Transactions of the Korean Nuclear Society Virtual Autumn Meeting
December 17-18

Probabilistic Analysis of the Inadvertent Boron Dilution Accident for WH Nuclear Power Plant

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1. Introduction

The inadvertent boron dilution accident may be caused by improper operator action or by a failure in the boric acid makeup flow path, which reduces the flow of borated water to the charging pump suction. Either cause can produce a boron concentration of the charging flow, which is below the concentration of the reactor coolant. This event is classified as an Anticipated Operational Occurrences (AOO) [1].

The inadvertent boron dilution accident is performed through deterministic safety analysis method, and the result is very limited because the most limited boron dilution flow rate is assumed in deterministic safety analysis. Therefore, in this study, boron dilution accident was performed using probabilistic safety analysis method, thereby eliminating unnecessary conservatism of boron dilution accident. A more realistic analysis of boron dilution accident was performed for all flow paths that could be caused by boron dilution through the assessment of probability of accident and maximum dilution flow rate by the relevant equipment and operator error. As a result of the probabilistic safety analysis, loss of shutdown margin frequency was compared with the frequency of AOO occurrence to verify the validity of the probabilistic safety analysis.

2. Methods and Assumption

A probabilistic risk analysis of the potential inadvertent boron dilution events was performed on the domestic 2-loop nuclear power plant and the scope of analysis was performed only for an inadvertent boron dilution of the Reactor Coolant System (RCS) during shutdown mode 5. The potential inadvertent boron dilution initiator is evaluated using the criterion in NUREG-0800 [2]. This ensures the time available for operator corrective action should be at least 15 minutes from flux multiplication alarm activation to the total loss of shutdown margin.

The method for performing this analysis incorporates Failure Modes Effects Analysis (FMEA) to determine potential failures of the Chemical Volume and Control System (CVCS) resulting in an inadvertent boron dilution of the RCS. FMEA is performed to determine equipment failures and operator errors that could lead to an inadvertent boron dilution of the RCS during shutdown mode 5. Shutdown mode 5 is the condition at cold shutdown where the pressurizer and steam generators are filled with RCS coolant. Passive components (heat exchangers, tanks, pipes, and manual valves) were not included in this analysis. However, the operator errors to open or close manual valves that could lead to an inadvertent boron dilution initiating event are considered in this analysis. The output from the FMEA is suggested chapter 3 for potential boron dilution initiating events.

The initiating event frequency for each of the potential boron dilution initiators is calculated. The initiating event frequencies for the CVCS demineralizer flushing operations and chemical addition are determined using available data for human reliability analysis and mechanical failure probabilities. There is more than one boron dilution initiating event that could result from the reactor makeup functions therefore, a boron dilution initiating event tree is constructed to determine the reactor makeup initiating event frequency.

An event tree is constructed to assess mitigation of the inadvertent boron dilution initiating events. An event tree considers the dilution flows to the RCS for each inadvertent boron dilution initiating event and corresponding available time that the operator has after the neutron flux multiplication alarm activates in order to prevent the total loss of shutdown margin.

Probabilities are assigned to each event tree branch point in the boron dilution mitigation event tree. The event tree for each boron dilution initiating event is quantified to determine the total loss of shutdown margin frequency (per reactor year).

3. Analysis Results

The potential initiators identified in the FMEA that could result in an inadvertent boron dilution event are three cases (Chemical addition, CVCS mixed bed demineralizer flush, Reactor makeup system).

3.1 Chemical addition

A boron dilution event could be initiated either during or after chemical addition, if both the inlet and outlet valves to the chemical mixing tank are not closed. The initiating event frequency of a dilution event occurring during chemical addition is 4.0E-04 per reactor years and these values were calculated by quoting the values in [3].

3.2 CVCS mixed bed demineralizer flush

CVCS mixed bed demineralizer flush is divided to 2 cases (Boron dilution event during and after the CVCS mixed bed demineralizer flushing operation). The failure of the operator to close inlet valve or outlet valve would deliver unborated water to the VCT. The failure to close the inlet or outlet valve during the flushing operation is 6.4E-04 and this value was calculated by quoting the values in [3].

If the outlet valve is not closed and the demineralizer is placed in operation, unborated water would be delivered to the VCT anytime whenever the reactor makeup water pump is running. This valve must be verified locked closed. The failure probabilitiy used to calculate the boron dilution initiating event frequency after the flushing operation is 8.0E-04.

One demineralizer is assumed to be flushed once per reactor year. The initiating frequencies for Mode 5 is 1.4E-03 per reactor year

3.3 Reactor makeup system

An event tree is constructed to determine the total initiating event frequency contribution from the reactor makeup function that could result in inadvertent dilution of the RCS. The event tree is depicted in Figure 1, and the description of the failure mode is given in Table 1 and the results of the reactor makeup system operation are summarized in Table 2.

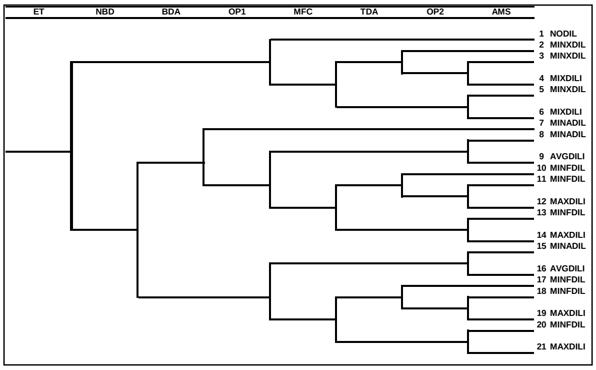

Fig 1. Event Tree for Determining Reactor Makeup Initiating Event Frequency

Table. 1. Description of the failure mode

Failure	Description
NBD	Boric acid is not delivered to the makeup operation
BDA	Boric acid deviation alarm fails to activate
OP 1	Operator fails to diagnose the cause of the boric acid deviation alarm and fails to stop the reactor makeup water pump
MFC	The reactor makeup water flow control valve fails to wide open position
TDA	Total makeup deviation alarm fails to activate
OP 2	Operator fails to diagnose the cause of the total makeup deviation alarm
AMS	Reactor makeup is not automatically stopped by the VCT level controller

Table. 2. The result of the reactor make up system operation

Parameter	Description
NODIL	No boron dilution event is initiated
MINXDIL	The incorrect boron concentration has been delivered to the RCS. RCS boron concentration is being diluted to maximum value
MIXDILI	The incorrect boron concentration has been delivered to the RCS and a boron dilution event is initiated. Reactor makeup water is being blended with boric acid.
MINADIL	Boric acid is not being delivered to the reactor makeup system. RCS boron concentration is being reduced by reactor makeup water at the setpoint flowrate average value
AVGDILI	Boric acid is not being delivered to the reactor makeup system. Reactor makeup water is delivered at the setpoint flowrate average value
MINFDIL	Boric acid is not being delivered to the reactor makeup system. RCS boron concentration is reduced by reactor makeup water at the maximum flow rate
MAXDILI	Boric acid is not being delivered to the reactor makeup system. Reactor make up water is delivered at the maximum flowrate

According to Table 2, the dilution flowrate is divided into three category. Table 3 lists the initiating event probabilities and frequencies (per reactor year) for an inadvertent boron dilution event during reactor makeup operation.

Table 3. Reactor Makeup Initiating Events

Initiator	Designator	Dilution Flowrate to RCS(gpm)	Probability	Frequency (per reactor year)
RMW Case 1	MIXDILI	Minimum	9.10E-05	1.82E-04
RMW Case 2	AVGDILI	Average	2.74E-04	5.49E-04
RMW Case 3 *	MAXDILI	Maximum	8.85E-08	1.77E-07

* Assuming this flowrate when using deterministic safety analysis.

3.4 Boron dilution mitigation event tree results

Once a dilution event has initiated, it is assumed that the flux multiplication alarm will activate. If the alarm succeeds, the operator will assess the situation to determine that a boron dilution event is occurring, and take the appropriate operator action to restore the required shutdown margin. The operator will isolate the boron dilution source. The operator will close the VCT outlet isolation valves and open the valve from the RWST to the suction line of the charging pump. Figure 2 depicts the boron dilution mitigation event tree, and the description of the failure mode is given in Table 4.

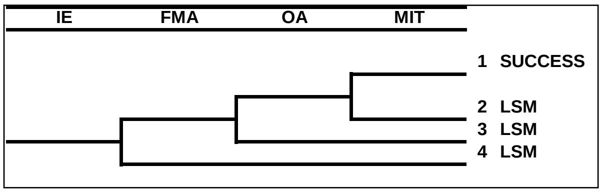

Figure 2. Boron Dilution Mitigation Event Tree

Table. 4. Description of the failure mode

Failure	Description
IE	The initiating event frequency of the boron dilution
FMA	Flux multiplication alarm activates
OA	Operator takes action on the flux multiplication alarm
MIT	The VCT valves are closed and RWST valve is opened
LSM	Total loss of shutdown margin occurs

The loss of shutdown margin frequencies (per reactor year) calculated by reflecting the results in Table 1 and 4 are depicted in Table 5.

Table 5. Loss of Shutdown Margin Frequency

Event	Frequency, Per reactor year
Chemical Addition	4.91E-07
CVCS Demineralizer Flush	1.13E-04
Reactor Makeup (Case 1, minimum dilution flowrate)	4.32E-07
Reactor Makeup (Case 2, average dilution flowrate)	4.43E-05
Reactor Makeup (Case 3, maximum dilution flowrate)	4.52E-08
Total	1.58E-04

3. Conclusions

Probabilistic boron dilution accident analysis was performed and through this analysis potential flow paths between the unborated water supply and RCS were identified. A failure modes and effects analysis was performed to identify the component failures associated with each CVCS operation that required unborated water.

Boron dilutions accident classified as an AOO, the frequency of AOO is 1.0E-01 per reactor year [1]. According to Table 5, Loss of shutdown margin frequency for total potential initiators (Chemical Addition, CVCS Mixed Bed Demineralizer Flush, Reactor Makeup System) is 1.58 E-04 and this fequency is more conservative than the occurrence frequency of AOO.

Dilution flowrate of Case 3 (maximum dilution flowrate) is the same assumption with deterministic safety analysis method. According to Table 5, frequency of Case 3 is only 4.52 E-08 and the probability of boron dilution is very low in all accident cases. Therefore, it is too conservative to assume maximum dilution flowrate in deterministic safety analysis. And Case 2 has the greatest frequency and this frequency is more conservative than the occurrence frequency of AOO. Therefore, it is reasonable to assume average dilution flowrate in deterministic safety analysis boron dilution accident analysis.

REFERENCES

[1] 10CFR50 Appendix A, General design criteria for Nuclear Power Plant, August 2017.
[2] NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, March 2007
[3] NUREG/CR-1278, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, U.S. Nuclear Regulatory Commission, August1983.