. | 21 | 345 ~ 395 |
| 110-2 | 2024.09.20. ~ 2024.09.23. | 23 | 308 ~ 450 |
| | 2024.09.23. ~ 2024.10.01. | 27 | 450 ~ 525 |
| 111-1 | 2024.10.17. ~ 2024.10.19. | 27 | 260 ~ 395 |
| 111-2 | 2024.10.23. ~ 2024.10.31. | 27 | 264 ~ 460 |
| 111-3 | 2024.11.06. ~ 2024.11.23. | 27 | 320 ~ 574 |
| 112-1 | 2025.01.07. ~ 2025.01.24. | 17 | 250 ~ 412 |
| 112-2 | 2025.02.11. ~ 2025.02.28. | 27 | 300 ~ 545 |

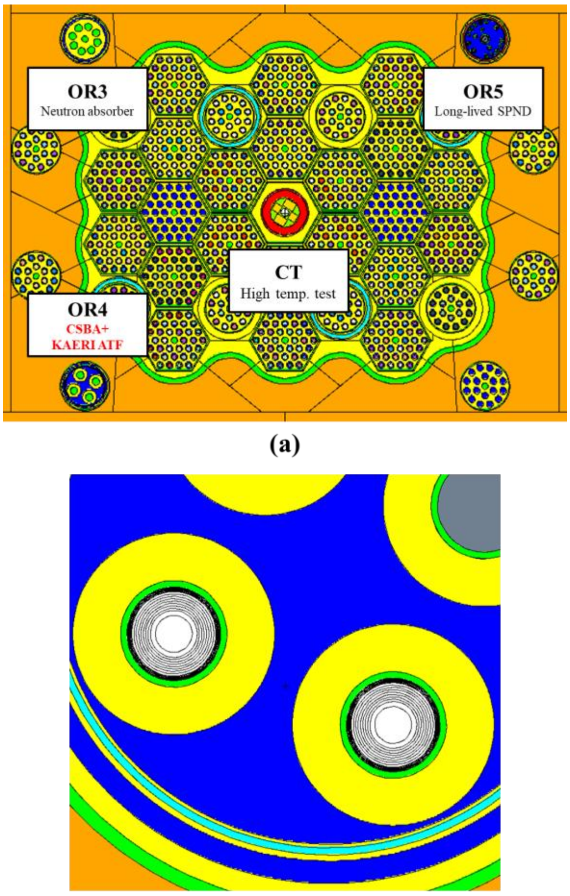
*Lower tip height position of CAR

## 3. Test evaluations

### *3.1 Methodology*

In order to accurately evaluate the test history in HANARO, linked calculations are performed using various computer codes. Since HANARO has a relatively compact core size, the depletion history of HANARO driver fuels and the irradiated materials in the other flux traps has a significant impact and must be considered. The depletion history of HANARO driver fuel is calculated for each cycle by the HANARO Fuel Management System (HANAFMS)[5]. Since the main interest is the test fuel in this study, the depletion of HANARO driver fuel is not considered and is acquired from HANAFMS.

The core analysis using MCNP6[6] under steady-state conditions of reactor core was applied. The irradiated materials realistically irradiated in the other irradiation flux traps were simulated. Fig. 1(a) shows the MCNP6 model used for the test analysis irradiated in HANARO operation cycle of 109$^{th}$. In particular, since the CSBA-loaded pellet is expected to have different radial power distribution from the conventional homogeneous $UO_2$ pellet, the test rod was divided into 20 sections radially and evaluated as shown in Fig. 1(b). The area was divided more finely at the periphery of the pellet. The microcell pellets among KAERI ATF were also divided into 20 sections and evaluated. The evaluation results of the radial power distribution will be verified through radial element analysis methods such as EPMA and WDS by the post-irradiation examinations in the future. The steady-state evaluation results by MCNP6 were linked to ORIGEN-2.2[7] to evaluate the change in nuclides inventory in each section. The test evaluation was conducted every 50 mm of control rod absorber movement. The predictor-corrector method was applied to prevent distortion due to the long test period. The linked calculation program was written in Python programming[8]. On average, 11 linked calculations were required per divided cycle. The each evaluation time for the single divided cycle was approximately 55 hours.




(a)

(b)

Fig. 1. Test evaluation model using MCNP6: (a) 109-1 cycle's core configuration and (b) divided regions of CSBA pellets for radial power distribution calculations

### *3.2 Results and discussions*

Fig. 2 shows the accumulated burnup history of the test rods obtained through the HANARO operation conducted until 2024. Since the CSBA-loaded pellets have large neutron absorbing materials installed in the center of the pellets and the neutron flux is relatively low, the linear heat generation rate (LHGR) was lower than the microcell pellets. Consequently, the accumulated burnup was also evaluated to be relatively low about 20%. The HANARO test is scheduled to be conducted for about 174 days in 2025, which is almost twice as long as the test period in 2024. Therefore, if the test is conducted without any problems, it is expected to obtain the burnup of about 15,000 MWD/MTU or more.

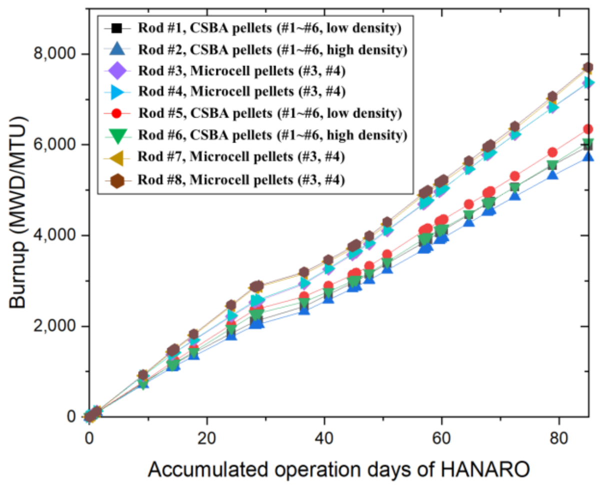



Fig. 2. Achieved average burnup history for CSBA-loaded and microcell pellets in the test rods: Rod #1 ~ Rod #4 in lower cluster and Rod #5 ~ Rod #8 in upper cluster

The burnable absorbing materials containing erbium and gadolinium were applied in this test. Therefore, the LHGR change of the test fuel according to the depletion of the corresponding nuclides is very important. Fig. 3 shows the LHGR change of the microcell pellets with gadolinium added in KAERI ATF. The pellets with added erbium have an only small amount of erbium and a smaller neutron absorption cross-section than gadolinium, so no significant effect could be observed. The LHGR of the pellets was gradually increased with the depletion of gadolinium. It was increased rapidly after the 60 days irradiation period. The LHGR change should be accurately evaluated because it affects the thermal and mechanical performance of the test rod. In the case of the CSBA-loaded pellet, the residual Gd-157 at the end of 111th cycle was evaluated to be 16.19~29.97% of the initial charge. The depletion was progressed slowly as the density of CSBA increased.

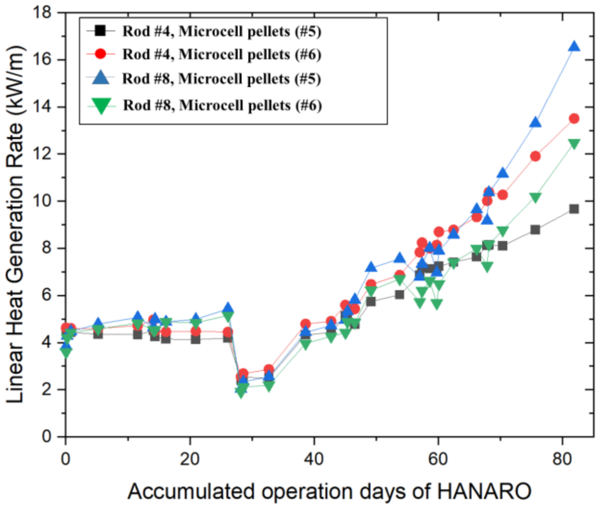



Fig. 3. Linear heat generation change of microcell $UO_2$ +8wt%$Gd_2O_3$ pellets: Rod #4 in lower cluster and Rod #8 in upper cluster

Fig. 4 shows the data evaluating the radial power distribution at the end of 111th cycle. As a result of comparing the CSBA-loaded pellet with the microcell pellet, which is expected to have similar results to the conventional homogeneous $UO_2$ pellet, the LHGR at the center of the test fuel was very low due to the influence of CSBA. The relative power at the periphery was relatively high. In addition, it was predicted that the behavior of test rods in the upper and lower clusters would be different in the long term test duration due to the influence of the control rod operation[9]. As shown in table II, the operation history of HANARO is different for each operating cycle. The test objects might be changed according to each operation cycle, so the influence of thermal and mechanical performance is different at each test duration. Therefore, a separate evaluation program will be needed to reflect these test characteristics different from conventional fuel performance evaluation method.

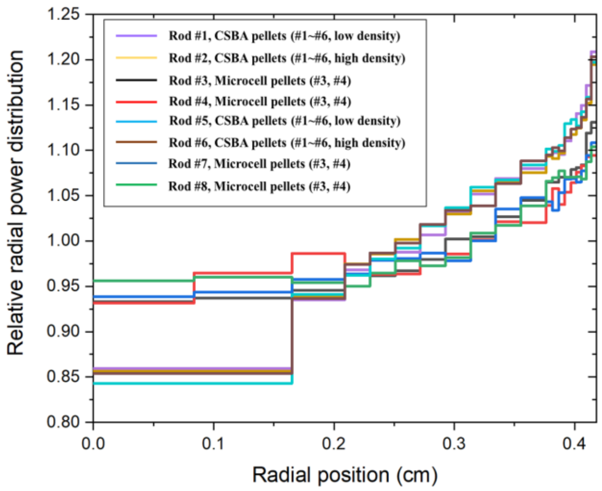



Fig. 4. Comparison of relative radial power distribution between CSBA-loaded pellets and microcell pellets at the end of 111-3 operation cycle: Rod #1 ~ Rod #4 in lower cluster and Rod #5 ~ Rod #8 in upper cluster

## 4. Conclusions

The HANARO test of the CSBA-loaded pellets and KAERI ATF was initiated. The evaluation according to the HANARO operation history was performed for them. The following conclusions were obtained from the results.

(1) Since the HANARO operation cycle is relatively short and the reactor core environment of each operation cycle is not consistent, an effective evaluation system is needed to reflect various operating variables.

(2) The average burnup of the CSBA pellets was evaluated to be lower than that of the microcell pellets depending on the installed position in the cluster and the addition of neutron absorbing materials.

(3) Considering the planned HANARO operation in the future, it is expected to achieve burnup of more than 15,000 MWD/MTU in 2025.

(4) Since the test fuel is unique and the core characteristics are different for each short operation cycle, the test fuel performance evaluation program is required to evaluate its behavior during the test.

## ACKNOWLEDGEMENTS

This work was supported by the Korean government (Ministry of Science and ICT) (2710007351).

## REFERENCES

[1] X. H. Nguyen, C. Kim, and Y. Kim, An advanced core design for a soluble-boron-free small modular reactor ATOM with centrally-shielded burnable absorber, Nuclear Engineering and Technology, vol. 51, p.369, 2019.

[2] D. Kim, K. S. Kim, D. S. Kim, J. S. Oh, J. H. Kim, J. H. Yang, and Y. Koo, Development status of microcell UO2 pellet for accident-tolerant fuel, Nuclear Engineering and Technology, vol. 20, p.253, 2018.

[3] D.J. Park, Y.I. Jung, J.H. Park, Y.H. Lee, B.K. Choi, and H. G. Kim, Microstructural characterization of accident tolerant fuel cladding with Cr-Al alloy coating layer after oxidation at 1200℃ in a steam environment, Nuclear Engineering and Technology, vol. 52, p. 2299, 2020.

[4] S. Yang, S. Park, Y. Shin, J. Park, Y. Na, D. Kim, and H. Kim, IRRADIATION OF CSBA-LOADED PELLETS AND KAERI ATF IN HANARO, Proceedings of Topfuel 2024 conference, Sep. 29 – Oct. 3, 2024, Grenoble, France.

[5] C.S. Lee, Analysis of reactor characteristics for equilibrium core of HANARO, KAERI/TR-2320/2002.

[6] D.B. Pelowitz, MCNP6TM User’s Manual Version 1.0, LA-CP-13-00634 Rev.0, 2013.

[7] A.G. Croff, A User’s Manual for the ORIGEN2 Computer Code, ORNL/TM-7175, 1980.

[8] Welcome to python.org, https://www.python.org/.

[9] S. Yang and S. Park, Characterization of Radial Power Distribution for In-Reactor Testing of Fuel Rods in HANARO, Transactions of the Korean Nuclear Society Autumn Meeting, Oct. 24-25, 2024, Changwon, Korea.