**EFFECTIVENESS OF A HYPOTHETICAL
AIR-POLLUTION EPISODE-CONTROL STRATEGY
FOR TWO CHICAGO EPISODES**

by

T. P. Wangler and A. D. Rossin

ARGONNE NATIONAL LABORATORY

CENTER FOR ENVIRONMENTAL STUDIES

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January 1973

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	9
1. INTRODUCTION	10
2. ARGONNE INTEGRATED-PUFF AND STEADY-STATE PLUME MODELS.	13
3. FEBRUARY 25-26, 1967, EPISODE.	17
3.1 Comparison of Calculated and Observed Concentrations for February 25-26, 1967	24
3.2 Calculated Concentrations for February 25-26, 1967	26
3.3 Calculated Effect of a Strategy upon the February 25-26, 1967, Episode.	34
4. NOVEMBER 5-11, 1969, EPISODE	39
4.1 SO ₂ Emissions for November 5-11, 1969	50
4.2 Comparison of Calculated and Observed Concentrations for November 5-11, 1969.	50
4.3 Calculated Concentrations for November 5-11, 1969, Episode	52
4.4 Effect of a Strategy upon the November 5-11, 1969, Episode	58
5. SUMMARY AND CONCLUSIONS	62
ACKNOWLEDGMENTS	64
REFERENCES	65

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.1.	Chicago Map of Major Sources Showing Location of Eight Telemetered Air Monitoring (TAM) Stations	11
3.1.	Surface Weather Map at 0000 CST, February 25, 1967	18
3.2.	Surface Weather Map at 0000 CST, February 26, 1967	19
3.3.	Midway Temperature	20
3.4.	Midway Wind Speed	20
3.5.	Midway Wind Direction	20
3.6.	Meigs Temperature	20
3.7.	Stability Index	20
3.8.	Estimated Mixing Height	20
3.9.	Chicago Map of SO ₂ Sources	21
3.10.	Observed SO ₂ Concentrations, 0200 CST, February 25, 1967 .	22
3.11.	Observed SO ₂ Concentrations, 0600 CST, February 25, 1967 .	22
3.12.	Observed SO ₂ Concentrations, 1000 CST, February 25, 1967 .	22
3.13.	Observed SO ₂ Concentrations, 1400 CST, February 25, 1967 .	22
3.14.	Observed SO ₂ Concentrations, 1800 CST, February 25, 1967 .	22
3.15.	Observed SO ₂ Concentrations, 2200 CST, February 25, 1967 .	22
3.16.	Observed SO ₂ Concentrations, 0200 CST, February 26, 1967 .	23
3.17.	Observed SO ₂ Concentrations, 0600 CST, February 26, 1967 .	23
3.18.	Observed SO ₂ Concentrations, 1000 CST, February 26, 1967 .	23
3.19.	Observed SO ₂ Concentrations, 1400 CST, February 26, 1967 .	23
3.20.	Calculated and Observed SO ₂ Concentrations at TAM 1	24
3.21.	Calculated and Observed SO ₂ Concentrations at TAM 2	24
3.22.	Calculated and Observed SO ₂ Concentrations at TAM 3	24
3.23.	Calculated and Observed SO ₂ Concentrations at TAM 4	24
3.24.	Calculated and Observed SO ₂ Concentrations at TAM 5	24
3.25.	Hourly Emissions from Power Plants, Industries, and Residential/Commercial Sources	27
3.26.	Hourly Emissions from Loop and Hyde Park	27

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
3.27.	Sixty-six-point Receptor Grid	28
3.28.	Hourly Power-plant Emissions,	29
3.29.	Average SO ₂ Concentration over 32 hr from the Model	30
3.30.	Average Power-plant Contribution to SO ₂ Concentration over 32 hr from the Model.	30
3.31.	Average Industrial Contribution to SO ₂ Concentration over 32 hr from the Model	30
3.32.	Average Residential/Commercial Contribution to SO ₂ Concentration over 32 hr from the Model.	30
3.33.	SO ₂ Concentrations Predicted by the Model for 4-hr Intervals	31
3.34.	Average SO ₂ Concentration Predicted over 32 hr with Strategy.	34
3.35.	SO ₂ Concentrations Predicted with the Strategy for 4-hr Intervals	35
4.1.	Weather Map at Surface and at 500 mbar for November 5, 1969	40
4.2.	Weather Map at Surface and at 500 mbar for November 6, 1969	41
4.3.	Time-series Plots of SO ₂ Concentrations and Meteorological Variables at TAM 7	42
4.4.	Time-series Plots of SO ₂ Concentrations and Meteorological Variables at TAM 7 and 5	44
4.5.	Calculated Mixing Height for November 5-11, 1969	46
4.6.	Calculated Ventilation for November 5-11, 1969	46
4.7.	Observed SO ₂ Concentrations, 0800 CST, November 5, 1969. .	47
4.8.	Observed SO ₂ Concentrations, 1600 CST, November 5, 1969. .	47
4.9.	Observed SO ₂ Concentrations, 0900 CST, November 6, 1969. .	47
4.10.	Observed SO ₂ Concentrations, 1200 CST, November 6, 1969. .	47
4.11.	Observed SO ₂ Concentrations, 1600 CST, November 6, 1969. .	47
4.12.	Observed SO ₂ Concentrations, 0900 CST, November 7, 1969. .	48
4.13.	Observed SO ₂ Concentrations, 1800 CST, November 7, 1969. .	48

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
4.14.	Observed SO ₂ Concentrations, 0800 CST, November 8, 1969. .	48
4.15.	Observed SO ₂ Concentrations, 1800 CST, November 8, 1969. .	48
4.16.	Observed SO ₂ Concentrations, 0800 CST, November 9, 1969. .	48
4.17.	Observed SO ₂ Concentrations, 1800 CST, November 9, 1969. .	49
4.18.	Observed SO ₂ Concentrations, 0800 CST, November 10, 1969. .	49
4.19.	Observed SO ₂ Concentrations, 1800 CST, November 10, 1969. .	49
4.20.	Observed SO ₂ Concentrations, 0800 CST, November 11, 1969. .	49
4.21.	Observed SO ₂ Concentrations, 1200 CST, November 11, 1969. .	49
4.22.	Average SO ₂ Concentrations Predicted by Model for 24-hr. Intervals	53
4.23.	Average SO ₂ Concentrations Predicted on November 5, 1969 .	55
4.24.	Average SO ₂ Concentrations Predicted on November 6, 1969. .	56
4.25.	Average SO ₂ Concentrations Predicted on November 7, 1969. .	57
4.26.	Average SO ₂ Concentrations with Strategy, Predicted by Model for 24-hr Intervals	59

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.1.	National Ambient Air Quality Standards for SO ₂	12
1.2.	Watch, Alert, and Emergency Levels for SO ₂	12
2.1.	Comparison of Calculations and Observations for Winter 1967	15
2.2.	Frequency of SO ₂ Levels Exceeding 0.30 ppm for TAM Stations 1-5 for 6-hr Periods during Winter 1967	16
2.3.	Frequency of SO ₂ Levels Exceeding 0.30 ppm for TAM Stations 1-5 for 24-hr Periods during Winter 1967	16
2.4.	Summary of Ability of Puff-model Calculations to Predict Episodes	16
3.1.	Comparison of Calculations with Observations for 36-hr Period, February 25-26, 1967	25
3.2.	Frequency of SO ₂ Levels Exceeding 0.30 ppm at TAM Stations 1-5 for 6-hr Intervals during 36-hr Period, February 25-26, 1967.	25
3.3.	Average Emission of SO ₂ per Hour	27
3.4.	SO ₂ Concentration from the Model	33
3.5.	Average Emissions of SO ₂ per Hour with Strategy	37
3.6.	SO ₂ Concentration with Strategy	37
3.7.	Effect of the Strategy on the Locations with 4-hr-average SO ₂ Calculated Concentration ≥ 0.50 ppm	38
4.1.	Average Daily Ventilation Rate	46
4.2.	Commonwealth Edison Gas Conversion	50
4.3.	Comparison of TAM-observed SO ₂ Concentrations with Calculation at Nearest Grid Point Over a Six-day Period	51
4.4.	Average Daily Calculated SO ₂ Concentration at Grid Point Nearest to TAM Stations.	51
4.5.	Average Daily Observed SO ₂ Concentration at TAM Stations	51
4.6.	Frequency of Daily SO ₂ Levels ≥ 0.10 ppm at TAM Stations 1, 2, 4, and 5 for November 5-10, 1969	52
4.7.	Daily Average Calculated SO ₂ Concentrations	58
4.8.	Daily Average Calculated SO ₂ Concentrations for 64 Worst Points	58

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
4.9.	Daily Average Calculated SO ₂ Concentrations with Strategy	60
4.10.	Daily Average Calculated SO ₂ Concentration for 64 Worst Points with Strategy	60
4.11.	Four-hour Average Calculated SO ₂ Concentrations for Three Points ≥ 0.50 ppm	61

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ABSTRACT

Episode-control programs have been developed to reduce the hazard to the public from possible air-pollution episodes in major urban regions of the United States. Strategies employ staged reductions in emissions from power plants, industrial sources, and residential and commercial heating facilities. This report investigates the potential effectiveness of a selected control strategy.

The Argonne air-pollution dispersion model was used to simulate historical episodes that occurred during February 1967 and November 1969 in the Chicago region. Hourly sulfur dioxide concentrations were calculated from the regional emission inventory and from measured and derived meteorological parameters. These are compared statistically with concentrations measured by the Chicago air-monitoring system.

Concentrations are also calculated on a 66-point 2-mile-square grid over the city of Chicago. These calculations are repeated with the source SO_2 emissions reduced so as to give an idealized simulation of the strategy now specified in the State of Illinois episode-control regulations. In the idealized strategy, power-plant emissions are reduced to zero, industrial emissions are reduced by 50%, and residential and commercial emissions are reduced by 10%.

The results show that the strategy proved generally effective in reducing the highest concentrations to below the Alert criteria, except for those hours when atmospheric ventilation was so low that residential and commercial emissions alone caused excessive concentrations.

1. INTRODUCTION

Air-pollution episodes occur when the volume of air in which pollutants are mixed and diluted by nature is reduced so that unusually high concentrations are observed. These concentrations may reach levels that are hazardous to human health. Episode situations arise in large metropolitan areas where and when emission of pollutants is high. They are characterized by the presence of an atmospheric inversion, which prevents diffusion through vertical mixing, and by a low horizontal wind speed, which decreases the amount of air mixed with the pollutants at the time of emission.

The city of Chicago has continuously monitored sulfur dioxide levels at eight Telemetered Air Monitoring (TAM) stations since 1966 (see the starred locations in Fig. 1.1), and thus a data base exists for studies of episodes. The Argonne Integrated-puff Model¹⁻³ was developed at Argonne National Laboratory. This model can predict the concentrations resulting from the known Chicago emission inventory and from any given meteorological data. In this model, pollutants from time-dependent sources are transported and dispersed in a time-dependent wind, thereby allowing the simulation of the transient situations that characterize episodes. An alternative Steady-state Plume Model, which uses less computation time, was also developed.⁴

In recognition of the dangers of high concentrations over short periods, the National Ambient Air Quality Standards⁵ for SO₂ include both 3- and 24-hr levels as shown in Table 1.1. With the objective of meeting these standards, the Illinois Implementation Plan⁶ uses a four-level strategy for dealing with episodes. The threshold levels for these stages are shown in Table 1.2.

This report consists of a simulation study of two historical episodes. The first covers 32 hr during February 25-26, 1967. The second covers 6½ days during November 5-11, 1969. The best hourly estimates obtainable for the meteorological conditions and SO₂ emissions for these specific dates are used as input to the calculations. Emissions are adjusted to simulate shift operation for industrial sources. Residential and commercial emissions from space-heating systems are corrected for ambient temperatures and for day or night demand. Power-plant emissions are based on operating records of the Commonwealth Edison Co.

The model calculations are first compared with the data from the Chicago monitoring network. Then new model calculations are made by changing the emissions to simulate the effect of the episode control strategy called for by the State of Illinois regulations. A comparison between the calculations, both with and without the control strategy, gives a measure of effectiveness of such a strategy at a number of times and locations.

Fig. 1.1. Chicago Map of Major Sources Showing Location of Eight Telemetered Air Monitoring (TAM) Stations. ANL Neg. No. 112-8979 Rev. 3.

TABLE 1.1. National Ambient Air Quality Standards for SO₂^a

	Primary Standard	Secondary Standard
Annual mean	0.03 ppm Arithmetic	0.02 ppm Arithmetic
Maximum concentration not to be exceeded more than once per year	0.14 ppm, 24 hr	0.10 ppm, 24 hr 0.50 ppm, 3 hr

^aFederal Register, Vol. 36, No. 84 (Apr 30, 1971).

TABLE 1.2. Watch, Alert, and Emergency Levels for SO₂^a

Stage	SO ₂ , ppm
Watch	0.30, 2-hr average or air-stagnation advisory
Yellow Alert	0.30, 4-hr average and Watch in effect for 4 hr
Red Alert	0.35, 4-hr average and Yellow Alert in effect for 4 hr
Emergency	0.40, 4-hr average and Red Alert in effect for 12 hr

^aVolume I, State of Illinois Air Pollution Implementation Plan.

Section 2 briefly discusses the Integrated-puff and Steady-state Plume Models used to generate the calculated concentrations. The February 25-26, 1967, episode is discussed in Sec. 3, and the November 5-11, 1969, episode is discussed in Sec. 4. The summary and conclusions are presented in Sec. 5.

2. ARGONNE INTEGRATED-PUFF AND STEADY-STATE PLUME MODELS

Only a brief discussion will be given here; detailed description of the Argonne Integrated-puff Model may be found in Refs. 1-3. The pollutant concentration from each individual source is calculated at any receptor location, given the hourly emissions and atmospheric parameters. The observed pollutant concentrations are not used. The concentration at receptor point x, y, z at time t due to a source with an emission per unit time at time t' of $Q(t')$ is given by

$$\chi(x, y, z, t) = \int_{t_0}^t dt' Q(t') G(x, y, z, t - t'), \quad (1)$$

where x, y , and z are the relative coordinates of source and receptor, t_0 is the time at which emissions began, and $G(x, y, z, t - t')$ is the Gaussian-puff kernel that describes the transport and diffusion of the pollutant between source and receptor:

$$G(x, y, z, t - t') = \frac{\exp\left(-\left\{\frac{[x - u(t - t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} - \frac{0.693(t - t')}{T_{1/2}}\right\}\right)}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \quad (2)$$

The x axis is chosen along the wind direction. The wind is assumed to be uniform with speed u . $T_{1/2}$ is the half-life of the pollutant. The dispersion coefficients σ_x , σ_y , and σ_z are functions of time and atmospheric stability. Sources are characterized by an effective stack height that includes the plume rise effects.

For the Steady-state Plume Model,⁴ the expression of Eq. 1 for the concentration is replaced by

$$\chi(y, z) = \frac{Q \exp\left[-\left(y^2/2\sigma_y^2 + z^2/2\sigma_z^2\right)\right]}{2\pi u \sigma_y \sigma_z}, \quad (3)$$

where y and z are transverse to the wind direction and z is vertical. This expression is valid if steady-state conditions exist, as expressed either by the transit time of the pollutant being much less than the time interval between emission and observation, or by unchanging emissions and meteorological conditions. This situation is frequently approximated by nearby sources and by those distant sources with a steady emission rate during a period of relatively unchanging meteorological conditions.

Calculations are done hourly, using piecewise constant values appropriate for each hour. For the February 25-26, 1967, calculations, hourly estimates are made for the mixing height using radiosonde data from Peoria, Illinois, and Green Bay, Wisconsin, at 0600 and 1800, and

interpolations are made in both space and time using Chicago hourly surface-temperature values.^{7,8} The spatial interpolations are necessary because no soundings were taken in Chicago before 1969. For the November 1969 calculations, radiosonde data were acquired twice daily at Midway Airport in Chicago.

The emissions are characterized by point sources that include power plants, large industries, and residential/commercial sources; and by area sources that group together the numerous smaller sources composed of industrial, low-rise residential/commercial, and high-rise residential/commercial varieties. Hourly power-plant emissions are calculated from the actual hourly megawatt load data from each Commonwealth Edison plant. Algorithms have been developed to simulate the seasonal and diurnal variations of the industrial and residential/commercial sources and to produce SO₂ emissions on an hourly basis.

A study has also been made that compares the predictions of the model with measurements made at five TAM stations.⁹ A detailed study of the model sensitivity^{4,10} to the various assumptions and to meteorological parameters used includes some recommendations likely to bring improvements. Some of the results of the first study are shown in Tables 2.1-2.3 for December 1966, January 1967, and February 1967. The variables tabulated in Table 2.1 are:

μ_{obs} = observed concentration averaged over the period,

μ_{calc} = calculated concentration averaged over the period,

and

σ_{rms} = root-mean-square deviation of hourly observed and calculated concentrations.

The columns for μ_{obs} and μ_{calc} indicate that average winter concentrations at individual points are predicted to within about 10% of the observed values. Averages over the month of February are somewhat less in agreement with observations. The relatively large size for the ratio $\sigma_{\text{rms}}/\mu_{\text{obs}}$, shown in the last column, suggests that detailed simulation at a given point on a time scale as short as 6 or 24 hr is difficult.

Another comparison, of relevance to episodes, was the comparison of levels exceeding 0.30 ppm in both the calculations and the observed data. Tables 2.2 and 2.3 show these results for 6- and 24-hr averages, respectively, for TAM stations 1-5 during winter 1967. The results, summarized in Table 2.4, imply that if the model predicts high levels to be present at a given location, it is rather likely to be correct. It is somewhat less consistent in its ability to predict all the high levels that do occur.

TABLE 2.1. Comparison of Calculations and Observations for Winter 1967

TAMS	Month/Season	Period, hr	μ_{obs} , ppm	μ_{calc} , ppm	$\sigma_{\text{rms}}/\mu_{\text{obs}}$
1-5	December 1966	1	0.13	0.15	1.2
		6			1.0
		24			0.6
1-5	January 1967	1	0.12	0.11	0.8
		6			0.6
		24			0.4
1-5	February 1967	1	0.16	0.12	0.9
		6			0.7
		24			0.5
1-5	Winter	1	0.14	0.13	1.0
		6			0.8
		24			0.5
1	Winter	1	0.03	0.03	1.7
		6			1.3
		24			0.9
2	Winter	1	0.12	0.10	0.8
		6			0.6
		24			0.4
3	Winter	1	0.34	0.31	0.8
		6			0.6
		24			0.4
4	Winter	1	0.17	0.16	0.8
		6			0.7
		24			0.5
5	Winter	1	0.07	0.07	1.1
		6			0.8
		24			0.5
1	February 1967	1	0.04	0.03	1.3
		6			1.0
		24			0.6
2	February 1967	1	0.15	0.11	0.6
		6			0.5
		24			0.4
3	February 1967	1	0.35	0.30	0.6
		6			0.5
		24			0.3
4	February 1967	1	0.25	0.15	0.6
		6			0.5
		24			0.5
5	February 1967	1	0.09	0.09	1.0
		6			0.8
		24			0.6

TABLE 2.2. Frequency of SO₂ Levels
Exceeding 0.30 ppm for TAM Sta-
tions 1-5 for 6-hr Periods during
Winter 1967

	Occur	Predict
42	Yes	No
109	Yes	Yes
1222	No	No
21	No	Yes

TABLE 2.3. Frequency of SO₂ Levels
Exceeding 0.30 ppm for TAM Sta-
tions 1-5 for 24-hr Periods during
Winter 1967

	Occur	Predict
11	Yes	No
30	Yes	Yes
301	No	No
4	No	Yes

TABLE 2.4. Summary of Ability of Puff-model
Calculations to Predict Episodes

Predicted 6-hr episodes observed	84%
Observed 6-hr episodes predicted	72%
Predicted 24-hr episodes observed	88%
Observed 24-hr episodes predicted	73%

3. FEBRUARY 25-26, 1967, EPISODE

Figures 3.1 and 3.2 show the surface weather maps at 0000 CST for Saturday, February 25, and Sunday, February 26, 1967. The 500-mbar contours (not shown) at 1800 on February 25 give an upper-level, 60-mph northwest wind. The period was characterized by the passage of a continental arctic high through the region. This resulted in conditions with sub-zero temperatures, which would have contributed to greater-than-normal SO_2 emissions, a clear sky, which is conducive to a nocturnal radiation inversion, and a weak pressure gradient, resulting in light winds. Figures 3.3-3.5 are time-series plots of temperature, wind speed, and wind direction at Midway Airport (location shown in Fig. 1.1). The anticyclonic clockwise wind pattern caused the wind direction to change from northwest to west to south as the center of the high moved through the area on February 25. The light wind speeds reached a low value of about 4 mph near 0000 on February 26, 1967. The change from a northwest wind to a south wind is also accompanied by a rise in the temperature curve for February 26, relative to that of February 25. Figure 3.6 shows the temperatures recorded at Meigs Field (location shown in Fig. 1.1). These are generally 1-3° higher than the Midway values. Figure 3.7 shows an estimated atmospheric-stability index on a scale of 1 to 5, where 4 corresponds to neutral stability and 5 is stable. The mixing height, shown in Fig. 3.8, is estimated from the Peoria and Green Bay soundings, as described in Sec. 2. This prediction gives a mixing height of a few hundred feet at night and shows a lifting to about 2000 ft during the daytime on February 25.

The distribution of sources (see Fig. 3.9) shows large yearly averaged emissions along the southwest-northeast column adjacent to the Chicago Ship and Sanitary Canal, consisting of three power plants and some other industrial emissions. More large sources within this corridor, outside the city limits (not shown), may also contribute. The other largest sources are seen to be located in the downtown Loop area. With the exception of the previously mentioned corridor and the Calumet River area, sources are more widely separated and source strengths are generally smaller with increasing distance from the downtown Chicago Loop area.

Figures 3.10-3.19 show some hourly observations recorded at the eight TAM stations. The SO_2 concentrations are shown in large print. The arrows give the wind direction, and the numbers near each arrow give the wind speed in miles per hour. In general, the largest SO_2 concentrations appear to be downwind of the major sources, as would be expected.

It should be mentioned that SO_2 levels were already high at TAM 3 and 4 on February 24, 1967. In fact, Table 2.1 shows that the average levels at both TAM 3 and 4 over the February 1967 period were very high. The TAM 3 average over the three winter months of 1967 nearly equaled today's present Red Alert level. One reason for isolating February 25-26, 1967, as a special situation lies in the fact that high levels were simultaneously observed at four TAM stations (TAM 2, 3, 4, and 7), and therefore the

Fig. 3.1. Surface Weather Map at 0000 CST, February 25, 1967

Fig. 3.2, Surface Weather Map at 0000 CST, February 26, 1967

Fig. 3.3 Midway Temperature

Fig. 3.4, Midway Wind Speed

Fig. 3.5. Midway Wind Direction

Fig. 3.6, Meigs Temperature. (Early-morning data not available.)

Fig. 3.7. Stability Index

Fig. 3.8. Estimated Mixing Height

Fig. 3.9. Chicago Map of SO₂ Sources. ANL Neg. No. 112-9133 Rev. 1.

Fig. 3.10

Observed SO_2 Concentrations (ppm), 0200 CST, February 25, 1967

Fig. 3.11

Observed SO_2 Concentrations (ppm), 0600 CST, February 25, 1967

Fig. 3.12

Observed SO_2 Concentrations (ppm), 1000 CST, February 25, 1967

Fig. 3.13

Observed SO_2 Concentrations (ppm), 1400 CST, February 25, 1967

Fig. 3.14

Observed SO_2 Concentrations (ppm), 1800 CST, February 25, 1967

Fig. 3.15

Observed SO_2 Concentrations (ppm), 2200 CST, February 25, 1967

Fig. 3.16

Observed SO₂ Concentrations
(ppm), 0200 CST, February 26,
1987

Fig. 3.17

Observed SO₂ Concentrations
(ppm), 0600 CST, February 26,
1967

Fig. 3.18

Observed SO₂ Concentrations
(ppm), 1000 CST, February 26,
1967

Fig. 3.19

Observed SO₂ Concentrations
(ppm), 1400 CST, February 26,
1967

short-term area coverage of these high levels appears to be a significant increase over the average. During these two days, the present 3-hr SO₂ standard of 0.50 ppm was exceeded at both TAM 3 and 4, and the 24-hr primary standard of 0.14 ppm was exceeded at TAM 2, 3, 4, and 7.

In general, the weather conditions do not appear atypical of other episode situations in this area.¹¹ The total impact of an episode upon human health presumably involves a detailed correlation of the air-quality distribution at each hour with the population distribution, taking into account the biological effects of the pollutant, a task for which insufficient knowledge is presently available.

3.1 Comparison of Calculated and Observed Concentrations for February 25-26, 1967

Puff-model concentrations were evaluated at TAM stations 1-5, where each calculation assumes a uniform wind speed and direction over the city given by the measured wind at that TAM location. The hourly mixing height and stability values shown in Figs. 3.7 and 3.8 were used. The calculation begins at 0000 on Saturday, February 25, and extends until 1200 on Sunday, February 26, 1967. Figures 3.20-3.24 show the calculated

Fig. 3.20. Calculated and Observed SO_2 Concentrations (ppm) at TAM 1

Fig. 3.21. Calculated and Observed SO_2 Concentrations (ppm) at TAM 2. (No data available for February 26, 1967.)

Fig. 3.22
Calculated and Observed SO_2 Concentrations (ppm) at TAM 3

Fig. 3.23. Calculated and Observed SO_2 Concentrations (ppm) at TAM 4

Fig. 3.24. Calculated and Observed SO_2 Concentrations (ppm) at TAM 5

and observed SO₂ concentrations as a function of time. Table 3.1 shows the 36-hr observed and calculated average values at the five individual TAM locations and the average including all stations. Comparisons for TAM 2 were made only over the first 24 hr due to a lack of observations on February 26, 1967. The high value of these concentrations by comparison to the 24-hr primary standard of 0.14 ppm can be seen at TAM 3 and 4. In general, the differences observed are about the same as those for February 1967 shown in Table 2.1. The difference in these calculated and observed averages for TAM 1-5 is even slightly less than the corresponding monthly difference. The ratio of hourly root-mean-square deviations to the observed 36-hr averages in column 3 compares roughly with the 24-hr numbers in Table 2.1 for the entire month. At least as far as all these numbers are concerned, the model is as successful during this 36-hr period as it is during the entire month.

TABLE 3.1. Comparison of Calculations with Observations for 36-hr Period, February 25-26, 1967

Station	μ_{obs} , ppm	μ_{calc} , ppm	$\sigma_{\text{rms}}/\mu_{\text{obs}}$	$\frac{\mu_{\text{calc}} - \mu_{\text{obs}}}{\mu_{\text{obs}}} \times 100\%$
1	0.05	0.02	1.18	-60%
2	0.12	0.10	0.34	-17%
3	0.47	0.48	0.60	+2%
4	0.36	0.27	0.40	-25%
5	0.07	0.12	1.60	+71%
1-5	0.22	0.19	0.61	-14%

The last column of Table 3.1 shows the percent deviation of the 36-hr average calculations from the observations. The deviations for the two stations recording high average levels (TAM 3 and 4) are +2 and -25%. Although two of the three remaining stations have high percent deviations, the absolute differences are low. (The worst case is TAM 5, with a deviation of 0.05 ppm.) The same comment can, of course, apply for the hourly root-

mean-square deviations in column 3.

TABLE 3.2. Frequency of SO₂ Levels Exceeding 0.30 ppm at TAM Stations 1-5 for 6-hr Intervals during 36-hr Period, February 25-26, 1967

	Occur	Predict
5	Yes	No
6	Yes	Yes
17	No	No
0	No	Yes

Table 3.2 shows the frequency of correct and incorrect predictions for exceeding a threshold of 0.30 ppm for 6-hr intervals and may be compared with the results for winter 1967 as shown in Table 2.2.

The question arises whether the simulation of this episode is accurate enough to correctly evaluate the effectiveness of an episode strategy. To examine this, we com-

pare the deviations discussed above with the contributions from the sources that the strategy will affect. The model predictions for 32-hr average

concentrations over 66 grid locations from power plants, industry, and residential/commercial sources are 18, 21, and 61%, respectively. For each receptor location during those hours when concentrations greater than or equal to 0.30 ppm were observed, the average percentage contributions are 26, 23, and 51%, respectively.

An evaluation of the effectiveness of the strategy for this real episode should presumably require an accuracy in the predicted concentrations of at least the amount of the power-plant or industrial contributions, since the strategy will primarily affect these sources. It would not appear that such accuracy has been demonstrated for the short-term averages. However, the sensitivity of the model to details of the meteorological parameters has been well documented, and our present crude estimates of these parameters will surely prevent the detailed agreement that is ideally desired. The need for better meteorological data during an episode is also clear from other studies.¹¹

Nevertheless, it is our objective to determine the potential effectiveness of an episode-control plan through modeling its performance. Therefore, it is assumed that these calculations are representative of a hypothetical episode for which the meteorological conditions are exactly those we have input to the puff model. Insofar as the calculation has successfully approximated the trends of the real episode, we have some confidence that conclusions deduced from the model will also apply to real episodes arising from similar meteorological situations.

3.2 Calculated Concentrations for February 25-26, 1967

The puff-model calculations on a 66-point grid were made for a 32-hr period beginning at 0400 on February 25 and ending at 1200 on February 26. Power plants, industries, and residential/commercial sources within the city are included, as well as large industrial and power-plant sources outside the city limits.

The actual stack heights are used for point sources, but for the area sources the stack heights used represent average values of 100, 200, and 150 ft for the low-rise residential/commercial, high-rise residential/commercial, and industrial sources, respectively.

Table 3.3 shows the average total emissions per hour during the period for power plants, industrial, and residential/commercial sources. The emissions are seen to be dominated by the industrial sources and power plants. Figure 3.25 shows the emission distribution as a function of time for the 36-hr period beginning at 0000 on February 25. The emissions from two 1-mi² areas are shown in Fig. 3.26. These areas (#206 and #1604 shown on the map in Fig. 3.27) represent the Chicago Loop region and the Hyde Park region.

TABLE 3.3. Average Emission of SO_2 per Hour

	SO_2 , 10^5 lb/hr	Percentage
Power plants	0.80	37
Industries	1.15	53
Residential/Commercial	0.21	10
Total	2.16	100

Fig. 3.25

Hourly Emissions from Power Plants, Industries, and Residential/Commercial Sources

Fig. 3.26
Hourly Emissions from Loop (#206)
and Hyde Park (#1604)

Fig. 3.27. Sixty-six-point Receptor Grid. The 2-mile-square grid is shown as 11 horizontal lines, each consisting of six grid points. The grid numbering referred to in the text begins with number 1 in the northwest corner and increases from west to east, continuing from west to east on the next horizontal level until point 66 is reached in the southeast corner. ANL, Neg. No. 112-8979 Rev. 4.

The individual power-plant emissions are shown in Fig. 3.28 for the six power plants inside the city limits. The Roman numerals and

Fig. 3.28. Hourly Power-plant Emissions

Fig. 3.27 can be used to identify the plant locations. The largest emissions arise from the State Line plant (VI), but because of its location in the southeast sector and because of the wind direction for this period, its emissions do not strongly affect SO₂ levels over the city. The Crawford (III) and Ridgeland (IV) plants, with the next largest emissions, are in a much more unfavorable location, since they are both generally upwind of some part of the city.

The observed ground-level concentrations, however, will be expected to be influenced less by the power-plant and industrial emissions, since the stack heights for these sources are considerably higher than the residential and commercial stack heights. High stacks produce more dispersion

by the time emissions reach the ground. Depending on location and wind direction, they may reach ground level out in Lake Michigan or beyond heavily populated areas.

The puff-model concentrations were generated at 66 points on a grid as shown by the circles in Fig. 3.27. The hourly wind speed and direction were assumed to be uniform over the city and to have hourly values as measured at TAM 4. The resulting concentrations at a 75-ft height are displayed in the form of contour plots in Figs. 3.29-3.33.

The 32-hr average, displayed in Fig. 3.29, shows that the 0.10- and 0.20-ppm levels are exceeded over a large area of the city. Concentrations above 0.30 ppm are observed at the Loop and at Hyde Park. The highest 32-hr average value in the city is 0.37 ppm and occurs in the Loop. The worst Hyde Park receptor has a value of 0.31 ppm.

Figures 3.30-3.32 show the contributions to the 32-hr averages from power-plant, industrial, and residential/commercial sources, respectively.

Figure 3.33 shows the average concentration for eight 4-hr periods during the episodes beginning at 0400 on February 25 and ending at 1200 on

Fig. 3.29. Average SO₂ Concentration (ppm) over 32 hr from the Model

Fig. 3.30. Average Power-plant Contribution to SO₂ Concentration (ppm) over 32 hr from the Model

Fig. 3.31. Average Industrial Contribution to SO₂ Concentration (ppm) over 32 hr from the Model

Fig. 3.32. Average Residential/Commercial Contribution to SO₂ Concentration (ppm) over 32 hr from the Model

a. 0400-0800, February 25, 1967

b. 0800-1200, February 25, 1967

c. 1200-1600, February 25, 1967

d. 1600-2000, February 25, 1967

Fig. 3.33. SO₂ Concentrations (ppm) Predicted by the Model for 4-hr Intervals

e. 2000-2400, February 25, 1967

f. 0000-0400, February 26, 1967

g. 0400-0800, February 26, 1967

h. 0800-1200, February 26, 1967

Fig. 3.33 (Contd.)

February 26. The 0400-0800 period (Fig. 3.33a) shows concentrations that exceed 0.30 ppm at the Loop and at Hyde Park. The location with the highest concentration of 0.46 ppm is in Hyde Park. Power-plant, industrial, and residential/commercial sources contribute 0.12, 0.05, and 0.29 ppm, respectively. The high Loop concentration of 0.31 ppm results from 0.00, 0.11, 0.20 ppm due to power-plant, industrial, and residential/commercial sources. The next period, from 0800 to 1200 (Fig. 3.33b), brings a concentration of 0.38 ppm into the west side, which comes entirely from the power plants. The contributions of other sources amount to less than 0.01 ppm.

Concentrations at Hyde Park and the Loop are lower than for the previous 4-hr period. The rising mixing height (Fig. 3.8) presumably will contribute to this. The largest reading of 0.41 ppm is in Hyde Park. The rising lid height reduces concentrations still further, as can be seen for the 1200-1600 period in Fig. 3.33c. During the 1600-2000 interval (Fig. 3.33d), the wind speed has shifted more to the west at TAM 4 and the lid height has dropped. A location in the Loop has a concentration of 0.31 ppm, this time dominated by the power plants with a contribution of 0.20 ppm.

The next three intervals, covering the period from 2000 on February 25 to 0800 on February 26, are shown in Figs. 3.33e-g. The low lid heights and wind speed during this period create a situation with very poor ventilation, as indicated by the extent of the 0.30-ppm contour. During the night, concentrations higher than 0.60 ppm are present at several locations. The 0800-1200 period on February 26 is shown in Fig. 3.33h. The 0.30-ppm contour has been pushed north by the south wind, which has by now increased to about 10 mph. The episode diminishes in the next 4-hr time period (not shown) as the wind speed increases further.

Table 3.4 summarizes the concentrations from the 66 grid points and the eight 4-hr intervals. The residential/commercial sources were responsible for 61% of the SO_2 concentration; power plants and industries contributed 18 and 21%, respectively. This is in contrast to the relative emissions as shown in Table 3.3, where the residential/commercial contribution was only 10%. The relative power-plant and industrial percentages for the points with concentrations greater than 0.30 ppm, as seen in the last

TABLE 3.4. SO_2 Concentration (in ppm) from the Model

	Average Concentration for All Points	% Concentration for All Points	Average Concentration of 63 Points ≥ 0.30 ppm	% Concentration of 63 Points ≥ 0.30 ppm
Power plants	0.02	18	0.10	26
Industry	0.02	21	0.09	23
Residential/Commercial	0.07	61	0.20	51
Total	0.12	100	0.39	100

column of Table 3.4, are larger. This result is expected if the residential/commercial sources are thought of as providing a smoothly varying concentration over the city and the large-point-source power plants and industries add a contribution along the instantaneous wind direction, which will add to the already existing concentration.

3.3 Calculated Effect of a Strategy upon the February 25-26, 1967, Episode

We now investigate the consequences of imposing an idealized first-stage or Yellow Alert strategy, which reduces power-plant emissions to zero (in practice accomplished by fuel or load switching), industrial emissions by 50%, and residential/commercial emissions by 10%.

Fig. 3.34. Average SO₂ Concentration (ppm)
Predicted over 32 hr with Strategy

Figure 3.34 shows that the contour plot for the same 32-hr period under the idealized episode control contains no regions with concentration greater than 0.30 ppm. The largest 32-hr average concentration in the Loop is now 0.24 ppm. As is suggested by Fig. 3.34, a 24-hr average still gives violations of both the 0.10-ppm secondary standard and the 0.14-ppm primary standard,⁵ even with the strategy in effect.

Figure 3.35 shows the contour plots for the eight 4-hr periods with the strategy in effect. A comparison of Figs. 3.33 and 3.35 shows a reduction for all cases. However, for the three periods covering 2000 on February 25 to 0800 on February 26, the strategy is unsuccessful at preventing the occurrence of concentrations greater than 0.30 ppm, and on February 26 from 0400 to 0800 (Fig. 3.35g) the 0.40-ppm level is exceeded, which is more than sufficient to cause initiation of a Red Alert. For these hours, the ventilation is so poor that the residential/commercial concentration itself exceeds the 0.30-ppm level at many points. Thus for these hours, peak shaving of the large point sources, while reducing the concentration at the worst points, does not give much leverage in affecting the overall total concentrations. Table 3.5 gives the average hourly emissions with the strategy and may be compared to Table 3.3 for emissions without the strategy. The total emissions affecting the city are reduced from 2.16×10^5 to 0.76×10^5 lb/hr of SO₂, a reduction of 65%. Table 3.6 shows the effect of the strategy upon the overall air quality. The average concentration over the same hours and over all grid points was reduced

and on February 26 from 0400 to 0800 (Fig. 3.35g) the 0.40-ppm level is exceeded, which is more than sufficient to cause initiation of a Red Alert. For these hours, the ventilation is so poor that the residential/commercial concentration itself exceeds the 0.30-ppm level at many points. Thus for these hours, peak shaving of the large point sources, while reducing the concentration at the worst points, does not give much leverage in affecting the overall total concentrations. Table 3.5 gives the average hourly emissions with the strategy and may be compared to Table 3.3 for emissions without the strategy. The total emissions affecting the city are reduced from 2.16×10^5 to 0.76×10^5 lb/hr of SO₂, a reduction of 65%. Table 3.6 shows the effect of the strategy upon the overall air quality. The average concentration over the same hours and over all grid points was reduced

a. 0400-0800, February 25, 1967

b. 0800-1200, February 25, 1967

c. 1200-1600, February 25, 1967

d. 1600-2000, February 25, 1967

Fig. 3.35. SO_2 Concentrations (ppm) Predicted with the Strategy for 4-hr Intervals

e. 2000-2400, February 25, 1967

f. 0000-0400, February 26, 1967

g. 0400-0800, February 26, 1967

h. 0800-1200, February 26, 1967

Fig. 3.35 (Contd.)

TABLE 3.5. Average Emissions of SO₂ per Hour with Strategy

	SO ₂ , 10 ⁵ lb/hr	Percentage
Power plants	0.00	0
Industries	0.57	75
Residential/Commercial	0.19	25
Total	0.76	100

TABLE 3.6. SO₂ Concentration (in ppm) with Strategy

	Average Concentration for All Points	% Concentration for All Points	Average Concentration for 63 High Points	% Concentration for 63 High Points
Power plants	0.000	0	0.00	0
Industry	0.01	16	0.05	22
Residential/Commercial	0.07	84	0.18	78
Total	0.08	100	0.23	100

from 0.12 to 0.08 ppm, a reduction of 33%. This nonlinear relationship between emissions and concentrations results from stack-height differences, which couple the residential/commercial sources more strongly to the ground-level air quality, and also from the detailed distribution of the different classes of sources relative to the wind direction. Thus an east wind, for example, might give different couplings of emission to average ground-level concentrations than exist during the present episode.

Table 3.6 also shows the effect of the strategy on the 63 points that previously had concentrations exceeding 0.30 ppm. The average concentration for these points drops from 0.39 to 0.23 ppm. The larger drop here, relative to the overall average of 33%, is a consequence of the fact that, without the strategy, the power-plant and industrial sources, which the strategy strongly affected, contributed more at these points. Of these 63 points, 46 were reduced to a level below 0.30 ppm by the strategy. Of the remaining 14 points still above 0.30 ppm, 14 occurred during the period of 0400-0800, Sunday, February 26, when the ventilation was very poor.

The calculations without strategy give eight occurrences for which a 4-hr average at some grid location exceeds 0.50 ppm. Table 3.7 shows the effect of the strategy on these points. The locations may be found with the help of the grid-location numbers and Fig. 3.27, using the coordinate-system definition as given in the Fig. 3.27 caption. Although the strategy is seen to have been effective in reducing all eight concentrations below 0.50 ppm, four cases still give averages in excess of the Red Alert level of 0.35 ppm.

TABLE 3.7. Effect of the Strategy on the Locations with
4-hr-average SO₂ Calculated Concentration ≥ 0.50 ppm

Grid-location Number	Hour	Date, February	Concentration with No Strategy, ppm	Concentration with Strategy, ppm
35	2000-2400	25	0.52	0.18
36	2000-2400	25	0.54	0.19
23	0000-0400	26	0.67	0.38
24	0000-0400	26	0.52	0.24
29	0000-0400	26	0.54	0.21
17	0400-0800	26	0.60	0.38
23	0400-0800	26	0.62	0.40
42	0400-0800	26	0.51	0.45

4. NOVEMBER 5-11, 1969, EPISODE

During early November 1969, an air-pollution episode occurred over Chicago. A previous study has reported upon the air quality and meteorological conditions associated with the period.¹² An increase in the SO₂ concentrations occurred on Wednesday, November 5, with light winds from the southwest. On Thursday, November 6, light winds from the east pushed high concentrations to the western part of the city. Figures 4.1 and 4.2 show the surface and 500-mbar charts for November 5 and 6, during the early and most severe stages. From November 7-11, the high-pressure system over the city continued to give low wind speeds, a variable wind direction, and stagnant vertical mixing conditions.

Figures 4.3 and 4.4 are time-series plots of meteorological variables and some SO₂ concentrations. Concentrations are shown for TAM stations 5 and 7, the least and most polluted stations, respectively. The wind at TAM 7 was frequently less than 5 mph and variable in direction. The average temperature is seen to be about 45°F. The space-heating requirements for this period were therefore expected to be less than for episodes occurring in the winter.

The hourly mixing heights, shown in Fig. 4.5, were estimated by using the two daily soundings at Midway Airport, along with dry-adiabatic curves constructed through the measured hourly surface pressure and temperature values at Midway. Figure 4.6 shows the time-series plot of the ventilation rate, which was calculated by taking the product of the mixing-height estimate and the surface wind speed at TAM 7, and which is a measure of the capacity of the air for dilution of pollutants. A diurnal pattern is generally observed, which corresponds to the lifting and falling of the mixing height. Table 4.1 lists the daily average ventilation rates for November 5-10 and shows a minimum on November 6.

Figures 4.7-4.21 show some hourly observations recorded at the eight TAM stations at intervals throughout the episode. (In some cases, individual readings for certain TAM stations were missing from the data. These could have been due to telemetering errors, noise problems, or equipment malfunctions.) The SO₂ concentrations are shown in large print. The arrows give the wind direction, and the wind speed is shown in miles per hour. These plots reveal the spatial complexity and variability of the wind field associated with the light winds during this period. Lake-breeze effects appear to be present at some hours.¹³ High SO₂ concentrations are seen at some but not all TAM stations.

Fig. 4.1. Weather Map at Surface and at 500 mbar for November 5, 1969. ANL Neg. No. 149-4496.

Fig. 4.2. Weather Map at Surface and at 500 mbar for November 6, 1969. ANL Neg. No. 149-4497.

a. November 1-7, 1969

Fig. 4.3. Time-series Plots of SO₂ Concentrations and Meteorological Variables at TAM 7. ANL Neg. No. 149-4292 Rev. 1.

b. November 8-15, 1969

Fig. 4.3 (Contd.). ANL Neg. No. 149-4293 Rev. 1.

a. November 1-7, 1969

Fig. 4.4. Time-series Plots of SO₂ Concentrations and Meteorological Variables at TAM 7 and 5. ANL Neg. No. 149-4301 Rev. 1.

b. November 8-15, 1969

Fig. 4.4 (Contd.). ANL Neg. No. 149-4300 Rev. 1.

Fig. 4.5. Calculated Mixing Height for November 5-11, 1969

Fig. 4.6. Calculated Ventilation for November 5-11, 1969

TABLE 4.1. Average Daily Ventilation Rate

Date, November	Ventilation Rate, ft x mph
5	4200
6	3310
7	4860
8	4580
9	5370
10	7360

Fig. 4.7

Observed SO₂ Concentrations
(ppm), 0800 CST, November 5, 1969

Fig. 4.8

Observed SO₂ Concentrations
(ppm), 1600 CST, November 5, 1969

Fig. 4.9

Observed SO₂ Concentrations
(ppm), 0900 CST, November 6, 1969

Fig. 4.10

Observed SO₂ Concentrations
(ppm), 1200 CST, November 6, 1969

Fig. 4.11

Observed SO₂ Concentrations
(ppm), 1600 CST, November 6, 1969

Fig. 4.12

Observed SO₂ Concentrations
(ppm), 0900 CST, November
7, 1969

Fig. 4.13

Observed SO₂ Concentrations
(ppm), 1800 CST, November
7, 1969

Fig. 4.14

Observed SO₂ Concentrations
(ppm), 0800 CST, November
8, 1969

Fig. 4.15

Observed SO₂ Concentrations
(ppm), 1800 CST, November
8, 1969

Fig. 4.16

Observed SO₂ Concentrations
(ppm), 0800 CST, November
9, 1969

Fig. 4.17

Observed SO₂ Concentrations
(ppm), 1800 CST, Novem-
ber 9, 1969

Fig. 4.18

Observed SO₂ Concentrations
(ppm), 0800 CST, Novem-
ber 10, 1969

Fig. 4.19

Observed SO₂ Concentrations
(ppm), 1800 CST, Novem-
ber 10, 1969

Fig. 4.20

Observed SO₂ Concentrations
(ppm), 0800 CST, Novem-
ber 11, 1969

Fig. 4.21

Observed SO₂ Concentrations
(ppm), 1200 CST, Novem-
ber 11, 1969

4.1 SO₂ Emissions for November 5-11, 1969

The distribution of SO₂ sources in Chicago was discussed in Sec. 3 and shown in Fig. 3.9. An aspect of importance was the use of natural gas during this autumn episode. About 95% of the dual-fuel users with interruptible-rate contracts and about 15% with off-peak summer contracts were still using natural gas.¹⁴ Furthermore, at various times during the episode, Commonwealth Edison responded by voluntarily switching some units from coal to natural gas, in order to reduce SO₂ emissions.¹⁵ The natural-gas switchover is displayed in Table 4.2. Also, some of the load was transferred away from the six Chicago-based power plants to units outside the Chicago area. Thus the utility company voluntarily used available means during the episode to reduce SO₂ emissions within the densely populated regions.

TABLE 4.2. Commonwealth Edison Gas Conversion^a

Time Interval	Power Unit Converted
1530, November 6, to 1200, November 7	State Line (VI) #4 Crawford (III) Fisk (II)
0900, November 10, to 1900, November 10	Fisk (II) #19
0845, November 11, to 1600, November 11	Crawford (III)

^aTime intervals during which power-generating stations switched fuel from coal to natural gas.

4.2 Comparison of Calculated and Observed Concentrations for November 5-11, 1969

The puff and plume models were used, along with available information on emissions and meteorology, to simulate as closely as possible the period from 0000 on November 5 to 1200 on November 11. The SO₂ hourly concentrations due to power-plant emissions were calculated from the Integrated-puff Model. The actual hourly power load at each plant and the natural-gas conversion¹⁵ were used as input to determine the SO₂ emission pattern. When natural gas was not used, it was assumed that the fuel was coal with a 3% sulfur content. The industrial and residential/commercial emissions are determined by algorithms as discussed in Sec. 2.

The emissions for the 10 largest industrial SO₂ emitters, which are treated as point sources, were adjusted according to their actual use of natural gas during the episode.¹⁴ Nine out of the 10 were using natural gas. The 42 next largest industrial dual-fuel users with interruptible contracts, which are also treated as point sources, were assumed to be using the maximum fraction of natural gas that their operation allowed. It was assumed

that none of the remaining industrial and residential/commercial coal and oil burners, which are treated as area sources, used natural gas. It was further assumed that the Steady-state Plume description was valid for the area-source industrial and residential emitters.

The hourly mixing heights from the Midway data and hourly wind speeds and directions from TAM 7 were used as input. Since the calculations assume a uniform wind over the city at each hour, the spatial variability that occurs at many hours will not be properly included. The hourly calculations give SO_2 concentrations at a height of 75 ft and at 66 points on a grid as shown in Fig. 3.28. Table 4.3 compares the six-day average SO_2 concentrations observed at four TAM stations and the average calculated value from the nearest grid point. The four TAM stations shown were chosen because they were located close to a grid point and had receptor heights close to 75 ft, thus allowing for a valid comparison with the calculations.

TABLE 4.3. Comparison of TAM-observed SO_2 Concentrations with Calculation at Nearest Grid Point over a Six-day Period

TAM	Distance from Nearest Grid Point, miles	Receptor Height, ft	TAM-observed Average SO_2 , ppm	Grid-point Calculated SO_2 , ppm	Root-mean-square Deviation of Daily SO_2 Values, ppm
1	0.2	60	0.06	0.02	0.02
2	0.1	80	0.07	0.11	0.02
4 ^a	0.1	70	0.08	0.09	0.02
5	0.4	75	0.06	0.08	0.02

^aThe TAM 4 average is taken over 5 days.

Tables 4.4 and 4.5 show the data from which the averages in Table 4.3 were calculated. Table 4.6 shows the frequency of correct and incorrect predictions for daily concentrations ≥ 0.10 ppm at the four TAM stations. Three of the six predicted high daily levels were observed to occur. The

TABLE 4.4. Average Daily Calculated SO_2 Concentration at Grid Point Nearest to TAM Stations

TAM	Nov 5	Nov 6	Nov 7	Nov 8	Nov 9	Nov 10
1	0.01	0.04	0.01	0.03	0.00	0.02
2	0.20	0.13	0.09	0.09	0.06	0.09
4	0.13	0.12	0.08	0.09	0.09	0.04
5	0.06	0.09	0.11	0.12	0.09	0.01

TABLE 4.5. Average Daily Observed SO_2 Concentration at TAM Stations

TAM	Nov 5	Nov 6	Nov 7	Nov 8	Nov 9	Nov 10
1	0.02	0.15	0.03	0.04	0.01	0.08
2	0.09	0.12	0.05	0.03	0.03	0.10
4	0.11	0.16	-	0.03	0.02	0.06
5	0.04	0.09	0.04	0.06	0.07	0.05

TABLE 4.6. Frequency of Daily SO₂ Levels ≥ 0.10 ppm at TAM Stations 1, 2, 4, and 5 for November 5-10, 1969

	Occur	Predict
2	Yes	No
3	Yes	Yes
14	No	No
3	No	Yes

three high predictions that did not occur corresponded to values of 0.12, 0.20, and 0.11 ppm, compared to observed values of 0.06, 0.09, and 0.04 ppm, respectively.

The question of the accuracy of the simulation of an episode was discussed in Sec. 3.1. Additional complications of this episode arise from the spatial complexity of the wind field, for example, when lake-breeze effects are present, and also from the greater uncertainty in SO₂ emissions, when many dual-fuel sources are using natural gas.

We will again take the point of view that the calculations are representative of a hypothetical episode that has to some degree approximated the real episode in November 1969. We have used the best hourly-emission information at our disposal, especially for the power plants and for the largest industrial sources. We have used radiosonde data at Midway Airport for the mixing-height calculations. We therefore have some confidence that the qualitative conclusions based upon these calculations will be representative of the real episode, except for those considerations that might critically depend upon locally variable winds and lake-breeze effects.

4.3 Calculated Concentrations for November 5-11, 1969, Episode

The hourly calculated concentrations on the 66-point grid, as discussed in Sec. 4.2, were averaged over 24 hr to give the daily average concentrations for November 5-10, shown in Fig. 4.22. Contour lines at concentrations of 0.10, 0.20, and 0.30 ppm are shown. Concentrations greater than the 0.10-ppm standard are observed on all 6 days, and they extend over much of the city on some days. Concentrations exceeding 0.20 ppm are observed on November 5, 6, and 8.

The 0.30-ppm level is exceeded only on November 5. The southwest wind on Wednesday, November 5, pushes the pollutant toward the northeast part of the city (see Fig. 4.22a). Winds on the morning of November 6, the day of lowest average ventilation, are highly variable. In the afternoon and during the following day (November 7), the winds come generally from the east and northeast.

The directional variability of the wind on November 6 may account for some of the widespread distribution and lower peak values (see Fig. 4.22b) than observed on November 5, although some peak shaving may result from the fact that at 1600 on November 6, Commonwealth Edison switched to natural gas at Fisk (II), Crawford (III), and State Line (VI)-Unit 4. Concentrations on Friday, November 7 (see Fig. 4.22c), are observed to be pushed toward the southwest, as would be expected from the predominantly northeast

a. November 5, 1969

b. November 6, 1969

c. November 7, 1969

d. November 8, 1969

Fig. 4.22. Average SO_2 Concentrations (ppm) Predicted by Model for 24-hr Intervals

Fig. 4.22 (Contd.)

wind. Again the directionally variable winds on Saturday, November 8, may give rise to the widespread pollutant distribution observed on Saturday, November 8 (see Fig. 4.22d).

The concentration on Sunday, November 9, when the wind changed from northeast to west to southwest, is shown in Fig. 4.22e. Three patches of concentration greater than 0.10 ppm are observed on Monday, November 10. The two westerly patches are predominantly from the power plants, whereas the downtown (east) location arises mainly from commercial and industrial sources.

Figures 4.23-4.25 show contour plots of 24-hr average SO₂ calculated concentrations due to power plants, industries, and residential/commercial sources separately for November 5-7. Contours at 0.05, 0.10, and 0.15 ppm are indicated. In general, the power-plant (Figs. 4.23a, 4.24a, and 4.25a) and industrial sources (Figs. 4.23b, 4.24b, and 4.25b) appear to be somewhat localized, by comparison with the residential/commercial concentrations (Figs. 4.23c, 4.24c, and 4.25c). The peak values of the concentrations from these three categories are roughly comparable. Clearly, the dominant source of pollution depends upon the precise location considered.

a. From Power Plants

b. From Industrial Sources

c. From Residential/Commercial Sources

Fig. 4.23

Average SO₂ Concentrations (ppm)
Predicted on November 5, 1969

a. From Power Plants

b. From Industrial Sources

c. From Residential/Commercial Sources

Fig. 4.24

Average SO_2 Concentrations (ppm)
Predicted on November 6, 1960

a. From Power Plants

b. From Industrial Sources

c. From Residential/Commercial Sources

Fig. 4.25

Average SO₂ Concentrations (ppm)
Predicted on November 7, 1969

Table 4.7 gives the daily average concentration over the 66-point grid for November 5-10 and gives the average percentage contribution of power plants, industries, and residential/commercial establishments. The 6-day average concentration amounts to 0.08 ppm, of which power plants, industries, and residential/commercial sources contributed 29, 20, and 51%, respectively. Table 4.8 shows the same breakdown for 64 points at which concentrations equaled or exceeded 0.14 ppm, the primary standard for SO_2 . For these points, the power plants and industrial sources on the average contributed relatively more, namely, 35 and 24%, respectively. This lends some hope to the possibility that a strategy involving the power plants and industries will be effective in shaving the peaks from these high concentrations.

TABLE 4.7. Daily Average Calculated SO_2 Concentrations

Date, November	Daily Average Concentration over 66-point Grid, ppm	% Power Plants	% Industry	% Residential/Commercial
5	0.10	30	23	47
6	0.11	28	19	53
7	0.08	15	23	61
8	0.08	22	21	57
9	0.06	43	18	39
10	0.04	48	15	37
Six-day average	0.08	29	20	51

TABLE 4.8. Daily Average Calculated SO_2 Concentrations for 64 Worst Points

Source Types	Average Concentration of 64 Points ≥ 0.14 -ppm Daily Average, ppm	% Concentration of 64 Points ≥ 0.14 -ppm Daily Average
Power plants	0.06	35
Industry	0.04	24
Residential/Commercial	0.07	41
Total	0.18	100

4.4 Effect of a Strategy upon the November 5-11, 1969, Episode

We now investigate the consequences of imposing the same idealized Yellow Alert strategy that was applied to the February 1967 episode, whereby power-plant emissions are reduced to zero, industrial emissions are reduced by 50%, and residential/commercial emissions are reduced by 10%. It is assumed that the strategy was imposed at 0000 on November 5 and was in effect throughout the entire period.

Figure 4.26 shows the contour plots of daily average SO_2 concentration with the strategy in effect. No daily concentrations exceed 0.20 ppm with the strategy in effect. Figure 4.26 (with strategy), when compared with Fig. 4.22 (with no strategy), shows that the extent of the 0.10-ppm contour is significantly reduced.

Fig. 4.26. Average SO_2 Concentrations (ppm) with Strategy, Predicted by Model for 24-hr Intervals

Fig. 4.26 (Contd.)

Table 4.9 gives the daily average concentration over the 66-point grid with the strategy in effect, for comparison with Table 4.7 with no strategy. It is seen that the strategy reduces the average concentration of 0.08 to 0.05 ppm. Table 4.10 shows the average concentrations of the

TABLE 4.9. Daily Average Calculated SO₂ Concentrations with Strategy

Date, November	Daily Average Concentration over 66 Points, ppm	% Power Plants	% Industry	% Residential/Commercial
5	0.05	0	21	79
6	0.07	0	16	84
7	0.06	0	17	83
8	0.05	0	17	83
9	0.03	0	21	79
10	0.02	0	17	83
Six-day average	0.05	0	18	82

TABLE 4.10. Daily Average Calculated SO₂ Concentration for 64 Worst Points with Strategy

Source Types	Average Concentration of 64 Worst Points	% Concentration for 64 Worst Points
Power plants	0.00	0
Industry	0.02	24
Residential/Commercial	0.07	76
Total	0.09	100

64 worst points, namely those locations at which the daily average concentrations with no strategy exceeded the 0.14-ppm primary standard. Comparison with Table 4.8 shows that the strategy reduced the average value of 0.18 to 0.09 ppm.

In 61 of the 64 worst cases, the strategy was successful in reducing the concentration to below the primary standard of 0.14 ppm. The three cases that failed occurred on November 5 at locations in the northeast part of the city, which had large residential/commercial contributions. The strategy affected these concentrations by reducing them from 0.23 to 0.14 ppm, 0.26 to 0.15 ppm, and 0.35 to 0.17 ppm. In 23 of the 64 worst cases, the concentrations still exceeded the secondary standard of 0.10 ppm after the strategy was introduced.

Table 4.11 shows the effect of the strategy upon the three locations where a short-term, 4-hr-average calculated concentration exceeded 0.50 ppm. Two of the points occurred at different times, but at the same location, which was just downstream of the Crawford Generating Station. In both cases, as is expected, the strategy effectively reduced the high concentration to almost nothing. The remaining point occurred in the downtown area and was influenced by roughly equal amounts from power plants, industries, and residential/commercial sources. An inspection of all 4-hr-average calculated concentrations reveals that, with the strategy in effect, neither the Red Alert level of 0.35 ppm nor the Emergency criterion level of 0.40 ppm would have been reached anywhere in the city. (Declaration of an Emergency would require the Red Alert to have been in effect, an air-stagnation advisory for the next 12 hr, and 4 hr above 0.40 ppm SO₂.)

TABLE 4.11. Four-hour Average Calculated SO₂ Concentrations for Three Points ≥0.50 ppm

Grid-location Number	Date, November	Hours	Calculated SO ₂ (4-hr average in ppm)	% Power Plant	% Industry	% Residential/Commercial	Calculated SO ₂ (4-hr average in ppm) with Strategy
33	5	16-19	0.50	93	4	3	0.02
23	6	00-03	0.51	34	38	28	0.23
33	9	16-19	0.51	98	1	1	0.01

Note that the calculated 24-hr averages are taken between midnight of one day and midnight of the following day. Also, the short-term air-quality standards refer to 3-hr averages rather than the 4-hr averages discussed above.

Nevertheless, it appears that the strategy would have been rather successful, although not entirely successful, at meeting all the air-quality standards during the episode. It is also probably significant that more trouble occurred with the 24-hr SO₂ air-quality standards, especially the secondary standard, than with the short-term, 3-hr standard. The real TAM data reveal that this was true. Concentrations in excess of the 3-hr standard of 0.50 ppm were observed twice during the real episode (at TAM 1 and 7 on November 6). The 24-hr primary standard of 0.14 ppm was exceeded at various TAM stations six times between November 5 and 10 during the real episode, and the 24-hr secondary standard was exceeded eight additional times.

5. SUMMARY AND CONCLUSIONS

The Argonne Integrated-puff and Steady-state Plume Models have been used to study the potential effectiveness of imposing an idealized abatement strategy during SO_2 episode conditions. The strategy was tested for episodes that occurred on February 25-26, 1967, and November 5-11, 1969. Comparison of the calculations with actual observed SO_2 concentrations shows a coarse agreement, which probably will not be improved until even more sophisticated atmospheric-dispersion models are developed and more complete meteorological data are available. A step in this direction is the radiosonde data that is now obtained twice daily at Midway Airport, but was not available for the period of the February 1967 episode. Nevertheless, predictions of high concentration are usually confirmed by observations, although the model is less successful in predicting all the high-level cases that do occur.

This study covers only SO_2 . In any urban area, the stagnating meteorological conditions that cause high SO_2 levels will obviously result in increased concentrations of other pollutants. In Chicago, high levels of suspended particulates always accompany high SO_2 , but the quantitative relationship is complex. It depends on season, temperature, winds, and other variables. Depending on these factors, the day of the week, and the time of day, carbon monoxide and nitrogen oxides (primarily from motor vehicles) add to the problem. With sunshine, photochemical oxidants can accompany the others. Any epidemiological analysis of health effects should take into consideration the many pollutants and other variables that accompany SO_2 during an air-pollution episode.

The February 25-26, 1967, episode was characterized by concentrations in excess of the present 3-hr, 0.50-ppm SO_2 standard at two TAM stations and by concentrations in excess of the present 24-hr, 0.14-ppm primary standard at four TAM stations (see Table 1.1 for SO_2 air-quality standards). The Integrated-puff Model calculations achieved moderate success in reproducing the general trends of the episode. Comparison of the results of the model using no strategy with the implementation of an episode-control strategy (in which power-plant emissions are reduced by 100%, industrial emissions by 50%, and residential/commercial emissions by 10%, simulating a very idealized first stage, or Yellow Alert action) shows a 65% reduction in emissions, but only a 33% reduction in average concentrations. Such nonlinear behavior is caused by the effect of high stacks of larger sources and the geographical distribution of various types of sources relative to the wind direction.

For the February 25-26, 1967, period, the strategy is found to be effective in 46 of 63 cases in reducing 4-hr average concentrations from above the 0.30-ppm, Yellow Alert criterion to below 0.30 ppm. This level is arbitrary in that no air-quality standard is associated with it, but it has

been selected for the Yellow Alert criterion in Illinois. The 17 cases for which the strategy is not successful occur when the ventilation conditions are worst, so that the residential/commercial contribution alone exceeds the 0.30-ppm threshold over a large area. Nevertheless, even for these locations, the strategy does reduce the average calculated concentration by about 25%.

In eight instances, the 3-hr air-quality standard of 0.50 ppm is exceeded in the calculations. Although the strategy is successful in reducing all six concentrations to below 0.50 ppm, the Red Alert level of 0.35 ppm is still exceeded in four of these cases. In addition, the strategy still leaves fairly large areas in excess of both the 24-hr, 0.14-ppm primary standard and the 0.10-ppm secondary standard. Because of extensive fuel conversions in Chicago from coal to natural gas, SO₂ emissions are much lower in 1972. A similar set of meteorological conditions would result in an episode that might well be less severe in many locations.

The November 5-11, 1969, episode occurred with an average temperature of about 45°F and therefore, by comparison to the February 1967 episode, was characterized by less fuel burning for space heating and by a greater natural-gas usage by industries that have dual-fuel capability. The hourly SO₂ emissions from the power plants, including the fuel-switching and load-switching strategy voluntarily implemented by Commonwealth Edison, was reproduced as closely as possible in the calculations. The actual natural-gas usage for the 10 largest industrial dual-fuel users was also incorporated, and the remaining large dual-fuel industries were assumed to be using the maximum fractions of natural gas possible in each individual plant. The remaining industrial and residential/commercial sources were assumed to be operating to give their normal SO₂ emissions as determined by time and hourly temperature algorithms. The real TAM air-quality data show that the present 3-hr air-quality standard of 0.50 ppm was exceeded twice during the episode at two different locations. The 24-hr primary standard of 0.14 ppm was exceeded six times and the 24-hr secondary standard of 0.10 ppm eight additional times at various locations.

The calculated concentrations for the November 1969 episode were obtained by using the Integrated-puff Model for the power plants and the Steady-state Plume Model for the smaller numerous industrial and residential/commercial sources. Comparison of the calculated concentrations, with and without the idealized Yellow Alert strategy, reveals an average reduction from 0.08 to 0.05 ppm over a 6-day period. For the 64 grid points that exceed the 24-hr primary standard of 0.14 ppm in the calculations, 61 are reduced to below 0.14 ppm, although 23 still exceed the 0.10-ppm secondary level. All three 4-hr average concentrations, that are in excess of 0.50 ppm in the calculations, are reduced to below 0.50 ppm with the strategy. In addition, the Red Alert level of 0.35 ppm over a 4-hr average would not have been exceeded at any location with the strategy.

The strategy would have been more successful in a number of respects during the November 1969 episode than for the February 1967 episode. This can be accounted for by the fact that the average percent concentration due to residential/commercial emissions, which is less affected by the idealized strategy, is calculated to be larger during February 1967 than for November 1969, just due to the difference in space-heating requirements for these two periods. For both episodes, more violations of the 24-hr SO_2 air-quality standards are observed than of the 3-hr standard. This result appears to hold for both the calculations and the real data. The 24-hr secondary standard of 0.10 ppm appears in both episodes as a difficult standard to meet, even after imposition of the first stage of an idealized episode-control strategy.

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