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**Plume Washout from a Major
Coal-Fired Power Plant—A Case Study**

N. C. J. Chen

R. E. Saylor

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Contract No. W-7405-eng-26

Engineering Technology Division

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Date Published - November 1980

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PLUME WASHOUT FROM A MAJOR COAL-FIRED POWER PLANT — A CASE STUDY

N. C. J. Chen R. E. Saylor

ABSTRACT

A precipitation chemistry network ($\sim 300 \text{ km}^2$) consisting of 19 automatic collectors was installed around a 3200-MW coal-fired power plant located in northwest Georgia. The purpose of this study was to investigate the local plume washout from two 300-m smokestacks.

Rain samples and plume directions for a single storm (December 13, 1979) were analyzed. The maximum target area deposition rates for sulfate and nitrate were found to be $\sim 45\%$ above the mean deposition rate of the control area (SO_4^{2-} , 1.23 ± 0.14 ; NO_3^- , $0.65 \pm 0.09 \text{ nmol cm}^{-2} \text{ h}^{-1}$). The maximum deposition rates for sulfate and nitrate were reached for a plume residence time of $\sim 1 \text{ h}$ at a site $\sim 12 \text{ km}$ SE of the power plant. Aerosol washout modeling suggested that $\sim 70\%$ of the observed excess deposition rate could be attributed to sulfate aerosol derived from the plume. However, nitrate aerosol modeling could account for only 36% of the observed excess nitrate deposition rate. The variability in rainfall intensity makes it impossible to ascribe all of the differences in sulfate and nitrate deposition to plume washout alone.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) conducted a Winter Study of Power Plant Effects (WISPE) as a part of the Meteorological Effects of Thermal Energy Releases (METER) program sponsored by the Department of Energy during the first three weeks of December 1979. This study was a joint field experiment with the Pennsylvania State University (PSU) and Battelle Northwest Laboratories (BNL) around the Bowen Electric Generating Plant (Plant Bowen) in northwestern Georgia (Chen and Patrinos, 1979). The goal of WISPE was to improve the understanding of the effects of smokestack plumes on local precipitation chemistry.

In the joint experiment, PSU used an instrumented airplane to measure smokestack plume's sulfur dioxide concentration, sulfur aerosol characteristics, and various meteorological parameters; BNL provided the needed wind profiles with pilot balloons and a tether sonde; ORNL focused on

sampling event data for plume washout studies by a network of automatic rainfall-activated Health and Safety Laboratory (HASL) collectors.

A number of papers (Högström, 1974; Hutcheson and Hall, 1974; Dana et al., 1975; Li and Landsberg, 1975; Wiebe and Whelpdale, 1977; Marsh, 1978; Lindberg et al., 1979) pointed out the importance of sulfate plume washout from local emissions. The analysis of WISPE data (a single storm on Dec. 13, 1979) tends to support the existence of a local plume washout, although variability in rainfall makes it impossible to ascribe all differences in sulfate and nitrate deposition to plume washout alone.

EXPERIMENTAL

Plant Bowen is a 3160-MW coal-fired power plant with four 118-m natural-draft cooling towers and two 300-m smokestacks. Throughout the experiment, Plant Bowen generated ~1600 MW using ~1.8% sulfur coal.

The wetfall chemistry network (Fig. 1) consists of a 3×5 matrix of automatic HASL-type collectors. The chemistry network is a subset of the METER-ORNL automatic rain gage network, which is a 7×7 matrix of rain gages measuring 42 km on a side (Patrinos et al., 1979). Four additional HASL collectors were installed at key locations to increase sampling density. Rainfall was monitored continuously at each rain gage site. Similarly, winds were monitored both continuously (windsets) and routinely (pilot balloons and tethered flights) for various altitudes. Surface winds were measured by two windsets located 1 km north of the smokestacks. A third windset was installed on a 30-m meteorological tower, located on the crest of a 120-m hill, 5 km NE of the power plant. In addition, a continuous visual observation of the plume was conducted during the December 13 storm.

A polyethylene bottle-funnel combination was placed in each HASL collector and sealed against dryfall deposition ~2 d prior to the onset of the storm. The samples were retrieved as rapidly as possible (<7 h) after the cessation of rain and stored at 4°C.

The limited amount of sample collected per site (<25 ml) was enough only for pH, sulfate, nitrate, and ammonium analyses. A combination

Fig. 1. Map showing the chemistry network (open circles with the site number indicated) in relation to the rain gage network (solid dots). The topography of northwest Georgia (with the location of Plant Bowen and several other major features) is superimposed with the values of the contour lines indicating feet above mean sea level.

reference-pH electrode was used to measure pH within 24 h. Further analysis was performed within 3 d using a modified methylthymol blue colorimetric method for sulfate, a cadmium reduction method for nitrate, and an indophenol method for ammonium.

RESULTS AND DISCUSSION

Analysis of wind data and visual observations of the plume revealed that the wind data measured at the meteorological tower was an acceptable predictor of the smokestack plume direction. High-frequency fluctuations of the wind unnecessarily complicated the determination of the plume direction; therefore, a low-pass filter was used to reduce these fluctuations. The low-pass filter was a seven-point weighting scheme (Panofsky and Brier, 1968) performed on windset readings taken at the meteorological tower at 10-min intervals. The derived plume direction (plume centerline) was assumed to spread by 10° on each side of the plume centerline. Each time interval (10 min) that the plume remained over a sampling station was summed to obtain a plume residence time during rain, as shown in Table 1. This analysis established the target area to be the eastern half of the chemistry network (the sites listed in Table 1) and the control area to be in the western half of the chemistry network. The predominant

Table 1. Plume residence time during rain

Site	Plume residence time (h)	Event duration
18	0	1030-1730
MET	0.17	1030-1730
19	0.17	1000-1730
25		Inoperable
26	1.83	1000-1700
32	2.00	1030-1700
33	3.00	1030-1810

downwind direction was identified to be the southeast sector of the network, which had a plume residence time of ~ 3 h.

A comparison of rainfall statistics (Table 2) between the full METER rain gage network and the subset of this network, which included the rain chemistry samplers, indicated no significant differences in the means or standard deviations, suggesting that the rainfall amounts in the chemistry network for the December 13 storm were comparable to those of the larger region. Within the rain chemistry network, however, there were well defined trends in both intensity (Fig. 2) and rainfall volume (not shown) of increasing values from northwest to southeast across the network. This variation in rain volume complicates the analysis of the plume washout effect because of the inverse relationship between volume and rain concentration. With this caveat in hand, the wetfall chemistry in the target and control areas and one possible hypothesis to explain the significant difference in sulfate and nitrate deposition rates are described.

Table 2. Characteristics of December 13 storm^a

	METER-ORNL rain gage network (7 x 7)	Chemical network (subset METER-ORNL)
Mean rainfall, mm	6.74 (49 sites)	6.76 (17 sites)
Standard deviation, mm	1.52	1.43
Coefficient of variation, %	23	21

^aType: cold front; rain period started at 0830, ended at 1800.

The deposition rates of sulfate (Fig. 3) and nitrate (Fig. 4) demonstrated well-defined spatial patterns suggesting possible plume washout effects, whereas the deposition rates of hydrogen and ammonium ions occurred in random patterns (not shown). In general, deposition of sulfate produced a pattern fanning out from the bottom row of the network with increasing deposition rates from west to east. The gradient was weaker in the control (western) area and stronger in the target (eastern) area, with the maximum deposition rate occurring at site 33, located southeast

Fig. 2. Rainfall rate contours in mm/h for the storm of Dec. 13, 1979.

of the power plant. These effects are further supported by t-tests, shown in Table 3.

A plume washout model was used to compare predicted excess deposition rates to observed excess deposition rates for sulfate (~ 0.55) and nitrate ($\sim 0.31 \text{ nmol cm}^{-2} \text{ h}^{-1}$) at the site 33 as indicated in Figs. 3 and 4. The excess deposition rate is defined as the difference in the deposition rate between any sites in the target area and the mean deposition rate of the control area. The common set of parameters used for calculations is: a $500\text{-}\mu\text{m}$ mean raindrop radius, a collection efficiency of ~ 0.1 (Stensland, 1973), a plume thickness of $\sim 300 \text{ m}$ at 12 km downwind of the stack, and a rain intensity of 1 mm/h . For sulfate [assuming a $1\text{-}\mu\text{m}$ mean radius for

Fig. 3. Contours of sulfate ion deposition rate in $\text{nmol cm}^{-2} \text{ h}^{-1}$ for the storm of Dec. 13, 1979.

Table 3. Statistics of the t-test showing sulfate and nitrate deposition rate effects^a

	Sulfate		Nitrate	
	Target area	Control area	Target area	Control area
Sample size	6	10	6	10
t-value	5.25		3.23	
Probability	0.02		0.43	

^aThree collectors malfunctioned.

Fig. 4. Contours of nitrate ion deposition rate in $\text{nmol cm}^{-2} \text{h}^{-1}$ for the storm of Dec. 13, 1979.

SO_4^{2-} aerosol in the plume with a particulate number density of ~ 1 per cubic centimeter, as measured by the PSU airplane at Plant Bowen (de Pena, 1980)], the SO_4^{2-} aerosol washout was estimated to be about $0.4 \text{ nmol cm}^{-2} \text{h}^{-1}$. This washout accounts for $\sim 70\%$ of the observed excess deposition rate. For nitrate (assuming a mean plume concentration of nitrate aerosol of $\sim 1 \mu\text{g m}^{-3}$, as reported recently by Hegg and Hobbs 1979), NO_3^- aerosol washout was estimated to be about $0.1 \text{ nmol cm}^{-2} \text{h}^{-1}$. This washout accounts for about 36% of the observed excess deposition rate. For these calculations, it appears that the aerosol washout is a predominant mechanism for sulfate but not for the nitrate. These conclusions must be

considered tentative, since the data used in the calculations were either obtained prior to the December 13 storm or from other power plant plumes.

The measured and calculated $[\text{H}_3\text{O}^+]$ -ion deposition rates are compared in Fig. 5, where the calculated $[\text{H}_3\text{O}^+]$ -ion deposition rate is defined as the algebraic sum of $2[\text{SO}_4^{2-}] + [\text{NO}_3^-] - [\text{NH}_4^+]$. Also included in Fig. 5

Fig. 5. Scatter diagram of measured deposition rate of $[\text{H}_3\text{O}^+]$ -ion vs calculated $[\text{H}_3\text{O}^+]$ -ion at each site. The calculated $[\text{H}_3\text{O}^+]$ -ion is defined as the sum of $2[\text{SO}_4^{2-}] + [\text{NO}_3^-] - [\text{NH}_4^+]$.

are two error bounds ($\pm 30\%$) denoted by the broken lines. The $\pm 30\%$ error bounds, chosen arbitrarily, are the maximum and minimum errors that the calculated $[\text{H}^3\text{O}^+]$ deposition rate could have if the total error of the three components is 30% of the error-free case. Only 8 out of 15 sites for which $[\text{H}^3\text{O}^+]$ could be calculated have results within these two error bounds, suggesting some inherent uncertainties associated with sampling procedures and/or analysis techniques.

To see plume washout, the excess deposition rate is normalized by the control area's mean deposition rate and plotted (Fig. 6) as a function of the plume residence time during rain over a sampling location. Both sulfate and nitrate show an increase in plume washout with increasing plume residence time; however, the plume remained over site 18 for ~ 10 min, 40 min prior to the onset of rain. Plume derived pollutants remained over

Fig. 6. Characteristics of plume washout of sulfate and nitrate as a function of the plume residence time during rain for the storm of Dec. 13, 1979.

this site until the outset of rain, causing a 15% increase in SO_4^{2-} and an 8% increase in nitrate. Plume washout is seen to rise rapidly at the onset of rain and to reach a near steady-state condition for plume residence time of ~ 1 h. The observed nitrate deposition rate at site 19 was excluded for curve fitting. The low value, shown in Fig. 6, cannot be resolved at this time.

CONCLUSION

Results of chemical analyses of the December 13 storm rainfall samples suggest the presence of a measurable plume washout of sulfate and nitrate in the target area. The maximum deposition rate of sulfate and nitrate was about 45% above the mean deposition rate of the control area. The maximum deposition rates were reached after a plume residence time of ~ 1 h at a site ~ 12 km from the stack. Aerosol washout calculations suggested that 70% of the observed excess deposition rate of sulfate could be attributed to sulfate aerosol in the plume; however, nitrate aerosol could account for only 36% of the nitrate washout. Although these findings are encouraging, the variability in rainfall intensity makes it impossible to determine if all differences in sulfate and nitrate deposition are due to plume washout alone. Future event samples should provide additional insight into local plume washout.

ACKNOWLEDGMENTS

This work was sponsored by the Department of Energy as part of the program on the Meteorological Effects of Thermal Energy Releases. The authors are indebted to A. A. N. Patrinos, L. Jung, and R. L. Miller of Oak Ridge National Laboratory for their help in sampling. The advice of R. de Pena of Pennsylvania State University is greatly appreciated.

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