DEVELOPMENT OF INTEGRATED SEVERE ACCIDENT ANALYSIS CODE, SPECTRA FOR SODIUM-COOLED FAST REACTOR

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Abstract

A new computational code has been developed for integrated analysis of some in- and ex-vessel phenomena of severe accidents in sodium-cooled fast reactors. The paper provides newly developed analytical models and application to a loss of reactor level event as one example. This code consists of in- and ex-vessel modules which include a thermal hydraulics module as a base part. The in-vessel thermal hydraulics module computes complicated multidimensional behavior of liquid sodium and gas by using a multifluid model considering compressibility. Relocation of a molten core is computed by a dissipative particle dynamics method which has an advantage from the viewpoint of its wide applicability. A lumped mass model is employed for computing behavior of ex-vessel compressible multicomponent gas including aerosols. A fully implicit scheme is applied to both the in- and ex-vessel thermal hydraulics modules to enable stable computation with a large time step width. Analytical models for sodium fire, sodium–concrete interaction, and debris–concrete interaction are integrated into the ex-vessel thermal hydraulics module. The in- and ex-vessel modules are coupled by exchanging the amount of leaked sodium and debris at every time step. Event progress starting from leakage of sodium coolant from a failed primary cooling pipe was computed for a simplified domain including a reactor vessel, a primary cooling loop, and ex-vessel multiple cells. Numerical result showed lowering of a liquid level due to sodium leakage, boiling of the coolant around a core region, and core meltdown in the in-vessel region. As for the ex-vessel region, atmosphere temperature and pressure increased due to sodium fire, sodium–concrete, and debris–concrete interaction. Basic capability to reproduce severe accident progress was demonstrated through this analysis.

1. INTRODUCTION

Computational evaluation of Severe Accidents (SAs) in Sodium-cooled Fast Reactors (SFRs) has become increasingly important in recent years. In the case of a Loss Of Reactor Level (LORL) as one example scenario of SA, sodium coolant leaks from a failed pipe in a primary cooling loop and causes sodium fire in an ex-vessel compartment. A possibility of core meltdown due to significant lowering of a liquid level and loss of a cooling path is considered in the evaluation. In case a molten core is released to a compartment below a reactor vessel (RV), sodium–concrete or sodium–debris–concrete interaction occurs. Each phenomena progress while being mutually influenced.

There are several computational codes to evaluate plant safety of Light Water Reactors (LWRs), such as MAAP [1], MELCOR [2], and IMPACT/SAMPSON [3]. Each of these codes can compute consistently in- and ex-vessel phenomena during a SA. As for SFRs, several computational codes have been also developed, such as SAS-4A [4] for an initiation phase of core disruption, SIMMER [5] for a transition phase, and CONTAIN-LMR [6] for ex-vessel phenomena. Efficiency of these codes have been demonstrated well through many applications. To realize entire evaluation from in- to ex-vessel phenomena, users should take care for temporal and spatial connection between these codes. A method that transfers boundary conditions between the codes provides excessive conservativeness in some cases and makes many parametric analyses difficult to achieve. Using a single code like the above-mentioned LWR safety evaluation codes is a best way to realize in- and ex-vessel entire evaluation. Some research projects was started to develop integrated codes for SFRs. ASTEC-Na [7] has been under development in a JASMIN project in Europe. This code is extension of ASTEC which is a safety analysis code for LWRs. MELCOR developed by Sandia National Laboratories is also being enhanced for sodium chemistry appearing in SFRs [8, 9]. The multiphysics integral codes, EUCLID [10] and SOCRAT-BN [11], have

been developed in frame of "Codes of new generation" subproject of Proryv project in Russia [12]. The EUCLID/V2 code is designed to analyze and justify the safety of nuclear power plants with fast neutron reactors with liquid metal coolants in the normal and abnormal operation modes, including accidents, severe ones as well. The SOCRAT-BN code is intended for the analysis of design and beyond design basis accidents in sodium cooled fast reactors. Those codes allow modeling both in- and ex-vessel stages of severe accident using coupled modules.

The authors also started to develop a new computational code, SPECTRA (Severe-accident PhEnomenological computational Code for TRansient Assessment) to compute in- and ex-vessel phenomena integratedly and to evaluate various SA scenarios in SFRs. Figure 1 shows elemental phenomena to be considered in SPECTRA, which was identified from an importance analysis. This paper provides newly developed computational models for in-vessel thermal hydraulics phenomena including molten core relocation and ex-vessel phenomena including sodium–debris–concrete interaction and sodium fire as a part of SPECTRA. Application to the LORL event starting from leakage of sodium coolant from a failed primary cooling pipe is also presented.

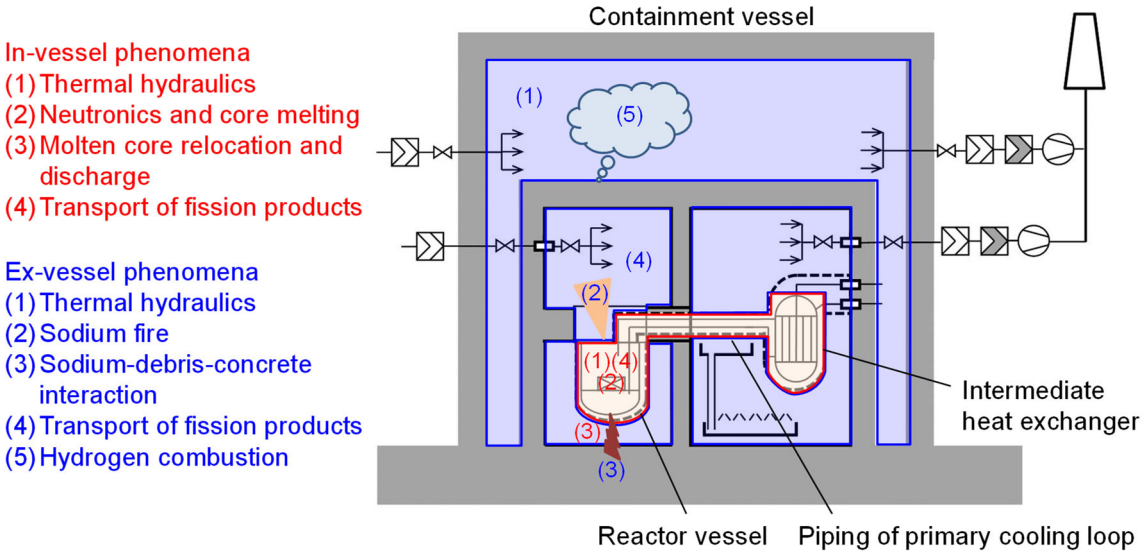


FIG. 1. Identified phenomena to be considered in SPECTRA.

2. ANALYTICAL MODELS OF SPECTRA CODE

2.1. Overview

SPECTRA consists of an in- and ex-vessel module as illustrated in Figure 2. Each module has a thermal hydraulics model as a base part. The in- and ex-vessel module are coupled by exchanging their boundary parameters at every time step. For example, the amount of sodium which leaks from a failed pipe is computed from a pressure difference between inside and outside of the pipe. Several models for elemental physical phenomena are integrated into the thermal hydraulics model. Each module will be expanded by improving the current models and integrating other models.

2.2. In-vessel module

In-vessel coolant flow during a SA includes cover gas and vaporized sodium in some cases. A possibility of core meltdown due to loss of a cooling capability should also be considered in SA evaluation. The in-vessel module computes behaviors of liquid sodium, gas, and molten core. A multidimensional multifluid model are adopted for analysis of two-phase coolant flow because SA progress depends on the complicated behavior of coolant flow inside RV. Solving procedure of mass, momentum, and energy conservation equations were constructed by considering compressibility and volume conservation of gas and liquid phase. A fully implicit scheme is applied to this model to enable stable computation with a large time step width.

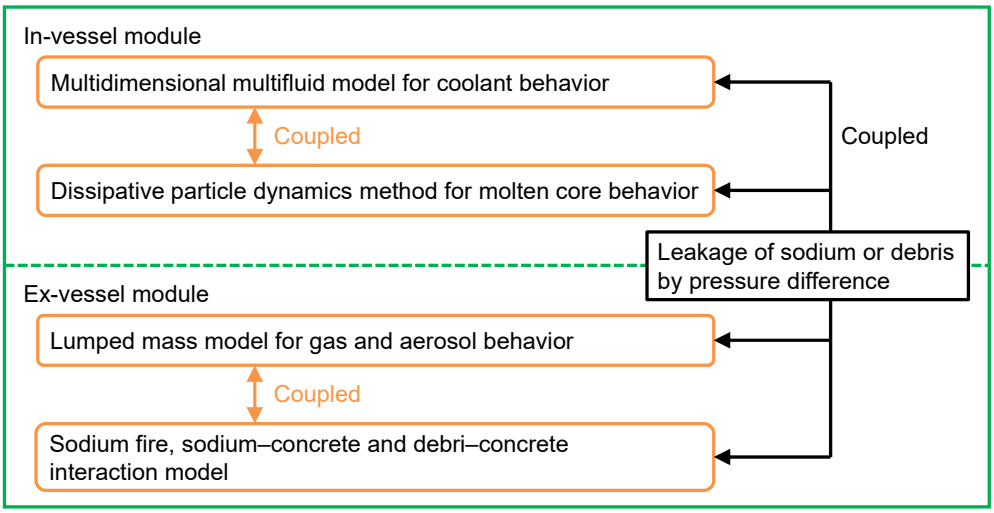


FIG. 2. Current structure of modules and models in SPECTRA.

Relocation of a molten core is computed by a Lagrange-based particle method. A Dissipative Particle Dynamics (DPD) method is chosen from the viewpoint of its low computational load compared with other particle methods. The method can compute behavior of high-viscosity fluid by using empirical parameters. The molten core analysis model is coupled with the multifluid model by considering porosity and permeability. Momentum and heat are exchanged between the two models.

The core disruption model is being developed. The model is targeted for both mixed oxide fuel and metal fuel. This model will be coupled with the above-mentioned in-vessel thermal hydraulic model and model relocation model.

2.3. Ex-vessel module

The ex-vessel thermal hydraulics model evaluates pressure, temperature, and concentration in each cell and velocity between the cells by using a lumped mass model. This model consists of mass, momentum, and energy conservation equations for a multicomponent atmosphere including aerosols. Area, length, and pressure loss of a piping is considered in the momentum conservation equation. These equations were discretized with a fully implicit method for fast computation as with the ex-vessel thermal hydraulics model. A pressure equation was derived by eliminating atmosphere velocity in the mass and momentum conservation equation. Each equation is solved by a successive over relaxation method. Thermal hydraulics model can consider any number of a wall and compute convection and radiation heat transfer between atmosphere and the wall.

In case a lower head of a RV fails, a concrete floor is ablated by chemical reaction with a sodium pool and debris. This sodium–concrete and debris–concrete interaction is one of the key phenomena under core melt through event. Sodium–concrete and debris–concrete interaction model was constructed based on models in CONTAIN-LMR [6]. The sodium–concrete interaction model considers one-dimensional state change in a depth direction from a sodium–concrete contact surface to a bottom concrete surface. A computational region is divided into the three layers: dry reaction layer, dry non-reaction layer, and wet layer. Chemical reaction and mass diffusion occur in the dry reaction layer. Ablation depth is evaluated from the amount of chemical reaction. Heat of the reaction is calculated from enthalpy difference before and after of the reaction. The dry non-reaction region includes concrete and water vapor. Water vapor in this layer comes from thermolysis of bonding water in its own layer and transfer from the wet layer. The wet layer includes only water. Mass and energy transport is solved in each layer. The sodium–concrete interaction, sodium–debris–concrete interaction, and sodium fire described below are computed in the different mesh systems. The new integral model for these ex-vessel phenomena is being developed [13].

Aoyagi, et al [14] implemented sodium fire models. Outline of the model are described briefly below. The sodium fire models consist of a spray fire model and a pool fire model. The spray fire model in SPECTRA is based on a model of a multidimensional computational fluid dynamics code, AQUA-SF [15]. The implemented model has some modifications for a lumped mass model, such as eliminations of spray-droplets spreading and of

effect of gas-phase velocity on spray-droplets motion. Combustion rate of spray droplets is modeled for pre- and post-ignition phases separately. The pre-ignition phase employs a surface reaction model assuming that chemical reaction is dominated by mass flux of oxygen or water vaper. In the post-ignition phase, a combustion model is based on a well-known theory. Mass consumption or production of oxygen, water vapor and sodium compounds, and heat transfer to atmosphere are considered as source terms of mass and energy transportation, respectively. On the other hand, the pool fire model is based on a model in SPHINCS [16]. SPHINCS has a multidimensional sodium pool model. The pool and floor structure are divided into two-dimensional ring-shaped regions in a radial and vertical directions. This ring model is applicable to a pool spreading. Combustion rate of pool fire is determined by a flame sheet model. This model employs four conservation equations in terms of mass and energy transfer on the flame sheet layer with zero thickness: molar flux of sodium vapor and oxygen (or water vapor), and heat transfer between pool and flame sheet, and atmosphere and flame sheet. Atmospheric reactions are computed by considering chemical equilibrium of gas and aerosol components in the atmosphere. The validation of the sodium fire model is progressing. Aoyagi, et al [14] demonstrated the capability of the sodium fire model to be applied to the pool fire phenomena.

3. NUMERICAL ANALYSIS

3.1. Analysis of 2-cells ventilation problem

This section describes analysis of 2-cells ventilation problems by the ex-vessel thermal hydraulics model of SPECTRA as a representative verification. The other models were also verified through analysis of basic problems or code–to–code comparison.

Large-volume two cells are filled with air at atmospheric pressure and room temperature, as depicted in Figure 3. The cells are connected through a flow path with cross-sectional area of 0.6 m2 and length of 0.1 m. Pressure in the cell 1 is slightly higher than another. Air moves from cell 1 to 2 by the pressure difference. Effect of change of density and temperature is negligibly small in this first problem. Numerical result was compared with a theoretical result and a result by SPHINCS which has a lumped mass thermal hydraulics model. One of the aim of SPECTRA is to provide stable computation with a large time step width by using a fully implicit scheme. To confirm numerical stability, this problem was computed with four different time step width: $\Delta t = 1.0 \times 10^{-4}$, 1.0×10^{-3}, 1.0×10^{-2}, 1.0×10^{-1} s.

As shown in Figure 4a, mass flow rate from between the cells increased after the start of computation and reached to a steady state. Pressure difference ΔP balances with pressure loss of the flow path at this steady state as follows:

$$\Delta P = \frac{1}{2} f \rho u^2 , \tag{1}$$

where f is pressure loss coefficient, ρ is density, u is velocity. In the case of $\Delta t = 1.0 \times 10^{-4}$ s, numerical results by the two codes almost completely agreed each other. A theoretical solution of this problem is obtained from the balance equation given by Eq. (1). The numerical result by SPECTRA corresponds with the theoretical solution with a relative error of 7.09×10^{-12}. As shown in Figure 4b, SPECTRA kept numerical stability even in the case of $\Delta t = 1.0 \times 10^{-1}$ s. The results of four cases reached to a same value. Numerical stability shown in this computation will be extremely useful for many parametric analyses.

In second verification problem, large-volume cell is connected to small cell through a flow path as illustrated in Figure 5. Nitrogen is charged in the cell 2 due to small pressure difference. Gas charging causes pressure and temperature change. This problem was set to verify the thermal hydraulics model considering compressibility.

Figure 6 shows numerical results by SPECTRA and SPHINCS. Both codes showed that temperature in the cell 2 gradually approaches to a steady value with oscillation. Temperature transition calculated by the two codes almost completely agreed each other. Under the condition of the constant specific heat ratio γ, temperature of the cell 2 at the steady state is theoretically given by

$$T_{theory} = \frac{\gamma P_1 T_1 T_2}{(P_1 - P_2) T_2 + \gamma P_2 T_1}, \tag{2}$$

where P and T in the right side denote initial pressure and temperature in each cell, respectively. Temperature at steady state by SPECTRA corresponds with a theoretical solution with a relative error of 2.94×10^{-6} K/K.

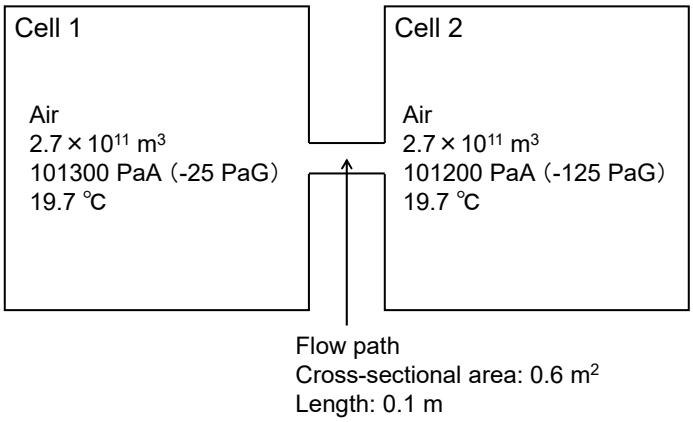
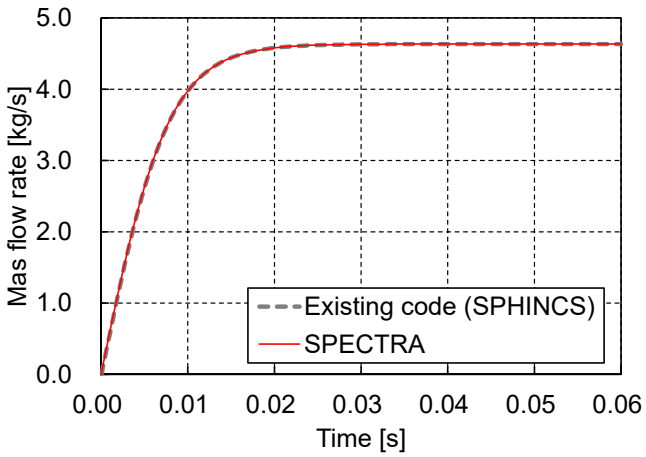
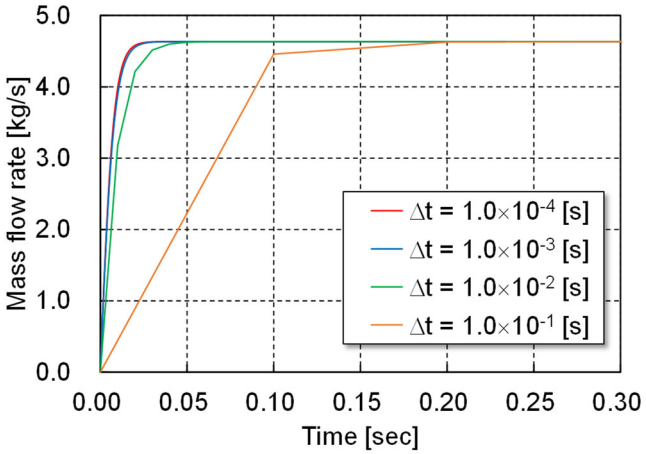


FIG. 3. 2-cells ventilation problem without effect of compressibility.



(a) Code–to–code comparison



(b) Numerical results for different time step width

FIG. 4. Computed mass flow rate in 2-cells ventilation problem without effect of compressibility.

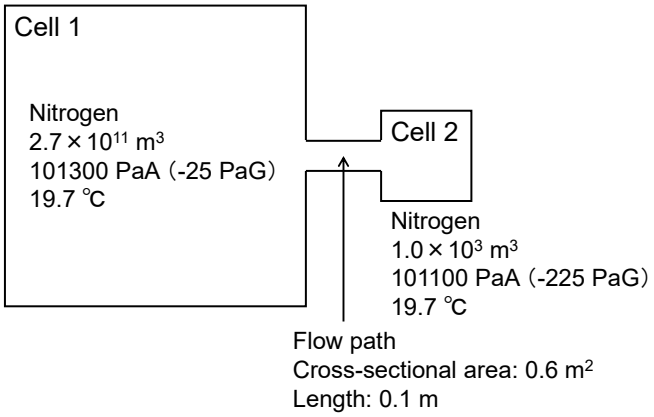


FIG. 5. 2-cells ventilation problem with effect of compressibility.

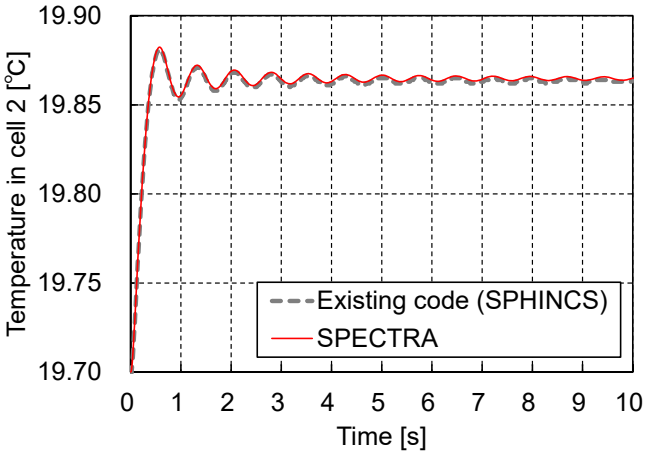


FIG. 6. Computed temperature in 2-cells ventilation problem with effect of compressibility.

3.2. Analysis of LORL event for overall test

Analysis of LORL event was performed for overall test of SPECTRA integrating the thermal hydraulics, the sodium fire, the sodium-concrete, and the debris-concrete interaction models. This analysis considers a two dimensional in-vessel part and a five-cells ex-vessel part. As shown in Fig. 7, the in-vessel part consists of a reactor vessel (RV) and two primary cooling loops. RV includes a core, a core structure, liquid sodium, and cover gas. There are a pump region and an Intermediate Heat Exchanger (IHX) region in the primary cooling loop. A momentum corresponding a pump head was given in the cells of the pump region. A heat is removed in the cells of the IHX region. Before starting the LORL analysis, an analysis only for the in-vessel part was done under a normal operation condition until the coolant flow reached to a steady state. This steady state was used as an initial condition of the LORL analysis. At 0 second of the LORL analysis, liquid sodium starts to leak from a cell as shown in Fig. 7. Pump drive and heat removal by IHX stops simultaneously. A decay heat is given in the several cells at the center of the core region. The core is assumed to melt at 800 °C of its temperature for simplicity.

The sodium and debris were assumed to start to leak from a lower head of RV at 200 seconds for simplicity. This assumption is based on mean temperature of the debris particle accumulated at the lower head of RV. Mass of the leaked debris is calculated from the number of the debris particles which go out from the opened boundary of the bottom cells of RV. On the other hand, the ex-vessel part consists of an upper and a lower part of a containment vessel (CV), a compartment in the primary cooling system, and the two environment cells outside of CV. The primary compartment was initially filled with 97 mol% Nitrogen gas and 3 mol% Oxygen. The leaked sodium reacts with oxygen in this cell. Pressure and temperature will increase due to sodium fire. Sodium leak rate is calculated from pressure difference between the pipe internal and the primary compartment. The sodium-concrete and debris-concrete interaction starts in this cell from 200 seconds.

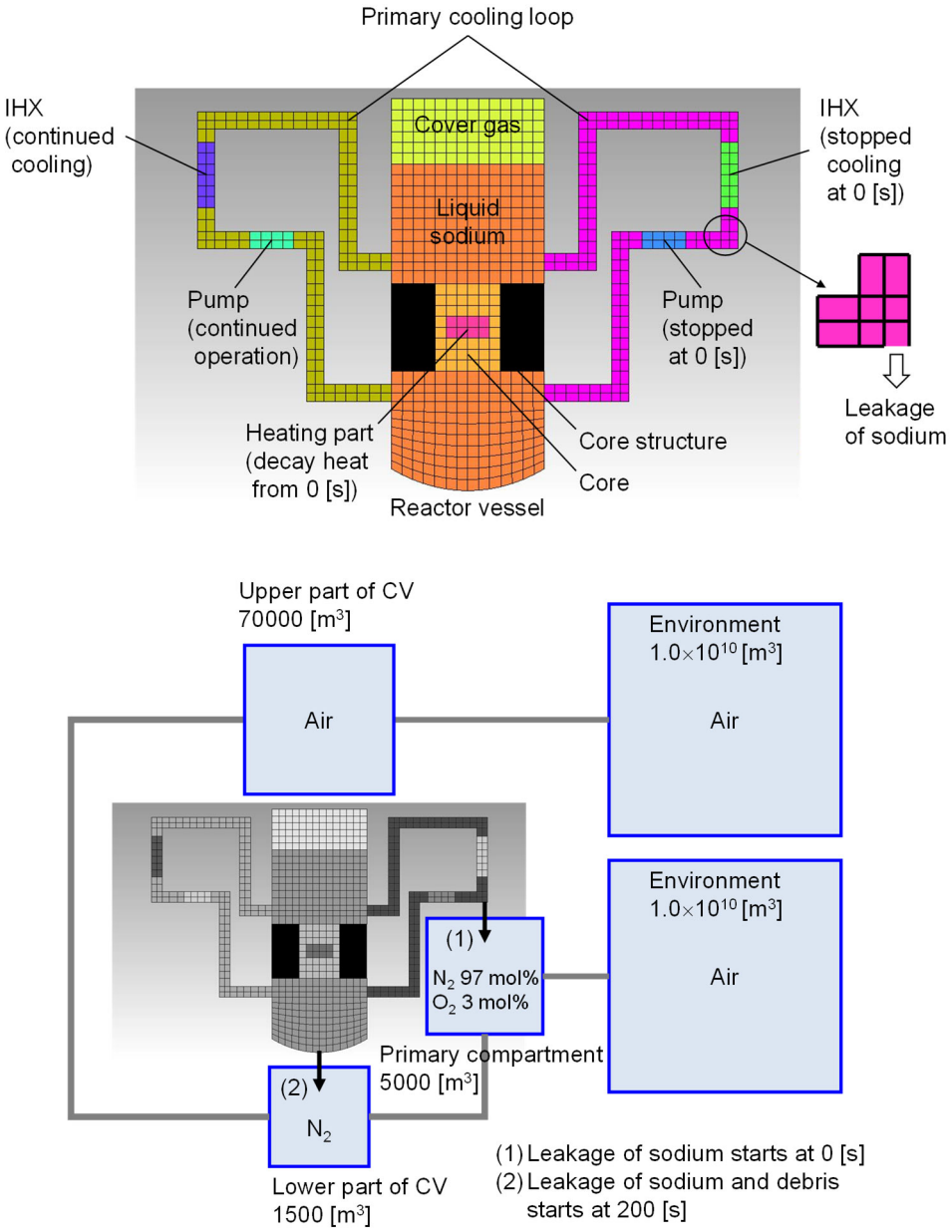


FIG. 7. Computational setup for LORL analysis.

Figure 8 shows computed in-vessel coolant temperature and ex-vessel atmosphere temperature at different six times. Amount of the leaked debris is shown by a bar indicator below the lower part of CV. At 0 second, in-vessel coolant temperature is in a steady state. Inlet and outlet temperature of RV is 370 and 500 °C on average, respectively. Due to sodium leakage and sodium fire, liquid level in RV drops and atmosphere temperature in the primary compartment reached to 552 °C at 15 seconds. Atmosphere temperature decreases after 15 seconds because leak rate of sodium decreases due to change of pressure difference. At 90 seconds, liquid level drops to the level of the outlet pipe. Coolant temperature increases locally in the core heating part and the particles expressing a molten core falls down toward the lower head of RV. Cooling loop from RV and primary loop completely breaks at 210 seconds. Debris started to go out from RV at 200 seconds. At 270 and 400 seconds, atmosphere temperature in the lower part of CV continues to increase due to the occurrence of sodium-concrete and debris-concrete interaction. This analysis demonstrated that SPECTRA could evaluate SA event progress by in which in-vessel and ex-vessel physical phenomena influence each other. This integrated analysis with a low computational cost will be effective for exhaustive evaluation of SA scenarios and dynamic probabilistic risk assessment.

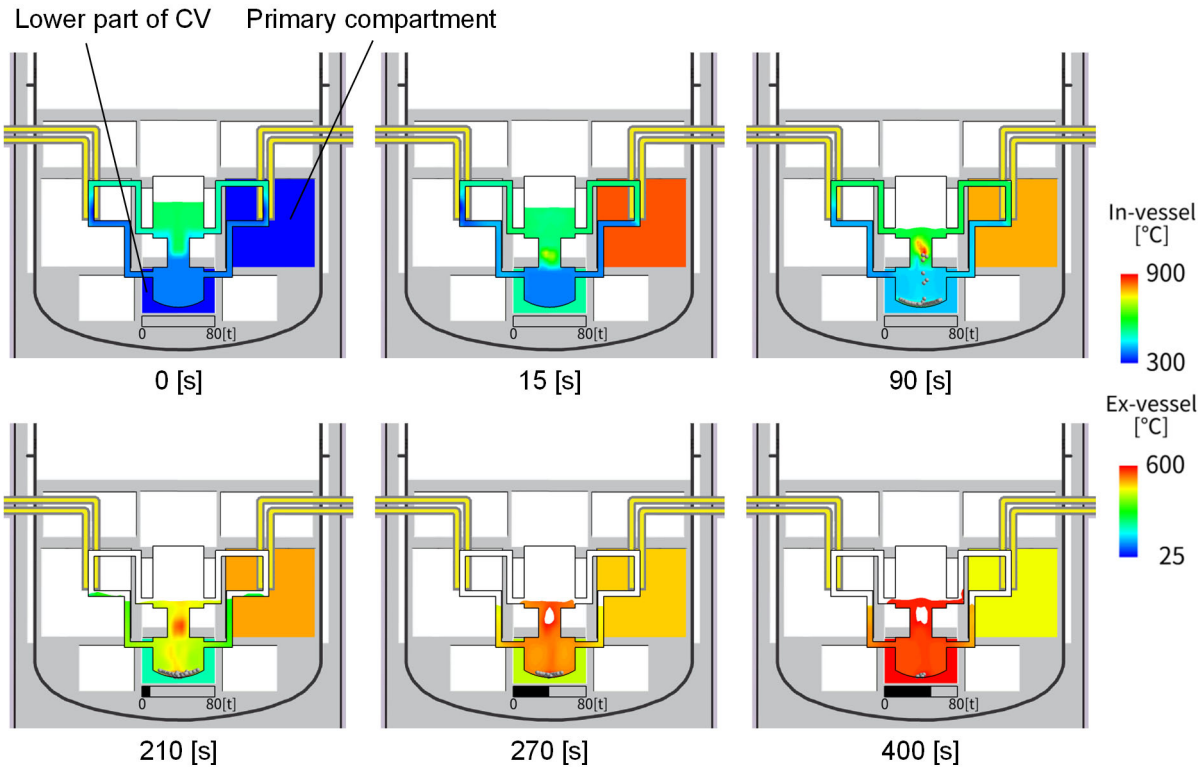


*FIG. **8**. Results of LORL analysis.*

4. CONCLUSION

A new computational code, SPECTRA has been developed for integrated analysis of some in- and ex-vessel phenomena of severe accidents in sodium-cooled fast reactors. This code consists of in- and ex-vessel modules which include a thermal hydraulics module as a base part. The in- and ex-vessel modules are coupled by exchanging the amount of leaked sodium and debris at every time step. Event progress starting from leakage of sodium coolant from a failed primary cooling pipe was computed for a simplified domain including a reactor vessel, a primary cooling loop, and ex-vessel multiple cells. SPECTRA successfully reproduced lowering of a liquid level due to sodium leakage, boiling of the coolant around a core region, and core meltdown in the in-vessel region. As for the ex-vessel region, atmosphere temperature and pressure increased due to sodium fire, sodium–concrete, and debris–concrete interaction. SPECTRA can evaluate SA in which in-vessel and ex-vessel physical phenomena progress concurrently.

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