Rainfall Enhancement Due to Scavenging of Cooling Tower Condensate

by
M. T. Dana
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September 1977

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ABSTRACT

Estimates of rainfall enhancement resulting from scavenging of cooling tower condensate droplets were made using relevant aerosol scavenging theory and a range of meteorological conditions. For a large natural-draft tower, releasing 1.7×10^5 g/sec of condensate, plume centerline rainfall enhancement is predicted to be measurably high at downwind distances between 100 m and 1 km for moderate wind speeds and rainfall rates. The cumulative removal of condensate by scavenging should be significant, even in a light rain (1 mm/hr), where removal "half-distances" are predicted to be 2.5, 10, and 20 km for wind speeds of 1, 5, and 10 m/sec, respectively.

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NOMENCLATURE

Units: l, length; t, time; m, mass; none, dimensionless;
e, energy; T, temperature

<u>Symbol</u>	<u>Units</u>	<u>Definition</u>
A		Subscript denoting "at sampling point"
a	l	Condensate droplet radius
C	m/l^3	Concentration of scavenged water in raindrop
CW	m/m	Condensed water in plume-ambient mixture (mass per unit mass of effluent)
E		Collection efficiency
EN	e/m	Enthalpy
F	$l^{-2}t^{-1}$	Flux
f		Fraction of number of raindrops
H	l	Real cooling tower height
H'	l	Height of virtual source point
h	l	Source height of plume model
i		Subscript denoting number of interval in discrete spectrum or number of downwind distance calculation point
J	l/t , or m/l^2t	Rainfall rate, or mass flux of rain
k	t^{-1}	Scavenging ("washout") coefficient
LWC	m/l^3	Liquid water content
MR	m/m	Mixing ratio
mix		Subscript denoting "of mixture"
n		Total number of intervals i

<u>Symbol</u>	<u>Units</u>	<u>Definition</u>
p	l	Dimension of path of raindrop
Q	m/t	Source term for condensate
Q_0	m/t	Source term for condensate at time $t = 0$
R	l	Raindrop radius
S		Stokes parameter
T_w	T	Wet-bulb temperature
t	t	Time
u	l/t	Wind velocity
V_l	l/t	Average loft velocity of plume
V_t	l/t	Terminal velocity of raindrop
W	l	Diameter of cooling tower mouth
x	l	Dimension downwind from virtual source
x'	l	Distance downwind where raindrop crosses plume centerline
x_L	l	Distance downwind where plume levels off
x_r	l	Distance of real source downwind of virtual source
Y	l	Total width of plume or deposition pattern
y	l	Cross-plume dimension
z	l	Vertical dimension
ΔH	l	Height of leveled-off plume above real source height
ν	l^2/t	Kinematic viscosity of air
ρ_a	m/l^3	Mass density of air
ρ_w	m/l^3	Mass density of condensate droplets (water)

Symbol	Units	Definition
σ_y, σ_z	l	Standard deviation of plume spread in y and z directions
χ	m/l^3	Air concentration of plume droplets
χ_v	m/l^2	Vertical integral (z-direction) of χ
χ_w	m/l^2	Integral of χ in p-direction (along raindrop path)

RAINFALL ENHANCEMENT DUE TO SCAVENGING OF COOLING TOWER CONDENSATE

INTRODUCTION

The recent increase in the number of electrical generating plants which use cooling towers and projections for further expansion have prompted considerable concern about the environmental impact of large releases of energy and water effluent. One aspect of a comprehensive research program, Meteorological Effects of Thermal Energy Releases (METER), sponsored by the Energy Research and Development Administration, is an examination of the physical effects of the vast amounts of water vapor and condensate (tens of thousands of kg per second) regularly released by modern cooling towers. Such large releases can significantly affect water vapor and cloud-related natural processes at least in the immediate vicinity. One question concerns the effect on natural precipitation; namely, the potential for significant enhancement of precipitation rates and amounts in the sector traversed by the condensate plume.

In this report, we consider theoretically the question of precipitation scavenging of condensate droplets by natural precipitation, and the resultant enhancement of precipitation under the plume. Scavenging of the vapor component of the effluent is not considered here, nor are scavenging processes occurring purely as a result of cloud droplet-water vapor interactions (nucleation, droplet growth by accretion, etc.), which are commonly referred to as "in-cloud" scavenging processes, or "rain out." We consider the interaction between raindrops and condensate cloud droplets, generally called "below-cloud" scavenging or "washout" (although, of course, these interactions do occur within clouds as well as outside them). The approach is to use the currently accepted below-cloud scavenging theory to estimate for somewhat ideal cases the degree of potential rainfall enhancement; comments regarding the efficacy of this approach and recommendations for experimental evaluations and other calculations appear in the concluding section.

AEROSOL SCAVENGING THEORY

In treating the removal of water droplets from a plume by rainfall, we will use the traditional concept of a scavenging ("washout") coefficient, or fraction of the emitted liquid water which is removed per unit time. This removal may be expressed as an exponential decay process

$$Q(t) = Q_0 \exp (- kt) \quad , \quad (1)$$

where Q_0 and $Q(t)$ are the source terms (mass/time) at times $t=0$ and t , respectively. The theoretical derivation of k for the removal of aerosol particles by raindrops is treated in detail elsewhere;¹ for present purposes, it is useful to consider the case where monodisperse particles are scavenged by a distribution of raindrop sizes. A simple geometrical argument leads to the familiar form for the differential scavenging coefficient corresponding to a given single particle size:

$$k(a,R) = \int_0^\infty \pi R^2 E(a,R) F(R) dR, \quad (2)$$

where a is the particle radius, $E(a,r)$ is the collection efficiency (fraction of the particles encountered by the falling raindrop which is removed*), and $F(R)dR$ is the flux (number/area·time) of raindrops with radii R to $R + dR$.

Polydispersity of the particle sizes can be treated through a second integration,¹ but for reasons listed below we will approximate the particle size spectrum by a mean radius, and use the monodisperse form for sample calculations.

Theoretical estimates based on evaluation of (2) thus require the specification of a mathematical form for the collection efficiency as a function of a and R , and a suitable raindrop size distribution or probability

*For simplicity we are assuming perfect retention of particles scavenged by raindrops. Thus the theoretical efficiencies, which are actually *collision* efficiencies, are here equated to and called *collection* efficiencies.

density function. As will be shown below, the important condensate drop-let sizes are in the several μm range, so the choice of collection efficiency will be limited to a consideration of the inertial scavenging process, which is the predominant mechanism for removal of particles larger than about 1 μm radius.

Slinn² has derived a convenient form for the inertial collection efficiency, a semiempirical expression fitted to experimental results of Walton and Woodcock³ and the numerical calculations of Fonda and Herne.⁴ The form is

$$E(a,R) = \left(\frac{S - 1/12}{S + 7/12} \right)^{3/2}, \quad (3)$$

where S is the Stokes parameter

$$S = \frac{2 a^2 \rho_w V_t}{9 R \rho_a \nu} \quad (4)$$

In (4), ρ_w and ρ_a are the mass densities of the particles and air, respectively, V_t is the raindrop terminal velocity and ν is the kinematic viscosity of air.

CALCULATION OF RAINFALL ENHANCEMENT

Evaluation of (2) with the substitution of a suitable raindrop flux distribution and collection efficiency given by (3) cannot generally be done analytically; numerical integration has been performed¹ using log-normal raindrop distributions. For present purposes, however, a computer program^{5,6} which utilizes a discrete raindrop spectrum to provide accurate approximations was used. For a given raindrop size R_i characterizing a discrete size interval i , (2) reduces to

$$k_i = k(a, R_i) = \frac{3E(a, R_i) J_i}{4 R_i} \quad (5)$$

J_i is the rainfall rate (length/time) for raindrops of size R_i , given by

$$J_i = \frac{4}{3} \pi R_i^3 F_i \quad (6)$$

where F_i is the flux of raindrops of radius R_i .

Since we are interested in the enhancement of rainfall by scavenging of water droplets, it is useful then to consider the mass flux of water to the ground (mass/area·time or length/time) as a result of scavenging. The flux at a point on the ground (x, y) for the raindrops R_i is given by $k \chi_w(x, y)$, where

$$\chi_w(x, y) = \int_0^\infty \chi(x, y, z) dp \quad (7)$$

is the integral of the air concentration of water droplets $\chi(x, y, z)$ along the path p of the raindrop. That is, the total mass of plume droplets in a unit area column along the path of the raindrop is χ_w , k is the fraction per unit time removed, so the flux to the ground is $k\chi_w$. But the flux is also $C_i J_i$, where C_i is the concentration (mass/volume) of scavenged water in the raindrop. Thus, at a point on the ground (x, y)

$$C_i(x, y) = \frac{k_i \chi_w(x, y)}{J_i} = \frac{3 E(a, R_i) \chi_w(x, y)}{4 R_i} \quad (8)$$

The enhancement of rainfall, or fractional increase in mass of water deposited on the ground is equal numerically to the concentration of scavenged water in g/cm^3 units, since the concentration of water in the raindrop alone (ρ_w) is 1 g/cm^3 :

$$\text{Fractional Enhancement} = \frac{C_i}{\rho_w} \quad (\text{dimensionless}). \quad (9)$$

The evaluation of the net enhancement of rainfall due to scavenging by the whole raindrop spectrum at a point (x,y) is the mass weighted sum of the individual concentrations C_i :

$$C(x,y) = \frac{\sum_{i=1}^n C_i(x,y) f_i R_i^3}{\sum_{i=1}^n f_i R_i^3} \quad (10)$$

In (10), f_i is the fraction of the total number of raindrops residing in the interval i , n is the total number of intervals, and $C_i(x,y)$ is given by (8).

Evaluation of (10) at a point on the plume centerline $(x,0)$ gives the peak rainfall enhancement; a subsequent integration or summation of $C(x,y)$ in the cross-plume direction y leads to a cross-plume integrated enhancement. This, divided by an effective total width of the plume (or scavenging deposition pattern) Y gives an estimate of the average rainfall enhancement at a distance x :

$$C(x) = \frac{\int_{-\infty}^{+\infty} C(x,y) dy}{Y} \quad (11)$$

The following calculations of cross-plume average enhancement were done by a summation over discrete points y_i similar in form to (10). The effective total width of the deposition pattern was taken as 6 times the standard deviation in the y direction of the plume model chosen (see below) at the appropriate downwind distance x .

The mathematical form for the air concentration of condensate droplets chosen was a bivariate normal plume model:⁷

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp \left[-\frac{1}{2}(y/\sigma_y)^2 \right] \left\{ \exp \left[-\frac{1}{2} \left(\frac{z-h}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{z+h}{\sigma_z} \right)^2 \right] \right\} \quad (12)$$

where Q is the source term (g/sec),

σ_y, σ_z are the standard deviations of plume spread in the cross-plume y and vertical z directions (cm),

u is the wind speed (cm/sec), and

h is the source height (cm).

The standard deviations of plume spread used are those of Smith and Singer⁸ for neutral conditions, which best approximate conditions during frontal (nonconvective) rainfall:

$$\begin{aligned} \sigma_y &= 0.69 x^{0.86} \\ \sigma_z &= 0.63 x^{0.86} \end{aligned} \quad (13)$$

(σ_y, σ_z , and x in cm).

The use of this point-source model directly for a cooling tower plume is inappropriate, since the source (the cooling tower mouth) is far from being a point. To approximate the area source of the cooling tower exit, a virtual source point, as illustrated in Figure 1, was determined as follows. At the real source, the plume was assumed to have diffused from a point at $x = 0$ to $x = x_r$, where the mouth diameter W encompasses $6\sigma_y$ of the plume. Thus

$$W = 6\sigma_y(x_r) = 4.116 x_r^{0.86} \quad (14)$$

FIGURE 1. Schematic of Plume and Raindrop Trajectory Geometry

In addition, the plume is assumed to be rising linearly at an average velocity V_1 such that the virtual source height is defined by

$$H' = H - \frac{x_r V_1}{u} \quad (15)$$

where H is the true height of the cooling tower. Combining (14) and (15),

$$x_r = \left[\frac{W}{4.116} \right]^{1.16} \quad (16)$$

$$H' = H - \left[\frac{W}{4.116} \right]^{1.16} \frac{V_1}{u} \quad (17)$$

The lofting plume is assumed to rise to an elevation $H + \Delta H$, at downwind distance x_L , where it levels off. ΔH is evaluated as a function of temperature lapse rate, condensate exit temperature and wind speed u .⁹ Thus, use of (12) to describe the plume involves definition of x as the downwind distance from the virtual source (where the real sampling distance of interest, the distance from the real source, is $x_A - x_r$) and use of a plume height which increases with x as follows:

$$h = H' + \frac{x V_1}{u} \quad x < x_L \quad (18)$$

$$h = H + \Delta H \quad x \geq x_L$$

The plume-derived quantity of interest for scavenging calculations (cf. (8)) is $\chi_w(R_i)$, the raindrop-path integral of (12). For vertically falling raindrops this is expressed by the vertical integral

$$\chi_v(x, y) = \frac{Q}{\sqrt{2\pi}\sigma_y(x)u} \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y(x)} \right)^2 \right] \quad (19)$$

But raindrops never fall vertically if the wind speed is above zero. The trajectories of raindrops are approximated here as merely the resultants

of the wind speed and terminal velocity (a function of raindrop size) vectors (Figure 1). The paths of a collection of raindrops of various sizes, all of which fall at the sampling point x_A , thus cross the plume at various distances from the source, "seeing" different plume shapes and total mass of cooling tower droplets. Indeed, some of the raindrops close to the real source will pass under the source, and be deposited at x_A without scavenging anything.

Evaluation of the raindrop path integral χ_w can be done analytically¹⁰ for the paths as defined in Figure 1, but a good approximation to that rather complicated process involves use of (19) to derive χ_w , where the distance x involved is different from the sampling distance x_A . The value of x used is that distance where the raindrop crosses the plume center line on the way to deposition at x_A . The vertical integral at that point is a generally close approximation to the integral along the slanted path passing through that point. The plume centerline crossing distance x' is defined by the plume geometry and the trajectory as follows:

$$x'(R_i) = \left[x_A + \frac{H'u}{V_t(R_i)} \right] / \left[1 - \frac{V_1}{V_t(R_i)} \right] . \quad (20)$$

In the calculation process used here, then, (19) is evaluated at x' for each R_i , the concentration derived from (8), and the subsequent raindrop spectrum-mean concentration and cross-plume average concentration (enhancement) by (10) and (11). When $x' < x_r$, the drop is assumed to have missed the source and the concentration is set to zero. If $x' > x_L$, x' is constrained by holding the corresponding plume elevation to $H + \Delta H$. The terminal velocity expression used is an empirical expression¹¹ fitted to the data of Gunn and Kinzer.¹²

SAMPLE CALCULATIONS

The geometrical, meteorological, and source data listed in Table 1 were used to make sample calculations of condensate droplet scavenging and estimates of rainfall enhancement. The model cooling tower used is a typical modern natural draft tower: the source term for condensate was derived from thermodynamic considerations detailed in Appendix I, and the mass mean droplet radius taken from measurements described in Appendix II.

For a particular tower and source term Q_0 , the major meteorological variables are wind speed, rainfall rate, and raindrop size spectrum. Three choices of u and two of J were chosen to test; only one raindrop spectrum was used, that of a typical Pacific Northwest frontal rain. This spectrum (Table 2) was derived from numerous measurements in pre-frontal rains of low to moderate rate (<5 mm/hr). For heavier rains and/or convective showers, a somewhat different spectrum may apply; however, the raindrop size dependency of the inertial collection efficiency is weak for most drop sizes encountered naturally.¹ Thus for rain spectra with a different overall mean radius than that used here (mass mean radius ~ 0.045 cm), one may apply the R^{-1} dependency of (5) to make estimates of departure.

Table 3 is a list of the plume parameters derived from the input data for the various wind speed cases. These and the other data were used to estimate centerline rainfall enhancement, cross-plume average enhancement, and plume depletion at downwind distances (actual) ranging from 100 m to 50 km. These are expressed as percentages and plotted in Figures 2-11. Because of the rather high rate of removal of water from the plume in all cases, it was necessary to account for depletion of the plume by scavenging as x was increased. This was done using the exponential decay expression (1). If x_{Ai} is the i th sampling distance considered

$$Q(x_{Ai}) = Q(x_{Ai-1}) \exp \left(- \frac{k \Delta x_{Ai}}{u} \right) , \quad (21)$$

TABLE 1. Input Parameters Used in Calculations
of Rainfall Enhancement

	<u>Item</u>	<u>Value</u>	<u>Units</u>
<u>Source</u>	Liquid water source	1.7×10^5	g/sec
	Cooling tower height	150	m
	" " mouth diameter	80	m
	Loft velocity (average)	2.5	m/sec
	Plume droplet radius (mass mean)	5	μm
<u>Meteorology</u>	Wind speed	1,5,10	m/sec
	Rainfall rate	1,5	mm/hr

TABLE 2. Discrete Raindrop Spectrum Used in Calculations
of Rainfall Enhancement

<u>Radius, cm</u>	<u>Fraction of total number in interval</u>
0.0095	0.18
0.013	0.14
0.0175	0.18
0.0235	0.20
0.032	0.14
0.0435	0.09
0.059	0.05
0.080	0.013
0.1075	0.006
0.1475	0.001

TABLE 3. Plume Parameters Derived From Input Data of Table 1, and Geometry of Figure 1

Parameter	Value (meters) for wind speed u		
	1 m/sec	5 m/sec	10 m/sec
H'	-13.2	117	134
x_r	65.3	65.3	65.3
x_L	308	900	1430
ΔH	770	450	350

where $\Delta x_{Ai} = x_{Ai} - x_{Ai-1}$. Although the actual distance at which scavenging takes place is some mean x' (cf.(19)), the x_A 's were used since the difference in distance between the i and $i-1$ points are nearly the same for each. k in (21) is a simple mean scavenging coefficient $[(k_{Ai} + k_{Ai-1})/2]$ where the k_i values are derived from the cross-plume integrated concentrations. In practice, these are constant for all x_A large enough so that all raindrops are involved in the calculation (no "under cutting" of the real source). This follows from the fact that k is not a function of Q , nor does it vary as long as the raindrop spectrum and particle size are fixed.

As Figures 2-4 show, the plume centerline rainfall enhancement values are clearly significant close to the source for all three wind cases and both rainfall rate cases. For $u = 1$ m/sec, the highest centerline enhancement occurs within the starting sampling distance (100 m), and is apparently very large. The peak values for $u = 5$ and 10 m/sec are 46 and 17 percent, respectively. These peaks occur near the value of x where all of the raindrops are involved in the calculation. According to (8), it should be noted, the removal rate is greatest for the smallest values of R_i . The effect of wind speed here, of course, is just that more time is allowed in reaching a given distance, so that more water droplets are removed by that point. The variation as a function of rainfall rate J arises solely from the inclusion of depletion of the source by prior

FIGURE 2. Rainfall Enhancement (Concentration of Scavenged Condensate) at the Plume Centerline vs. True Downwind Distance: Cases of $u = 1$ m/sec and $J = 1$ and 5 mm/hr

FIGURE 3. Rainfall Enhancement (Concentration of Scavenged Condensate) at the Plume Centerline vs. True Downwind Distance: $u = 5 \text{ m/sec}$

FIGURE 4. Rainfall Enhancement (Concentration of Scavenged Condensate) at the Plume Centerline vs. True Downwind Distance: $u = 10 \text{ m/sec}$

scavenging. In the absence of depletion, there would be no difference in the concentrations for different J input.

It should be noted that the scavenging and resulting rainfall enhancement calculated at the plume centerline is often sufficiently large to imply an actual growth in the mass of the raindrops. This apparent growth in principle can increase the size of the raindrops to such an extent that the collection efficiency is changed (cf (3)). However, the raindrop size is related to the one-third power of the mass, so a considerable mass increase is required before this effect becomes significant, especially since, through the Stokes parameter S , the collection efficiency dependency on R is rather weak. In fact, in none of the calculations done here was this apparent growth great enough to warrant accounting for the change in the collection efficiency due to raindrop growth.

The cross-plume-integrated rainfall enhancement (Figures 5 through 7), or overall average enhancement at the given distance, generally reflects the character of the centerline value. In fact, the use of a bivariate normal plume allows that the cross-wind value for each R_i be proportional to the product of the centerline concentration and $\sigma_y(x')$. However, each raindrop size considered has a different x' value ($x' < x_A$); thus the cross-plume deposition pattern for the whole raindrop spectrum is not Gaussian. Figure 8 compares the cross-plume rainfall enhancement profile for one case ($u = 5$ m/sec, $J = 1$ mm/hr, $x_A - x_r = 400$ m) with that which would result if all the drop size categories were assumed to be falling vertically. The curve for the case where slanted raindrop trajectories are considered is more peaked because the raindrops cross the plume at a point where it is less diffuse than it is above the point where they land. Correspondingly, the edge values are reduced because of the narrower plume "seen." The areas under the two curves of Figure 8 are identical, since the integral of the plume over both vertical and horizontal dimensions is $Q(x_A)$, and the distance of plume travel for depletion purposes was defined, for convenience, as $x_A - x_r$ in both cases.

FIGURE 5. Cross-plume Average Rainfall Enhancement: Cases of $u = 1 \text{ m/sec}$ and $J = 1$ and 5 mm/hr

FIGURE 6. Cross-plume Average Rainfall Enhancement:
 $u = 5 \text{ m/sec}$

FIGURE 7. Cross-plume Average Rainfall Enhancement:
 $u = 10 \text{ m/sec}$

FIGURE 8. Examples of Cross-plume Rainfall Enhancement Patterns When Calculation is Done Using Either Slanted Raindrop or Vertical Raindrop Trajectories

The cumulative removal of cooling tower condensate as a function of distance downwind (Figures 9-11) is significant for all cases, with plume "half-distances" ranging from about 600 m to 25 km. It should be noted that the decay shown is essentially exponential (cf. (21)) with time constant k (k being proportional to J). The value of k/J , or fraction of the source removed per unit depth of rainfall, for the present rain spectrum and droplet size is about 1 mm^{-1} .

FIGURE 9. Cumulative Removal of Condensate by Scavenging: Cases of $u = 1 \text{ m/sec}$ and $J = 1$ and 5 mm/hr

FIGURE 10. Cumulative Removal of Condensate by Scavenging:
 $u = 5 \text{ m/sec}$

FIGURE 11. Cumulative Removal of Condensate by Scavenging:
 $u = 10 \text{ m/sec}$

CONCLUSIONS AND RECOMMENDATIONS

The integral process of removal of cooling tower condensate by scavenging, leading to depletion of the plume in time downwind, is essentially independent of plume or raindrop trajectory geometry. This follows from the basic premise that the scavenging rate k is a function of only the raindrop and condensate droplet size spectra. Integration over both these spectra leads to a fixed mean removal rate when the spectra are considered constant in time. The condensate size spectrum was represented by a single mean radius in the estimates made here; this was justified on the basis of the Gaussian appearance of the measured spectrum. Other spectra, typically log normal, may be treated explicitly by the model. Although measurements and suppositions about the sizes (particularly the sizes containing the most mass of water) of cooling tower droplets vary, most point to a predominant size in the μm range. The $5\ \mu\text{m}$ radius used here is probably a good average value for cooling tower droplets in general. It should be noted as well that the mean collection efficiency for this size of droplet (and for typically sized raindrops) is about 0.75. In the absence of extreme electric fields or other exotic scavenging mechanisms, the collection efficiency for droplets should not exceed 1.0. Thus, for spectra whose "scavenging effective" radius is in the $5\ \mu\text{m}$ or larger area, estimates made using inertial scavenging theory should not exceed those herein by a factor of 1.5 or so.

The effects on plume depletion of using different rain spectra should be less significant; the inertial collection efficiency is essentially independent of raindrop size, and the scavenging rate is inversely proportional to raindrop radius. For rainfall rates exceeding about 5 mm/hr, and for convective showers, the raindrop size spectrum may differ significantly from that used here. In general, larger raindrops will result in smaller collection efficiencies (cf. (3) and (4)) and a slower rate of removal (cf. (5)) per unit rainfall rate.

The plume and raindrop trajectory geometries will, on the other hand, affect the *pattern* of deposition of condensate droplets. In particular,

the plume shape near the cooling tower mouth, and the character of the plume rise will profoundly affect the location and magnitude of the maximum rainfall enhancement. Use of more sophisticated cooling tower condensate plume models will probably result in better estimates of rainfall enhancement near the source.

Much of the information about plume configuration and, indeed, atmospheric conditions such as temperature profiles, turbulence, and condensate droplet spectra come from (by necessity) fair weather measurements. Complicating factors, such as low ceilings (plume disappearing into natural clouds) and stormy conditions, make measurements under actual precipitation conditions difficult, if not impossible. Therefore, it is questionable at this time whether it is useful to refine the model to include more detailed plume descriptions, because of the lack of experimental guidance under precipitation conditions.

Since there are normally considerable uncertainties in raindrop and condensate droplet spectra, turbulence (affecting the raindrop trajectories), and plume behavior, the deposition patterns estimated here should be considered order-of-magnitude. The two significant results, and those which should be measurable in the field, are: the overall significant rainfall enhancement and resultant rapid depletion of the plume; and the peakedness of the rainfall enhancement relatively near the cooling tower due to raindrops traversing a more concentrated, narrower plume than that directly above their deposition point.

We suggest two types of field experiments to examine the two features of the scavenging process noted above. The first involves a concentrated network of precipitation collectors, deployed on a short-term, precipitation event basis, arrayed in lines or arcs under the plume to detect the cross-plume shape of the deposition pattern near the cooling tower. For the situation illustrated in Figures 6 and 8, about 20 collectors at $2\frac{1}{2}^\circ$ spacing at each of several distances downwind should be sufficient to detect the peakedness of the rainfall enhancement pattern. Given a rain of sufficient depth and relatively constant wind speed and direction, this could be done using ordinary buckets or funnel-and-bottle collectors. Many

similar experiments detecting scavenging of SO_2 and other pollutants from power plants have been done successfully and practically^{5,6}.

A second type of experiment could detect the degree of overall rainfall enhancement in the downwind area by monitoring precipitation over a longer period with an array of recording rain gauges. Given a fairly constant wind direction during precipitation, the typical situation of Figure 6 could be examined by using about 40 such gauges. This experiment probably would require data from a number of rainstorms in order to catch the proper conditions several times.

Selection of a proper site for these experiments is a very important practical consideration. Sufficient rainfall, preferably mostly of a frontal variety, is a requirement, as is a dependable wind direction during precipitation (the second experiment in particular would probably not be practical if more than an approximately 90 degree sector needs to be monitored). Also important are accessibility, reasonably flat terrain, and dependable operation of the cooling towers.

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APPENDIX I

DETERMINATION OF APPARENT CONDENSATE FLOW RATE FROM A TYPICAL, LARGE NATURAL DRAFT COOLING TOWER

The behavior of a saturated, heated plume relative to its liquid water content as it mixes with the ambient air is determined by the enthalpy, which is conservative. The wet bulb temperature completely defines the enthalpy and under saturated conditions it defines the water vapor mixing ratio as well. Thus, two saturated air masses at different temperatures are completely defined by their wet bulb temperatures and the properties of their mixture are defined as well.

In practice, the enthalpy (EN) of the mixture is determined and this in turn specifies the wet bulb temperature. The wet bulb temperature (T_w) defines the water vapor mixing ratio of the mixture which is subtracted from the mixing ratio determined as the mean of the mixing ratios of the two air masses to give the liquid water content (LWC).

An example is provided in Tables 4 and 5 of mixing a saturated plume at 34°C with ambient air saturated at 10°C.

TABLE 4. Conditions for Example Condensed
Water Calculation

	<u>Ambient</u>	<u>Plume</u>
Wet bulb temperature T_w , C	10	34
Enthalpy EN, cal/kg	6939	27507
Mixing ratio MR, gm/kg	7.76	35.13

TABLE 5. Condensed Water Calculations for Example Cooling Tower Plume

Ratio of ambient to plume masses	EN _{mjx} (cal/kg)	Tw (C)	MR (gm/kg)	MR _{mjx} (gm/kg)	ΔMR (gm/kg)	LWC (gm/m ³)	CW ^a
1	17223	24.55	19.89	21.44	1.55	1.83	3.10
2	13795	20.55	15.49	16.88	1.39	1.67	4.17
5	10367	15.75	11.38	12.32	0.94	1.15	5.64
10	8809	13.30	9.69	10.25	0.56	0.69	6.16
15	8224	12.30	9.07	9.47	0.40	0.49	6.40
20	7918	11.80	8.77	9.06	0.29	0.36	6.09
30	7602	11.25	8.45	8.64	0.19	0.24	5.89
40	7441	10.90	8.25	8.43	0.18	0.22	7.38
50	7342	10.72	8.15	8.30	0.15	0.19	7.65
60	7276	10.60	8.09	8.21	0.12	0.15	7.32
80	7193	10.45	8.01	8.10	0.09	0.11	7.29
100	7143	10.35	7.95	8.03	0.08	0.10	8.08
200	7041	10.20	7.87	7.90	0.03	0.04	6.03

^aCondensed water in the mixture, grams per each kg of effluent

The product of ΔMR and the total mass of the mixture containing 1 kg of the effluent yields the total liquid water (CW) in the mixture for each kg of effluent (last column of Table 5).

Except in the early stages of dilution when temperatures are quite elevated, the amount of condensed water is fairly constant. For a typical effluent flow of 2.5×10^4 kg/sec, the condensed water flow would be approximately 1.7×10^5 gm/sec under the assumed conditions.

This is the condition which is of maximum interest in regard to the washout of cloud droplets by natural precipitation.

APPENDIX II

PLUME DROPLET SIZE DISTRIBUTION USED IN SCAVENGING ESTIMATES

A series of plume traverse measurements were made at Trojan power plant in northwest Oregon in May 1976. The results of these and others are described in more detail elsewhere;⁹ for purposes of the scavenging calculations, a spectrum measured on May 13 was chosen. On one traverse, where the plume width was about 250 m, the mean liquid water content (LWC) was 0.15 g/m^3 . The droplet size spectrum, measured with a laser spectrometer, at the apparent center of the plume ($\text{LWC} = 0.22 \text{ g/m}^3$) is shown in Table 6.

Both the number and mass (LWC) distributions appear nearly Gaussian, though slightly offset in size. Because of the general characteristics of the measuring instrument, there may be a tendency for a small deficiency in the numbers reported in the first two intervals ($0.5\text{-}2.5 \text{ }\mu\text{m}$ radius); thus, the actual distribution may be more lognormal in character. However, this correction should not significantly affect the mass mean droplet radius ($\sim 5 \text{ }\mu\text{m}$).

The near-Gaussian nature of the droplet size distribution in this case simplifies the plume droplet size input to scavenging calculations. Such calculations for non-Gaussian, or, in general, polydisperse aerosol spectra, require integration over the aerosol spectrum, or at least, a strong knowledge of the "scavenging-effect" mean radius. These are related to the moments of the distribution, or mean length radius, mean area radius, etc. In the case of the inertial scavenging scheme used for estimation here, the area mean is of importance. However, approximation of the spectrum as a Gaussian one, where all the mean radii are the same, allows the specification of a single parameter to describe the scavenging characteristics of the spectrum. We have chosen in this case $5 \text{ }\mu\text{m}$, or the approximate mass mean radius.

TABLE 6. Plume Droplet Spectrum Used in Scavenging Estimates.
Measured at Trojan Power Plant on May 13, 1976

<u>Radius interval</u> <u>(μm)</u>	<u>Fraction of total in interval</u> <u>(%)</u>	
	<u>Number</u>	<u>Mass</u>
0.5- 1.5	3	0
1.5- 2.5	11	1
2.5- 3.5	25	9
3.5- 4.5	30	24
4.5- 5.5	20	30
5.5- 6.5	7	19
6.5- 7.5	3	11
7.5- 8.5	1	6
8.5- 9.5	0	0
9.5-10.5	0	0
10.5-11.5	0	0
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