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Low Power Shutdown PSA for CANDU Type Plants

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1. Introduction

Historically, most probabilistic safety assessments (PSAs) for nuclear power plants (NPPs) have focused on full power operation of the plants [1]. KHNP also have concentrated on full power PSA. Some recently constructed OPR1000 type plants and APR1400 type plants have performed the low power and shutdown (LPSD) PSA. The purpose of LPSD PSA is to identify the main contributors on the accident sequences of core damage and to find the measure of safety improvement.

After the Fukushima accident, Korean regulatory agency required the shutdown severe accident management guidelines (SSAMG) development for safety enhancement. For the reliability of SSAMG, KHNP should develop the LPSD PSA. Especially, the LPSD PSA for CANDU type plant had developed for the first time in Korea.

This paper illustrates how the LPSD PSA for CANDU type developed and the core damage frequency (CDF) is different with that of full power PSA.

2. Analysis and Results

2.1 Categorization of plant operational states

Plant operational states (POSs) for CANDU type reactor is divided into 10 based on the planned refueling outage experience and standard procedure for outage. We analyzed recently performed 5 planned outage schedules. We selected two general outage schedules to calculate the duration of POS.

The defining of the POSs considers also following items.

- Power level of reactor
- Water level and pressure of reactor coolant system
- Maintenance of frontline system and supporting system

Examples of POSs of CANDU type reactor are presented in Table 1.

Table 1: characteristics for each plant operation state

POS No.	description	Status
1	From desynchronization to reactor trip	PHT temp: 290℃ PHT press: 9.89MPa(g) PHT level: similar to full power
2	PHT first cooldown operation(260℃~149℃)	PHT temp: 260℃ PHT press: 9.89MPa(g) PHT level: 5m
3	PHT second cooldown operation(149℃~100℃) = Mid loop operation	PHT temp: 149℃ PHT press: 7MPa(g) PHT level: Solid mode
4	PHT second cooldown operation(100℃~54℃)	PHT temp: 100℃ PHT press: 3MPa(g) PHT level: Solid mode
5A 5B	Guaranteed shutdown state	PHT temp: 54℃ PHT press: 0.5MPa(g) PHT level: RHR
6	Guaranteed shutdown state	PHT temp: 54℃> PHT press: 0.5MPa(g) > PHT level: RIH/ROH
7	Heat up	PHT temp: 100℃ PHT press: 7MPa(g) PHT level: Solid mode
8A	Increase power, criticality, and synchronization state	PHT temp: 150℃ PHT press: 7MPa(g) PHT level: 5m
8B	After criticality	Power: 20%FP PHT temp: 270℃ PHT press: 9.89MPa(g) PHT level: Similar to full power

Duration times with POSs and main parameters such as temperature, water level for primary heat transport (PHT) are illustrated in figure 1.

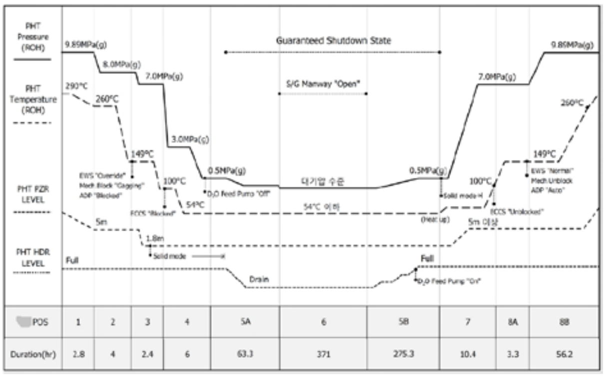

Fig.1. Plant operation states, duration, and status for CANDU type reactor

2.2 The initiating events

In order to decide initiating events (IEs) in LPSD PSA, we considered IEs in full power PSA and IEs which may be probable during low power and shutdown state. All 38 IEs including loss of shutdown cooling (LOSDC) were selected final IEs.

Bayesian approach was applied to calculate the IE frequency based on actual operating experience and those of generic CANDU PSA in case of specific CANDU IEs. The frequency of IE similar to PWR was used analysis results of all operating experience in

KHNP. Plant specific analysis was performed for interfacing loss of coolant (ISLOCA).

2.3 Accident sequences

The event trees developed for full power PSA need to be modified for use in LPSD PSA. POS 2, 8A, 8B use the same event trees due to similar full power condition [2]. The modification regarding the feature of LPSD PSA in event trees includes removal of some headings like reactor trip.

The fault tree models developed for the full power PSA could be revised due to the following reasons [1]:

- Plant configuration during outage is different from that during power operation. System in the standby mode during power operation is operational in shutdown.
- Automatic actuation signal in power operation is manual.
- System success criteria changes with POS
- Recovery possibilities are different for individual POS.

2.4 The human reliability analysis

Human reliability analysis (HRA) is the most important in LPSD PSA due to a large number of operator actions during outage. The K-HRA [3] methodology is used to evaluate the human error probability.

HRA is performed as following assumptions.

- Operator action should be performed to ensure the heat sink source during maintenance.
- Safety manager monitors critical safety parameter (CSP).
- Operator action outside MCR needs at least 10minutes to get to certain location.

2.5 Qualification of accident sequences

Quantification of accident sequences consists of pre-quantification state and post-quantification state. The former checks errors of event trees and fault trees in PSA model using minimal cutsets. The latter calculate the final core damage frequency (CDF) including HRA. POS1 is excluded in this analysis because it is identical to full power operation.

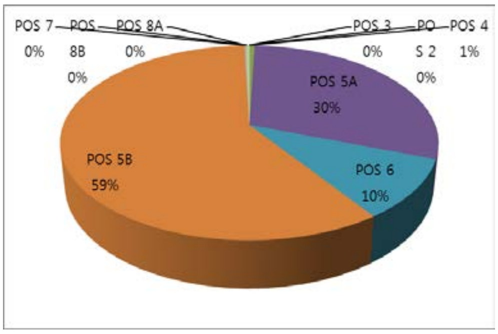

Fig. 2 CDF distribution with POS

The results show that the dominant contributors to the total CDF are POS 5A, 6, and 5B. The combined contribution of these POSs is 99% of total CDF according to figure 2.

Table 3 depicts the top 5 IEs contributed to the total CDF. The combined contribution of loss of class 4 power (LOCL4) and loss of shutdown cooling is 94.79% of total CDF. We are able to understand that these two systems play very important role in low power and shutdown state.

Table 3: CDF contributions of the dominant initiating events

Initiating events	Contribution to total CDF (%)
Total loss of class 4 power	58.28
Loss of shutdown cooling	36.51
Loss of raw service water	1.96
Loss of recirculated cooling water	1.77
Loss of coolant	1.06

Table 4 shows that the main dominant contributions to the total CDF are recovery failure of LOCL4, operation failure of standby generator during out-of-service of one class 3 power, frequency of LOSDC at POS 5 in the importances.

Table 4: The importances results of LPSA PSA

Event	mean	F_V	RAW	RRW
REC-CL4-A	1.34E-01	5.64E-01	4.64E+00	2.29E+00
%BE-IE-CL4-P5B	4.56E-03	4.12E-01	9.11E+01	1.70E+00
C3DGR-5211-SG2	2.01E-02	3.4E-01	1.75E+01	1.52E+00
%BE-IE-LOSDC-P5A	4.15E-04	1.93E-01	4.62E+02	1.24E+00
%BE-IE-LOSDC-P5B	1.8E-03	1.72E-01	9.61E+01	1.21E+00

3. Conclusions

KHNP performed LPSD PSA to develop the SSAMG after the Fukushima accidents. The results show that risk at the specific operation mode during outage is higher than that of full power operation. Also, the results indicated that recovery failure of class 4 power at the POS 5A, 5B contribute dominantly to the total CDF from importances analysis. It was found that the most important IEs during outage are loss of power and loss of shutdown cooling from the PSA results.

LPSD PSA results such as CDF with initiating events and POSs, risk results with plant damage state, and containment failure probability and frequency with POSs can be used by inputs for developing the SSAMG.

REFERENCES

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