Layout Study of Nuclear Instrumentation System for Gas-Cooled Microreactor and Its Application to Core Monitoring

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Abstract

Gas-cooled micro-reactors are constrained by their compact arrangement and high-temperature operating environment, which limits core monitoring to only a small number of ex-core detectors. A nuclear measurement system layout scheme coupling neutron sources with ex-core detectors for micro-reactors is proposed, and its feasibility is verified through physical experiments and simulations. The results demonstrate that source-free startup of micro-reactors requires sensitivities of no less than 290 and 980 cm^2 for temporary in-core detectors and ex-core source range detectors, respectively. Conversely, an active nuclear measurement system coupling a lower-intensity startup neutron source, lower-sensitivity ex-core boron-lined neutron tubes, and gamma-compensated ionization chambers is more appropriate for long-lifetime, unmanned intelligent operation of mobile micro-reactors. The neutron source must be positioned within the active zone to achieve a fission neutron fraction exceeding 95%, while detectors utilize cadmium and polyethylene sleeves to measure high-energy neutrons, thereby enhancing core monitoring accuracy. In the first criticality experiment, the extrapolated critical loading aligns with theoretical values, the single-rod extrapolated critical position shows a deviation of merely -2 cm, and the keff deviation remains within 6×10^-4. The detector calibration experiment yields absolute deviations within 0.2% and 0.4% for power level and axial power offset AO, respectively. These research results provide a valuable reference for gas-cooled micro-reactor core monitoring.

Full Text

Preamble

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Research on Nuclear Detection System Arrangement for Gas-Cooled Micro Reactors and Its Application in Core Monitoring

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Abstract

[**Background**] Gas-cooled micro reactors, constrained by their compact layout and high-temperature operating environment, can only accommodate a limited number of ex-core detectors for core monitoring. [**Purpose**] This study proposes a nuclear detection system arrangement scheme that couples a neutron source with ex-core detectors for micro reactors, with feasibility validated through physical experiment simulations. [**Methods**] A three-dimensional integrated reactor model incorporating the core, ex-core structures, and detectors was constructed using the Monte Carlo code RMC. By referencing relevant standards, an arrangement methodology for micro-reactor nuclear detection systems was developed, covering design approaches for neutron count rate, detector sensitivity, measured neutron component, and detector range. The feasibility of source-free startup for micro reactors was analyzed, along with the system layout scheme incorporating an external source. The validity of these approaches was verified through computational simulations of the first criticality experiment and ex-core detector calibration experiment. [**Results**] The results demonstrate that source-free startup requires in-core temporary detectors and ex-core source-range detectors with sensitivities no less than 290 cm^2 and 980 cm^2, respectively. For mobile micro reactors requiring long-life, unmanned intelligent operation, an active detection system coupling a low-strength startup neutron source, low-sensitivity ex-core boron-coated neutron tubes, and gamma-compensated ionization chambers is more suitable. The neutron source must be positioned in the active zone to ensure the fission neutron fraction exceeds 95%. Detectors equipped with cadmium and polyethylene sleeves measure high-energy neutrons to improve core monitoring accuracy. In the first criticality experiment simulation, the extrapolated critical loading matched the theoretical value, with single-rod extrapolated critical position deviating by only -2 cm and keff deviation within 6×10 . In the detector calibration experiment simulation, absolute deviations in power level and axial power offset (AO) were within 0.2% and 0.4%, respectively. [**Conclusions**] The nuclear detection system layout is reasonable and feasible, providing valuable guidance for core monitoring of gas-cooled micro reactors and advancing the development of mobile intelligent

micro nuclear power sources.

Keywords: Gas-cooled micro reactor; Source-free startup; Active nuclear detection system layout; First criticality experiment; Ex-core detector calibration experiment

1. Design Methodology

No specific regulations or standards currently exist in China for nuclear detection system arrangement in micro reactors. However, relevant standards [13-14] can be referenced to establish a design methodology for gas-cooled micro reactors that provides reactor status information during loading, shutdown, startup, and power operation, thereby 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 count rate limit N is given by:

where represents the thermal neutron flux per unit source strength in the detector' s sensitive region, and is the engineering uncertainty factor, taken as 20%. The source strength Q is determined by the spontaneous fission and (,n) decay of ^{23} U in fresh fuel for source-free startup, and by the startup neutron source strength for active startup. The count rate limit N varies under different operating conditions: during fuel loading, the first fuel assembly column requires a neutron count rate of at least 0.5 s ^{1}; for a fully loaded core in complete shutdown, the count rate must be at least 2 s ^{1}; and at approximately 1% subcriticality, the count rate must be at least 10 s ^{1}.

Therefore, the sensitivity requirement for pulse-type detectors is:

where i represents the operating condition number that the detector must satisfy.

During active startup, some measured neutrons are produced directly by the startup neutron source rather than by core fission, a phenomenon potentially more pronounced in micro reactors. Consequently, the measured neutrons must satisfy:

where and represent the total thermal neutron flux and non-fission thermal neutron flux, respectively, in the detector' s sensitive region at a core keff of approximately 0.99.

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

where and represent the lower and upper limits of the neutron measurement range for source-range and power-range detectors, respectively, while and denote the thermal neutron flux in the sensitive regions of source-range and power-range detectors at full-power operation. This ensures complete coverage and range overlap from startup to 200% FP (Full Power) overpower conditions.

2. Micro-Reactor Model

The gas-cooled micro reactor features a horizontal active zone composed of identically structured hexagonal fuel assemblies arranged in radial zones and axial layers. [Figure 1: see original paper] illustrates the reactor model schematic. Thirty fuel assembly columns are arranged sequentially in the radial direction, with three axial layers per column. The fuel consists of cylindrical pellets formed by dispersing UO kernel ceramic particle fuel in a matrix. Both the moderator and reflector are graphite materials. Reactivity control is achieved through separate gadolinium-containing burnable poison rods, six first-set control rods in the side reflector, and one second-set control rod at the core center. Ex-core structures include boron-containing carbon bricks, a pressure vessel, and shielding/insulation layers. Table 1 lists the main parameters of the core model.

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

3. Source-Free Startup Detection

If the micro-reactor nuclear detection system operates without an external neutron source (source-free startup), it not only saves source procurement costs and avoids issues related to source transportation, storage, and management but also enhances deployment flexibility. The key challenge is whether the naturally occurring neutron source from ^{23}U spontaneous fission and (,n) decay in fresh fuel can meet the neutron count rate requirements for startup.

The neutron source strength and energy spectrum can be calculated using the burnup and decay code Origen-S. The gas-cooled micro reactor contains approximately 140 kg of UO fuel, yielding 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, a detailed three-dimensional core and ex-core structure model was developed using the Monte Carlo code RMC (Reactor Monte Carlo Code) [15]. [Figure 3: see original paper] shows the schematic of loading one fuel assembly column and the in-core temporary detector position, with pre-startup full loading and ex-core detector arrangement shown in Figure 2. Calculations based on Equation 2 are presented in Table 2 . Due to the difficulty for thermal neutrons to penetrate ex-core structures and the significant absorption by boron-containing carbon bricks, polyethylene sleeves are installed on ex-core detectors to improve detection efficiency.

Table 2. Sensitivity requirements for detectors under loading and startup conditions without external neutron sources

Condition	Source strength (n · s $^{\ 1}$)	Counting requirement (s $^{\ 1}$)	Detector layout	Thermal neutron flux (n · cm $^{\ 2}$ · s $^{\ 1}$)	Sensitivity requirement (cm^2)
Loading 1 fuel column	1.80×10^{3}	0.5	In-core temporary detector	$2.16\times10^{\ 3}$ (52%)[1]	290
Full loading before startup	1.80×10^{3}	2	Ex-core source-range detector	$2.55\times10^{\ 3}$ (67%)	980

[1] $2.16\times10^{\ 3}$ (52%) indicates a thermal neutron flux of $2.16\times10^{\ 3}$ n · cm $^{\ 2}$ · s $^{\ 1}$, with thermal neutrons below 0.625 eV accounting for 52% of the total neutron population.

The results indicate that source-free startup for gas-cooled micro reactors requires in-core temporary detectors and ex-core source-range detectors with sensitivities no less than 290 cm^2 and 980 cm^2, respectively, necessitating high-sensitivity ^{3}He proportional counters.

4. Active Nuclear Detection System

Source-free startup demands extremely high detector sensitivity, and ^{3}He detectors have short irradiation lifetimes. Using a low-strength startup neutron source reduces detector sensitivity requirements, enabling the selection of detector types with stronger gamma radiation resistance and longer lifetimes, thereby improving the long-life, unmanned operation performance of micro reactors.

4.1 Neutron Source Placement

Common neutron sources for nuclear reactors include californium and americium-beryllium (Am-Be) sources. Californium sources have high neutron emission rates but a short half-life of only 2.65 years. Am-Be sources, with a half-life of 432 years, stable neutron output, and low associated gamma radiation, are more suitable.

The average neutron energy of Am-Be sources is 4.3 MeV. According to Equation 3, Table 3 presents the proportion of measured neutrons produced by fission at 1% subcriticality when the neutron source is placed at the rear of the front reflector at the radial center position. Due to graphite' s weak moderation capability, more source neutrons leak from the reflector and are directly captured by detectors as source neutron energy increases, significantly reducing the fission neutron fraction. Higher source neutron energy imposes stricter placement requirements for the neutron source.

Table 3. Proportion of fission neutrons detected under different neutron source energy spectra

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

The side reflector and front reflector (coolant inlet end) offer low temperatures and ample space. Table 4 shows the proportion of measured neutrons produced by fission at 1% subcriticality for typical Am-Be source positions, revealing that none meet the 95% requirement. Therefore, the neutron source must be placed within the core active zone.

Table 4. Proportion of fission neutrons detected under different neutron source positions

Serial number	Radial position	Axial position	Proportion of fission neutrons
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	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 therefore arranged from the front of the active zone (coolant inlet end) through the central assembly. [Figure 4: see original paper] shows the variation curve of the measured fission neutron fraction at 1% subcriticality for different axial depths of the Am-Be source in the active zone. At a depth of 15 cm, the fission neutron fraction reaches 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 influenced by ex-core structures. Table 5 presents calculated neutron flux results for different energy groups at various positions.

Table 5. Neutron flux at different positions (n · cm ² · s ¹)

Energy groups	Outside pressure vessel	Source-range detector without sleeve	Source-range detector with sleeve
Thermal neutron (<0.625 eV)	1.6×10 (0.02%)[1]	1.1×10 (15%)	4.4×10 (68%)
Moderate neutron (0.625 eV–0.1 MeV)	5.4×10^{1}	3.9×10	1.9×10
Fast neutron (0.1 MeV–1 MeV)	3.0×10^{1}	2.1×10	2.4×10
Fast neutron (>1 MeV)	7.3×10	5.7×10	1.7×10
All energy neutron	9.0×10^{1}	7.2×10	6.5×10

[1] 1.6×10 (0.02%) indicates a thermal neutron flux of 1.6×10 n · cm ² · s ¹, accounting for 0.02% of the total neutron population.

The results demonstrate that: (1) Boron-containing carbon bricks significantly reduce thermal neutron flux outside the pressure vessel to only 1.6×10 n · cm ² · s ¹ (0.02% of total), making direct reaction with thermal neutrons in the detector sensitive region impractical. (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, higher-energy moderate and fast neutrons undergo fewer nuclear reactions before reaching detectors, providing more accurate signals for core monitoring. (3) Installing 0.05 cm-thick cadmium and 3 cm-thick polyethylene sleeves [16] outside detectors reduces thermal neutron interference while largely preserving response to moderate and fast neutrons. The thermal neutron flux in the detector sensitive region increases to 4.4×10 n·cm ²·s ¹ (68% of total), improving detector efficiency and reducing sensitivity requirements. [Figure 5: see original paper] illustrates the detector and sleeve structure.

4.3 Detector Selection

Source-range detectors are pulse-type neutron proportional counters, including boron-coated, BF , and ^{3}He types. BF detectors have long plateaus but poor gamma radiation resistance and the shortest burnup lifetime, requiring specialized radiation protection measures [9]. ^{3}He detectors exhibit extremely high sensitivity but the poorest gamma radiation resistance, with a burnup lifetime [12] of approximately 1.0×10¹ n · cm ², making them unsuitable for long-term unmanned operation. Boron-coated detectors, while relatively less sensitive, offer the strongest gamma discrimination and radiation resistance with the longest burnup lifetime, making them most appropriate for long-life, unmanned applications.

Located outside the reactor vessel, source-range detectors avoid stringent size and temperature requirements, with sensitivity and range being key parameters. Based on Equations 1 and 2, Table 6 presents sensitivity requirements for source-range detectors under various conditions with an Am-Be source strength of 5×10 n/s.

Table 6. Sensitivity requirements for source-range detector under different conditions

Conditions	Counting requirement (s ¹)	Sensitivity requirement (cm²)
Condition 1: Loading 1 fuel column	0.5	6.2
Condition 2: Full loading, shutdown	2	6.2
Condition 3: Full loading, keff 0.99	10	6.2

The results indicate that source-range detectors require sensitivity no less than 6.2 cm². The power measurement range is 10 %FP–10 ³%FP [9], corresponding to a thermal neutron flux of 4.4×10 ²–4.4×10 n · cm ² · s ¹. A typical selection is the ZJ1520 boron-coated neutron counter tube, with main parameters listed in Table 7 .

Table 7. Main performance indicators of ZJ1520 neutron counter tube

Parameters	Values
Sensitivity (cm^2)	6.2
Useful life of detector (n · cm ²)	1.0×10^1
Measurement range of detector (n · cm ² · s ¹)	1.2×10 ²–2.0×10

Power-range detectors are current-type, including boron-coated ionization chambers, gamma-compensated ionization chambers, and fission chambers. Fission chambers use fissile materials like ²³ U as neutron-sensitive materials, producing strong signals but with very thin sensitive coatings resulting in low neutron detection efficiency [17]. Ionization chambers also respond to gamma rays, which is particularly problematic during post-shutdown restart when neutrons decay rapidly while gamma rays decay slowly, creating significant interference. Therefore, gamma-compensated ionization chambers are more suitable.

According to Equation 4, power-range detectors require a power measurement range of at least 10 %FP–200%FP, corresponding to a thermal neutron flux of 2.7×10^3–5.5×10 n · cm ² · s ¹. A typical selection is the DL129 gamma-compensated ionization chamber, with main parameters listed in Table 8 .

Table 8. Main performance indicators of DL129 -compensated ionization chamber

Parameters	Values
Sensitivity (A/n · cm ² · s ¹)	3.0×10 ¹
Useful life of detector (n · cm ²)	1.0×10^1
Measurement range of detector (n · cm ² · s ¹)	5.0×10^2–1.4×10^1

5. Experimental Simulation

5.1 First Criticality Simulation

The critical experiment principle employs the inverse neutron count rate extrapolation method [18]. For a subcritical core, the total neutron population approaches a stable value given by Equation 5, where S is the neutron source strength and l is the neutron generation time.

From Equation 5, the neutron population increases as criticality is approached. By fitting the inverse neutron count rate (1/N) curve against fuel loading, the critical loading can be estimated, producing the extrapolation curve.

When keff = 0, N = S l, yielding Equation 6. Based on the count rate N after fuel loading, keff can be estimated.

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

The critical experiment simulation includes: (1) The theoretical critical loading is 14 fuel assembly columns. Following the "1/3 loading principle" (or "1/2 loading principle" at higher count rates), fuel is gradually loaded 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 keff estimated values, with preliminary calibration indicating the control rod value (lower left control rod in Figure 6) equivalent to 3.9 fuel assembly columns. (2) After inserting the calibrated control rod, 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 single control rod extrapolation curve and keff estimated values for the first criticality.

The results demonstrate: (1) The extrapolated 1/N curve exhibits an overall concave trend, providing greater safety margins. (2) The extrapolated critical loading is 14 fuel assembly columns, consistent with theoretical results. At 14 columns loading, the extrapolated critical rod position is 128 cm, only -2 cm from the theoretical value. (3) During loading extrapolation, keff estimated values from two ex-core source-range detectors show significant differences due to loading sequence effects. At deep subcriticality, keff estimated values differ substantially from theoretical values because Equation 6 estimates are source neutron importance-weighted, while theoretical values are core lumped parameters independent of neutron source position [19]. (4) As criticality is approached, keff estimated values converge toward theoretical values. In the final rod withdrawal step, keff estimated values are 0.99839 and 0.99865, deviating from the theoretical value of 0.99897 (standard deviation 5×10) by less than 6×10 , proving the feasibility of the extrapolation method for gas-cooled micro reactors and the rationality of the detection system arrangement.

5.2 Ex-Core Detector Calibration Simulation

Ex-core power-range detector calibration [20] experiments avoid monitoring deviations in power level P and axial power offset AO caused by burnup and power distribution [21].

The front and rear core powers (PH, PB) are calculated as follows:

where m represents different detector channels, with analysis conducted for the lower right detector channel shown in Figure 2. KH and KB are power correction coefficients, represents front core current obtained from two axial front gamma-compensated ionization chamber current values, and represents rear core current.

The axial power offset AO is calculated as:

where is determined by ex-core power-range detector signals and is determined by in-core power distribution, obtainable through nuclear design software calculations or micro-reactor online monitoring power reconstruction methods [22-23].

Based on the least squares method, monitors as shown in Equation 11, where a and b are coefficients to be determined. Introducing parameter k, the calibration factors KH and KB are given by Equations 13 and 14.

Table 9 and Equation 15 present the experimental simulation results, with calibration factors KH and KB of 6069.30 and 6073.48, respectively.

Table 9. Results of calibration experiment for ex-core detector with power range

FP theoretical	AOin theoretical	IH (×10 A)	IB (×10 A)	FP calculated	AOin calculated	FP deviation	AOin deviation
9.97%	-3.03%	0.60	0.64	9.97%	-2.81%	0.00%	0.22%
19.92%	-2.62%	1.21	1.27	19.92%	-2.64%	0.00%	0.02%
30.00%	-2.42%	1.82	1.91	30.00%	-2.38%	0.00%	0.04%
40.10%	-2.03%	2.43	2.55	40.10%	-1.83%	0.00%	0.20%
50.07%	-1.62%	3.04	3.18	50.07%	-1.85%	0.00%	0.23%
60.01%	-1.06%	3.64	3.81	60.01%	-1.35%	0.00%	0.29%
70.19%	-0.50%	4.25	4.44	70.19%	-0.58%	0.00%	0.08%
79.97%	-0.21%	4.85	5.07	79.97%	-0.15%	0.00%	0.06%
89.87%	0.12%	5.46	5.70	89.87%	0.18%	0.00%	0.06%
100.20%	0.66%	6.07	6.33	100.20%	0.33%	0.00%	0.33%
119.93%	1.38%	7.28	7.59	119.93%	1.77%	0.00%	0.39%

The results show that absolute deviations in axial power offset 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 detection system arrangement is reasonable.

6. Conclusions

Addressing the challenge of core monitoring in gas-cooled micro reactors using only a limited number of ex-core detectors, this paper proposes a nuclear detection system arrangement methodology and scheme, validated through physical experiment simulations. The conclusions are as follows:

(1) Source-free startup is feasible for gas-cooled micro reactors. The spontaneous fission and (,n) decay of ^{23} U in fresh fuel produce a source strength of 1.80×10^3 n/s. By deploying high-sensitivity ^{3}He proportional counters with sensitivities no less than 290 cm^2 and 980 cm^2 as in-core temporary detectors and ex-core source-range detectors, respectively, a core monitoring platform for fuel loading and startup can be established.

(2) An active detection 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 placed at 15 cm depth in the front of the active zone with a strength of 5×10 n/s. Source-range detectors are boron-coated proportional counters with sensitivity above 6.2 cm^2. Power-range detectors are gamma-compensated ionization chambers. To improve nuclear measurement signal accuracy, cadmium and polyethylene sleeves are installed outside detectors to measure moderate and fast neutrons with less interference from ex-core structures.

(3) Using the extrapolation critical method with ex-core source-range detectors, the extrapolated critical loading matches theoretical values, with the extrapolated critical rod position deviating by only -2 cm from theory. The keff deviation is within 6×10 when approaching criticality. Through ex-core power-range detector calibration simulation, maximum absolute deviations in power level FP and AO are within 0.2% and 0.4%, respectively, verifying the feasibility of the detection system arrangement for core monitoring.

The proposed micro-reactor nuclear detection system arrangement considers compact core design and intelligent operation scenarios, providing a reference for core monitoring research across different micro-reactor types. Based on the limited ex-core nuclear measurement signals provided by this system, reduced-order models such as principal component analysis [22] or higher-order harmonic expansion methods [23] can achieve micro-reactor in-core power distribution reconstruction and monitoring, supporting online core monitoring research.

Author Contributions

Zhang Chenglong: Design of micro-reactor nuclear detection system arrangement methodology; drafting of manuscript.
Yuan Yuan: Computational simulation of first criticality and ex-core detector calibration physical experiments.
Liu Guoming: Overall paper design; critical review of manuscript.
Zhang Peng: Data analysis; critical review of manuscript.
Xiao Huiwen: Detector selection and arrangement analysis.
Dong Jianhua: Temperature field calculations for neutron source and detector positions; critical review from thermal-hydraulic perspective.

Guan Jingyu: Neutron source selection and arrangement 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.