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Preliminary Numerical Analysis of Heat Load Sharing Characteristics between PAFS and PCCS under PECCS Failure Conditions

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1. Introduction

In the post-Fukushima era, safety requirements for extreme accidents exceeding the Design Basis Accident (DBA) have intensified, leading the development of next-generation reactors to focus on the integration of Passive Safety Systems (PSS) that operate without external power. The Innovative Small Modular Reactor (i-SMR), currently under development in Korea, adopts a multi-layered passive cooling architecture—including the PECCS, PAFS, and PCCS—to maintain core cooling during potential accident scenarios. [1]. Due to its integral reactor configuration, where major components are housed within a single vessel, and its design feature of shared Ultimate Heat Sinks such as the Emergency Cooling Tanks (ECT), the thermal-hydraulic behaviors of these passive systems are characterized by strong interdependency.

To verify the safety of the i-SMR, it is essential to clearly understand these complex interactions between systems. In particular, a quantitative understanding of how the decay heat generated during an accident is distributed across various passive pathways is a critical factor for design optimization and ensuring safety margins. While previous studies on large-scale reactors have focused on the ability of the PCCS to ensure containment integrity [2], and preliminary research on the i-SMR has been limited to analyzing the impact of single-system PAFS performance on core water level maintenance [3]. However, as most existing analyses have focused on single-system performance or utilized simplified nodalization models, there remains a significant gap in the integrated understanding of how multiple systems share and manage heat loads from a total energy balance perspective.

This study utilizes the multi-dimensional thermal-hydraulic analysis code, SPACE, to quantitatively analyze the heat load sharing characteristics between passive safety systems in the i-SMR. The PAFS directly removes core heat through the steam generator secondary side, while the PCCS manages the energy in the containment by condensing steam released through the break, forming a physical division of cooling roles. Reflecting these systematic characteristics, this research analyzes the heat removal contributions at the system level. Specifically, by investigating the heat load sharing behavior between the PAFS and PCCS under various operational configurations of the PECCS, this work aims to identify the heat removal allocation and complementary behavior of both systems across diverse depressurization and cooling conditions. Through the quantitative analysis of these system-level contributions, this study provides a technical basis for supporting the design reliability of the i-SMR's integrated passive safety architecture.

2. Numerical Modeling and Analysis Methods

2.1 System Description and Numerical Modeling

In this study, the innovative i-SMR, characterized by its integrated passive safety features, was selected as the reference reactor. As illustrated in **Fig. 1**, the i-SMR employs an integral configuration where the core, steam generators (SG), pumps, and safety systems are housed within a single reactor vessel (RV). The primary passive safety systems include the Passive Auxiliary Feedwater System (PAFS), Passive Containment Cooling System (PCCS), and Passive Emergency Core Cooling System (PECCS).

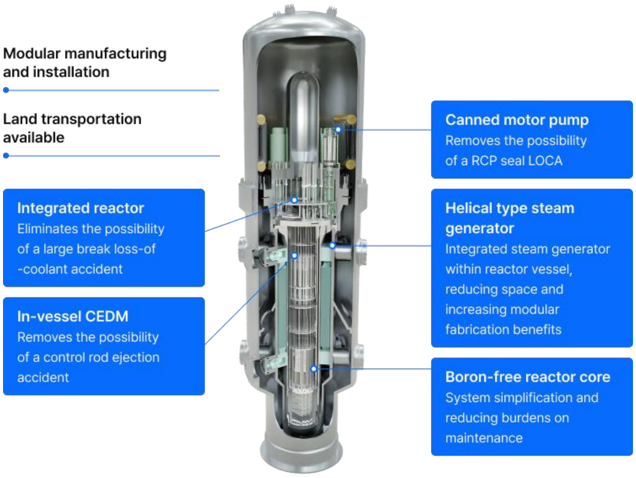


Fig. 1. Conceptual design and integral configuration of the i-SMR [4]

- PAFS & PCCS: The PAFS is connected to the secondary side of the SG to transfer decay heat to the Emergency Cooling Tanks (ECT), while the PCCS, located at the top of the containment vessel (CV), condenses released steam to regulate internal pressure and temperature. Each system consists of four independent trains, with two trains sharing a single ECT as the ultimate heat sink.
- PECCS: This system comprises three Emergency Depressurization Valves (EDVs) atop the pressurizer and two Emergency Relieving Valves (ERVs) positioned slightly above the core level to connect the RV and CV. The EDVs facilitate rapid depressurization, while the ERVs enable coolant recirculation via gravity and pressure differentials.

To simulate the integrated behavior of these systems, the multi-dimensional thermal-hydraulic analysis code, SPACE, was utilized. The input model encompasses the primary and secondary systems as well as the containment. **Table 1** provides a summary of the key modeling parameters derived from standard design data, including heat transfer areas, supply line K-factors, and thermal center elevations, all of which are critical to the heat removal analysis. In particular, specialized condensation models, including the PAFS model and the Colburn-Hougen model, are incorporated into each system to accurately reflect the complex heat transfer phenomena during transients. Furthermore, as shown in **Table 2**, steady-state validation confirmed that major operational parameters of the RCS and secondary system remained within a 0.5% error range compared to design values, ensuring the reliability of the base model.

Table 1: Key design and modeling parameters of i-SMR passive safety systems

System	Parameter	PAFS	PCCS
Key Parameter	Normalized Value (Ratio)	1.0	-
	Total Heat Transfer Area	1.000	0.746
	Tube Wall Thickness	1.000	1.517
	Thermal Center Elevation	1.000	0.698
Design Specs	Tube Material	Inconel	
	K-factor (Supply line)	0.3	0.42
	Condensation Model	PAFS model	Colburn-Hougen model

Table 2: Steady-state validation results of the i-SMR model

Parameter	**Error (%)**
Core Power (MWt)	0.192
Core Inlet Temperature (°C)	0.007
Core Outlet Temperature (°C)	0.005
RCS Flow Rate (kg/s)	0.001
Pressurizer Pressure (MPa)	0.0
Steam Generator Pressure (MPa)	0.003
SG Feedwater Temperature (°C)	0
SG Outlet Temperature (°C)	0.463
Main Feedwater Flow Rate (kg/s)	0.103
Main Steam Flow Rate (kg/s)	0.299

The actuation logic for the PECCS is modeled based on the relative pressure levels of the primary system and the containment. The EDVs are triggered when the sum of the pressurizer (PZR) pressure and the containment (CV) pressure falls below a predefined threshold, ensuring that depressurization occurs effectively during a LOCA. Similarly, the ERVs are initiated under a specific pressure-summation logic to facilitate gravity-driven recirculation when the RCS pressure is sufficiently equalized with the CV pressure.

2.2 Accident Scenario and Failure Matrix

Based on the validated model, a Loss-of-Coolant Accident (LOCA) was simulated to analyze the inter-system interactions between the passive safety features. The scenario assumes a 2-inch break in the MMPS letdown line connected to the upper downcomer of the reactor vessel. While a break in the MMPS charging line (located at a lower elevation) is known to facilitate a passive recirculation path similar to ERV functionality as the CV condensate level rises [1], this study specifically selected the letdown line break to eliminate such unintended recirculation effects. By excluding the inherent recovery path provided by a lower-elevation break, this research focuses strictly on the impact of PECCS (EDV and ERV) performance on the heat sharing characteristics between the PAFS and PCCS. This approach allows for a more conservative and clear evaluation of the functional complementarity and safety margins under various multiple-failure scenarios of the depressurization system.

The PECCS consists of a total of three EDVs and two ERVs, which are designed to actuate based on the pressure-summation and equalization logic described in Section 2.1. The analysis assumes that all four trains of the PAFS and PCCS are fully operational without further single failures to focus specifically on the impact of PECCS performance. To investigate the heat sharing characteristics, a systematic matrix of 12 multiple-failure scenarios was constructed by combining the failure of EDVs (0 to 3) and ERVs (0 to 2), as detailed in **Table 3**. This matrix covers conditions ranging from all systems functional (Case 1) to a total failure of the PECCS (Case 12), allowing for a comprehensive evaluation of the safety margins and the functional complementarity between the PAFS and PCCS under varying depressurization conditions.

Table 3: Matrix of multiple failure scenarios for EDV and ERV combinations

Case No.		Failed EDVs (Total: 3)			
		0	1	2	3
Failed ERVs (Total: 2)	0	No.1	No.2	No.3	No.4
	1	No.5	No.6	No.7	No.8
	2	No.9	No.10	No.11	No.12

2.3 Definition of Heat Load Sharing Factor

During a LOCA transient in an i-SMR, the decay heat generated from the core is removed through various paths to maintain the structural integrity of the reactor pressure vessel and the containment. The overall energy balance of the system can be expressed as:

$$Q_{in} = Q_{out} + \frac{dU}{dt}$$

where Q_{in} is the decay heat from the core, and Q_{out} represents the total heat dissipated from the system. In this study, Q_{out} is categorized into (1) active heat removal by passive safety systems, (2) natural heat loss through the RV and CV walls, and (3) energy discharged through the break.

Among these paths, the PAFS and PCCS are the primary engineered safety features designed to manage the long-term cooling of the secondary system and the containment, respectively. While the break flow and wall heat loss are dependent on the physical environment, the heat removal rates of the PAFS and PCCS are mechanistically coupled through the primary-to-containment pressure balance. Therefore, to quantify the functional complementarity and the role allocation between these two pivotal systems, the Heat Load Sharing Factor (HLSF) is defined based on their integrated energy removal:

$$HLSF_{PAFS} = \frac{Q_{PAFS}}{Q_{PAFS} + Q_{PCCS}} \times 100\ (\%)$$

$$HLSF_{PCCS} = \frac{Q_{PCCS}}{Q_{PAFS} + Q_{PCCS}} \times 100\ (\%)$$

Where Q_{PAFS} and Q_{PCCS} represent the cumulative heat removed by each heat exchanger throughout the transient ($Q = \int \dot{q} dt$). This metric systematically quantifies how the total decay heat load is distributed between the secondary side cooling (PAFS) and the containment pressure control (PCCS), providing a clear indicator of system-level synergy under various failure scenarios.

3. Results and Discussion

To evaluate the system response of the i-SMR under multiple failure conditions, a sensitivity analysis was conducted based on various combinations of PECCS failures. In addition to the reference case (Case 1), three representative scenarios (Cases 6, 11, and 12) were selected, reflecting a stepwise increase in the number of failed EDVs and ERVs.

By analyzing the transient behavior of each selected case, the thermodynamic interaction between the passive cooling systems was evaluated, ultimately providing an integrated safety assessment of the i-SMR.

3.1 Global Energy Balance

To evaluate the performance of the passive safety systems in the i-SMR, a global energy balance was analyzed from the initiation of the accident to the stabilization phase. This process is essential to verify whether the energy introduced by the accident is effectively discharged to the external environment through passive systems and whether the system can sustain a stable, safe state over the long term.

As illustrated in **Fig. 2**, the RV pressure decreases sharply following the break, while the CV pressure rises instantaneously. Significant deviations in the pressure convergence points and durations were observed depending on the specific combination of PECCS failures. As summarized in **Table 4**, the system pressure reaches equilibrium within a range of 1,100 to 6,700 seconds. Notably, in Case 12, where all PECCS valves fail, the pressure convergence is delayed until 6,700 seconds due to the degraded depressurization performance. Nevertheless, the fact that pressure equalization is achieved in all scenarios demonstrates that the i-SMR's passive safety systems successfully regulate system pressure and transition the reactor into a quasi-steady state, even under extreme failure conditions.

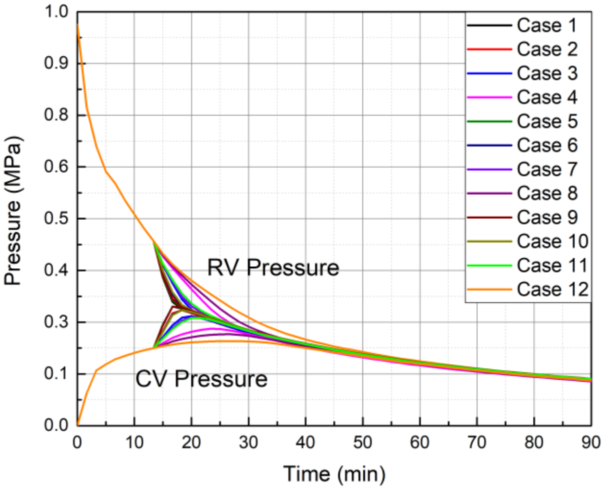


Fig. 2. Pressure responses of the RV and CV under various PECCS failure scenarios

Table 4: Summary of Normalized Pressure Equalization Points for Each Test Case

Case No.	Equilibrium Pressure (%)	Time (s)	Case No.	Equilibrium Pressure (%)	Time (s)
1	70.84	1100	7	75.81	1700
2	72.90	1300	8	82.65	3000
3	74.58	1500	9	71.36	1200
4	78.20	2000	10	74.00	1500
5	71.48	1200	11	77.03	1900
6	73.42	1400	12	90.65	6700

Fig. 3 compares the core decay heat (Q_{decay}) with the total passive heat removal rate (Q_{out}). In all cases, a

crossover point where the heat removal rate exceeds the decay heat occurs within approximately 5 minutes of the accident initiation. This quantitatively proves that the energy accumulated within the system is successfully transferred to the external heat sinks.

A notable observation is the difference in the Total Heat Removal Rate behavior depending on the actuation of the PECCS. In Case 1 (Normal operation), the direct injection of cold emergency coolant effectively absorbs core heat, rapidly reducing the internal energy of the system. This leads to a relatively low driving force for heat discharge through the PAFS and PCCS, resulting in lower heat removal values on the graph. Conversely, in Case 12 (Total failure), the absence of early-phase internal cooling leads to the accumulation of high-temperature and high-pressure energy within the system. These harsh conditions increase the thermal load transferred to the passive heat removal systems (PAFS, PCCS) and the containment structures (Q_{wall}), leading to a significantly higher observed heat removal rate compared to Case 1. This serves as critical evidence that the i-SMR's passive safety architecture can successfully discharge excess energy and maintain an energy balance, even when initial cooling functions are lost.

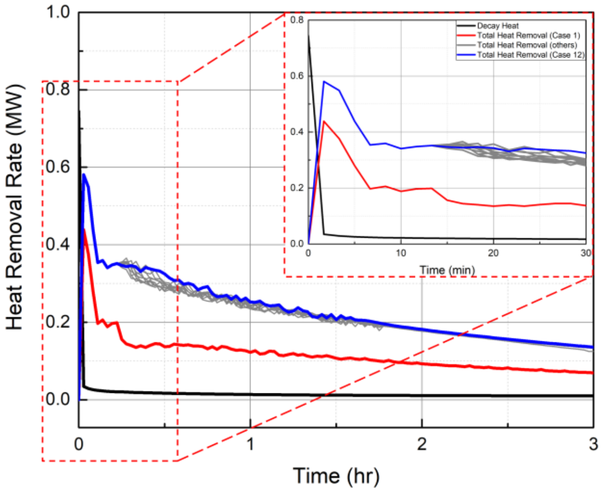


Fig. 3. Comparison between decay heat generation and total passive heat removal rate.

In conclusion, both the pressure stabilization and heat balance analyses confirmed the effectiveness of the i-SMR's passive cooling capability across all scenarios. However, while global equilibrium remains stable, the specific proportions of the thermal load distributed to each safety system vary dynamically based on the PECCS failure combinations.

3.2 Heat Load Sharing Mechanism

This section focuses on identifying the Heat Load Sharing (HLS) characteristics between the PAFS and PCCS. The objective is to investigate how these passive systems distribute and complement the overall heat removal load under demanding conditions where emergency injection is limited.

Fig.4 illustrates the integrated heat removal contributions at 7,200 seconds, a point where the system has transitioned into a quasi-steady state following the initial transients. In the reference case (Case 1), the PAFS serves as the primary heat sink, accounting for 75% of the total heat removal, as the PECCS effectively manages the internal energy through direct coolant injection. Consequently, the contribution of structural wall heat transfer (Q_{wall}) remains minimal at approximately 4%.

Scenarios involving PECCS failures (Cases 2–12) exhibit a markedly different heat-sharing behavior compared to the reference case. The absence of PECCS causes the energy to be discharged into the CV, raising its internal temperature and pressure, which subsequently increases the wall heat transfer contribution to approximately 50%. Notably, even under these demanding conditions, the PAFS and PCCS maintain a consistent ratio in sharing the remaining thermal load. This suggests that the system maintains consistent thermal behavior regardless of the specific combination or number of failed valves.

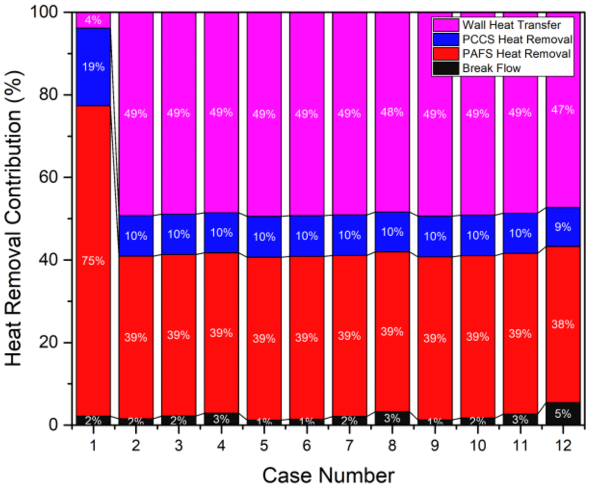
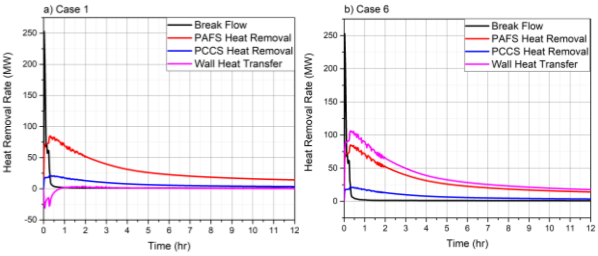


Fig. 4. Relative contribution of each heat removal path to the total integrated heat at 7,200 s.

The transient heat removal rates for each representative scenario are shown in **Fig. 5**. These results illustrate how the energy discharge path changes from the early stage of the accident to the long-term cooling phase.



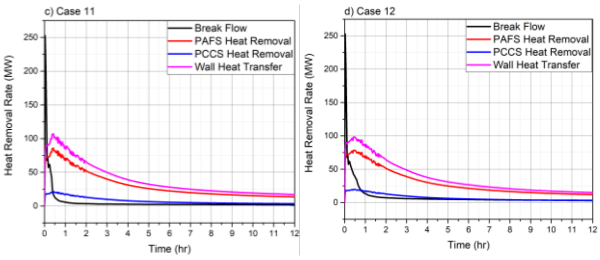


Fig. 5. Transient heat removal rates for representative cases: (a) Case 1, (b) Case 6, (c) Case 11, and (d) Case 12.

Immediately following the accident (0–0.5 hr), a substantial amount of energy is discharged through the break flow, serving as the primary driver for initial system depressurization. However, the break flow rate diminishes sharply within the first 30 minutes. Subsequently, a clear shift in the cooling priority takes place, where the primary heat removal burden is successfully transferred to the PAFS and the structural wall heat transfer (Q_{wall}). This seamless transition demonstrates that the i-SMR's cooling path shifts effectively from transient accident-driven flow to stable, passive heat removal mechanisms.

During the intermediate phase (1–5 hr), the main heat removal path varies by scenario following the shift in cooling priority. In the reference case (Case 1), the PAFS functions as the core heat removal path, complemented by the internal cooling provided by the PECCS. In contrast, under the demanding conditions of PECCS loss (Cases 6, 11, and 12), the sustained high temperature and pressure within the containment vessel (CV) result in a larger thermodynamic driving force (ΔT). This gradient accelerates the heat removal rates of both Q_{wall} and the PAFS. During this phase, Q_{wall} acts as a critical heat sink, effectively offsetting the initial energy accumulation and ensuring system stabilization despite the absence of active injection.

After approximately 5 hours, all heat removal curves enter a quasi-steady state, Decreasing gradually following with the core decay heat trend. Notably, an analysis of the cumulative behavior over the 12-hour transient reveals that the hierarchy of heat removal contributions—ordered as Q_{wall} > PAFS > PCCS—is consistently maintained without reversal. This stability implies that the heat removal performance does not fluctuate abruptly due to the significant thermal inertia of the passive systems and the containment structures. Such a consistent hierarchy proves that the i-SMR architecture establishes a highly reliable and predictable safety framework for long-term cooling.

Finally, the Heat Load Sharing Factor (HLSF) was calculated to quantify the relative distribution between the two main passive safety systems. The HLSF is defined as the ratio of heat removed by the PAFS or PCCS, excluding the wall heat transfer (Q_{wall}).

As summarized in **Table 5**, the HLSF values for the PAFS and PCCS converged to approximately 80% and 20%, respectively, across all failure scenarios (Cases 2–12). The extremely low standard deviation (less than 0.05%) indicates that this 80:20 ratio is a consistent characteristic of the i-SMR's integrated passive architecture. This proves that the heat partitioning is not sensitive to specific valve failure combinations but is determined by the inherent physical design of the system.

Table 5: Statistical summary of Heat Load Sharing Factor (HLSF) across all 12 test cases.

Heat Load Sharing Factor	Mean Value (%)	Standard Deviation (%)
PAFS Contribution	80.01	0.05
PCCS Contribution	19.99	0.05

The consistent 80:20 ratio is attributed to the inherent differences in the heat removal mechanisms and locations of the two systems. The PAFS serves as the primary heat sink by directly cooling the reactor vessel (RV) inventory, utilizing the high temperature gradient between the core and the PCCT. This proactive energy removal within the RV significantly reduces the amount of steam and energy discharged into the containment. Consequently, the PCCS manages the condensation of the remaining vapor, leading to a relatively lower thermal load compared to the PAFS. This indicates that the PAFS effectively 'shields' the containment from excessive energy, while the PCCS provides essential backup for pressure control and long-term cooling.

3.3 Integrated Safety Assessment

Despite the excellent heat removal performance of the passive safety systems, the water level behaviors in the reactor vessel (RV) and containment vessel (CV) were analyzed to identify the physical safety limits under extreme accident conditions involving a loss of coolant injection. **Fig. 6** compares the transient responses of the normalized water levels in the RV and CV for the reference case (Case 1) and the most severe failure scenario (Case 12).

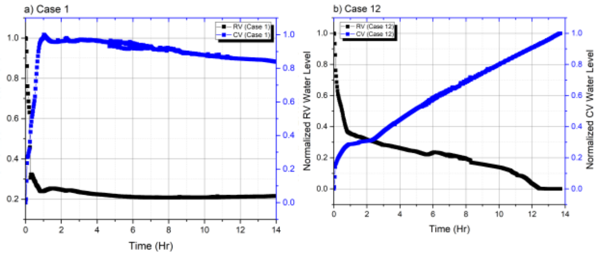


Fig. 6. Comparison of normalized water levels in RV and CV: (a) Case 1 and (b) Case 12.

In the CV, the water level consistently increases and remains stable across all scenarios, thanks to the reliable steam condensation performance of the PCCS. This indicates that the discharged steam is effectively condensed and redistributed to the lower part of the containment. In contrast, the RV water level exhibits opposite behaviors between Case 1 and Case 12. In Case 12, where the PECCS is completely lost, the RV water level continues to decline without recovery, unlike the reference case. This demonstrates that while the passive systems are effective at removing heat, there is a clear physical limitation in replenishing the coolant mass required to reflood the core.

Fig. 7 illustrates the transient behavior of the void fraction and Peak Cladding Temperature (PCT) following core uncovery in the Case 12. For approximately 13 hours, the PCT remains stable due to the heat removal capability of the passive systems. However, as the RV water level drops to the bottom of the core and the core void fraction reaches 1.0, core uncovery occurs. Immediately after this point, the sudden loss of cooling capability causes the PCT to surge, surpassing 1,200 K. This result clearly defines a physical safety limit: no matter how superior the heat-sharing capability of passive systems may be, core melt cannot be fundamentally prevented without maintaining a minimum level of coolant inventory.

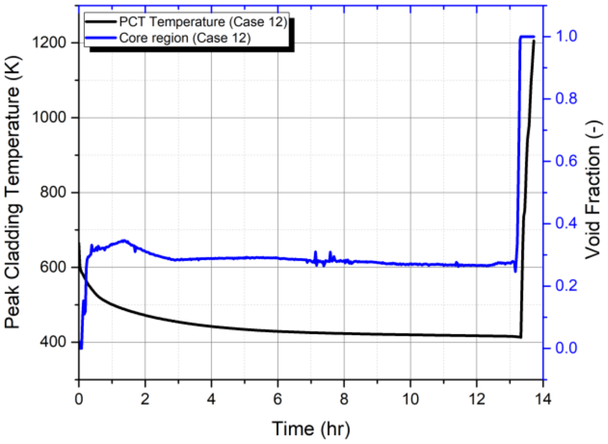


Fig. 7. Transient behavior of Peak Cladding Temperature (PCT) and core void fraction in Case 12.

4. Conclusions

The present work analyzed the heat load sharing characteristics between the PAFS and PCCS in the i-SMR under various PECCS failure scenarios using the SPACE code. The major findings are as follows.

- The i-SMR successfully achieves a global energy balance under extreme multiple-failure conditions, where the combined passive heat removal rate exceeds the core decay heat. This balance allows the system to effectively transition into a stable, quasi-steady state across all analyzed scenarios.
- The Heat Load Sharing Factor analysis confirms that the heat-sharing ratio between the PAFS and PCCS remains constant at 80:20 across all scenarios. This result is attributed to the distinct physical roles of each system where the PAFS proactively removes energy directly from the reactor vessel while the PCCS manages the pressure by condensing the discharged steam in the containment. These inherent characteristics allow the i-SMR's passive safety architecture to maintain steady and consistent heat removal performance even under extreme conditions involving PECCS failures.
- Despite the excellent synergistic heat removal, the complete loss of coolant makeup led to core uncovery and a rapid surge in PCT after approximately 13 hours. This underscores that maintaining a minimum coolant inventory is a vital prerequisite for preventing core damage.

In conclusion, the identified consistent heat-sharing ratio confirms that the i-SMR architecture can effectively distribute thermal loads based on its inherent physical design, regardless of specific system failures. This integrated analysis of the passive safety systems demonstrates the functional cooperation between the PAFS and PCCS, providing a technical foundation for assessing the thermal safety of next-generation SMRs. Future work will focus on design enhancements to delay core uncovery and ensure reflooding reliability, while also analyzing the specific heat transfer characteristics that drive the constant 80:20 heat distribution.

Acknowledgement

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