RCP Seal Leakage in the Loss of Ultimate Heat Sink Accident for APR1400 Nuclear Power Plant

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1. Introduction

The Reactor Coolant Pump (RCP) applied to the APR1400 is supplied with sealing water through charging pumps to prevent leakage caused by seal damage. Such charging pumps can experience a loss of sealing water supply capability due to power failure or degradation in the performance of the heat exchanger. The loss of sealing water supply capacity can lead to RCP seal damage and leakage, potentially resulting in core exposure due to loss of Reactor Coolant System (RCS) inventory. RCP seal leakage should be considered, as it can occur when the performance of charging pumps is compromised during a Loss of Ultimate Heat Sink (LOUHS) accident. LOUHS is a multiple failure accident that must be considered as part of the accident management program development, aiming to assess the power plant's capability to cope with multiple failure scenarios.

Various definitions exist for LOUHS; however, this paper conservatively assumes that both the primary side's Essential Service Water System (ESWS) and the secondary side's Circulating Water System (CWS) for ultimate heat removal are lost as initial conditions during a LOUHS accident. Sensitivity study on some leakage rates were performed to assess the effect on RCS behavior. Since multiple failure accidents fall within the category of beyond design basis accidents, a Best Estimated (BE) methodology was deemed suitable for LOUHS assessment, and thus, such an approach was employed in this evaluation.

The BE methodology through the SPACE code has been widely presented and utilized[1], and in this assessment, the integrity of the core for LOUHS with RCP seal leakage was confirmed using the SPACE code.

2. Analysis Methodology

The initial and boundary conditions of the BE methodology can be applied to the actual conditions of the power plant; therefore, the evaluation is conducted considering the normal operating conditions of the APR1400 design. Thus, as shown in Table I, a steady-state simulation representing the design values for normal operation was modeled, and this was employed as the initial condition for the analysis. The node diagram for the SPACE code analysis is presented in Fig. 1, mirroring the conditions of steady state operation with very small discrepancies from design values.

Table I. Initial Conditions

Parameter	Design Value
Core Power(MWt)	3,983
RCS flow rate(kg/s)	20,991
Core Inlet Temperature(°C)	323.85
Pressurizer pressure(psia)	2,250
Pressurizer Level(%)	50.0
SG level(%WR)	76.82

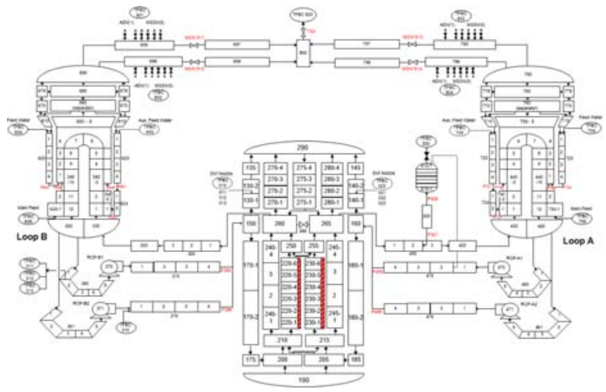

Fig. 1. APR1400 Node diagram

2.1 Assumptions

The loss of the primary side's ESWS during a LOUHS accident leads to the loss of the Component Cooling Water System (CCWS), which, in turn, results in reduced cooling capacity of the charging pump. This leads to performance degradation of the charging pump, affecting the injection of sealing water into the RCP. Some delay from the LOUHS to the performance degradation of charging pump is anticipated, for conservative assumptions regarding sealing water injection, it was assumed that the function of the charging pump is lost immediately at the onset of the accident, resulting in seal damage and coolant loss due to seal leakage. In addition to charging pumps, other crucial equipment that must be considered during a LOUHS accident includes Safety Injection Pump (SIP) and Shutdown Cooling Pump (SCP). These pumps are also cooled by CCWS and are assumed not to operate immediately at the beginning of the accident, similar to the charging pump.

The secondary side's ultimate heat removal mechanism is through the CWS, which leads to Loss of Condenser Vacuum (LOCV) due to reduced cooling capability. The exact timing of vacuum loss in the condensers is uncertain; however, since LOCV inevitably leads to the interruption of the Feedwater Pump (FWP) and turbine stop, it is assumed that these events also occur simultaneously with the accident's initiation. The RCP is assumed to stop 30 minutes after the accident occurs, delaying primary side cooling by reducing heat transfer from the primary side to the secondary side. Additionally, the assumption of an Atmospheric Discharge Valve (ADV) opening by the operators along with the RCP shutdown is considered. All of the above assumptions are summarized in Table II.

Table II. Assumptions for Analysis

Assumption	Affected Component
Loss of ESWS (CCWS)	Unavailable SIP & SCP Letdown HX → Letdown isolation CP Stop → RCP seal leakage
Loss of CWS	LOCV → TBN stop → FWP stop
Operator Actions (30 min.)	RCP stop ADV open RCGVS open

2.2 RCP Seal Leakage

The seal leakage rates were analyzed in four scenarios, considering leak rates of 0, 30, 100 and 300 gpm/RCP, assuming flow rates greater than the sealing water injection rate from the charging pump. In cases where the leakage flow rate is relatively small to allow cooling of the reactor system up to the conditions for entry into the Shutdown Cooling System (SCS), core exposure does not occur. However, in scenarios where the leakage flow rate is relatively large, making the operation of SIP and SCP impossible, a time frame for recovery of the ultimate heat removal mechanism through the connection of the high capacity mobile pump system which is provided to mitigate the accident. This approach is well-established and validated in accident management program as a common strategy.

After cooling and depressurizing the RCS up to the conditions for entry into the SCS, subsequent cooling can be performed up to stable safe shutdown condition. Therefore, the evaluation criteria are based on the time required for entry into the safe shutdown conditions based on the seal leakage rate and the time required to secure the inventory, following established practices.

3. Analysis Results

3.1 LOUHS Event

Among the four scenarios based on seal leakage rates, the representative case is the one where the value of 100 gpm/RCP seal leakage occurs. This is illustrated in Table III, depicting the sequence of events. The assumption regarding the system most affected by LOUHS is the LOCV scenario, which involves pressurization of the primary side, leading to reactor shutdown due to high pressurize pressure trip.

Table III. Sequence of Events for LOUHS

Event	Time (sec)
LOUHS	0.0
Reactor trip by HPPT	4.4
MSSV first open	4.8
POSRV first open	6.6
AFW actuation	289.6
Operator action	1,800
Safety Injection Tank actuation	2,237
SCS pressure entry condition reached	2,400
End of simulation	12 hours

Steam generator water level is influenced by the discharge of the Main Steam Safety Valve (MSSV). The discharge rate of the MSSV is illustrated in Fig. 2. Subsequent heat removal by the secondary side is facilitated by the opening of the ADV by operator, which occurs 30 minutes after the accident initiation. An ADV depressurization rate of 12.8°C/hour (50°F/hour) was applied by the operator, which is sufficient for heat removal along with auxiliary feedwater injection to remove heat.

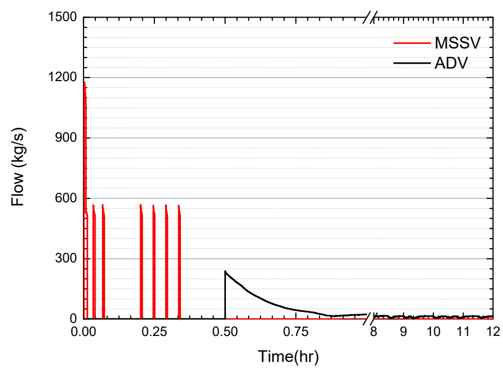

Fig. 2. MSSV & ADV Flow

The removal of core decay heat is achieved through a decrease in RCS pressure and temperature by MSSV and ADV. The RCS pressure decreases as shown in Fig. 3, indicating smooth natural circulation on the primary side for heat removal facilitated by the secondary side. To maintain effective natural circulation, the Reactor Coolant Gas Vent System (RCGVS) is used to remove gas from the reactor vessel or the pressurizer top. This is a manual action by operator and is initiated 30 minutes after the accident initiation. It can be observed that approximately 2,400 sec. after the accident, the RCS pressure reaches the conditions for entry into the SCS.

Similarly, the RCS temperature continues to decrease over time. However, for the high temperature region at the core inlet, it takes about 3,080 sec., as shown in Fig. 4, to reach the conditions for entry into the SCS. Nevertheless, as depicted in the figure, there are fluctuations in temperatures between the high temperature and low temperature regions at around the SCS entry temperature conditions. In practical terms, considering appropriate actions by operator, it is reasonable to anticipate that the initiation of the SCS operation could be faster than indicated by the results, given the temperature fluctuations observed in the actual situation.

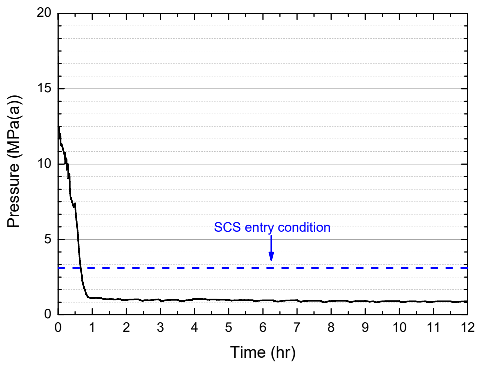

Fig. 3. RCS Pressure

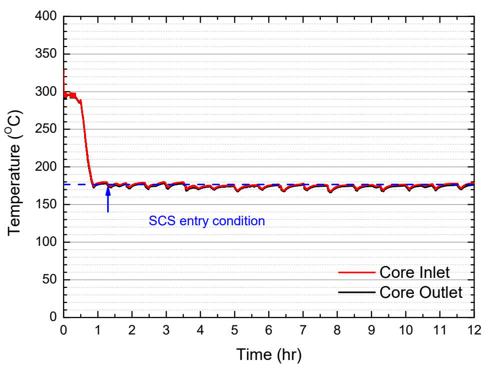

Fig. 4. RCS Temperature

3.2 Comparison of Seal Leakage

The time to reach the conditions for entry into the Shutdown Cooling System (SCS) has been summarized based on different seal leakage rates, as presented in Table IV. While there are variations in leak rates, in all cases, the conditions for SCS entry are met, indicating that the power plant can be maintained safely by restoring the heat removal mechanism at an appropriate time. As leak rates increase, as depicted, the RCS depressurization progresses rapidly. However, even in the case of the largest leak rate, the core water level is maintained above the upper effective core height. This confirms that there is no fuel heat-up as shown in Fig. 5.

Table IV. SCS Pressure Entry Time regarding Cases with Seal Leakage

Case	Seal Leakage (gpm/RCP)	SCS Pressure Entry Time (sec)
1	0	3,080
2	30	3,100
3	100	2,400
4	300	2,210

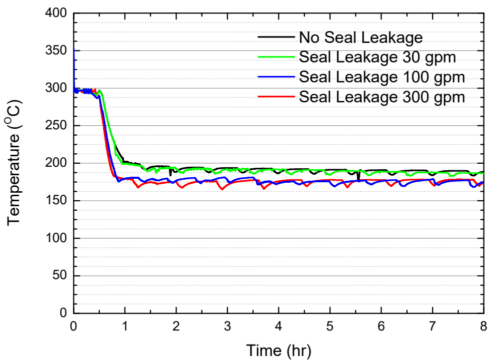

Fig. 5. Comparison of Fuel Temperature

4. Conclusions

In the event of a LOUHS accident, RCP seal leakage could have a significant impact on RCS thermal hydraulic behavior. Sensitivity analyses regarding leakage rates during LOUHS indicate that, if the heat removal mechanism is restored at the appropriate time, the reactor safety is maintained.

REFERENCES

[1] H. K. Ahn, I. H. Song, S. J. Park, J. M. Lee, Evaluation of the Increase in Feedwater Accident with Common Cause Failure during Flexible Operation using SPACE Code, Transactions of the Korean Nuclear Society Spring Meeting, 2023