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The Study for Containment Aerosol and Iodine Removal Rates

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1. INTRODUCTION

When analyzing the behavior of fission products from design basis accident using the LOCA methodology, the removal mechanism of the iodine and the particulate aerosol species is credited by R.G. 1.195 considering the natural deposition and the containment spray.

This study determines the appropriate time-dependent removal rates inside containment.

The modeling method is introduced in the cases of the natural deposition removal and the containment spray removal. Generally natural deposition removal model is based on the concept of SRP section 6.5.2 and NUREG/CR-6189. Otherwise containment spray removal model is based on the concept SRP section 6.5.2 and NUREG/CR-5966[1-5]. In this paper, the iodine removal rate modeling is different from current methodology in the view of considering time period and event sequence. In the current method, the removal rate is just fixed as a constant value during accident.

2. METHODOLOGY

2.1. Regulations

As shown previously, the reduction in airborne radioactivity in the containment by the natural deposition and the spray system within the containment can be credited in SRP 6.5.2. In this study, both of the natural deposition and the spray removal phenomena are considered in detail from NUREG/CR-6189 and NUREG/CR-5966.

2.2. Modeling Assumptions

The natural deposition removal and the containment spray removal modeling are required some assumption.

The assumptions are below:

a. Containment surface area is used for natural deposition phenomena. The same size of the surface area is the same heat sink in containment. And the natural deposition model considers the elemental iodine as bulk gas which is well-mixed by natural convection.
b. Containment spray system flow rate is used as two phase of operation which is an injection phase and a recirculation phase
c. Spray liquid density is assumed to be equivalent to water at standard condition. The value is 1 gram/cm^3.
d. Containment sump volume is the liquid volume which is emergency sump volume available at the start of post-LOCA containment spray system and safety injection recirculation mode of operation.
e. Spray droplet temperature is required to calculate the elemental iodine removal rate. It is assumed that the post-LOCA containment condition and each individual spray droplet are reached into the equilibrium temperature with bulk containment atmosphere temperature.

2.3. Basic Information for Modeling in Domestic NPP

Some information is required in modeling the natural deposition removal rate and the containment spray removal rate. The represent parameters of the natural deposition removal rate modeling are reactor power, containment type, time period (the gap-release stage to the early in-vessel stage), containment elevation and wall surface area. Otherwise, in case of the containment spray removal rate modeling, the represent parameters are the falling height of droplet, droplet size, the fraction of droplet to containment volume and the water spray flux.

In domestic NPP as Westinghouse type, the modeling information is below:

a. Spray pump: the containment spray is provided with two centrifugal pumps with NPSH 480 feet.
b. Spray water flux: the spray header’s flux is 3,000 gpm.
c. Droplet size: the droplet size of spray is known as the maximum value of 0.12 inch diameters.
d. The mean drop size per nozzle: the nozzle’s droplet mean size is less than 1000micron.
e. The flux and pressure per spray nozzle: the averaged spray nozzle outlet pressure is 40psig and the nozzle averaged flux is 15.2 gal /min.
f. Spray ring header location: two containment spray ring headers are located between 250 and 295 feet in domestic Westinghouse type NPP in this case of ground level (100feet ~ 150feet).
g. Droplet falling height: spray droplet falling height is ranged from 130 feet to 145 feet based on the spray ring header location elevation against the ground level (120feet~150feet).
h. Containment free volume: the free volume is 2.08e + 06 cubic feet.
i. Reactor power level: the power is 2,958 Mwt.

Above all things are used as the basic information for Powers model to calculate the natural deposition removal rate and the spray removal rate.
In the chapter 2.4 and 2.5 of this paper, the modeling strategy and usage are shown.
The basic information is based on domestic FSAR of three loops Westinghouse type NPP.

2.4. Natural Deposition Removal Rate Modeling

This model was developed by Powers et al. [4,5]. According to their study results, this model (Powers model) explains the effects due to turbulence and to the multiple aerosol release specified in NUREG-1465 experiment. To estimate the uncertainty, a large number of calculations were carried out to get the correlation equations using mechanistic model, reactor containment type, reactor power, and the source term release stage for various uncertainty parameters. Typical uncertainty parameters were the containment press during the various release 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)

In the previous equations from (1-1) to (3-3), “Power” is same as “Reactor Power level”.

d. Combined effective deposition removal rate

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

where
$\lambda_{(eff)}$: effective natural 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

2.5. Spray Removal Rate Modeling

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

The spray system decontaminates an aerosol-iodine using the number of spray droplets falling through the containment atmosphere with the falling distance of the droplet passing through. The water spray flux into the containment atmosphere is time dependent and the fall distance is dependent on the containment design. In Powers model, a single falling droplet behavior is verified by the various experiment conditions [4-5].

The water spray flux, the falling height, and the droplet size distributions are considered by calculating a large number of case and many kinds of correlations. From Powers model’s correlation, the calculation result can be shown as the shape of 10 percentile, 50 percentile and 90 percentile for deviation distributions.

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

And also the model is verified in the range of spray water flux between 0.001 and 0.25cm^2-H_2O/cm^2 in the case of the accuracy for predicting the spray removal rates [4-5].

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

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

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

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

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

Where, $\lambda(Q, H, m_f)$ is 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 is the spray removal rate for only 90% mass distribution and equation 8 shows the correlation between the $\lambda(Q, H, m_f)$ of equation 6 and the $\lambda(Q, H, m_f{=}0.9)$ of equation 7.

3. RESULTS AND DISCUSSIONS

3.1. Time Period

In order to consider the event sequence and event duration characteristic, the natural deposition removal rates and the spray removal rates are time independent during each time step of Table 1. Event sequence is based on LOCA. The averaged removal rates are calculated during each LOCA stages.

LOCA time steps or stages are shown in Table 1 and the sequence stages and the time periods are shown in detail.

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

Duration (hours)	Descriptions and Events
0.00e+00~8.20E-03	Gap release onset

8.20e-03~1.80E-02	Containment spray system actuation
1.80e-02~8.50E-02	Containment spray actuation beginning
8.50e-02~3.40E-01	Recirculation start for two trains
3.40e-01~5.05E-01	ESF recirculation
5.05e-01~5.10E-01	Gap release termination, Early in-vessel release start
5.10e-01~6.95E-01	Spray injection end, recirculation begin
0.695~1.0	Intermediate time
1.0 ~ 1.8	End of Early in-vessel release
1.8 ~ 2.0	X/Q changed, spray manually operated
2.0 ~ 3.7	Aerosol deposition rate changed
3.7 ~ 4.0	Containment spray manually operated
4.0 ~ 8.0	X/Q changed, spray manually operated
8.0 ~ 12.0	Aerosol deposition rate changed
12.0 ~ 22.0	Aerosol deposition rate changed
22.0 ~ 24.0	X/Q changed, spray manually operated
24.0 ~ 48.0	Spray manually operated
48.0 ~ 96.0	X/Q changed, spray manually operated
96.0 ~ 720.0	End of time

3.2. Natural Deposition Rates

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 each time period are calculated as shown in Table 2. The natural deposition rates for duration less than 1,800 seconds and for duration greater than 6,480 seconds are calculated in this study including the gap release and the early in-vessel. The values of Table 2 are calculated using equations of (1-1) ~ (3-3).

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	4.92e-02	3.90e-02		
1,800 ~ 6,480	1.10e-01	8.99e-02	5.54e-02	4.25e-02
6,480 ~ 13,680	4.25e-01	1.95e-01		
13,680 ~ 49,680	1.89e-01	1.67e-01		
49,680 ~ 80,000	1.05e-01	9.52e-02		

3.3. Spray Removal Rates

Powers model of aerosol removal is valid for total water spray flux between 0.001 and 0.25cm^2-H_2O/cm^2 and a fall height between 500 and 5,000cm. In this study, total spray flux is calculated as 0.00617cm^3-H_2O/cm^3-s. This flux is used to apply to spray removal rate. In addition, spray droplet's fall height is needed to calculate the spray removal rate. In this study, minimum fall height is 3,962 cm and maximum fall height is 4,419 cm.
These values are very suitable to calculate by Powers model compare with the verified range. The position of represent spray headers is selected as five points. So that, we calculate the spray removal rate for the five represent spray header ring. The results are in the Table 3.

Table 3. Calculation results of spray removal rate during early in-vessel period.

Spray information	Spray Removal Rate (hr^{-1})
Header 1	50% : 12.54 90% : 25.79 10% : 4.95
Header 2	50% : 12.99 90% : 26.75 10% : 5.55
Minimum Value	50% : 12.54 90% : 25.79 10% : 4.95

3.4. Some Discussions from Calculation Results

According to the domestic nuclear power plant's final safety reports, Westinghouse type's spray removal rate is known as the range between 20 and 28. And the natural deposition removal rate is known as the range between 0.06 and 0.33.
From Table 2 and Table 3, 90 % cutoff value is in good agreement with Westinghouse type's known value in the case of spray removal rate of early in-vessel duration and in the case of natural deposition rate in duration of 1,800sec ~ 6,480 sec in the gap release.

4. CONCLUSIONS

Natural deposition removal rate and spray removal rate for aerosol iodine are modeled and calculated by SRP 6.5.2 concept.
Some input parameters are calculated for iodine removal rate and the calculated values are within the validation range of Powers model.
From these results, we find some conclusions as below:

a. Natural deposition removal rate is range 4.92e-02 ~ 1.05e-01 in the condition of 90% cutoff. And the range of 50%cutoff is between 3.90e-02 and 1.95e-01.
b. Spray removal rate is range 25.79 ~ 26.75 in the condition of 90% cutoff. And the range of 50% cutoff is between 12.54 and 12.99. Additionally, the range of 10% cutoff is between 4.95 and 5.55.
c. Falling height is the minimum value of 3,962 cm and the maximum value of 4,419 cm.
These parameters are ranged within analytic scope.
d. From calculations, the total spray flux is 0.00617cm^3-H_2O/cm^3-s and is allowable.
e. In comparing with domestic Westinhouse three-loop FSAR, this study results are very similar to that in the early in-vessel and duration of 1,800sec ~ 6,480sec of Gap release.

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