EVALUATION OF MAINTENANCE EFFECTS ON THE SHUTDOWN RISK OF WESTINGHOUSE PWRS IN KOREA

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Low Power and Shutdown (LPSD) operations can be considered as relatively varying situations when compared to full-power operations. In addition, the operational mode changes as the process of outage during LPSD operation. It also consisted of a number of distinct and significantly different sets of plant configurations. These various plant configurations are required to accomplish the refueling, maintenance, and testing activities associated with an outage. Therefore, the disabled state of the system and equipment caused by maintenance and testing is an important factor in LPSD operation. In this study, based on maintenance effects of Westinghouse PWRs in Korea, the shutdown risk of LPSD PSA was evaluated. LPSD PSA models have been developed for Westinghouse Type Reactors in Korea in accordance with NUREG/CR-6144 methodology. The overhaul history for each reactor was analyzed based on daily process records and operator records over the past 10 years in order to identify the maintenance practices of equipment, because it is important to reflect the operational status of the power plants during LPSD operation. The maintenance practices were different significantly for each reactor. Thus, shutdown risk was evaluated by defining other maintenance practices for the same power plant. So, well planned maintenance practices are required to ensure the plant safety in LPSD operation.

I. INTRODUCTION

Before the 1980s, probabilistic safety assessments (PSAs) for nuclear power plants were considered only for the full power operation of the plants, but, during the low power and shutdown (LPSD) operations the amount of residual heat increases and thus, substantially contribute to the risk of plant, LPSD PSA was initiated to ensure the safety of the plants.

LPSD operations present a relatively dynamic situation when compared to the full power operations, consisting of a number of distinct and significantly different sets of plant configurations. These varying plant configurations are required in order to accomplish the refueling, maintenance, and testing activities associated with an outage. The variability in plant configurations, simultaneous unavailability of systems, blocking of automatic actuation of safety systems are the main risk characteristics significant for LPSD operational states. Particularly, the maintenance practices have a significant impact on the result of risk for LPSD PSA. Thus, this paper discusses the LPSD risk according to the maintenance practices for the power plant.

II. METHOD

LPSD PSA models for the Westinghouse type reactors have been developed in accordance with the methodology published in NUREG/CR-6144 (Ref. 1). For the purpose of the LPSD model, the Plant Operational states (POS) was divided into 15 parts according to the outage states. Also by analyzing the initial event and accident sequence, we were able to deduce the core damage scenario for each POS. The overhaul history for each reactor was analyzed based on daily process records and operator records over the past 10 years in order to identify the maintenance practices of equipment, realizing that it is important to reflect the actual operational status of the power plants during LPSD operations.

II.A. Review of Maintenance Practices

The plant A of TABLE I shows the result of maintenance practices for the major system operating states of each POS. In the chemical and volume control system, Train A pump is assumed to be unavailable for maintenance in POS 3 through POS 8; train S pump is assumed to be unavailable for maintenance in POS 3 through POS 9; and train B pump is assumed to be unavailable for maintenance in POS 8 through POS 11. In addition, the maintenance practices confirmed that maintenance of the containment spray system train A is assumed to be performed from POS 3 to POS 8, and train B maintenance is assumed to be performed from POS 8 to POS 11. In the case of the essential chilled water system (ECW), the maintenance of ECW cooler is performed from POS 3 to POS 8. The emergency diesel generators (EDG) are unavailable for maintenance. EDG A is unavailable for maintenance from POS 3A to the first half of POS 8. EDG B is unavailable for maintenance from the second half of POS 8 to POS 12B. The stand-by aux. transformer (SAT) 1 is assumed to be unavailable for maintenance in POS 3 through POS 8, and SAT 2 is assumed to be unavailable for maintenance when in POS 8 through POS 12B.

Since maintenance practices were considerably different for each reactor, the overhaul experiences of the same type reactors were reviewed for the maintenance practices. The plant B of TABLE I shows the result of maintenance practices for the major system operating states of each POS. The EDGs are unavailable for maintenance. EDG A is unavailable for maintenance from POS 3 to the first half of POS 8. EDG B is unavailable for maintenance from the second half of POS 8 to POS 12B.

TABLE I. The Major System Operating States of each POS

<Plant A >

POS	CHP			DG		CSP		ECWC		SAT1	SAT2
	A	B	S	A	B	A	B	A	B		
1	S	R	RO	S	S	S	S	S	S	R	R
2	S	R	RO	S	S	S	S	S	S	R	R
3	M	R	M	M	S	M	RO	M	R	M	R
4	M	R	M	M	S	M	RO	M	R	M	R
5	M	R	M	M	S	M	RO	M	R	M	R
6	M	R	M	M	S	M	RO	M	R	M	R
7	M	R	M	M	S	M	RO	M	R	M	R
8	M	M	M	M	M	M	M	M	M	R	M
9	R	M	M	S	M	RO	M	R	M	R	M
10	R	M	RO	S	M	RO	M	R	M	R	M
11	R	M	RO	S	M	RO	RO	R	M	R	M
12A	R	S	RO	S	M	RO	RO	R	M	R	M
12B	R	S	RO	S	M	RO	RO	R	S	R	M
13	R	S	RO	S	S	RO	RO	R	S	R	R
14	R	S	RO	S	S	S	S	S	S	R	R
15	R	S	RO	S	S	S	S	S	S	R	R

<Plant B >

POS	CHP			DG		CSP		ECWC		SAT1	SAT2
	A	B	S	A	B	A	B	A	B		
1	S	R	RO	S	S	S	S	S	S	R	R
2	S	R	RO	S	S	S	S	S	S	R	R
3	RO	R	RO	M	S	RO	RO	RO	R	R	R
4	RO	R	RO	M	S	RO	RO	RO	R	R	R
5	RO	R	RO	M	S	RO	RO	RO	R	R	R
6	RO	R	RO	M	S	RO	RO	RO	R	R	R
7	M	R	M	M	S	M	RO	M	R	R	R
8	M	M	M	M	M	M	M	M	M	R	R
9	R	M	M	S	M	RO	M	R	M	R	R
10	R	RO	RO	S	M	RO	RO	R	RO	R	R
11	R	RO	RO	S	M	RO	RO	R	RO	R	R
12A	R	RO	RO	S	M	RO	RO	R	RO	R	R
12B	R	RO	RO	S	M	RO	RO	R	RO	R	R
13	R	RO	RO	S	S	RO	RO	R	RO	R	R
14	R	S	RO	S	S	S	S	S	S	R	R
15	R	S	RO	S	S	S	S	S	S	R	R

R	: operating	S	: stand-by
RO	: racked out	M	: maintenance
POS	: plant operating state	CHP	: charging pump
DG	: emergency diesel generator	CSP	: containment spray pump
ECWC	: essential chilled water chiller	SAT	: stand-by aux. transformer

II.B. Evaluation of Maintenance Effects

Risks of LPSD PSA were evaluated based on the maintenance practices. In LPSD PSA, plant conditions in the transition modes (POS 1, POS 2, POS 14, and POS 15) are similar to those considered in the at-power internal events PSA. Similarly, POS 7 and 9 are screened as the cavity is flooded and no fuel is in the core, or the core is partially offloaded. Thus, model quantification was performed for 11 POSs.

II.B.1 Application of Maintenance Practices of W.H Type Plants

The core damage frequency (CDF) contributions by POS are presented in Fig. 1. The result of LPSD PSA for the Westinghouse PWR shows that the most risk values are concentrated on the RHR cooling to POS 3 as shown Fig. 1. The CDF in POS 3 contribute 25.9% of the total shutdown CDF. The POS 5 is mid-loop operation before offload. The contribution to the total CDF is 22.7%. The POS 4 is draining the RCS to mid-loop and its contribution to the total CDF is 15.0%.

The underlying reason for POS 3 having the greatest contribution is explained by the maintenance practice inferred from the plant records. According to the daily process records and operator records over the past 10 years, it is confirmed that main equipment (EDG, charging pumps, containment spray pump, and essential chiller) for safety functions are unavailable for maintenance from POS 3. When a loss of 4.16 kV (LOKV) occurs in POS 3, it would be revealed that feed and bleed operation using the charging pumps would be unavailable as the maintenance practices. At the same time, if it ends up being the case that the secondary heat removal fails due to the auxiliary feedwater pump or SG PORV failure, then it may be inferred that POS 3 is the highest contributor. Thus, when LPSD risk is analyzed for each plant operating states, POS 3 (RHR cooling) is the most dominant state at 25.9%.

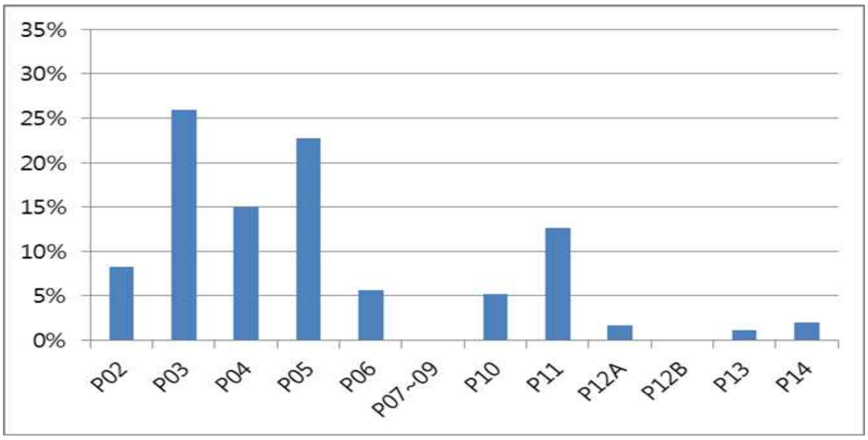

Fig. 1. CDF for each POS

In terms of the LPSD initiating events, a station black out (SBO) is the most significant initiating event, contributing 31.9% of the total CDF. The CDF of loss of offsite power (LOOP) is estimated to contribute 18.5% of the total CDF. Over-drain, during mid-loop operation (SO), loss of 4.16 kV AC (LOKV), POSRV's fail to reclose (PL), and level control failure during mid-loop operation (SL) are dominant, and take 13.9%, 8.5%, 5.6%, 5.3% and 3.6% portions of the total LPSD CDF, respectively.

The top 15 cutsets are summarized in TABLE II below. In the minimal cutsets (MCSs) analysis, the most probable sequence occurred in POS 5 and the sequence takes 8.6% of the total LPSD CDF. The sequence can be demonstrated by the following detailed scenario description: during the start of mid-loop operation, operator actions failed initial makeup to restore inventory. And then, operators tried feed & bleed (F&B) operation using the available charging pump, but failed. The scenario of the second high sequence is loss of offsite power (LOOP) in POS 4 resulting in failing to restore RHR cooling and failure of recovery offsite power within three hours. The CDF is contributing 2.8% of the total shutdown CDF. The scenario of the third high sequence is similar to that of the first one except the initiating event and first mitigation action. The CDF, due to a Level Control Failure during POS 5, is estimated and the contribution to the total CDF is 2.7%. In the case of Over-Drain, during mid-loop operation in POS 11, the operator failed to initiate recovery of makeup, F&B operation, and the gravity feed. The CDF takes up 2.1% of the total CDF. In POS 3, the operator failed to initiate the secondary heat removal in LOKV, while B train was in operation. The CDF takes up 2.0% of the total CDF.

TABLE II. Minimal Cutsets

NO	(%)	CUTSET			
1	8.6	%IE-SOP05	HR-MK-SOP05	HR-MKFB-SOP05-02-LD	
2	2.8	%IE-LPP04	LSMP0025SB-SMPS	R-LPSD-LOOP-3HR	
3	2.7	%IE-SLP05	HR-MK-SLP05	HR-MKFB-SLP05-02-LD	
4	2.1	%IE-SOP11	HR-FBGF-SOP11-02-HD	HR-MK-SOP11	HR-MKFB-SOP11-02-LD
5	2.0	%IE-KVP03	HR-SG-KVP03		
6	2.0	%IE-NCP04			
7	2.0	%IE-PSVLOCA-P2	LSOPSLPPHS		
8	1.5	%IE-LXP03	EGDGE001RS	EGDGZ002SB	R-LPSD-LOOP-3HR
9	1.4	%IE-KVP03	IAVV0186UA		
10	1.3	%IE-HLP03			
11	1.2	%IE-SOP11	CWCU0006RA	EKOPRSRCVS	
12	1.1	%IE-PSVLOCA-P2	CSOPSCSPHS	MD-LSOPLPCRHS-SCSF	
13	1.1	%IE-SLP11	HR-FBGF-SLP11-02-HD	HR-MK-SLP11	HR-MKFB-SLP11-02-LD
14	1.0	%IE-PSVLOCA-P2	LSOPLPCRHS-SCSS		
15	0.9	%IE-KVP03	HR-RMC-AFRM		

II.B.2. Application of Maintenance Practices of Same Type Plants

Risk of LPSD PSA was evaluated by applying maintenance practices. According to the analysis results in TABLE II, The maintenance of the charging pump, containment spray pump and essential chiller, except for EDG, was assumed to be performed only from the POS 7~9. Analyzing these operations, the total CDF during LPSD operation was calculated. Compared with the base model; the CDF was reduced to 17.6%.

Fig. 2 shows CDF applied by the maintenance practice of the same type of plant distinguished by POS. The CDF in POS 5 is contributing 26.2% to the total shutdown CDF. The CDF in POS 3 is contributing 21.2% of the total shutdown CDF. Analyzing the results of the MCS review, it can be observed that the maintenance of the charging pump, containment spray pump, and essential chiller were only performed in POS 7-9. Thus, as displayed in TABLE II, cutset 5, 9, and 15 were found to be in the process of removal, POS 3 having a decreasing risk value. Therefore, it was confirmed that contribution of the POS 5 appears to have the highest risk values.

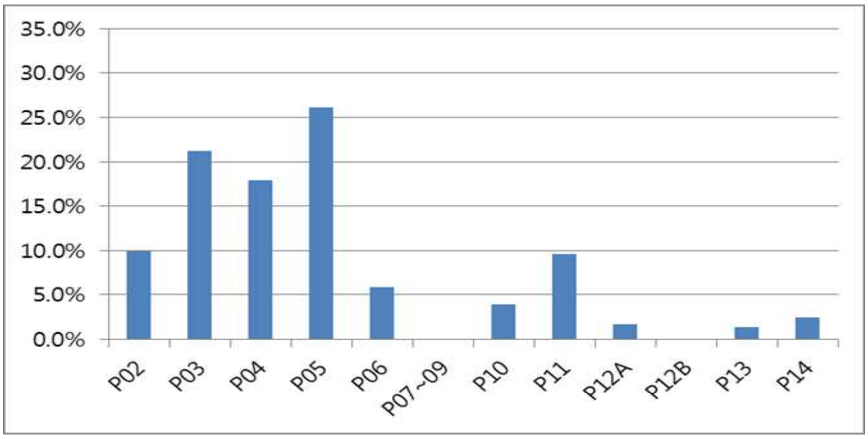

Fig. 2. CDF for each POS of Same Type Plants

II.B.3. Application of Conservative Assumptions

Adding onto the analysis results in TABLE II, a conservative estimate and evaluation was made for operation of EDG maintenance, in POS 7-9, was unavailable. Thus, looking at the conservative estimate and evaluation, the total CDF was reduced 55.9%. The CDF in POS 5 is contributing 33.8% of the total shutdown CDF. The CDF in POS 2 is contributing 18.6% of the total shutdown CDF. As a result, it was confirmed that contribution of the POS 5 appears to have the highest risk value, as shown in Fig. 3.

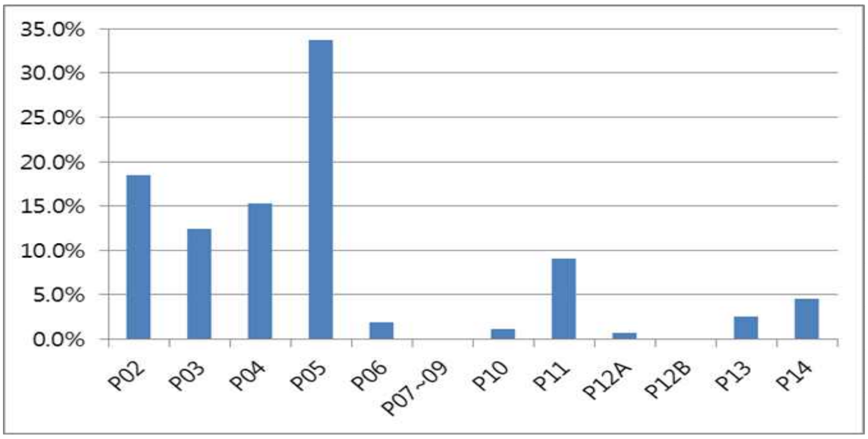

Fig. 3. CDF for each POS of Conservative Assumptions

II.C. Comparison of Results

As shown in TABLE III, It was confirmed that despite the nuclear power plants being the same type, maintenance practices for each reactor appeared to be significantly different. After the LPSD model was applied, the evaluation results confirmed that the maintenance practices had a significant influence on CDF. As the bottom part of TABLE II confirms, when safety-related equipment was performed in POS 7-9, the CDF was the lowest. Therefore, safety during outage would likely be improved if the maintenance period for safety-related equipment was performed during POS 7-9.

TABLE. III Comparison of Results

TOPIC	ΔCDF
BASE	-
Application of Maintenance Practices of same type plants	-17.6%
Application of Conservative assumptions	- 55.9%

III. CONCLUSIONS

LPSD PSA models have been developed for Westinghouse type reactors. The maintenance effects on the shutdown risk are discussed. This analysis shows that the evaluation of shutdown risk changed greatly according to the respective maintenance practice, despite the nuclear plants being the same type. It also confirmed that maintenance practices have influence on CDF in LPSD PSA. Therefore, well-planned maintenance practices are required to ensure plant safety in LPSD operation.

REFERENCES

1. USNRC, Evaluation of Potential Severe Accident During Low Power and Shutdown Operations at Surry Unit 1, NUREG/CR-6144 (1995)
2. KHNP, Level 1 Internal Event Probabilistic Safety Assessment Report for Low-Power and Shutdown Operation of Kori unit 3&4, Korea Hydro & Nuclear Power (2015)

3. KHNP, Level 1 Internal Event Probabilistic Safety Assessment Report for Low-Power and Shutdown Operation of Hanbit unit 1&2, Korea Hydro & Nuclear Power (2015)
4. IAEA, Probabilistic Safety Assessments of Nuclear Power Plants for Low Power and Shutdown Modes, IAEA-TECDOC-1144(2000).
5. EPRI, An Analysis of Loss of Decay Heat Removal Trends and Initiating Event Frequencies (1989-2000), EPRI-TR-1003113(2001)
6. ANS, Low-Power and Shutdown PRA Methodology, ANSI/ANS-58-22-2014(Trial-Use)(2014).
7. NRC, Guidelines for Industry Actions to Assess Shutdown Management, NUMARC 91-06(1991).
8. KEPCO E&C, SAREXTM User's Manual Version 1.2, KEPCO Engineering & Construction Company (2011).