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Sixth ATLAS Domestic Standard Problem (DSP-06): A Comparison of Blind and Open Calculation Results for CRDM Nozzle Rupture, Accompanied by a Failure of the Safety Injection Pump

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1. Introduction

As part of Korea Atomic Energy Research Institute (KAERI)'s ATLAS experimental program, the Domestic Standard Problem (DSP) was proposed at the 3rd Nuclear Safety Analysis Symposium in 2005 [1]. Beginning with the DVI line break test as DSP-01 in 2009, the program has continued through to DSP-06 in 2023 [2]. The progression of exercises has encompassed various scenarios, including small break loss-of-coolant-accidents (SBLOCAs) and steam-line breaks. These DSP exercises have played a vital role in resolving safety issues, validating safety analysis codes, and enhancing the understanding of nuclear reactor behavior. The series has significantly contributed to the advancement of safety analysis technology for PWRs and has been pivotal in the effective utilization of the ATLAS facility within the Korean nuclear community.

DSP-06 accepted experimental proposals from various institutions through an operating committee in June 2020, and in August 2020, conducted the CRDM-SIP-03 experiment, considering the CRDM penetration nozzle rupture issue and multiple failure accidents [3]. DSP-06 was carried out during the COVID-19 pandemic, so the distribution of experimental specifications and meetings were conducted through online. The open phase analysis results and reports were compiled in July 2022.

2. Objectives of the ATLAS DSP-06

The objectives of the DSP-06 exercise can be summarized as follows:

1) Verification of the transient simulation capability of the selected experiment using safety analysis codes
2) Derivation of key modeling methods and variables for predicting thermal-hydraulic phenomena
3) Technical advancement through sharing safety analysis methods and experiences among participants

As a joint operation agency Korea Institute of Nuclear Safety (KINS) and KAERI were responsible for coordination support, code calculation, and progress meetings.

3. Code assessment results

3.1 List of participants and summary of implemented model improvements

In the DSP-06 exercise, 17 institutions participated with 12 institutions involved in the blind phase and 10 in the open phase as shown in Table I. For safety analysis, the code MARS-KS and SPACE were widely used.

Table II summarizes the modeling modifications made by each institution for the open phase analysis. Half of the participants incorporated detailed modeling of the break line, and seven institutions applied the Henry-Fauske (H-F) model as a choked flow model. The remaining simulated choked flow using the Ransom-Trapp (R-T) model. To match the discharge flow, most participants modified the discharge coefficient, and KEPCOEnC, KINS, KNF adjusted the heat loss on the primary system. INU modified the heat loss on the secondary system.

Figure 1 shows the changes in calculation speed and time resolution between the blind and open phases. Most participants exhibited a tendency for reduced calculation speed in the open phase, which is believed to be due to the optimization of modeling for transient result during the open phase. In case of INU, it is assessed that the calculation speed increased during the open phase as nodes were expanded for precise thermal-hydraulic simulation of the RPV’s upper head.

3.2 Comparison of steady-state results

Figure 2 shows the differences between the steady-state analysis results and experimental result for both (a) blind and (b) open phases. As shown in Fig. 2, the calculation results generally showed good agreement with experimental result. Compared to the blind phase, the estimation of loop flow rate and primary/secondary system static pressure improved in the open phase, but the temperature and water level prediction in the RPV's upper head became more divers despite efforts such as modifying the heat loss on the primary system.

3.3 Comparison of core heat-up when uncovered

Figure 3 compares the experimental result with the calculation results, showing the behavior of (a) maximum cladding surface temperature and (b) collapsed water level in the core for the open phase. An appropriate break line model will predict the coolant discharge through the RPV's upper head due to CRDM nozzle rupture, and this can be verified by the water level prediction inside the core and the start time of core heat-up. Symbols of Fig. 4 show the core heat-up time (T1) on the x-axis, and the collapsed water level in the core at T1 on the y-axis. Figure 4 (a) shows the results of the blind phase, and (b) shows the results of the open phase, with the black circle symbol representing the experimental result. The closer the calculation results are to the black circle symbol, the better the prediction for core heat-up. As can be seen in Fig. 4 (a), in the blind phase, most participants predicted the water level in the core at the point when core heat-up occurs well, but they overestimated the coolant discharge due to SBLOCA, predicting that core heat-up would occur earlier than in the experiment. In the open phase as shown in Fig. 4 (b), most participants improved the prediction of coolant discharge by modifying the break line modeling, predicting the point of core heat-up occurrence more in line with the experiment compared to the blind phase.

Figure 5 visualizes the time taken for core heat-up (T2-T1) and rewet (T3-T2), corresponding to the time of start of core heat-up (T1), time of peak cladding temperature (T2), and time of end of quenching with SIT injection (T3). In the blind phase, all calculations underestimated the time taken for core heat-up and rewet as shown in Fig. 5 (a). This occurred because the cooling effect of depressurization through the atmospheric dump valve (ADV) on the secondary system as part of accident management (AM) was overestimated, resulting in a shorter duration for core heat-up and rewet compared to the experiment. In open phase as shown in Fig. 5(b), by adjusting the depressurization through the ADV close to the experiment, the time for core heat-up and rewet was well predicted.

3. Conclusions

The DSP-06 exercise, conducted through both a blind phase before the release of experimental result and an open phase afterward, emphasized the critical role of break line modeling in accident prediction. The iterative process allowed participants to refine their models and methodologies, leading to improved predictions for core heat-up and rewet times. The exercise confirmed the importance of accurate break line modeling in understanding complex thermal-hydraulic phenomena and validated the effectiveness of collaborative efforts in enhancing safety analysis technology within the Korean nuclear industry.

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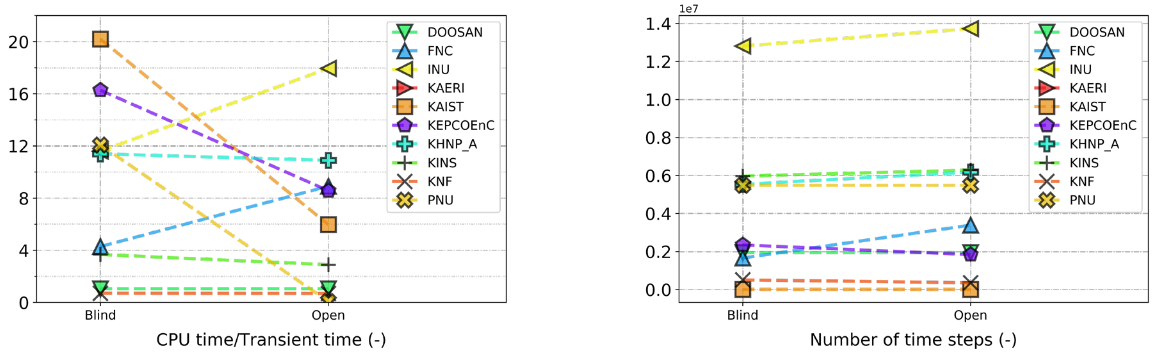
Table I: List of participating organizations

Participant	Short form (symbol)	Code	Blind phase	Open phase
Doosan Enerbility	DOOSAN	RELAP5 MOD3.3 Patch 5	Y	Y
FNC Technology	FNC	SPACE 3.22	Y	Y
Incheon National University	INU	MARS-KS 1.5	Y	Y
Korea Atomic Energy Research Institute	KAERI	SPACE	Y	Y
Korea Advanced Institute of Science and Technology	KAIST	MARS-KS 1.5	Y	Y
KEPCO Enginnering & Construction Company	KEPCOEnC	SPACE 3.21	Y	Y
KHNP Nuclear Safety Analysis	KHNP_A	SPACE 3.22	Y	Y
KHNP Adcanced Reactor Development Laboratory	KHNP_B	MARS-KS	Y	N
Korea Institute of Nuclear	KINS	MARS-KS 1.5 -> 1.6	Y	Y
KEPCO Nuclear Fuel	KNF	SPACE 3.2.2	Y	Y
Pusan National University	PNU	MARS-KS 1.5	Y	Y
Ulsan National Institute of Science and Technology	UNIST	MARS-KS 1.5 + SNAP 3.0.2	Y	N

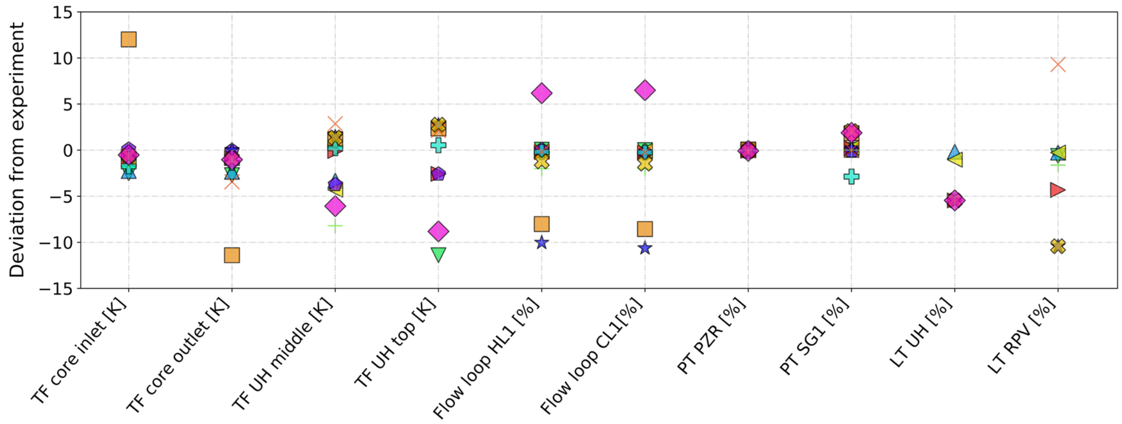
Table II: Open phase – features of adopted models

Participant	Break line modelled	Choked flow model	Remark
DOOSAN	N	-	
FNC	N	H-F	Discharge coefficient and thermal non-equilibrium constant are selected as 0.75 and 0.14 from sensitivity study
INU	Y	H-F	1) RPV upper head renodalized with 14 subvolumes in order to consider the effect of the stratification in the upper head. 2) New Correlation for the heat loss estimation on the secondary system
KAERI	N	R-T	
KAIST	Y	H-F	
KEPCOEnC	N	R-T	1) Modification of the K-factor in the primary system for simulating steady-state flow without RCP operation 2) Modeling feedwater control system for the initial SG water level 3) Adjusting the heat transfer coefficient between the primary/ secondary system and the environment 4) Modification of the heat transfer coefficient for the heat loss from the RPV upper head to the environment
KHNP_A	Y	R-T, H-F-m, H-F	Modification on Nodalization for the end of break valve
KINS	Y	H-F	1) Changing the discharge coefficient of the break nozzle 2) Increasing the heat transfer coefficient for the primary system's heat loss by 14% to compensate for the reduction in heat loss at the upper head
KNF	N	H-F	Adjusting the heat transfer coefficient to account for varying heat loss across different components within the primary system
PNU	Y	H-F	Reducing the loss coefficient of the upper side of RPV by 50% to take into account the loop seal clearing

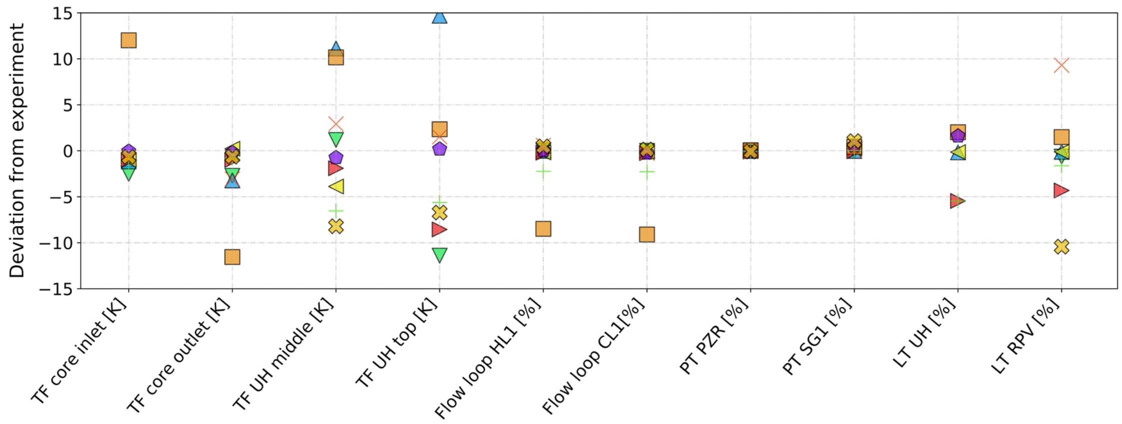


(a) Computing speed (b) Computing temporal resolution

Fig. 1. Code environment and run statistics.

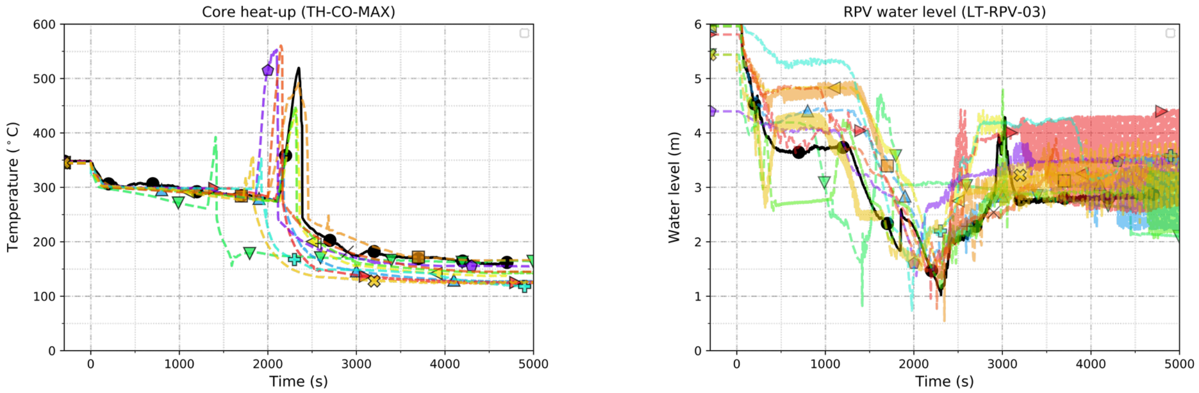


(a) Blind phase



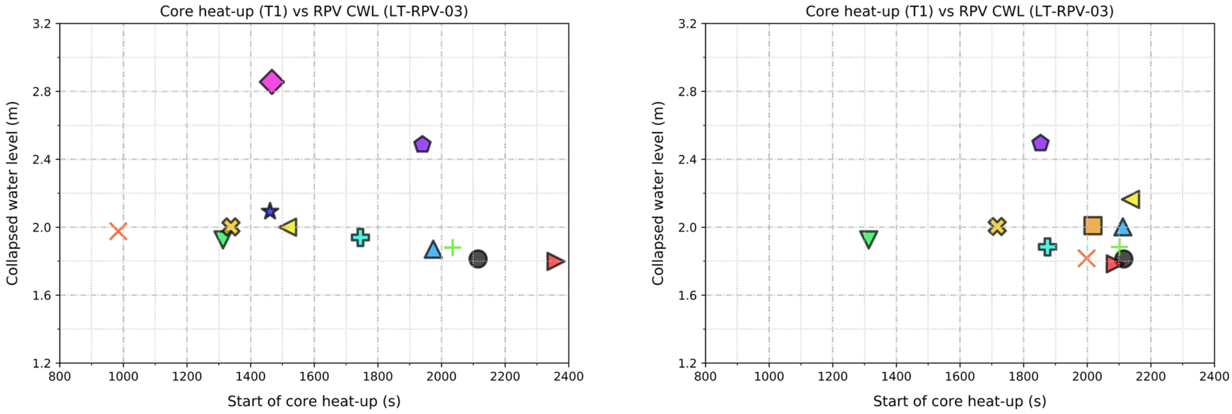
(b) Open phase

Fig. 2. Steady-state comparison between blind and open phases.



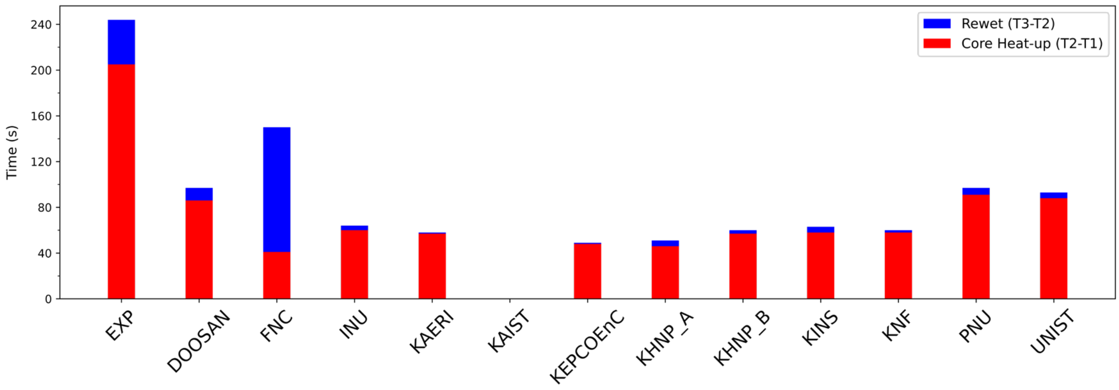
(a) Maximum cladding surface temperature (b) collapsed water level in RPV

Fig. 3. Open phase: code comparison of thermal-hydraulic behavior during the transient

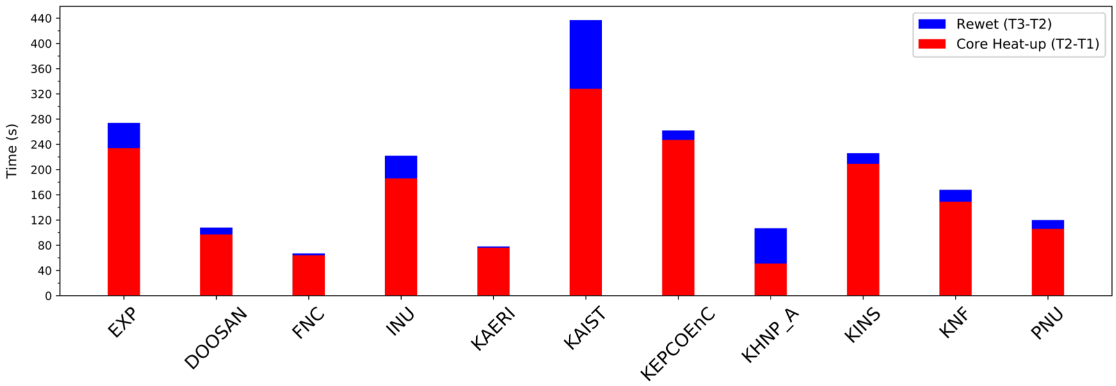


(a) Blind phase (b) Open Phase

Fig. 4. Comparison of core water level at start of heat-up between blind phase and open phase



(a) Blind phase



(b) Open phase

Fig. 5. Comparison between blind and open phases for core heat-up and rewet.