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Editorial: Nuclear reactor safety and accident mitigation management

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Editorial on the Research Topic
Nuclear reactor safety and accident mitigation management

Overview

Nuclear reactor safety and accident mitigation are critical pillars in the design, licensing, and operation of a nuclear reactor. Ensuring high safety standards not only enables regulatory approval and public acceptance but also underpins the reliable deployment of nuclear energy for sustainable development. As nuclear energy continues to play a vital role in global decarbonization efforts, rigorous safety protocols, robust containment systems, emergency preparedness, and continuous research form the foundation of modern reactor safety philosophy. Major nuclear accidents (e.g., TMI, Chernobyl, Fukushima Daiichi) have demonstrated the need for continuous safety improvement in hardware, operating protocols and the scientific understanding of accident progression and mitigation. Accurate estimation of accident source terms, the release and transport of radioactive material, remains a complex multiphysics problem to study for the reactor safety of next-generation reactor designs and accident management strategies to minimize off-site radiological consequences.

The Research Topic, "Nuclear Reactor Safety and Accident Mitigation Management," was established to showcase state-of-the-art research that supports reactor safety from a mechanistic, experimental, and system-level perspective. This Research Topic comprises five diverse yet interconnected studies covering aerosol transport and deposition in the cover gas space of sodium-cooled fast reactors (SFRs), aerosol deposition and resuspension in piping, iodine oxide aerosol formation and characterization, iodine capture by zeolite filters, and modelling of debris-bed dryout and cooling. Each contribution aligns with the objective of the Research Topic: to reduce uncertainty in reactor safety analyses and reinforce accident mitigation strategies using validated models, experiments, and new insights into severe accident phenomena. Specifically, the studies examine radionuclide aerosols transport and deposition processes Patel et al., Kumar et al., Mariam et al., iodine retention in engineered filter systems Lind et al., and the thermal-hydraulic conditions governing debris-bed coolability Peng et al. Collectively, these works integrate the advanced modelling approaches, digital technologies, and state-of-the-art experimental methods to provide a more comprehensive understanding of accident progression, radionuclide transport, and system responses under extreme conditions. The findings have direct implications for enhancing the resilience of future reactor designs, including Generation IV and sodium-cooled fast reactors. Below is the summary of their findings and implications.

Mechanistic aerosol transport in cover gas of SFR

Patel et al. conducted a mechanistic assessment of sodium aerosol transport in the cover gas space of a pool-type sodium-cooled fast reactor (SFR) following a core-disruptive accident (CDA). They modelled annular leak paths through the reactor roof slab and loss of its cooling lines. Using sodium aerosols as a representative for radioactive particles, they found that most particles escaping through the slab are 5–25 μm in diameter, with peak leak rates for ~17–23 μm particles. Crucially, complete roof-slab cooling failure yields much higher aerosol release rates, emphasizing the critical role of passive heat removal systems. This implies that maintaining roof-slab cooling integrity is vital to limit radioactive aerosol escape from roof-slab leak paths. Air ingress was observed only in annular leak paths, with negligible mixing into the cover gas, suggesting minimal fresh air entrainment under the studied conditions. Overall, this study provides the first quantitative assessment of cover-gas source terms in SFRs, offering parameters (particle sizes, leak rates) needed for containment safety analysis.

Aerosol deposition and resuspension in straight test pipes

Kumar et al. performed scale-down experiments on aerosol deposition and resuspension in a 4 m long horizontal pipe. Zinc-oxide particles (surrogate for radioactive aerosols) were injected at 180 L/min for the deposition phase, then the flow was ramped to 1265 L/min for resuspension. They observed that thermophoretic forces (due to hot gas) dominated particle deposition that occurred under the initial warm flow. When flow velocity increased, a larger fraction of deposited particles resuspended, especially toward the downstream end. In fact, the “resuspended-to-deposited” mass ratio rose with Reynolds number. The spatial profiles of deposited and resuspended aerosol mass were also tracked over 20-minute experiment and compared with the ASTEC (SOPHAEROS) code, showing fair agreement. The authors underlined that resuspension can significantly impact source-term estimates during an accident. The authors emphasize that resuspension, often neglected in simple models, warrants further study because it “impacts the accuracy of estimation of the source term.”

Iodine retention by Ag–zeolites under high humidity

Lind et al. examined silver-exchanged zeolite filters (Ag-zeolites) intended for Filtered Containment Venting Systems (FCVS) during accident scenarios. Two Ag-zeolites were tested: one engineered also for hydrogen recombination and one primarily for iodine capture. Tests introduced methyl-iodide (CH_3I) and hydrogen into a humidified flow (steam 32%–90%, air 0%–19%, H_2 2.5%–5%, N_2 balance) with residence times of 100 ms and 200 ms. Both zeolites achieved very high CH_3I retention at 200 ms residence time, essentially removing all organic iodine (retention efficiencies are> 99%) from the gas under those conditions. However, at the shorter 100 ms contact time, the capture efficiency dropped significantly. Hydrogen recombination (via the catalytic Ag) also depended strongly on the gas composition, as expected from the different zeolite designs. These results confirm that properly sized Ag-zeolite beds can effectively trap volatile iodine species even in high humidity conditions. In practical terms, dual-purpose Ag-zeolites (capable of both trapping iodine and catalyzing H_2 recombination) performed well, but their efficiency is sensitive to flow rates and gas composition. In this context, FCVS systems normally scrub aerosols well, but organic iodides resist aqueous scrubbing; thus, Ag-zeolites are essential as a final iodine capture stage.

Formation and characterization of iodine oxide aerosols

Mariam et al. conducted laboratory experiments on iodine oxide aerosol formation from I_2/ozone chemistry, a less-studied part of the iodine source term. They generated aerosols by mixing ~1 ppm iodine vapor with ~30 ppm ozone at ambient temperature/humidity, reacting in a controlled chamber. By continuously measuring ozone concentration decay, they indirectly tracked iodine oxidation. The formed particles were collected using impactors and analyzed by SEM, EDX, and XPS. The analyses revealed that the dominant chemical species was iodine pentoxide (I_2O_5), and particle morphologies ranged from small porous clusters to larger rod-like agglomerates. The study further confirms that ozone decay follows first-order kinetics ($R^2 > 0.99$), validating the reaction pathway and enabling future kinetic modelling. This approach, using ozone as a tracer rather than radioactive isotopes, provides new experimental data on iodine aerosol chemistry. Such insights fill gaps in understanding how volatile iodine can form particulate oxides in containment, which in turn informs source-term modelling and safety codes.

Debris-bed dryout modelling (homogeneous and stratified)

Cooling of molten-core debris (in-vessel) is a crucial defence in severe accident studies. Peng et al. developed mechanistic enhanced models for the dryout heat flux (DHF) of core-melt debris beds, addressing key physics missing in earlier models. DHF is the threshold heat flux above which water cannot cool the bottom of a debris bed, so it gauges the coolability of molten debris (a core-melting accident scenario). Their new model incorporates two-phase flow effects (capillary action, relative permeability) and gas–liquid interfacial shear stress. They extended their models to both homogeneous and stratified (layered) debris configurations. When models validated against experimental data (POMECO test conducted by KTH, and STYX-3.1 test conducted by VTT), the refined model dramatically improved accuracy: the base model had ~20% prediction error, which fell to 8.9% after adding interfacial shear terms. For stratified beds (i.e., layered debris), the error was further reduced to 4.5%. This shows that stratification and interfacial physics are critical to capturing real debris cooling. By lowering DHF errors, the models give safety analysts greater confidence. As the authors note, these validated models provide a robust foundation for debris-bed cooling analysis, which significantly improves safety assessments.

Conclusion and outlook

Collectively, these five studies advance the mechanistic understanding of accident source terms while contributing to both fundamental science with mitigation strategies. Improvements in aerosol transport and deposition models in cover gas space Patel et al., new aerosol deposition/resuspension data from scale-down experiments Kumar et al., and insights into iodine oxide aerosol formation chemistry Mariam et al. improve the fidelity of source-term predictions. Likewise, the iodine-trapping experiments Lind et al. inform containment filter design criteria, and the refined debris-bed coolability models Peng et al. strengthen confidence in in-vessel retention strategies. Each paper brings critical knowledge that contributes to enhancing the safety analysis of current and future reactors. The accurate source terms require detailed physico-chemical modelling and targeted experiments. For example, the SFR study quantifies aerosol size distributions and leak rates through annular gaps of the top shield; the pipe experiments show that flow-induced resuspension can enlarge source terms; the zeolite tests confirm that high-humidity iodine retention is feasible but flow-dependent; and the debris-bed model demonstrates that including interfacial shear and stratification improves debris-bed coolability predictions. The iodine-oxide aerosols formation and characterization study further grounds iodine chemistry in experimental evidence, bridging knowledge gaps essential for safety codes.

Together, these contributions enrich the databases and models underpinning the next-generation severe-accident analysis codes and emergency guidelines. They emphasise the importance of maintaining engineered safety systems (e.g., coolant integrity, filter capacity, adequate filter sizing) and sustaining continuing integrated experiments coupled with advanced simulations. By improving predictive capability (e.g., reducing model errors) and identifying sensitivity to key parameters (flow rates, residence times, debris-bed structures), this body of work supports more reliable accident management strategies. Ultimately, these contributions help ensure reactor safety by sharpening our ability to predict and mitigate severe accident outcomes in advanced nuclear systems. Continued work along these lines, combining experiments and simulation, will further improve mitigation strategies (e.g., optimized venting filters, enhanced debris-bed cooling) and help ensure that severe accidents remain tightly controlled.

This summary reflects five Frontiers in Nuclear Engineering articles from the *Nuclear Safety* section of the "Nuclear Reactor Safety and Accident Mitigation Management" Research Topic. Each article provides data and models for refining safety assessments and accident-management guidelines. As nuclear technologies evolve with Gen-IV reactors, SMRs, and hybrid energy systems, this type of work will only grow in importance. We hope this Research Topic will continue to inspire contributions that bridge experiment, modelling, and application, which advance the science of safety for nuclear systems worldwide.

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