EXPERIMENTAL STUDIES ON SEVERE ACCIDENTS IN SFRS
Experimental Facilities, R&D Activities at IGCAR-DAE, India

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INTRODUCTION: Sodium-cooled Fast Reactors (SFRs) incorporate inherent as well as engineered safety features, aligned with the defence-in-depth philosophy, to ensure safe operation and reduce the probability of severe accidents to extremely low levels. Nevertheless, comprehensive safety assessment is critical to validate these systems and to demonstrate the effectiveness of Severe Accident Management (SAM) strategies. Following the Fukushima incident, enhanced safety requirements have made it mandatory to consider severe accidents under Design Extension Conditions (DEC). However, considerable uncertainties persist in the current understanding and prediction of severe accident phenomena in SFRs, primarily due to the scarcity of high-quality experimental data. Addressing these gaps is essential for developing reliable models and ensuring the robustness of safety strategies. Towards this, IGCAR is actively engaged in experimental research aimed at advancing the understanding of severe accidents specific to SFRs. Dedicated experimental facilities have been established, and comprehensive programs have been designed to investigate critical aspects of accident progression and mitigation. These efforts target key areas for strengthening the scientific basis for safety evaluations. The knowledge generated through these experimental studies is instrumental in supporting the design, licensing, and deployment of advanced SFR technologies. The paper provides an overview of the established facilities, summarizes key experimental findings, and outlines the future research directions to enhance severe accident management in SFRs.

1. OVERVIEW

Severe accidents in SFRs are hypothetical events that could involve a partial/ complete core meltdown, or a Hypothetical Core Disruptive Accident (HCDA). In such accidents, the molten fuel and structural material (corium) can relocate to the cold pool sodium, leading to corium-sodium interaction known as Molten Fuel-Coolant Interaction (MFCI). During MFCI, the corium fragments due to thermal and hydrodynamic instabilities, with the debris forming a bed on the core catcher at the bottom of the reactor vessel. Decay heat from the bed is dissipated by sodium via natural convection, which establishes a flow between the bed and safety-grade decay heat exchangers positioned at the top of the reactor vessel. The characteristics of the debris bed are critical for evaluating coolability and ensuring effective Post-Accident Heat Removal (PAHR). In case of a core meltdown, the Reactor Containment Building (RCB) is not expected to experience sodium leakage or fire. However, few kilograms of sodium can be released into the RCB during a CDA and can lead to combustion resulting in pressure buildup. To investigate these phenomena dedicated facilities have been developed and several experiments are conducted.

1.1. Experiments on MFCI

For studies on MFCI, two test facilities: Sodium Fuel Interaction (SOFI) and Thermite Melt (THEME) are set up. The SOFI facility [1] comprises cold crucible induction melting system (shown in Fig. 1) for generating the molten metal composition while the THEME facility [2] utilises aluminothermy reaction for producing the simulated MOX fuel composition at high temperatures upto 2400 °C. In SOFI facility, the fragmentation behaviour of molten stainless steel was studied in sodium as well as water, to compare the energetics of the interaction and size distribution of the fragmented debris for both the coolants. The results indicated the MFCI in sodium to be less energetic and debris generated in sodium to have a flaky sheet like morphology, indicating thermal fragmentation to be dominant mechanism.

In the THEME facility, a simulated corium comprising a mixture of alumina and iron produced via the aluminothermy process was tested under various sodium conditions and water. A real-time X-ray imaging system (shown in Fig.2), featuring a 450 kV X-ray source and a Digital Flat Panel Detector (DFPD), was used along with the in-house image processing tool 'VISTA' to study melt fragmentation behaviour. The processed X-ray images from the MFCI experiments showed fragmentation of the simulated corium within short travel in sodium (shown in Fig. 2), indicating the chances for direct corium impingement on core catcher are very remote. The images also indicated minimal sodium vaporization from the fragmented finer particles, and absence of vapor film barrier that les to significantly lower potential for energetic MFCI in sodium compared to water [3]. The X-ray images downstream the interaction zone and transient pressures measured by dynamic in-sodium pressure sensors also confirmed the same. Post-experimental debris analysis indicated that the debris generated comprised majority of small size particles, which were observed to solidify almost instantaneously indicating formation of debris in solid phase. Further, the high thermal conductivity of sodium led to complete solidification of fragmented particles before settlement, reducing the likelihood of re-fusion. The absence of large debris and interface temperatures below the stable film boiling point further indicated a low risk of large-scale vapor explosions and favourable conditions for early-stage post-accident cooling. These findings offer critical insights into molten fuel–sodium interactions, essential for safety of SFRs. Further experiments are underway using higher melt-to-coolant ratios and more realistic melt compositions to better simulate reactor conditions.

FIG.1 Experimental setup with cold crucible and melt chamber at SOFI facility

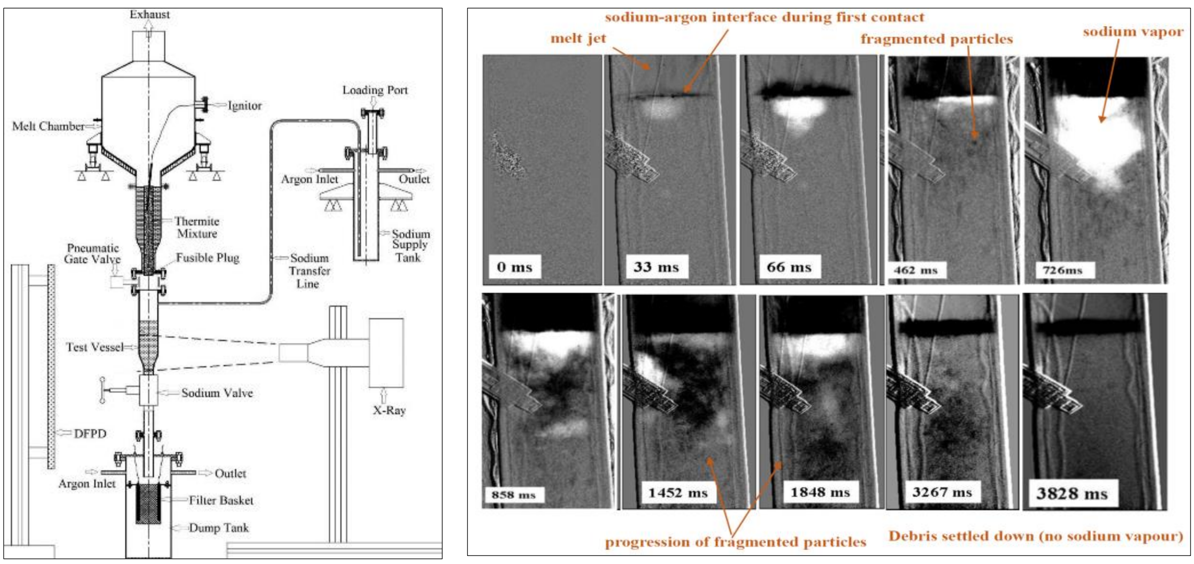

FIG. 2 Setup with X-ray imaging system at THEME facility & X-ray images of MFCI [3] (courtesy of Mr. E. Hemanth Rao)

1.2. Experiments for Assessment of Combustion Potential of Sodium Ejected during HCDA

In case of a HCDA in an SFR, the core undergoes rapid vaporisation leading to slug impact of primary sodium on the bottom of the top shield resulting in ejection of sodium into the Reactor Containment Building (RCB) through clearances between the rotatable plugs [4]. To determine the possible quantity of sodium ejection and to assess its burning potential, a series of experiments were performed using a scaled model of reactor assembly as shown in Fig. [4]. The sodium slug impact at bottom of the model top shield was generated under simulated pressure and temperatures, and the ejected sodium was quantified for assessment of its burning potential. Results indicated the quantity and temperature of the ejected sodium to be much lesser than the theoretical predictions, confirming the chances of instantaneous sodium combustion in RCB are very remote.

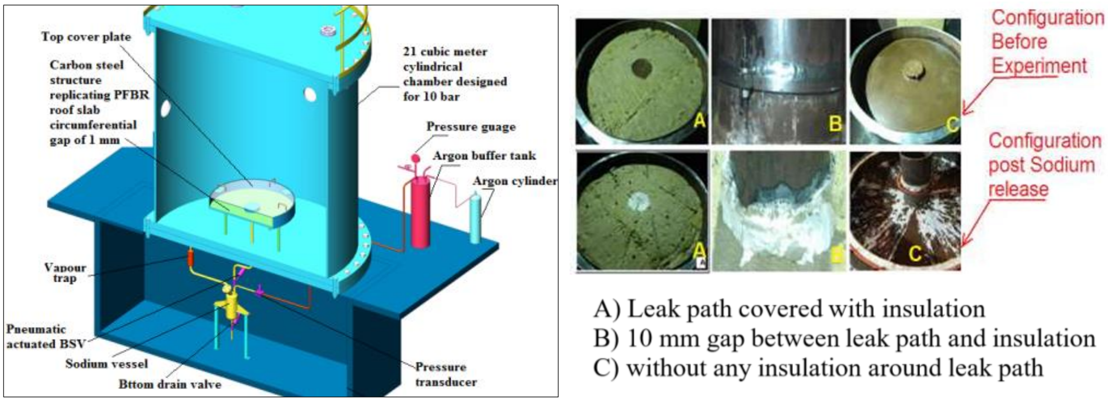

FIG. 3 Experimental setup and photographs of sodium leak from top shield [5] (courtesy of Mr. Ch.S.S.S. Avinash)

1.3. Experiments on Post Accident Heat Removal

Several experiments were conducted towards investigating the coolability of the debris bed during the post-accident phase. Important studies include determination of the effective thermal conductivity of the simulated debris bed in sodium, single phase and boiling heat transfer from the heat generating debris bed [6] in 1-D and 2-D geometries. Further, experiments were conducted in Post-Accident Thermal Hydraulic (PATH) facility [7], which comprises a 1:4 scale reactor assembly with internals, for confirmation of natural convection flow from a heat generating debris bed on the model core catcher to the decay heat exchangers as shown in Fig. 3. The results indicated good agreement between the experimental findings and numerical predictions. Additionally, experiments were also conducted on melt progression in simulated fuel subassembly, sodium boiling in simulated fuel subassemblies [8], and benchmark MFCI tests for validation of codes being developed at IGCAR.

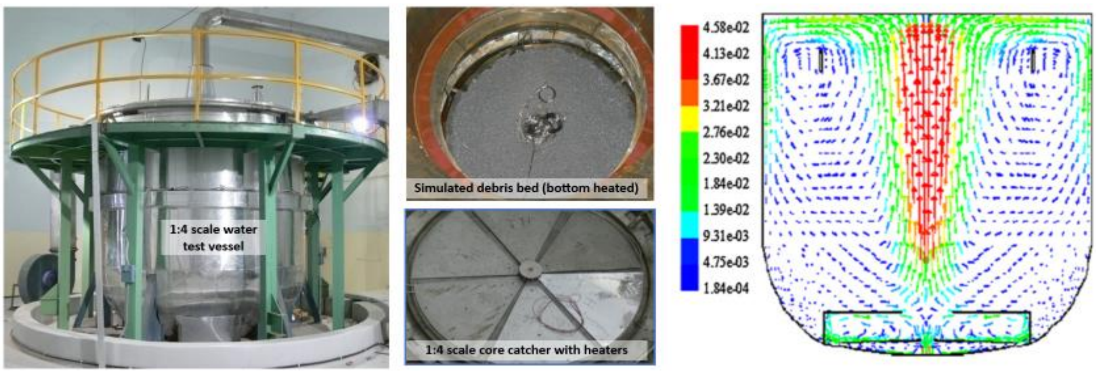

FIG. 4 PATH facility: setup and Experiments on post-accident heat removal [7] (courtesy of Mr. E. Hemanth Rao)

1.4. Development and Qualification of Advanced Core Catcher

For the future SFRs, effective retention and long-term cooling of corium during a whole core melt accident is a key design requirement for the Core Catcher (CC). Ensuring that the downward heat flux and CC temperature remain within acceptable limits is essential for successful in-vessel retention. To address this, IGCAR is developing an advanced core catcher featuring a refractory magnesia protection layer over SS316 LN substrate capable of safely withstanding whole core melt relocation. As part of its qualification, standard magnesia specimens have been tested under prolonged sodium exposure and subjected to thermal shock conditions [9–11]. Results demonstrate that refractory-grade magnesia is a promising candidate for CC lining. Ongoing efforts focus on developing reliable lining techniques and studying the lining's performance during long-term corium retention under large-scale melt relocation with simulated decay heat.

2. FUTURE DIRECTIONS

While earlier studies have demonstrated key safety features and provided critical data for Sodium-cooled Fast Reactors (SFRs), notable gaps remain due to uncertainties in scaling ratios, simulation parameters, and measurement techniques. Many current safety analyses rely on conservative assumptions that warrant re-evaluation. Addressing these issues requires development of advanced numerical models, validated through extensive experimental data under realistic conditions. However, conducting experiments at ultra-high temperatures, especially with sodium, poses significant technical challenges and demands careful planning. Hence, a coordinated program integrating computational modelling with experimental efforts is essential to enhance safety features and ensure effective implementation of Severe Accident Management Guidelines (SAMG) in Small Modular Reactors (SMRs) and advanced reactor designs. To support this, the IGCAR has initiated design and development of a large-scale severe accident test facility. This facility will use prototypic corium to enable realistic studies on fuel slumping, melt relocation, MFCI, core catcher performance, and other phenomena. It aims to support the qualification of accident mitigation strategies and the deployment of enhanced safety systems in both water- and sodium-cooled reactors.

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