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Developed Modeling of Spray Removal Rates for Design Basis Accidents

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1. INTRODUCTION

In DBA(Design Basis Accident), the fission products are reduced by decontamination effects by spray droplet. Previously, the study has been carried out by Seung Chan LEE et al. in 2019. In this paper, from the previous study, modified scenario is applied and is calculated by LOCA scenario. In this study, Power model's correlation parameters are handled in more detail.

Specially, LOCA dose calculation is carried out in the case of containment leakage model. Otherwise, natural deposition model is based on SRP section 6.5.2 and NUREG/CR-6189. Containment spray model is based on SRP section 6.5.2 and NUREG/CR-5966. [1-6].

In this study, from spray removal modeling results, some dose calculation is carried out for LOCA conditions.

2. METHODOLOGY

2.1. Natural Deposition Removal Rate Modeling

This model was developed by Powers et al., which explains the turbulence effects in containment and is used to model multiple aerosol release based on NUREG-1465 experiment. In order to calculate the uncertainty of this model, a large number of calculations were carried out using the mechanistic correlation equation, including the reactor containment type, the reactor power, and the source term release stage. The Key uncertainty parameters are the containment pressure during the accident's release timing stage, floor elevation, wall surface area and the ratio between containment volume and reactor power.

Generally, equation models are below[4-5]:

a. Natural deposition model for gap release (0 ~ 0.5 hr) : cutoffs of 90%, 50% and 10%

$\lambda(90) = \delta_1(90) + [\delta_2(90) \times 10^{-6} \times \text{Power}]$ (1-1)
$\lambda(50) = \delta_1(50) + [\delta_2(50) \times 10^{-6} \times \text{Power}]$ (1-2)
$\lambda(10) = \delta_1(10) + [\delta_2(10) \times 10^{-6} \times \text{Power}]$ (1-3)

b. Natural deposition model for gap release (0.5 ~ 1.8 hr) : cutoffs of 90%, 50% and 10%

$\lambda(90) = \delta_3(90) + [1- \exp((\delta_4(90) \times \text{Power})/1000)]$ (2-1)
$\lambda(50) = \delta_3(50) + [1- \exp((\delta_4(50) \times \text{Power})/1000)]$ (2-2)
$\lambda(10) = \delta_3(10) + [1- \exp((\delta_4(10) \times \text{Power})/1000)]$ (2-3)

c. Natural deposition model for early in-vessel (0.5 ~ 1.8 hr) : cutoffs of 90%, 50% and 10%

$\lambda(90) = \delta_5(90) + [1- \exp((\delta_6(90) \times \text{Power})/1000)]$ (3-1)
$\lambda(50) = \delta_5(50) + [1- \exp((\delta_6(50) \times \text{Power})/1000)]$ (3-2)
$\lambda(10) = \delta_5(10) + [1- \exp((\delta_6(10) \times \text{Power})/1000)]$ (3-3)

d. Combined effective deposition removal rate

$$\lambda_{(eff)} = \lambda_{(gap)} \times r_{(gap)} \times \lambda_{(iv)} \times r_{(iv)} [r_{(gap)} \times r_{(iv)}]^{-1} \quad (4)$$

where

$\lambda_{(eff)}$: effective nature deposition rate (hr^{-1})
$\lambda_{(gap)}$: gap release stage natural deposition rate (hr^{-1})
$\lambda_{(iv)}$: early in-vessel natural deposition rate (hr^{-1})
$r_{(gap)}$: the release rate during gap stage
$r_{(iv)}$: the release rate during the early in-vessel

2.2. Spray Removal Rate Modeling

Aerosol iodine removal by spray is determined using the Powers model from NUREG/CR-5966.

In Powers model, the water spray flux, the falling height, and the droplet size distributions are considered by calculating a large number of case and the many kind of correlations. The calculation results' correlations are distributed as the shape of 10 percentile, 50 percentile, 90 percentile for deviation distributions.

The Powers model is very accurate in the falling heights range between 500cm and 5000 cm.

And also the range of spray water flux between 0.001 and 0.25 cm^2-H_2O/cm^2 verify the accuracy for predicting the spray removal rates.

Spray removal rate's equation model is shown below[4-5]:

$$(d\, m_f)/(dt) = - \lambda(Q, H, m_f) \cdot m_f \quad (5)$$

$$\lambda(Q, H, m_f) = \lambda(Q, H, m_f{=}0.9) [\lambda(m_f)/ \lambda(m_f{=}0.9)] \quad (6)$$

$$\lambda(Q, H, m_f{=}0.9) = \exp[A+B\ln Q+CH+DQ^2H+EQH^2+FQ+GQ^2H^2] \quad (7)$$

$$[\lambda(m_f)/\lambda(m_f{=}0.9)]=[a+b\log_{10}Q][1-(m_f/0.9)^c]+(m_f/0.9)^c \quad (8)$$

Where

$\lambda(Q, H, m_f)$: the aerosol removal coefficient for a given water flux Q, falling height H, and aerosol mass fraction m_f.

Equation 5 is for the aerosol mass fraction in the containment atmosphere, which is time independent.

Equation 6 is the spray removal rate for the mass fraction between any given mass distribution and the mass distribution of 90% in the containment atmosphere.

Equation 7 and 8 are shows the correlation between $\lambda(Q, H, m_f)$ and $\lambda(Q, H, m_f{=}0.9)$.

3. RESULTS AND DISCUSSIONS

3.1. Time Period for Accident Scenario

Natural deposition and spray removal rates are time independent. These removal rates are used to determine the release and subsequent dose from facility in the LOCA conditions.
Table 1. shows the LOCA events, the sequence stage and the time periods in detail. In this study, initial duration is selected conservatively with subtracting spray duration time of 0.2hours.

Table 1. Time periods and the event sequence for application of Iodine removal rates

Duration (hours)	Descriptions and Events
0.00e+00~8.33E-03 8.33e-03~1.65E-02 1.65e-02~8.31E-02 8.31e-02~3.33E-01 3.33e-01~5.00E-01 5.00e-01~5.10E-01	Gap release onset Containment spray system actuation Containment spray actuation beginning Recirculation start for two trains ESF recirculation Gap release termination, Early in-vessel release start
5.08e-01~6.94E-01 0.694~1.0 1.0 ~ 1.85 1.85 ~ 2.0 2.0 ~ 3.8 3.8 ~ 4.0 4.0 ~ 8.0 8.0 ~ 13.8 13.8 ~ 22.2 22.2 ~ 24.0	Spray injection end, recirculation begin Intermediate time End of Early in-vessel release X/Q changed, spray manually operated Aerosol deposition rate changed Containment spray manually operated X/Q changed, spray manually operated Aerosol deposition rate changed Aerosol deposition rate changed X/Q changed, spray manually operated
24.0 ~ 48.0 48.0 ~ 96.0 96.0 ~ 720.0	Spray manually operated X/Q changed, spray manually operated End of analysis

3.2. Natural Deposition Rates for DBA

Natural deposition correlations are shown on Table 2.
And the core thermal power level, the natural deposition aerosol removal rates for the gap release and the early in-vessel release during the different time periods are calculated and shown in Table 2.
The natural deposition rates for time periods less than 1,800 seconds and for time periods greater than 6,480 seconds for all aerosol groups are taken from the gap release in Table2. The effective natural deposition rate is calculated using equation 1.

Table 2. Calculation results of natural deposition rate

Duration (sec)	Rates (hr^{-1}) (Gap Release)		Rates (hr^{-1}) (Early in -vessel)	
	90 %	50%	90 %	50%
0 ~ 1,800	4.81e-02	3.07e-02		
1,800 ~ 6,480	1.02e-01	8.55e-02	5.42e-02	4.99e-02
6,480 ~ 13,680	4.19e-01	1.80e-01		
13,680 ~ 49,680	1.77e-01	1.52e-01		
49,680 ~ 80,000	1.01e-02	7.12e-02		

3.3. Spray Removal Rates

Power model of aerosol removal is valid for total water spray flux between 0.001 and 0.25 cm^3-H_2O/cm^2 and a fall height between 500 and 5,000cm. In this study, total spray flux is calculated as 0.00615 cm^3-H_2O/cm^3-s. This flux is used to apply to spray removal rate.
In this study, minimum fall height is 2,344 cm and maximum fall height is 3,611 cm.
These values are very suitable to calculate spray removal rate because it's range is within the correlation range between 500 cm and 5000 cm.

Table 3. Calculation results of spray removal rate

Spray information	Spray Removal Rate (hr^{-1})
Header 1	50% : 11.31 90% : 25.08 10% : 4.63
Header 2	50% : 11.83 90% : 26.00 10% : 4.92
Minimum Value	50% : 11.31 90% : 25.08 10% : 4.63

3.4. Parameters of Containment leakage model

From Technical Specification, the containment leak rate of the first duration of initial 24 hours is selected as 0.1% containment volume per day. Since 24hours, the containment leak rate is reduced as 0.05% containment volume per day. The calculated key parameters of containment leakage model are shown Table 4 in detail.

Table4. Calculation results of key parameters and the offsite dispersion factors

Input	Calculated results
Containment leakage flow rate (Vol% per day)	Containment leakage - 0 ~ 24 hours : 0.1 - 24 ~ 720 hours : 0.05
Removal rate or Decontamination Factors	Elemental Iodine removal rate - Main spray region : 20 - Sub spray region : 45.1 - Unsprayed region : 0.0 Particulate iodine removal rate - Main spray region : 0.33 - Sub spray region : 0.067 - Unsprayed region : 0.0 Natural deposition removal rate - Main spray region : 1.62 - Sub spray region : 5.50 - Unsprayed region : 5.50 Iodine Decontamination Factor - Elemental iodine by spray : 8.57 - Iodine by deposition : 100
Offsite Dispersion Factors (sec/cubic meter)	EAB : 5.334e-04 (0~2hours) LPZ : 3.264e-05(0~8hours) 2.329e-05(8~24hours) 1.120e-05(24~96hours) 3.913e-06(96~720hours)

3.5. Parameters of Containment purge system leak

Containment purge system is closed during accident. But the system's close actuation function is delayed about 5 seconds. During this time, the purge system is open and some radioactive materials is directly release into environment. For 5 seconds, the release speed is assumed as sonic velocity. After 5 seconds, the purge system release is rapidly closed and stopped. The release rate through into environment is about 23,363cfm for 5 seconds.

3.6. Recirculation Sump leakage model

Recirculation sump leak occurs by pump operation and valve operation and go to the aux building. The aux building HVAC filter efficiency is 99% and the filter flow rate is 1.2e+04 cfm.
From this modeling, the calculated pump leakage is 0.0057 cfm and the calculated valve leakage is 0.0016 cfm. These values are general in domestic NPP compared with FSAR.

3.7. Results from Dose Calculation EAB and LPZ in LOCA analysis

Table 5 shows the final results of LOCA analysis. According to R.G. 1.195, the dose limits are 300 rem (thyroid) and 25 rem (whole body). In this study, the results of EAB are 259 rem at thyroid dose and 10.1 rem at whole body dose. The results of LPZ are 135 rem at thyroid dose and 2.42 rem at whole body dose.
The both of EAB and LPZ meet the dose criteria with the safety margin of 14% ~ 55.3% in case of thyroid dose.
And also, the whole body's safety margins of EAB and LPZ are in the range between 59.6% and 90.3%.

Table5. Calculation results of LOCA analysis

Location	Results of LOCA analysis
EAB (rem)	Containment leakage model - Thyroid : 261 - Whole body : 10.9 Containment purge system model - Thyroid : 2.46 - Whole body : 0.0057 Recirculation Sump leakage model - Thyroid : 0.42 - Whole body : 0.0016
LPZ (rem)	Containment leakage model - Thyroid : 139 - Whole body : 2.57 Containment purge system model - Thyroid : 0.143 - Whole body : 0.0004 Recirculation Sump leakage model - Thyroid : 1.1 - Whole body : 0.0014
Dose Criteria (rem)	EAB & LPZ Thyroid : 300 Whole body : 25

4. CONCLUSIONS

Natural deposition removal rate and spray removal rate for aerosol iodine are modeled and calculate by SRP 6.5.2
Using the Powers model, some input parameter are calculated for iodine removal rate. The calculated value is within the validation range of Powers model.
From these results, we find some conclusions as below:

a. Natural deposition removal rate is range 1.01e-02 ~ 4.19e-01 in the condition of 90% cutoff. And the range of 50%cutoff is between 3.07e-02 and 1.80e-01.
b. Spray removal rate is range 25.08 ~ 26.00 in the condition of 90% cutoff. And the range of 50% cutoff is between 11.31 and 11.83. Additionally, the range of 10% cutoff is between 4.63 and 4.92.
c. Falling height is the minimum value of 2,344 cm and the maximum value of 3,611 cm.
   From this results, input parameter is ranged within analytic scope.
d. In LOCA analysis, containment leakage model is strongly sufficient than any other case. And recirculation sump leakage model is less than any other case.

REFERENCES

[1] Seung Chan LEE et al., "The Study for Containment Aerosol and Iodine Removal Rates", Transactions of the Korean Nuclear Society Spring Meeting Jeju Koera, May 23-34 (2019)
[2] Final Safety Analysis Report in Westinghouse NPP
[3] NRC Regulatory Guide 1.195
[4] US NRC Standard Review Plan 6.5.2
[5] NUREG/CR-6189, A Simplified Model of Aerosol Removal by Natural Processes in Reactor Containment (1990)
[6] NUREG/CR-5966, A Simplified Model of Aerosol Removal by Containment Sprays (1991).