Preliminary Evaluations of CSPACE for a Station Blackout Transient in APR1400

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1. Introduction

Since the Fukushima accident resulted from the earthquake and the ensuing tsunami, the simulations associated with the severe accidents have been reconsidered in the nuclear engineering realm. This paper discusses the preliminary results of the simulated station blackout (SBO) transients using the CSPACE code and presents the information pertinent to the related safety issues. CSPACE is a merged program of a master processer of Safety and Performance Analysis Code (SPACE) for nuclear power plants [1] and a child processer of Core Meltdown Progression Accident Simulation Software (COMPASS) [2] generated as a dynamic-link library (DLL) codes. It has been developed to predict the best-estimate transient in the pressurized water reactor (PWR) for severe accidents. SPACE and COMPASS codes take charge of the thermal-hydraulic response of PWRs and the analysis of the severe accident progression in a vessel, respectively.

In this study APR1400 is selected for SBO transient simulation. The selected PWR is composed of two coolant loops. In each loop, heated primary coolant leaves the reactor pressure vessel via a hot leg passing through a steam generator (SG) and then returns to the reactor vessel through two cold legs. The specific SBO scenario is determined by a TMLB sequence without reactor coolant pump (RCP) seal leak, which is initiated by the loss of both offsite and onsite electric power and simultaneous loss of auxiliary feedwater. The potential effects of operator actions for accident recovery are not considered.

2. CSPACE model

2.1 Description of the Code

The thermal hydraulic calculation of the CSPACE is performed by SPACE. The SPACE code is a non-homogeneous, non-equilibrium code that solves nine conservation equations. There is a separate set of conservation equations for two-fluids with three fields. Although the SPACE code has a function of multi-dimensional analysis, the CSPACE input model to simulate the SBO severe accident uses only the one-dimensional (1D) calculation. Hence, in this study the fluid and energy flow paths are approximated by the 1D stream volume and the 1D conduction slab model. SPACE of the CSPACE is based on the version 2.16 distributed by KHNP.

COMPASS is a package of new models developed to support calculations for severe accident phenomena, which are not available in SPACE. These models include an improved cladding deformation model, an improved high temperature cladding oxidation model, a model to present the material interactions at high temperature (eutectics interactions), and a model to present the molten formation and the relocation in the vessel. The heat conduction model as well as the radiation heat transfer model associated with an interaction of the fuel-to-fuel, fuel-to-control rod, and fuel-to-vessel structure (i.e., shroud or support plates, and so on) are also available. COMPASS of the CSPACE is based on the version 2.1 [2]. The COMPASS code has been verified through the internal assessment activities by KAERI.

To perform the parallel calculation between COMPASS and SPACE, it is necessary to employ the SAM component in an input model of SPACE. The structure of the SAM component is identical to that of the BRANCH component except for an initial power fraction.

2.2 Description of the Input Model

The CSPACE input model used for the simulation of a postulated SBO transient in APR1400 is shown in Fig. 1. It includes the reactor vessel, each loop composed of two cold legs, a hot leg, the steam lines of the SG secondary side, and a pressurizer. The model contains 165 cells, 214 faces, and 189 heat structures. The input model is identical to that for a large break loss of coolant accident (LBLOCA) analyses [3] except the SG secondary side including the main steam isolation valves (MSIVs) and the main steam safety valves (MSSVs), an emergency core cooling system (ECCS), and the vessel part of the primary system.

As mentioned above, the reactor vessel is modeled with the SAM components in lieu of the fixed nodding structure of COMPASS. The CSPACE calculation has to be accompanied with a distortion of the flow area in the vessel since the vessel nodalization using the SAM components is composed entirely of the coarse nodes compared with the fine nodes employed in the LBLOCA best-estimate evaluation model [3].

The reactor vessel includes representations of the downcomer (Component 196), lower plenum, lower head (Component 197), upper plenum (Component 198), upper head (Component 199), and core (Components 181-195). The core is modeled with three radial channels including five axial nodes. The pilot operated safety and relief valve (POSRV) at the top of the pressurizer (Component 530) is modeled with the minimum flow area. There is no discharge models following surge line failure or any other reactor coolant system (RCS) pressure boundary failure. Instead, the calculation is allowed to proceed without RCS depressurization to determine the timing of the designated event.

The steam lines of SG secondary side are modeled by the CELLs (Components 695-698, 795-798, and 800) with TFBCs (Components 801-804) employed as the multi-valves to simulate a MSIV and the MSSVs. The boundary condition for the simulation of the turbine and the turbine stop valve (TSV) is utilized as a TFBC (Component 805) with the pressure boundary condition assumed as 69.0 bar and the TRIP valve.

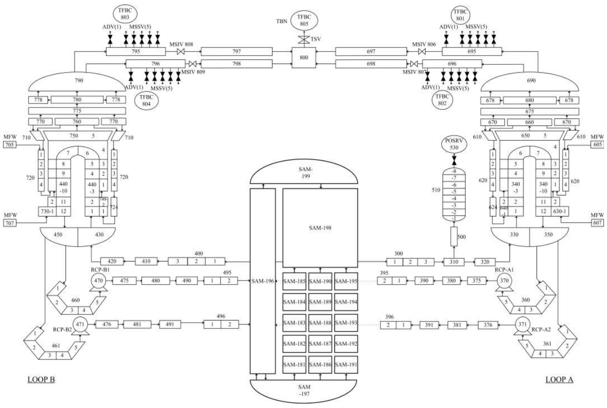

Fig. 1. CSPACE Nodalization for Simulation of APR1400 SBO

3. Results and Discussion

3.1 Full-Power Steady State Calculation

Table I: CSPACE Full-Power Steady State Results

Parameter	Target Value	CSPACE Calculated Value
Reactor power (MWt)	3983.0	3983.0
Pressurizer pressure (MPa)	15.51	15.51
RCS Hot leg flow rate (kg/s)	10495.6	10547.0
Cold leg temperature (K)	563.7	566.0
Hot leg temperature (K)	598.4	598.2
SG secondary pressure (MPa)	6.86	6.86
Steam flow rate (kg/s)	2262.42	2258.9
Liquid level of SG 2ndary (%)	75.0	73.6

The steady-state calculation of the CSPACE plant model is run to perform the null transient before the beginning of the transient accident. Table I compares the predictions with target values for a typical APR1400 plant in normal full-power operation with 10% SG tube plugging. The comparisons show that the code-calculated parameters are in reasonable agreement with the target values. Therefore the calculated steady-state solution represents an acceptable set of initial condition, which is a starting point for the transient calculation of the SBO severe accident.

3.2 Transient Calculation for SBO Severe Accident

The transient calculation for the SBO severe accident is simulated to start from time zero when the loss of off-site power occurs. Table II compares CSPACE results to foregoing research using SCDAP/RELAP5 for the sequence of events for the SBO simulation. The event sequence with respect to the fluid and the core responses can be divided into four phases: initial response, secondary heat-up, primary heat-up and boil-off, and core melting. CSPACE predicts reasonably compared with SCDAP/RELAP5 except for the time of the pressurizer empty and fuel rod melting.

Table II: Sequence of Events from SBO simulations

Phases	Event Description	Event Time (s)	
		CSPACE	SCDAP [4]
Initial	SBO event initiation (loss of AC power, reactor trip, turbine trip, FW flow stops, RCPs trip)	0.0	0.0
	RCP rotors coast to stop, coolant loop natural circulation begins	75.0	58.0
Secondary Heat-up	SGs dry-out (SG-A, SG-B)	1230.0, 1280.0	1924.7
	Economizers of SG empty (SG-A, SG-B)	2973.0, 3028.0	unavailable
Primary Heat-up and Boil-off	First pressurizer POSRV cycle, open/close	3170.0	2935.6
	Loop natural circulation flow interrupted by steam collecting at the top of the SG tube U-bends (SG-A, SG-B)	4245.0, 4244.0	4549.2
	Second pressurizer POSRV cycle, open/close	5248.0	4685.0
	Steam at the core exit begins to superheat	5513.0	5574.0
	Pressurizer empties	6985.8	7428.0
	Core empties	7024.0	unavailable
Core melting	Control rod melting occurs	7573.0	unavailable
	Fuel rod melting occurs	8253.0	7073.0

The calculated time-history results for key parameters are shown in Figs. 2 through 7. The pressure responses of the RCS and SG secondary sides during the postulated SBO transient are illustrated in Fig. 2. The pressure initially decreases from the operating pressure of 15.51 MPa because the energy removed from the RCS by the SGs is higher than that added into the core.

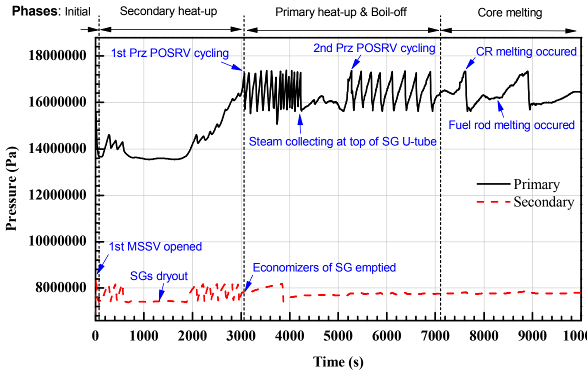

Fig. 2. RCS and SG Secondary System Pressures

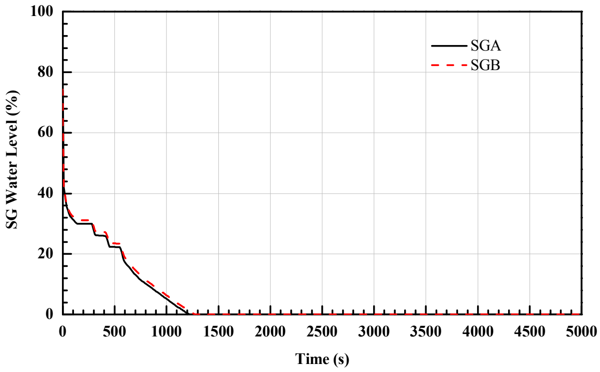

Fig. 3. Steam Generator Secondary Liquid Levels

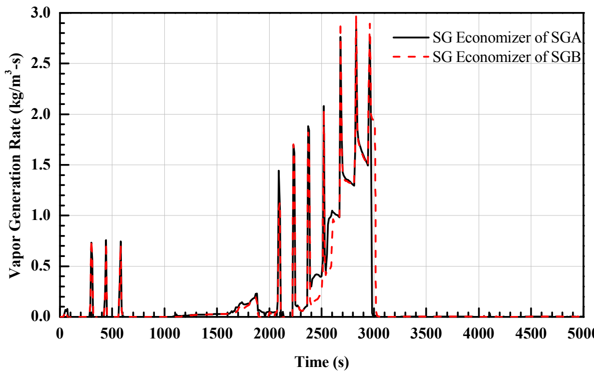

Fig. 4. Vapor Generation Rates at the SG Economizers

After the short period, the pressure response is oscillated by the MSSVs cycling with respect to an inventory of the SG secondary side as shown in Fig. 3. Subsequently SGs almost dry out at about 1,300 seconds, and the calculated pressure response of RCS remains nearly constant as shown in Fig. 2. Fig. 4 shows the vapor generation rates in the economizer of the SGs. The water inventory in the economizer of the SGs still remains until around 3,000 seconds. The constant RCS pressure is evidence that energy is still being removed from the secondary side on account of a flashing generated in the SG secondary side. Fig. 5 shows the comparison of the core power with the power transferred from the primary to the secondary system. Even though the inventory of SG secondary side completely dries out during the period of the secondary heat-up phase, the SGs continue to be active sinks to remove the core energy intermittently via the second open/close actuations of the MSSVs.

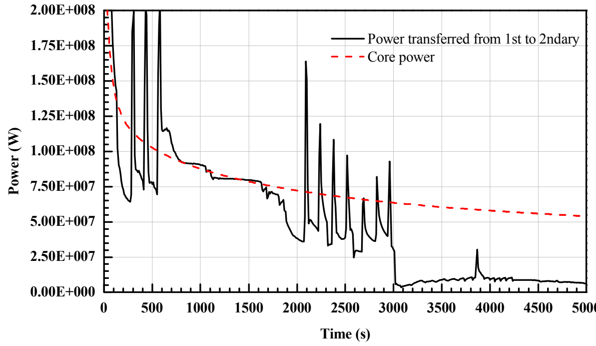

Fig. 5. Core Power and Energy Transferred from the Primary to the Secondary fluids

Fig. 6 presents the predicted result of the pressurizer water level response. The pressurizer water level sharply increases as soon as the SGs no longer serve as heat sinks for the primary system. After this point the first open/close actuations of the pressurizer POSRV are experienced. The pressure response shown as the density-wave oscillations between the reactor core and two SGs are established until the reactor vessel (RV) upper plenum approaches to the saturation condition, then completely filling the pressurizer with water. The pressurizer level is to start decrease. The RCS pressure oscillations are temporarily damped out since the loop natural circulation flow is interrupted by the steam collected in the top of the U-tube bends in SG as shown in Fig. 2.

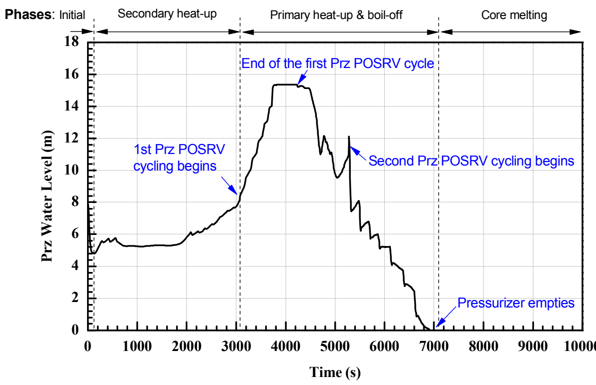

Fig. 6. Pressurizer Collapsed Liquid Level

The prediction of the collapsed water level in the RV is illustrated in Fig. 7. In accordance with venting of the coolant via the pressurizer POSRV at 4,610 seconds, an inventory of the RCS liquid is reduced. The water level in the RV shows quite a large decrease until an active core initiates to be uncovered. As soon as the liquid level in the active core is decreased by more than 50%, the RCS pressure increases sharply up to the opening set point of POSRV as shown in Fig. 2 owing to enormous steam generated in the core. And then a sudden increase of the collapsed water level of the reactor vessel at about 5,200 seconds is caused by the liquid in the coolant loops draining into the vessel through the hot and cold leg nozzles. The period of the second pressure-drop oscillation is somewhat longer than that of the first oscillation due to gradual decrease of a sonic velocity at the throat followed by the inventory of the RCS being reduced. The second open/close actuations of the pressurizer POSRV progress until the pressurizer empties at around 7,000 seconds.

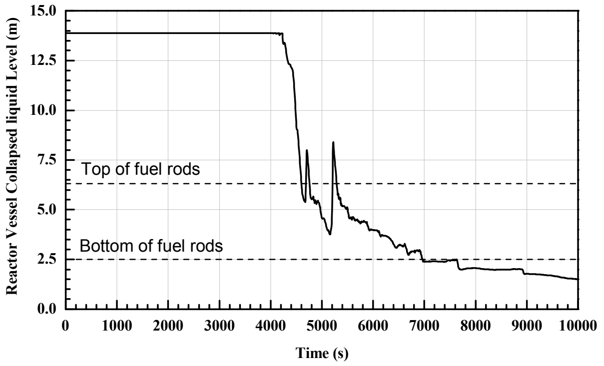

Fig. 7. Reactor Vessel Collapsed Liquid Level

The calculations performed in this study are preliminary and are not approved as CSPACE is under development. The code also lacks the plot variables corresponding to the corium relocation. For this reason the condition of the core is represented by the surface temperature of the fuel rod after an onset of the fuel failure. The axial temperatures of the cladding surface and control rod (CR) along a center channel of the core are shown in Fig. 8. The center channel represents a hot channel defined by the maximum radial peaking factor. The heat-up of the fuel rods progresses from the top down as the liquid boiled out of the core. Thereafter the upper portion of the fuel rods begins to oxidize at about 6,000 seconds, when the cladding temperature exceeds 1,170.0 K. Subsequently, the cladding is failed when the temperature reaches to 2,400 K. The oxidized cladding and dissolved fuel are relocated downward as a molten Zr-UO_2 eutectic. Eventually the oxidation reaction stops.

The CR consists of a boron carbide (B_4C) and Inconel. As indicated in Fig. 8, the cladding surface of the CR begins to melt at about 6,500 seconds. After a eutectic interaction between Zircaloy and Inconel occurs at the 3.429-m elevation, a temperature of CR reaches to the melting temperature of B_4C throughout a liquefaction between Inconel and B_4C. According to the Fig. 8, the melted fuel rod is easily found where the cladding temperature reaches about 3,000 K. Hence, the fuel rods located above 1.905-m from the core entrance are melted from a top of the core. The surface temperatures predicted by zero K indicate that the fuel rod as well as CR materials constituted in the node were moved to the other locations. Hence, the fuel rods and the CR above the 1.905-m elevation are exhibited in the relocation. The relocation is generated by the rapidly increased temperature of the adjacent nodes because the temperature of the melted rod is higher than that of undissolved fuels. As a result, the molten fuel pool begins to form near center of the hottest core channel and then the partial blocking of the core flow occurs.

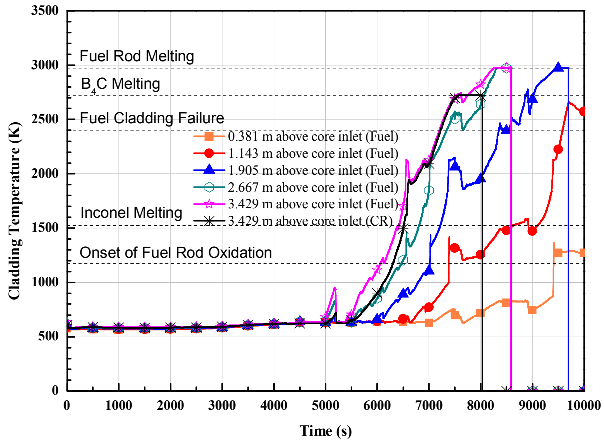

Fig. 8. Fuel and Control Rod Cladding Surface Temperatures in the Center Fuel Channel

4. Conclusions

The preliminary calculation for the postulated SBO severe accident in APR1400 has been performed with the CSPACE. The initial phase is estimated starting from time zero when the loss of off-site and on-site powers occurs simultaneously. Shortly after the RCS pressure initially falls and rises slightly due to the effects of the reactor and turbine trips, the RCS pressure declines in response to the cooling provided by heat removed to the SGs. During the period of the primary heat-up and boil-off, the RCS pressure increase is limited by two cycles of the POSRV. The RCS fluid mass is lost through the pressurizer POSRV and then the core uncovers and superheated steam flows out from the RV into the coolant loops starting at 5513.0 seconds. Following core uncovery, CR and the fuel rod melt at 7573.0 and 8253.0 seconds, respectively. Based on the discussion above, it is concluded that the calculation results for the overall RCS thermal-hydraulic response and CSPACE-using fuel rod behavior of the SBO severe accident in APR1400 are reasonable predictions.

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