

## Feasibility of Hybrid Architected Phase Change Materials for Passive Containment Cooling Systems

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### 1. Introduction

Fukushima Daiichi nuclear accident served as the watershed moment that fundamentally shifted the paradigm of safety systems of Nuclear Power Plants (NPP). The prolonged Station Blackout (SBO) during the accident demonstrated the critical vulnerabilities of relying on active cooling mechanisms. Consequently, the global nuclear industry has increasingly prioritized development of fully passive safety system, one that is entirely independent of operator intervention or external voltage, to ensure ultimate plant safety and containment integrity during severe accident transients.

Phase Change Materials (PCMs) represent a highly promising pathway for implementing these advanced passive safety measures. By integrating solid PCMs within the containment structure, the massive latent heat of fusion can be utilized to passively absorb decay heat and steam released during a Loss of Coolant Accident (LOCA). There has been historic usage of this concept, where cooling system was deployed as ‘ice condensers’, which were utilized in specific Westinghouse NPPs like DC Cook and McGuire. However, ice condensers present significant



Figure 1. Ice condenser of DC Cook NPP (US)

operational challenges. Primarily, they require

continuous active refrigeration to maintain sub-zero temperatures, which relies on external power. Also, the sublimation caused by low temperature could cause the cooling system to fail by clogging up the drain or sumps where the drained water flows. DC Cook NPP had to shut down for 3 years in 1997 due to cleaning task of foreign materials found in the ice condenser. [1]

To overcome the limits of sub-zero systems, most modern research focuses on high temperature PCMs that remain completely solid under normal temperatures and passively melt only under accident conditions. While PCMs are currently a prominent focus in the broader energy sector for applications such as solar thermal storage and waste heat recovery, their application in nuclear safety faces a critical bottleneck: inherently poor thermal conductivity (labeled  $k$  onwards). In accident scenarios where the containment heat and pressure spike rapidly, a low heat transfer rate can cause the system to reach peak design pressure before the bulk PCM can absorb the necessary energy. This paper aims to evaluate whether recent technological advancements in PCM composite structures can successfully overcome these thermodynamic challenges and meet the rigorous engineering thresholds required for passive containment cooling in nuclear reactors.

### 2. Establishing the Design Baseline

To accurately evaluate the viability of new PCM technologies, a modern engineering baseline must be established. Shin et al. (2022) conceptualized a Passive Containment Cooling System (PCCS) using a PCM condenser for the APR1400, providing strict thermal-hydraulic thresholds required to mitigate a Double-Ended Discharge Leg Slot Break (DEDLSB) LOCA. [2]

For the Saeul NPP (APR1400), the safety standards dictate that containment building pressure must not exceed 0.52 MPa and that the temperature must

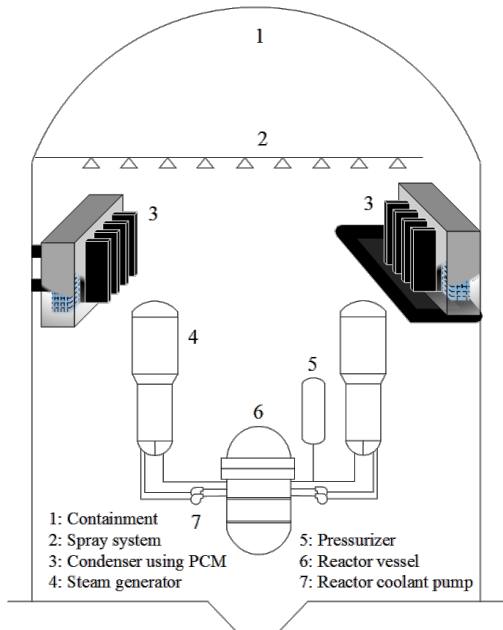


Figure 2. Concept of containment with cooling systems using PCM

remain below 160°C. Through extensive parametric studies utilizing the Containment Analysis Package (CAP) code, Shin established the following critical thresholds for a viable PCM condenser, as shown in Table 1. [2] Volume is relevant because less free-volume means the pressure spikes faster. Higher melting point means that condenser starting time is delayed, since it has to wait until system temperature reaches the higher melting point.  $k_{eff}$  effects how fast the heat is absorbed by PCM; if too slow, the system reaches peak pressure too early and too high. Shin concludes that volume must not exceed 25% of the free-volume in APR1400, and melting point and  $k$  should be within the critical threshold in Table 1.

Table I. Critical thresholds that must be considered for a PCM condenser

Threshold Variable	Limit
Volume	< 22,144 m <sup>3</sup>
Melting Point	< 78 °C
$k_{eff}$	> 6.25 W / (m·K)

Because base organic PCMs and salts typically possess low  $k$ , meeting the threshold is the primary engineering challenge. Shin’s theoretical solution relied on a structural approach. She inserted massive copper fins into the PCM to artificially force the  $k_{eff}$  up to 12.5 W/(m·K). While effective in simulation, relying on heavy macroscopic fins introduces geometric complexity, localized ‘dead zones’ of insulating solid PCM between fins, and severe weight penalties to the containment structure. The subsequent

sections evaluate whether modern architecture materials can bypass this brute-force requirement.

### 3. Evaluation of Recent PCM Advancements

#### 3.1 Metal Foam-PCM Composites (MF-PCMs)

Relying on discrete fins introduces a fundamental heat transfer limitation: while the metal fin conducts heat rapidly, the thermal energy must still conduct perpendicularly through the insulating bulk PCM between the fins. This creates thermal ‘dead zones’, regions inside PCM that are furthest from the fins, which melts at a severely delayed rate, stifling the overall transient response of the passive system.

Recent advancements in architected materials have introduced MF-PCMs as a highly viable alternative to overcoming this problem. Instead of discrete plates, MF-PCMs utilize a continuous, highly porous 3D metallic matrix (typically composed of copper, aluminum, or nickel). For instance, Oya (2012) developed porous nickel impregnated with the Erythritol under vacuum conditions and increased the  $k_{eff}$  by 16 times compared to the pure base material. [3] Li (2020) developed this further by impregnating surface-roughened hydrophilic metal foam, where he still managed to boost  $k_{eff}$  by 5 times while solving supercooling problem by providing numerous nucleation sites. [4]

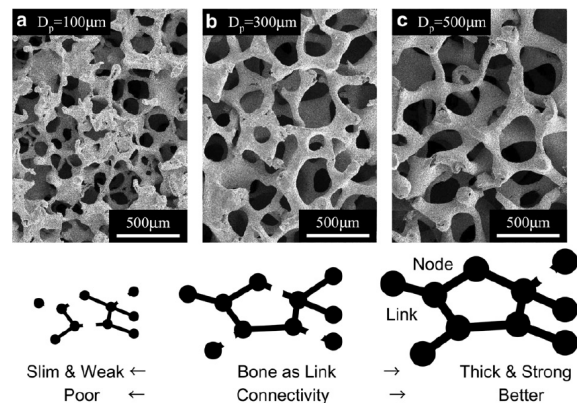


Figure 3. SEM images of porous Nickel of varying pore sizes with schematic bone structure by Oya [3]

The primary breakthrough of MF-PCM lies in their 3D thermal percolation network. Because the metallic ligaments are interconnected in all directions, heat is distributed uniformly and simultaneously throughout the entire PCM volume, eliminating solid dead zones. Furthermore, modern metal foams can achieve extremely high porosities (up to 95%). This structural efficiency implies that most of the composite volume remains dedicated to the high-capacity PCM, preserving the volumetric latent heat advantage while the remaining metal fraction easily elevates the  $k_{eff}$

well beyond the containment requirement.

From a structural integrity standpoint, MF-PCMs offer an additional passive safety benefit: the microscopic pores retain the liquid PCM via strong capillary and surface tension forces. This prevents liquid sloshing, suppresses phase-segregation, and severely limits the potential for liquid PCM leakage within the containment building during the intense vibrations of a LOCA blowdown phase.

Consequently, when evaluated against Shin's APR1400 baseline, MF-PCMs represent a highly viable and structurally sound technological breakthrough. By fundamentally eliminating localized 1D thermal resistance and easily exceeding the minimum thermal conductivity thresholds with minimal metal mass, foam composites can successfully mitigate the early-phase pressure transient without violating the 25% containment volume limit or incurring the extreme structural weight penalties associated with solid copper fins.

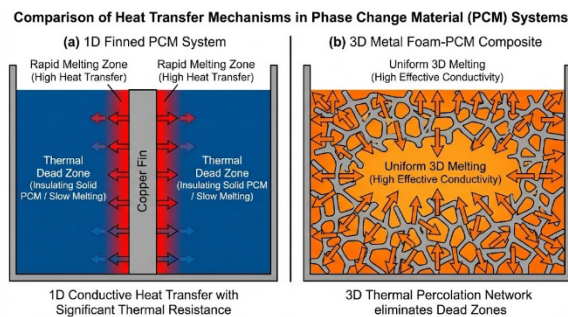


Figure 4. Comparison of 1D vs 3D Heat Transfer Mechanisms (generated by AI, Nano Banana)

However, the deployment of high-performance organics like Erythritol (which both Li and Oya used as their base PCM) reveals a fundamental thermodynamic mismatch for early-phase accident mitigation. Erythritol possesses a high melting point of approximately  $118^{\circ}\text{C}$ . While this is safely below the  $160^{\circ}\text{C}$  peak containment design limit, parametric performance maps by Shin indicate that a  $118^{\circ}\text{C}$  PCM fails to mitigate the containment pressure spike. [2] The core issues lie in the severely reduced thermal gradient between the hot containment steam and the  $118^{\circ}\text{C}$  PCM wall, which results in a sluggish heat absorption rate. Consequently, the PCM remains in a solid, sensible-heating state during the critical first few minutes of the blowdown phase, taking up to 250 seconds to initiate melting. By the time its massive latent heat capacity is finally activated, the containment may already exceed design pressure limits. As Shin established, to successfully catch the early transient with a base PCM that has  $k$  near  $1\text{ W}/(\text{m}\cdot\text{K})$ , melting point must remain at or below  $78^{\circ}\text{C}$ .

### 3.2 Nano-Enhanced PCMs (NePCMs)

While MF-PCMs provide macroscopic structural solutions by utilizing a stationary metal sponge, NePCMs focus on microscopic fluidic enhancement. Instead of integrating PCM into a macroscopic metal lattice, this approach involves directly doping the base PCM fluid with highly conductive nanostructures, such as Graphene Nanoplatelets (GNPs) or Expanded Graphite (EG) to establish a microscopic thermal percolation network by fundamentally altering the intrinsic thermophysical properties of the material itself. Recent characterizations by Ma (2022) demonstrated the immense material potential of these composites by synthesizing an Erythritol-based PCM doped with 2% EG and 1% Calcium Pimelate. [5]

From a volumetric and stability point of view, NePCMs offer a massive advantage over traditional organics. The 2% EG-Erythritol composite exhibits an exceptional latent heat capacity of  $352.66\text{ kJ}/\text{kg}$ . Compared to the  $225\text{ kJ}/\text{kg}$  of PureTemp58 utilized in Shin's baseline APR1400 model [2], this represents an over 50% increase in energy density. Utilizing such NePCMs could drastically shrink the physical footprint of the cooling condenser, safely mitigating the containment free-volume reduction penalty that accelerates early-phase overpressurization. Furthermore, the addition of CaPi successfully suppresses the severe supercooling inherent to Erythritol, ensuring reliable and stable phase transitions across thermal cycles, which is a mandatory prerequisite for decades of standby in a nuclear facility.

However, Ma also uses Erythritol, which takes too much time to start melting. This thermodynamic mismatch severely exacerbates the  $k$  requirements, exposing the limitations of purely nanoscale enhancements. While the dispersion of 2% EG successfully increases the  $k$  of Erythritol by 52.5% to achieve a  $k$  of  $1.287\text{ W}/(\text{m}\cdot\text{K})$ , this value falls drastically short of resolving the containment pressure spike. For a low-temperature PCM, Shin established a minimum  $k_{\text{eff}}$  of  $6.25\text{ W}/(\text{m}\cdot\text{K})$ . However, for higher temperature PCMs, she states that required  $k_{\text{eff}}$  exceeds  $25\text{ W}/(\text{m}\cdot\text{K})$  just to compensate for the delayed melting rate. Therefore, even with nanoscale doping, NePCMs fundamentally fail to satisfy the macro-scale thermal-hydraulic requirements on their own, proving that chemical enhancements cannot yet replace the need for massive structural heat exchanges in nuclear safety systems.

## 4. Discussion

The independent evaluation of contemporary PCM advancements reveals a critical contradiction in passive containment cooling design. While chemical

and nanoscale enhancements successfully maximize volumetric energy density and cycle stability, they fundamentally fail to satisfy the macroscopic heat transfer rates and rapid transient response times required to mitigate heat released in an accident. Conversely, relying solely on macroscopic brute-force structures, such as heavy copper fins, to achieve  $k_{eff}$  above 6.25 W/(m·K) introduces severe economic, geometric, and seismic penalties to the containment building. Furthermore, the deployment of high-capacity organic PCMs like Erythritol, despite reaching a latent heat of 352.66 kJ/kg and an enhanced  $k$  of 1.287 W/(m·K) through 2% EG doping, is thermodynamically mismatched for early-phase accident mitigation due to its high melting point.

Therefore, to achieve a breakthrough in passive containment cooling, future designs must abandon single-technology approaches in favor of Hybrid Architected Materials. This involves the synthesis of both macroscopic 3D structures and microscopic fluid enhancements. By selecting a base medium that strictly adheres to the melting point threshold (such as PureTemp58) and doping it with carbon-based nanomaterials like EG or GNPs, designers can locally eliminate severe supercooling and boost the boundary-layer heat transfer rate of the fluid.

This NePCM mixture can then be impregnated into a highly porous 3D Metal Foam matrix. This coupled architecture solves the inherent flaws of both previous systems. The continuous metallic ligaments of the foam provide the macroscopic thermal highway necessary to instantly distribute heat deep into the condenser volume, effortlessly surpassing the  $k_{eff}$  requirement. Simultaneously, the nano-dopants bridge the microscopic thermal resistance between the metal foam ligaments and the bulk PCM, accelerating the solid-liquid melting front.

Ultimately, while the deployment of a purely fluid-based PCM cooling condenser is still technologically far off, the transition towards multi-scale hybrid composites provides a highly viable and realistic scope for implementation. By maximizing porosity to maintain latent heat capacity and utilizing 3D thermal percolation to guarantee rapid transient response, advanced reactor concepts like the i-SMR or APR1400 can significantly shrink the spatial footprint of their passive safety systems while rigorously ensuring containment integrity during prolonged SBO scenarios.

## 5. Conclusions & Further Works

This study evaluated recent advancements in phase change technologies against the strict thermal-hydraulic baseline required for the APR1400 passive containment cooling system. The analysis

demonstrates that while MF-PCM composites resolve macroscopic thermal resistance and NePCMs maximize energy density while suppressing supercooling, neither technology is viable as a standalone solution when utilizing high-temperature organics like Erythritol. To meet the  $k_{eff}$  and melting point thresholds without reintroducing the extreme weight penalties of solid copper fins, future passive safety designs must transition to Hybrid Architected Materials.

Further experimental works should focus on impregnating low-temperature, nano-doped base fluids into highly porous 3D metallic lattices to validate long-term dispersion stability and transient heat absorption rates under simulated accident conditions.

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