# Thermal-Hydraulic Analyses for Low Power/Shutdown PSA in Various Plant Operating States

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## 1. Introduction

The methods developed for full-power probabilistic safety assessment(PSA), including thermal-hydraulic methods, have been widely applied to low power and shutdown(LPSD) conditions. Experience from current LPSD PSA [1,2], however, indicates that the thermal-hydraulic methods developed for full-power PSA are not always reliable when applied to LPSD conditions and consequently may yield misleading and inaccurate risk insights. To increase the usefulness of the LPSD risk insights, the current methods and tools used for thermal-hydraulic calculations should be examined to ascertain whether they function effectively for LPSD conditions.

In this study, a platform for relatively detailed thermal-hydraulic calculations applied to LPSD conditions in a pressurized water reactor was developed based on the best-estimate thermal-hydraulic analysis code, MARS2.1. Many thermal-hydraulic analyses were comprehensively performed for the loss of shutdown cooling system(SCS) events for various plant operating states(POS) at the Korean standard nuclear power plant in order to confirm the applicability of the MARS platform to LPSD conditions.

## 2. Analysis

When performing PSA on the accidents during LPSD operations, it is convenient to define several POS's in which the plant configurations and operating conditions can be assumed to be the same. Fifteen POS's are defined in LPSD PSA for the Korean standard nuclear power plant [3]. In each POS, plant operating conditions and configurations are assumed to be identical.

To utilize the results of PSA in risk informed regulation, it is better to use the best estimate results instead of conservative assumptions or calculations in determining the success criteria or operator's grace time. MARS2.1 code [4] is used in this study, which is a best estimate thermal-hydraulic analysis code that can analyze low pressure low temperature accidents as well as high pressure high temperature accidents.

## 3. Results and Discussion

The main objective of this study is to confirm the applicability of the MARS platform to LPSD conditions by analyzing the detailed thermal-hydraulic behavior of the RCS in the loss of SCS accident during LPSD operations in various operating states. Among the above-mentioned POS's, POS's where fuel is loaded in the reactor vessel and the SCS is in operation are selected to analyze. Therefore, POS3, 4A, 4B, 5, 6(early POS's), and POS10, 11, 12A, 12B, 13(latter POS's) are simulated to develop thermal-hydraulic analysis platform for LPSD PSA. The plant operating conditions of each latter POS are the same as those of each early POS except the core decay heat level and initial temperature. Therefore, POS10 corresponds to post POS6, POS11 to post POS5, POS12A to post POS4B, POS12B to post POS4A, POS13 to post POS3, respectively.

To compare the indispensable thermal-hydraulic parameters in performing LPSD PSA of each POS, the maximum RCS pressure and temperature are shown in Fig. 1 and the core boiling and damage time after the accident are shown in Fig. 2. As shown in Fig. 1, the maximum RCS pressures of POS3 and POS4A are high compared with those of the other early POS's(POS4B, POS5, POS6). There are no vent path for POS3 and a pressurizer head vent having small cross sectional area for POS4A, while there are large openings for the other early POS's. The maximum RCS temperature of each POS, which is the saturation temperature corresponding to the maximum RCS pressure, shows a similar trend as the maximum RCS pressure of each POS. For latter POS's, the maximum pressure and temperature of each POS are similar to those of each corresponding early POS. The maximum pressure of POS12B will increase up to that of corresponding POS4A if simulation is continued over 86,400 sec.

For POS's having openings with small cross sectional area(POS3, 4A, 12B,13), the pressure increases over the

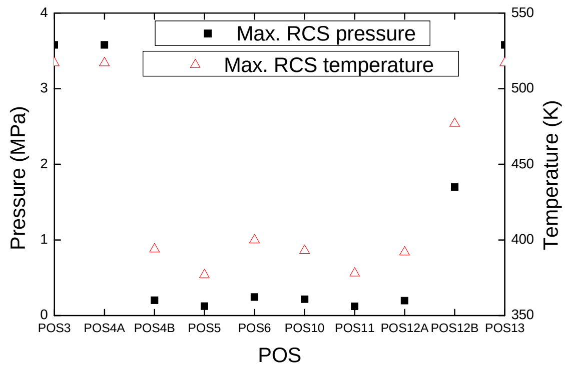


Figure 1. Maximum RCS pressure and temperature of each POS.

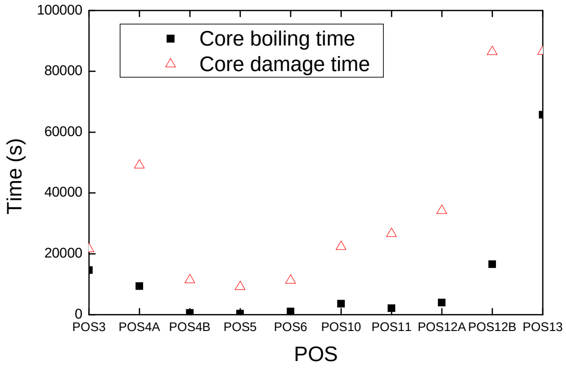


Figure 2. Core boiling and damage time of each POS.

RCS temporary boundaries(such as thimble tube seal) design pressure of 0.25 MPa. Therefore, there is a possibility of breaking the RCS temporary boundaries due to the over pressurization in the RCS. If the RCS temporary boundaries such as thimble tube seal were broken, the loss of SCS accident could cause serious problem due to the loss of large amounts of coolant.

In early POS's, core damage occurs at 21,610 sec. and 49,140 sec. in POS3 and POS4A, respectively, where SG's are available for the alternative means of core decay heat removal after the accident as shown in Fig. 2. In POS4B, POS5, and POS6 where SG's are unavailable for the alternative means of core decay heat removal, core damage occurs at 11,380 sec., 9,180 sec., and 11,220 sec., respectively. Therefore, it is known that core damage occurs earlier when the SG's are unavailable for the alternative means of core decay heat removal compared with the cases where the SG's are available. Because pressurizer manway in POS4B, pressurizer and SG inlet plenum manways in POS5, and pressurizer manway and ICI tubes in POS6 are open, core damage occurs earlier due to the large amount of coolant loss through these openings after the accident. Especially, core damage occurs at the earliest time in POS5 because both the pressurizer and SG inlet plenum manways are open and RCS water level is low(at the middle position of the hot leg) due to the midloop operation in POS5.

Thermal-hydraulic analysis results of loss of SCS accident during LPSD operations in each latter POS are compared with those of corresponding early POS. Core damage occurs at 22,356 sec. in POS10 because the accident is mitigated due to the low decay heat while core damage occurs at 11,220 sec. in POS6 which is the early POS corresponding to POS10. In the same manner, core damage occurs later in other latter POS's, POS11, POS12A, POS12B, POS13, comparing with the corresponding early POS's, POS5, POS4B, POS4A, POS3, respectively.

From the analysis results, it is known that there is a general tendency that core damage occurs earlier when the SG's are unavailable for the alternative means of core decay heat removal compared with the cases where the SG's are available. It is also known that when openings with large cross sectional area such as pressurizer manway, SG inlet plenum manways, and ICI tubes are open core damage occurs earlier due to the large amount of coolant loss through these openings after the accident. Accidents are mitigated in latter POS's due to the low decay heat comparing with the early POS's.

## 4. Conclusions

When no vent path or vent paths with small cross sectional area are open during the accident, there is a possibility of breaking the RCS temporary boundaries such as thimble tube seal due to the over pressurization in the RCS. When steam generators are unavailable for the alternative means of core decay heat removal after the accident, the core damage occurs earlier than the cases of steam generators available. When vent paths with large cross sectional area such as pressurizer manway, steam generator inlet plenum manways, and ICI tubes are open during the accident, core damage occurs early because large amounts of coolant are lost through these opened vent paths. In case of loss of SCS accident during latter POS, the accident is mitigated due to the lower core decay heat level comparing with that in early POS.

In this study, the thermal-hydraulic analysis platform for LPSD PSA is developed by providing input data and occurring time of the related thermal-hydraulic parameters such as core damage in various POS's during LPSD operations. The MARS platform developed in this study can be effectively used for LPSD conditions. The results of this study can be used as fundamental data to develop event tree and to quantify event sequence in the development of PSA methodology during LPSD operations.

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