Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

The Effectiveness of Emergency Injection to RCS for Risk Reduction in Low Power and Shutdown Operation

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1. Introduction

It was believed that the risk of low power and shutdown (LPSD) was not significant because the core decay heat level is very low. But it was found that the risk of LPSD would not be ignorable comparing to that of full power according to the NRC investigation. On the following, USNRC GL 88-17 [1] and NUMARC 91-06 [2] were issued by NRC and the industry to implement programmed enhancements for LPSD.

APR1400 has various advanced safety features and the risk for full power is low. But the risk for LPSD is relatively high comparing to that of full power. So, this paper discusses the appropriate method to reduce the overall risk associated with all modes to deal with the LPSD risk.

The process performs the conceptual level design for the alternative and the sensitivity analyses associated with the design alternative are evaluated.

2. Characterization of LPSD operation

2.1 Identification of Plant Operational State (POS)

According to the plant configuration in planned refueling outage, plant operational states (POSs) are defined and characterized.

The six operating modes are defined in technical specification. The six operating modes are not enough to define the characteristic of each POS. The total number of 15 POSs are divided according to the Reactor Coolant System (RCS) water level, RCS opening (pressurizer manway, SG manway), and maintenance schedule of major systems. On the following, POSs will cover the LPSD evolution from full power operation to refueling conditions.

2.2 Initiating Event for LPSD operation

NUREG/CR-6144 [3] provides a shutdown PRA for surry Unit 1 in 1994. It provided a comprehensive set of initiating events and their frequencies. In addition to that, EPRI TR-1003113 [4] is reviewed to identify LPSD initiating events. It provides a detailed survey of industry initiating events and groupings. and identified human errors as dominant contributors to most initiating events. The loss of shutdown cooling of over-drainage and mid-loop during reduced inventory operation is the most significant risk contributors as initiators in LPSD operation modes.

2.3 The Analysis Results in Base Case

According to the Table Ⅰ, the result of LPSD PRA for APR1400 shows that the most risk values are concentrated on the mid-loop and associated drain operation such as POS4B ~ 6 and POS10 ~ 12A. In terms of the LPSD initiating events, over drain, the loss of SCS, the loss of component cooling water, and station blackout are the most significant because some of AC sources might not be available since the component maintenance activities.

In the MCS (Minimal Cutset) analysis, operator errors or system failures lead to core damage. Operator actions for recovering RCS inventory or shutdown cooling using the available safety injection pumps are failed after the loss of shutdown cooling. All these mitigation systems with associated operator actions are failed sequentially and finally, core damage is occurred.

Table Ⅰ Minimal Cutset for APR1400 (Base Case)

Rank	Contribution (%)	Minimal Cutsets		
1	17.0	%SOP05	HR-FB-SOP05-02-DEP	HR-MK-SOP05
2	12.3	%LPP04B	HR-FB-LPP04B-DEP	HR-RS-LPP04B
3	10.0	%S1P04B	HR-FB-S1P04B-DEP	HR-RS-S1P04B
4	8.5	%SOP11	HR-FB-SOP11-02-DEP	HR-MK-SOP11
5	8.4	%LPP12A	HR-FB-LPP12A-DEP	HR-RS-LPP12A
6	6.8	%S1P12A	HR-FB-S1P12A-DEP	HR-RS-S1P12A
7	3.7	%PLP02	WOCHKQ4-CH01A/B/C/D	
8	1.8	%PLP02	SICVWQ4-V540/41/42/43	
9	1.8	%PLP02	SICVWQ4-V113/23/33/43	
10	1.8	%PLP02	SICVWQ4-V217/27/37/47	
11	1.6	%S2P04B	HR-FB-S2P04B-DEP	HR-RS-S2P04B
12	1.4	%SOP05	HR-FB-SOP05-01	SIMPS-B-SCPP01B
13	1.4	%SOP11	HR-FB-SOP11-01	SIMPS-A-SCPP01A
14	1.4	%LPP05	HR-FB-LPP05	HR-RS-LPP05
15	1.1	%S1P05	HR-FB-S1P05	HR-RS-S1P05
16	1.1	%S2P12A	HR-FB-S2P12A-DEP	HR-RS-S2P12A
17	0.8	%LPP11	HR-FB-LPP11	HR-RS-LPP11
18	0.7	%SOP05	HR-FB-SOP05-01	WOCHR-B-CH01B
19	0.7	%SOP11	HR-FB-SOP11-01	WOCHR-A-CH01A
20	0.6	%S1P11	HR-FB-S1P11	HR-RS-S1P11

The alternatives to reduce the risk of LPSD are identified based on the risk analysis results in the Base Case. It is associated with the prevention of core damage for the initiating event caused by the loss of shutdown cooling.

3. Design Alternatives

The design alternatives provide additional safety functions to mitigate accidents during LPSD operation modes. The design effectiveness is evaluated by the sensitivity analyses with the related with risk parameters.

3.1 Design alternatives

RCS levels during mid-loop operation are controlled by shutdown cooling system (SCS) and chemical & volume control system (CVCS). The decay heat is removed by shutdown cooling system.

This design alternatives prevent the RCS inventory loss during the accident with an emergency injection to SCS discharge line. If all safety systems including injection are failed, safety injection using the emergency source such as fire truck can be used for decay heat removal. Since the flow path from the emergency source is connected to SCS discharge line and there is a motor-operated isolation valve in this line, a local-manual action to open this valve must be performed. This action is considered when the RCS is depressurized with vent and more than a couple of hours are available for the action. Figure Ⅰ shows the outline of emergency injection to SCS discharge line as design alternative.

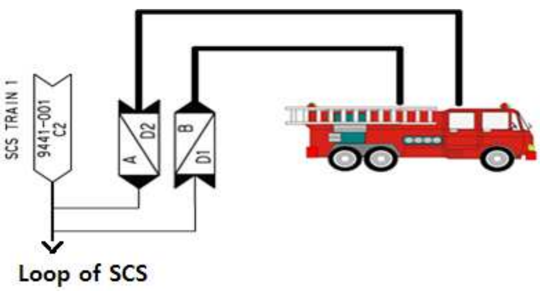

Figure Ⅰ emergency injection to SCS discharge line

3.2 Sensitivity analyses results for design alternatives

Sensitivity analyses are used to evaluate the effectiveness of the proposed design alternatives. The effectiveness of the design alternative are interpreted based on the results of the sensitivity analyses.

The alternatives for sensitivity are mainly effective for reduced inventory operation because emergency injection is possible when the pressure of RCS is low. When RCS has Manway Open (POSs 4B through 6 and 10 through 12A) including reduced inventory operation, RCS pressure is low.

According to the thermal hydraulic analyses, the available time of operator during before refueling, POSs 4B through 6, is less than half of that after refueling, POSs 10 through 12A, due to high decay heat. The performing the accident mitigating operation using emergency water source, such as fire truck may not be possible because the available time is not enough. So, two sensitivity analyses are performed.

The sensitivity 1 has assumed that emergency injection may be possible in POSs 4B through 6 and 10 through 12A. The sensitivity 2 has assumed that emergency injection may be possible in only POSs 10 through 12A except for POSs 4B through 6.

As a results, the total LPSD CDF (Core Damage Frequency) in case of sensitivity 1 is reduced to 66.8% whereas that of sensitivity 2 is reduced to 26.2% from its original value. The CDF reduction due to design alternative for each POS and I.E (Initiating Event) are summarized in Table Ⅱ and Ⅲ.

Table Ⅱ: CDF reduction due to design alternatives for each POS

POS NO	CDF (%) comparing to Base Case	
	Sensitivity 1	Sensitivity 2
POS01	0.0	0.0
POS02	0.0	0.0
POS03A	0.0	0.0
POS03B	0.0	0.0
POS04A	0.0	0.0
POS04B	-75.0	0.0
POS05	-75.0	0.0
POS06	-75.5	0.0
POS10	-73.3	-75.5
POS11	-75.0	-75.0
POS12A	-75.0	-75.0
POS13	0.0	0.0
POS14	0.0	0.0
POS15	0.0	0.0
Sum	-66.8	-26.2

Table Ⅲ: CDF reduction due to design alternatives for each I.E.

Initiating Event	CDF (%) comparing to Base	
	Sensitivity 1	Sensitivity 2
Recoverable Loss of Shutdown Cooling System	-74.9	-30.2
Unrecoverable Loss of Shutdown Cooling System	-74.9	-30.5
Over-Drainage During Reduced Inventory Operation	-75.0	-28.3
Failure to Maintain Water Level During Reduced Inventory Operation	-75.1	-38.0
Unrecoverable LOCA	-56.6	-15.0

Loss of Offsite Power	-74.8	-30.1
Station Blackout	-73.9	-24.7
Partial Loss of Component Cooling Water	-75.3	-29.7
Total Loss of Component Cooling Water	-68.7	-13.9
Loss of 4.16 kV AC Bus	-81.8	-25.0
Sum	-66.8	-26.2

4. Conclusion

This paper proposes design alternative to reduce LPSD risk for APR1400 design. The sensitivity analyses have been performed to measure the effectiveness of the proposed alternative. According to the results, if emergency injection to SCS discharge line is available during all POSs with depressurized RCS pressure, it is very effective to reduce LPSD risk. So, plant specific procedure need to be prepared to perform the accident mitigating operation using emergency water source, such as fire truck within available time.

REFERENCES

[1] USNRC generic letter No. 88-17, Loss of Decay Heat Removal, October 17, 1988.
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[3] USNRC NUREG/CR-6144, “Evaluation of Potential Severe Accidents during Low Power and Shutdown Operations at Surry, Unit 1,” October, 1995.
[4] EPRI TR-1003113, “An Analysis of Loss of Decay Heat Removal Trends and Initiating Event Frequencies (1989 − 2000),” Electric Power Research Institute, November 2001.