A Simulation of Main Steam Line Break Accidents Using Coupled MASTER/CUPID/MARS Code

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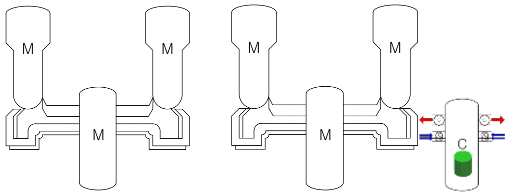
1. Introduction

Main steam line breaks (MSLBs) in pressurized water reactors (PWRs) is an issue for which the 3-D approach has been raised. This event is characterized by significant space-time effects in the core caused by asymmetric cooling and an assumed stuck-out control rod after the reactor trip. Major concerns for main steam line break (MSLB) accidents include the return-to-power and criticality. The coupled 3-D kinetics/core thermal-hydraulic (T/H) code was used to address these in the best-estimate manner because the T/H system analysis code with point kinetics did not provide reliable solutions [1]. A DNB, another primary concern in MSLB accidents, is, however, a local phenomenon, and thus the accuracy of the calculated Departure Nucleate Boiling Ratio (DNBR) depends on the accuracy of the power distribution as well as the global core power level [2]. In this regard, the refined core T/H nodalization feature is desirable because incorporation of the detailed thermal feedback is crucial in producing accurate power distribution.

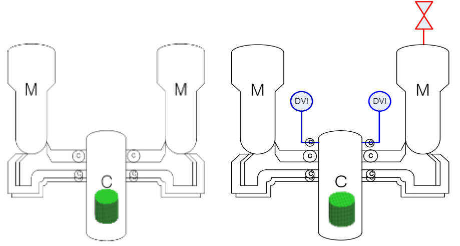
Expansion of the 1-D system analysis codes has some technical and economic limitations; therefore, code coupling was adopted as another strategy for multi-scale and multi-physics safety analysis. This paper presents an application that combines the calculations of a multi-scale and multi-physics analysis code, MASTER/CUPID/MARS, which combines MASTER/CUPID and CUPID/MARS, as mentioned above. In the simulation, CUPID covers the reactor pressure vessel and reactor core, MASTER covers the reactor core power, and MARS covers all the other reactor components.

2. Coupled Calculation Concept

The concept of the four-step coupled nuclear safety analysis [3] used in the CUPID/MARS multi-scale integral effect analysis is adopted in this MASTER/CUPID/MARS coupled nuclear safety calculation. As shown in Fig. 1, the coupled nuclear safety analysis using MASTER/CUPID/MARS is composed of four step simulations, which is extended from the two-step calculations of steady state and the transient in the MARS standalone system analysis. MASTER is imbedded in the CUPID code and is operated like the heat source of the CUPID thermal-hydraulics, although the restart files of MASTER are handled separately.



(1) Steady State for 1D System (2) Steady States for 3D RPV



(3) Steady State for 1D/3D (4) Transient for 1D/3D

Fig. 1. Configuration of the four step coupled safety analysis: M=MARS, C=CUPID , 🟩=MASTER, SI=Safety Injection, © =CUPVOL

First, the steady state calculation is conducted for a 1-D reactor system, in which the 1-D Reactor Pressure Vessel (RPV) system is included. Then, the steady state calculation for a 3-D RPV (including the reactor core), is added as another separate system with the nodalization.

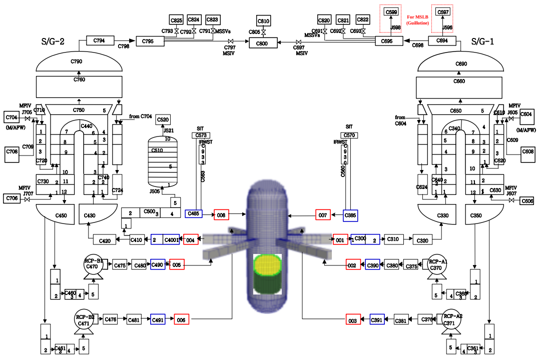


Fig. 2. MASTER/CUPID/MARS nodalization

In the third step, the two steady states of the 1-D reactor and 3-D RPV systems are consolidated into one steady state using the three individual restart functions of MASTER, CUPID, and MARS. In the MARS restart input, the 1-D RPV model is erased, and the 6 CUPVOL components connect the 1-D reactor and the 3-D RPV CUPID systems with each other.

Finally, a transient calculation can be started with the third step steady-state calculation results. In the coupled calculations of the third and fourth steps, the APR1400 PWR is modeled using about two hundred 1-D volumes and 3-D mesh of 44,467 cells, including 8 1-D CUPVOL cells, as shown in Fig. 2.

3. Results

2.1 Steady State Calculation

The coupled calculation is carried out for normal operation. As the first step in Fig. 1-1, the null transient calculation was done until 2050 s for the 1-D system, and the second step calculation in Fig. 1-2 was conducted separately for the 1-D reactor and 3-D RPV system to 2100 s. Finally, the coupled steady state results for a consolidated 1-D and 3-D reactor system were obtained at 2200 s through the third step calculation in Fig. 1-3. The calculated steady state results for flow rates are presented in Fig. 3.

In the first step 1-D calculation to 2050 s, the mass flow rates of the four cold legs are the same 5248 kg/s and the mass flow rates of the two hot legs are the same 10496 kg/s. In the second step, mass flow rates are maintained at the level obtained from the first step calculations, although there are perturbations and minor discrepancies in the calculation results. In this step calculation, the MASTER core power is set to 3983 MWth in the initialization mode.

After the flow conditions reach steady state at 2100 s, the 1-D RPV is replaced with the 3-D RPV and a consolidated 1-D and 3-D reactor system is analyzed in the third step. MASTER is changed from the initialization mode to the operation mode at 2150 s, and then MASTER can respond to the reactivity change induced by the reactor coolant and fuel temperature transient.

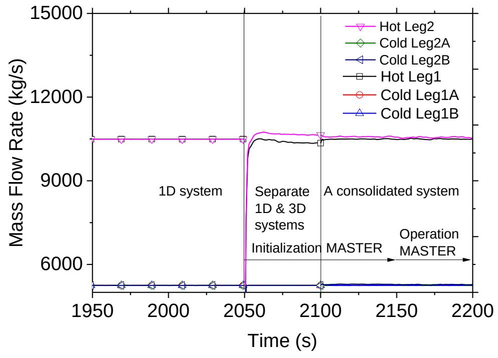


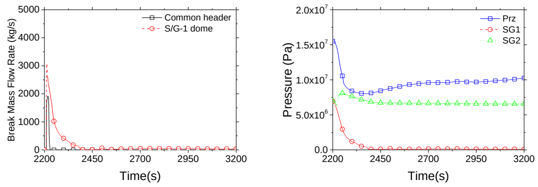
Fig. 3. Mass flow rates at two hot legs and four cold legs

2.2 MSLB Transient Calculation

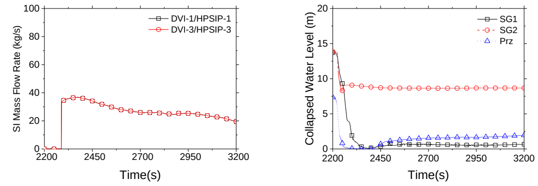
The fourth step transient calculation in Fig. 1-4 is conducted using the third step calculation results and the restart functions of MASTER/CUPID/MARS, each part of which maintains its own individual characteristics. The MSLB simulation is started with the two main steam line break valves open. The transient calculation is started at 2200 s and the MSLB occurs at 2210 s. The reactor is shut down by dropping all the control rods and the reactor coolant pumps are stopped at the low pressurizer-pressure signal after the MSLB event.

The break mass flow rates, pressure, safety injection mass flow rates, collapsed water levels are presented in Fig. 4. The break flows due to the SG-1 (Steam Generator, see Fig. 2) steam line double-ended break occurs on both of the common header and SG-1 dome sides (Fig. 4-1). The primary pressure and affected SG-1 pressure decrease sharply to 7 MPa and atmospheric pressure, as shown in Fig. 4-2, but the intact SG-2 pressure recovers its steady state value due to actuation of Main Steam Isolation Valves (MSIVs). The safety injection rates reach 35 kg/s as soon as High Pressure Safety Injection Pump (HPSIP-1) and HPSIP-3 are actuated at 2288.66 s. The primary pressure increases slowly, and therefore the safety injection flow rates decrease according to the pressure increase shown in Fig. 4-3.

The water levels of the affected SG-1 and pressurizer decrease to the ground level, while the water level of the intact SG-2 is maintained at about 9 m in Fig. 4-4.



(1) Break flow rates (2) Pressures



(3) SI mass flow rates (4) Collapsed water levels

Fig. 4. MSLB transient calculation results at the fourth step

4. Conclusion

In this study, a multi-dimensional reactor safety analysis code, MASTER/CUPID/MARS, (made from coupling MASTER, CUPID, MARS codes) was applied to PWR MSLB analysis. In the simulation, the MASTER, CUPID, and MARS covered core neutronics, RPV thermal hydraulics, and all the other reactor components including two steam generators. The calculation was conducted in four steps: a steady state for 1-D reactor system, two separate steady states for a

1-D reactor and 3-D RPV (including the core), a steady state for a combined 1-D and 3-D reactor system, and a transient calculation. In this way, a multi-scale and multi-physics analysis for the PWR MSLB was successfully accomplished. This method is expected to provide more realistic nuclear safety analysis results after maturation and validation of the individual codes.

ACKNOWLEGEMENTS

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