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Thermal-Hydraulic Analysis of the Hottest Channel in the Core of TNRR Under Natural Convection Cooling Using ANSYS-Fluent

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التحليل الحراري-الهيدروليكي لأكثر القنوات سخونةً في قلب مفاعل *TNRR* تحت التبريد بالحمل الطبيعي باستخدام برنامج *ANSYS-Fluent*

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Abstract:
A study of thermal-hydraulic behavior of the core of Tajoura Nuclear Research Reactor (TNRR) under natural convection cooling was performed. A narrow gap between two cylindrical elements in IRT-4 type fuel in the hottest fuel assembly was considered as the most critical. A two-dimensional CFD model of the narrow gap was developed using ANSYS Fluent code and to obtain admissible margins of core power and safe operation time before reaching the maximum allowable fuel cladding temperature of 102^∘ "C" . The effect of coolant mixing ratio in the pool was investigated for three different cases: 100% (complete mixing), 75% and 50% of total pool volume. Results from the study of transient cooling indicate that at 100% mixing in the pool, the hottest channel in the core can safely operate the reactor for about 42 hours at 100 kW, 10.5 hours at 400 kW, 8.3 hours at 500 kW and about 7 hours at 600 kW. Reducing the coolant pool mixing volume ratio to 75% or 50% greatly reduces the system’s thermal inertia, causing a rapid increase in temperature and greatly reducing safety time margins. This study establishes a basis for assessing the thermal capacity of the TNRR core under natural convection cooling and the limits of safe operation following a scram event or loss of flow of coolant.

Keywords: Natural Convection, Two-Dimensional CFD, Narrow Gap Channel.

الملخص
أُجريت دراسة للسلوك الحراري والهيدروليكي لقلب مفاعل تاجوراء للأبحاث النووية (TNRR) في ظل التبريد بالحمل الحراري الطبيعي. وقد تم اعتبار الفجوة الضيقة بين عنصرين أسطوانيين في وقود من نوع (IRT-4) داخل تجميعة الوقود الأكثر سخونة على أنها الجزء الأكثر حرجاً. طُور نموذج ثنائي الأبعاد لديناميكا الموائع الحسابية (CFD) لهذه الفجوة الضيقة باستخدام برنامج (ANSYS Fluent) للحصول على الهوامش المسموح بها لقدرة القلب ووقت التشغيل الآمن قبل الوصول إلى أقصى درجة حرارة مسموح بها لغلاف الوقود. تم فحص تأثير نسبة خلط المبرد في الحوض لثلاث حالات مختلفة: 100% (خلط كامل)، 75%، و50% من إجمالي حجم الحوض. وتشير نتائج دراسة التبريد العابر (الانتقالي) إلى أنه عند نسبة خلط 100% في الحوض، يمكن للقناة الأكثر سخونة في قلب المفاعل تشغيل المفاعل بأمان لمدة 42 ساعة تقريباً عند قدرة 100 كيلوواط، و10.5 ساعة عند 400 كيلوواط، و8.3 ساعة عند 500 كيلوواط، وحوالي 7 ساعات عند 600 كيلوواط. إن تقليل نسبة حجم خلط المبرد في الحوض إلى 75% أو 50% يقلل بشكل كبير من القصور الحراري للنظام، مما يتسبب في زيادة سريعة في درجة الحرارة ويقلل بشكل كبير من هوامش وقت الأمان.
تؤسس هذه الدراسة قاعدة لتقييم السعة الحرارية لقلب مفاعل تاجوراء (TNRR) في ظل التبريد بالحمل الطبيعي، وحدود التشغيل الآمن عقب أي حدث للإيقاف الطارئ (Scram) أو فقدان لتدفق المبرد.

الكلمات المفتاحية: الحمل الحراري الطبيعي، ديناميكا الموائع الحسابية ثنائية الأبعاد (D CFD2)، قناة الفجوة الضيقة.

1. Introduction

Research reactors are critical tools in producing radioisotopes, testing material resistance to irradiation, studying nuclear physics phenomena, and training nuclear engineers. Nevertheless, due to the reactors' growing safety requirements, it is essential to assess their performance under both normal and postulated accident conditions. Codes commonly used to simulate such processes, such as RELAP, ATHLET, or CATHARE were originally developed for commercial reactors, which makes their application to research reactors challenging.

Open-pool research reactors typically rely on forced convection for primary cooling, shifting to natural convection during low-power modes or post-scram configurations. In natural convection mode, coolant flow is entirely driven by buoyancy forces arising from density differences between the heated core zone and the ambient pool water volume. It is therefore essential to determine the natural convection cooling capacity to ensure that the clad temperature remains below the local boiling point and prevents fuel plate dry-out.

This study presents a two-dimensional thermal-hydraulic analysis of the hottest channel in the Tajoura Nuclear Research Reactor (TNRR). A finite volume method employed in the ANSYS Fluent code software was used to simulate natural convection in TNRR under various operational scenarios. The goal was to estimate the maximum allowable operating time at different power levels. Another objective of the study was to determine how decreased coolant mixing capability in the pool (75% and 50% reductions) would affect the reactor's operation. The results of the simulations were compared to the conservative preliminary analysis and narrow channel assumption calculations previously performed for TNRR.

2. Reactor Core Geometry Description

TNRR is a tank/pool-type research reactor with a rated thermal power of 10 MW. The core of the reactor is relatively compact and houses 36 lattice positions, of which 16 are filled with fuel assemblies (FAs) and the rest are beryllium (Be) reflectors, as shown in Figure 1. Low-enriched uranium (LEU) fuel is used in TNRR with a uranium-235 content of 19.7 wt%. The enriched uranium is formed into fuel meat as a dispersion of uranium dioxide in aluminum alloy AL-SAV-1. Table 1 shows the design parameters of the TNRR core and materials.

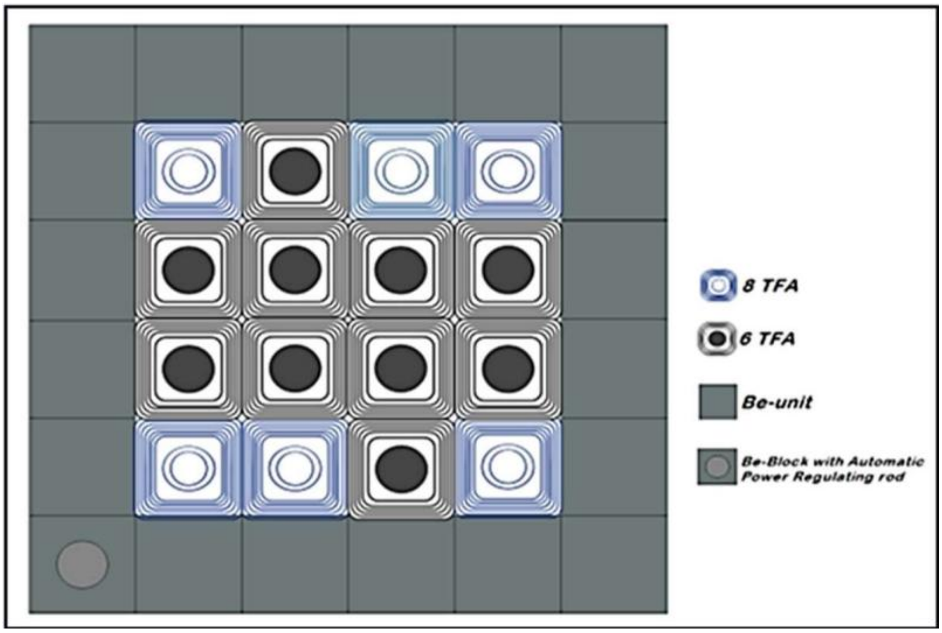

Figure 1: Core assemblies' arrangement

The core consists of two types of IRT-4M FAs with different geometry:

- 8-tube Fuel Assemblies: Comprising one central displacement tube, one cylindrical fuel element, and seven concentric square fuel elements, as shown in Figure 2.
- 6-tube Fuel Assemblies: Comprising one guide tube for control rod absorption surrounded by six concentric square fuel elements.

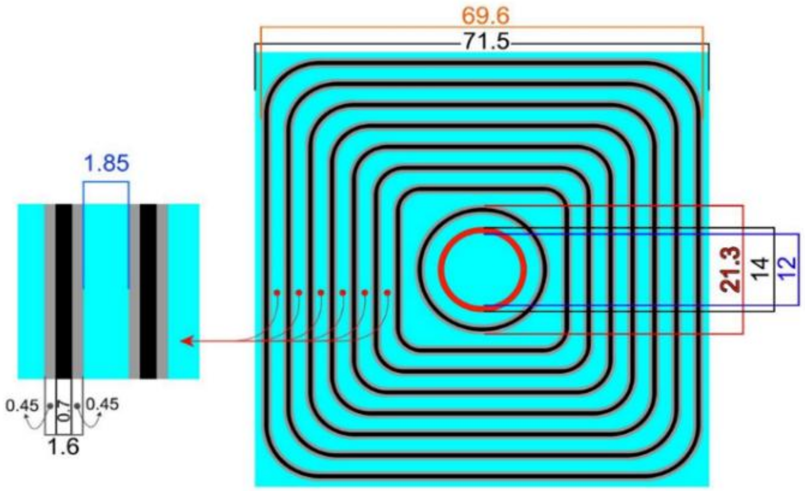

Figure2: Cross section of 8-tube Fuel Assemblies.

The square fuel elements in both types are arranged concentrically at a distance of 1.85 mm from each other and have a total active length of 600 mm.

Table 1: Design Parameters of the TNRR Core and Materials

Component / Parameter	Material / Specification	Value
Fuel Meat Material	UO_2-Al dispersion	Thickness: 0.7 mm
Cladding Material	AL-SAV-1 Aluminum Alloy	Thickness: 0.45 mm
Coolant / Moderator	Light Water (H_2O)	Nominal channel gap: 1.85 mm
Reactor Pool Volume	H_2O Inventory	68 m^3
Fuel Thermal Conductivity	UO_2-Al	138 W/m·°C
Clad Thermal Conductivity	AL-SAV-1	187 W/m·°C

3. Computational Model and Methodology

3.1 Domain Physics and Governing Equations

The computational domain consists of a representative portion (symmetrical slice) of the hottest fuel assembly (cell 8). It includes the single gap (1.85 mm) between the fuel meat and the cladding on both sides of the modeled domain, as shown in Figure 3. The domain extends vertically across 600 mm.
The cladding and the fuel meat are modeled with their respective thicknesses (0.45 mm for the cladding and 0.35 mm for the fuel meat half-thickness).

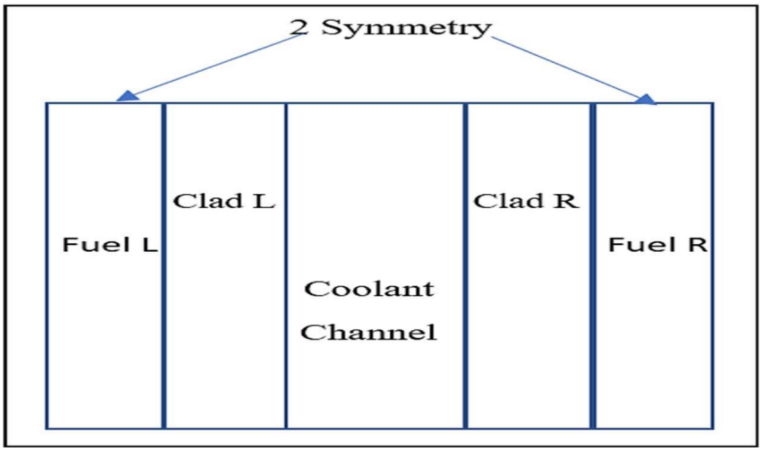

Figure 3: Hottest channel model with symmetric fuel elements.

The buoyancy forces driving the coolant flow upward against gravity are calculated using the Boussinesq approximation that accounts for the density variation resulting from the temperature difference between the fuel assembly and the coolant.
The fluid flow field is modeled as a two-dimensional, incompressible, Newtonian, and viscous flow. The buoyancy forces driving the fluid flow have been accounted for by using the Boussinesq approximation.

According to this approximation, the buoyancy force vector in the vertical momentum equation, assuming a linear dependence on temperature:

$$\rho = \rho_0[1 - \beta(T - T_0)]$$

Where ρ_0 is the reference density ($996.56\ \mathrm{kg/m^3}$) at a reference temperature $T_0 = 300\ \mathrm{K}$, and β represents the volumetric thermal expansion coefficient ($2.9 \times 10^{-4}\ \mathrm{K^{-1}}$).

For the fluid domain, the governing conservation laws for mass, momentum, and energy are expressed as follows:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \rho g$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

Where u and v represent the horizontal (x) and vertical (y) velocity components, μ is the dynamic viscosity ($0.00085\ \mathrm{Pa \cdot s}$), κ is the thermal conductivity of water, c_p is the specific heat capacity of water.

For the solid domain, the fuel meat and the cladding, the governing conservation laws for energy are expressed as follows:

$$\rho_f c_f\left(\frac{\partial T}{\partial t}\right) = \kappa_f\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + S_f$$

$$\rho_c c_c\left(\frac{\partial T}{\partial t}\right) = \kappa_c\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

Where κ_f and κ_c are the thermal conductivity of fuel and cladding, c_f, c_c is the specific heat capacity of fuel and cladding, and S_f represents the localized volumetric power source within the fuel zone.

3.2 Boundary Conditions and Mesh Layout

A highly structured, quadrilateral mesh was applied across the domain using ANSYS SpaceClaim and Fluent meshing extensions to minimize numerical diffusion and ensure finite volume method-based local mass conservation, as shown in Figure 4.

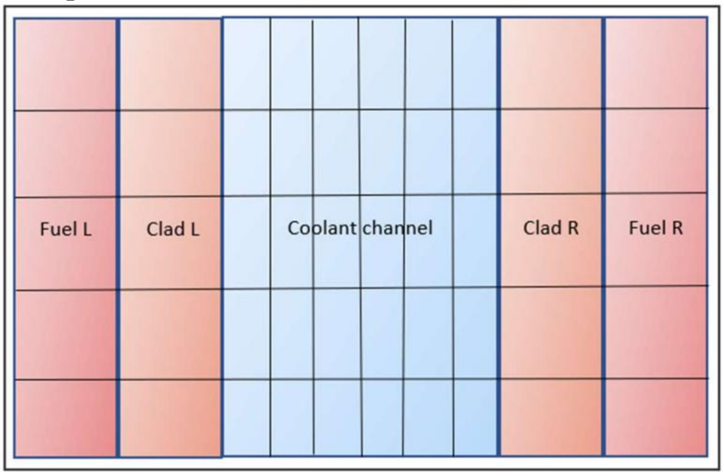

Figure 4: Structured quadrilateral mesh of the hottest channel.

The mesh cells were refined near fluid-solid interfaces to capture the flow field and thermal boundary layer development accurately.

- **Inlet and Outlet Boundaries:** Modeled using hydrostatic pressure configurations to simulate the physical fluid column heights. The inlet pressure ($84{,}075.78\ \mathrm{Pa}$) accounts for both the pool volume height and the total vertical height of the core, whereas the outlet pressure ($78{,}052.28\ \mathrm{Pa}$) is calculated relative to the standalone pool level.

- **Lateral Walls:** Outermost horizontal fuel boundaries were assigned a symmetry condition to account for the replication of the same geometry structure in the horizontal direction.
- **Solid-Fluid Interfaces:** Enforced as coupled no-slip walls to facilitate exact conjugate heat transfer calculations between the conducting metal clad and the fluid channel.
-

3.3 Core Power Distribution and Transient Pool Heating

The volumetric heat source S_f in the fuel region is non-uniform along the vertical coordinate in order to simulate realistic reactor flux profiles. The axial power density profile was defined by a position-dependent piecewise function, along the active core, as shown in table 2.

Table 2: Axial power density at different segment along hottest cell

Δz (cm)	Power density $(\mathrm{W/cm^3})$	Δz (cm)	Power density $(\mathrm{W/cm^3})$
9.12	1.131138E02	2.7	3.58507E02
10.99	2.23016E02	0.45	3.59458E02
3.54	2.83759E02	10.99	3.33417E02
13.09	3.31219E02	9.12	2.36799E02

Since the reactor is operating on natural circulation only, the coolant is circulated through the core and the pool in a loop. The bulk temperature of the coolant entering the core at the bottom increases as the pool is heated. The temperature of the pool is determined by a global energy balance on the volume of the mixing pool defined by:

$$T^{\text{new}} = \left(\frac{P}{\rho c_p V_p} \cdot \Delta t\right) + T^{\text{old}}$$

Where P is the thermal operating power level, V_p represents the effective mixing volume of the reactor pool, and Δt is the step size. Transient operations were tested at power steps ranging from 100 kW to 600 kW.

4. Results and Discussion

4.1 Transient Cladding Thermal Responses under 100% Mixing Volume

The primary safety limit imposed is that the maximum local fuel cladding surface temperature ($T_{\text{max, clad}}$) must remain below $102^\circ\mathrm{C}$ to prevent localized nucleate boiling. The baseline scenario assumes complete mixing with the entire $68\ \mathrm{m^3}$ pool volume.

Figure 5 illustrates the spatial temperature development across the fluid domain at an operating power of 600 kW at 7 hours. The temperature rises from approximately 82 C° at the channel entrance to nearly 92 C° near the outlet. This behavior is consistent with natural convection flow, where the fluid absorbs heat from the fuel plates as it moves upward, resulting in a continuous increase in temperature along the flow path.

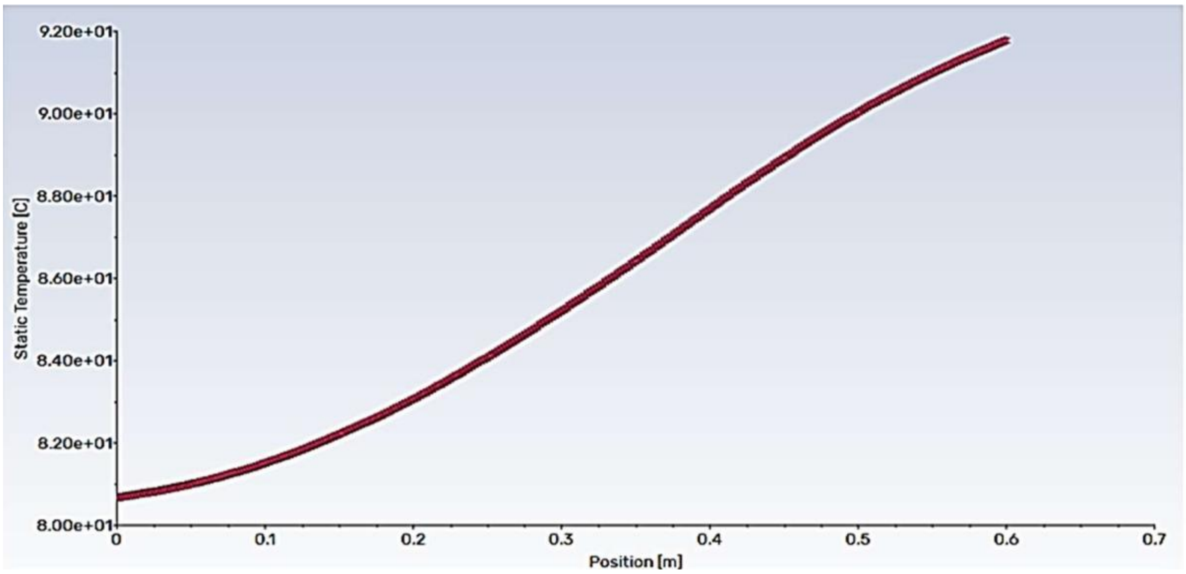

Figure 5: Temperature variation along the mid-width line at 7 hours (operating power 600 kW).

To confirm temporal numerical convergence, simulations were conducted utilizing two distinct time steps ($\Delta t = 50\ \mathrm{s}$ and $\Delta t = 100\ \mathrm{s}$); both yielded identical operational safety durations, verifying independence from time-step discretization error.

Table 3 presents the maximum allowable reactor operation time at various power levels under natural convection cooling conditions. The results are reported using two different time step sizes ($\Delta t = 50\,s$ and $\Delta t = 100\,s$) and are compared with data obtained from a previous study. The corresponding maximum cladding temperature for each power level is also listed. As shown in the table, increasing the reactor power leads to a significant reduction in the maximum allowable operation time.

At a power level of 100 kW, the reactor can be safely operated for up to 42 hours, whereas at 600 kW the allowable operation time decreases to approximately 7 hours. This behavior is expected, as higher power levels result in increased heat generation within the fuel, which accelerates the temperature rise of the cladding. It is observed that the maximum cladding temperature remains nearly constant for all investigated power levels, with values close to $102^{\circ}C$.

Table 3: Safety Operating Durations Across Varied Core Power Levels (100% Mixing Volume)

Core Thermal Power (kW)	Operational Limit Duration (hr)			Maximum Clad Temp(°C)
	Current study Δt=50s	Current study Δt=100s	Other Study [7]	
100	42.0	42.0	47.0	102.08
200	21.0	21.0	20.0	102.08
400	10.5	10.5	7.0	102.06
500	8.3	8.3	5.0	102.02
600	7.0	7.0	3.0	102.10

The 2D CFD model accounts for an extended range of safe operation at higher power compared to the narrow channel analytical model. This is attributed to the 2D model's capability to capture complex interactions and multidimensional effects such as the development of fully established boundary layers and local fluid momentum distributions without resorting to oversimplified geometric cross-sections.

4.2 Impact of Fluid Mixing Volume Fractions (75% and 50% Scenarios)

To evaluate the effect of reducing the mixing ratio of reactor pool water, the effective mixing pool volume V_p was postulated to be 75% and 50% percent of the total volume.

Table 4: Safe Operating Lifetimes under Restricted Pool Mixing Percentages.

Core Thermal Power (kW)	75% Mixing Volume Ratio		50% Mixing Volume Ratio	
	Operational Limit Duration (hr)	Maximum Clad Temp (C°)	Operational Limit Duration (hr)	Maximum Clad Temp (C°)
100	31.58	102.02	21.05	102.10
200	15.77	102.06	10.52	102.06
400	7.88	102.10	5.27	102.08
500	6.33	102.02	4.22	102.10
600	5.27	102.08	3.50	102.02

A linear reduction in the available heat sink capacity leads to a proportional decrease in safe operating times. Limiting pool mixing to 50% drops the maximum operating time at 600 kW from 7 hours down to 3.5 hours. This behavior highlights how heavily pool-type research reactors rely on global thermal inertia. When the effective mixing volume is restricted, the bulk inlet fluid heats up much faster, causing the fuel cladding to reach its maximum safe threshold ($102^{\circ}C$) significantly earlier.

5. Conclusions

A transient two-dimensional finite volume computational fluid dynamics (CFD) analysis was carried out in order to assess the natural convection cooling performance of the hottest channel in the core of the TNRR using ANSYS-Fluent. The calculations show that natural circulation alone has the capacity to provide the necessary cooling capability for the core at reduced power levels, provided that the operation time is limited to those values corresponding to the allowable clad temperature.

Specifically, the maximum allowable operating time under natural convection cooling is approximately 42 hours at 100 kW, 10.5 hours at 400 kW, 8.3 hours at 500 kW, and 7 hours at 600 kW, with the cladding temperature not exceeding the safety limit of 102 °C. Furthermore, the study investigated the effect of reducing the mixing ratio of reactor pool water, considering cases where the coolant mixing ratio is 75% or 50% of the original reactor pool volume. The results indicate that when the coolant mixing volume ratio is reduced, the safety temperature of the cladding is reached in a shorter period compared to the full mixing scenario, thereby significantly reducing allowable safe operating times. Overall, these findings emphasize the critical role of the ratio of mixing with the reactor pool volume in determining thermal–hydraulic behavior and ensuring safe operation under natural convection cooling, highlighting the importance of considering the ratio of mixing with the reactor pool water when evaluating safe operating limits for the TNRR.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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