

Safeguards by Design Approach for a Sealed-Core Microreactor: Design Elements for Sealing and Remote Monitoring

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1. Introduction

The development of small modular reactors (SMRs) and microreactors has increased the need for safeguards considerations different from those applied to large-scale light water reactors (LWRs) with power outputs exceeding 1000 MWe.

A Heat Pipe Microreactor (HPMR) is based on a heat pipe-driven heat transfer mechanism, a compact core configuration, and a sealed-core structure enabling long-term operation without refueling. Such reactors are manufactured and assembled at a factory and subsequently transported to their deployment sites. This sealed configuration can enhance resistance against nuclear material diversion during operation; however, it may also limit the ability to add or modify safeguards equipment after reactor deployment. Therefore, safeguards for microreactors should be considered from the early design stage through a Safeguards by Design (SBD) approach rather than through post-deployment installation of additional safeguards measures.

In this study, a design-stage safeguards approach is proposed by identifying sealing and monitoring design elements that should be predetermined prior to factory shipment, considering the structural and operational characteristics of HPMR. A realistic Heat Pipe Microreactor (rHPMR) design model was adopted as a reference case to examine specific design conditions for the proposed safeguards approach.

2. Review of HPMR Design and Previous Safeguards Studies

Existing SBD guidelines for nuclear reactors were reviewed to identify key design considerations for safeguards implementation. IAEA TRS No. 392 and NP-T-2.9 emphasize the incorporation of safeguards requirements from the early design stage [1,2]. In addition, the Idaho National Laboratory (INL) HTGR-related SBD guidance proposes instrumentation and data interfaces for remote monitoring and access structures for gamma-ray and neutron detector deployment [3]. The NuScale SBD study also highlights the importance of considering facility interfaces, including space, power supply, cabling, and data transmission, during the design stage [4].

Fig. 1 presents the schematic structure of the rHPMR [5]. The rHPMR consists of fuel compacts embedded within a graphite monolith, with a multi-layer shielding structure composed of SS316 and B₄C outside the core region. In addition, multiple detector holes are considered for neutron flux measurement, indicating that physical provisions for instrumentation access are incorporated into the reactor design. These characteristics suggest the necessity of considering the location of monitoring equipment and verification access paths during the HPMR design stage.

Existing SBD guidelines commonly consider physical access structures, sealing, instrumentation and monitoring interfaces, and data transmission paths as important design elements. However, conventional reactors such as LWRs and HTGRs generally assume refueling operations or fuel movement, whereas HPMRs operate with fixed fuel and a sealed-core configuration for long-term operation. Therefore, this study reconfigures existing SBD design elements according to the unique sealed-core characteristics of HPMRs.

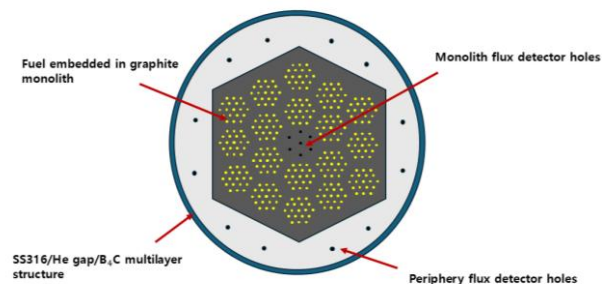


Fig. 1. Schematic structure of the rHPMR, reproduced based on Ref. [5].

3. Approach for Deriving Sealing and Remote Monitoring Design Elements

Applying existing SBD design elements to the sealed-core characteristics of HPMR indicates that the fundamental safeguards principles remain applicable; however, their implementation requires reconsideration due to limited access and difficulty in adding safeguards equipment after reactor deployment. Therefore, this study established a design approach in which physical and instrumentation-related elements for sealing and monitoring are defined around a predetermined access structure prior to factory shipment.

IAEA safeguards concepts utilize containment and surveillance (C/S) and unattended monitoring systems to maintain Continuity of Knowledge (CoK) between inspections [7]. In addition, IAEA verification activities include follow-up actions when questions, inconsistencies, or anomalies are identified during safeguards evaluation [8]. Based on this operational framework, this study applies the concept of continuous monitoring followed by follow-up verification to HPMR and proposes a two-stage safeguards approach consisting of normal-operation monitoring and anomaly-triggered verification.

Table I summarizes the proposed two-stage safeguards approach. In Stage 1, sealing and remote monitoring elements are configured to continuously monitor the reactor sealing integrity and operational conditions. In Stage 2, additional nuclear material verification is performed when anomalies are identified during Stage 1 monitoring. Furthermore, the HTGR SBD guidance (INL/EXT-12-26561, 2012) proposes an instrument well that enables insertion of gamma-ray and neutron detection probes near the reactor vessel for follow-up verification [3]. Based on this concept, this study incorporates a pre-installed interrogation well as a design element for HPMR safeguards, where its location and accessibility are determined at the design stage to enable additional nuclear material verification under anomaly conditions.

Table I: Two-stage safeguards design approach

Stage	Safeguards Objective	Key Design Elements
Stage 1: Normal-operation Monitoring	Maintaining continuity of knowledge (CoK) and monitoring diversion indicators	Safeguards seals, surveillance cameras, remote monitoring, and independent safeguards data transmission path determined before factory shipment
Stage 2: Anomaly-triggered Follow-up Verification	Additional nuclear material verification after anomaly detection	Pre-installed interrogation well for gamma-ray and neutron probe access, with detector accessibility considered at the design stage

4. Results

4.1. Stage 1: Normal-operation Monitoring

Fig. 2 presents the proposed design concept for Stage 1 normal-operation monitoring. To maintain continuity of knowledge (CoK) and monitor potential diversion indicators, safeguards seals with electronic/optical

monitoring capabilities and remote monitoring elements were considered at the design stage. The locations of major access boundaries requiring safeguards seals, surveillance cameras, and interrogation wells for potential follow-up verification were predetermined prior to factory assembly.

In addition, operational instrumentation signals with potential relevance to safeguards were considered as reference information for monitoring. When operational instrumentation is utilized for safeguards purposes, an independent safeguards data transmission path separated from the conventional operational data network should be provided to ensure protected transmission of monitoring information [9,10]. The criteria for anomaly detection were also established based on pre-shipment commissioning data.

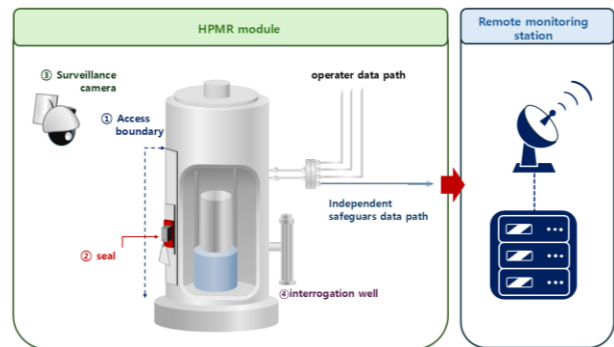


Fig. 2. Stage-1 normal-operation monitoring concept

4.2. Stage 2: Anomaly-triggered Follow-up Verification

Fig. 3 presents the proposed design concept for Stage 2 anomaly-triggered follow-up verification. When an anomaly is identified during Stage 1 monitoring, additional verification is proposed using gamma-ray and neutron-based nondestructive assay (NDA) techniques, such as the miniature multichannel analyser with a CdZnTe detector (MMCC), whose probe is less than 1 cm in diameter and is designed for insertion into narrow guide tubes [7].

For this purpose, a pre-installed interrogation well defined at the design stage is utilized to provide access for gamma-ray and neutron detectors near the reactor core region. Based on the existing instrumentation structure of HPMR, including the planned detector holes in the rHPMR design, a verification access path is incorporated into the design [5,6]. This enables additional nuclear material verification without opening the sealed-core itself, supplementing the information obtained from Stage 1 remote monitoring.

Through the proposed two-stage approach, HPMR safeguards can be configured by integrating normal-operation monitoring and anomaly-triggered follow-up verification. This indicates the necessity of determining physical access structures and instrumentation/data

interfaces prior to factory shipment.

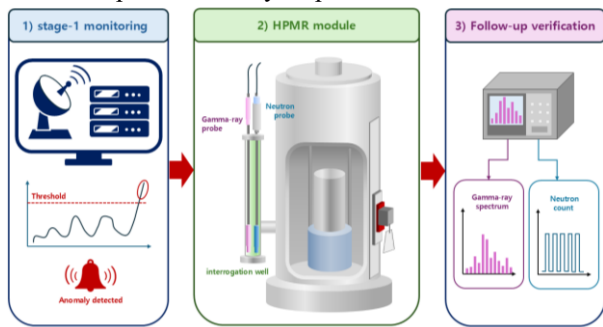


Fig. 3. Stage-2 anomaly-triggered follow-up verification concept

5. Conclusions

This study investigated safeguards design elements for a Heat Pipe Microreactor (HPMR) with a sealed-core structure from the perspective of Safeguards by Design (SBD), and proposed design elements to be incorporated prior to factory shipment. Based on existing safeguards guidelines and the structural and operational characteristics of HPMR, a two-stage safeguards approach was established: normal-operation monitoring through sealing and remote monitoring to maintain CoK, followed by additional nuclear material verification when anomalies are identified.

The results of this study demonstrate that, for HPMRs where internal access and the addition of safeguards equipment are limited after deployment, access structures, instrumentation and monitoring interfaces, and data transmission paths should be considered from the early design stage. Furthermore, this staged safeguards approach integrates normal-operation monitoring and anomaly-triggered follow-up verification, enabling continuous monitoring and additional verification while maintaining the sealed-core characteristics.

However, this study is a preliminary investigation proposing applicable safeguards design elements and their implementation approaches for HPMR. Further evaluation is required regarding access structures, instrumentation arrangement, signal transmission methods, and verification performance based on specific reactor design conditions. Future work will focus on assessing the applicability of the proposed safeguards design elements under detailed HPMR design conditions and further developing the corresponding design concepts.

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