The Design Effectiveness of Mid-Loop Control System in APR1000 LPSD Level 1 Internal PSA

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1. Introduction

The level 1 and level 2 PSA for internal/external events are included in the scope of the standard design of the APR1000. The PSA is performed during all operation modes, which are At-Power (AP) and Low Power and Shutdown (LPSD) modes of operation, to follow the EUR Rev.E Chapter 2.17 requirements. APR1000 has various safety system functions to limit core damage that can occur in the internal/external events, to control, mitigate, or terminate decay heat low before core damage occurs.

In terms of the safety systems, this study deals with the design effectiveness in LPSD level 1 internal PSA. The sensitivity analysis is performed about safety feature of Mid-Loop Control System (MLCS) in the design phase of APR1000.

2. High Risk Contribution of Mid-Loop Operation in LPSD Level 1 Internal PSA (POS 5, 11 Duration)

2.1 Description of POS

First of all, the LPSD level 1 internal PSA is performed by determining Plant Operational States (POSs). Low temperature and pressure of Reactor Coolant System (RCS) or depressurized RCS conditions, and low decay heat characterize the plant conditions evaluated in the LPSD level 1 internal PSA. Therefore, plant configurations and conditions change significantly during LPSD operation. The function of systems for LPSD accident mitigation is not same as at-power accident mitigation, and the availability of systems for accident mitigation is also different. The Technical Specifications defines the operational modes (1~6) in the reference plants [Reference 4] in terms of reactor criticality, power, and temperature, but they are not detailed enough to determine the interfaces and characterize the operational modes in the LPSD level 1 internal PSA. The POSs were classified in the LPSD level 1 internal PSA with adjustments made to account for some experiences of refueling outage in reference plants. The POSs defined in the APR1000 LPSD level 1 internal PSA are presented in the following Table I.

Table I: Description of POSs

POS	Description	Reactor Coolant System Water Level	TS Mode
1	Reactor Trip and Subcritical Operation	In Pressurizer	1,2
2	Cooldown with Steam Generators to Mode 4		3
3A	Cooldown with Shutdown Cooling System to Mode 5		4
3B	Cooldown with Shutdown Cooling System and Fill the Pressurizer Fully		5
4A	Reactor Coolant System Drain-Down (Pressurizer manway Closed)		
4B	Reactor Coolant System Drain-Down (Manway Open)	Below Reactor Flange	
5	Reduced Inventory Operation and Nozzle Dam Installation		
6	Fill for Refueling		
7	Offload	Cavity Flooded	6
8	Defueled	N/A	Defueled
9	Onload	Cavity Flooded	6
10	Reactor Coolant System Drain-Down to Reduced Inventory after Refueling	Below Reactor Flange	5
11	Reduced Inventory Operation with Steam Generator Manway Closure		
12A	Refill Reactor Coolant System (Pressurizer Manway Open)		
12B	Refill Reactor Coolant System (Manway Closed)	In Pressurizer	
13	Reactor Coolant System Heat-Up with Shutdown Cooling System Isolation		4
14	Reactor Coolant System Heat-Up with Steam Generators		3
15	Reactor Startup		2,1

2.2 The Background of High Risk Contribution in Mid-Loop Operation

The mid-loop operation is defined as the RCS level is lowered to the mid-plane of the hot leg. This operation is performed to install or eliminate the Steam Generator (SG) nozzle dam at the connected part of hot leg. The operation is segregated into two durations based on high or low decay heat level. When the reactor core contains only spent fuels, which is before the refueling, the decay heat is in high level. When the reactor core contains some new fuels, which is after the refueling, the decay heat is in low level.

The mid-loop operation represents the reduced inventory operation and if the sufficient water level is not maintained at the pump inlet, air would be drawn into the pump resulting failure of the shutdown cooling.

In addition, because the Engineered Safety Features Actuation System (ESFAS) is bypassed switching operational mode to cold shutdown (Mode 5), only manual operations are available to start the system functions for accident mitigation. It means the risk of mid-loop operation is relatively high due to human errors and short available time for operators. The CDFs in POS 5 and 11 durations were estimated as dominant contribution to the total CDF of LPSD level 1 internal PSA.

Therefore, to reduce the risk during the mid-loop operation, various strategies have been established and the Mid-Loop Level Control System (MLCS) is the one of the strategies that is adopted in the design phase of APR1000.

3. Mid-Loop Level Control System (MLCS)

For taking advantages of the preliminary PSA in results and severe accidents evaluation, evaluation for prevention and mitigation of severe accidents is performed. Therefore, safety features have been introduced to prevent or mitigate the accidents in the design phase APR1000. For example, the preliminary LPSD level 1 internal PSA of the reference plant is identified that the mid-loop operation is one of the significant contributors to the total risk. The strategies to enhance the safety in this duration have been developed and the Mid-Loop Control System (MLCS) has been adopted to reduce the risk in the APR1000.

The MLCS keeps monitoring the RCS level, controlling the charging and letdown flow rates, to provide automatic controls for RCS water inventory when they are demanded. For instance, if the RCS water level is lowered to the low level setpoint of the narrow range refueling water indicators, the MLCS actuates SI pumps automatically with signal. The borated water will be injected into the RCS to make up the inventory and the level will be raised up to the required setpoint. When the RCS level uncontrollably drops below low level alarm setpoint in the mid-loop operation (e.g. the level drops caused by leakage in letdown line), the letdown containment isolation valves are automatically closed by the signal from the MLCS.

4. Sensitivity Analysis Results for Design Effectiveness of MLCS in LPSD Level 1 Internal PSA

With automatic controls of RCS inventory that actuate the SI pumps or close letdown containment isolation valves, the MLCS provides safety functions to control, mitigate, or terminate internal events in mid-loop operation. To evaluate the effectiveness of MLCS application, sensitivity analysis was performed comparing base plant that adopted MLCS and the plant without it. In the base case, which is similar to design phase of APR1000, automatic controls are provided by MLCS. In contrast, only manual operations are available in the mid-loop operation without MLCS in the sensitivity case.

Since MLCS is applied only to mid-loop operation, CDFs of POS 5, 11, and total of LPSD are selected and compared below. Descriptions of POS 5 and 11 are presented in table 2-1 above.

Table II: Result of Sensitivity Case for MLCS

Case No	Base	Sensitivity (without MLCS)	CDF comparing to Base
01	Designed with the MLCS for Mid-Loop Operation	Impact on POS 5	+2054%
02		Impact on POS 11	+1271%
03		Impact on Total CDF	+460.3%

As shown in the Table II, it was evaluated that the CDFs during mid-loop operations as well as the total CDF of LPSD level 1 internal PSA in APR1000 are increased significantly in the sensitivity case.

5 Conclusion

In this study, the effectiveness of MLCS was evaluated as a design improvement in LPSD level 1 internal PSA. According to the sensitivity analysis, the total CDF of LPSD level 1 internal PSA is increased 350.0% without MLCS in the sensitivity case01. The results from the analysis show that adoption of MLCS significantly reduces the risk of plant in LPSD level 1 internal PSA by adding automatic safety injection through continuous water level monitoring and automatic close of letdown containment isolation valves.

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