CONSIDERATIONS OF SULPHUR DIOXIDE GROUND-LEVEL CONCENTRATIONS FOR POWER OPERATIONS

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Plans have been prepared for building fossil-fuel power plants and coal gasification plants for large-scale utilization of North Dakota's lignite resources. The general public is greatly concerned about the possible environmental impacts of these coal developments. One of the problems that might arise is a high sulfur dioxide (SO_2) ground-level concentration in the downwind distance from power plant stacks. Excess sulfur dioxide would not only have a detrimental effect on agricultural production, but would also be harmful to the health of residents around the plants. This paper uses a mathematical model to predict SO_2 ground-level concentrations downwind from a stack, and the relationships between the concentration level and plant design parameters. Two alternative engineering approaches to SO_2 controls are briefly discussed.

A Mathematical Model

The behavior of an effluent plume in the atmosphere is a complicated process. Mathematical management of the dispersion process requires two major segments: (1) the stack effluents rise on their own momentum and buoyancy forces when atmospheric stability and turbulence are operative, but their influence on plume behavior is secondary, and (2) the momentum and buoyancy forces become relatively weak and the effluent plume starts to dilute by mixing with surrounding ambient air. Fundamentally, the two parameters of atmospheric system which have a strong influence on the dispersion of stack gases are wind velocity and characteristics of turbulence (atmospheric stability).

Mathematically, the above-mentioned two segments of process can be described by the following equations (1):

$$\Delta H = \frac{V_s d}{u} \left(1.5 + 2.68 \times 10^{-3}\, p\, \frac{T_s - T_a}{T_s}\, d \right) \quad [1]$$

and

$$\left\{ \exp\left(-\frac{1}{2} \left(\frac{z-H}{\sigma_z} \right)^2 \right) + \exp\left(-\frac{1}{2} \left(\frac{z+H}{\sigma_z} \right)^2 \right) \right\} \quad [2]$$

To predict the maximum ground-level concentration from several stacks, the following approximation equation is suggested (2):

$$\bar{\chi}_{total} = n^c\, \bar{\chi}_{single} \quad [3]$$

The maximum or axial time-mean concentration of effluent generally decreases with increasing sampling time. This is due to the fact that the lateral dispersion of effluent increases with time. The functional relationship can be shown as:

$$\frac{\bar{\chi}}{\bar{\chi}_r} = \left(\frac{t_r}{t} \right)^b \quad [4]$$

where $\bar{\chi}$ is the desired concentration estimate for the sampling time t, and $\bar{\chi}_r$ is the concentration estimate for the reference sampling time t_r. In this study the exponent b is set equal to 0.2 as recommended by Turner (3).

Numerical Calculations

Using these equations, we predicted the wind distances from stack. Table 1 contains the emission and stack information. All data are for one unit at the full load. There are four identical generating units in the plant. It is possible in the near future that two more units would be added. Each unit has a net capacity of 800 MW. Table 2 shows the windrose tabulations for the plant site. For the computation of this study, the local atmospheric stability has been predicted with the

Table 1. Emission and Stack Information.

SO_2 emission rate	11,130 lbs/hr.
NOx emission rate	6,354 lbs/hr.
Particulate emission rate	907.8 lbs/hr.
Effluent temperature	280 F
Ambient air temperature	80 F
Inside stack diameter	27 ft.
Exit velocity	90 ft/sec.
Stack height	800 ft.

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Table 2. Windrose Tabulations.

Direction		Spring & Fall Wind mph	Spring & Fall Freq.	Winter Wind mph	Winter Freq.	Summer Wind mph	Summer Freq.	Annual Wind mph	Annual Freq.
N	36	8.7	.0255	10.0	.0259	7.3	.0145	8.7	.0220
	01	9.0	.0182	9.6	.0185	8.3	.0072	9.0	.0145
	02	8.2	.0237	9.8	.0333	8.6	.0109	8.9	.0226
	03	9.6	.0109	10.3	.0593	8.0	.0181	9.3	.0294
NE	04	7.8	.0210	10.8	.0333	6.7	.0217	8.4	.0287
	05	8.6	.0328	8.7	.0370	7.0	.0290	8.1	.0329
	06	7.4	.0474	9.5	.0444	6.6	.0435	7.8	.0451
	07	7.7	.0219	7.6	.0481	6.6	.0362	7.3	.0354
	08	6.5	.0237	6.2	.0222	5.4	.0181	6.0	.0213
E	09	7.9	.0128	7.6	.0185	5.3	.0254	6.9	.0189
	10	7.8	.0164	7.5	.0074	5.8	.0435	7.0	.0224
	11	7.0	.0128	6.7	.0148	5.5	.0217	6.4	.0164
	12	5.2	.0109	5.9	.0148	6.1	.0254	5.7	.0170
SE	13	6.7	.0273	6.4	.0185	5.4	.0181	6.2	.0213
	14	6.9	.0364	7.6	.0148	5.2	.0326	6.6	.0279
	15	6.1	.0273	8.0	.0481	5.0	.0290	6.4	.0348
	16	6.6	.0474	6.2	.0148	5.6	.0290	6.1	.0304
	17	7.1	.0364	7.3	.0259	7.0	.0399	7.1	.0341
S	18	8.0	.0383	6.9	.0444	7.4	.0399	7.4	.0409
	19	9.1	.0455	8.4	.0444	6.0	.0435	7.8	.0445
	20	8.3	.0710	10.9	.0222	6.6	.0652	8.6	.0528
	21	8.7	.0346	9.4	.0407	7.2	.0906	8.4	.0553
SW	22	8.0	.0383	8.3	.0519	8.4	.0870	8.2	.0591
	23	8.4	.0437	10.0	.0333	8.1	.0435	8.8	.0402
	24	8.3	.0200	11.1	.0407	7.9	.0435	9.1	.0347
	25	9.4	.0219	10.4	.0148	7.7	.0181	9.2	.0183
	26	9.9	.0237	8.3	.0148	6.9	.0290	8.4	.0225
W	27	8.6	.0219	8.3	.0111	6.0	.0072	7.6	.0134
	28	9.5	.0164	11.3	.0111	7.7	.0109	9.5	.0128
	29	10.1	.0310	10.6	.0185	6.4	.0217	9.0	.0237
	30	8.9	.0237	11.1	.0333	9.2	.0072	9.7	.0214
NW	31	9.9	.0164	9.4	.0222	7.8	.0036	9.0	.0141
	32	9.3	.0237	10.1	.0259	6.0	.0036	8.5	.0177
	33	10.4	.0255	11.8	.0222	6.8	.0036	9.7	.0171
	34	9.4	.0200	11.4	.0296	7.2	.0145	9.7	.0214
	35	9.1	.0219	10.0	.0222	7.3	.0036	8.8	.0159

Table 3. Per Cent Frequency Occurrence of Stability Standards.

Wind Velocity (mph)	Stability Class	N	NNE	NE	ENE	E	ESE	SE	SSE
	A	.055	.110	.074	.103	.111	.204	.258	.148
	B	.021	.105	.298	.125	.252	.280	.270	.173
5	U_1*	.160	.312	.331	.512	.318	.679	.791	.656
	U_2*	.172	.169	.367	.388	.343	.509	.417	.442
	A		.131	.119	.218	.296	.267	.327	.266
	B	.934	.701	.802	.949	1.249	1.394	1.233	1.175
	C	.655	.575	1.394	.966	1.075	1.371	1.239	1.143
6-14	D	1.170	1.281	1.033	.630	.571	.381	.567	.646
	E	1.061	.564	.771	.803	.475	.479	.544	.720
	F	.173	.402	.337	.272	.076	.279	.284	.479
	C	.140					.028	.006	.013
15-24	D	.516	.162	.262	.217	.110	.117	.125	.212
	C								
25	D								

Wind Velocity (mph)	Stability Class	S	SSW	SW	WSW	W	WNW	NW	NNW
	A	.186	.116	.148	.167		.034	.086	.086
	B	.220	.212	.178	.124	.063	.048	.109	.063
5	U_1*	.665	.273	.677	1.587	.428	.042	.085	.111
	U_2*	.346	.519	.228	.552	.118	.119	.057	.161
	A	.097	.145	.245	.382	.042	.028	.011	.097
	B	1.640	1.185	1.392	1.704	.693	.479	1.018	1.012
	C	1.818	1.644	1.065	1.202	.561	.710	.978	.909
6-14	D	1.646	1.419	1.019	.620	.372	.722	.969	.632
	E	1.439	.676	.959	1.899	.859	.320	.356	.349
	F	.984	.637	.992	2.119	1.197	.237	.115	.154
	C	.131	.237	.245	.196	.055	.140	.537	.263
15-24	D	.372	.697	.612	.196	.187	.401	.479	.338
	C								
25	D		.029	.006			.034		

* *U^1 and U^2 are unclassified.*

available climatological data. Table 3 indicates the per cent frequency occurrence of stability class. The stability class B has been selected as the typical condition.

Ground-level SO_2 concentration beneath the axis of a plume would vary as the downwind distance from stack increases. In general, the concentration will first increase, and then decrease gradually. Naturally, the variation of ground-level concentrations would depend upon many factors such as the atmospheric stability conditions, wind speed and stack design parameters. Table 4 shows some of the calculated results for the stack of recommended height (800 feet) under an unstable atmospheric condition. It is seen that at each wind speed there is a critical downwind distance at

Table 4. Ground-Level SO_2 Concentrations at Various Downwind Distances - ug/m[3].

km Distance from Stack	Wind Speed (m/sec.) 5.0	6.0	7.0	8.0	9.0	10.0
2.0	22.8	31.9	61.0	76.6	87.1	96.1
3.0	114.4	131.9	138.9	140.4	138.4	136.7
4.0	139.3	135.9	130.5	122.9	115.3	109.0
5.0	125.3	116.5	105.1	95.7	87.6	81.1
10.0	49.2	41.9	36.4	32.2	28.7	26.1
20.0	13.2	11.0	9.5	8.3	7.4	6.7
50.0	2.5	2.1	1.8	1.6	1.4	1.3

which the maximum concentration occurs. Also, for each stack height there is a critical wind speed at which the maximum ground-level concentration will appear. In this case, the critical wind speed is approximately equal to 8 meters/sec. and the maximum ground-level SO_2 concentration occurs at the downwind distance about 3 km.

Ground-level SO_2 concentration would not only vary with the downwind distance from the stack, but also with the cross wind distance from the plume centerline. As the crosswind distance from the plume centerline increases, the ground-level SO_2 concentration would decrease rapidly. The relationship is similar to the Gauss distribution function.

This study also found that SO_2 concentration level would decrease as the vertical distance from the axis of the plume increases. Thus, ground-level SO_2 concentration is always lower than that at the center of the plume. However, it is the maximum ground-level SO_2 concentration that is important in selecting stack height.

Plant Design Parameters Affecting SO_2 Ground-Level Concentrations

Different design parameters greatly affect SO_2 ground-level concentrations. The obvious parameter is the stack height. Table 5 indicates the effects of stack heights on the maximum ground-level SO_2 concentrations. It should be emphasized that the maximum value would occur only at a certain downwind distance and at the critical wind speed. As the stack height increases, SO_2 ground-level concentrations would decrease.

Table 5. Effects of Stack Height on the Maximum Ground-Level SO_2 Concentrations.

Stack Height Ft.	Maximum Ground-Level SO_2 Concentration - ppm (the Sampling Time = 0.5 hr.) Single Unit	Four Units	Six Units
800	0.0433	0.173	0.259
900	0.0396	0.158	0.237
1000	0.0363	0.145	0.217
1100	0.0336	0.134	0.200

The idea of using different stack heights for different generating units is worth investigation. Plant contributions of various pollutants can be predicted by procedures similar to those for the plant with stacks of equal height. Table 6 presents the approximate maximum ground-level SO_2 contributions for various stack arrangements. These calculations indicate that when the stacks do not have the same height at the plant site, the maximum ground-level SO_2 concentration contributed by the plant is always less than the sum of maximum ground-level concentrations of all stacks. However, the differences seem to be insignificant in this study.

Table 6. Maximum Ground-Level SO_2 Concentrations[1] Contributed by the Plant.

Case No.	Arrangements	Maximum Ground-Level SO_2 Concentration[2]	Safety Factor[3]
1.	4 stacks (each 700 ft.)	633.6	1.03
2.	4 stacks (each 800 ft.)	561.6	1.17
3.	4 stacks (each 900 ft.)	506.5	1.29
4.	4 stacks (two 600 ft. and two 800 ft).	630.8	1.04
5.	4 stacks (three 600 ft. and one 900 ft.)	650.9	1.01

[1] *The allowable limit is approximately 655.3 ug/m[3] in the 10 minute sampling average.*

[2] *All SO_2 concentrations are in terms of micrograms per cubic meters (10 minute sampling average).*

[3] *Safety factor is defined as the ratio of allowable limit to the calculated maximum concentration.*

The possibility of using one stack for two generating units was considered. Calculations show (Table 7) that the idea of one stack for two units is attractive from an air pollution control viewpoint. Such an arrangement generally results in the maximum rise of hot gas, an increase in the plume's ability to pierce inversions and main-

Table 7. Stack Heights under Various Constraints.

No.	Constraints	Calculated Stack Height, Ft.
1.	One stack for one generating units and 4 units at the site	800
2.	One stack for one generating unit and 6 units at the site	1,100
3.	One stack for two generating unit and 4 units at the site	800
4.	One stack for two generating units and 6 units at the site	900

tenance of reasonable exit velocity. Offsetting these advantages are such factors as the loss of operational flexibility. This investigaton is intended to evaluate these arrangements only in terms of SO_2 dispersion.

An examination of any mathematical model for predicting the ground-level concentrations of SO_2 would reveal an importance of plume rise calculations. With the emission data used in this investigation, it was found that an overestimate of plume rise by 25 per cent will lower the prediction of the maximum ground-level SO_2 concentration by 17.5 per cent. In other words, the factors affecting the plume rise would affect the SO_2 dispersion. There are many of these factors, including, in general: (1) gas exit velocity, (2) wind velocity, (3) inside diameter of stack, (4) ambient air temperature, (5) gas temperature, (6) atmospheric stability conditions, and (7) stack height.

In-line stack arrangement was compared in this study with staggered stack arrangement. It was found that the staggered arrangement would not significantly reduce the maximum SO_2 ground-level concentration. Also, the effects of spacing distance between the stacks could be neglected.

Discussion

Accuracy of dispersion calculations depends largely on the availability of wind information for the plant site. In addition to data on wind speed and direction, variation of the horizontal wind with height must be available. From this data, standard deviations (both azimuth and elevation angles) of wind direction fluctuation are calculated, and with them the diffusion parameters in the dispersion model are determined. It should be stressed that vertical wind speed profile is also affected by changes in underlying terrain and atmospheric thermal stability.

In the study, we have neither information about the wind variation with height, nor any data from which the diffusion parameters can be determined. Because of this lack of weather data, we have made two assumptions: (1) no variation of wind speed and direction with height, and (2) diffusion parameters are those specified in the stability class B.

Local atmospheric stability is one of many factors whch affect the dispersion of effluents. Atmospheric stability is mainly influenced by the atmospheric temperature structure at the plant site. It varies from season-to-season, and from hour-to-hour within a day. Naturally, atmospheric stability changes from area to area, and also varies with altitude. Details of the local temperature structure must be available for a complete picture of atmospheric stability at the plant site. Daily hourly temperatures can be prepared from local weather data to predict environmental lapse rates at different altitudes, size of inversion layers (which may exist simultaneously at different altitudes), and depth of the convective layer. This data is necessary to accurately predict ground-level concentrations, also helps predict ground-level concentrations and their frequencies of inversion breakup and trapped fumigations.

Since we lacked local temperature data as described above for this study, we estimated the local atmospheric stability by using near-by airport weather information and the method of stability classification suggested by D. B. Turner (3).

A multi-stack system generally presents problems which are not encountered in a single-stack system. One of them is the interference among the plumes from the stacks. Close to the stacks, the plumes may keep their individual pattern, while at a longer distance, they would tend to merge. Generally, the plumes from multiple stacks will rise higher than from one of them. This is especially true when the wind direction is parallel to the row of stacks. However, methods for quantitative prediction are not yet available. Another problem is the aerodynamic downwash phenomenon between the stacks. Because there is no theory to predict their effects on the ground-level concentrations, scale model experiments are generally needed for economic design of a multi-stack system.

Stack height is generally based on an analysis of the area meteorological considerations, satisfaction of regulatory standards, emission data and interaction of the effluent plumes. Maximum allowable effluent ground-level concentrations are either those set by the Environmental Protection Agency (EPA) or those adopted by the state government. However, this choice will have the following implications:

1. In the area where the power plant is situated, the state government and community will have 100 per cent of the air quality standards pre-empted by this new

source. It means that the area will have no more industrial and other developments that may emit the regulated pollutants such as SO_2.

2. The air of the region is not polluted by the regulated pollutants. The level of present pollution, referred to as the background level, is assumed to be zero.
3. The dispersion model developed for an unimpeded level terrain, is completely valid for the present project. Realistically, the regulatory agency and the community may wish to invoke the foregoing constraints. If and when this is the case, the correction factor for determination of the allowable air quality standards should be applied.

The expression of the correction factor is:

$$F = F_1 F_2 (1 - \frac{C_b}{C_s}) \quad [5]$$

As shown in previous sections, the SO_2 ground-level concentration can be reduced by using a tall stack. However, the reduction would diminishingly decrease as the stack height increases. In addition to this approach, the SO_2 removal system can be installed in the flue gas stream. This system would reduce the SO_2 emission rate and thus reduce ground-level concentration. The sulfur dioxide removal technology has been well recognized in power industry. The processes applicable to the power electric-generating system are according to the principles of operation:

1. Dry metal oxide or carbonate processes.
2. Wet limestone processes.
3. Wet lime and magnesium processes.
4. Ammonia rerubbing processes.
5. Other aqueous scrubbing processes.
6. Activated carbon processes.
7. Direct oxidation processes.

While removal systems effectively reduce SO_2 ground-level concentrations, they are expensive to own and to operate. One utility company study (4) indicates that the cost of a retrofit limestone wet scrubbing system for their existing power plants would be about $40-$50/KW, and the operating costs for such a system would be from 0.30 - 1.0 mills/KWH.

As an alternative to stack gas cleanup, sulfur content in fuels may be removed before combustion. One such system which may particularly be attractive in this area is the coal-gasification—combined cycle power plant. In this system, coal, air and steam are fed into a pressure gasifier. Gas from the gasifier is cooled and scrubbed with chemicals to remove the H_2S and remaining ash. The cleaned gas is then burned and expanded in a gas turbine. The exhaust gas high temperature is further utilized in a steam generator. In this system, removal of sulfur and ash from the fuel is expected to be close to 100 per cent. NOx generation is expected to be very low.

In summary, the reduction of SO_2 ground-level concentrations from electric-power generation can be achieved through a proper plant design. Further development of coal-gasification-combined cycle power plants and SO_2 removal systems will be extremely important in the utilization of coal resources in the nation.

References

1. Pollution Control Technology, Research and Education Association, New York. 1972.
2. **Recommended Guide for the Prediction of the Dispersion of Airborne Effluents.** 1973. The American Society of Mechanical Engineers, New York.
3. Turner, D. B. 1969. **"Workbook of Atmospheric Dispersion Estimates."** U.S. Public Health Service.
4. Gray, C. Ashley. 1972. **"Coal-Energy Conversion Technology."** Research Dept. Northern States Power Company.

Nomenclature

b	exponent, dimensionless
c	exponent, dimensionless
C	background pollution level, ppm
C	secondary air pollution standard, ppm
d	inside stack diameter, meter
F	correction factor, dimensionless
F_1	factor for future development, dimensionless
F_2	factor for confidence level of dispersion model, dimensionless
h	stack height, meter
H	height of the plume centerline, meter
ΔH	plume rise above the stack, meter
n	number of stacks in the plant, dimensionless
P	atmospheric pressure, mb
Q	emission rate, gram per sec.
T	air temperature, °k
T	stack gas temperature, °K
u	wind speed, meter per sec.
V	stack gas exit velocity, meter per sec.
x	downwind distance from stack, meter
y	crosswind distance from plume centerline, meter
z	vertical distance from ground level, meter
x	concentration level, ppm
y	diffusion parameter in y direction, meter
z	diffusion parameter in z direction, meter