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Feasibility Analysis of Micro Reactor Core Monitoring based on Ex-core Nuclear Measurement System

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1. Introduction

The micro reactor is becoming a promising candidate in developing the next generation nuclear energy system for its low cost and high flexibility. The on-line core monitoring is an important basis to support the start-up, operation and safety protection of these reactors. Among the monitoring systems in a reactor core, the nuclear monitoring system of the micro reactor encounters the most differences from the common ones in current commercial nuclear power plants.

Neutron detectors used for core monitoring are generally categorized into in-core neutron detectors and ex-core neutron detectors. Currently, the on-line core monitoring systems are mainly developed for commercial light water reactors (LWRs) with fixed in-core detectors [1-4]. Due to the compact space in the core, it is difficult to set up in-core neutron detectors in micro reactors. The core monitoring based on the ex-core detector is simultaneously becoming an important technology for the microcore development.

However, ex-core detectors typically are not used to extract detailed core information. The detector's signal mainly comes from the core leakage, for which the magnitude of flux is low and the responses are not sensitive to the inner part of core according to the existing experiences from LWRs.

For large nuclear reactors such as pressurized water reactors or boiling water reactors, most of the contribution to the response of ex-core detector comes from the reactor peripheral fuel assemblies [5,6]. Their combined contribution exceeds 90%, which is concentrated in the reactor peripheral assemblies near the detector. In addition, neutrons produced by fission in the center assemblies of the reactor are difficult to reach the detector's sensitivity region due to the effect of self-shielding in the active region. As a result, peripheral assemblies of the reactor, which are far away from the detector, contribute more to the response function than center assemblies. Therefore, the ex-core monitoring system of pressurized water reactors is difficult to accurately obtain the in-core status information. It is generally only used for core axial power distribution monitoring.

Fortunately, researches on the flux mapping of small reactors showed that, the detector response from the center assemblies was much higher compared to that of large nuclear reactors. Li carried out preliminary numerical validation calculations on the low-temperature heating reactor and the high-temperature gas-cooled reactor [7,8]. The results validated that the main state parameters such as reactor control rod position and power distribution can be captured by the ex-core detector.

Compared to the small reactors, the micro reactors have smaller core sizes and stronger neutron leakage. Theoretically, the core monitoring based on the ex-core detectors are feasible. Therefore, this paper analyzes the feasibility of using the ex-core detector to monitor the operating state parameters of the micro reactor core, which aims to provide the references of developing an on-line nuclear monitoring system for a heat-pipe cooled micro reactor.

In Section II, the calculation of spatial response function is described. Section III introduces the reactor model used for the analysis. The sensitivity analysis of spatial response function to different core parameters are shown in Sec. IV, and the feasibility analysis of on-line core monitoring based on the ex-core detectors is carried out. Finally, it is summarized in Section V.

2. Detector Response Function

The detector spatial response function is mainly related to the core power distribution and the regions penetrated by the fission neutrons that reach the detector, such as the core and reflector [9,10]. Fission neutrons from the core pass through the core, reflector and other areas, undergo absorption, scattering and other reactions, eventually reach the ex-core detector and react with its sensitive zone to produce the electrical signal.

Denoting the detector sensitive region's volume is V_d, the center position is r_0, and the response cross section is Σ_d, then the neutron injection rate at the detector can be calculated by the neutron transport equation (1):

$$L\Phi\left(\boldsymbol{r},E,\boldsymbol{\Omega}\right)=S\left(\boldsymbol{r},E,\boldsymbol{\Omega}\right) \tag{1}$$

where L is the neutron transport operator, $\Phi(\boldsymbol{r},E,\boldsymbol{\Omega})$ is the neutron angular flux which is related to the spatial position, angle and energy and $S(\boldsymbol{r},E,\boldsymbol{\Omega})$ is the fission neutron source. The detector response can be calculated as:

$$R_d\left(r_0\right)=\int_{V_d}\int_{\boldsymbol{\Omega}}\int_0^{\infty}\Phi\left(\boldsymbol{r}_0,E,\boldsymbol{\Omega}\right)\Sigma_d\left(\boldsymbol{r}_0,E\right)\mathrm{d}E\,\mathrm{d}\boldsymbol{\Omega}\mathrm{d}V \tag{2}$$

If there are fission neutron sources of unit strength at different positions in fuel regions, the contribution of fission neutrons generated at different positions is various by reason of the different distances from fuel region to detector. If the spatial response function of a detector characterizes the relative contribution of unit fission neutron sources at distinct positions in the core fuel region to the detector's readings, the response of the ex-core detector to the core power can be expressed as the integral of fission neutrons' contributions from different fuel regions to the detector:

$$R_d\left(r_0\right)=\int_V P\left(r\right)\omega\left(r\rightarrow r_0\right)\mathrm{d}V \tag{3}$$

where $P(r)$ is the three-dimensional core power distribution, V is the volume of the core active region, and $\omega(r\rightarrow r_0)$ is the detector spatial response function.

There are two commonly employed algorithms for calculating the spatial response function of a detector: the forward transport method and the adjoint transport method. In the forward transport method, it is necessary to perform N calculations in order to ascertain the detector response function corresponding to N different positions in the reactor core. In contrast, the adjoint transport method requires only a single calculation, significantly enhancing computational efficiency [11].

The adjoint form of Eq. (1) is $L^+\Phi^+=S^+$, then the detector response can be rewritten as Eq. (4):

$$R_d\left(r_0\right)=\int_{V_d}\int_{\Omega}\int_0^{\infty}\Phi^+\left(\boldsymbol{r},E,\boldsymbol{\Omega}\right)S\left(\boldsymbol{r},E,\boldsymbol{\Omega}\right)\mathrm{d}E\,\mathrm{d}\boldsymbol{\Omega}\,\mathrm{d}V \tag{4}$$

If the fission neutron source S in the core is isotropically distributed:

$$S\left(\boldsymbol{r},E,\boldsymbol{\Omega}\right)=\frac{1}{4\pi}\chi\left(E\right)S\left(r\right) \tag{5}$$

where $\chi(E)$ is the fission neutron spectrum in the active region of the reactor core.

Dividing the core into N grids, where the volume of the i-th grid is denoted as ΔV_i, and considering a group structure with G energy groups, the normalized detector response function for the i-th grid can be expressed as:

$$\omega_i=\frac{\Delta V_i\sum_{g=1}^{G}\chi_{i,g}\Phi^+\left(\boldsymbol{r}_i,E_g\right)}{\sum_{i=1}^{N}\Delta V_i\sum_{g=1}^{G}\chi_{i,g}\Phi^+\left(\boldsymbol{r}_i,E_g\right)} \tag{6}$$

In this paper, the feasibility analysis of core power distribution reconstruction only analyzes the radial detector response function distribution of fuel assemblies in the x-y plane, so it is necessary to convert the grid response function in the x-y-z space into the assembly response function in the x-y plane.

$$\omega_{xy_i}=\frac{\sum_{(x,y,z)\in xy_i}\omega\left(x,y,z\right)P\left(x,y,z\right)}{\sum_{(x,y,z)\in xy_i}P\left(x,y,z\right)} \tag{7}$$

3. Calculation Model

3.1 Core Design Scheme

The analysis in this paper focuses on a heat pipe microreactor. It is a fast reactor cooled by heat pipes with MW-level power output. The modeling and calculations of the core were carried out by using the SARAX code system [12,13]. The core model was established as depicted in Figs. 1 and 2. To get accurate detector responses, the unstructured geometric modeling was performed outside the active core including the control drums and detectors. In all the calculation in this paper, the control drum was fully rotated out.

3.2 Detector Location

The location of detector outside the core is relatively flexible. However, considering the axial positioning of drive mechanisms and other components, this paper opts for the placement of detectors outside the radial reflector. Furthermore, due to the short length of the active region, only one detector is positioned at the axial midpoint.

The neutron detector employed in this study is a boron-coated proportional counter. The operational principle of a boron-coated proportional counter relies on the nuclear reaction method, where neutrons interact with the coating material containing ^{10}B on the inner surface of the counter [14]. This interaction induces nuclear reactions, generating charged particles, namely alpha particles (α) and lithium ions (Li). The ionization of the gas medium by these particles causes the ions to move towards the two poles of the detector under the influence of an electric field, resulting in the production of an electric signal from the ionization process. In the SARAX simulations, to avoid the influence of detector location on the results, the detector is uniformly positioned at 5 cm from the radial reflector.

To improve computing efficiency, this study utilizes the adjoint transport method to calculate the response function of the detectors.

4. Results and Feasibility Analysis

This paper calculated and compared the changes in detector response functions under the influence of different core parameters. Four core parameters were considered: core size, neutron spectrum, reflector material, and reflector thickness.

First, the detector response function of the original heat-pipe cooled micro reactor was calculated. The distribution of the detector response function is shown in Figure 3.

As the results, the peripheral proximal assemblies near the detector side make significant contributions to the detector response, which are similar to other reactors currently operated. However, the collective contribution of these assemblies' accounts for only about 20% of the total contribution, thus it has minimal impact on the overall monitoring of the internal state of the core. In contrast to large nuclear reactors, it is noteworthy that the minimum value of the detector response function occurs on the peripheral assemblies

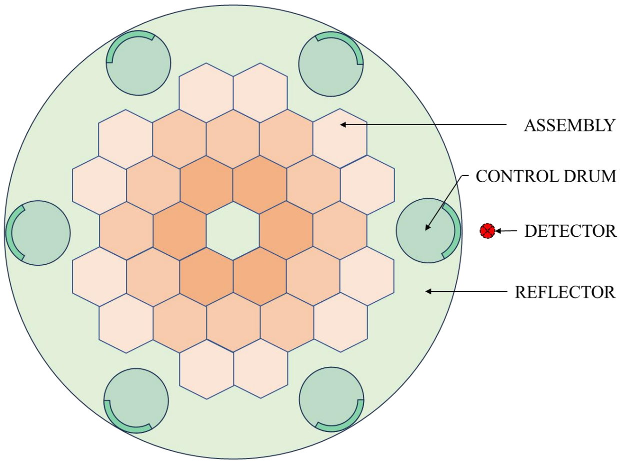


Fig. 1. Horizontal Cross Section View of the Microreactor Core.

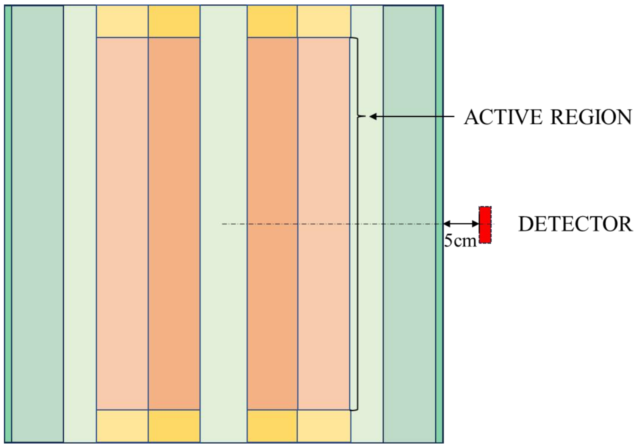


Fig. 2. Vertical Cross Section View of the Microreactor Core.

of the reactor far away from the detector, rather than the central assemblies in the core. This result suggests that the self-shielding effect in the active region of the heat pipe microreactor is relatively weak, allowing neutrons generated by the internal assemblies to effectively interact with the detector and induce measurable current signals.

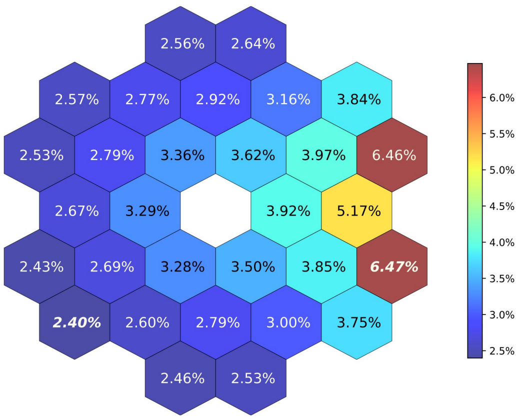


Fig. 3. Detector response function distribution of the original heat pipe micro reactor core.

For the feasibility analysis of core monitoring, the key is that all assemblies inside the reactor can be accurately monitored. As shown in Fig. 3, even for the inner core assembly, its response contribution is greater than 3%. From this analysis, it can be inferred that using ex-core nuclear measurement system to conduct core monitoring of the analyzed heat pipe microreactor is theoretically feasible.

To meet the diverse needs of different design purpose, the micro nuclear reactors have a variety of core configurations. The design parameters and subsequent core characteristics will make changes to the responses to the ex-core detectors. Therefore, the impact of different core sizes, neutron spectra, reflector materials, and serve as references for the feasibility analysis of ex-core monitoring.

4.1 Core Size

When examining the influence of core size on the feasibility of ex-core monitoring, the original model of the heat-pipe cooled microreactor was simplified: replacing the central rod with a fuel assembly, arranging the fuel assemblies in a regular hexagonal lattice configuration and removing the control drums.

The simplified core arrangement is shown in Figure 4. By simplifying the model while ensuring the radial reflector thickness of 30 cm, the influence of core size on the feasibility of core monitoring in micro nuclear reactors using the ex-core nuclear measurement system is analyzed by varying the number of rings of core assemblies.

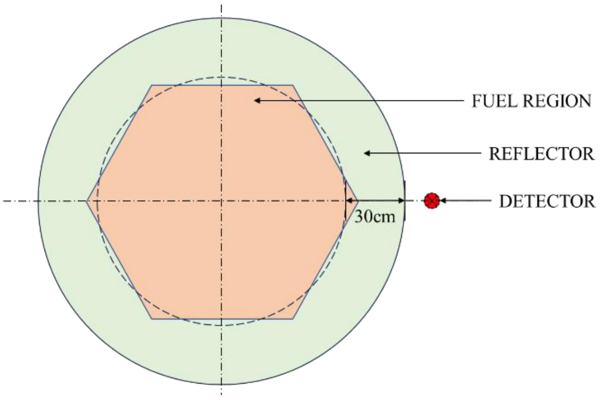


Fig. 4. Simplified Core Schematic.

By analyzing the calculation results of detector response functions for different sizes of cores, which are shown in Fig. 5, it can be concluded that: (1) The maximum contribution to the detector response from the fuel assemblies still occurs at the peripheral assemblies near the ex-core detector, while the minimum response value is observed at other peripheral assemblies; (2) Even for the core with 127 assemblies, the minimum normalized response value remains at the order of 10^{-3}; (3) Even the central fuel assemblies, which are the most difficult to monitor, still have response contribution greater than 7‰. Therefore, it can be concluded that utilizing ex-core detectors for core monitoring is feasible in the context of micro nuclear reactor sizes.

The detailed results of the detector response functions for different core sizes can be found in Appendix.

4.2 Neutron Spectrum

By using different materials in the matrix, the neutron spectrum of core can be significantly changed for a heat-pipe cooled micro reactor. To analyze the impact of different neutron spectra on the feasibility of ex-core monitoring, the matrix material was replaced with ZrH_2 which exhibits excellent moderation. This transformation effectively converts the original micro fast reactor into a thermal reactor.

Figure 6 is the distribution of neutron spectra for these two corresponding cores.

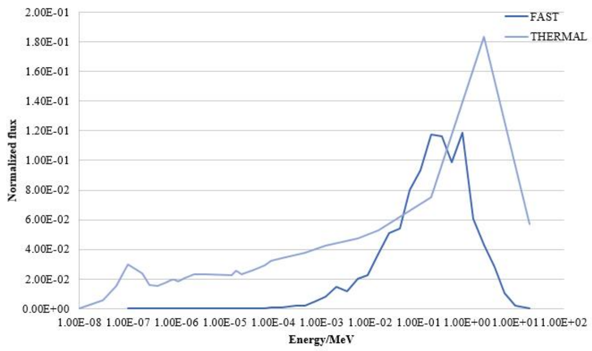
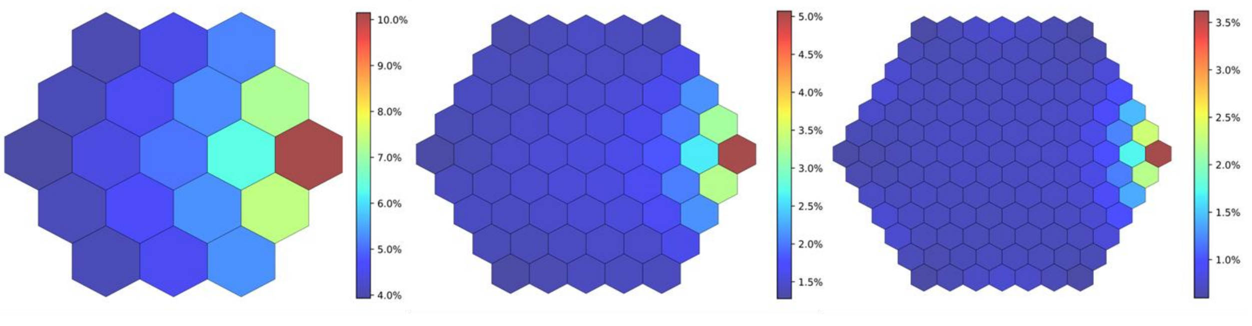


Fig. 6. Schematic Diagram of Neutron Spectra for the Fast Reactor and the Thermal Reactor.

The calculation results are shown in Fig. 7. For the reason of the strong neutron moderation of ZrH_2, it becomes more challenging for the fission neutrons produced by the inner assemblies of the thermal spectrum core to reach the sensitive region of the ex-core detector. But the neutrons generated by peripheral assemblies can reach the ex-core detector through reflector. As a result, the minimum response value transitions from the far peripheral assemblies to the assemblies located in the innermost ring. Although the proximal assemblies of the detector have a proximity advantage, their response functions do not exhibit a significant elevation compared to other assemblies. The response function distribution of the entire thermal spectrum core is relatively uniform, with the response contributions of all assemblies ranging between 3% and 4%.

In comparison to the fast spectrum core, the response



(a) 3 rings (b) 5 rings (c) 7 rings

Fig. 5. Distribution of Ex-Core Detector Response Function for Different Sizes of Cores.

of the inner ring assemblies in the thermal spectrum core only experiences a slight decrease. Therefore, it is evident that using ex-core nuclear measurement system to achieve core monitoring of the thermal heat-pipe cooled micro reactor remains theoretically feasible. Moreover, taking into account the uniformly distributed characteristics of the response functions of the core assemblies in the thermal spectrum microreactor, it is possible to consider reducing the number of measurement points for ex-core detectors when performing core monitoring.

4.3 Reflector Material

The materials of reflector are commonly selected based on their weak absorption ability and moderate ability for neutron. In micro nuclear reactors, solid-state materials such as stainless steel, beryllium metal, beryllium oxide ceramics, graphite, or aluminum oxide are commonly chosen as neutron reflector materials.

This paper compared the effects of using aluminum oxide and metal beryllium as neutron reflector materials to analyze the impact of reflector materials on core detection. From the response function distribution shown in Fig. 8, it can be observed that due to the prime moderation capability of beryllium, reactors using beryllium as the neutron reflector represent the response function distribution with the highest response at the outermost periphery assemblies and decreasing towards the center. Similar to the thermal spectrum reactor, the distribution of detector response function is not significantly influenced by the distance from the ex-core detector. The minimum response value of reactor assemblies is found on the internal assemblies, which are the most challenging to monitor. Compared to the original reactor scheme, the decrease in response exceeds 50%. This highlights the significant impact of the reflector material on the feasibility of ex-core monitoring in micro reactors. Additionally, for the more pronounced moderation effect of the radial reflector on external assemblies, there has been a visible change in the power distribution. Compared to the original core as well as the thermal spectrum core, the power distribution of core with Be reflector shifts from a decreasing pattern from the inside out to the outside in (cf. Figure 9). Consequently, compared to the thermal spectrum reactor, the variation in the distribution of response functions is even more obvious.

Although the response values exhibit relatively large variations, they remain within the same order of

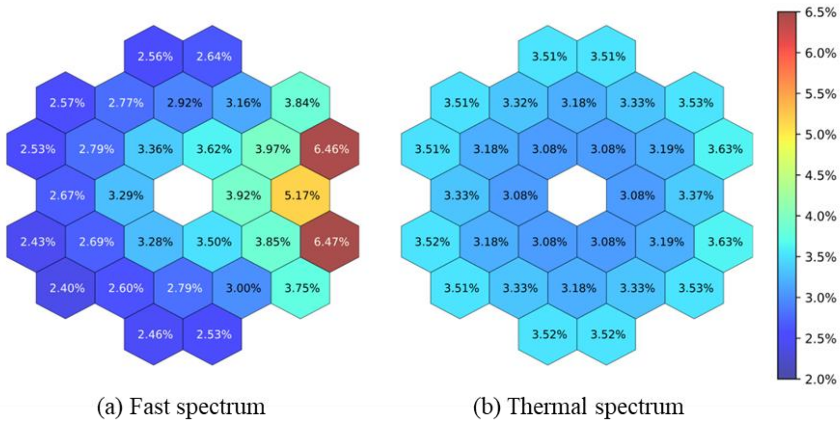


Fig. 7. Distribution of Ex-Core Detector Response Function for Different Spectra of Cores.

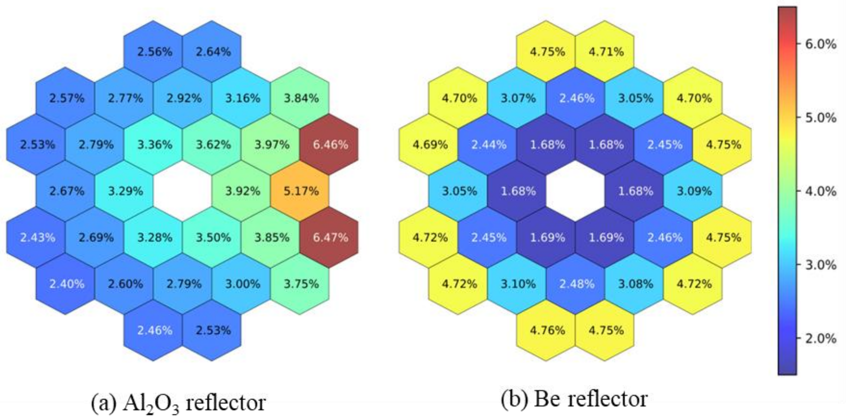
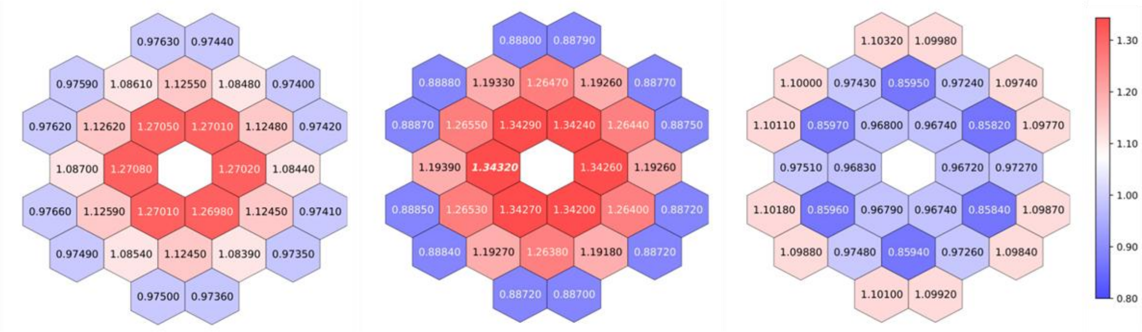


Fig. 8. Distribution of Ex-Core Detector Response Function for Different Reflector Materials.



(a) Original core (b) Core with thermal spectrum (c) Core with Be reflector

Fig. 9. Intensity Map of Core Power Distribution.

magnitude with the original one, unlike the drastic drop across multiple orders of magnitude as observed in PWR. Therefore, core monitoring of micro reactors remains feasible in this context.

4.4 Reflector Thickness

The neutron reflector in the micro nuclear reactor not only offers a wide range of material choices but also varies in thickness to match the corresponding design requirements of shielding systems, control systems, and other components of the reactor. In this study, based on the original heat pipe microreactor core design, the radial reflector was varied with thicknesses of 5cm, 10cm, 15cm, 20cm, and 25cm (Fig. 10). It aims to analyze the influence of reflector thickness on core monitoring.

Upon analyzing the results shown in Fig. 11, the following conclusions can be drawn: (1) The response

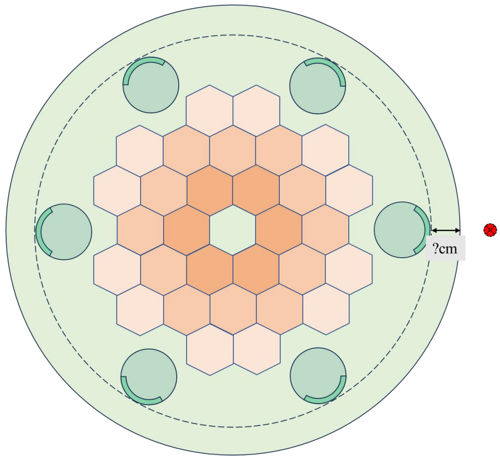


Fig. 10. Illustration of Core with Radial Reflector Thickness changing.

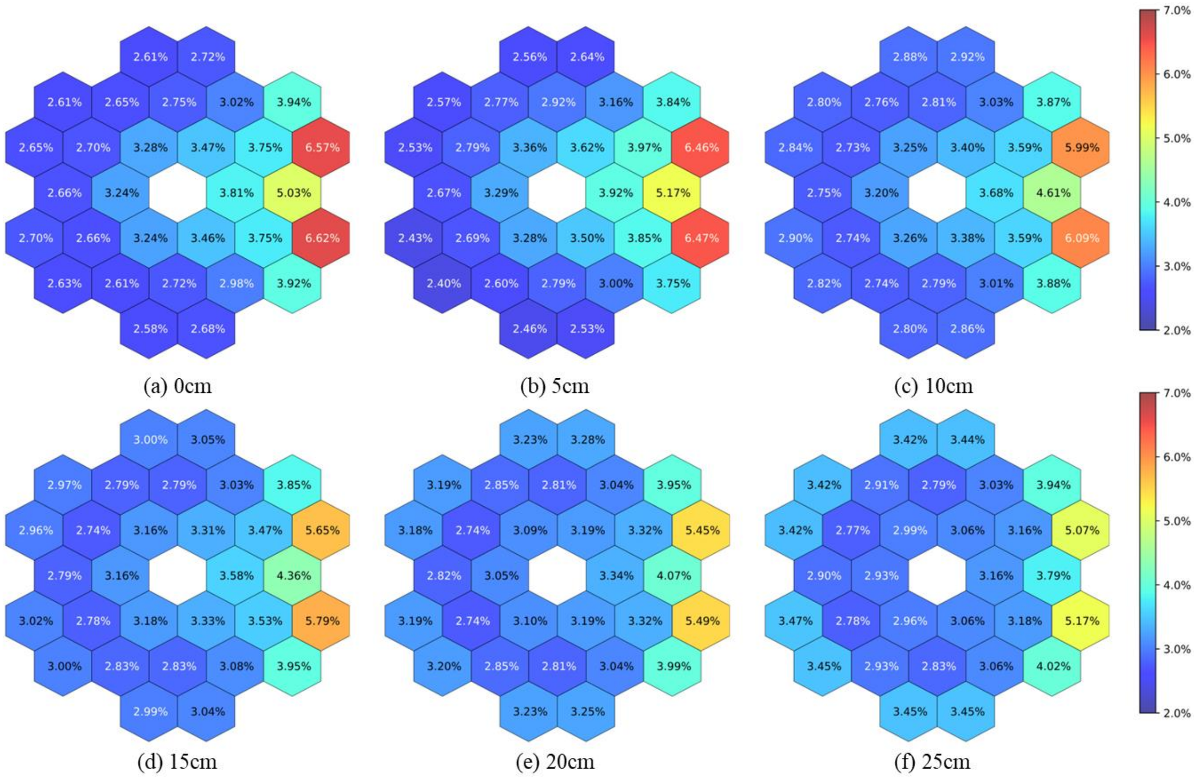


Fig. 11. Distribution of Ex-Core Detector Response Function for Different Reflector Thicknesses.

functions of the assemblies consistently show the distribution where the response is higher for assemblies closer to the detector and lower for those farther away. The distance between the assemblies and the detectors plays a major role in influencing the response; (2) As the thickness of the reflector increases, the proportion of the maximum response contribution to the total contribution decreases, resulting in a more uniform distribution of core response; (3) As the thickness of the reflector increases, the minimum response value gradually moves towards the inner core, making core monitoring become more challenging.

5. Conclusions

This paper performs the analysis of detector response distributions of a heat-pipe cooled micro reactor based on the adjoint transport theory. By varying core parameters (core size, neutron spectrum, reflector material, and reflector thickness), the corresponding response functions of ex-core detectors were calculated. The obtained results were discussed to evaluate the feasibility core monitoring based on the ex-core nuclear measurement system in the heat-pipe cooled micro reactor. The results can be concluded as:

(1) As the size of the core or the thickness of the reflector increases, the minimum detector response gradually moves towards the interior of the core, posing greater difficulty in core monitoring.

(2) In the case of a transition from the fast spectrum to the thermal one in the core, or when using reflector materials with better moderation capabilities, the influence of the distance between the assemblies and the detector on the response function distribution is weakened. Both show a decreasing trend from the exterior of the core to the interior.

(3) Although different core parameters have varying influence on detector response, unlike in PWR, the assembly response in the microreactor does not exhibit significant orders of magnitude changes.

(4) The smallest contribution to the response reached over 7‰, indicating that using ex-core detectors can accurately capture the internal state of the micro reactor.

In conclude, the micro reactor can be feasibly monitored only using the ex-core nuclear measurement system. Based on this work, future studies will focus on the development of methods for core monitoring in microreactors.

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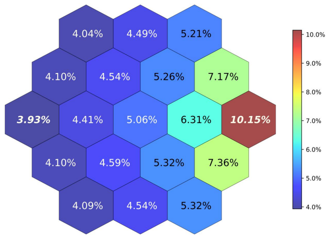
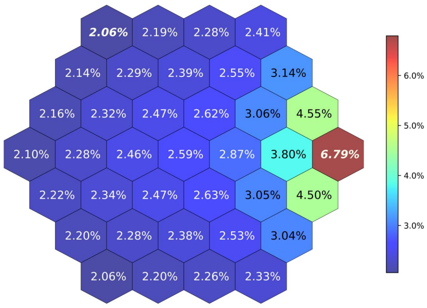
APPENDIX

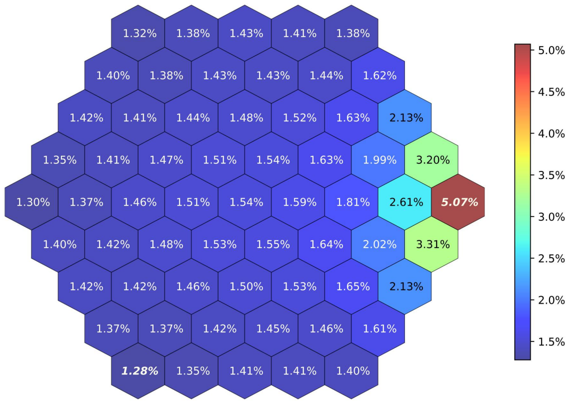
Detailed distribution of detector response functions for different sizes of cores.



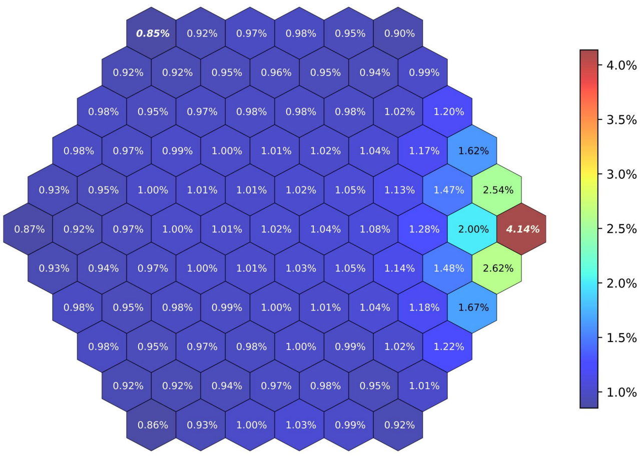
(a) core with 3 round assemblies



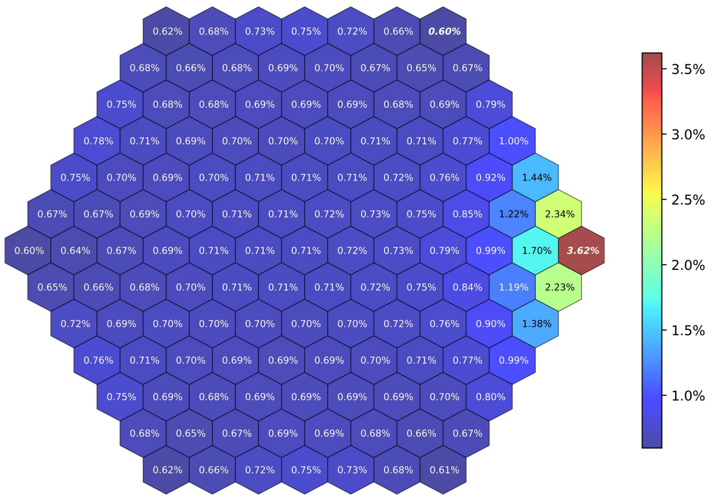
(b) core with 4 round assemblies



(c) core with 5 round assemblies



(d) core with 6 round assemblies



(e) core with 7 roundring assemblies

Fig. A1. Distribution of Ex-Core Detector Response Function for Different Sizes of Cores.