Evaluation of Safety Margin for LOCA Using SPACE–CAP Analyses with Conservative and Realistic Input Conditions

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1. Introduction

Following the Fukushima Daiichi nuclear power plant accident, the importance of evaluating plant safety under accident conditions beyond the conventional design basis has increased. The IAEA safety requirements introduced the concept of Design Extension Conditions (DECs) to address accident sequences more severe than design basis accidents or involving additional failures, and allow the use of a best-estimate approach for the analysis of DECs [1]. In addition, the European Utility Requirements (EUR) Revision E recommends a best-estimate approach with an adequate level of confidence for DEC-A and emphasizes the demonstration of sufficient safety margins [2]. In Korea, the scope of accident management has also been expanded to include design basis accidents, accidents involving multiple failures, and severe accidents [3].

Conventional safety analyses are generally performed using conservative assumptions and boundary conditions to demonstrate compliance with specified acceptance criteria. Although such an approach is appropriate for licensing safety analyses, excessive conservatism may obscure the actual response of the reactor coolant system (RCS) and containment and may limit the quantitative evaluation of available safety margins. Therefore, an analysis approach incorporating more representative system conditions is useful for evaluating the plant response and the remaining safety margin under accident conditions.

In this study, the effect of conservative and more realistic input conditions on the containment pressure and temperature response during an MLOCA is evaluated using the SPACE–CAP analysis system. Prior to the MLOCA analysis, an SBLOCA calculation is performed to confirm the proper coupling behavior between SPACE and CAP. The MLOCA is then analyzed under the two input conditions, and the resulting mass and energy release into the containment and the corresponding containment pressure and temperature responses are compared to evaluate the influence of the input assumptions on the predicted containment behavior.

2. Modeling of Realistic APR1400

2.1 Nodalization of APR1400

The conservative input conditions were established based on the limiting conditions adopted in the APR1400 safety analysis [4]. These conditions include a high core power, elevated reactor coolant system temperatures and pressures, reduced reactor coolant flow, and a high steam generator pressure.

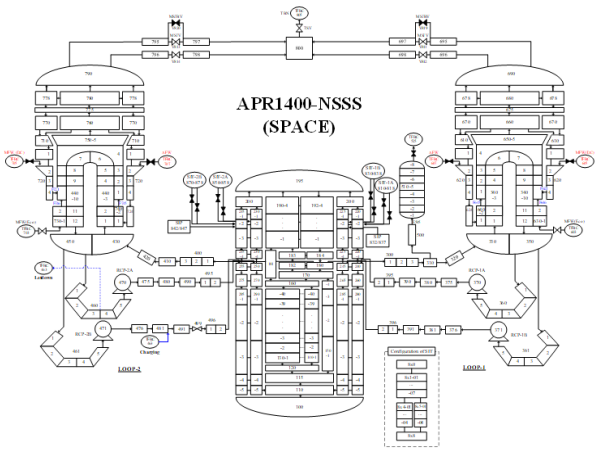


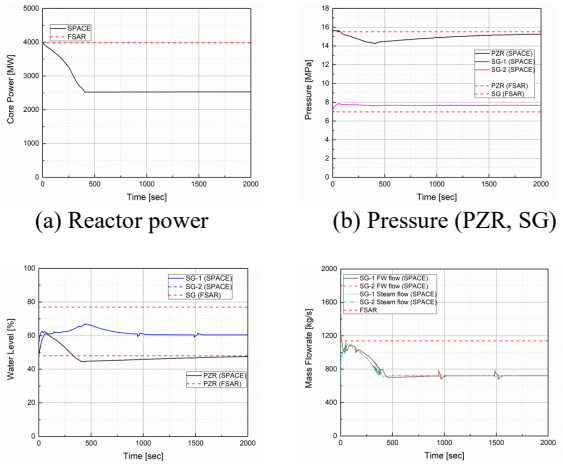
Fig. 1. Nodalization of APR1400 [4]

2.2 Modeling Modifications

For the modified input model, selected conservative initial and boundary conditions were replaced by the nominal values specified in the APR1400 DCD [5]. The nominal set points were also applied to the relevant control systems. In addition, the Feedwater Control System (FWCS), Steam Bypass Control System (SBCS), Pressurizer Pressure Control System (PPCS), and Pressurizer Level Control System (PLCS) were incorporated into the SPACE input model to represent the plant system response under less conservative conditions.

2.3 Assessment of the Modified Model

trip transient. As shown in Fig. 2, the reactor power decreased following the turbine trip, while the excess steam generated in the steam generators was controlled by the SBCS. The primary and secondary system parameters subsequently stabilized, and the system gradually approached a new steady-state condition. These results indicate that the implemented control systems responded appropriately during the transient.



(a) Reactor power (b) Pressure (PZR, SG)

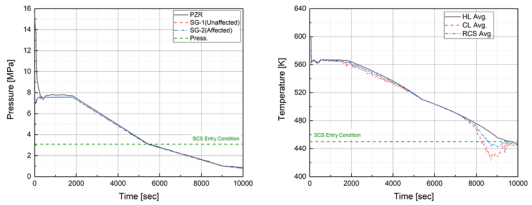
(c) Water level (PZR, SG) (d) Flowrate – SG & Feedwater

Fig. 2. Turbine trip analysis results for the APR1400 using the SPACE code

3. Results and Discussion

An SBLOCA+LOSIP analysis was first performed using the standalone SPACE calculation to establish a reference transient response. The reactor coolant system behavior and the break discharge characteristics were evaluated without considering the containment pressure feedback.

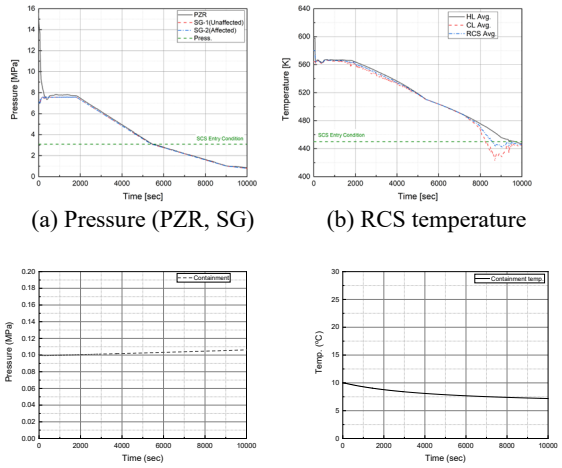
Figure 3 shows the major transient responses obtained from the standalone SPACE calculation. In this calculation, the downstream pressure at the break was fixed at 1 atm to represent the containment-side boundary condition without considering the transient containment pressure response. Following the initial pressure decrease, the RCS pressure was maintained nearly constant until 1,800 s by the operation of the SBCS. After 1,800 s, the RCS temperature and pressure were reduced by operator action, assuming cooldown at the maximum allowable cooldown rate. Consequently, the system reached the entry conditions for the Shutdown Cooling System (SCS) within 10,000 s.



(a) Pressure (PZR, SG) (b) RCS temperature

Fig. 3. SBLOCA+LOSIP analysis results for the APR1400 using the SPACE code

Subsequently, the SBLOCA+LOSIP was analyzed using the SPACE–CAP coupled calculation. As shown in Fig. 4, the containment pressure increased only slightly from approximately 1.0 bar to a maximum of about 1.05 bar due to the operation of the containment spray system. Consequently, the containment pressure feedback had only a minor effect on the SPACE calculation, and no significant difference was observed compared with the standalone SPACE results. Nevertheless, the calculation demonstrated that the pressure response calculated by CAP was successfully reflected in the SPACE calculation during the transient, confirming the feasibility of the SPACE–CAP coupled calculation.



(a) Pressure (PZR, SG) (b) RCS temperature

(c) Pressure (CTMT) (d) Temperature(CTMT)

Fig. 4. SBLOCA+LOSIP analysis results for the APR1400 using the SPACE-CAP

4. Conclusions

In this study, a modified APR1400 SPACE input model was developed by applying nominal plant conditions and control system set points and by incorporating the major plant control systems. The response of the modified model was assessed through a turbine trip transient, and the primary and secondary system parameters showed stable behavior toward a new steady-state condition.

An SBLOCA+LOSIP analysis was first performed using the standalone SPACE calculation, in which the containment-side pressure boundary condition was fixed at 1 atm. The same accident condition was subsequently analyzed using the SPACE–CAP coupled calculation. In the coupled calculation, the containment pressure calculated by CAP was directly reflected in the SPACE calculation during the transient, enabling an implicit calculation between the reactor coolant system and containment.

Due to the operation of the containment spray system, the containment pressure increased only slightly from approximately 1.0 bar to about 1.05 bar. Therefore, the containment pressure feedback had only a minor influence on the SPACE results under the present SBLOCA+LOSIP condition. Nevertheless, the calculation was successfully completed while continuously reflecting the containment response in the SPACE calculation. These results demonstrate the feasibility of implicit SPACE–CAP coupled calculations for evaluating the interaction between the

reactor coolant system and containment during LOCA conditions.

5. Further work

As a next step, the SPACE–CAP coupled analysis will be extended to an MLOCA with containment spray failure to evaluate the effects of conservative and modified input conditions on the mass and energy release and containment pressure and temperature response. In addition, further analysis is required to account for the thermal energy stored in the RCS metal structures, since the coupling of the corresponding heat structures has not yet been implemented in the current SPACE–CAP model.

ACKNOWLEDGEMENT

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