Criticality Safety Study of Heat Pipe Microreactors for Terrestrial and Marine Applications

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Abstract

Heat pipe micro-reactors can satisfy the special requirements of land, sea, air, and space application scenarios, and have become a focus of micro-reactor research both domestically and internationally in recent years. This study focuses on land and marine application scenarios, conducting criticality safety analysis for heat pipe micro-reactors under accident conditions including core water ingress, control drum failure, safety rod ejection, core compression, and heat pipe rupture with water ingress. The reactivity insertion under various conditions is calculated and analyzed, and with reference to relevant regulatory standards for conventional pressurized water reactors, analytical judgments are performed and recommendations are provided.

Full Text

Preamble

Criticality Safety Analysis of Heat Pipe Microreactors for Onshore and Marine Applications

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Abstract

Heat pipe microreactors have emerged as a focal point in micro-reactor research both domestically and internationally due to their ability to meet the special requirements of land, sea, air, and space applications. This paper investigates the criticality safety of heat pipe microreactors under accident conditions for onshore and marine scenarios, including core water ingress, control drum failure, safety rod ejection, core compression, and heat pipe fracture with water ingress.

The reactivity insertion under various conditions is calculated and analyzed. Based on relevant regulations and standards for conventional pressurized water reactors, the analysis provides evaluations and recommendations.

Keywords: Heat pipe microreactor, Criticality safety, Accident safety

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0 Introduction

Heat pipe microreactors have become a research hotspot in recent years for micro-reactor development worldwide, as they can satisfy the special demands of land, sea, air, and space applications. Characterized by fully passive operation, static components, no coolant loops, system simplification, compact size and weight, and flexible deployment, these reactors offer unique advantages.

The solid-state core characteristics and mobility of heat pipe microreactors necessitate rigorous criticality safety analysis. For fast-spectrum cores in particular, water ingress can significantly increase the system' s effective multiplication factor. Consequently, criticality safety analysis is essential for heat pipe microreactors. While considerable research has been conducted on criticality safety for space applications of heat pipe microreactors [1], studies focusing on onshore and marine applications remain relatively limited. This paper presents a criticality safety analysis for land-based vehicle-mounted and marine applications based on a heat pipe microreactor design featuring rod-type fuel and control drums.

1 Regulatory Framework and Standards

As no specific regulatory standards currently exist for criticality safety calculations of vehicle-mounted heat pipe microreactors in China, a preliminary study of relevant regulations was conducted to establish appropriate criteria for high-temperature heat pipe reactor criticality safety analysis.

The primary regulations governing fuel handling and storage system design for nuclear power plants include: - HAF 102 *Safety Regulations for Nuclear Power Plant Design* (2016 Edition) [2] - HAD 102/15 *Design of Fuel Handling and Storage Systems for Nuclear Power Plants* (2021 Edition) [3] - GB15146.8 *Nuclear Criticality Safety for Fissile Materials Outside Reactors - Part 8: Criticality Safety Criteria for the Handling, Storage, and Transportation of LWR Fuel* (2008 Edition) [4]

Key requirements for new fuel storage criticality safety are as follows:

HAF 102 Requirements: The design of unirradiated fuel handling and storage systems must ensure subcriticality under all conditions, including optimum moderation, through physical means or process measures (with geometrically safe arrangements preferred) while maintaining specified margins.

GB 15146.8 Requirements: During criticality safety evaluation, fuel characteristics affecting reactivity (such as material composition, geometry, or temperature) should be selected within credible ranges to obtain the maximum neutron multiplication factor for the system under evaluation.

The maximum effective neutron multiplication factor used to demonstrate that the storage system meets criticality safety requirements (including biases and uncertainties) is determined through comprehensive evaluation of calculation uncertainties. The following definitions apply to the uncertainty components:

- $k_{\text{eff, nominal}}$: Calculated effective multiplication factor based on nominal design values
- Δk_{bias}: Reactivity calculation difference due to computational method bias and temperature variations
- U_{CU}: Computational method bias uncertainty
- $\sum U_i$: Uncertainties from manufacturing tolerances and off-center fuel assembly placement
- $\sigma_{k_{\text{eff}}}$: Standard deviation of the effective multiplication factor calculated from nominal design values

HAD 102/15 (2021 Edition) stipulates that new fuel handling and storage systems must maintain subcriticality under all conditions and at all locations to prevent severe radiological impacts on workers and the public. The design must ensure subcriticality during simultaneous occurrence of two independent abnormal events.

For new fuel storage, HAD 102/15 (2021 Edition) [3] specifies that the maximum k_{eff} should not exceed 0.95 under normal operating conditions and should be less than 0.98 under anticipated operational occurrences and accident conditions. The analysis must consider optimum moderation conditions.

2 Analysis Assumptions

The criticality safety analysis in this study is based on the following assumptions:

1. The nuclear fuel is fresh (unirradiated)
2. Water entering the core after an accident is pure water
3. The core temperature reactivity coefficient is negative; conservatively, cold-state parameters (300 K) are used in the analysis
4. Based on storage limits and conditions for high-enrichment fissile materials, calculations assume a 20 cm thick water reflector surrounding the core [5]
5. Following an accident, control drums are assumed to have lost position limiting capability. Under gravity and buoyancy forces, they will rotate to the same orientation. Since absorber density is lower than reflector density, the absorber is assumed to face upward and the reflector downward

3 Core Design and Analysis Methodology

3.1 Core Configuration

The fuel assembly consists of multiple hexagonal fuel lattice matrices with gaps maintained between adjacent matrices. Fuel rods and heat pipes are inserted into the matrices, with gaps between both the fuel rods and heat pipes and the matrix material. Reactivity control is achieved through two independent systems: a central safety rod and peripheral control drums, either of which can shut down the reactor independently. The core configuration is shown in [Figure 1: see original paper].

3.2 Analysis Code and Methodology

Monte Carlo codes are used for criticality safety calculations in this study. Continuous-energy cross-section libraries at multiple temperatures based on the ENDF/B-VII.0 nuclear data evaluation library are employed, with the 300 K (03c) library used for calculations.

For Monte Carlo simulations, the number of active cycles and particles per cycle significantly affect result variance. The following parameters are used: - Particles per cycle: 20,000 - Active cycles: 1,000 - Inactive cycles: 50

Convergence analysis has been performed to ensure adequate convergence with these parameters, yielding an effective multiplication factor standard deviation within 20 pcm.

To comprehensively account for uncertainties, Equation 1 is applied in the analysis.

3.3 Initial State

The initial state for the water ingress analysis is illustrated in [Figure 2: see original paper].

4 Onshore Application Criticality Safety Analysis

Due to their compact size and flexible deployment, heat pipe microreactors can provide power and heat in high-altitude and cold regions. For onshore applications, these reactors typically require vehicle transport capability. Considering potential traffic accidents during transport that could compromise core integrity and the possibility of reactor modules falling into water, the following representative cases were selected for detailed calculation and analysis.

4.1 Core Water Ingress

During transport conditions, control drum absorbers are fully rotated toward the core and the safety rod is fully inserted. Core water ingress scenarios include water entering the gaps between fuel assemblies and water entering the gaps between fuel rods/heat pipes and the fuel lattice matrix, as shown in [Figure 2: see original paper].

The calculated system reactivity under this condition is: $k_{\text{eff}} = 0.95675$

4.2 Control Drum Limiter Failure

During transport, control drum absorbers should be oriented toward the core. In accident conditions, drum position limiters may fail. The design ensures that with the safety rod inserted, the system remains subcritical even if all control drum absorbers rotate outward. Building upon the water ingress condition described in Section 4.1 and following Assumption 5, the absorbers will face upward and reflectors downward. The calculated system reactivity is: $k_{\text{eff}} = 0.98855$

4.3 Safety Rod Ejection from Core

During transport, the safety rod should be fully inserted into the core. In accident scenarios, the safety rod may be ejected. Under the water ingress condition described in Section 4.1, water would fill the space originally occupied by the safety rod. The calculated system reactivity is: $k_{\text{eff}} = 0.96543$

With the safety rod fully inserted and all control drum absorbers rotated toward the core, the calculated effective multiplication factor is: $k_{\text{eff}} = 0.89296$

5 Marine Application Criticality Safety Analysis

Research indicates that heat pipe microreactors are increasingly considered a viable solution for marine power applications [6]. Unlike onshore applications, marine heat pipe microreactors require pressure vessels to withstand seawater pressure at depths exceeding one kilometer. Under certain extreme accidents where the pressure vessel is breached or emergency-opened, the reactor faces new criticality safety challenges. Based on comprehensive evaluation, the following representative cases were selected for analysis.

5.1 Fuel Assembly Gap Compression

With the safety rod fully inserted and control drum absorbers rotated toward the core, combined with the water ingress condition from Section 4.1, the immense seawater pressure would compress and eliminate gaps between fuel assemblies, causing them to fit tightly together. The calculated system reactivity is: $k_{\text{eff}} = 0.92386$

5.2 Heat Pipe Fracture with Water Ingress

This scenario builds upon the condition in Section 4.1, considering heat pipe fracture with water ingress. Since heat pipes are not designed to withstand seawater pressure, the pipe walls may fracture during accidents, allowing seawater to enter the core through the heat pipes and fill the space originally occupied by the heat pipes. The calculated system reactivity is: $k_{\text{eff}} = 1.11980$

6 Conclusions and Recommendations

6.1 Conclusions

The reactivity insertion under different accident conditions is summarized in .

Reactivity Insertion Under Different Accident Conditions

Accident Condition Description	Reactivity Insertion (pcm)
Core water ingress + Control drum limiter failure	-
Core water ingress + Safety rod ejection	-
Fuel assembly gap compression	-
Heat pipe fracture water ingress	-

Based on the design limit recommendation of $k_{\text{eff}} < 0.98$ for accident conditions in commercial PWR spent fuel storage [3], the following results are obtained for this heat pipe microreactor:

Reactivity Insertion Under Different Accident Conditions

Accident Condition Description	Meets Limit
Core water ingress + Control drum limiter failure	-
Core water ingress + Safety rod ejection	-
Fuel assembly gap compression	-
Heat pipe fracture water ingress	-

6.2 Recommendations

From a criticality safety perspective, the following design recommendations are proposed:

For land-based vehicle-mounted heat pipe microreactors: - The core design should maintain sealing during accidents to prevent water ingress - Control drums should incorporate fail-safe limiter mechanisms to maintain safe positions - Measures should be implemented to prevent safety rod ejection from the core - These features ensure the core remains subcritical under accident conditions

For marine heat pipe microreactors: - Pressure vessel integrity should be maintained - Heat pipe pressure-bearing capacity should be considered in the design

This study conservatively used pure water for calculations. Future criticality safety analyses for marine heat pipe microreactors should use actual seawater properties for more specific evaluations.

Additionally, dedicated criticality safety criteria and design basis accidents should be developed for mobile reactors such as heat pipe reactors to support design development and safety regulation.

Author Contributions

Chi Liu was responsible for criticality safety analysis and manuscript preparation. Chuntao Tang, Qichang Chen, and Chanyun Liu provided technical support and guidance. Jinming Li and Jinkun Zhao provided heat pipe microreactor core design input and criticality safety analysis verification.

References

1. Yao Chengzhi, Zhao Shouzhi, Hu Gu, et al. Criticality safety analysis of nuclear reactors for planetary surface applications[J]. Atomic Energy Science and Technology, 2018, Vol.52, No.12.
2. National Nuclear Safety Administration. Design of Fuel Handling and Storage Systems for Nuclear Power Plants[S]. HAD102/15, 2021.
3. Standardization Administration of China. Nuclear Criticality Safety for Fissile Materials Outside Reactors - Part 8: Nuclear Criticality Safety Criteria for the Handling, Storage, and Transportation of LWR Fuel[S]. GB15146.8, 2008 Edition.
4. Standardization Administration of China. Nuclear Criticality Safety for Fissile Materials Outside Reactors - Part 3: Nuclear Criticality Safety Requirements for the Storage of Fissile Materials[S]. GB 15146.3, 2008 Edition.
5. Yunqin Wu, et al. The low-enriched uranium core design of a MW heat pipe cooled reactor. Nuclear engineering and design[J]. 404(2023) 112195.
6. Wu Pan, Zhu Yu, Ouyang Zeyu, et al. Study on characteristics of reactivity insertion accidents in heat pipe reactors with different thermoelectric conversion systems[J]. Nuclear Techniques, 2024, 47(11).
7. Wang Zhenlan, Gou Junli, Xu Shihao, et al. Analysis of heat pipe failure accidents in a new megawatt-class heat pipe reactor[J]. Nuclear Techniques, 2022, 45(11).

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