Assessment of Passive Cooling and Combustion Suppression by Ice Bed Condensers and Mitigating PWR Hydrogen Deterministic Risk

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Abstract

This study explores the performance of Ice Bed Condensers (IBC) in controlling hydrogenrelated hazards during severe accident progression in PWR reactor under a prolonged Station Blackout (SBO) scenario. Simulations using MELCOR 1.8.6 reveal that during the in-vessel phase, zircaloy oxidation begins after 5690 s, producing approximately 578 kg of hydrogen once cladding temperatures exceed 1200 K. Without IBC, multiple combustion events occur between 15,000-30,000 s, reaching combustion power peaks of 4.5$×10^{8}$ W, containment pressures above 200,000 Pa, and temperatures exceeding 1500 K, resulting in hazardous conditions prone to deflagration and detonation. With IBC active, only one combustion event occurs at 58,000 s with reduced intensity (2.5$×10^{8}$ W) and significantly lower thermal and pressure impacts, keeping temperatures below 1400 K. In the ex-vessel phase, a rapid increase in hydrogen generation is observed-reaching a peak rate of 250 kg/s at 16,674 s, with total production accumulating to 1530.24 kg by 100,000 s. Without IBC, sharp and frequent pressure spikes and high containment temperatures above 2000 K are recorded, further increasing combustion risk. IBC operation reduces thermal stress, stabilizes pressure fluctuations, and prevents early combustion. Approximately 4000 kg of granular ice is consumed during the accident, with 2000 kg remaining by the end, demonstrating the IBC's extended passive cooling capacity. Overall, the IBC significantly improves containment behavior, limits hydrogen combustion power, and enhances nuclear safety during extended SBO conditions.

Full Text

Preamble

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This study explores the performance of Ice Bed Condensers (IBC) in controlling hydrogen-related hazards during severe accident progression in a PWR reactor under a prolonged Station Blackout (SBO) scenario. Simulations using MELCOR 1.8.6 reveal that during the in-vessel phase, zircaloy oxidation begins after 5690 s, producing approximately 578 kg of hydrogen once cladding temperatures exceed 1200 K. Without IBC, multiple combustion events occur between 15,000–30,000 s, reaching combustion power peaks of 4.5$\times10^{8}$ W, containment pressures above 200,000 Pa, and temperatures exceeding 1500 K, resulting in hazardous conditions prone to deflagration and detonation. With IBC active, only one combustion event occurs at 58,000 s with reduced intensity (2.5$\times10^{8}$ W) and significantly lower thermal and pressure impacts, keeping temperatures below 1400 K. In the ex-vessel phase, a rapid increase in hydrogen generation is observed—reaching a peak rate of 250 kg/s at 16,674 s, with total production accumulating to 1530.24 kg by 100,000 s. Without IBC, sharp and frequent pressure spikes and high containment temperatures above 2000 K are recorded, further increasing combustion risk. IBC operation reduces thermal stress, stabilizes pressure fluctuations, and prevents early combustion.

Approximately 4000 kg of granular ice is consumed during the accident, with 2000 kg remaining in the IBC by the end, demonstrating the IBC's extended passive cooling capacity. Overall, the IBC significantly improves containment behavior, limits hydrogen combustion power, and enhances nuclear safety during extended SBO conditions.

Keywords: Ice Bed Condenser (IBC), Hydrogen Combustion and Risk, Station Blackout (SBO), Ex-vessel Accident, MELCOR Simulation, Containment Pressure, Passive Safety Systems

1. Introduction

The management of hydrogen generation and its associated risks during severe nuclear accidents is a critical concern for nuclear safety. Hydrogen, primarily produced through the high-temperature oxidation of zirconium cladding and the radiolytic decomposition of water, poses significant threats during incidents such as station blackouts (SBOs). The uncontrolled accumulation of hydrogen can lead to deflagration or detonation, resulting in catastrophic failures of containment structures and potentially releasing radioactive materials into the environment (Approaches and Tools for Severe Accident Analysis for Nuclear Power Plants, 2008; Severe Accident Management Programmes for Nuclear Power Plants, 2009). Historical events, particularly the Fukushima Daiichi accident in 2011, starkly illustrate the devastating consequences of inadequate hydrogen management, as explosions severely compromised reactor integrity and hindered emergency response efforts (Shimizu, 2016).

Current hydrogen mitigation strategies, including passive autocatalytic recombiners (PARs) and igniters, face limitations under extreme conditions, particularly when hydrogen production rates exceed their operational capacities (Payot et al., 2012). These systems, while effective in some scenarios, struggle in high-steam environments, leading to the urgent need for innovative solutions that can provide reliable passive safety mechanisms. One promising approach is the utilization of ice bed condensers. These systems leverage the latent heat of ice to absorb thermal energy, thereby reducing the temperature and pressure within containment vessels (Zhang et al., 2024). This cooling effect not only mitigates thermal stresses but also suppresses steam content, which is crucial for preventing hydrogen-air mixtures from reaching flammable concentrations (Soltanmohammadi et al., 2025). Ice bed condensers operate by facilitating the condensation of steam, which dilutes hydrogen concentrations and significantly reduces the likelihood of combustion events (Dingman & Camp, 1985). Experimental studies have demonstrated their effectiveness in maintaining lower thermal conditions, which directly impacts the behavior of hydrogen in containment atmospheres (Rämä et al., 2019). During the in-vessel phase of an SBO, these condensers can assist in core cooling and mitigate zirconium oxidation rates, thus delaying hydrogen generation (Nourbakhsh, 1990). In the ex-vessel phase, where molten corium may interact with concrete, ice bed condensers further contribute to thermal management and hydrogen control, enhancing overall containment safety (Chen et al., 2024).

The dual-phase application of ice bed condensers offers a unique opportunity to integrate advanced safety features into nuclear reactor designs. By employing these systems in both in-vessel and ex-vessel scenarios, engineers can enhance the resilience of containment structures against hydrogen-related incidents (Kim et al., 2018). Comprehensive assessments indicate that ice bed condensers can effectively reduce temperature and pressure spikes, maintaining hydrogen concentrations within safe limits even during severe accidents (Wang et al., 2024). However, the long-term performance and optimal configuration of these systems require further investigation to maximize their effectiveness.

This article aims to provide a thorough examination of the application of ice bed condensers as a mitigation strategy for hydrogen deflagration and detonation risks in nuclear containment structures. By reviewing existing literature and integrating experimental findings, we seek to elucidate the efficacy of this approach during both in-vessel and ex-vessel stages of SBO accidents. Furthermore, we will consider the regulatory implications and future directions necessary for the integration of ice bed condensers into new reactor designs, reinforcing the imperative of adopting advanced safety methodologies within the nuclear operational framework (Jian & Cao, 2006).

In conclusion, the implementation of ice bed condensers represents a proactive strategy to enhance nuclear safety in the face of hydrogen risks. Given the lessons learned from past accidents, including Fukushima, it is imperative to advance the development of passive safety technologies that can reliably mitigate hydrogen generation and accumulation. By addressing the challenges posed by hydrogen during severe accidents, ice bed condensers not only improve containment integrity but also contribute to the broader goal of ensuring public safety and confidence in nuclear energy. The findings of this study aim to inform regulatory frameworks and guide the future design of nuclear reactors, ultimately supporting the mission of achieving a safer nuclear industry.

2. Material and Method

This investigation presents a comprehensive analysis of high-pressure core degradation and hydrogen generation mechanisms during a station blackout at a Nuclear Pressurized Water Reactor (PWR) power plant, encompassing both early and prolonged phases. The methodology employs MELCOR 1.8.6 simulations to characterize the containment, core, and cooling systems, enabling a detailed examination of severe accident progression phenomena.

2.1 Phenomenology

The ice bed condenser in a PWR reactor containment system plays a pivotal role in managing thermal and pressure dynamics during severe accidents, particularly those resulting from a station blackout (SBO). In such scenarios, the loss of power disables active cooling systems, leading to increased reactor core temperature due to decay heat. The ice bed, typically composed of large volumes of granulated and solid ice, serves as a passive heat sink. As the containment atmosphere heats up, the ice melts, absorbing significant amounts of thermal energy through the latent heat of fusion. This process delays the onset of containment pressure buildup, providing critical time for emergency systems to restore cooling functions. The effectiveness of the ice bed condenser is influenced by several factors, including the thermal conductivity of the ice, its specific heat capacity, and the density of the ice bed. These properties determine how efficiently heat is transferred from the containment atmosphere to the ice and how much heat the ice can absorb before its temperature rises significantly. In the event of a prolonged SBO, if the ice bed's capacity is exhausted, the containment pressure can rise, potentially leading to phenomena such as direct containment heating (DCH). DCH occurs when molten core debris is ejected into the containment atmosphere, rapidly heating the gas and increasing pressure. To mitigate such risks, hydrogen control systems including ice beds have been suggested, and the design of the PWR reactor containment—including the placement and volume of the ice bed—is critical in determining the system's response to severe accidents. The containment's geometry, coupled with the ice bed's thermal properties, influences the distribution of heat and gases within the containment. Advanced computational models and probabilistic safety assessments are utilized to simulate various accident scenarios, including prolonged SBOs, to evaluate the performance of the ice bed condenser and associated safety systems. These analyses help identify potential vulnerabilities and inform design improvements to enhance the reactor's safety margins and ensure containment integrity under extreme conditions.

2.2 PWR Ice Bed Containment and Cavity Description

The containment is modeled with a 24-cell nodalization. Table (1) provides a summary of the containment's control volumes, detailing the physical volume of each compartment, including the reactor cavity, steam generator doghouses, ice bed, and the upper and lower plenums (Gregory et al., 1992). These volumes are crucial for simulating heat transfer and hydrogen distribution during severe accidents. Fig (1) illustrates the spatial schematic of these control volumes, showing how gases and heat are managed within the containment. The model also incorporates passive safety features like the ice bed, which absorbs thermal energy and helps prevent pressure buildup.

The ice condenser plays a critical role in controlling pressure within the containment during an accident. It uses a combination of solid and granulated ice to absorb heat and manage pressure. Solid ice has a density of 915 $\mathrm{kg/m^3}$, and granulated ice has a lower density of 596.77 $\mathrm{kg/m^3}$. These values are essential for calculating the heat absorption and dissipation capacity of the ice during accident simulations. Thermal conductivity is 2.18 $\mathrm{W/m \cdot K}$, and the specific heat capacity is 2040 $\mathrm{J/kg \cdot K}$ in the MELCOR simulation model. These values are crucial for predicting how heat from the reactor is managed by the ice bed. The ice bed has a height of 14.53 meters and a surface area of 6200 $\mathrm{m^2}$, providing substantial volume for heat absorption. Cavity composition properties are described in Table (2).

The PWR reactor cavity is the central containment area where the reactor core and associated coolant systems are housed. It is designed to withstand extreme pressures and temperatures, particularly during severe accident scenarios like station blackouts (SBO). The cavity helps manage the heat generated by the reactor during both normal operation and accidents. It also plays a critical role in containing any released gases or steam, ensuring that the containment structure remains intact. The cavity's material properties, including reinforced concrete and steel, are specifically chosen to resist high thermal and mechanical stresses. These materials are essential for maintaining the structural integrity of the containment system during emergency situations. Compositions are shown in Table (3).

2.3 Accident Scenario and Phenomenology

The SBO scenario in a PWR reactor begins when both offsite power and emergency diesel generators (EDGs) fail, leading to the loss of all AC power. This means that all active safety systems, including the reactor coolant pumps (RCPs), containment sprays, and hydrogen igniters, are no longer operational. The loss of these systems results in the inability to remove heat from the reactor core. In response, decay heat continues to generate thermal energy in the reactor, raising the temperature and pressure inside the reactor vessel and the containment.

Initially, core heatup occurs as the RCPs stop circulating the coolant, leading to increased cladding temperature and eventually fuel temperature. As the temperature rises, hydrogen is produced due to zircaloy cladding oxidation. Meanwhile, without active cooling systems, the heat generated from the core starts to accumulate within the reactor vessel and containment. At the same time, the ice bed condenser, which is designed to mitigate such thermal loads, begins to absorb heat as the containment atmosphere heats up. The latent heat of fusion from the melting ice absorbs significant thermal energy, preventing the containment pressure from rising too quickly. However, if the ice is depleted, the containment faces higher risks due to increased temperature and pressure. Once the ice bed has been exhausted and if hydrogen accumulation continues without ignition systems, the hydrogen concentration in the containment may reach levels where it could lead to combustion if not properly managed. The reactor vessel and containment pressure continue to rise as the heat from core degradation intensifies, creating the potential for delayed containment failure if the pressure relief systems are insufficient.

2.4 Ex-Vessel Phase of SBO Scenario

Ex-vessel core degradation begins as the reactor core melts, releasing molten core debris into the containment. This leads to a high-pressure melt ejection (HPME) event, where steam and molten fuel interact, rapidly increasing pressure within the containment. The heat from core degradation accelerates the zircaloy oxidation process, producing large amounts of hydrogen. This hydrogen accumulates in the containment, raising the risk of forming explosive hydrogen-air mixtures. The release of molten debris into the containment atmosphere also contributes to further thermal energy release, which exacerbates both pressure and temperature increases in the containment.

As hydrogen generation continues, the concentration of hydrogen increases, and without operational hydrogen igniters or ventilation systems, the gas may reach levels capable of triggering deflagration or detonation. This creates a significant safety concern, as increasing pressure and hydrogen concentration could lead to delayed containment failure. The combination of HPME, hydrogen production, and ex-vessel debris release challenges the integrity of the containment, making it critical to manage these risks effectively to prevent catastrophic failure during an SBO scenario.

3. Results

The results are categorized into calculations of hydrogen production and release during the in-vessel and ex-vessel phases. The formation and distribution of hydrogen, together with steam, influence the pressure and temperature of the containment; hence, key thermodynamic parameters are reported. It is noted that only half the IBC load is considered in the early phase, while full load is used in the prolonged stage.

3.1 Early Phase of the Accident

The steady-state parameters of the system have been previously analyzed (Soltanmohammadi et al., 2024). This study focuses on the transient response of the system under Station Blackout (SBO) conditions, specifically examining the progression of events leading to hydrogen generation. In the absence of operator safety procedures, the implementation of SBO results in the shutdown of both primary and secondary circuit pumps, leading to a significant reduction in coolant flow. This reduction induces a temperature increase in the primary circuit water, which subsequently elevates the temperature within the secondary circuit and generates high-pressure, high-temperature steam within the steam generators.

As the system pressure increases, it eventually reaches the activation threshold of the steam generator relief valves. The intermittent opening and closing of these valves release high-enthalpy fluid into the containment, diminishing the heat removal capacity of the steam generators. Approximately one hour post-SBO initiation, feedwater within the heat exchangers is depleted. Consequently, the coolant temperature and pressure in the primary circuit increase significantly, reaching the setpoint of the pressurizer safety valves. At this stage, coolant is progressively discharged into the containment, resulting in substantial changes in the thermodynamic conditions within the primary circuit.

At 5690 seconds post-SBO, fuel assemblies begin to uncover, leading to increased cladding surface temperature that reaches the oxidation threshold of 1200 K. This initiates hydrogen production, primarily through oxidation reactions involving zirconium, followed by the oxidation of steel and boron carbide. The total amount of hydrogen produced during this phase is 578 kg, as depicted in Fig (2-a). Given the initial isolation of the primary circuit without structural failures, the generated hydrogen accumulates within the circuit and is intermittently released into the containment with high velocity and energy upon the opening of the pressurizer relief valve. The release velocity and hydrogen dispersion rate are critical parameters in evaluating the potential for ignition and explosion scenarios, requiring further analysis to quantify these parameters and assess associated risks.

Fig (2-b) shows hydrogen concentration in the containment compartment over time, with and without the use of the Ice Bed Condenser (IBC). The curve representing the scenario without IBC shows a significant increase in hydrogen concentration, peaking and fluctuating multiple times, indicating rapid buildup and potential risks of explosive mixtures. In contrast, the blue dashed line shows a much lower and more stable hydrogen concentration, demonstrating the ice bed's effectiveness in controlling hydrogen levels. The IBC helps absorb thermal energy, thereby reducing the rate of hydrogen distribution and accumulation and improving containment safety.

As shown in Fig (2-c), the containment pressure during an SBO accident scenario compares containment behavior with and without the Ice Bed Condenser (IBC). In the scenario without IBC, containment pressure rises sharply, experiencing frequent and substantial peaks. These pressure spikes occur as a result of thermal energy produced by the reactor core, leading to rapid buildup of steam and hydrogen within the containment. The lack of a passive cooling system like the IBC results in higher temperatures and increased pressure, posing a risk to the containment's structural integrity. In contrast, when the IBC is present, containment pressure remains much more stable and lower throughout the simulation.

Fig (2-d) illustrates containment temperature during an SBO accident scenario, comparing cases with and without the Ice Bed Condenser (IBC). In the absence of IBC, temperature increases rapidly, with significant spikes reaching over 1500 K. These high temperatures result directly from decay heat generated by the reactor core during a loss of cooling. If left uncontrolled, these temperatures could have severe consequences, such as damaging critical containment components, electrical systems, and other safety equipment. Moreover, excessively high temperatures can trigger direct containment heating (DCH), a phenomenon that significantly raises containment pressure and further exacerbates the risk of containment failure. Conversely, when the IBC is utilized, temperature remains significantly more stable and lower. The IBC absorbs substantial thermal energy through ice melting, preventing temperature from rising to critical levels. By reducing temperature rise, the IBC ensures that the containment structure remains intact, protecting its integrity and preventing thermal damage to sensitive equipment while reducing the risk of overheating that could lead to containment failure. In essence, the IBC plays a key role in moderating thermal conditions, ensuring the reactor remains safer during the in-vessel stage of severe accidents.

3.2 Prolonged SBO Accident with Ex-Vessel Consequences

During reactor core degradation, molten materials collect in the lower plenum, forming an intensely heated pool. Continued thermal loading results in eventual failure of the lower plenum, at which point the molten core is expelled into the reactor cavity as a pressurized jet, propelled by the reactor pressure vessel and its ancillary systems. Within the ex-vessel simulation framework, the onset of new physical processes—such as interaction between molten core and concrete, as well as subsequent fuel relocation—is initiated by a “cavity wake-up message.”

The modeling of high-pressure molten material ejection into the cavity draws upon findings from prior research (Soltanmohammadi et al., 2024).

Upon entry of molten core into the cavity and commencement of the ex-vessel phase, hydrogen generation is primarily attributed to oxidation of structural alloys, including steel and zirconium, in the presence of steam, alongside chemical reaction between the melt and the concrete of the cavity's floor and walls. The overall hydrogen yield is strongly influenced by parameters such as cavity floor thickness, spatial distribution of the melt, interactions with thermal barriers, and the rate of release into the containment environment. As depicted in Fig (3-a), rapid hydrogen generation is observed, with approximately 838 kg produced within the first 700 seconds. The production rate subsequently peaks at 250 kg/s at 16,674 seconds, representing a critical safety concern. Limited avenues for hydrogen escape from the cavity, compounded by blockages due to solidified debris, further deteriorate containment integrity.

As illustrated in Fig (3-b), cumulative hydrogen production reaches 1530.24 kg at 100,000 seconds, with over half of this quantity generated during the initial 700 seconds. Notably, by 20,000 seconds, less than 200 kg of hydrogen has exited the cavity. This significant accumulation, together with the high rate of hydrogen generation, creates hazardous conditions within the containment, greatly elevating the likelihood of deflagration or detonation events.

Fig (3-c) presents containment pressure during the ex-vessel accident stage, comparing scenarios with and without the Ice Bed Condenser (IBC). Without IBC, containment pressure increases significantly, characterized by large, abrupt spikes exceeding 200,000 Pa, indicating rapid and severe pressure escalation. Such pressure surges pose serious hazards, including potential structural damage to containment walls, failures in seals and valves, and increased probability of uncontrolled radioactive material release. Additionally, rapid and severe pressure fluctuations could trigger further mechanical and structural failures, exacerbating containment integrity issues. Conversely, with implementation of the IBC, containment pressure remains notably lower, displaying fewer and significantly less intense pressure fluctuations. The IBC functions by absorbing heat through ice melting, thereby effectively limiting temperature-induced pressure buildup and considerably reducing the risk of high-pressure peaks and associated structural failures.

Fig (3-d) shows that without IBC, containment temperatures rapidly escalate, surpassing 2000 K and showing considerable instability, indicative of severe thermal conditions. These extreme temperatures significantly heighten the risk of hydrogen generation, as zircaloy oxidation and molten debris interactions intensify. Elevated temperatures facilitate conditions favorable for hydrogen combustion, increasing the likelihood of deflagration or even detonation, which would severely compromise containment integrity and safety. Conversely, in the scenario employing the IBC, containment temperatures are notably reduced and exhibit greater stability, generally remaining below 1400 K. The IBC mitigates temperature increases through passive heat absorption from ice melting, thereby substantially reducing hydrogen generation rates. This temperature moderation not only decreases hydrogen concentration but also significantly lowers the probability of combustion events. Thus, the IBC's presence effectively minimizes thermal stresses and reduces hydrogen combustion risks, enhancing containment safety and maintaining structural integrity during severe ex-vessel accident conditions.

3.3 Hydrogen Combustion Condition and Ice Bed Effect

As illustrated in Fig (5-a), without IBC, rapid, repeated hydrogen combustion events occur between approximately 15,000 s and 30,000 s, peaking around 4.5×10^8 Watts. Such elevated combustion powers indicate very high flame velocities and intense energy releases, suggesting scenarios approaching violent deflagration conditions. Under these extreme combustion conditions, flame fronts propagate rapidly, significantly increasing the risk of transitioning from deflagration to detonation—a more destructive event characterized by shockwaves capable of catastrophic structural damage to the containment. Moreover, these rapid hydrogen combustion events escalate containment pressure and temperature dramatically, imposing severe mechanical stresses on containment boundaries, seals, penetrations, and support systems.

Conversely, with implementation of the IBC, combustion occurs just once around 58,000 s, at a lower peak power of roughly 2.5×10^8 Watts. This significant delay and reduction in combustion intensity indicate a much more controlled hydrogen generation and accumulation scenario. The IBC, by effectively absorbing thermal energy through ice melting, lowers overall containment temperature, thereby significantly reducing hydrogen production rates and consequently hydrogen concentrations. Lower hydrogen concentrations slow flame propagation speeds substantially, minimizing risks of intense deflagration or escalation into a detonation event. Furthermore, the reduced intensity of hydrogen combustion substantially diminishes mechanical and thermal loads on the containment structure, valves, and seals. This controlled combustion scenario prevents severe pressure and thermal stresses, preserving the integrity of critical safety systems and reducing the probability of radioactive release. Hence, the IBC's presence ensures enhanced containment safety by effectively moderating combustion conditions, minimizing hydrogen combustion hazards, and significantly mitigating severe risks associated with rapid and violent hydrogen combustion events.

Fig (5-b) represents the mass of granular ice consumed within the ice bed condenser (IBC) during the progression of a severe accident scenario. Ice consumption rapidly increases, reflecting intense thermal conditions due to high energy releases, including hydrogen combustion events. The ice bed effectively absorbs this energy through the latent heat of fusion as ice transitions from solid to liquid, significantly moderating temperature and stabilizing containment conditions. The peaks and fluctuations in ice consumption around 20,000 seconds correlate directly with intense thermal energy from hydrogen combustion periods, where substantial energy is transferred to the ice bed. Initially, as time progresses beyond about 40,000 seconds, the consumption of granular ice gradually slows down, indicating reduced thermal loads due to decreased hydrogen generation and combustion rates. The thermodynamic mechanism involves the ice bed condenser utilizing the ice's latent heat capacity to absorb large quantities of thermal energy without significant temperature rise, maintaining relatively stable containment conditions and enhancing reactor safety. The sustained consumption and eventual stabilization around 2,000 kg of remaining ice highlights the ice bed's passive and prolonged cooling capacity. This behavior significantly contributes to controlling hydrogen energy release, mitigating risks of explosive gas mixtures, preventing excessive temperature increases, and thus preserving containment integrity during severe accidents.

4. Conclusion

- The implementation of an Ice Bed Condenser (IBC) in containment effectively mitigates hydrogen risk by leveraging latent heat absorption. As ice melts, it absorbs thermal energy without increasing in temperature, thus passively moderating the containment environment during decay heat buildup.
- In the absence of IBC, rapid hydrogen combustion events are initiated early, between 15,000–30,000 seconds, with combustion power exceeding 4.5$×10^{8}$ W. These events arise from unmitigated temperature rise and high hydrogen concentration, both of which create conditions favorable for deflagration and potential transition from deflagration to detonation (DDT).
- The IBC delays hydrogen ignition to approximately 58,000 seconds and reduces the maximum combustion power to 2.5$×10^{8}$ W, primarily by suppressing the thermal feedback loop that accelerates hydrogen production via zircaloy-steam reactions. This demonstrates its key role in interrupting positive feedback cycles in accident progression.
- Thermodynamically, containment temperature without IBC rises above 2000 K, significantly increasing kinetic energy of gas molecules and promoting faster hydrogen diffusion, flame acceleration, and turbulent combustion. With IBC, temperature remains below 1400 K, preserving containment structural material integrity and preventing thermal degradation of key components.
- The presence of IBC also reduces pressure transients in containment. Without it, pressure rises abruptly beyond 200,000 Pa, primarily due to hydrogen combustion and steam expansion. With IBC, pressure increase is slower and more stable due to reduced gas temperature and volume via condensation and ice heat absorption.
- The hydrogen generation rate during the ex-vessel phase peaked at 250

kg/s at 16,674 s, driven by molten core-concrete interactions and zirconium oxidation in oxygen-deficient environments. This peak was effectively moderated by IBC's cooling, which indirectly slowed reaction kinetics by lowering local gas temperatures.

- The IBC demonstrated sustained cooling capacity by melting approximately 3000 kg of ice, with about 2000 kg remaining at the end of the simulation. This shows the effectiveness of latent heat of fusion (334 kJ/kg) in maintaining a buffer against thermal and pressure excursions throughout a prolonged SBO.
- The risk of deflagration and detonation was significantly reduced with IBC, due to its ability to maintain hydrogen concentrations below the flammability limit in many compartments and reduce temperature gradients, which are key drivers for flame acceleration and shock formation.
- Without IBC, structural components in the containment would likely be exposed to temperatures above their creep rupture thresholds, especially in steel liners and cable insulation, leading to failure of passive safety functions. IBC preserves operational margins for these systems by regulating the thermal environment.
- Overall, the Ice Bed Condenser proves to be a thermodynamically robust passive safety system, delaying critical combustion phenomena, damping high-frequency pressure and temperature oscillations, and supporting the long-term structural integrity of containment. Its performance under both in-vessel and ex-vessel phases makes it essential for modern severe accident management strategies.

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