# France-Japan Collaboration on Thermodynamic and Kinetic Studies of Core Material Mixture in Severe Accidents of Sodium-Cooled Fast Reactors

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**Abstract**

In the framework of the current implementing arrangement on France-Japan collaboration on Sodium-cooled Fast Reactors (SFRs) from 2020 to 2024, the research and development (R&D) tasks called “Thermodynamic and Kinetic Studies of Core Material Mixture” is intended to improve models on material interactions at thermodynamic equilibrium and kinetics of reactions for use in severe accident simulation codes with experimental data production. This task includes experimental study on chemical interaction between uranium/plutonium oxide ((U,Pu)O2), boron carbide (B4C) and stainless steel (SS), high temperature thermodynamic and thermo-physical properties of complex mixtures studies, and modelling of mixtures thermodynamics and liquefaction kinetics. During the previous implementing arrangement (2014-2019), first a comparison between the French and Japanese thermodynamic databases using the Calphad method has been performed. The second step focused on thermodynamic studies, experimental programs to support core material mixture modelling, and the development of models for severe accident simulation code. These collaborative tasks were successfully accomplished and continuous R&D items were identified. Based on the previous collaboration, CEA and JAEA defined new sub-tasks under the current implementing arrangement:

— Kinetics of interaction in core material mixtures;

— Physical properties of core material mixtures;

— High temperature thermodynamic data for the UO2-Fe-B4C system;

— Experimental studies on B4C-SS kinetics and B4C-SS eutectic material relocation (freezing);

— B4C/SS eutectic and kinetics models for SIMMER code systems;

— Methodology for the modelling of mixtures liquefaction kinetics.

The paper describes major R&D results obtained in the France-Japan collaboration under the previous implementing arrangement as well as experimental and analytical roadmaps under the current arrangement.

## INTRODUCTION

In the framework of the current implementing arrangement on France-Japan collaboration of sodium-cooled fast reactors (SFRs), one of the research and development (R&D) tasks called “Thermodynamic and Kinetic Studies of Core Material Mixture” is intended to improve models on material interactions at equilibrium as well as on kinetics of reactions to be used in severe accident simulation codes. This task includes experimental study on chemical interaction between uranium/plutonium oxide ((U,Pu)O2), boron carbide (B4C) and stainless steel (SS), high temperature thermodynamic and thermo-physical properties of complex mixtures studies, thermodynamic modelling of mixture at equilibrium and liquefaction kinetics. This task is scheduled from 2020 to 2024, consisting of three phases: Phase 1 for 2020-2021, Phase 2 for 2022-2023, and Phase 3 for 2024.

In the framework of the previous implementing arrangement (2014-2019), the first step focused on the comparison of French and Japanese thermodynamic database, which has been performed through data exchange between French and Japanese database. Furthermore, the development of a modelling approach for the SIMMER severe accident simulation code based on possible situations observed during the course of the degradation scenarios. In the second phase (2016-2019), CEA and JAEA has conducted thermodynamics studies and experimental programs for modelling core material mixture and model development for severe accident simulation code. These collaborative tasks were successfully accomplished and continuous R&D items were also identified.

Based on the previous collaboration above, CEA and JAEA defined the following collaborative achievement targets in 2024:

* To identify relevant phenomena of material mixture in SFR severe accident evaluation, i.e., primary phase, transition phase and secondary phase;
* To extend experimental data base on chemical interaction between UO2-B4C-SS and sub-systems;
* To extend thermo-physical properties of UO2-B4C necessary to simulate the mixing material behaviour during severe accident;
* To propose thermodynamic meta models for UO2-B4C-SS mixture equilibrium calculations;
* To establish a modelling of B4C-SS mixture behaviour for SIMMER and show its reactor application capability.

In the paper, the experimental programs as well as the analytical studies in support of the current implementing arrangement will be described.

## EXPERIMENTAL PROGRAM

This section gathers the experimental activities performed in the frame of the France-Japan collaboration on SFR. Some of the results obtained during the previous implementing arrangement will be presented.

### Experimental study in France

The experimental roadmap in France is summarized in *FIG. 1*. The sub-tasks are described in detail in the following sections.



*FIG. 1. Experimental roadmap in France.*

#### UO2-B4C-SS interaction tests in “sandwich” configuration

In some particular accidental scenarios, the fuel pellets can be in direct contact with the SS cladding of the B4C neutron absorbers. The initial chemical interaction between B4C and SS may lead to the formation of a liquid phase [1]. As the temperature rises, the liquid phase fraction can significantly increase until the loss of the mechanical stability of the steel rod. The liquid mixture may then be exposed, and in direct contact with the ejected fuel. The aim of these tests is to identify the physical mechanism driving the interaction between UO2 and a SS/B4C couple.

A new experimental configuration has been conceived. A B4C crucible has been fabricated started from a nuclear grade B4C hexagonal block (CEA supply). The internal surfaces have been polished to maximize the contact with the SS disc. The thickness of the SS disc can vary from 1 mm to 3 mm. Finally, a piece of UO2 pellet (CEA supply) is placed on top of the metallic disc. In order to protect the experimental furnace, the UO2/SS/B4C “sandwich” sample will be placed in an Al2O3 crucible. The packed configuration will be then placed inside a screwed W-crucible to limit the contamination of the furnace by released vapor species. The preparation of the sample setup will be performed in a glove-box with a controlled inert atmosphere, in order to minimize parasitic oxidation.

The samples will be heated in a controlled Ar atmosphere. Both the inlet and outlet of the gas supply system of the furnace is equipped with an O2 detector. Once the heat treatment is finished, the W-crucible will cool down in the lower cold zone of the furnace.

In order to study the effect of temperature and duration of the experiment, a test matrix will be implemented. In a first step, three tests will be performed at 1200°C, 1400°C and 1600°C, respectively. The duration of the tests is fixed at 1 hour. This time is a first choice which allow to define the test schedule for the next steps of the experimental campaign.

These tests will provide data on the predominant chemical interaction in a prototypic accidental scenario involving solid UO2 in contact with an initially intact neutron absorber rod. The test matrix will help identifying the crucial steps – in temperature and time – leading to the degradation of the SS cladding. The couple SS-B4C is representative of the interaction inside the cladding, while the UO2-SS couple will address the interaction contact on the outer surface of the cladding. Depending on the exposing time, the SS cladding disc separating UO2 and B4C may be severely degraded, and under certain conditions it can be partially or completely molten. In this frame, the coupled effect of temperature and time may help in the interpretation of the role of kinetics.

SEM-EDS analyses will be performed to identify the evolution of the interfaces between the three layers as well as to detect the formation of new phases. Dissolution and diffusion phenomena can be also investigated.

#### B4C dissolution tests in a UO2 molten pool

The molten fuel pool may extend and reach some absorber rods composed of SS cladding and containing B4C pellets. The interaction of the molten fuel may produce dissolution of the control rod. This phenomenon is not driven by thermodynamics but by kinetics of thermic and chemistry interactions.

In order to get some knowledge about the dissolution phenomenon and an order of magnitude of the kinetics, it is necessary to perform experiments of rod dissolution in a UO2-containing molten fuel pool. The influence of B4C and of SS should be investigated step by step. First dissolution of B4C pellets in UO2 molten fuel pool must be performed using the VITI facility. A pool made of UO2, CeO2 (surrogate for PuO2 which cannot be manipulated outside of a hot cell) and oxidic fission products will be used to complement the first dissolution tests. Then dissolution of absorber rod (SS cladding containing B4C pellets) in a molten pool (UO2, CeO2, FPs) will be investigated. The crucible used to contain this “lower liquidus” molten pool could be made of hafnia or zirconia that resists to the metallic phase that will appear in the pool (volume of the pool 30 cm3). Temperature homogeneity is monitored multiple pyrometers pointing at the top and the bottom of the crucible. The thermal gradient is normally lower than 1%. However, this consideration does not account for the “cold source” effect when immersing B4C rod into the liquid pool.

To provide some data on reaction kinetics, interaction will be conducted for various durations, then the pool will be rapidly cooled. Post-test analyses of both pool and pellets shall provide insights on the dissolution after the limited times of interaction.

#### Thermophysical properties of core material mixtures

This task is dedicated to the experimental determination of thermophysical properties of molten core mixtures. Liquid phase density and surface tension will be measured in the VITI-MBP facility. The main difference with the layout represented in the previous section consists in the use of the tungsten capillary tube which is placed above the crucible and connected with the micrometer translation stage. The latter allows for the control of the immersion of the capillary into the liquid pool. The flowmeter controls the gas flow (argon) in the capillary at a low gas flow rate (below 0.9 mL/min). The pressure sensor is connected to the capillary thanks to an insulating connection to measure the pressure difference between the capillary and the confinement vessel. The use of the Maximum Bubble Pressure (MBP) technique allows to trace back to both density and surface tension. In a first step, (U,Ce)O2 will be studied as surrogate for molten (U,Pu)O2. Then, some oxidic FPs compounds (representative of maximum burnup) will be included to investigate their surfactant effect. The final step will consist in the study of a (U,Ce)O2+B4C mixture.

The following stage of this task will focus on B4C-SS eutectic melts and SS-B-U mixtures observed during the B4C dissolution tests in molten UO2.

#### Thermodynamic analyses and High Temperature Mass Spectrometry tests on UO2-B4C-SS mixtures

Depending on the considered accidental scenario, neutron absorbers rods may be severely damaged, leading to the formation of a liquid phase composed of SS and B4C. The formation of this phase is mainly driven by the low temperature eutectic reaction between the SS cladding and B4C [2]. The amount of liquid phase formed during an ULOF (Unprotected Loss Of Flow) accidental scenario depends on the temperature and on the temporal stage of the accident. This situation may eventually lead to the formation of a large liquid pool. The nuclear fuel may indeed interact with the liquid pool. Kleykamp [3] showed that UO2 exhibits a repulsive behavior when in contact with molten SS: a very poor wetting and a limited diffusion of the elements have been observed, suggesting a poor interaction between UO2 and a SS-based liquid pool.

 However, the presence of B4C modifies the physical properties of the liquid pool [4] leading to a better chemical exchange with the nuclear fuel. This phenomenon is essential from the mitigation point of view. In fact, an efficient mixing of the fuel with a B4C-containing liquid may reduce the reactivity and therefore limit the risk of re-criticality.

Previous studies conducted on a UO2-B4C [5] samples showed that a carbo-reduction reaction is the leading phenomenon, driving the system to a massive loss of CO(gas) and the reduction of the nuclear fuel. A significant amount of BxOy(gas) compounds where also detected. SEM-EDS analyses performed on the sample showed the presence of uranium boride phases: UB2 and UB4. The presence of Fe in the mixture can affect the reaction. Indeed, a large amount of liquid phase is formed starting from around 1200°C.

This study aims to obtain experimental information about the efficiency of mitigation by fissile material incorporation in a neutron absorber–rich mixture during an ULOF scenario. The formation of uranium borides is of particular interest since it may allow to obtain an efficient mitigation (chemical bond between a neutron absorber and a fissile atom).The study of the vapor phase in equilibrium with the condensed phases will also help to identify the major reaction taking place at high temperature.

Heat treatments will be performed in a high temperature W-furnace coupled with a mass spectrometer [6].

B4C pieces obtained from a reactor grade hexagonal block (CEA supply), Fe and depleted UO2 pellets fragments (CEA supply) are used as starting materials for samples preparation. The samples are then annealed at 1900°C for 1 hour in the W-resistive furnace. After the heat treatment, the samples cross-sections will be analyses using SEM-EDS to identify the phases formed during the solidification. The analysis of the microstructure of the samples after the test can also give information about the presence of a liquid phase, and on the dissolution of U in such a liquid.

A second set of samples will be prepared to study the vapor phase composition with temperature. The same W-furnace describe above will be used [6]. This time, the samples will be placed in a Knudsen cell: the gas phase in equilibrium with the condensed phases in the crucible will therefore be allowed to reach the high temperature mass spectrometer (HTMS).

### Experimental study in Japan

The experimental roadmap in Japan is summarized in *FIG. 2*. The sub-tasks are described in detail in the following sections.



*FIG. 2. Experimental roadmap in Japan.*

#### Reaction rate experiments with B4C pellet immersion into liquid SS

Chemical-analytical examinations of B4C-SS reaction couples were carried out by Hofmann et al. [7][8]. It was found that the growth of the different layers of the reaction zone obeys parabolic rate law for all temperatures examined. The experimental results showed that the liquefaction occurs at ≈1523 K below the melting points of the components due to eutectic interactions. Chemical interactions of reaction couples of B4C pellet/powder and a SS crucible were investigated in the temperature range 1073 K to 1623 K [1]. The growth of the reaction layer was measured as a function of temperature and time and the overall reaction generally obeyed a parabolic rate law. An obvious discontinuity was seen at the temperature between 1473 and 1498 K. This is due to the formation of the liquid phase at reaction interface. Veshchunov and Hofmann have developed mathematical models for B4C/SS [9]. One theoretical model (parabolic rate law) by Arrhenius Correlation had been developed according to experiments at temperatures of 1273 K, 1373 K and 1473 K. When T ≥ 1473 K, an abrupt jump of the reaction rate was observed.

The thickness of the reaction layer formed by the chemical reaction between B4C and SS has been reported to obey the parabolic law, which is expressed by the following equation.

 (1)

where *K, x, t, A, H*, and *T* are the parabolic rate constant in m2/s, the thickness of the reaction layer in m, the heating period in s, the pre-exponential factor, the activation energy in J/mol, and the contact temperature in K, respectively. *R* is the ideal gas constant: 8.314 J/mol·K.

Nagase et al. have derived the following parabolic rate constants of the reaction layer (SS thinning) formed between B4C pellet and SS [1].

 for 1073 K < T < 1473 K (2)

 for 1498 K < T < 1623 K (3)

Equation (1) can be replaced by the following logarithmic expression.

 (4)

 is expressed by a linear formulation against reciprocal temperature using two constants  and .

Recently, the chemical reaction between SS and B4C in the temperature range of 1455–1481 K was investigated using 304L-type SS and granular B4C, which are the materials used in control rods in BWRs in Japan [10]. The effective rate constant between 304L-type SS and granular B4C was evaluated to be approximately one order of magnitude smaller than the previously reported values for B4C pellets or powers. A difference in the reaction-layer growth rate of approximately one order of magnitude was also reported by Shibata et al. [11]. This difference might originate from the loose contact between SS and the granular B4C.

The previous studies measured the reaction rate up to 1623 K, at which SS is still solid. As far as the authors know, the reaction rate beyond 1623 K has never been measured. The purpose of this study is to measure the B4C-SS reaction rate at a temperature range beyond 1623 K corresponding to a liquid SS condition.

This study used an experimental apparatus of a graphite heater furnace [12]. In the furnace filled with argon gas, a test-section crucible made of alumina was placed in the middle of two heaters (260 mm in distance between the heaters) on a support plate. A thermal insulator supporting the crucible prevents heat loss to the lower part of the furnace. SS melt was initially contained in an alumina crucible into which a cylinder-shaped B4C pellet fixed by a movable rod was inserted. The furnace has windows to visualize the reaction using a video camera. A Type B (Pt-Rh) thermocouple was used to measure the SS in the crucible. A radiation thermometer was used to measure the surface temperature of the graphite heater.

Main test parameters are temperature and immersion time. To realize liquid SS conditions, the test parameter range is set between 1773 K and 2073 K, which correspond nearly to just above the liquidus temperature of SS and the maximum design temperature of the furnace, respectively. This experiment will be able to derive a parabolic rate constant of the B4C melting under liquid SS conditions above 1723 K.

#### Reaction rate experiments between B4C-SS eutectic material and solid B4C or solid SS

In reactor situations, a B4C pellet can be contact with liquid or solid SS (cladding or wrapper tube), thereby leading to the formation of B4C-SS eutectic material. The eutectic point of Fe-B alloy is about 1,473 K [13]. Fe-B-C alloy liquefies at around the same temperature due to the eutectic reaction [14]. According to the Fe-B binary phase diagram, the eutectic point is about 5 mass % of B. Assuming that the eutectic point is about 5 mass % of B4C in the B4C-SS system, the molten eutectic material at 5 mass % of B4C relocates widely in the core. In other words, the B4C-SS eutectic material could be contact with other B4C pellets away from the original position or with SS structures (i.e., wrapper tube, cladding) at different positions. The B4C concentration of the eutectic is envisaged to change around 5 mass % of B4C.

The previous studies measured the reaction rate between B4C and SS. As far as the authors know, the reaction rates between B4C-SS eutectic and B4C or between eutectic and SS have never been investigated. The purpose of this study is to measure the reaction rates between B4C-SS eutectic and solid B4C or solid SS.

Test specimens are heated up in a Keramax electric furnace. The test specimen consists of a pellet (10.0 mm in diameter and 5.0 mm high) contained in a crucible (10.1 mm in inner diameter, 20.0 mm in outer diameter and 10.0 mm high), which is placed on an alumina board. The test specimen on the board is standby away from a heating position before reaching a prescribed temperature in the furnace inside which Argon gas environment is kept. The test specimen is moved to stay at the heating position for appropriate retention time.

In a B4C-SS experimental case, a B4C pellet is contained in the SS crucible. The reaction rate is calculated by the reaction thickness in the SS side and the retention time at a prescribed temperature. The retention time corresponds to duration at a plateau temperature. Two contact mode experiments are prepared to measure the reaction rates between eutectic pellet and SS crucible and between eutectic pellet and B4C crucible. When the experimental temperature is high, the eutectic is expected to be molten for a short time. The retention time should be short in high temperature experiments.

Main test parameters are combination of materials to be reacted, temperature, and retention time. The B4C concentrations of B4C-SS eutectic are 2.5, 5 and 10 mass % in principle. The maximum experimental temperature is 1673K which is below the melting temperature of SS used as a crucible material. Reproduction testing in the B4C-SS system was also conducted in order to compare with the previous experimental data [1].

This experiment is able to derive parabolic rate constants, namely  and  in Eq. (4), of the eutectic-B4C and eutectic-SS systems for 1473–1673 K as a function of B4C concentration [15].

#### Thermophysical property measurement of eutectic material

In 2015, a high temperature thermophysical property measurement technique was developed through measuring liquid-state SS thermophysical properties, such as density, surface tension, specific heat and thermal conductivity. In 2016, eutectic test samples of 5mass% of B4C containing SS were synthesized, and then this study measured thermophysical properties of the eutectic sample at liquid state [16] and solid state [17]. 10mass% and 7mass% of eutectic test samples were synthesized and measured in 2017 and 2018, respectively [18][19][20]. The solidus and liquidus temperatures have been measured using different mass fraction of eutectic samples. Since the liquid temperature of 2.5mass% of eutectic test sample was lower than that of 5mass% one, this measurement implied the eutectic point between 2.5 and 5mass% of B4C containing SS. In 2019, therefore, the 2.5mass% of eutectic test sample was used to measure the liquid-state thermophysical properties. For the solid-state thermophysical properties, this study selected to measure 17mass% of eutectic test sample, the density of which should be lower than those of other samples. This is because a low-density eutectic material could be important for vertical separation due to the density difference in reactor situation. These thermophysical property data are used for the severe accident simulation code SIMMER.

#### B4C-SS eutectic melting visualization experiments

Relocation behaviour of the molten eutectic material after the reaction is important in severe accident simulation. The purpose of this study is to investigate the eutectic reaction and relocation progression under high temperature conditions using new relocation measurement techniques. Such quantitative experimental data can be used for validation of the computer simulation code. For this purpose, in 2020, we have launched two eutectic visualization experiments. The first-series of experiment is simple melting visualization experiments using an existing experimental apparatus in an inert atmosphere with radiation heating of the test samples. This existing apparatus has been used in the previous study [10]. They used B4C powder to simulate BWR control rods, whereas B4C pellets are used in this study. Transient progression of the eutectic melt can be observed and quantified in a test sample with a rectangular geometry. Additional experiments by using cylindrical samples similar to a reactor control rod are also carried out, temporal evolution of the melt flow can be quantified with dynamic visualization.

Since the temperature condition is limited in the first-series of experiments, the second-series of experiments can realize eutectic melting experiments at higher temperatures than in the first-series of experiments using a Joule heating experimental apparatus. To observe SS tubes containing B4C pellets, degradation of the electricity conductivity of SS can be quantified with variation of the electricity current to estimate the reaction rate and progression level in overall control sample. Progression of the eutectic reaction can be visualized and quantified through observation windows with the high-speed cameras.

Visualization data could be used for validation of the simulation code. By measuring temperatures in detail, the visualization technique could give overall relocation information. For instance, the eutectic melting starts at the inner surface of SS cladding. After several seconds or less than one second, the outer surface of cladding would melt and molten eutectic material could relocate downward along the outer surface of cladding. Relocated eutectic could interact with SS cladding although the reaction rate is low. The newly developed measurement technique would be applied to the estimation of SS melting mass.

#### B4C-SS eutectic freezing experiments

Eutectic melt flow and freezing are a few of the complicated phenomena which should be investigated for an accurate prediction of the reactivity transients during the abnormal conditions of an SFR because such freezing experimental data with B4C-SS eutectic have never been measured as far as the authors know. JAEA has carried out many freezing experiments with various melts injected into a cylindrical tube [21] with referring to previous experiments, such as the GEYSER experiment [22]. The purpose of this study is to obtain basic experimental data of eutectic freezing inside a cylindrical tube, which can be compared with other materials experiments and physical modelled developed in the simulation code. This study could also expect the co-existence of the B4C-SS eutectic freezing and melting on the surface of the SS tube if temperature conditions are high.

The same experimental apparatus as the B4C pellet immersion experiments can be used for this experimental purpose. The experimental apparatus will be modified to investigate the melt flow and freezing inside a cylindrical tube. Since the eutectic melt can be formed firstly at the eutectic temperature, a high-priority experimental condition for the B4C concentration is the eutectic point. The dependence of the B4C concentration is the next-step issue. By utilizing the real-time temperature measurements at outside of the SS tube by using thermocouples and infrared camera, real-time progression and freezing along the axial direction can be quantified. The penetration length can be measured during the transient using thermocouples embedded into the SS tube wall. The physical model incorporated into the severe accident code can predict penetration lengths which can be compared to the experimental ones.

#### Fuel-coolant interaction (FCI) experiments with B4C-SS eutectic

Fuel coolant interaction (FCI) is one of important phenomena in severe accidents. As far as the authors know, FCI experimental data have never been measured using B4C-SS eutectic which is injected into sodium pool. The purpose of this study is to obtain FCI experimental data with B4C-SS eutectic using the MELT experimental facility. The same procedure as the previous FCI experiments with liquid SS into sodium [23] can be applied except for the synthesis of eutectic melt. The FCI experiments would measure pressure and temperature with video recording during transient, followed by debris size measurements after the experiment. An X-ray image processing system can visualize melt penetration and fragmentation. Experimental analyses using the pressure and temperature data with visualization could identify a fragmentation length, which can be compared to predicted one based on an experimental correlation with other melt materials. Post-test examination could investigate a debris size distribution of eutectic melt.

## Analytical program

### Analytical study in France

The first objective is to provide readable thermodynamic datasets to support physical models in order to mimic chemical interaction in the core during a severe accident. Computational thermodynamics based on the CALPHAD method [24] can be coupled using application programming interfaces (APIs) with other codes by off-line batch data generation. This case refers to situations in which a code needs some data as input. These data can be pre-computed using a script and then stored in data files for future use. The important aspect of the APIs in this case is that calculations can be done automatically with a given resolution and sample a wide parameter space, generating large volumes of data with minimal human intervention. This is a way of accounting for thermochemistry in calculations such as finite elements simulation or fuel performance modelling. In this frame, massive thermodynamic calculations will be provided to map interesting phase diagrams and obtain phase equilibrium 3D surfaces (i.e., liquidus and solidus surfaces, eutectic transitions, solubility limits).

Then, thermodynamic calculations performed using the TAF-ID [25] database will be compared to SIMMER calculations output. The aim of this comparison is to identify the difference between a purely thermodynamic approach and the SIMMER output. Specific SIMMER calculations cells will be firstly selected. The physical state of these cells (temperatures, pressures, fractions of phases, nature of the phases) will be compared to thermodynamic equilibrium calculation. This action will help SIMMER users to identify the most suitable ways to manage the thermochemistry contribution to the progression of a severe accident. Furthermore, depending on the chosen accidental scenario timescale, the differences between the thermodynamic calculations and the SIMMER outputs will be treated to understand whether the thermochemistry contribution is predominant compared to kinetics and convection.

### Analytical study in Japan

Since 2016, JAEA have developed the physical model on B4C-SS eutectic reaction by referring past studies, and modified a fluid-dynamics module of the severe accident analysis code SIMMER. It is known that the eutectic reaction between B4C and other materials generally obeyed parabolic rate laws. The eutectic reaction is modelled using the parabolic rate law constant for interactions between B4C and SS estimated in the experiments [1]. Using the mass fraction of Boron, the eutectic point (melting point of the eutectic material) can be obtained from the Fe-B phase diagram. In the present model, eutectic reaction between B4C and molten SS will form molten eutectic material. Eutectic point will be defined on the basis of our experimental data. Two liquid field components are newly added to model the liquid and solid eutectic materials. Heat and mass transfer processes are also modelled considering both the equilibrium and non-equilibrium phase changes of eutectic material. These models were implemented into the SIMMER code [26][27]. The thermophysical properties of eutectic material obtained from the experimental measurements were included in the analytic thermophysical property model and analytic equation-of-state model of SIMMER.

Test calculations were conducted to validate the developed eutectic reaction model and simulated growth rate of the eutectic layer was compared with experimental measurements [10]. The developed model well reproduced the experimental observation that the accumulation of boron element near the surface is obviously large due to buoyancy effect [28].

## Conclusions

The joint task “Thermodynamic and Kinetic Studies of Core Material Mixture” started in the frame of the France-Japan collaboration on SFRs led to fruitful discussions and relevant experimental and calculation results. The first steps achieved during the 2014-2019 implementing arrangement allowed to share information about the performances of the thermodynamic tools available in France and Japan. Experimental work was also performed and drove the discussion for the current implementing arrangement. During the 2020-2024 period, French and Japanese teams will continue to collaborate to provide robust and reliable data in support to severe accident studies for SFRs.

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