INTERNATIONAL COLLABORATION ON SEVERE ACCIDENT STUDIES FOR SODIUM-COOLED FAST REACTOR DEVELOPMENT IN JAEA

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Japan Atomic Energy Agency (JAEA) has been developing sodium-cooled fast reactors (SFRs): the experimental reactor Joyo, the prototype reactor Monju, and a demonstration reactor under design. One of key issues in developing these SFRs is to address severe accidents, design measures against which are validated in safety analyses. Phenomena in severe accidents are complicated under very high temperatures. To efficiently develop safety analysis codes and experimental databases related to severe accidents, international collaboration plays a crucial role. JAEA has been promoting the international collaboration as the main pillar of bilateral collaborations with France and US as well as multilateral collaborations. The present paper describes the overview of activities on severe accident studies in JAEA and international collaborations of individual bilateral collaborations with France, US, Kazakhstan, and the multilateral collaboration on the SIMMER code development.

1. OVERVIEW

International Atomic Energy Agency organized a Technical Meeting on “The Safety Approach for Liquid Metal Cooled Fast Reactors (LMFRs) and the Analysis and Modelling of Severe Accidents” in March 2023 to exchange information on the design of LMFRs, with regard to the general approach to design safety and safety assessment of these technologies, with an emphasis on the consideration of severe accidents, including their analysis and modelling [1]. The general event progression is usually divided into the initiating phase, the transition phase, the expansion phase, and the long-term cooling phase in accordance with the degree of core damage progression and the type of phenomena involved in the accident [1]. Many countries have been making efforts on analytical and experimental studies in each phase.

During the early stages of fast reactor development, the evaluation of the energy release associated with prompt criticality was based on conservative scenarios and hypothetical initial conditions. Subsequently, safety research utilizing in-pile facilities such as CABRI in France [2] and TREAT in US [3], as well as a multitude of out-of-pile tests, has advanced our understanding of accident phenomena. Furthermore, advancements in computer technology have facilitated the development of safety analysis computer codes, such as SAS4A [4] and SIMMER [5]. These mechanistic analysis codes have paved the way for more realistic assessments of severe accident sequences, supplanting the previously used overly conservative evaluations that relied on arbitrary initial conditions and hypothetical scenarios. Severe accident analysis methodologies in the four phases of the event progression have been recently applied to licensing calculations [6].

For the initiating phase analysis, the SAS4A code, originally developed by ANL in US, for oxide fuel has been validated mainly using the CABRI experimental data, for which international program has been implemented by France, Germany and Japan [4]. This code has been applied to reactor analyses in Japan [7,8].

For the transition phase analysis, the two-dimensional SIMMER-III and three-dimensional SIMMER-IV codes have been developed and validated by France, Germany and Japan since 1992 [9]. These codes have been applied to a licensing calculation in Japan [10]. These codes play important role in the feasibility study of design measures to eliminate the recriticality issue [11]. JAEA has been collaborating with NNC in Kazakhstan to investigate a fuel discharge behavior though a duct in the EAGLE program including in-pile and out-of-pile experiments since 1998 [12]. To solve a connection issue between the SAS4A output and the SIMMER input, JAEA has been developing the SIMMER-V code with CEA in France since 2014 [13]. Event sequence analysis of core disruptive accident in a metal-fueled SFR has been carried out using a simplified fuel model [14]. Recently, JAEA has developed a preliminary metal fuel version of SIMMER-III/IV [15].

For the expansion phase analysis, the SIMMER-III code has been validated through a wide variety of experimental analyses in the trilateral code assessment program [16]. The code has been applied to reactor analyses in Japan [17]. A mechanical consequence can be calculated with a structural analysis code [18].

For the cooling phase analysis, a debris bed module has been incorporated into a plant dynamics code Super-COPD to evaluate the coolability of the debris bed on a core catcher [19]. To evaluate the three-dimensional thermal hydraulic effect for the coolability, a debris bed model has also been developed in a commercial computational fluid dynamics code [20].

2. FRANCE-JAPAN COLLABORATION

Severe accidents of SFRs have been studied between France and Japan over 10 years in the first framework from 2014 to 2019 and the second framework from 2020 to 2024, and many findings have been accumulated through experiments and analyses [21]. Based on these findings, France (CEA, Framatome and EDF) and Japan (JAEA, MFBR and MHI) continue the collaboration of severe accident studies in third framework from 2024 to 2028, focusing on evaluating the effectiveness of mitigation measures against core damage during a severe accident as well as the development of analytical methodologies and experimental databases.

2.1. Severe Accident Scenario Assessment

The mitigation of core damage is commonly made in France and Japan by introducing design measures to achieve an in-vessel retention strategy and demonstrating their efficiency based on experimental data and analysis results. A joint study has conducted to develop generic event trees and phenomena identification and ranking table [22]. This includes fission product release and transfer towards the environment. To improve the calculation methodologies for severe accident assessment, these methodologies have been applied to reactor cases as benchmark analyses to investigate the phenomenology and the consequences of severe accident, such as: core damage progression during primary and transition phases, mechanical consequences of rapid vapor expansion, and core material relocation and long-term cooling phases [23]. The common subject for the reactor assessment was the French ASTRID design until 2024 and is currently the Japanese SFR design after 2024.

2.2. SIMMER-V Development and Validation

JAEA has developed a detailed fuel pin model for the SIMMER-V code which can calculate the initiating phase [24]. This code was verified based on a code-to-code benchmark analysis with SAS4A. The SIMMER-V code is parallelized for a high-performance computing and a boundary coupling method is being developed by CEA [25]. It is necessary to validate SIMMER-V to improve the reliability of the code for future licensing application. The EAGLE experimental data is useful for its validation, for which the EAGLE FD experimental analysis has been started as a benchmark analysis [26]. Further validation of detailed fuel pin failure behavior, neutronic calculation, etc. are continued in the current collaboration framework after 2024.

2.3. Molten Core Material Interaction Studies

JAEA has developed a eutectic reaction model between boron carbide and stainless steel for SIMMER-III/IV based on various experimental data obtained in the previous framework [27]. This reaction could occur in a whole-core scale molten pool if control rods are present in the core. Furthermore, the reaction product might react with solid fuel, for which interaction studies with uranium, boron carbide and stainless steel have been conducted by CEA. These studies with thermodynamic analyses are continued in the current framework.

JAEA has conducted in-sodium fuel-coolant interaction tests using molten stainless steel, which were used for image processing by CEA to examine the jet breakup mechanism [28] The eutectic reaction product of boron carbide and stainless steel was also tested in 2024. CEA is also conducting experiments using sodium, so that further collaborative experimental studies are continued in the current framework.

3. US-JAPAN COLLABORATION

3.1. Benchmark Analysis

JAEA has been collaborating with US DOE (ANL) as part of a civil nuclear energy research and development working group since 2013. One of modelling and simulations tasks in fast reactors is the SAS4A analysis improvement through the CABRI experimental analysis [29]. A joint project on metal fuel accident analyses started since 2018 has three tasks: a core bowing reactivity assessment, core damage analysis and mechanistic source term assessment. For the core damage task, benchmark analyses of transient-overpower type TREAT M-series experiments have been performed using the metal fuel versions of SAS4A by ANL, CANIS by CRIEPI and SIMMER-III by JAEA after their code improvement.

3.2. Experimental Studies

JAEA and ANL have been jointly conducting metal fuel freezing experiments in the CAFÉ experimental program since 2024 to obtain basic experimental data of fuel penetration for the code validation. It is crucial to obtain in-pile experimental data under loss-of-flow conditions which have never been acquired. JAEA recently started discussion with INL and ANL for the feasibility of the TREAT testing.

4. KAZAKHSTAN-JAPAN COLLABORATION

As mentioned, JAEA has been collaborating for more than 20 years with Kazakhstan NNC in the EAGLE program using the IGR in-pile test and out-of-pile test facilities to investigate the fuel discharge behavior through the duct as well as the coolability of the remaining fuel in the core [12].

5. MULT-LATERAL COLLABORATION ON THE SIMMER CODE DEVELOPMENT

The SIMMER-III/IV code system has been developed and validated until 2000 [30-32]. Since then, extensive validation efforts and various reactor applications have been conducted with new partners (Italy and Belgium) in addition to three countries. A new collaboration framework is started in 2025 to proceed closely cooperation on the SIMMER-III/IV code development with European partners.

6. CONCLUSIONS

International collaboration plays a crucial role in the severe-accident studies in SFRs to efficiently develop safety analysis codes and experimental databases for designing the severe accident mitigation measures. The present paper described the overview of activities on severe accident studies in JAEA and international collaborations of individual bilateral collaborations with France, US, Kazakhstan, and the multilateral collaboration on the SIMMER code development.

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