

Sensitivity Dose Analysis of the Main Steam Line Break Accident Considering Core Purification Flow

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1. INTRODUCTION

The main steam line break (MSLB) represents a design basis accident characterized by an increase in the heat removal capability of the secondary system.

In this accident scenario, the iodine spike phenomenon is influenced by factors such as the core purification flow and iodine escape rate, which governs the release of iodine into the reactor core following fuel damage. These physical mechanisms and phenomena highlight the necessity for a more precise, rigorous and detailed radiological dose assessment in MSLB.

This study aims to examine the factors influencing the core purification flow and the generation rate of radioactive iodine, and to establish an assessment methodology that demonstrates how these factors can be incorporated into the radiological dose evaluation of MSLB. The proposed approach will provide a methodological basis applicable to design basis accident dose assessments as well as to control room dose evaluations.

2. METHODOLOGY

2.1. Main Factors of Iodine Spike Phenomena

In MSLB, the principal factors influencing the iodine spike phenomenon include the core purification flow, the iodine escape rate from defected fuel that affects iodine fission products by the purification flow, the equilibrium concentration of radioactive iodine, and the leakage flow incorporated within the purification flow.

Another factor to be considered is the decay constant of iodine isotopes.

The iodine escape rate is typically expressed as the fraction of accumulated fission products that escape from a defective fuel rod per unit time. The escape rate is quantitatively evaluated through fuel defect experiments and is generally reported in the range of 1.2×10^8 to 1.4×10^8 s⁻¹. Furthermore, the release behavior per unit time is characterized by an exponential function.

The purification flow represents the flow rate of the reactor's chemical purification system.

During a design-basis accident, the purification flow increases in proportion to the specific activity concentration in the reactor core, and therefore it is employed as a measure of the rate of increase in the core's specific activity per unit time.

The equilibrium concentration of radioactive iodine

means the specific activity in the reactor core under the assumption of a 1% fuel defect.

The leakage flow is an additional leakage rate, which is conservatively assumed into the purification flow.

The iodine decay constant directly influences the radioactivity generation of iodine, since radiation is emitted during its decay.

The sensitivity input variables considered in this study are represented by the following equations.

$$R = A \times \lambda_{\text{total}} \quad (1)$$

R : Iodine appearance rate (Ci/min)

A: Nuclide activity (Ci)

λ_{total} : Total concentration coefficient (min⁻¹)

$$\lambda_{\text{total}} = \lambda_{\text{purification}} + \lambda_{\text{leakage}} + \lambda_{\text{decay}} \quad (2)$$

$$\lambda_{\text{total}} = \lambda_{\text{purification}} + \lambda_{\text{leakage}} + \lambda_{\text{escape rate}} \quad (3)$$

$\lambda_{\text{purification}}$: Letdown flow rate per RCS Mass

λ_{leakage} : Leakage Flow rate per RCS Mass

λ_{decay} : Iodine isotopes decay constant

$\lambda_{\text{escape rate}}$: Iodine escape rate

From the above three equations, the source term generation can be derived by considering the factors associated with the purification flow rate as well as the iodine spike phenomenon.

In order to calculate the iodine spiked source term, equation (1) must be calculated from equation (2) and equation (3). From these equations, calculation results are discussed in the chapter "results and discussions."

2.2. Analysis of Main Steam Line Break

In MSLB, GIS (Generated Iodine Spiking) case analysis is addressed by RADTRAD code. Fig.1 shows the primary to secondary (P-T-S) leakage, iodine activity release, the noble gas activity release, and the secondary liquid iodine release in MSLB modeling.

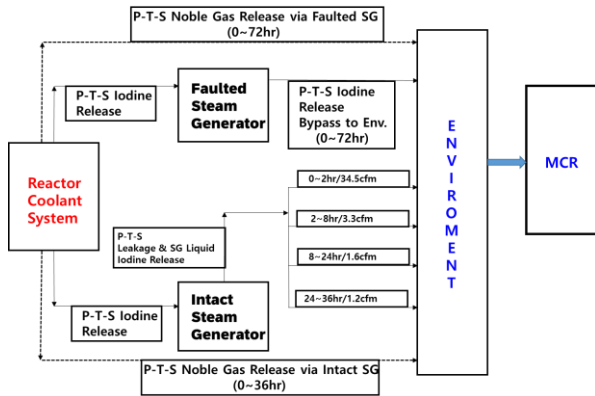


Fig. 1 Concept of Main Steam Line Break Dose Analysis

The cumulative source term generation considering the spike phenomenon is determined by the iodine appearance rate shown in equation (1). The cumulative source term is timely release into reactor coolant system gradually and linearly over 8 hours. An 8-hour release is sufficient time to reach shut down cooling condition.

However, the MSLB is characterized by a rapid drop in secondary pressure at the rupture point, while the primary pressure remains high for a considerable period. Therefore, the analysis showed that even after 8 hours, the release of tube leakage persisted for up to 72 hours.

2.3. Sensitivity Parameters for Analysis

Several strategies for applying variables for sensitivity analysis have been developed. The strategies for applying sensitivity variables are as follows.

- Purification flow rate: Nominal value and Maximum value are applied to analysis.
- Iodine escape rate: Using a Monte-Carlo simulation, a random distribution is generated within the experimentally known range of iodine escape rates. The geometric mean of the random distribution is calculated.
- Leakage Flow rate: As conservative assumption, it is applied to purification flow rate as an additional 1gpm.
- Iodine isotope decay constant: A separate decay constant is calculated by applying the half-lives of iodine isotopes presented in ICRP 30.

3. RESULTS AND DISCUSSIONS

3.1. Purification Flow Rates and Iodine Escape Rates

In domestic NPP, in case of WH 3-loop, the nominal purification flow rate is ranged between 60gpm and 70gpm. And maximum nominal purification flow rate is about 120 gpm.

In calculation of iodine escape rate, Monte-Carlo simulation technique is applied to determine the geometric mean value. Monte-Carlo simulation results

are shown in Fig. 2.

Fig. 2 and Fig. 3 are generated by PERL program using random sampling distribution generation technique.

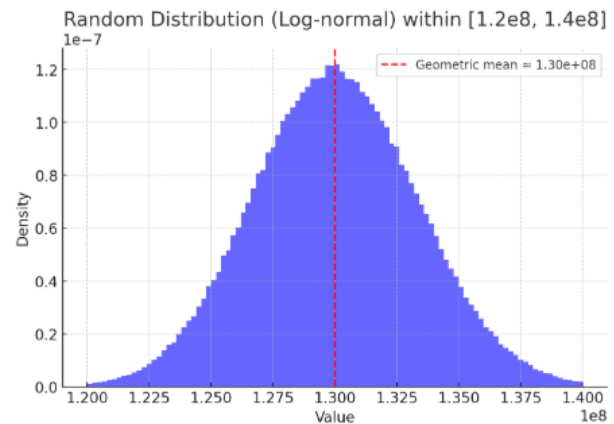


Fig. 2 Iodine escape rates result by calculating from Monte-Carlo simulation

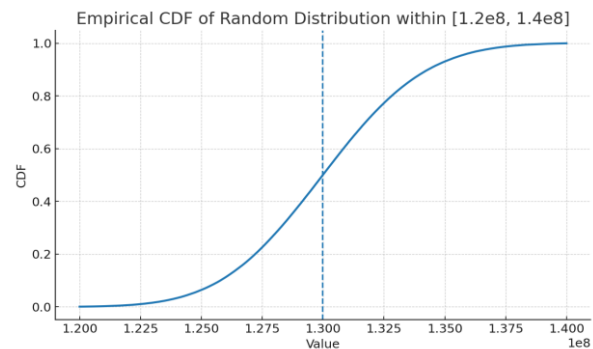


Fig. 3 Iodine escape rates in accumulated distribution

As shown in Figures 2 and 3, from iodine escape rate random distribution, geometric mean value is calculated as $1.3e8 \text{ s}^{-1}$. According to fuel defect experimental test results, generally iodine escape rate is ranged in $1.2e8 \sim 1.4e8 \text{ s}^{-1}$.

From these results, purification flow rate input parameters are selected as 60 gpm, 70 gpm and 120gpm. In case of iodine escape rate, $1.2e8 \text{ s}^{-1}$, $1.3e8 \text{ s}^{-1}$ and $1.4e8 \text{ s}^{-1}$ are selected as sensitivity input parameters.

3.2. Leakage Flow Rate and Iodine Decay Constant

The leakage flow rate was conservatively assumed to be 1 gpm, added to the purification flow rate. For the sensitivity analysis, values of 0 gpm, 0.5 gpm, and 1 gpm were applied.

Because the decay constant reflects the radiation released during nuclide decay, it acts as a key indicator of the radioactivity of iodine isotopes and has a direct impact on the iodine appearance rate and the total concentration coefficient as shown in equation (1) ~ equation (3).

Based on the half-lives recommended by ICRP 30, the decay constants of the individual isotopes were

calculated as Table 1 resented below.

Table 1. Iodine half –life & decay constants

Nuclides	Half-life (sec)	Decay Constant (sec ⁻¹)	Decay Constant (min ⁻¹)
I-131	694656	9.978E-07	0.000060
I-132	8280	8.371E-05	0.005023
I-133	74880	9.257E-06	0.000555
I-134	3156	2.196E-04	0.013176
I-135	23796	2.913E-05	0.001748

3.3. Each Factor's Concentration Coefficient

Based on the results obtained so far, the concentration coefficients for each factor, as well as the total concentration coefficient, are summarized in Table 2.

Table 2. Each factor's concentration coefficients

Items	Range	Each concentration coefficient (min ⁻¹)
Purification	60 ~ 120 (gpm)	0.0007~0.00153
Leakage	0 ~ 1 (gpm)	0 ~ 0.000011
Decay	9.978E-07	0.000060
	~	~
	2.196E-04 (sec ⁻¹)	0.013176
Escape rates	1.2×10 ⁻⁸ ~ 1.4×10 ⁻⁸ (sec ⁻¹)	7.2×10 ⁻⁷ ~ 8.4×10 ⁻⁷

From the concentration coefficients given in Table 2, the two types of total concentration coefficients introduced earlier are calculated.

Using Equations (1) to (3), the total concentration coefficient is obtained: when based on the iodine escape rate, the result is ranged in 0.0007 ~ 0.001541 min⁻¹, and when based on the decay constant, the result is ranged in 0.00076 ~ 0.014717 min⁻¹. With these calculated total concentration coefficients, the iodine source term can be accurately evaluated using Equation (1). The results of the iodine appearance rate for the source term calculation are summarized in the following table.

Table 3. Iodine appearance rate for source term calculation

Nuclide	Minimum Appearance Rate (Ci/min)	Maximum Appearance Rate (Ci/min)
I-131	1.29E-01	2.72E-01
I-132	7.70E-01	8.84E-01
I-133	2.72E-01	4.54E-01
I-134	3.59E-01	3.80E-01
I-135	2.76E-01	3.71E-01

3.4. Source Term Generation and MSLB Analysis Results

Using Table 3, the source term results generated with an iodine spiking factor of 500 are shown in Tables 4 and 5. Table 4 presents the source term calculated based on the iodine appearance rate, while Table 5 shows the result considering only the effect of the purification flow rate. It can be seen that the source term is strongly influenced by the purification flow rate.

Table 4. The source term result generated based on the iodine appearance rate in Equation (1)

Nuclide	Spiking Factor	Minimum Source Term (Ci)	Maximum Source Term (Ci)
I-131	500	6.20E+01	1.31E+02
I-132	500	3.70E+02	4.24E+02
I-133	500	1.30E+02	2.18E+02
I-134	500	1.72E+02	1.83E+02
I-135	500	1.32E+02	1.78E+02

Table 5. Results of source term generated considering only the purification flow rate

Nuclide	Spiking Factor	Minimum Source Term (Ci)	Maximum Source Term (Ci)
I-131	500	5.71E+01	1.25E+02
I-132	500	4.52E+01	9.89E+01
I-133	500	7.27E+01	1.59E+02
I-134	500	8.69E+00	1.90E+01
I-135	500	3.79E+01	8.27E+01

Table 6 shows the MSLB dose analysis results using the source terms from Table 4, based on the modeling presented in Figure 1.

The calculations in Table 6 use the maximum source terms from Table 4.

In the sensitivity analysis, the contribution of source terms generated using the concentration coefficient based on the purification flow rate to the dose assessment is shown as fractions in Figure 4.

Table 6. Results of MSLB dose analysis in the Maximum case from Table4

Release Item	EAB (rem)	LPZ (rem)	Control Room (rem)
Noble Gas	4.30E-04	1.97E-04	1.99E-03
Iodine Release	5.23E-01	2.17E-01	1.91E+00
RCS Activity Release	7.13E-02	3.30E-02	2.03E-01
Initial SG Secondary Iodine	7.00E-02	1.11E-02	7.17E-01
Total	6.65E-01	2.61E-01	2.83E+00
Accepted Limit	2.50E+00	2.50E+00	5.00E+00

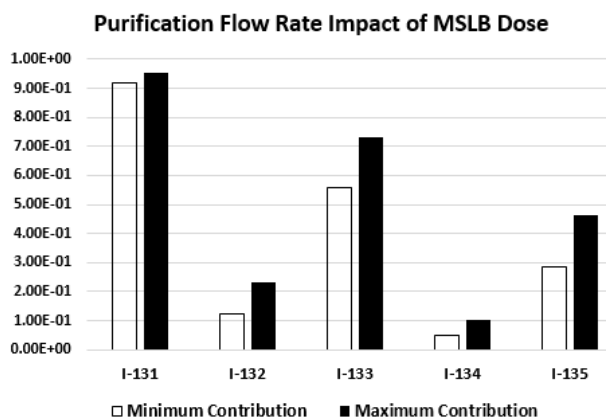


Fig. 4 Contribution fraction of MSLB dose based only on the purification flow rate

Table 6 shows that iodine has the largest impact among the radionuclides, mainly due to iodine release and the spiking phenomenon. Figure 4 highlights that the purification flow rate contributes significantly to the dose, especially for I-131, accounting for about 90% of the dose. These results indicate that carefully considering the main source term generation factors can improve the accuracy of MSLB dose assessments.

4. CONCLUSIONS

This study evaluated MSLB dose assessment by focusing on the purification flow rate and considering various source term generation patterns. Sensitivity analysis examined how variations in core purification flow rate affect dose contributions. The results indicate that, for MSLBs experiencing iodine spikes, up to four source term patterns may occur, with the purification flow rate contributing most significantly to the dose—particularly for I-131, accounting for approximately 90% of the dose. These findings highlight the key factors influencing source term generation and suggest that systematic analysis of these factors can improve the precision of dose assessments.

REFERENCES

- [1] Final Safety Analysis Report.
- [2] ICRP Publication 30, “Limits for Intakes of Radionuclides by Workers”, (1979).