Progress in Nuclear Science and Technology
Volume 8 (2025) pp. 181-184

DOI: 10.15669/pnst.8.181

ARTICLE

Core Power Distribution Reconstruction Based on the Neutron Detectors outside a Biological Shield of the UTR-KINKI

Yuki NAKAI [1]*, Rei KIMURA [1], Atsushi SAKON [2], Satoshi WADA [1] and Tadafumi SANO [2]

[1] *Toshiba Energy Systems and Solutions Corporation, 4-1 Ukishima-cho, Kawasaki-ku, Kawasaki-shi, Kanagawa, 210-0862, Japan*
[2] *Atomic Energy Research Institute, Kindai University, 3-4-1 Kowakae, Higashi-Osaka, Osaka, 577-0818, Japan*

In the past decade, various institutions have developed small modular reactors and microreactors with the aims of reducing capital costs and improving safety through simplified reactor systems. Monitoring the core power distribution is crucial for detecting abnormal core conditions. Although in-core neutron detectors are currently used for this purpose, they face harsh environments, increasing the risk of failure. In contrast, ex-core detectors, placed outside the reactor, offer a milder environment. We have developed a monitoring method using ex-core detectors, called PHOEBE. In this study, we experimentally reconstruct the power distribution of the Kindai University Research Reactor (UTR-KINKI) using neutron detectors placed outside a thick shield. We develop a new method for adjusting the neutron detector response coefficients to reproduce a known power distribution based on measurement results. With the new method, the results show good agreement with a 4.06% average difference from the reference power distribution.

KEYWORDS: Ex-core detector core monitoring, reactor experiment, power distribution, PHOEBE, UTR-KINKI

I. Introduction

Small modular reactors (SMRs) and microreactors have been developed by various institutions over the last decade. These small-scale nuclear reactors aim to reduce capital costs and improve safety through simplified reactor systems.

In terms of assuring nuclear safety, monitoring of the core is one of the key technologies. Monitoring the core power distribution is important for detecting abnormal core conditions. Currently, in-core neutron detectors are used for this purpose. However, these are exposed to the harsh environment of the in-core, including high temperature, high pressure and high radiation, and this increases the risk of detector failure. In contrast, ex-core detectors are placed outside the reactor where the environment is milder. Therefore, if ex-core detectors are able to monitor the core conditions of the SMRs, the risk of detector failure can be decreased.

Against this background, we have proposed a core power distribution monitoring method by ex-core detectors based on power correlation between fuel regions, called PHOEBE. [1)] Furthermore, PHOEBE was demonstrated on a research nuclear reactor and a critical assembly, specifically, Kindai University Reactor (UTR-KINKI) and Kyoto University Critical Assembly.[2-4)]

In these demonstration experiments, neutron detectors were placed near the fuel assembly within 50 cm from the core. However, it is expected that neutron detectors will be placed in more peripheral regions of the nuclear reactor.

Thus, the present study experimentally examined the possibility of power distribution reconstruction based on ex-core detectors placed in more distant regions from the core. Specifically, neutron detectors were placed outside the biological shield.

II. Theory of the Reconstruction Method: PHOEBE

PHOEBE uses the detector response coefficients $c_{i,j}$ and the power correlation coefficients between fuel regions $f_{i,j}$, which constitute matrices C and F as shown in Eqs. (1) and (2).

$$C = \left(c_{ij}\right)_{m\times n(1\le i\le m, 1\le j\le n)} \quad (1)$$

$$F = \left(f_{ij}\right)_{m\times m,(1\le i\le m, 1\le j\le m)} \quad (2)$$

where n is the number of detectors and m is the number of fuel regions. **Figure 1** shows an outline. The detector response coefficient is defined as the number of neutron counts in the detector from a specific fuel region, while the power correlation coefficient is defined as the fission reaction induced by another fuel region.

The matrix C can be rewritten as Eq. (3) in terms of F and C where C' includes the factor of power correlation between fuel regions, and the sizes of matrices C and C' are the same.

$$C' = FC \quad (3)$$

Furthermore, detector response $D^{\mathrm{T}} = (d_1, d_2, \ldots, d_n)$ can be evaluated using Eq. (4),

$$\boldsymbol{D} = C'\boldsymbol{R} \quad (4)$$

where $R^{\mathrm{T}} = (r_1, r_2, \ldots, r_m)$ is the power density vector in each fuel region. In this equation, D and C' are known by measurement and pre-evaluation, respectively. Consequently, power distribution R is reconstructed by solving an inverse problem of Eq. (4). The PHOEBE improves the estimation

*Corresponding author, E-mail: yuki1.nakai@toshiba.co.jp

ability by considering the interactions between fuels by Eq. (3).

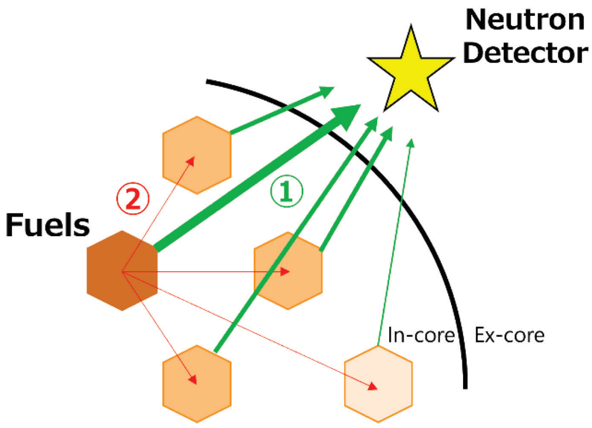

Fig. 1 Outline of detector response and power correlation coefficients. The former represents the relationships between fuel and detectors shown as ① in this picture, while the latter represents the relationships between fuel shown as ②.

III. Criticality Experiment with UTR-KINKI

1. Experimental Setup

We carried out a criticality experiment with a test reactor, UTR-KINKI,[5)] to examine the reconstruction of the power distribution in a reactor from neutron detectors outside the thick shield. The reactor is a light-water moderated, graphite reflected, heterogeneous enriched uranium thermal reactor with a thermal power of 1 W. **Figure 2** illustrates the core configuration of the reactor. This core is separated into north and south sides, with six fuel assemblies in each. Each fuel assembly is numbered from west to east, like N1, N2, … N6 for the north side.

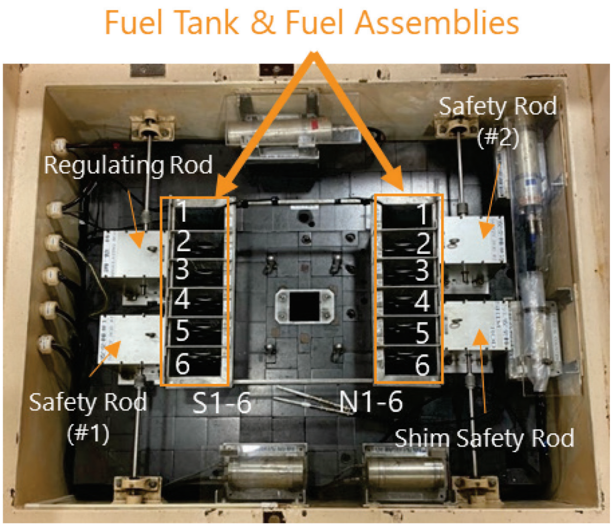

Fig. 2 Configuration of UTR-KINKI core. The right side of the picture corresponds to the north and the left to the south. Fuel assemblies are separated into north and south sides.

The reactor is equipped with a regulating rod (RR), a shim safety rod (SSR), and safety rods. During the experiment, the safety rods are completely extracted so that the RR and SSR are used to alter the power distribution of the core. In the present experiment, two cases were measured. The experiment conditions are shown in **Table 1**. Note that 0% represents full insertion and 100% represents full extraction of the rod position of each rod. Case A was measured as the nominal condition and Case B was measured as a distorted power distribution case. Their power distributions are shown in **Fig. 3**, as evaluated by MVP3 (Monte Carlo code for Vector Processors[6)]) with JENDL-4.[7)] This figure shows that the output of the south side (S) is higher than that of the north side (N) for Case B. In this experiment, we referred to the simulation result and aimed to reproduce this distorted distribution of case B.

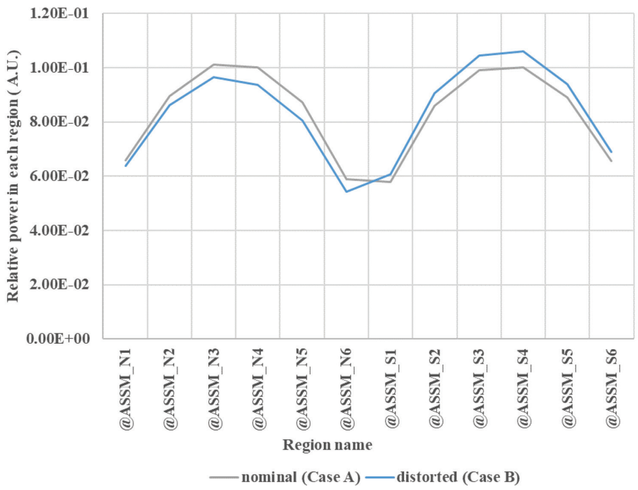

Fig. 3 Simulated results of the relative power distribution. The horizontal axis shows the fuel assembly number and the vertical axis shows the relative power. The gray line represents the nominal case (A), and the blue line represents the distorted case (B).

We measured neutron counts for the two cases at various positions outside the biological shield. The neutron detector positions are shown in **Figure 4**. Neutron counts at four positions are measured in the experiment. A single neutron rem counter was used for neutron detection to mitigate the impact of detector variability. Hence, four measurements were taken for 10 minutes each, changing the detector positions during reactor operation.

Table 1 Conditions of the experiment.

Case ID	Power [W]	SSR Position [%]	RR Position [%]
Case A (Nominal)	1.0	94.7	10
Case B (Distorted)	1.0	67.3	100

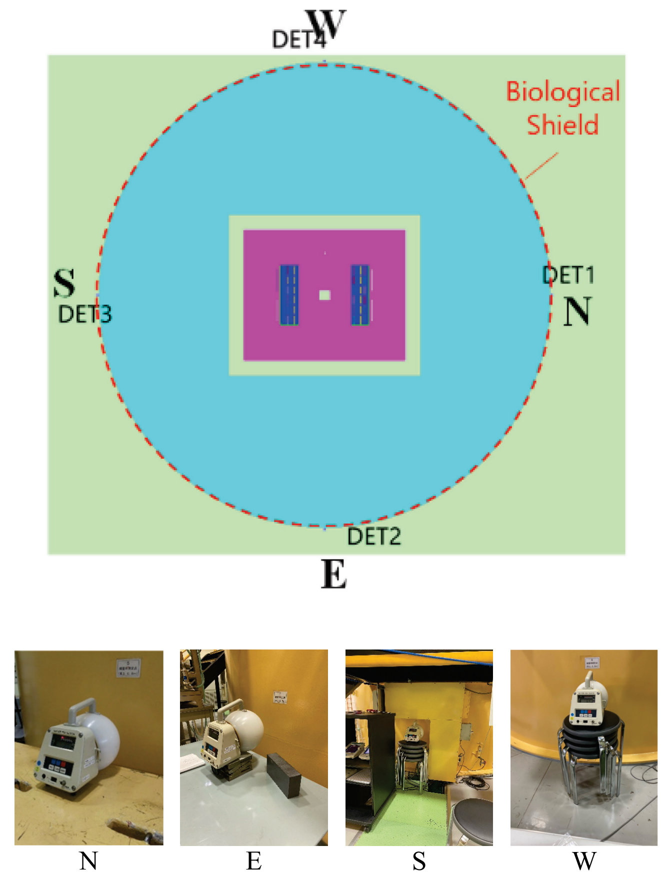

Fig. 4 Schematic view of the rector and neutron detector positions (top). The square area indicated by magenta in the center is the reactor, and the cyan area around it is biological shielding. Each picture (bottom) shows the measurement point.

2. Reconstruction Result with the Existing Method

We reconstructed the relative power distribution of the fuel assemblies from the neutron counts at the positions by using PHOEBE. The detector response coefficients calculated by MVP3 were used for the reconstruction.

The reconstructed power distribution of Case B is shown in **Figure 5**. In this figure, the blue line for MVP is the reference power distribution. The horizontal axis shows the fuel assembly number as defined in Fig. 2 and the vertical axis shows their relative power. In Case B, in which the output distribution is distorted, the output of the south side (S) is higher than that of the north side (N). However, the estimated result shown by the orange line did not reproduce the reference power distribution, and the north-south difference is overestimated. This seems to be because the outside environment of the biological shield is so complex that the actual coefficients deviate from those of the simulation. Since this kind of situation is expected to occur in real cases, correction methods for the coefficients are needed.

3. A New Reconstruction Method Adjusting the Coefficients

Precise evaluation of the detector response coefficients was difficult for the detector positions in the experiment. We

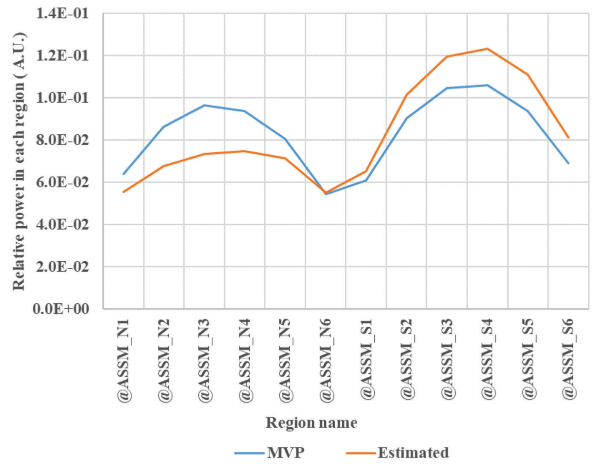

Fig 5. Relative power distribution of fuel assemblies. The orange line shows the estimate by the existing reconstruction method and the blue line shows the reference calculated by MVP simulation.

therefore developed a new method as shown in **Fig. 6**. Although it prepares the coefficient table in advance by simulation, the same as before, we also added a new part to modify the coefficient table to reproduce the actual data of the detectors in the nominal distribution before reconstruction.

The adjustment was performed by solving the inverse problem of Eq. (4). Since the power density vector (R) is obtained by simulation, we can adjust C' by reproducing the measured detector counts D. Since the coefficients can correct the difference between simulation and actual environment, this is expected to improve the reconstruction ability.

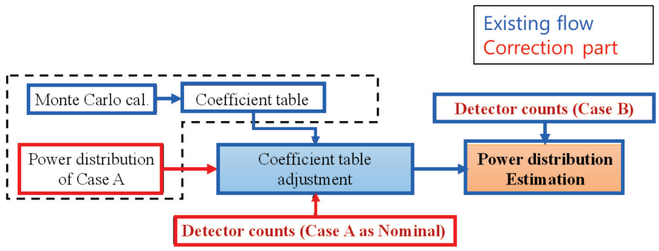

Fig. 6 Overview of the reconstruction method. The blue box shows the existing flow, and the red box shows the new part for adjusting the detector response coefficients. The adjustment part corrects the coefficient to reproduce the measured detector count.

4. Results and Discussion

The power distribution reconstruction results of Case B before and after adjustment of the detector response coefficient table are shown in **Fig. 7**. In this figure, the blue line for MVP shows the reference power distribution, and the orange line shows the estimated power distribution by the new method. Thanks to the new correction method of the coefficients, the estimated results show good agreement with the reference power distribution, with an average difference of 4.06%.

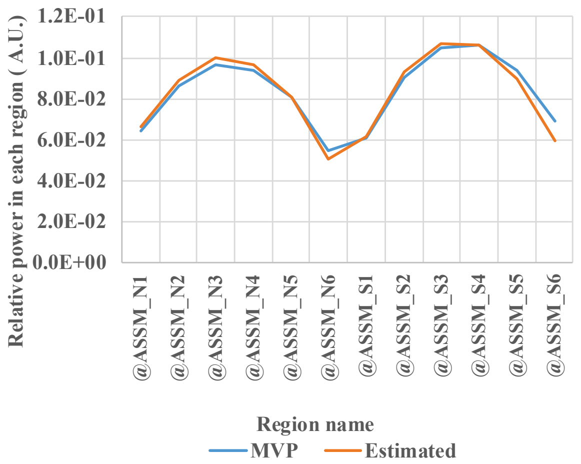

Fig. 7 Relative power distribution as reconstructed by new method. The orange line shows the estimated result and the blue line shows the reference. The estimated result reproduces the reference distribution well.

This improvement indicates that the deviation of the coefficients can be modified using measured data. The new method is applicable to complex environments which makes it difficult to evaluate the coefficients precisely on simulations.

IV. Conclusion

The power distribution of UTR-KINKI was experimentally estimated with an average difference of 4.06% from the reference power distribution. This result was evaluated based on the ex-core detector outside the biological shield. Initially, the power distribution could not be reconstructed without adjusting the detector response coefficient table. By contrast, the estimated power distribution was improved by the table adjustment.

The results suggest that the present method of detector response coefficient table adjustment is effective. In future work, this method will be expanded to other geometries.

Acknowledgment

We are grateful to Dr. Kenichi Yoshioka and Dr. Haruo Miyadera for providing advice on this research. We also thank Dr. Kunihiro Nakajima, Mr. Takashi Kanda, and Mr. Masaki Goto for assisting the experiment on UTR-KINKI.

References

1) R. Kimura, Y . Nakai, Wada S, "Reactor Core Power Distribution Reconstruction Method by Ex-Core Detectors Based on the Correlation Effect Between Fuel Regions," Nuclear Science and Engineering, **195**[12], 1279-1290 (2021).
2) R. Kimura, Y. Nakai, S. Wada, A. Sakon, T. Sano, "Demonstration of power distribution estimation using ex-core detectors by reactor experiment at UTR-KINKI," *Journal of Nuclear Science and Technology*, **59**[12], 1487-1498 (2022).
3) R. Kimura, Y. Nakai, S. Wada, A. Sakon, T. Sano, "Time-Dependent Experiment on Reactor Power Distribution Estimation by Ex-Core Detectors at UTR-KINKI," *Nuclear Technology*, **209**[11], 1589-1866 (2023).
4) R. Kimura, T. Sano, Y. Nakai, A. Sakon, S. Wada, K. Nakajima, T. Kanda, M. Goto, Y. Takahashi, C. H. Pyeon, "Power Distribution Estimation Method for SMR Using Ex-Core Detectors: Experimental Demonstration by Plural Control Rod Patterns at KUCA," International Conference on Physics of Reactors 2022 (PHYSOR 2022), May, Pittsburgh, PA (2022).
5) Kindai University Atomic Energy Research Institute, https://www.kindai.ac.jp/rd/research-center/aeri/facility
6) Y. Nagaya, K. Okumura, T. Sakurai, T. Mori, "MVP/GMVP Version 3 : General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculations Based on Continuous Energy and Multigroup Methods," JAEA-Data/Code 2016-018 (2017).
7) K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohsawa, T. Murata, H. Matsunobu, A. Zukeran, S. Kamada, and J. Katakura: "JENDL-4.0: A New Library for Nuclear Science and Engineering," Journal of Nuclear Science and Technology, **48**[1], 1-30 (2011).