THE EFFECT OF FOG ON RADIONUCLIDE DEPOSITION VELOCITIES

R. Gibb[1], P. Carson[2], W. Thompson[2]

[1]New Brunswick Power,
Point Lepreau Nuclear Generation Station,
P.O.Box 10, Lepreau,
New Brunswick, E3O 2H0

[2]Atlantic Nuclear Services Ltd,
P.O. Box 1268, Fredericton,
New Brunswick, E3B 5C8

ABSTRACT

Current nuclear power station release models do not evaluate deposition under foggy atmospheric conditions. Deposition velocities and scavenging coefficients of radioactive particles entrained in fog are presented for the Point Lepreau area of the Bay of Fundy coast. It is recommended to calculate deposition based on fog deposition velocities. The deposition velocities can be calculated from common meteorological data. The range of deposition velocities is approximately 1 - 100 cm/s. Fog deposition is surface roughness dependent with forests having larger deposition and deposition velocities than soil or grasses.

1 INTRODUCTION

As part of the accident analysis sequence required to provide information for the site license, it is necessary to model the release of airborne radioactive materials from the reactor and their subsequent transport to individual and group receptors. These releases are in the form of a cloud or plume. There is a depletion of the radioactive material from the cloud as a result of natural deposition processes. Many models are currently available to describe this deposition for dry and wet (rain and snow) meteorological conditions. Current standards and models have not yet addressed deposition of nuclear particles in foggy conditions. This report recommends deposition velocities and scavenging coefficients for nuclear particles in fog at Point Lepreau NB, where fog is a common weather condition.

2 CURRENT APPROACH TO WET/DRY DEPOSITION

The current standard in Canada that addresses airborne radioactive material is CAN/CSA-N288.2-M91, "Guidelines for Calculating Radiation Doses to the Public from a Release of Airborne Radioactive Material under Hypothetical Accident Conditions in Nuclear Reactors". This standard lists three deposition processes that might contribute to the depletion of radioactive material in the cloud:

a) gravitational deposition
b) dry deposition
c) wet deposition

The effect of gravitational deposition is negligible compared to dry and wet deposition, and is ignored when calculating plume depletion and ground deposition.

The CSA standard (1) describes in detail the complete process, from the release of particles to the dose estimates received, whereas this paper focuses on providing deposition velocity and scavenging coefficient values for fog entrained particles. These values are used when calculating radioactive material depletion in the cloud, and ground deposition of material. The depletion and deposition calculations contribute to the overall dose estimate calculations.

The following equation describes the radioactive material concentration in the cloud at the receptor location.

$$\chi\ (Bq\cdot s\ /\ m^3) = (\chi/Q)\ (Q_0\ )\ (DEC)\ (DEP)$$

where: χ/Q = dilution factor ($s\ /\ m^3$)
Q_0 = initial released activity (Bq)
DEC = radioactive decay factor
DEP = depletion factor due to deposition

2.1 Dry Deposition

The effect of dry deposition on the depletion of airborne radioactive material is not usually large. The radioactive material concentration in the plume is reduced by approximately fifty percent or less over the first one hundred kilometers (1). The CSA standard (1) lists values for deposition velocities, V_{dL} and V_{dH}. V_{dL} is a relatively low value used in airborne depletion calculations. V_{dH} is a relatively high value used for ground contamination calculations.

The activity per unit area deposited on the ground is calculated from the following formula :

$$\omega_d\ (Bq\ /\ m^2\ ) = V_{dH} \cdot \chi$$

where: V_{dH} = radioactive material deposition velocity ($m\ /\ s$)
χ = airborne concentration ($Bq\cdot s\ /\ m^3$)

Table 1 is taken from the CSA standard and lists values for V_{dH} and V_{dL} for different airborne materials and surface conditions. The values tabulated are the highest and lowest reported values.

Table 1

Recommended Values for Dry Deposition Velocities (cm/s)

Element	Water	Soil	Snow	Grass	Forest
	Surface Type				
Iodine					
V_{dL}	0.2	0.07	0.07	0.2	1.0
V_{dH}	2.0	1.0	0.7	3.0	10.0
Ruthenium					
V_{dL}	0.2	0.06	0.2	0.1	0.5
V_{dH}	3.0	0.3	1.0	1.0	5.0
Cesium					
V_{dL}	0.1	0.03	0.1	0.07	0.4
V_{dH}	1.0	0.1	0.3	0.3	2.0
Others					
V_{dL}	0.2	0.2	0.2	0.2	1.0
V_{dH}	3.0	3.0	3.0	3.0	10.0

2.2 Wet Deposition

The effect of wet deposition can be significantly larger than that of dry deposition. Wet deposition can deposit more than ninety percent of the airborne radioactive material in the first hour (based on values in Table 2). When considering wet deposition, the CSA standard (1) uses scavenging coefficients in the calculations of airborne depletion and ground deposition. Table 2 is taken directly from the CSA standard, and lists values for the scavenging coefficient, Λ. The scavenging coefficients listed are for varied precipitation rates of rain and snow only. Similar to deposition velocities, the selection of high and low values for the scavenging coefficient are reported values from literature. Λ_H is a relatively high value to be used in the calculation of ground contamination, Λ_L is a relatively low value to be used in airborne depletion calculations.

The activity per unit area deposited is calculated from the following formula :

$$\omega_w \,(Bq / m^2) = \int_0^{\xi} \Lambda_H \cdot \chi \, dz$$

where:
- ξ = height over which the cloud is subject to scavenging (m)
- Λ_H = Scavenging coefficient (s^{-1})
- χ = airborne concentration ($Bq \cdot s / m^3$)

Table 2

Recommended Values for Wet Deposition Scavenging Coefficients (s^{-1})

Radionuclide or element	Rain (mm / hr) 0.5	1	3	5	Snow (mm /hr) (equivalent water) 0.5	1	3	5
Tritium and Iodine								
Λ_L (s^{-1})	5×10^{-6}	1×10^{-5}	2×10^{-5}	3×10^{-5}	$< 10^{-7}$	1×10^{-7}	2×10^{-7}	3×10^{-7}
Λ_H (s^{-1})	1×10^{-4}	2×10^{-4}	4×10^{-4}	6×10^{-4}	2×10^{-7}	4×10^{-7}	8×10^{-7}	1×10^{-6}
Others								
Λ_L (s^{-1})	1×10^{-5}	2×10^{-5}	3×10^{-5}	5×10^{-5}	3×10^{-4}	5×10^{-4}	8×10^{-4}	1×10^{-3}
Λ_H (s^{-1})	2×10^{-4}	3×10^{-4}	7×10^{-4}	1×10^{-3}	1×10^{-2}	2×10^{-2}	4×10^{-2}	5×10^{-2}

3 LITERATURE SEARCH

3.1 Method

The information search for fog deposition velocities was performed through the University of New Brunswick, and with Internet search tools. Through these searches a number of articles on fog deposition were gathered. Also, as a result of this search, personal contacts were made with some leading authorities in the field of fog deposition. The data presented in this paper is based on these articles and personal communications.

The Internet searches generated websites which generally led to summaries of articles with a contact person listed. The summaries themselves often contained little relevant information. However, the contacts listed led to further contacts which led to the majority of the articles listed in the Reference Section.

Three authorities who were most helpful in the search for information were:

1) Stephen Beauchamp, Environment Canada, Bedford NS
2) Ray Hosker, Oak Ridge National Laboratory, NOAA, Oak Ridge TN
3) John Ogren, Climate Monitoring and Diagnostics Laboratory, NOAA, Boulder CO

Conversations with these authorities and others listed in the Reference Section were carried out regarding fog deposition. The common field of expertise of these people was in the area of industrial pollutant deposition during fog (acid fog). None were aware of any work being done involving radioactive material deposition in fog. The conversations included discussion of possible similarities between industrial pollutant deposition and radioactive material deposition. Areas such as particle size, entrainment in fog, and deposition to different surfaces were discussed.

3.2 Results

Many articles relating to fog deposition were obtained by Atlantic Nuclear Services from the Internet and University searches. The information in the articles was useful in describing the deposition process in fog. Although the information collected pertained mainly to industrial pollutants, the basic principles of fog deposition are applied to radioactive particles (results section), as they are expected to behave similarly in fog (based on their ability to be captured by water droplets).

The information from the literature search was used to compile the results section. The results are based on theories, formulae, and measured data from respected authors in the fog deposition field.

When characterizing fog deposition, the choice on whether to use deposition velocities or scavenging coefficients is not obvious. Each method (deposition velocities or scavenging coefficients) produces similar quantitative output (deposition). The users should choose the method they feel is more appropriate for their application. If the computational ability exists, the output from each method can be compared for consistency. A separate section : Comparison of Depletion During Fog for Scavenging Coefficient and Deposition Velocity Input, is presented later in this paper.

4 ANALYSIS

4.1 Fog Deposition Velocities

The deposition velocity (V_d) is defined as the deposition flux (F) divided by the atmospheric concentration (C) at a defined reference height (1),(2).

$$V_d = -F/C$$

The units for flux are g/m^2s and for concentration are g/m^3.

In fog, the particles of interest are entrained in the water droplets of the fog. When the fog comes into contact with the earth's surface the particles are deposited. The deposition rate of particles varies greatly with the surface condition (deposition to trees is significantly larger than that to grasses). Table 3 lists deposition velocities for particles scavenged and deposited by fog. These values are calculated based on the premise that the concentration of particles in the deposited liquid fog does not change during its deposition. That is to say the chemical composition of the liquid is the same before and after deposition. This same assumption is used in the calculation of industrial pollutant deposition (3). This allows for deposition calculations from atmospheric measurements instead of much more difficult ground measurements.

Example:

fog flux (F) = 1mm/hr = 0.278 g/m^2s

concentration (C) = 0.2 g/m^3
of fog

$$V_d = -F/C$$

or $V_d = -0.278 / 0.2$

or $V_d = -1.39$ m/s = -139 cm/s

Table 3 lists deposition velocities for released particles at the Point Lepreau site based on the local meteorological conditions for fog. The deposition velocities recommended here are similar to fog deposition velocities reported in References 4 , 5 and 6.

Table 3

Recommended Fog Deposition Velocities (cm/s) for All Released Particles

	Fog (mm/hr)					
	0.01	**0.05**	**0.10**	**0.50**	**1.00**	**2.00**
V_{dL} (cm/s)	1	3	7	35	70	140
V_{dH} (cm/s)	3	14	28	140	280	560

4.2 <u>Fog Scavenging Coefficients</u>

The deposition of nuclear particles could alternatively be determined based on scavenging coefficients. The scavenging coefficient (Λ) is used to describe the depletion of airborne radioactive material during wet deposition (1),(7).

The equations shown here are the same equations (7) used to calculate the rain scavenging coefficients of CAN/CSA-N288.2-M91 (1).

$$\Lambda\ (s^{-1}) = 8 \times 10^{-5}\ I^{0.6}\ \text{(iodine vapor)}$$

$$\Lambda\ (s^{-1}) = 1.2 \times 10^{-4}\ I^{0.5}\ \text{(aerosols)}$$

Where: I = rain precipitation intensity (mm/hr)

The increased concentrations of particles in fog water compared to rain water is accounted for in this calculation with increases similar to accepted values for industrial pollutants chosen (4),(5),(6),(8),(9),(10),(11).

Example:

fog precipitation intensity = 1mm/hr $\approx$10 mm/hr(rain)

$$\Lambda\ \text{(iodine)} = 8 \times 10^{-5}\ I^{0.6}$$
or
$$\Lambda\ \text{(iodine)} = 8 \times 10^{-5}\ (10)^{0.6}$$
or
$$\Lambda\ \text{(iodine)} = 3 \times 10^{-4}\ s^{-1}$$

Table 4 lists recommended scavenging coefficients for released particles at the Point Lepreau site based on local meteorological and industrial pollutant measurements for fog.

Table 4

Recommended Scavenging Coefficients (s^{-1}) for Fog Deposition

Radionuclide or element	Fog (mm / hr)					
Tritium and Iodine	0.01	0.05	0.10	0.50	1.00	2.00
Λ_L (s^{-1})	5×10^{-6}	1×10^{-5}	2×10^{-5}	5×10^{-5}	8×10^{-5}	1×10^{-4}
Λ_H (s^{-1})	4×10^{-5}	1×10^{-4}	2×10^{-4}	4×10^{-4}	6×10^{-4}	9×10^{-4}
Others						
Λ_L (s^{-1})	1×10^{-5}	3×10^{-5}	4×10^{-5}	8×10^{-5}	1×10^{-4}	2×10^{-4}
Λ_H (s^{-1})	7×10^{-5}	1×10^{-4}	2×10^{-4}	5×10^{-4}	7×10^{-4}	9×10^{-4}

4.3 Precipitation Rates

The values for the deposition velocities and scavenging coefficients found in Tables 3 and 4 are listed for different fog precipitation rates. If fog precipitation rates are known for a location of interest, then the appropriate value for deposition velocity or scavenging coefficient can easily be found in Tables 3 and 4.

If precipitation rates are not known for a location of interest then typical precipitation rates for the Fundy coast can be found for the surface types of Table 5. This method is useful as precipitation rates are rarely measured frequently at many locations.

Table 5

Typical Fog Precipitation Rates (mm/hr) for Different Surface Conditions

	Surface Type					
	Soil	Snow	Water	Grass	Closed Forest	Forest Edge
Fog $(mm/hr)_{Low}$	0.01	0.01	0.01	0.01	0.10	0.50
Fog $(mm/hr)_{High}$	0.05	0.05	0.10	0.10	0.50	2.00

5 COMPARISON OF DEPLETION DURING FOG FOR SCAVENGING COEFFICIENT AND DEPOSITION VELOCITY INPUT

The PEAR (Public Exposure for Accidental Releases) Code was utilized to examine the results obtained when using Table 3 (Deposition Velocities) and Table 4 (Scavenging Coefficients). The variable selected for comparison was the depletion correction factor (DEP). Results presented in Table 6 represent a grassland surface condition over a one kilometer distance. The deposition velocity approach produced more conservative results (more deposition) than the scavenging coefficient approach with a reasonable amount of agreement between the two approaches. Over longer distances (100 km) of grasslands the dominating characteristic was the weather stability category. The agreement between the two approaches ranged from very good to poor depending on the weather stability category. Again, the deposition velocity approach produced more conservative values.

The deposition velocity method as it is believed to produce the more reliable and conservative output. Due care should be taken when choosing a weather stability category for the PEAR Code as the deposition output can vary significantly depending on the category selected.

Table 6

Comparison of Depletion Factors for Deposition Velocity and Scavenging Coefficient Input

		DEPLETION VALUES	
Distance (km)	Stability Category	V_d Method	S. C. Method
1.0	A	0.832	0.992
1.0	B	0.769	0.992
1.0	F	0.557	0.992

6. DEPOSITION VELOCITY CALCULATION FROM MEASURED DATA

Since the fog flux is often unknown, it is not possible to directly establish either the deposition velocity or scavenging coefficient. However, the Unsworth-Crossley equation (8),(12) may be used to calculate deposition velocity for a forested surface condition, if the wind-speed is known :

$$F = C\{[\ k^2\mu \ /\ \ln^2(19.1/h + 3.18)] + v_s\}$$

Based on the definition of deposition velocity this equation can be expressed as :

$$V_d = [-\ k^2\mu \ /\ \ln^2(19.1/h + 3.18)] - v_s$$

where : k = von Karman's constant = 0.41
μ = tree top wind speed (m/s)
h = height of trees (m)
v_s = sedimentation velocity (m/s)

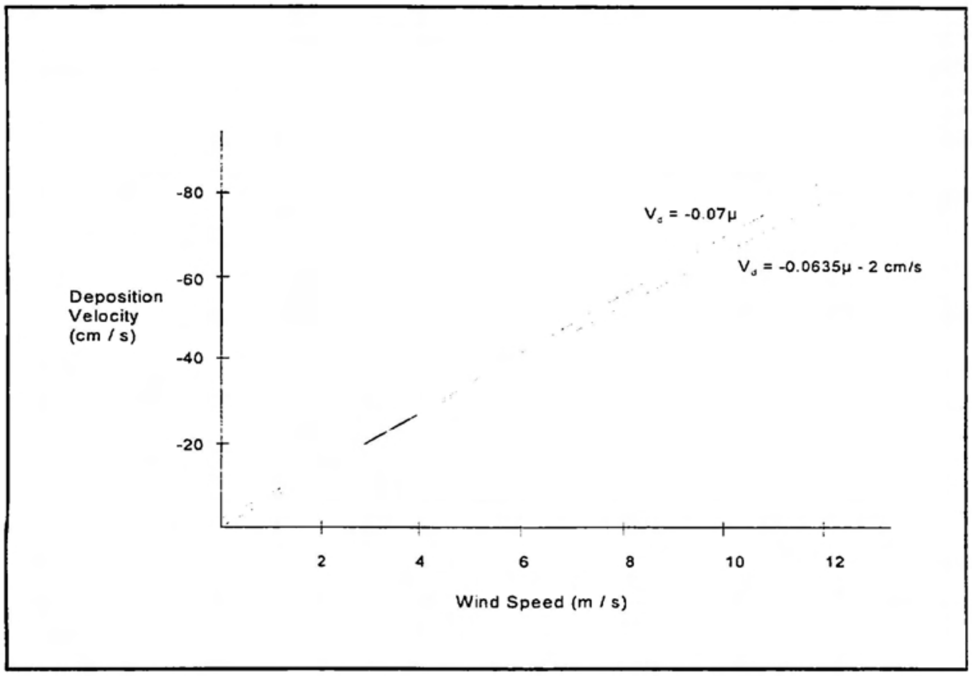
If the height of the forest is set at 10.0 m, and the sedimentation velocity is 2 cm/s, then the preceding equation can be reduced to:

$$V_d = -0.0635\ \mu - 2\ \text{cm/s}$$

Since the sedimentation velocity is not easily attainable it is recommended to use the following equation which is more conservative at higher wind velocities.

$$V_d = -0.07\ \mu$$

Based on a known treetop wind velocity (μ), this equation allows for the calculation of the deposition velocity of particles entrained in fog (V_d). This equation is for forested situations. The values produced by this equation are in very close agreement with measured data for wind speed and fog deposition velocities (6).



Example:

treetop wind speed (μ) = 20 km/hr = 5.56 m/s

$$V_d = -0.07\ \mu$$
$$V_d = -0.07\ (5.56\ \text{m/s})$$
$$V_d = -0.39\ \text{m/s} = -39\ \text{cm/s}\ (\text{forest})$$

For non-forested situations (grasslands) the deposition velocity is a fraction of the forested deposition velocity. When determining deposition velocities to grasslands a conservative ratio of grassland deposition to forest deposition of one quarter is chosen (12). The following equation can be used to calculate fog deposition velocities to grasslands.

$$V_d = - 0.07\ \mu / 4$$
$$V_d = - 0.0175\ \mu$$

Table 7 lists the deposition velocity to wind velocity ratio for different surface conditions. This table produces low deposition velocities if the wind speed is very low (< 0.5 m / s). At this wind speed the fog deposition velocities are similar to the dry deposition velocities of Table 1. Based on the dry deposition velocity values, the minimum fog deposition velocity to be used for modeling is set at 1 cm / s.

Table 7

Deposition Velocity to Wind Velocity Ratios for Fog Entrained Particles

	Surface Type						
	Soil	Snow	Water	Grass	Brush	Closed Forest	Forest Edge
V_d / V_{wind}	0.018	0.018	0.018	0.018	0.030	0.070	0.300

7 SUMMARY

To date, there is little or no published information on airborne nuclear particle deposition in fog. However, there are a substantial number of articles regarding industrial pollutant deposition in fog. The results presented here are based on these articles, and the similarities between industrial pollution and nuclear particle interaction with water droplets.

The resulting scavenging coefficients for radioactive particles in fog (Table 4) are similar to those of rain (Table 2). This is consistent with pollutant inputs from fog and rain along the Bay of Fundy coast. A wide range of deposition values is produced when fog or rain (CSA standard) scavenging coefficients are used in the calculation.

Alternatively, when deposition is calculated from deposition velocities (Table 3) , it is somewhat more reliable, particularly if measured data (fog flux and fog concentration) are used to calculate the deposition velocity.

Table 5 lists typical fog precipitation rates for different surface conditions. This table allows for Table 3 (deposition velocities) and Table 4 (scavenging coefficients) to be utilized if precipitation rates are unknown.

If the precipitation rates are unknown, and the user prefers to calculate the deposition velocity from measured data (not approximated values) then this can be achieved if the treetop wind velocity is known. It is recommended that this method be used in the calculation of airborne nuclear particle deposition because of the availability of the input (treetop wind velocity) and its close agreement with measured values of deposition velocities for fog entrained particles.

8 REFERENCES

(1) CAN/CSA-N288.2-M91, "Guidelines for Calculating Radiation Doses to the Public from a Release of Airborne Radioactive Material under Hypothetical Accident Conditions in Nuclear Reactors."

(2) CONCORD ENVIRONMENTAL CORPORATION, "Adaption and Application of a Model for Predicting Wet Sulphate Deposition in New Brunswick", 1991.

(3) ARP P.A. and YIN X., "Fog Contributions to the Deposition of Heavy Metals in the Gulf of Maine: Algorithm", Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton NB.,1995.

(4) BARRIE L.A. and SCHEMENAUER R.S., "Pollutant Wet Deposition Mechanisms in Precipitation and Fog Water", Water Air and Soil Pollution, 30, pg. 91-104, 1986.

(5) VONG R.J., SIGMON J.T. and MUELLER S.F., "Cloud Water Deposition to Appalachian Forests", Environmental Science and Technology, 25, pg.1014-1021, 1991.

(6) LOVETT G.M.," Rates and Mechanisms of Cloud Water Deposition to a Subalpine Balsam Fir Forest", Atmospheric Environment, 18, pg. 361-371, 1984.

(7) BRENK H.D. and VOGT K.J.," The Calculation of Wet Deposition from Radioactive Plumes", Nuclear Safety, 22, pg. 362-371, 1981.

(8) COX R.M., SPAVOLD-TIMS J. and HUGHES R.N.," Acid Fog and Ozone: Their Possible Role in Birch Deterioration Around the Bay of Fundy, Canada", Water, Air and Soil Pollution, 48, pg. 263-276, 1989.

(9) COX R.M., LEMIEUX G. and LODIN M.," The Assessment and Condition of Fundy White Birches in Relation to Ambient Exposure to Acid Marine Fogs", Canadian Journal of Forestry Research, 26, pg. 682-688, 1996.

(10) TRAUTNER F., FRANK G. and TSCHIERSCH J.," Deposition of Particle Bound Substances in Wintertime Fog", Journal of Aerosol Science, 22, pg. S529-S532, 1991.

(11) VONG R.J. and KOWALSKI A.S.," Eddy Correlation Measurements of Size-Dependent Cloud Droplet Turbulent Fluxes to Complex Terrain", Tellus, 47B, pg.331-352, 1995.

(12) YIN X. and ARP P.A.," Fog Contributions to the Water Budget of Forested Watersheds in the Canadian Maritime Provinces: A Generalized Algorithm for Low Elevations", Atmosphere-Ocean, 32, pg. 553-566, 1994.

9 BIBLIOGRAPHY

(1) MUELLER S.F.," Estimating Cloud Water Deposition to Subalpine Spruce-Fir Forest", Atmospheric Environment, 25A, pg. 1093-1122, 1991.

(2) CALSPAN CORPORATION," The Characteristics of Marine Fog Occurring Off the Coast of Nova Scotia", U.S. Dept. of Commerce doc. # AD-A027 379, 1976.

(3) NOONE K.J., OGREN J.A., HALLBERG A. et al.," Changes in Aerosol Size and Phase Distributions Due to Physical and Chemical Processes in Fog", Tellus, 44B, pg. 489-504, 1992.

(4) VOLKEN M. and SCHUMANN T.," A Critical Review of Below Cloud Aerosol Scavenging Results on Mt. Rigi", Water, Air and Soil Pollution, 68, pg. 15-28, 1993.