Study on Nuclear Instrumentation System Layout for Gas-Cooled Microreactors and Its Application in Core Monitoring

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Abstract

Gas-cooled micro-reactors are constrained by compact arrangement and high-temperature operating environments within the core, allowing only a limited number of ex-core detectors to be deployed for core monitoring. This paper proposes a deployment scheme for a micro-reactor nuclear measurement system coupling a neutron source with ex-core detectors, and verifies its feasibility through physical experiment simulation. Research results indicate that passive startup of micro-reactors requires sensitivity of temporary in-core detectors and ex-core source-range detectors to be no less than 290 and 980 cm^2, respectively, while an active nuclear measurement system coupling a low-intensity startup neutron source, low-sensitivity ex-core boron-coated neutron tubes, and γ-compensated ionization chambers is more suitable for long-life, unmanned intelligent operation of mobile micro-reactors; the neutron source must be positioned within the active zone to ensure the fraction of fission neutrons exceeds 95%; detectors measure high-energy neutrons through cadmium and polyethylene sleeves to improve core monitoring accuracy. The extrapolated critical loading in the first criticality experiment agrees with theoretical values, with single-rod extrapolated critical rod position deviating by only -2 cm, and keff deviation within 6$×$10^-4; the absolute deviations in power level and axial power offset (AO) in detector calibration experiments are within 0.2% and 0.4%, respectively. The research results provide a reference for core monitoring of gas-cooled micro-reactors.

Full Text

Preamble

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Research on Nuclear Detecting System Layout for Gas-cooled Micro Reactor and Its Application in Core Monitoring

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Abstract

[Background] The gas-cooled micro reactor represents an advanced reactor type that can serve as a mobile intelligent micro nuclear power source. However, nuclear detecting has posed a major challenge for its development due to the compact layout and harsh service environment inside the core, which limits deployment to only a small number of ex-core detectors for core monitoring. [Purpose] This study proposes a method and scheme for the layout of micro reactor nuclear detecting systems to address this challenge. [Methods] The approach explores the coupling of neutron sources with ex-core detectors based on detailed three-dimensional models of the core and external structures, using the Monte Carlo procedure RMC. Its feasibility was verified through calculating simulations of first critical experiments and ex-core detector calibration experiments. [Results] The results demonstrate that startup without external neutron sources is feasible if ^{3}He detectors with sensitivities no less than 290 and 980 cm^2 are used as in-core temporary detectors and ex-core source range detectors, respectively. For scenarios requiring long-time operation with minimal personnel, a detecting system incorporating an Am-Be neutron source with the lowest possible strength, ex-core boron-coated neutron counting tubes with low sensitivity, and ex-core gamma compensation ionization chambers with wide range is more suitable. The Am-Be neutron source must be arranged within the active core to ensure the proportion of fission neutrons exceeds 95%. By installing cadmium and polyethylene sleeve structures outside detectors to monitor high-energy neutrons, more accurate nuclear measurement signals can be obtained. In simulations of the first critical experiment, the extrapolated critical fuel assembly columns matched theoretical values, the deviation of extrapolated critical position for a single control rod was only -2 cm, and the keff deviation was within 6\$×10^{-4}\$. In simulations of ex-core detector calibration experiments, the absolute deviations of power level and axial power offset AO were within 0.2% and 0.4%, respectively. Conclusions The layout of the nuclear detecting system has been verified as reasonable and feasible. These results provide guidance for core monitoring of various advanced micro reactors and promote the development of mobile intelligent micro nuclear power source products.

Key words Gas-cooled micro reactor, Startup without external neutron sources, Layout of core detecting system with external neutron source, First critical experiment, Ex-core detector calibration experiment

Micro-reactor intelligent energy systems represent a new trend in future nuclear energy applications, with gas-cooled micro reactors being one of the mainstream types. Employing prismatic high-temperature gas-cooled thermal neutron reactor technology, gas-cooled micro reactors possess superior inherent safety characteristics. These reactors feature compact design, minimal systems, and flexible deployment, providing reliable electrical and thermal energy supply for remote areas, deep sea, space, and other applications. However, complex deployment scenarios impose higher requirements for intelligent control, unmanned or minimally-manned operation, and remote monitoring. Constrained by core volume and harsh in-core service environments such as high temperature, it is difficult to arrange detectors within the core and reflector. Therefore, relying solely on a small number of ex-core detectors to achieve core nuclear monitoring represents a significant challenge in their development.

Nuclear instrumentation system layouts for commercial reactor types are already well-established, but research for new micro reactors is still in its early stages. In-core detectors are primarily used for core flux mapping and calibrating ex-core detectors. Generation II and "II+" pressurized water reactors deploy movable fission chambers within the active core, while Generation III pressurized water reactors and compact small reactors generally use fixed self-powered detectors. New micro reactors typically avoid placing detectors in the active core and instead position them in the reflector whenever possible. For example, Japan' s HTTR (High-Temperature Engineering Test Reactor), a prismatic high-temperature gas-cooled reactor, arranges current-mode fission chambers in the permanent reflector and places pulse-mode fission chambers, BF_3 counting tubes, and gamma compensation ionization chambers in replaceable reflector assemblies. Huang et al. positioned ^{3}He startup detectors for thorium-based molten salt reactors in graphite reflectors with multi-layer piping and argon cooling to reduce operating temperature. Zhang et al. positioned BF_3 startup detectors with polyethylene sleeves above the core of a new heat pipe fast reactor to meet extrapolation critical experiment requirements. Ex-core detectors are mainly used for continuous real-time monitoring of total core power and providing nuclear measurement signals to control and protection systems. Through the overlapping ranges of source range, intermediate range, and power range detectors, monitoring requirements from fuel loading, startup to full power operation can be satisfied. Regarding neutron sources, to avoid startup monitoring blind zones, pressurized water reactors generally arrange both primary and secondary neutron sources. CPR1000 units have implemented engineering practices using activated secondary neutron sources to replace primary neutron sources, and VVER reactors at Tianwan Nuclear Power Station Unit 3 have also implemented passive startup engineering practices. New micro reactors generally only arrange startup neutron sources and are currently researching the feasibility of passive startup.

This study addresses the challenge of core nuclear monitoring for mobile reactors by employing Monte Carlo methods to construct accurate integrated three-dimensional models of the core, ex-core structures, and ex-core detectors. It proposes a layout method for micro reactor nuclear detecting systems that relies solely on a small number of ex-core detectors, investigates the feasibility of passive startup for gas-cooled micro reactors and active nuclear detecting system layout schemes, and verifies feasibility through simulations of first criticality and ex-core detector calibration experiments, providing technical support for gas-cooled micro reactor model development.

1 Design Method

Currently, no specific regulations or standards exist in China for micro reactor nuclear instrumentation system layout. Relevant standards can be referenced to construct a gas-cooled micro reactor nuclear detecting system layout method that provides reactor status information during fuel loading, shutdown, startup, and power operation conditions, establishing a core monitoring platform.

The Monte Carlo method solves the neutron transport equation in fixed source mode. The relationship between neutron source strength Q, pulse-type detector sensitivity S, and counting rate limit N is as follows:

$$S \geq \frac{N}{\phi_{th} \cdot Q} \cdot f$$

where ϕ_{th} is the thermal neutron flux in the detector sensitive region per unit source strength, and f is the engineering uncertainty factor considered, taken as 20%.

Source strength Q is determined by the spontaneous fission of ^{238}U and (α,n) decay in fresh fuel for passive startup, and by the startup neutron source strength for active startup. Counting rate limit N varies under different conditions: during fuel loading, the first fuel assembly column placed in the core requires a neutron counting rate no less than 0.5 s^{-1}; for a fully loaded core in complete shutdown, the counting rate must be at least 2 s^{-1}; and when the core is approximately 1% subcritical, the counting rate must be at least 10 s^{-1}.

Therefore, pulse-type detector sensitivity S requirements are as follows:

$$S \geq \max_i \left(\frac{N_i}{\phi_{th,i} \cdot Q} \cdot f \right)$$

where i represents the condition number that the pulse-type detector must satisfy.

During active startup, some measured neutrons are produced directly by the startup neutron source rather than by core fission, which may be more pronounced in micro reactors. Therefore, measured neutrons must satisfy the following relationship:

$$\eta = \frac{\phi_{th}^{total} - \phi_{th}^{non-fission}}{\phi_{th}^{total}} \geq 95\%$$

where ϕ_{th}^{total} and $\phi_{th}^{non-fission}$ are the total thermal neutron flux and non-fission-produced thermal neutron flux at the detector sensitive region when core keff is approximately 0.99.

Neutron flux in micro reactors generally varies by more than ten orders of magnitude under different conditions, requiring source range pulse-type detectors, power range current-type detectors, or other detector combinations to achieve core monitoring functions. The neutron measurement range requirements for different detector types are as follows:

$$\phi_{th}^{SR,min} > 2 \cdot \phi_{th}^{PR,max} \quad \text{and} \quad \phi_{th}^{PR,min} > 10 \cdot \phi_{Doppler}$$

where $\phi_{th}^{SR,min}$ and $\phi_{th}^{PR,min}$ are the lower limits of neutron measurement range for source range and power range detectors, $\phi_{th}^{PR,max}$ is the upper limit of power range detector measurement range, and $\phi_{Doppler}$ is the thermal neutron flux at the Doppler power point. $\phi_{th}^{SR,max}$ and $\phi_{th}^{PR,max}$ are the thermal neutron fluxes at the detector sensitive regions under full power operation conditions for source range and power range detectors, respectively. Consequently:

$$\phi_{th}^{SR,min} = \frac{N_{min}}{S_{SR} \cdot Q} \cdot f, \quad \phi_{th}^{PR,min} = \frac{I_{min}}{S_{PR} \cdot Q} \cdot f$$

2 Micro Reactor Model

The gas-cooled micro reactor features a horizontal active core composed of identically structured hexagonal fuel assemblies arranged in radial zones and axial layers. [Figure 1: see original paper] shows a schematic diagram of the reactor model. Thirty fuel assembly columns are arranged sequentially in the radial direction, with three axial layers of components in each column. The fuel consists of cylindrical pellets formed by dispersing ceramic particle fuel with UO_2 kernels in a matrix. Both the core moderator and reflector are graphite materials. Reactivity control is achieved through separated gadolinium-containing burnable poison rods and six first-set control rods located in the side reflector, plus one second-set control rod at the core center. Ex-core structures include boron-containing carbon bricks, pressure vessels, shielding insulation layers, etc.

Two types of neutron detectors are arranged, both located ex-core. The first type is source range detectors for monitoring neutron flux during initial core startup and restart after shutdown. The second type is power range detectors, with three channels arranged, each containing four axial detector groups for monitoring core power level, guiding operational control, and providing protection signals.

3 Passive Startup Nuclear Measurement

If the micro reactor nuclear measuring system has no external neutron source, i.e., passive startup, it not only saves source procurement costs and avoids issues related to source transportation, storage, and management, but also further improves deployment flexibility. The key is whether the neutron source naturally produced by ^{238}U spontaneous fission and (α,n) decay in fresh fuel can meet the neutron counting rate requirements for startup.

The neutron source strength and energy spectrum can be calculated using the burnup and decay program Origen-S. The gas-cooled micro reactor has a total UO_2 loading of approximately 140 kg, with a source strength of about 1.80×10^{3} n/s. [Figure 2: see original paper] shows the neutron source energy spectrum distribution.

To establish a core monitoring platform for fuel loading and startup, the Monte Carlo program RMC (Reactor Monte Carlo Code) was used to create a detailed three-dimensional model of the core and ex-core structures. [Figure 3: see original paper] shows a schematic diagram of loading one fuel assembly column and the location of the in-core temporary detector. The pre-startup full loading and ex-core detector arrangement are shown in [Figure 2: see original paper]. Calculation results based on Equation 2 are presented in . Since thermal neutrons have difficulty penetrating ex-core structures to reach detector positions, and boron-containing carbon bricks significantly absorb thermal neutrons, polyethylene sleeves are installed on ex-core detectors to improve detection efficiency.

TABLE:1 Sensitivity requirements for detectors under loading and startup conditions without external neutron sources

Conditions	Source strength / $n \cdot s^{-1}$	Counting requirement / s^{-1}	Layout of detector	Thermal neutron flux / $n \cdot cm^{-2} \cdot s^{-1}$	Sensitivity requirement / cm^2
Loading 1 fuel column	1.80×10^{3}	≥ 0.5	In-core temporary detector	2.16×10^{-3} (52%)	≥ 290
Full loading before startup	1.80×10^{3}	≥ 2	Ex-core source range detector	2.55×10^{-3} (67%)	≥ 980

Note : "2.16×10^{-3} (52%)" indicates that the thermal neutron flux is 2.16×10^{-3} $n \cdot cm^{-2} \cdot s^{-1}$, with thermal neutrons below 0.625 eV accounting for 52% of the total neutron population.

The calculation results in show that passive startup of the gas-cooled micro reactor requires in-core temporary detectors and ex-core source range detectors with sensitivities no less than 290 and 980 cm^2, respectively, necessitating the use of high-sensitivity ^{3}He proportional counter tubes.

4 Active Nuclear Measurement

Passive startup imposes very high requirements on detector sensitivity, and ^{3}He detectors have short irradiation lifetimes. Using a low-strength startup neutron source can reduce detector sensitivity requirements, allowing the selection of detector types with stronger gamma radiation resistance and longer lifetimes to improve the long-life, unmanned or minimally-manned performance of micro reactors.

4.1 Neutron Source Arrangement

Commonly used neutron sources in nuclear reactors include californium sources and americium-beryllium sources. Californium sources have high neutron emission rates but a short half-life of only 2.65 years. Americium-beryllium sources have a long half-life of 432 years, stable neutron output, and low accompanying gamma rays, making them a more suitable choice.

The average neutron energy of Am-Be sources is 4.3 MeV. According to Equation 3, shows the proportion of measured neutrons produced by fission under different energy spectra when the neutron source is positioned at the rear end of the front reflector and radial center. Due to the weak moderation capability of graphite, as source neutron energy increases, more source neutrons leak from the reflector and are directly captured by detectors, significantly reducing the proportion of fission neutrons. Higher source neutron energy places more stringent requirements on neutron source positioning.

TABLE:2 Proportion of fission neutron detected under different neutron source energy spectra

Energy spectra	Proportion of fission neutron
Neutron energy 0.1 MeV	99.9%
Neutron energy 2 MeV	93.6%
Energy spectrum of Am-Be source	81.4%

The side reflector and front reflector (coolant inlet end) have low temperatures and ample space. shows the proportion of measured neutrons produced by fission for typical Am-Be source positions at 1% subcriticality, indicating that none can meet the 95% proportion requirement. Therefore, the neutron source must be arranged within the core active region.

TABLE:3 Proportion of fission neutron detected under different neutron source positions

Serial numbers	Radial positions	Axial positions	Proportion of fission neutron
1	Outer region of side reflector	Front of side reflector	64.0%
2	Outer region of side reflector	Middle of side reflector	79.9%
3	Inner region of side reflector	Middle of side reflector	91.3%
4	Center of front reflector	Rear region of front reflector	81.4%

The metal cladding of neutron source assemblies cannot withstand excessively high temperatures. Neutron source channels are arranged from the front of the active core (coolant inlet end) and central core assembly. [Figure 4: see original paper] shows the variation curve of the proportion of measured fission neutrons at 1% subcriticality for Am-Be neutron sources at different axial depths in the active core. When the depth is 15 cm, the proportion of fission neutrons is 95.8%. CFD (Computational Fluid Dynamics) software calculations indicate the core temperature at this location is approximately 550°C.

4.2 Detector Structure

Ex-core detectors are significantly affected by ex-core structures. presents calculated neutron flux results for different energy groups at various positions.

TABLE:4 Neutron flux at different positions ($\mathrm{n\cdot cm^{-2}\cdot s^{-1}}$)

Energy groups	Outside of pressure vessel	Source range detector without sleeve	Source range detector with sleeve
Thermal neutron (< 0.625 eV)	1.6×10^{7} (0.02%)	1.1×10^{9} (15%)	4.4×10^{9} (68%)
Moderate neutron (0.625eV ~ 0.1MeV)	5.4×10^{10}	3.0×10^{10}	7.3×10^{9}
Fast neutron (0.1 MeV ~ 1 MeV)	3.9×10^{9}	2.1×10^{9}	9.0×10^{8}

Energy groups	Outside of pressure vessel	Source range detector without sleeve	Source range detector with sleeve
Fast neutron (above 1 MeV)	5.7×10^{7}	7.2×10^{9}	1.9×10^{9}
All energy neutron	2.4×10^{8}	1.7×10^{7}	6.5×10^{9}

Note : "1.6×10^{7} (0.02%)" indicates that the thermal neutron flux is 1.6×10^{7} $n \cdot cm^{-2} \cdot s^{-1}$, with thermal neutrons below 0.625eV accounting for 0.02% of the total neutron population.

The results in reveal that: (1) Boron-containing carbon bricks significantly reduce thermal neutron flux outside the pressure vessel to only 1.6×10^{7} $n \cdot cm^{-2} \cdot s^{-1}$ (0.02% of total), which is unfavorable for direct reaction between the detector sensitive region and thermal neutrons. (2) Thermal neutron flux at detector positions farther from the core is higher than outside the pressure vessel due to scattering by ex-core structures. Compared to thermal neutrons, intermediate-energy and fast neutrons undergo fewer nuclear reactions before reaching detectors after fission in the core, providing more accurate signals for core monitoring. (3) Installing 0.05 cm thick cadmium and 3 cm thick polyethylene sleeves outside detectors can reduce thermal neutron interference while largely preserving response to intermediate-energy and fast neutrons. The thermal neutron flux in the detector sensitive region increases to 4.4×10^{9} $n \cdot cm^{-2} \cdot s^{-1}$ (68% of total), improving detector efficiency and reducing sensitivity requirements. [Figure 5: see original paper] shows a schematic diagram of the detector and sleeve structure.

4.3 Detector Selection

Source range detectors are pulse-mode neutron proportional counters, including boron-coated, BF_3, and ^{3}He types. BF_3 types have long plateaus but poor gamma radiation resistance and the shortest burnup lifetime, requiring specialized radiation protection measures. ^{3}He types have extremely high sensitivity but the worst gamma radiation resistance, with a burnup lifetime of approximately 1.0×10^{15} $n \cdot cm^{-2}$, making them unsuitable for long-term operation without timely maintenance or replacement. Boron-coated types, while relatively less sensitive, offer the strongest gamma interference discrimination and radiation resistance with the longest burnup lifetime, making them more suitable for long-life, unmanned applications.

Source range detectors are located outside the reactor vessel, avoiding stringent size and temperature requirements. Their key parameters are sensitivity and measurement range. According to Equations 1 and 2, when the Am-Be source strength is 5×10^{6} n/s, presents calculated sensitivity requirements for source range detectors under different conditions.

TABLE:5 Sensitivity requirements for source range detector under different conditions

Conditions	Counting requirement / s^{-1}	Sensitivity requirement / cm^{2}
Condition 1: loading 1 fuel column	≥ 0.5	≥ 6.2
Condition 2: full loading and shutdown	≥ 2	≥ 6.2
Condition 3: full loading and keff 0.99	≥ 10	≥ 6.2

The results in indicate that source range detector sensitivity should be no less than 6.2 cm^{2}. Its power measurement range is 10^{-9}%FP ~ 10^{-3}%FP, corresponding to thermal neutron flux of 4.4×10^{-2} ~ 4.4×10^{4} $n \cdot cm^{-2} \cdot s^{-1}$. Typically, the ZJ1520 boron-coated neutron counting tube can be selected. lists its main parameters.

TABLE:6 Main performance indicators of ZJ1520 neutron counter tube

Parameters	Values
Sensitivity / cm^{2}	6.2
Useful life of detector / $n \cdot cm^{-2}$	1.0×10^{18}
Measurement range of detector / $n \cdot cm^{-2} \cdot s^{-1}$	1.2×10^{-2} ~ 2.0×10^{5}

Power range detectors are current-mode types, including boron-coated ionization chambers, gamma compensation ionization chambers, and fission chambers. Fission chambers use fissile materials like ^{235}U as neutron-sensitive materials, producing strong signals due to large reaction energy, but the sensitive material coating is very thin, resulting in extremely low neutron detection efficiency. Ionization chambers also respond to gamma rays, especially during restart after shutdown when neutrons decay rapidly while gamma rays decay slowly, creating significant interference. Therefore, gamma compensation ionization chambers are more appropriate.

According to Equation 4, the power measurement range of power range detectors should be at least 10^{-4}%FP ~ 200%FP, corresponding to thermal neutron flux of 2.7$×10^{3}$ ~ 5.5$×10^{9}$ n • cm^{-2} • s^{-1}. Typically, the DL129 gamma compensation ionization chamber can be selected. lists its main parameters.

TABLE:7 Main performance indicators of DL129 γ-compensated ionization chamber

Parameters	Values
Sensitivity / (A/n • cm^{-2} • s^{-1})	3.0$×10^{-14}$
Useful life of detector / n • cm^{-2}	1.0$×10^{18}$
Measurement range of detector / n • cm^{-2} • s^{-1}	5.0$×10^{2}$ ~ 1.4$×10^{10}$

5.1 First Criticality Simulation

The principle of critical experiments is the neutron counting rate inverse extrapolation method. For a subcritical core, the total neutron population tends to a stable value given by Equation 5, where S_0 is the neutron source strength and l is the neutron generation time.

$$N = \frac{S_0 \cdot l}{1 - k_{eff}}$$

Equation 5 shows that the neutron population N becomes larger as criticality is approached. By fitting the inverse neutron counting rate 1/N curve against fuel loading, the critical loading can be estimated. This curve is called the extrapolation curve.

When $k_{eff} = 0$, $N_0 = S_0 \cdot l$, yielding Equation 6. Based on the counting rate N after fuel loading, the estimated k_{eff} value can be obtained.

$$k_{eff} = 1 - \frac{N_0}{N}$$

The gas-cooled micro reactor undergoes fuel loading at room temperature in an air atmosphere with control rods fully withdrawn and neutron sources and detectors in place. Temporary graphite blocks are replaced with fuel assembly columns (three axial components constitute one column) sequentially from bottom to top and left to right. [Figure 6: see original paper] shows a schematic diagram of the loading sequence.

Critical experiment calculations include: (1) The theoretical critical loading is 14 fuel assembly columns. Following the "1/3 loading principle" (or "1/2 loading principle" when counting rates are higher), fuel is loaded progressively until the difference between extrapolated critical loading and current loading is less than one fuel assembly column. [Figure 7: see original paper] shows the loading extrapolation curve and estimated k_{eff} values. (2) After inserting one control rod group (the lower left control rod in [Figure 6: see original paper]), one additional fuel assembly column is loaded. Based on the theoretical critical rod position of 130 cm and the critical extrapolation method, the rod position is gradually raised until the difference between extrapolated critical rod position and current position or subcriticality is below the set value. [Figure 8: see original paper] shows the first criticality single control rod extrapolation curve and estimated k_{eff} values.

The results in [Figure 7: see original paper] and [Figure 8: see original paper] demonstrate that: (1) The extrapolated 1/N curve shows an overall concave trend, which is safer. (2) The extrapolated critical loading is 14 fuel assembly columns, consistent with theoretical results. When loading 14 columns, the extrapolated critical rod position is 128 cm, differing from the theoretical value by only -2 cm. (3) During loading extrapolation, the estimated k_{eff} values from two ex-core source range detectors differ significantly due to loading sequence effects. At deep subcriticality, the estimated k_{eff} values differ considerably from theoretical values because the estimate from Equation 6 is related to the neutron worth of the source, while the theoretical value, as a lumped parameter of the core, is independent of the neutron source. (4) When approaching criticality, the estimated k_{eff} values gradually converge to theoretical values. In the final rod withdrawal step, the estimated k_{eff} values are 0.99839 and 0.99865, respectively, deviating from the theoretical value of 0.99897 (standard deviation 5\$$\times 10^{\{-5\})bylessthan6\times 10}$\{-4\}\$, proving the feasibility of the extrapolation criticality method for gas-cooled micro reactors and the rationality of the nuclear detecting system layout.

5.2 Ex-core Detector Calibration Simulation

Ex-core power range detector calibration experiments can avoid monitoring deviations in power level P and axial power offset AO caused by burnup and power distribution.

The power of the front and rear core regions, P_H and P_B, are calculated as follows:

$$P_H = \sum_{m=1}^{3} K_H(m) \cdot I_H(m), \quad P_B = \sum_{m=1}^{3} K_B(m) \cdot I_B(m)$$

where m represents different detector channels. Analysis is conducted using the lower right detector channel in [Figure 2: see original paper] as an example. K_H and K_B are power correction factors, I_H represents the current from the front axial section obtained from two front axial gamma compensation ionization chambers, and I_B represents the current from the rear axial section.

Axial power offset AO is calculated as:

$$AO = \frac{P_H - P_B}{P_H + P_B} \times 100\%$$

Based on the least squares method, the relationship between P and I_H, I_B is established as shown in Equation 11, where a and b are coefficients to be determined. Parameter k is introduced, determined by ex-core power range detector signals, while AO_{in} is determined by in-core power distribution.

$$P = a \cdot I_H + b \cdot I_B, \quad k = \frac{I_H}{I_B}$$

The calibration factors K_H and K_B are then given by Equations 13 and 14:

$$K_H = \frac{P \cdot (1 + AO_{in}/100)}{2 \cdot I_H}, \quad K_B = \frac{P \cdot (1 - AO_{in}/100)}{2 \cdot I_B}$$

and Equation 15 present the experimental simulation results, with calibration factors K_H and K_B being 6069.30 and 6073.48, respectively.

$$P_{ex} = 0.03450 + 0.36599 \cdot I_H + 0.36599 \cdot I_B, \quad AO_{ex} = 0.97602 + 0.03450 \cdot k$$

TABLE:8 Result of calibration experiment for ex-core detector with power range

FP theoretical value	AOin theoretical value	IH/$\times10^{-6}$A	FP calculated value {-6}A|IB/×10{-	AOin calculated value	
9.97%	-3.03%	0.0016	0.0017	9.97%	-2.81%
19.92%	-2.62%	0.0033	0.0035	19.92%	-2.64%
30.00%	-2.42%	0.0050	0.0052	30.00%	-2.38%
40.10%	-2.03%	0.0067	0.0069	40.10%	-1.83%
50.07%	-1.62%	0.0083	0.0086	50.07%	-1.85%
60.01%	-1.06%	0.0100	0.0102	60.01%	-1.35%
70.19%	-0.50%	0.0117	0.0117	70.19%	-0.58%
79.97%	-0.21%	0.0133	0.0133	79.97%	-0.15%
89.87%	0.12%	0.0150	0.0149	89.87%	0.18%
100.20%	0.66%	0.0167	0.0164	100.20%	0.33%
119.93%	1.77%	0.0200	0.0194	119.93%	1.77%

The results in show that the absolute deviations of axial power offset AO and power level FP are within 0.4% and 0.2%, respectively, demonstrating high accuracy. Therefore, ex-core power range detector calibration experiments are feasible for gas-cooled micro reactors, and the nuclear measuring system layout is reasonable.

Conclusions

Addressing the development challenge of achieving core monitoring in gas-cooled micro reactors using only a small number of ex-core detectors, this paper proposes a micro reactor nuclear measuring system layout method and scheme, verifying its feasibility through physics experiment simulations. The conclusions are as follows:

(1) Passive startup of gas-cooled micro reactors is feasible. The spontaneous fission and (α,n) decay of ^{238}U in fresh fuel can produce a source strength of 1.80$×10^{3}$ n/s. By deploying ^{3}He proportional counter tubes with sensitivities no less than 290 and 980 cm^{2} as in-core temporary detectors and ex-core source range detectors, a core monitoring platform for fuel loading and startup can be established.

(2) The active nuclear measuring system, coupling a low-strength startup neutron source, low-sensitivity ex-core source range detectors, and wide-range ex-core power range detectors, is more suitable for long-life, unmanned core monitoring applications in micro reactors. The Am-Be neutron source is arranged at a 15 cm depth in the front of the active core with a strength of 5$×10^{6}$ n/s. The source range detector selects boron-coated proportional counter tubes with sensitivity above 6.2 cm^{2}. The power range detector selects gamma compensation ionization chambers. To improve nuclear measurement signal accuracy, cadmium and polyethylene sleeves are installed outside detectors to measure intermediate-energy and fast neutrons with less interference from ex-core structures.

(3) Using the extrapolation criticality method and ex-core source range detectors, the extrapolated critical loading matches the theoretical value, the extrapolated critical rod position differs from the theoretical value by only -2 cm, and the keff deviation is within 6$×10^{-4}$ when approaching criticality. Through ex-core power range detector calibration simulations, the maximum absolute deviations of power level FP and AO are within 0.2% and 0.4%, respectively, verifying the feasibility of the nuclear measuring system layout scheme for core monitoring applications.

The micro reactor nuclear measuring system layout proposed in this study considers compact core design and intelligent operation scenario requirements, providing references for core monitoring research of different micro reactor types. Combined with micro reactor power reconstruction methods, it can also provide technical support for core online monitoring research.

Author Contributions

ZHANG Chenglong: Design of micro reactor nuclear measuring system layout method, drafting the article; YUAN Yuan: Physics experiment calculation and simulation of first criticality and ex-core detector calibration; LIU Guoming: Overall paper design, critical review of the article; ZHANG Peng: Data analysis, critical review of the article; XIAO Huiwen: Detector selection and layout analysis; DONG Jianhua: Temperature field calculation for neutron source and detector positions, critical review from thermal-hydraulic perspective; GUAN Jingyu: Neutron source selection and layout analysis; HE Kai: Critical review from structural perspective, administrative and technical support; YI Xuan: Critical review from reactor physics perspective, technical support.

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Note: Figure translations are in progress. See original paper for figures.