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**STUDIES OF THE
ARGONNE INTEGRATED-PUFF MODEL**

by

**D. M. Rote, J. W. Gudenas,
and L. A. Conley**

ARGONNE NATIONAL LABORATORY

CENTER FOR ENVIRONMENTAL STUDIES

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Center for Environmental Studies

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October 1971

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ABSTRACT

This is the final report on progress made under the air-pollution meteorology and dispersion modeling contract sponsored by NAPCA (now EPA)/Division of Meteorology entitled "Studies of the Argonne Integrated-puff Model."

Objectives of the program included the development of a simple steady-state dispersion model based on the Gaussian plume expression to be used for comparison with the Argonne Integrated-puff Model. This report includes a complete documentation of the plume model along with computer program listings and an example computation of SO_2 concentrations.

To extend the applicability of the plume model to very low wind speeds, a special "calm algorithm" was developed.

The plume model was validated by comparing calculations both with observed concentrations and calculations using the puff model. When applied to a complete urban source emission inventory both the puff and plume models were found to be in relatively close agreement under a wide variety of circumstances. A good understanding of the relationship between the integrated puff kernel and the Gaussian plume expressions was obtained by performing detailed analytical and numerical analyses.

Finally a sensitivity analysis was carried out with the plume model. Sensitivity to the use of Midway measured winds instead of the more well defined TAM station winds was studied along with the effect of introducing systematic errors of $\pm 15^\circ$ in the TAM measured wind directions. In addition, the effect of introducing systematic errors into the lid height was also analyzed. A determination of the magnitude of expected errors in the lid height was obtained by making a comparison study of several techniques for estimating the lid height from radiosonde measurements.

1. INTRODUCTION

The City of Chicago, like many heavily industrialized metropolitan areas, has historically been plagued by high air-pollution concentrations of sulfur dioxide. This fact, coupled with the existence of a network of TAM stations (see Fig. 1) which continuously monitored SO_2 , suggested that Chicago would serve as a suitable region for a dispersion-modeling study. Such a program started about three years ago as the Chicago Air Pollution Systems Analysis Program.* Recognizing the substantial diurnal, as well as seasonal, variations in the weather elements and emission rates plus the need for reliable estimates of SO_2 concentrations on a short-term basis for purposes of episode analysis and control, it was decided to develop a transient-type dispersion model. The Argonne Integrated-puff Model was subsequently designed to calculate SO_2 concentrations on an hourly basis. This model is extensively documented in a number of reports,¹⁻³ including ANL/ES-CC-007.¹ The Chicago Air Pollution Systems Analysis Program is summarized in Ref. 2.

The central ingredient of the puff model is the puff kernel or point-source Green's function, which has been used by several other authors as well.⁴⁻⁶ When applied to a complete urban-source emission inventory for an extended historical period, the puff model has the principal disadvantage of requiring a relatively large amount of computer core storage and run time. Consequently, a question that arose in connection with such an application of the puff model was, "Could the same quality of fit of the computed SO_2 concentrations to the observed concentrations be achieved by a less sophisticated model?" Or, to put the question somewhat differently, "Is the accuracy of the model attributable to the puff kernel or to some other component of the model, such as the source emission inventory, or the source simulation routine PLANTSIM (see Ref. 1) or, to some combination of the algorithms which describe the plume rise, virtual point-source location, treatment of boundary conditions, lid penetration, etc.?"

During the past year a dispersion-modeling program** entitled "Studies of the Argonne Integrated-puff Model" was carried out. One of the principal goals of this program was to answer the above questions. To this end, a simple alternative model was developed and compared in detail to the integrated-puff model. The alternative model was developed by replacing the integrated-puff algorithm with a steady-state plume expression essentially the same as that used in a number of other steady-state Gaussian-plume-type urban models such as that of Clark⁷ or Turner.^{8,9} (See Moses¹⁰ for a review of these and other references cited there.) The

*This program was sponsored jointly by the Atomic Energy Commission, the U.S. Department of Health, Education, and Welfare (National Air Pollution Control Administration, Division of Meteorology), and the Chicago Department of Environmental Control.

**Sponsored by the then-named "National Air Pollution Control Administration," Division of Meteorology.

Fig. 1. Map of City of Chicago. Map shows origin of Cartesian-coordinate system (0,0), origin of area-source array (XSORIG, YSORIG) = (-2,-12), and 6 x 11 receptor grid denoted by ⊕. (Adapted from map prepared at the Department of Air Pollution by R. D. Colley, 1967.) ANL Neg. No. 112-8979 Rev. 4.

computer code resulting from this replacement, along with a few other minor changes in the original puff computer code, is referred to hereinafter as the "steady-state plume model" or "plume model" for short. By developing the plume model in this way, one could determine if the precision of the model when applied to an urban source inventory was limited by the degree of sophistication of the transport kernel or a combination of the remaining parts of the computer code as suggested above.

Another goal of the dispersion-modeling program was to establish the sensitivity of the puff or plume model to changes in various input parameters. A third goal was to obtain a better understanding of the relationship between the integrated-puff and Gaussian steady-state plume expressions and to determine under what conditions the puff and plume models could be expected to yield similar or different results. An additional goal was to attempt to reduce the computer run time requirements of the puff model.

The present report describes the results of the aforementioned program and includes a detailed description of the plume model as well as a copy of the computer code and an example of its use...

Early in the testing phase of the plume-model development, it was recognized that during periods of very low wind speed (calms) one obtained unrealistically high SO_2 concentrations. To rectify this problem, a "calm algorithm" was developed and tested. This special low-wind-speed transport function was set up so that it could be used in place of the standard plume expression wherever the wind speed fell below a certain predetermined value.

The plume model and the calm algorithm are described in detail in Sects. 2 and 3, respectively. For comparison, certain aspects of the puff model are also described in Sect. 2. However, since many algorithms are common to both the puff and plume models and since the puff model is already extensively described in Ref. 1, the reader will be referred to Ref. 1 for various details. The effect on the calculated results of using the calm algorithm in the plume model is illustrated in Sect. 4. Section 5 compares the results of the puff and plume models on both the short- and long-term bases. The results of these comparisons are discussed in Sect. 6. This is followed by an analysis (both numerical and analytical) of the relationship between the integrated puff and Gaussian plume mathematical expressions under special conditions in Sect. 7.

The results of a sensitivity analysis of the plume model to changes in certain input data are given in Sect. 8.

Some comments regarding the reduction in computer run time of the puff model are given in Appendix A.

Finally, a copy of the plume-model computer code, along with an example of its use, is included in Appendixes B and C, respectively. The code as presented here is a modified version of the puff-model code presented in Ref. 1 and is therefore not in its most efficient form. That is, the complications necessary to implement the puff kernel remain in the code, although they are not actually used by the plume model.

2. DESCRIPTION OF THE ARGONNE INTEGRATED-PUFF AND STEADY-STATE PLUME MODELS

The Argonne Integrated-puff Model has been described in the literature³ and more extensively in Argonne topical reports, especially Ref. 1. Consequently, only a brief description will be given here for purposes of comparison. Furthermore, since with the exception of the integrated puff kernel, the steady-state plume model is the same as the puff model, the reader is referred to Ref. 1 for a detailed description of the various model components common to both models, unless it is necessary to bring out a particular point of interest.

2.1 The Integrated-puff Transport Kernel

The Argonne Integrated-puff Model, as with similar puff models described in the literature, is based upon the Gaussian puff kernel (point source Green's function), which for a wind vector pointing along the x direction with magnitude u is given by

$$G(x, y, z, t - t') = \frac{\exp \left\{ - \left[\frac{[x - u(t - t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} - \frac{0.693(t - t')}{T_{1/2}} \right] \right\}}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z}, \quad (2.1)$$

where t' is the time of release of an instantaneous puff at a point source located at (x_s, y_s, z_s) and t is any time ($\geq t'$) at the receptor located at (x_r, y_r, z_r) so that $x = x_r - x_s$, etc. It is convenient to define the travel time or delay time for a given puff as $T = t - t'$.^{*} Note that, in general, the transit time $T_{tr} = x/u$ is quite distinct from the travel time T . The above Green's function includes an attenuation factor expressed in terms of a half-life $T_{1/2}$, which is supposed to allow for the gradual removal of SO_2 by some unspecified mechanisms. Now to calculate the concentration at the receptor at time t resulting from a continuous release of pollutant starting at time $t' = 0$ from the source, we form the convolution of the emission rate $Q(t')$ with the Green's function as follows:

$$\begin{aligned} \chi(x, y, z, t) &= \int_0^t dt' Q(t') G(x, y, z, t - t') \\ &= \int_0^t dT Q(t - T) G(x, y, z, T), \end{aligned} \quad (2.2)$$

^{*}Used in the context of the puff model, the travel or delay time T is the age of a particular puff and has nothing to do with the time required for a puff to be transported from a given source to a given receptor. The latter time is called the transit time $T_{tr} = x/u$.

where $T = t - t'$ is the delay time. In the present discussion, terms corresponding to reflections from the ground and lid are dropped for convenience. Causality is preserved by starting the latter integral at zero delay time (the present) and going backward in time to the maximum delay time of t hours (in this case, the start of the release). Since, beyond some large delay time earlier releases will not contribute to the concentration, it is physically reasonable and economical of computer time to restrict the maximum delay or look-back time to some small number. The present puff computer code restricts the look-back time to 6 hr. Since the meteorological variables and emission rates are assumed piece-wise continuous, the concentration at hour M becomes

$$\chi(M) = \sum_{N=1}^M Q_{M-N+1} \int_{(N-1)\Delta}^{N\Delta} dT G_N(x, y, z, T),$$

where Q_{M-N+1} is the emission rate between hours $M - N$ and $M - N + 1$ and the subscript N on the Green's function means that it should be evaluated with the meteorological parameters corresponding to the same time interval. As N increases from 1 to M , we are effectively stepping backward in time in 1-hr steps.

2.2 The Steady-state Plume Expression

Following a number of other authors, we have used the standard plume expression given by the following equation for a point source in an unbounded atmosphere:

$$\chi(y, z) = \frac{Q \exp \left[- \left(y^2 / 2\sigma_y^2 + z^2 / 2\sigma_z^2 \right) \right]}{2\pi u \sigma_y \sigma_z} \quad (2.3)$$

Boundary conditions are treated in Sect. 2.5.

No attempt is made to preserve causality in the plume model. That is, regardless of whether the transit time exceeds the time step ($x/u > 1$ hr), the plume expression is applied as though steady-state conditions existed.

2.3 Dispersion Coefficients

The dispersion coefficients used in Eqs. 2.1 and 2.3, namely σ_x , σ_y , and σ_z , are discussed in Ref. 1. Briefly, they are calculated from

$$\sigma(i, T) = \max \left\{ \sigma^{\text{TSL}}(T), \sigma^{\text{TWB}}(uT) \right\},$$

where i and T refer to the Turner stability class⁸ and travel time, respectively; TSL refers to the travel-time-dependent coefficients adapted from

Turner's St. Louis study⁹ (see Figs. 2 and 3); and TWB refers to the downwind, distance-dependent coefficients adapted from Turner's Workbook,¹¹ which are in turn adapted from Pasquill¹² and Gifford¹³ (see Figs. 4 and 5). For a particular source-receptor pair, stability class, and wind speed, the maximum value obtained from these two families of curves is used to avoid unrealistically narrow beams of pollutant predicted by σ^{TSL} at high wind speed. For lateral dispersion with $\sigma_x = \sigma_y = \sigma_l$ (used by both models), $\sigma^{\text{TSL}}(T) > \sigma^{\text{TWB}}(uT)$ for $u \lesssim 7$ mph. Also, generally, $\sigma_z^{\text{TSL}}(T) < \sigma_z^{\text{TWB}}(uT)$ for $u \gtrsim 20$ -30 mph, except for short times (< 0.2 hr) and for the more unstable stability classes. The exact wind speed for which the coefficients are equal depends upon the stability class.

The TWB set of curves given in Turner's Workbook¹¹ are characteristic of 10-min sampling times. The so-called "1/5 power law" (see Sect. 2.3.1) was used to convert these curves into those given in Figs. 4 and 5, which are characteristic of 1-hr sampling times.

The TSL set of curves used by Turner in his St. Louis study⁹ are characteristic of 2-hr sampling times. We discovered that the St. Louis coefficients were treated in Ref. 1 and consequently in the calculations reported here as though they were in fact for 1-hr sampling time. Hence,

Fig. 2. Time-dependent Transverse-dispersion Coefficients Characteristic of 1-hr Sampling Times (Turner⁹). ANL Neg. No. 113-2876.

Fig. 3. Time-dependent Vertical-dispersion Coefficients Characteristic of 1-hr Sampling Times (Turner⁹). ANL Neg. No. 113-2869.

Fig. 4. Downwind-distance-dependent Transverse-dispersion Coefficients Characteristic of 1-hr Sampling Times (Turner¹¹). ANL Neg. No. 113-1159.

Fig. 5. Downwind-distance-dependent Vertical-dispersion Coefficients Characteristic of 1-hr Sampling Times (Turner¹¹). ANL Neg. No. 113-1160.

no conversion to 1-hr sampling time was deemed necessary. However, recognition that these coefficients are actually characteristic of 2-hr sampling times means that they have been erroneously used. The values shown in Figs. 2 and 3 should be reduced by a factor $(60/120)^{1/5} = 0.87$. Fortunately, the erroneous use of 2-hr instead of 1-hr sampling time coefficients is not serious, for several reasons. First, the error in the values of the coefficients is only 13%, which is well within the accuracy of the coefficients to begin with. In addition, since the coefficients appear both in the exponentials and denominators of the transfer functions, small changes in their values tend to cancel at least partially. For a given set of meteorological conditions, depending upon the orientation of a given source-receptor pair, the concentration could increase, decrease, or remain roughly unchanged.

The travel-time-dependent coefficients labeled TLS and taken from Turner's St. Louis study⁹ are quite distinct from those used in his Nashville study.⁸ Both the characteristic sample time and the stability classification scheme are different. Whereas the Nashville time-dependent coefficients correspond closely to the downwind-distance-dependent coefficients from Turner's Workbook¹¹ at 5 mps, there does not seem to be any simple relationship between the St. Louis and workbook coefficients at the same wind speed. Consequently, further investigation is required to unravel the relationship between the St. Louis and workbook coefficients.

2.3.1 The "1/5 Law"

Both the puff and plume models use a basic time step of 1 hr. That is, the meteorological parameters are assumed constant during that period

so that concentrations are calculated on an hourly basis. Consequently, it is consistent to use dispersion coefficients that have been determined for 1-hr sampling times or are at least characteristic of 1-hr sampling times. Turner, in his Workbook,¹¹ gives values of the downwind-distance-dependent coefficients characteristic of a 10-min sampling time.

Several authors, including Cramer¹⁵ and his associates and Turner,¹¹ have recommended the so-called "1/5 Law" for making adjustments to various sampling times. The law states that

$$\sigma_y(\tau) = \sigma_y(\tau_0) \left(\frac{\tau}{\tau_0} \right)^{1/5},$$

where $\sigma_y(\tau)$ is the lateral dispersion at a fixed distance downwind measured for a sampling time τ , while $\sigma_y(\tau_0)$ is measured at the same location for a different sampling time τ_0 . The 1/5 Law, according to Cramer, apparently fits the data of several field experiments.

The same expression can be applied to the vertical dispersion, except that the data are not nearly so conclusive. This is especially true because most of the experiments were performed using ground-based sources, so that the solid earth boundary restricts meandering of the vertical direction of the velocity.

Slade¹⁶ feels that for vertical distances below about 1000 ft the vertical dispersion will be insensitive to sampling times greater than 20 min.

The puff model assumes that both the lateral and vertical dispersion coefficients that are functions of the downwind distance are modified with the 1/5 Law; i.e.,

$$\sigma_y(60) = \sigma_y(10) \left(\frac{60}{10} \right)^{1/5}$$

and

$$\sigma_z(60) = \sigma_z(10) \left(\frac{60}{10} \right)^{1/5}.$$

If we take Slade's comments seriously, then we should only be using

$$\sigma_z(60) = \sigma_z(20) = \sigma_z(10) \left(\frac{20}{10} \right)^{1/5},$$

which means that at present σ_z is being slightly overestimated.

2.3.2 Comment on Use of Travel-time-dependent Dispersion Coefficients in Plume Model

The use of the travel-time-dependent dispersion coefficients in both the puff and plume models requires some explanation. Since the puff model is formulated in terms of the travel or delay time T of individual puffs, the dispersion coefficients are evaluated for values of this time. That is, one uses these coefficients to describe the growth of each puff about its own center. This is basically a Lagrangian formulation. However, as has already been pointed out by a number of people including Pasquill,¹⁴ the term "puff model" is really a misnomer because one is not actually employing diffusion coefficients characteristic of individual puffs (that is, instantaneous releases of pollutants).

On the contrary, the diffusion coefficients being used are essentially a measure of the size of the plume envelope formed by sampling a real meandering plume emitted from a continuous point source for 1 hr. Consequently, to the extent that the integrated-puff kernel represents that plume envelope, one is treating the envelope as though it were composed of a continuous train of effective circular puffs ($\sigma_x = \sigma_y$) whose growth is specified by the above coefficients. This "decomposition" of the plume envelope into a continuous train of effective puffs is rigorously distinct from building up a plume envelope with an ensemble of isolated true puffs whose growth is specified by Lagrangian diffusion coefficients. This distinction arises because the effects of mutual interactions of overlapping puffs are taken into account in an average way in the effective puff picture but not in the true individual puff picture. It seems reasonable that this distinction is not very significant in urban dispersion modeling.

In regard to the use of these coefficients in the plume model, one point is worth mentioning. Physically, one recognizes that in the puff model the overlapping train of effective puffs that influence a receptor at a particular time have a range of delay times associated with them and therefore have undergone a range in degree of growth. For the steady-state plume model, there is, strictly speaking, only one time which can be defined, and that is the transit time x/u , where $x = x_r - x_s$. Consequently, the dispersion coefficients have been evaluated at the transit times corresponding to the various source-receptor pairs of interest, i.e., $\sigma_l^{TSL}(i, x/u)$ and $\sigma_z^{TSL}(i, x/u)$.

2.4 Low-wind-speed Behavior of Steady-state-plume Expression

The travel-time-dependent dispersion coefficients, namely $\sigma^{TSL}(i, T)$, can be expressed approximately as

$$\sigma_y(T) = aT^b, \sigma_z(T) = cT^d, \quad (2.4)$$

or alternatively, using the transit time, as

$$\sigma_y(x/u) = ax^bu^{-b}, \sigma_z(x/u) = cx^du^{-d}. \quad (2.5)$$

Substituting into the plume expression, we obtain

$$\frac{\chi}{Q} \propto f(u)g(u), \quad (2.6)$$

where

$$f(u) = u^{b+d-1}/x^{b+d}$$

and

$$g(u) = \exp \left[- \left(\frac{y^2}{2a^2x^{2b}} u^{2b} + \frac{z^2}{2c^2x^{2d}} u^{2d} \right) \right].$$

Since $f(u)$ is a slowly increasing function of u ($b+d > 1$) and $g(u)$ is an exponentially decaying function of u , the product is a function that starts off at zero when $u = 0$, rapidly rises to a peak at very small values of u (as it turns out), and then falls off exponentially to zero again as $u \rightarrow \infty$. Although χ/Q is consequently a well-behaved function of u for all values of u , nevertheless, for small values of u (≈ 1 mph), one obtains unrealistically large values of the concentration.

On the other hand, if the downwind distance-dependent family of dispersion curves were used, namely,

$$\sigma_y(x) = Ax^B \text{ and } \sigma_z(x) = Cx^D,$$

then $\chi/Q \propto 1/u$, which leads, as experience shows, to unrealistically high concentrations for wind speeds even as high as 3-4 mph.

Consequently, even though the use of the travel-time-dependent coefficients is not rigorously justified, nevertheless their functional dependence upon u is much more satisfactory than the downwind distance-dependent coefficients at low wind speeds and, when compared with observed concentrations, produce more realistic values of the concentration down to about 1 mph.

2.5 Boundary Conditions

In both the plume and puff models, the ground surface is assumed to be a perfect reflector of the pollutant and is therefore treated by the method of a virtual image source below the ground. In addition, if the mixing depth

is finite, then the top of the mixing layer or lid height is also assumed to be a perfect reflector, so that the combination of two parallel reflectors is treated as an infinite sequence of virtual image source terms (limited to nine terms). (See Ref. 1 for a complete description of the procedure.) The lid height is determined by an objective estimate of the mixing-height technique.¹⁷ As part of the dispersion modeling program, results of this technique have been compared in detail with estimates of the lid height based on radiosondes performed at Midway Airport. This work is described in a separate report.¹⁸

If the physical or effective stack height (see Sect. 2.6) is greater than the lid height, then the stability class used to calculate plume dispersion is set equal to 5 (stable) and the lid height is set equal to infinity; i.e., no reflection from the lid is considered. For the puff model, the time dependence of the lid height that leads to such phenomena as fumigations is taken into consideration, as described in Ref. 1.

2.6 Effective Stack Height (taken from Ref. 1)

The effective stack height H is the height above ground that best defines the centerline of the plume. The plume is assumed to originate as a point source at an altitude H ft above ground at the location of the stack. If aerodynamic downwash causes the plume to break up and mix rapidly downward in the vicinity of the stack, H may be set equal to the actual physical height, H_s . Observations of a local utility indicate that this phenomenon occurs frequently for wind speeds greater than 15 mph. Otherwise, a plume rise ΔH is added to the physical stack height H_s , so that

$$H = H_s + \Delta H,$$

where ΔH is estimated as described below.

Smoke plume-rise calculations in this model are based on a formula derived by Carson and Moses¹⁹ from observations at TVA stations and other power plants. (The momentum term in their original formulation is omitted in the equation since its contribution is generally negligible compared to thermal buoyancy.)

$$\Delta H = KQ_s^{1/2}/U, \quad (2.7)$$

where

ΔH = plume rise, ft,

Q_s = heat-emission rate from stack, Btu/hr,

U = wind speed, mph, at height of stack,

and

$K = 0.870$ (unstable; class 3), 0.354 (neutral; class 4),
 0.222 (stable; class 5).

Three restrictions placed on the use of Eq. 2.7 are listed in Table 2.1.

TABLE 2.1. Restrictions on Plume-rise Formula (Eq. 2.7)

1. Low Wind Speeds (U)

If U is estimated to be less than 4 mph, the value 4 mph is used in Eq. 2.7.

2. Stability Class and the Coefficient K

If the physical stack height (H_s) is equal to or greater than 200 ft, $K = 0.354$ (neutral) is used, even though the stability index indicates unstable conditions. ($K = 0.222$ if conditions are stable.)

3. Mixing-layer or Lid Height (H_m)

- a. If the physical stack height H_s is greater than H_m , an infinite value for H_m is assumed, with plume rise and dispersion according to stable atmospheric conditions.
- b. A minimum plume rise $\Delta H_{\min}$ (DHMIN in subroutine ISPDV) is calculated, based on the coefficients for stably stratified air. If this minimum effective stack height, $H = H_s + \Delta H_{\min}$, is greater than the lid height H_m , it is used; the plume is then analyzed as described in restriction 3a.
- c. If $H_s + \Delta H_{\min} < H_m$ and if the plume rise ΔH based on the actual stability class yields an effective stack height greater than H_m , i.e., if $H_s + \Delta H_{\min} < H_m$ and $H_s + \Delta H \geq H_m$, the effective stack height is restricted to the lid height H_m .

2.7 Effective Wind Speed

The mean wind speed at the physical stack height H_s should be used in the plume-rise equation (Eq. 2.7). In the evaluation of the puff kernel (Eq. 2.1), or the plume expression (Eq. 2.3), wind at the effective stack height H , corresponding to the plume centerline, is used. In each case, the desired value for the wind speed will usually be greater than that measured at a local airport (typically 20-100 ft above the ground). The following equation provides a correction term for altitudes up to about 1000 ft:

$$U(\text{at height } Z_2) = U(\text{at height } Z_1)(Z_2/Z_1)^P, \quad (2.8)$$

where the exponent P is dependent on the stability class, as shown in Table 2.2. The ratio $(Z_2/Z_1)^P$ is limited to a value of 3.

TABLE 2.2. Exponents for Wind-profile Law (taken from DeMarrais²⁰)^a

Stability Class	P
Stable (≥ 5)	0.5
Neutral (4)	0.2
Unstable (< 3)	0.2

^aThe experimental data from DeMarrais²⁰ indicated a slightly more uniform vertical-wind-speed profile for unstable than for neutral conditions, but the model is not sensitive to this distinction.

sources can be modeled more realistically by assigning initial dimensions to the plume in order to approximate, for example, multiple stacks or aerodynamic downwash.

Be it an area source or a point source with initial dimensions, the source of finite initial volume is approximated by a pseudoupwind point source.

The location of this point source is determined as follows: First, the source is assigned some initial values of the dispersion coefficients namely, σ_{x0} , σ_{y0} , and σ_{z0} according to a prescription defined below. For the plume model only σ_{y0} and σ_{z0} are relevant. In any case, because only circular puffs are presently considered, $\sigma_{x0} = \sigma_{y0}$. Second, the equations

$$\left. \begin{array}{l} \sigma_{x0} = \sigma_{y0} = \sigma_y(i, T_y) \\ \text{and} \\ \sigma_{z0} = \sigma_z(i, T_z) \end{array} \right\} \quad (2.9)$$

are solved by subroutine PSEUDO for the quantities T_y and T_z . From these initial time intervals, we calculate $\delta_x = uT_y$ and $\delta_y = vT_y$, where u and v are the x and y components of the wind velocity. Finally, Eqs. 2.1 for the puff and 2.3 for the plume are modified by replacing x , y , and T by $x - \delta_x$, $y - \delta_y$, and $T + T_y$, $T + T_z$, where appropriate.

The prescription for assigning initial values to the dispersion coefficients depends upon the source type (whether point or area), wind speed (whether downwash conditions prevail or not), and source classification. Table 2.3 shows values of building height, critical wind speeds, plume rise, and σ_{z0} for the three classifications of area sources in Chicago. For example, if the wind speed is 10 mph, low-rise residential buildings are

2.8 Finite-source Geometry (Adapted from Ref. 1)

The realistic modeling of residential, commercial, and industrial zones characterized by multiple sources too numerous to represent by individual plumes is critical to the success of a source-oriented atmospheric-dispersion model. A similar need for synthesizing emissions from these area sources arises in the design of regional implementation plans based on land use, a method whereby one seeks to assign emission-density limits (lb/hr-mi²) to land in each of several zoning classes (Roberts and Croke²¹). Often major point

represented by a source at $z = 50$ ft with $\sigma_{z0} = 50$ ft, and industrial-area sources by $z = 300$ ft and $\sigma_{z0} = 150$ ft. The initial value of the lateral dispersion $\sigma_{x0} = \sigma_{y0}$ is defined in terms of the side length n (mi) of the area source as $\sigma_{y0} = n/2.4$. (The factor 2.4 is discussed in Sect. 2.9 below.)

TABLE 2.3. Parameters Used to Describe Area Sources in Chicago

Source Class	Physical Stack Height, ft	Critical Wind Speed, WS_c , mph	$WS \leq WS_c$		$WS > WS_c$	
			Plume Rise, ft	σ_{z0} , ft	Plume Rise, ft	σ_{z0} , ft
Low-rise Residential/Commercial	50	6	50	50	0	50
High-rise Residential/Commercial	200	6	100	200	0	200
Industrial	150	15	150	150	0	150

Major point sources are also characterized by initial dimensions $\sigma_{x0}(= \sigma_{y0})$ and σ_{z0} , which, for properly designed stacks, depend upon whether a critical wind speed (here 15 mph at 75 ft) is exceeded. Downwash conditions are assumed to occur always for sources with poor aerodynamic characteristics, such as vents or stubby stacks. Under normal plume-rise conditions, the parameters σ_{x0} , σ_{y0} , and σ_{z0} are each set at 100 ft to describe the initial source volume. Under downwash conditions, σ_{x0} and σ_{y0} are set at 750 ft and σ_{z0} at 150 ft. As with area sources, these choices are somewhat intuitive and, since the downwash effect is a primarily local one, really should be tailored to each source or source type. For example, one may assume that large commercial and residential establishments are dominated by buildings with improperly designed stacks and that a good assumption for initial source dimensions to simulate downwash would then be the size of a representative building (Shieh⁵). In Chicago, major point sources in this category are typified by Union Station, approximately one city block wide and 100-150 ft high. This observation influenced our selection of initial source dimensions under downwash conditions. It is also worth noting that all sources homogenized and treated as area sources (with $n = 1$ mi) are effectively given as $\sigma_{x0} = \sigma_{y0} = 0.416$ mi.

2.9 Relation between Length of Side of an Area Source and Initial Value of Lateral-dispersion Coefficient

In Sect. 2.8 the prescription for assigning initial values of the dispersion coefficients to square area sources said that for a source of side length n , the initial value of the lateral dispersion coefficient ($\sigma_{x0} = \sigma_{y0}$) is given by $\sigma_{y0} = n/2.4$.

The following discussion is taken from Ref. 1:

"Figure [6] depicts a row of square area sources of uniform strength. Pollutant concentrations along the line A-A are determined by

summation of concentrations due to each individual area source. The concentration profile for each square is governed by σ_{y0} . Uniformity of emissions along A-A implies that, when the concentration fields for all squares are superimposed, the dose at point a in Fig. [6] should equal that at point b. [Choosing $\sigma_{y0} = n/2.4$] ensures this."

The statement that $\sigma_{y0} = n/2.4$ ensures the uniformity of concentration along the line A-A was examined in detail with some numerical experiments.

There is an inherent uncertainty about the location relative to a square area source where one should set $\sigma_{y0} = \sigma_y$ and $\sigma_{z0} = \sigma_z$. In both the puff and plume model codes, this location was chosen as the center of the square area source. Consequently, the quantities δ_x and δ_y (see Sect. 2.8) are the displacements of the virtual point source from the center of the square area source. Hence, in the discussion here, we shall refer to the concentration along a line passing through the center of a row of area sources (parallel to the row) rather than to the concentration along line A-A in Fig. 6.

Fig. 6. A Row of Square Area Sources Perpendicular to the WD. ANL Neg. No. 113-2867 Rev. 1.

In the steady-state case, assuming a Gaussian distribution, the pollutant concentration for a point source is given by the expression

$$\chi = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp(-y^2/2\sigma_y^2) \exp(-z^2/2\sigma_z^2),$$

where, for convenience, we are ignoring the boundary conditions.

If we now represent a single square area source by a virtual up-wind point source, then at the center of the square we have $\sigma_y = \sigma_{y0}$ and $\sigma_z = \sigma_{z0}$, so that, along the centerline passing through the single square area source perpendicular to the wind direction, the concentration is proportional to

$$\frac{\exp(-y^2/2\sigma_{y0}^2)}{\sigma_{y0}} \quad (2.10)$$

The emission pattern from a square area source is a square step function of width n (the side length). Hence, what we are attempting to do is fit a Gaussian to this square step function at the center of the square as well as possible. A reasonable approach is to require that the width w of the Gaussian at half-maximum should equal the side length n of the area source, i.e., $w = n$. But $w = 2\sigma_{y0} \sqrt{\ln 4} \approx 2.4\sigma_{y0}$, so that we have $\sigma_{y0} = n/2.4$.

Now we may inquire as to what happens when several area sources are lined up in a row. The concentration along the centerline parallel to the row of N sources is proportional to

$$\sum_{i=1}^N \frac{\exp[-(y - y_i)^2/2\sigma_{y0}^2]}{\sigma_{y0}}, \quad (2.11)$$

where y_i is the location of the center of the i th area source. Figure 7 shows plots of this quantity for various choices of N and σ_{y0} . The variable y is given in units of the side length n . Superimposed on these curves are the corresponding square step functions, which are normalized so that the areas under the curves are equal.

Note:

$$\int_{-\infty}^{+\infty} dy \frac{\exp(-y^2/2\sigma_{y0}^2)}{\sigma_{y0}} = \sqrt{2\pi} \approx 2.5.$$

Fig. 7. Concentration Patterns along Line Passing through Center of Row of Square Area Sources. Note: symmetry about $y = 4$. ANL Neg. No. 190-165.

The source pattern is centered at $y = 4$. Since $\chi(y)$ is symmetrical about $y = 4$, only the region $0 \leq y \leq 4$ is shown.

The choice $\sigma_{y0} = 0.25$ (in units of n) corresponds to $n/4$ as used by Turner in his St. Louis study.⁹ This choice not only distorts the single area source considerably, but does not provide a good approximation to the step function for several sources in a row.

Using $\sigma_{y0} = 0.417$ ($= n/2.4$) clearly provides a reasonable approximation to the single square area source as mentioned earlier and also provides a good fit to the sequence of sources.

The choice $\sigma_{y0} = 0.75$ ($= 3n/4$) provides a smooth distribution for a row of sources, but tends to spread the edges out too far and clearly distorts a single area source by quite a bit. Consequently, the choice $\sigma_{y0} = 0.417$ seems to provide the best compromise to fitting an arbitrary number of sources. By using a value of σ_{y0} somewhat greater than 0.417, we could get an idea of what the concentration will look like along the line A-A in Fig. 6. Without actually carrying out this exercise, we see that along the latter line the concentration pattern will fall somewhere between that of

$$\sigma_{y0} = 0.417 \text{ and } \sigma_{y0} = 0.75.$$

One can extend the numerical experiment to include several rows of area sources. The results are not essentially changed. Fortak²² has performed similar numerical experiments in an attempt to determine the density of individual point sources (with fixed initial dispersion) required to simulate a single area source with uniform distribution (a step function).

3. DERIVATION OF CALM ALGORITHM

For very low wind speed (≈ 1 mph), the concentrations predicted by the steady-state model tend to become quite large. This is true even when the travel-time-dependent dispersion coefficients are used (see Sect. 2.3). To implement the steady-state model under such conditions, it was therefore necessary to develop a calm algorithm which would be used whenever $u < u_{\text{critical}}$, where u_{critical} was some small velocity to be determined.

The concentration due to a point source with constant emission rate Q takes the general form, for the puff model,

$$\chi(x, y, z, \tau) = \int_0^\tau Q \, dT \frac{\exp \left\{ - \left[(x - uT)^2 / 2\sigma_x^2 + y^2 / 2\sigma_y^2 + z^2 / 2\sigma_z^2 \right] \right\}}{(2\pi)^{3/2} \sigma_x(T) \sigma_y(T) \sigma_z(T)}, \quad (3.1)$$

where the exponential attenuation factor has been ignored for simplicity and where the dispersion coefficients are of the TSL type.

By assuming $\sigma_x(T) = \sigma_y(T) = \alpha T$ and $\sigma_z(T) = \gamma T$, and by taking the limiting case where $\tau \rightarrow \infty$ and $u \rightarrow 0$, we can analytically perform the integration to obtain

$$\chi(r, z) = Q \left[(2\pi)^{3/2} \alpha^2 \gamma \left(\frac{r^2}{\alpha^2} + \frac{z^2}{\gamma^2} \right) \right]^{-1}. \quad (3.2)$$

To use this expression, we must obtain the values for the parameters α and γ . However, these are just the slopes of the curves $\sigma_x(T)$ and $\sigma_z(T)$, which can be approximately calculated within the computer code as follows:

$$\alpha = \sigma_x(T = 1 \text{ hr}) - \sigma_x(T = 0),$$

with a similar expression for γ . The beauty of this algorithm is that there are no arbitrary constants to be evaluated and it can be easily implemented within the original code.

Now Eq. 3.1 for χ is true only for the source in a boundary-free region. If images formed by reflection of the plume from both the ground and the lid are to be taken into account, the expression for χ must be augmented by a sum of multiple-image terms which are identical to the source term, except that z must be replaced by z_i , where z_i is the vertical distance between the receptor and the i th image.

Calculations with this multiple-image series (using three terms) unfortunately showed poor convergence most of the time, so that the results

were in fact underestimates of the true calculated concentrations. To rectify this problem, an average was performed over the mixing layer to obtain a uniform vertical concentration field,

$$\bar{\chi} = \frac{1}{L} \int_0^L \sum_{i=1}^{\infty} \chi_i(r, z) dz, \quad (3.3)$$

where L = lid height and $\chi_i(r, z)$ is the concentration due to the i th image.

It can be shown that Eq. 3.3 can be equivalently written as

$$\bar{\chi} = \frac{1}{L} \int_{-\infty}^{+\infty} \chi(r, z) dz, \quad (3.4)$$

where z is allowed to range over the entire interval from $-\infty$ to $+\infty$, and where $\chi(r, z)$ is given by Eq. 3.2. This integral is straightforward, and the result is

$$\bar{\chi} = \frac{Q}{L\sqrt{2\pi}2\alpha r}. \quad (3.5)$$

The $1/r$ dependence is characteristic of a cylindrically symmetric case with an infinite line source in the vertical direction. It results from setting the upper limit of the integral in Eq. 3.1 (τ) equal to infinity.

Use of Eq. 3.5 reveals that the $1/r$ dependence especially for distant sources is unrealistic. If an infinite time is permitted for the establishment of steady-state conditions, then the simple $1/r$ dependence is not unreasonable. This is precisely one case in which the puff model properly allows for the "true" buildup time for a given concentration. It is possible to approximate the true buildup by using a finite value for τ . That is, we assume that a calm condition lasts only for a finite time τ , perhaps 1 or 2 hr. If we make this assumption, we can obtain a more realistic calm algorithm which, however, is really only applicable to cases where indeed $\tau = 1$ or 2 hr. Provided that we are willing to ignore the variations in buildup times or calm durations, which is made partially acceptable by the decay time of SO_2 anyway, we can use some fixed value of $\tau = 1$ or 2 hr. Carrying out the puff integral for a finite time τ yields

$$\chi(r, z, \tau) = \frac{Q \exp[-f(r, z)/\tau^2]}{2(2\pi)^{3/2}\alpha^2\gamma f(r, z)}, \quad (3.6)$$

where

$$f(r, z) = \frac{r^2}{2\alpha^2} + \frac{z^2}{2\gamma^2}.$$

Clearly, as $\tau \rightarrow \infty$, the original calm algorithm is obtained. For finite values of τ , the exponential factor improves the convergence rate of the image series. However, calculation still shows that under certain circumstances the convergence will be poor. Again, for those cases we can resort to a uniform vertical distribution in the mixing layer by averaging over the variable z , as follows:

$$\begin{aligned}\bar{\chi}(r, \tau) &= \frac{1}{L} \int_{-\infty}^{+\infty} \chi(r, z) dz \\ &= \frac{Q}{L\sqrt{2\pi}2\alpha r} [1 - \text{erf}(r/\sqrt{2}\alpha\tau)],\end{aligned}\tag{3.7}$$

where erf stands for error function. Note that $\text{erf}(0) = 0$, so that

$$\bar{\chi}(r, \tau) \xrightarrow{\tau \rightarrow \infty} \bar{\chi}(r).$$

Also, $\text{erf}(\infty) = 1$, so that, in general, for finite values of τ , $\bar{\chi}(r, \tau)$ falls off more rapidly than $\bar{\chi}(r)$, as is physically desirable for finite-duration calm periods. In addition to the source term given by Eq. 3.6, the first ground-reflected image and the first lid-reflected image are also calculated and the convergence is tested. If the convergence is poor, then $\bar{\chi}(r, \tau)$ is used.

There is somewhat of an inconsistency in the way this special low-wind-speed function is used in the present computer code, whereas, the calm algorithm is used whenever $u < 1$ mph. The plume-rise formula used (see Sect. 2.6) is not really valid for $u < 4$ mph. Up to the present, no attempt has been made to incorporate one of the more recent plume-rise formulas especially designed for calm periods as given, for example, by Briggs.²³

4. EFFECT OF CALM ALGORITHM

To illustrate the effect of the use of the calm algorithm (CA) given by Eqs. 3.6 and 3.7, we have selected a historical air-pollution episode: February 16-18, 1967. The wind speeds recorded at TAM 5 (see Fig. 1) are shown in Fig. 8. Table 4.1 shows the analysis of the results for three different choices of the parameter τ (see Eqs. 3.6 and 3.7), which depict the effective duration of the calm. (See Appendix D for the definition of the symbols labeling the columns of the table.) For $\tau = 0$, the CA is suppressed. Because only a relatively small percentage of the total number

Fig. 8. Wind Speed Measured at TAM 5 Aerovane vs Time of Day, for February 16-18, 1967. ANL Neg. No. 190-141 Rev. 1.

of hours have $u \leq 1$ mph (when the CA is turned on), the percentile distribution is not very sensitive to the changes in the calculated results brought about by the use of the calm expressions. However, the relative standard deviations σ_{oe}/μ_o^* and, in these cases, the means* are quite sensitive to the changes in the results. The reductions in means follow from the reduction in the peak values of the concentrations occurring during calms. The fact that for TAM 2 and 4 the means were in better agreement without the CA arises from the general

TABLE 4.1. Effect of Calm Algorithm on Hourly Calculations with Steady-state Plume Model for Episode of February 16-18, 1967^a

TAM	Code ^b	μ_o	μ_e	σ_{oe}/μ_o	PN025	PN05	PN1
2	1	0.19	0.18	0.81	0.29	0.50	0.65
	2		0.15	0.75	0.29	0.49	0.62
	3		0.16	0.73	0.29	0.49	0.63
4	1	0.26	0.25	1.31	0.06	0.14	0.41
	2		0.14	0.65	0.07	0.14	0.42
	3		0.15	0.61	0.07	0.14	0.43
5	1	0.09	0.25	5.07	0.32	0.58	0.68
	2		0.10	0.97	0.38	0.64	0.78
	3		0.10	0.93	0.38	0.67	0.78

^aSee Appendix D for definitions of column headings.

^bCodes 1, 2, and 3 mean no calm algorithm and calm algorithm with $\tau = 1$ and $\tau = 2$, respectively.

*See Appendix D for definitions of these quantities.

underprediction of the plume model during the period which was compensated by the greatly overpredicted concentrations during the calms (because of the ill behavior of the plume expression as $u \rightarrow 0$). Although this compensation of errors is tolerable in long-term analysis, it is undesirable for an episode or short-term model. The reduction in the relative standard deviation of differences between the hourly observed and calculated results as the CA is turned on clearly indicates how the results are improved. Figures 9-11 show graphs of the calculated and observed hourly concentrations. The solid curves are the observed results, the open squares are the calculated plume results without the CA, and the stars are the plume model results with the CA (using $\tau = 2$ hr). The stars overlap the open squares when $u > 1$ mph.

The narrow peaks shown in these curves are the result of power plants, which happen to be upwind of the stations for the particular wind directions. The narrowness of these peaks results from the extreme sensitivity to small changes in the wind direction. The small displacement in time of the calculated from the observed power plant plume peaks results from the fact that, due to inhomogeneities in the wind field, the wind direction, which is slowly changing, is not the same, even synoptically, at the receptor and power plants. This is discussed further in Sect. 8.2.

Fig. 9. Observed (solid curve) and Calculated Hourly Concentrations at TAM 4 for February 16-18, 1967, Using Plume Model with (stars) and without (open squares) Calm Algorithm. Stars overlap squares when $u > 1$ mph. Symbol spacing not related to plotted points.

Fig. 10. Observed (solid curve) and Calculated Hourly Concentrations at TAM 5 for February 16-18, 1967, Using Plume Model with (stars) and without (open squares) Calm Algorithm. Stars overlap squares when $u > 1$ mph. Symbol spacing not related to plotted points.

Fig. 11. Observed (solid curve) and Calculated Hourly Concentrations at TAM 2 for February 16-18, 1967, Using Plume Model with (stars) and without (open squares) Calm Algorithm. Stars overlap squares when $u > 1$ mph. Symbol spacing not related to plotted points.

5. COMPARISON OF RESULTS OF PUFF- AND PLUME-MODEL CALCULATIONS

To compare the performance of the plume with the more sophisticated puff model (which requires substantially more computer time), we have selected a variety of historical periods which include a wide range of meteorological conditions. In particular, we have carried out statistical analyses on the short- and long-term basis.

The two models share all but one small part of a substantial computer code in common, so that a similarity in the quality of fit of the puff- and plume-model calculations to the observed data is to a large extent indicative of the quality of simulation produced by the common aspects of the computer codes. One expects at the onset that only where the steady-state conditions are far from the truth will there be any substantial discrepancies between the two models. We first present the results of some short-term calculations, followed by the results of calculation on a monthly basis. (The symbols used to depict various statistical quantities are defined in Appendix D.)

5.1 Short-term Comparisons

We first present a situation which is not atypical, where the puff and plume models show similar results. Figures 12 and 13* compare the SO_2 concentrations observed (solid curves) at TAM 2 and 4 on January 18-19, 1967, with those calculated with the puff model (open squares) and with the plume model (stars). The corresponding wind speeds were ≥ 2.5 mph, so that the calm algorithm was not used. TAM 2 showed a minimum wind speed of 5 mph from 1000 to 1400 on January 18; TAM 4 indicated a minimum wind speed of 2.5 mph on the same day at 1200 and 2000. Note that the agreement between the two models is quite close.

By way of contrast with January 18-19, the period of February 16-18, 1967, which was used to evaluate the calm algorithm in Sect. 4, includes a number of hours of very low wind speed (see Fig. 8). Figure 14 shows the hourly concentrations calculated at TAM 5 with the puff and plume (with the calm algorithm) models for this period. Calculations at TAM 2, 4, and 5 are compared statistically in Table 5.1. This analysis indicates that in the absence of the CA the two models differ substantially, whereas with the inclusion of the CA both models are in good agreement on the short-term basis.

*In Figs. 12 and 13, 3-hr average concentrations are plotted. For example, the average of the concentrations at hours 1, 2, and 3 is plotted at hour 2, the average of the concentrations at hours 4, 5, and 6 is plotted at hour 5, etc.

Fig. 12

SO₂ Concentrations at TAM 2 vs Time of Day, for January 18-19, 1967. Three-hour average concentrations are plotted. The solid curve is the observed, the open squares the puff-model, and the stars the plume-model calculations.

Fig. 13. SO₂ Concentrations at TAM 4 vs Time of Day, for January 18-19, 1967. Three-hour average concentrations are plotted. The solid curve is the observed, the open squares the puff-model, and the stars the plume-model calculations.

Fig. 14. SO_2 Concentrations at TAM 5 vs Time of Day, for February 16-18, 1967. Hourly average concentrations are plotted. The solid curve is the observed, the open squares the puff-model, and the stars the plume-model calculations with the calm algorithm.

TABLE 5.1. Comparison of Hourly Results of Puff (1), Plume (2), and Plume + CA (3) Calculations with Observations for February 16-18, 1967

TAM	μ_o	Model	μ_e	σ_{oe}/μ_o	50%	PN025	PN05	PN1
5	0.09	1	0.10	0.87	56	36	68	82
		2	0.25	5.07	47	32	58	68
		3	0.10	0.93	53	38	67	78
2	0.19	1	0.13	0.61	60	30	51	72
		2	0.18	0.81	60	30	50	65
		3	0.16	0.73	56	29	49	63
4	0.26	1	0.14	0.65	21	3	10	40
		2	0.25	1.32	28	6	14	42
		3	0.15	0.61	28	7	14	43

5.2 Long-term Comparisons

Table 5.2 compares puff- and plume-model calculations for January (only one-half month of data was available for TAM 5). The comparisons were carried out for $n = 1$ -, 6-, and 24-hr average concentrations. With the exception of the relative standard deviations for TAM 5, all indications are that both models produce similar results on the long-term basis. Note that the calm algorithm was not used in the steady-state plume model. Actually there were only 1 or 2 hr during January when it would have been

used anyway. There were 2 hr during which $u \leq 1$ mph at TAM 5 and the peak concentrations that occurred during these periods, along with a few other narrow but grossly overestimated power-plant peaks, resulted in the distortion of the values of σ_{oe}/μ_o indicated for TAM 5 in Table 5.2. The quantity σ_{oe}/μ_o is sensitive to the occurrence of a few large discrepancies, which generally will not show up very clearly in the percentile figures given.

TABLE 5.2. Comparison of Observed and Calculated SO_2 Concentrations for January 1967^a

TAM	Averaging Interval, hr	μ_o , ppm	μ_e , ppm	σ_{oe}/μ_o	50%	PN025	PN05	PN1
2	1	0.12	0.10/0.11	0.65/0.69	59/63	39/44	71/67	86/86
	6			0.52/0.48	66/71	50/54	75/78	92/92
	24			0.35/0.33	79/84	53/53	90/84	95/100
4	1	0.15	0.15/0.17	0.56/0.66	69/73	30/32	53/52	83/83
	6			0.41/0.47	85/83	38/33	65/58	92/88
	24			0.28/0.30	93/100	60/47	80/73	100/100
5	1	0.06	0.06/0.08	0.91/1.70	51/53	54/52	72/73	93/90
	6			0.63/1.01	65/60	60/53	83/75	95/93
	24			0.41/0.75	80/67	73/47	93/87	100/93

^aThe calculated results are given as PUFF/PLUME.

In general, the plume-model concentrations tend to be greater than those of the puff model.

Table 5.3 shows the results of calculations for August 1967, using both the puff and plume models compared with observed results.

TABLE 5.3. Comparison of Observed and Calculated SO_2 Concentrations for August 1967^a

TAM	Averaging Interval, hr	μ_o , ppm	μ_e , ppm	σ_{oe}/μ_o	50%	PN025	PN05
2	1	0.02	0.03/0.03	1.37/1.87	35/33	75/71	90/87
	6			1.04/1.45	42/46	82/75	96/91
	24			0.71/1.05	58/42	95/79	100/100
4	1	0.04	0.02/0.03	1.06/1.11	28/33	71/74	86/87
	6			0.90/0.75	31/40	72/79	85/90
	24			0.71/0.51	35/58	65/81	96/96
5	1	0.02	0.02/0.04	1.45/3.01	27/29	70/60	89/80
	6			1.19/2.41	38/28	72/60	92/83
	24			0.94/1.73	50/59	91/77	96/86

^aThe calculated results are given as PUFF/PLUME.

Unfortunately, the steps used in the percentile distribution analysis having been chosen for wintertime concentrations were much too large for

the substantially smaller summertime values, which are often close to the limits of observational accuracy (± 0.01 ppm). The puff model is superior, especially for TAM 5, which generally has very low summertime concentrations, except when TAM 5 comes under the influence of power-plant plumes. The nearest power plant is about 3 miles away. The plume model did not include the calm algorithm, so that on several occasions when the wind speed fell below 1 mph, the calculated concentrations became unrealistically high.

The relative standard deviation is probably not a good quantity to use when $\mu_0 \rightarrow 0$, since it blows up. For concentrations averaging 0.02 ppm, it is probably more reasonable to look at absolute errors as, for example, indicated by PN025 (the percent of the total number of differences between observed and calculated values within 0.025 ppm). The 50% figure, which is the percent of all differences within 50% of the corresponding observed values, is also somewhat misleading because many observed values are zero, and a nonzero calculated value no matter how small obviously would not be within 50% of zero.

6. DISCUSSION OF PLUME- AND PUFF-MODEL RESULTS

In Sect. 5 we have presented several comparisons of the results of the steady-state plume model with observed SO_2 concentrations. We have also compared these results with those of puff-model calculations, which consume substantially more computer time. The general conclusions that can be drawn from these comparisons are, first, that both models perform very well when compared with observations on both the short- and long-term basis. Marsh and Withers²⁴ have made a comparative study of several dispersion models, including their own versions plus those of several other authors. Comparing the results of 6-hr average concentrations in terms of σ_{oe}/μ_o , they found that the minimum value was 1.12. For January, the corresponding values for the puff model range from 0.41 to 0.63, and for the plume model from 0.47 to 1.01 (see Table 5.2). Second, the use of the calm algorithm for very low wind speeds (≤ 1 mph) makes a significant improvement in the plume model on the short-term basis. Third, by including the calm algorithm with the plume model, there is remarkably little difference between the calculated results of the latter model with those of the puff model, even when $u \leq 1$ mph.

Considering the increased sophistication of the puff model as well as its physical reasonableness, it is worth commenting on the relationship between the two models. Unfortunately, the puff kernel cannot be integrated analytically in general. However, under special conditions, one can treat the integral analytically in an approximate way. This is done in Sect. 7. In the present discussion, only some rather general remarks will be made.

The near equivalence of the puff- and plume-model results has been shown only for a complete urban source-emission inventory. In particular, the Chicago inventory is characterized by source-receptor distances averaging less than 10 miles, so that at a wind speed of 10 mph, one expects, on the average, that steady-state conditions will be established within 1 hr or less between most source-receptor pairs and certainly between a receptor and its corresponding local sources. Furthermore, a receptor within the urban area is subject to a superposition of a nearly isotropic distribution of local area sources as well as a very direction-dependent array of major point sources, generally 1-10 miles away. Unless one or more of these point sources are upwind of the receptor, most of the concentration will be due to the more local area sources. Consequently, except for certain wind directions, one is primarily concerned with transport distances of only a few miles and corresponding transit times substantially under 1 hr. Hence, the time step of 1 hr is more than adequate to establish steady-state conditions, assuming, of course, that the meteorological conditions and emission rates remain constant for the entire 1-hr interval. The establishment of steady-state conditions implies that one does not have to worry about causality, that is, the delay time required for transport of a plume segment from source to receptor. The question of causality only arises when the

transit time is equal to or greater than the time step since, then, not enough time will have elapsed during the time step to allow sufficient overlapping of a consecutive train of puffs to produce a steady-state condition. This point will be illustrated fully in Sect. 7.

Since the wind direction frequently remains constant for periods longer than 1 hr, one could allow for longer transit times in the plume model by increasing the time step accordingly at the expense of reduced time and spatial resolution. Alternatively, one could invoke the causality condition and simply ignore a source-receptor pair whenever $x/u >$ the time step. Unfortunately, if the wind continues to blow in the same direction during the next hour, then during that hour the plume may reach the receptor. Hence, one would be forced to track the plume in some effective way hour by hour, as is done in the model of Koogler *et al.*,²⁵ or in the more sophisticated pivoting plume model of Turner.⁹ However, as the present study indicates, at least for source distributions such as is found in Chicago, it does not seem to be the degree of sophistication of the transfer function that limits the accuracy of the model (the puff model is even more sophisticated than either of the above referenced models), but rather the combination of the remaining computer-code components plus the source inventory and meteorological input data.

Hence, for a given urban area, provided that x/u does not exceed 1 hr very often, the plume model with the calm algorithm to take care of cases in which $u \leq 1$ mph has been shown to be a reliable source-oriented dispersion model, useful for both short- and long-term analysis.

7. RELATIONSHIP BETWEEN PUFF AND PLUME EXPRESSIONS

The similarity of the results of the integrated-puff and plume models indicates that there must be an underlying relationship between the basic mathematical expressions given by Eqs. 2.2 and 2.3. To better understand this relationship, we have analytically and numerically investigated these expressions applied to a single source-receptor pair. The underlying basis for these investigations is the recognition that the primary ingredient of the puff kernel, namely,

$$\exp\{-(x - uT)^2/2\sigma_x^2(T)\},$$

is peaked about the value of the delay time $T = x/u$, which is just the transit time. Furthermore, this expression falls off exponentially for longer or shorter travel times T . Consequently, the major contribution to the concentration at a receptor in Eq. 2.2 comes from a range of values of T given roughly by $x/u - \sigma(x/u) < T < x/u + \sigma(x/u)$. This expression is not really symmetric about x/u because of the distortion caused by $\sigma_x(T)$. That is, the older puffs are larger than the younger ones. By rewriting the exponential argument as $(x/u - T)^2/[2(\sigma_x(T)/u)^2]$ we can see that the wind speed u scales the rate of fall-off of the integrand from its peak value. The smaller u is, the larger will be the range of T over which the integrand in Eq. 2.2 will contribute significantly. Hence, at low wind speed not only does the transit time x/u become large but so does the time required to achieve steady state. Consequently, the plume model is less satisfactory than the puff model at low wind speeds, both because of the wind-speed dependence of the plume expression (see Sect. 2.4) and because of the effect of the transit time described above, which is really a causality condition.

Section 7.1 presents an analytical analysis of the relationship between the puff and plume expressions under rather specialized conditions. This is followed by some numerical experiments.

7.1 Analytical Analysis of Relationship between Puff and Plume Expressions

For this analysis, we shall consider the case of constant meteorological conditions and a constant emission rate. For convenience, we average over the mixing layer (of depth H) to remove the dependence on the coordinate z . Finally, we ignore the exponential decay factor. Under these conditions, Eq. 2.2 for the integrated puff becomes

$$\frac{HX}{Q} = \int_0^T \frac{dT}{2\pi\sigma_y^2(T)} \exp\left[-\frac{(x - uT)^2 + y^2}{2\sigma_y^2(T)}\right]. \quad (7.1)$$

The corresponding plume expression is

$$\frac{HX}{Q} = \frac{1}{\sqrt{2\pi} u \sigma_y(x/u)} \exp\left\{-\left[y^2/2\sigma_y^2\left(\frac{x}{u}\right)\right]\right\}. \quad (7.2)$$

For convenience, we assume

$$\sigma_x(T) = \sigma_y(T) = aT^b. \quad (7.3)$$

A Taylor expansion of the puff kernel about the delay time $T = \frac{x}{u}$ is given by

$$\exp\left[-\frac{(x-uT)^2 + y^2}{2a^2T^{2b}}\right] = e^{-\eta} \left\{ 1 + \frac{T - x/u}{x/u} 2b\eta + \frac{1}{2} \left(\frac{T - x/u}{x/u}\right)^2 \times \left[(2b\eta)^2 - \frac{14}{4}(2b)^2\eta - \frac{2x^2}{2a^2\left(\frac{x}{u}\right)^{2b}} \right] + \dots \right\}, \quad (7.4)$$

where

$$\eta = y^2 / \left[2a^2 \left(\frac{x}{u}\right)^{2b} \right]. \quad (7.5)$$

We now assume, consistent with the Taylor expansion, that the major contribution to the integral comes from the range $x/u - \delta_- \leq T \leq x/u + \delta_+$, where the small quantities δ_- and δ_+ are yet to be determined.

Substituting Eq. 7.4 into Eq. 7.1 yields

$$\frac{XH}{Q} = \int_{\frac{x}{u}-\delta_-}^{\frac{x}{u}+\delta_+} \frac{dT}{2\pi a^2 T^{2b}} e^{-\eta} \left(1 + \frac{T - x/u}{x/u} 2b\eta + \dots \right). \quad (7.6)$$

If we assume that $\delta_- = \delta_+ = \delta$, then only the first term in the expansion will contribute to lowest order in δ since it can be shown that, to order δ ,

$$\int_{\frac{x}{u}-\delta}^{\frac{x}{u}+\delta} \frac{dT}{T^{2b}} (T - x/u)^n = 0 \text{ for } n \geq 1.$$

Consequently, to order δ ,

$$\frac{\chi H}{Q} = \frac{e^{-\eta}}{\pi \sigma^2 \frac{x}{u}} \delta. \quad (7.7)$$

Assuming $\delta_+ \neq \delta_-$, what values should one use? Two conditions assist in the specification of these quantities.

(1) Since $(T - x/u)/(x/u) < 1$ for convergence of the Taylor expansion, and since $x/u - \delta_-$ and $x/u + \delta_+$ are the limiting values of T , it follows that both $\delta_+/(x/u)$ and $\delta_-/(x/u)$ must be < 1 .

(2) The quantities δ_- and δ_+ must be sufficiently large so that a substantial portion of the entire integral is contained within the integration limits.

Consider now the integrand

$$I(T) = \exp \left[- \frac{(x - uT)^2}{2a^2 T^2 b} \right]. \quad (7.8)$$

Obviously,

$$I(T = x/u) = 1,$$

and

$$I(T = x/u \pm \epsilon) = \exp \left\{ - \left[\frac{\epsilon}{\frac{\sqrt{2}a}{u} \left(\frac{x}{u} \right)^b \left(1 \pm \frac{\epsilon}{x/u} \right)^b} \right]^2 \right\}.$$

The values of ϵ for which

$$I(x/u \pm \epsilon) = \frac{1}{e} \quad (e = 2.71 \dots)$$

are now designated by δ_- and δ_+ , where

$$\left. \begin{aligned} \delta_- &= \delta \left(1 - \frac{\delta_-}{x/u} \right)^b = \delta \left[1 - b \left(\frac{\delta_-}{x/u} \right) + b^2 \left(\frac{\delta_-}{x/u} \right)^2 - \dots \right] \\ \text{and} \\ \delta_+ &= \delta \left[1 + b \left(\frac{\delta_+}{x/u} \right) + b^2 \left(\frac{\delta_+}{x/u} \right)^2 + \dots \right], \end{aligned} \right\} \quad (7.9)$$

and where

$$\delta = \frac{\sqrt{2}a}{u} \left(\frac{x}{u} \right)^b.$$

Again, if we only keep terms of order δ in Eqs. 7.9 then only the first term in Eq. 7.6 contributes.

To lowest order in δ_- and δ_+ , the first term in Eq. 7.6 gives

$$\frac{\chi H}{Q} = \frac{\exp[-y^2/2\sigma_y^2(x/u)]}{\frac{\pi}{\sqrt{2}}\sigma_y(x/u)u} \left[1 + \frac{b^2\delta^2}{x^2/u^2} + \dots \right]. \quad (7.10)$$

The important point about this expression is that the general form, in particular the $1/u$ dependence, is the same as that of the plume expression. In addition, as long as δ remains small, the resemblance is quite close. The smallness of δ means that

$$\frac{\delta}{x/u} < 1, \quad (7.11)$$

which is the same criterion required for convergence of the Taylor expansion. Substituting Eqs. 7.9 into Eq. 7.11 gives

$$\sqrt{2}a\left(\frac{x}{u}\right)^b < \frac{x}{u}$$

or

$$\sqrt{2}\sigma_y\left(\frac{x}{u}\right) < x.$$

That is, the spread of the individual puffs is small compared to the downwind distance, or alternatively the diffusion rate is small compared to the advection rate. Evidently the lower the wind speed the worse the equivalence between the puff and plume expressions.

7.2 Numerical Analysis of Relationship between Puff and Plume Expressions

To augment the analytical analysis of Sect. 7.1, we have performed several numerical experiments in which we calculate the concentrations for given source-receptor pairs (values of x and y) and various values of the wind speed u and stability class (which determine the parameters a and b in Eq. 7.3). We calculate the concentration using, first, the plume expression (Eq. 7.2), and then the puff expression (Eq. 7.1). The puff integral is evaluated at 5-min intervals from the start of a continuous release of pollutant. Performing the calculations in this way, one is able to see the time dependence of the puff kernel and, in particular, the approach of the integrated puff kernel to the steady-state expression as time increases.

Figures 15 and 16 show the value of $\chi H/Q$ calculated from the puff expression given by Eq. 7.1 at receptors located 1, 5, and 10 miles downwind from a point source as a function of the time after start of a continuous release. The crosswind distance y is zero in Fig. 15 and $1/4$ mile in Fig. 16. The wind speed u is 5 mph in both figures. Two values of the stability class (SC) are given, namely, 1 (very unstable) and 5 (quite stable). Several things are worth noting in these figures. First, the time required for the integrated-puff expression to reach steady state is strongly dependent on the downwind distance x and somewhat less strongly dependent upon the crosswind distance y and stability class. Consequently, if one were working with a time step of 1 hr, then for x less than about 4 miles, steady-state conditions would essentially have been achieved, so that the puff and plume models would yield rather similar results. On the other hand, for distances x in excess of 5 miles, the causality requirement becomes important and the assumption of steady state would clearly lead to an overprediction. Such would be the case for important distant sources such as power plants. Another point worth noting is that the rise time from essentially zero to maximum value of $\chi H/Q$ depends both upon the stability class (increasing with decreasing stability) and the value of x/u . The dependence of the rise time on x/u comes about from the fact that the greater the travel time the more adjacent puffs tend to overlap, so that the significant values of the integrand are spread over a wider time span. For $y = 0.25$ mile, the concentration is actually greater at $x = 1$ mile for the more unstable case, whereas at $x = 5$ miles the concentration is greater for the more stable case. This is as one would expect.

Table 7.1 shows the results of a number of numerical experiments in which the puff and plume expressions (Eqs. 7.1 and 7.2, respectively) have been evaluated for a variety of values of u , x , y , and stability class. Both expressions agree over a remarkably wide range of these parameters, provided that an ample amount of time is permitted for steady-state conditions to be achieved. For $x = 1$ mile and $u = 5$ mph, steady-state conditions are reached in about 20-25 min, whereas for $x = 5$ miles it takes about $1\frac{1}{2}$ hr. In the latter case, using a basic time step of 1 hr, the steady-state-model result would be greater than the puff-model result. However, if the same input conditions persisted for the next hour, then both the puff and plume models would agree. On the other hand, if there were a wind-direction shift after 1 hr, then again the plume model would overpredict the puff model. Hence, for the puff and plume models to produce substantially different results, two things are necessary. First, $x/u \geq$ basic time step, and second, the wind direction or other input data must change significantly from hour to hour.

Fig. 15. XH/Q vs Time for the Integrated-puff Kernel as a Function of Stability Class (SC) and Downwind Distance (X) (see Eq. 7.1); $u = 5$ mph, $y = 0.0$. ANL Neg. No. 130-169.

Fig. 16. XH/Q vs Time for the Integrated-puff Kernel as a Function of Stability Class (SC) and Downwind Distance (X) (see Eq. 7.1); $u = 5$ mph, $y = 0.25$ mile. ANL Neg. No. 190-171.

TABLE 7.1. Relationship between Puff and Plume Expressions for Various Wind Speeds u , Crosswind Distances y , and Downwind Distances x

u, mph	y, mi	x, mi	$\frac{\delta a}{x/u}$	STABILITY CLASS 1					STABILITY CLASS 5				
				T10, ^b	TP, ^c	T90, ^b	$\chi H/Q$		T10, ^b	TP, ^c	T90, ^b	$\chi H/Q$	
				min	min	min	Puff	Plume	min	min	min	Puff	Plume
5	0	0.5	0.52	1	10	12	0.423	0.434	6	<10	<10	1.698	1.713
		1	0.47	7	15	17	0.236	0.241	12	<15	<15	0.922	0.918
		5	0.36	45	55	87	0.060	0.061	59	60	68	0.213	0.216
		10	0.33	92	115	160	0.032	0.034	111	120	132	0.114	0.116
	0.25	0.5	0.52	3	10	13	0.174	0.172	-	-	-	0	0
		1	0.47	9	15	22	0.175	0.181	12	<15	<15	0.017	0.014
		5	0.36	38	55	86	0.059	0.060	54	60	66	0.169	0.172
		10	0.33	87	115	161	0.032	0.034	110	120	129	0.107	0.108
	0.50	0.5	0.52	7	10	19	0.033	0.011	-	-	-	0	0
		1	0.47	10	15	24	0.081	0.077	-	-	-	0	0
		5	0.36	43	55	89	0.056	0.057	56	65	67	0.086	0.087
		10	0.33	87	115	162	0.032	0.033	112	120	133	0.088	0.089
10	0	0.5	0.29	<5	<5	<5	0.390	0.392	1	<5	<5	1.598	1.598
		1	0.26	4	<10	<10	0.213	0.217	7	<10	<10	0.856	0.856
		5	0.20	26	30	38	0.055	0.055	29	30	33	0.197	0.201
	0.25	0.5	0.29	1	5	9	0.026	0.019	-	-	-	0	0
		1	0.26	6	<10	<10	0.086	0.085	-	-	-	0	0
		5	0.20	27	30	36	0.051	0.052	29	35	33	0.089	0.091

^a $\delta/(x/u)$ is the expansion parameter in the Taylor expansion (see Sect. 7.1).

^bT10 and T90 are the times measured from the start of a continuous emission when the puff integral (evaluated at 5-min intervals) reaches 10 and 90% of its final value, respectively.

^cTP is the time when the integrand reaches its peak value.

8. SENSITIVITY ANALYSIS OF STEADY-STATE PLUME MODEL

This section presents an analysis of the effects of changing various meteorological input data on the calculated SO_2 concentrations using the plume model. In particular, we have investigated the sensitivity of the results to replacing the TAM station aerovane measured winds with the Midway Airport measured winds. In addition, we have also studied the specific effects of changes in the wind direction measured at various TAM winds on calculated concentrations at those TAM stations. We also determined the effect of modifying the mixing height in accordance with the expected errors obtained in the comparative study¹⁸ of techniques for estimating the mixing height.

8.1 Use of Midway Wind Field

The Chicago area is fortunate in having a network of TAM stations which continuously monitor the wind speed (WS) and wind direction (WD) as well as SO_2 concentrations (and other pollutant species).* (See Ref. 1 for a description of the location of each TAM station.) Advantage is taken of these wind measurements in both the puff and plume models by using the winds measured at the TAM station where SO_2 concentrations are being calculated. (The wind-profile law is used to convert the wind at the TAM aerovane height to the effective stack height for each source.) In this way, some of the inhomogeneity in the Chicago area wind field (to the extent that any inhomogeneity exists; see Sect. 8.2) is taken into account. That an inhomogeneity in the wind field on a scale of several miles can be important comes about because the concentration at a particular receptor is the result of the superposition of pollutants emitted from a roughly isotropic distribution of local area sources plus a very direction-sensitive distribution of point sources. In fact, experience shows that peaks in the concentrations resulting from a gradual change in the wind direction that slowly sweeps a power-plant plume across a particular receptor are frequently calculated to occur at a WD several degrees displaced from the corresponding directions for which the peaks are actually observed. This could arise because the wind direction at the source is somewhat different from that at the receptor, which in turn could be due to an inhomogeneity in the wind field and/or possible local effects due to poor siting of the TAM aerovanes.

In any case, we wished to examine the effect of using a wind field even less well defined than that which is specified by the TAM network. For this purpose, we chose to use the wind measurements taken at Midway Airport (see Fig. 1).

The effect of using the Midway winds instead of the TAM winds is examined in two ways. First, we compare calculations using Midway winds with observations to see statistically how the agreement between calculations using TAM winds and observations is modified. Second, we compare

*Species currently monitored include CO, NO, and NO_2 .

Midway results directly with TAM results in the more usual sensitivity test fashion to see what difference the use of a less well-defined wind field makes.

In performing these comparisons, it became apparent that the wind-profile law plays a significant part in this type of sensitivity study. Whereas the Midway winds are measured 20 ft above ground, in a completely open area (the center of the Midway Airport), unobstructed by buildings for at least 1/4 mile in all directions, the TAM aerovanes are located on 20-30-ft. masts atop three- or four-story school buildings in an urban environment.

Consequently, not only are the heights substantially different, but so are the surface-roughness conditions and therefore the degree and character of mechanical turbulence. In addition, whereas the Midway winds are 1-min averages, the TAM winds are continuously recorded and averaged over 15-min intervals. Strong,²⁶ however, claims that statistical analyses have shown that the 1-min readings at the Midway aerovane are quite satisfactory.

We determined that the fairest way to perform the calculations was to apply the same wind-profile law to the Midway winds as to the TAM winds. The form of the wind-profile law used in our computer code is

$$\frac{U(h_{\text{eff}})}{U(h_{\text{aero}})} = \left(\frac{h_{\text{eff}}}{h_{\text{aero}}} \right)^P,$$

where eff and aero refer to the effective stack height and aerovane height, respectively, and P varies from 0.2 to 0.5 as the stability increases from 1 to 5. This law is assumed to be valid to a height of approximately 1000 ft (De Marrais²⁰). Beyond 1000 ft, the velocity is assumed independent of height.

For the TAM aerovanes, the law was effectively restricted approximately to 1000 ft by setting an upper limit of 3 to the ratio $U(h_{\text{eff}})/U(h_{\text{aero}})$. However, because of the substantial difference between the heights of the TAM aerovane and the Midway aerovane, it was necessary to increase this upper limit to 5.6 in the latter case.

8.1.1 Direct Comparison of Observed with Calculated SO₂ Concentrations Using Midway Winds and Also with Calculations Using TAM Winds

Table 8.1 compares calculated and observed SO₂ concentrations using alternatively TAM and Midway winds for January 1967. The statistics are calculated using 1-, 6-, and 24-hr interval averages. Whereas the calculated monthly means using either the TAM or Midway winds appear to be about equally close to the observed means, the relative standard deviations for the Midway wind calculations are substantially larger than for the TAM wind calculations.

TABLE 8.1. Calculated vs. Observed Results
Using TAM and Midway Winds, January 1967

TAM	No.	μ_o	TAM, μ_e	Midway, μ_e	TAM, σ_{oe}/μ_o	Midway, σ_{oe}/μ_o	Average Interval, hr
2	456	0.12	0.11	0.14	0.69	1.02	1
					0.48	0.51	6
					0.33	0.34	24
4	360	0.15	0.17	0.15	0.66	1.07	1
					0.47	0.77	6
					0.30	0.53	24
5	360	0.06	0.08	0.08	1.70	3.10	1
					1.01	2.14	6
					0.75	1.11	24

On the other hand, in terms of the percentile distributions of the differences $\chi_o - \chi_e$ shown in Table 8.2, there is relatively little effect in changing from the TAM to the Midway winds.

TABLE 8.2. Percentile Distribution of Differences between Calculated and
Observed Results Using TAM and Midway Winds, January 1967

TAM	TAM PN025	Midway PN025	TAM PN05	Midway PN05	TAM PN1	Midway PN1	TAM, 50%	Midway, 50%	Average Interval, hr
2	0.44	0.39	0.67	0.65	0.86	0.82	0.63	0.64	1
	0.54	0.46	0.78	0.74	0.92	0.91	0.71	0.77	6
		0.42		0.95		0.95	0.84	0.89	24
4	0.32	0.30	0.52	0.51	0.83	0.77	0.73	0.58	1
	0.33	0.40	0.58	0.55	0.88	0.83	0.83	0.70	6
		0.47		0.80		0.87	1.00	0.80	24
5	0.52	0.54	0.74	0.75	0.90	0.93	0.53	0.48	1
	0.60	0.58	0.83	0.83	0.95	0.97	0.60	0.68	6
		0.73		0.93		0.93	0.67	0.80	24

The conclusions that one can draw from the direct comparison of observed results with calculations using Midway winds instead of TAM winds are:

- (1) As far as monthly averages are concerned, there is relatively little effect.
- (2) In terms of percentile distributions of the differences $\chi_o - \chi_e$, there is also relatively little difference.
- (3) To the extent that one is interested in long-term statistics, it makes little difference whether one uses TAM or Midway measured winds.

- (4) In terms of short-term analysis, the quality of fit of calculated to observed results, as expressed by the relative standard deviations σ_{oe}/μ_o , is significantly better for the TAM winds.

8.1.2 Comparison of Calculations Using Midway and TAM Winds

A comparison of the Midway wind-based calculations directly with the TAM wind-based calculations is also rather interesting from the classical sensitivity point of view. Table 8.3 compares these calculations. The magnitude of the error obtained in using the Midway winds (assuming the TAM winds to be exact at the TAM stations) depends significantly on the TAM station. Figure 1 shows a map of Chicago including the locations of the TAM stations and Midway Airport. TAM 5 is seen to be the closest to Midway, and TAM 2 the furthest away. TAM 4 is about 0.6 mile from the lake, whereas TAM 2 is 1.6 miles from the lake.

TABLE 8.3. Analysis of $\chi_{TAM} - \chi_{Mid}$ for January 1967

TAM	μ_d	$\sigma(TAM-Mid)$	PN025	PN05	PN1	Interval, hr
2	-0.03	0.13	47.1	63.4	81.1	1
	-0.03	0.08	43.4	64.5	84.2	6
	-0.03	0.07	38.6	68.4	94.7	24
4	0.02	0.16	37.5	66.4	88.6	1
	0.02	0.1	35.0	73.3	93.3	6
	0.02	0.06	26.7	73.3	93.3	24
5	0	0.21	67.2	81.1	89.2	1
	0	0.13	75.0	86.7	91.7	6
	0	0.03	73.3	86.7	93.3	24

In terms of the mean difference, μ_d , or the percentile distribution of the differences $\chi_{TAM} - \chi_{Mid}$, TAM 5 is seen to be in best agreement with the Midway wind calculations, presumably because it is also the closest and occupies the most similar environment (i.e., is farthest from the lake).

8.2 Sensitivity to Changes in Wind Direction

In order to examine the sensitivity of the plume model to changes in the wind direction (WD) somewhat more explicitly than in the Sect. 8.1, we compared calculations using the TAM WD modified by first adding then subtracting 15° with the calculations using the original TAM WD for selected short periods.

Table 8.4 compares the results of calculations using the three different choices for WD. The means are seen to be somewhat sensitive to changes of $\pm 15^\circ$ in the WD. Changes in WD of this magnitude produced changes in μ_e of the order of 15-30%. The original values of WD provided about the best overall fit to the observed means. However, there are some significant exceptions. The values of σ_{oe}/μ_o corresponding to the three different calculations are quite interesting. First, there appears to be a general asymmetry between the $\theta + 15^\circ$ and $\theta - 15^\circ$ calculations as compared to the θ (original WD) results. With the exception to TAM 5, January 12-15, there is a definite deterioration in the σ_{oe}/μ_o values when $\theta \rightarrow \theta + 15^\circ$. On the other hand, when $\theta \rightarrow \theta - 15^\circ$, there are significant improvements in the results at least for TAM 2, January 12-15, and TAM 4, January 12-15 and January 18-19. The fact that it was actually possible to improve the results averaged over 2- and 4-day periods (in these cases) is a bit remarkable. Since the improvement only occurred for some periods but not others, one can make two plausible deductions. First, there may have been something special about those particular periods, and second, for long-term analysis (one or more months) such short-term special conditions would be unimportant. The special circumstances could, for example, be that the prevailing wind directions combine with systematic wind-direction errors caused by real nonuniformities in the wind field. To explore the situation somewhat further, we analyzed the WD measurements at Midway and TAM stations 2, 4, and 5. Note that whereas the Midway aerovane is located on a 20-ft mast isolated from all other structures, the TAM aerovanes are placed on 20-40-ft masts on top of three- or four-story buildings in urban areas. Consequently, the effects of local obstructions to air-flow, including that of the building on which the TAM aerovane is mounted itself, cannot be ruled out.

TABLE 8.4. Comparison of Calculations for Different Wind-Direction (WD) Modifications (θ is the original wind direction)

TAM	Dates, January 1967	Interval, hr	μ_o	μ_e			σ_{oe}/μ_o		
				$\theta - 15^\circ$	θ	$\theta + 15^\circ$	$\theta - 15^\circ$	θ	$\theta + 15^\circ$
2	12-15	1	0.13	0.12	0.10	0.09	0.54	0.67	0.84
		6					0.35	0.53	0.78
	18-21	1	0.17	0.18	0.16	0.12	0.54	0.49	0.60
		6					0.34	0.34	0.53
4	12-15	1	0.17	0.15	0.17	0.22	0.46	0.52	0.62
		6					0.32	0.40	0.49
	18-19	1	0.24	0.18	0.21	0.24	0.39	0.51	0.60
		6					0.35	0.46	0.54
5	12-15	1	0.07	0.06	0.06	0.08	0.88	0.76	0.76
		6					0.56	0.49	0.51

Figure 17 shows plots of the wind direction measured at TAM 4 and 5 and at Midway Airport for the 4-day period January 12-15, 1967. Figure 1 shows that Midway Airport, TAM 5, and TAM 4, are roughly in line as one travels east toward the lake. TAM 2, on the other hand, is several miles to the north of TAM 5. The convention that a northerly wind (i.e., one coming from the north) has a direction of zero degrees, with the angular direction increasing in a clockwise rotation, is used in the following discussion.

Fig. 17. Measurements of WD at TAM 5 for January 12-15, 1967. ANL Neg. No. 190-170.

With the exception of a few hours on the 12th day, the WD systematically increases in the clockwise sense as one moves from Midway toward the lake during the entire period between hours 0 and 60. This strongly implies that wind coming out of the south-to-southwest sectors is gradually shifted to a more westerly direction as it moves closer toward the lake. This further suggests the existence of a convergence zone of northerly and southerly winds in the vicinity of the Chicago area during that period. The consequences of such small-scale nonuniformities in the WD on dispersion modeling can be substantial. Suppose, for example, we consider a major point source and a receptor several miles away. Whereas the wind direction measured at the receptor might imply that the point source was upwind, due to a nonuniformity in the wind field the plume trajectory could actually miss the receptor completely. Detailed analysis of the results of the January 12-15 calculations revealed that this is precisely what happened during those periods where subtracting 15° from the WD actually improved the results.

The fact that real nonuniformities can exist on a local scale has been demonstrated by other investigations. One of the earlier Argonne reports²⁷ indicates that "important local wind anomalies do occur (mostly lake breezes) and that their magnitude is such that TAM measurements are accurate enough to detect them." Lyons²⁸ has found complex flow patterns during the summer resulting from the influence of the lake. He has demonstrated that such spatial dependences of the wind field can have important effects on the transport of pollutants.

Consequently, it is recommended that these local WD anomalies be further investigated and that an attempt be made to introduce spatially dependent wind fields into the dispersion model.

One final comment regarding the effect of WD is worth mentioning. The fact that a dispersion model places a plume at an incorrect location on the map may or may not be significant, depending upon what the dispersion-model calculations are being used for. If, for example, one were trying to evaluate the effect of an air-quality regulation on the basis of calculated concentrations at a particular receptor, then the effect of the WD would be important. On the other hand, if calculations were performed over a reasonably fine mesh grid of receptors and isopleths were drawn in, then the precise location of the large plumes would not be very important.

8.3 Sensitivity to Changes in Lid Height

The effect of changing the lid height on the plume-model calculations was examined for the same short-term periods as in Sect. 8.2. To obtain an idea of the kind of errors that are typical when various techniques are used to estimate the lid height, the results of the Objective Estimate of the Mixing Height method¹⁷ was compared with results based on Midway soundings.¹⁸ This study indicated that most of both the morning and afternoon mixing-height estimates based upon the two techniques were within 50%. For the small mixing heights, a value of 300 ft seemed a reasonable estimate of the error. (We used 250 ft in the sensitivity analysis.)

Following these results, we compared calculations of SO₂ concentrations using the original lid-height (LH) estimates (objective estimates) with those obtained by making the following modifications of LH:

- if $LH \geq 500$ (ft), $LH \rightarrow LH \times (1 \pm 0.5)$;
- if $LH \leq 500$ (ft), $LH \rightarrow LH \pm 250$ ft;
- if $LH < 250$ (ft), $LH \rightarrow 0$, or $LH + 250$ ft.

Figure 18 is a plot of the hourly values of LH for January 18-19, 1967, along with the SO₂ concentrations calculated at TAM 2 with the standard LH values (solid line) and the reduced values (broken line). For $LH \geq 500$ ft,

the concentration increases with decreasing LH. However, for lower values, because of the effects of stacks (either the physical or effective stack height) penetrating the lid, the concentrations at TAM 2 (80 ft above ground level) actually decreases with decreasing LH. That is, account is taken, in the model, of the fact that pollutants emitted in or above an inversion layer do not mix down into the lower layers (unless something subsequently happens to the inversion layer).

Fig. 18. Effect of Reducing Lid Height on Plume-model Calculations (January 19-20, 1967). ANI, Neg. No. 190-148.

Table 8.5 compares the means (μ_e , μ_o) and relative standard deviations σ_{oe}/μ_o (see Appendix D for definitions of these quantities) obtained

TABLE 8.5. Comparison of Calculations for Different Lid-height (LH) Modifications

TAM	Dates, January 1967	Interval, hr	μ_o , ppm	μ_e , ppm			σ_{oe}/μ_o		
				LH - 50%	LH	LH + 50%	LH - 50%	LH	LH + 50%
2	12-15	1	0.128	0.098	0.104	0.087	0.78	0.67	0.76
		6					0.70	0.53	0.70
	18-21	1	0.169	0.166	0.158	0.144	0.61	0.49	0.44
		6					0.51	0.34	0.31
4	12-15	1	0.170	0.181	0.174	0.147	0.50	0.52	0.47
		6					0.43	0.40	0.43
	18-19	1	0.235	0.269	0.212	0.198	0.76	0.51	0.45
		6					0.79	0.46	0.40
5	12-15	1	0.072	0.059	0.059	0.053	0.76	0.76	0.75
		6					0.54	0.49	0.53

for the various LH modifications. The means are seen to be inversely proportioned to LH, although this proportionality is somewhat mitigated by the lid-penetration effects. The dependence of σ_{oe}/μ_o on the modifications to LH indicates that the spread of the differences remains essentially unchanged for LH + 50% (a slight reduction occurs in some cases) and is increased for LH - 50%. Note that the slight reductions in spread (σ_{oe}/μ_o) occurring for certain cases when LH $\rightarrow$ LH + 50% is accompanied by a significant overall reduction in the concentrations as indicated by the reduced mean values. Consequently, such overall changes in LH do not seem to produce any systematic improvement.

Table 8.6 shows the percent changes calculated from the results given in Table 8.5. From Table 8.6 it is seen that for the magnitude of variations of LH considered ($\pm 50\%$), one can expect changes in the concentration of the order of 15% on the short-term basis (periods of 2-4 days).

TABLE 8.6. Percent Changes in Mean Concentration Calculated for Selected Short Periods When Lid Height Is Modified

TAM	Dates, January 1967	% Change in μ_e	
		LH $\rightarrow$ LH - 50%	LH $\rightarrow$ LH + 50%
2	12-15	-6	-16
	18-21	5	-9
4	12-15	4	-16
	18-19	27	-7
5	12-15	0	-10

9. STRUCTURE OF STEADY-STATE PLUME COMPUTER CODE

The structure of the plume computer code is essentially the same as that of the puff-model code described in detail in Ref. 1. Figure 19 is a flow diagram indicating critical calculations and major subroutines in the model. It is not a traditional computer flow chart, in that some of the calculations (for example, the simulation of hourly emissions from major sources) are

Fig. 19. Flow Chart of Plume-model Code

performed by separate codes. The dispersion code begins with PROGRAM APDATA, a routine written in PL/1, which reads and organizes hourly source and meteorological data stored on magnetic tape. This routine reflects the special features of the Argonne Master Air Pollution Information and Computation (APICS) system,²⁹ and, for the purposes of this report, its main feature is the transmittal of the input data, one hour at a time, to the FORTRAN subroutine ISPDAV via the entry PUFF. The calculation of pollution levels over the receptor grid is then managed by ISPDAV according to Fig. 19. Listings for all routines appear in Appendix B. The code is designed to be coupled with the APICS system and is in a developmental stage. The logic can easily be made more efficient, and the multiplicity of DATA statements (for example, those describing additional point sources not already in the PLANTSIM file) could be handled as card input.

Subroutine ADAT2 is called from ISPDAV in order to read card input specifying the geometry of the region. Three grids are defined at this point:

- (1) The area-source grid for the region.
- (2) The receptor grid.
- (3) A standard area-source overlay grid to facilitate calculations of concentrations from actual area sources.

Comparing Fig. 19 with Fig. 1 in Ref. 1, it will be noted that subroutines INTEG1, which is a numerical integration routine, and KERN, which evaluates the puff kernel, have been deleted. In addition, the tasks performed by subroutine ITRAN have been significantly modified. The detailed programming changes required to implement the plume model occurred in subroutines ISPDAV, ITRAN, and ADAT2. These changes are described in Sect. 9.1. Another subroutine, CRDNTP, has been added to calculate the downwind and crosswind distances DW and CW, respectively.

9.1 Subroutine ISPDAV (Entry PUFF)

Subroutine ISPDAV, which is normally entered from APDATA via entry PUFF (see Fig. 19 and listing in Appendix B), is the principal subroutine of the dispersion code. It performs or controls eight major functions via other subroutines. These are denoted in the ISPDAV listing by numbered comment cards:

- (1) Initialize all arrays, including specifications of receptor grid and area-source data read in via subroutine ADAT2.
- (2) Store all meteorological data for hour M.
- (3) Calculate effective stack height for each major point source specified by PLANTSIM.

(4) Calculate concentration at each receptor point from point sources specified by PLANTSIM and from additional point sources.

(5) Calculate hourly emissions from area sources.

(6) Evaluate coupling coefficients between each square in a standard area-source grid and a reference receptor point.

(7) Apply the coupling coefficients to calculate concentrations due to actual area sources by applying the standard area-source grid to each receptor point.

(8) Print out concentrations at each receptor point, and, if desired, punch cards to serve as input to statistical codes.

These eight functions are described in detail in Ref. 1.

The parameter NMAX (see listing in Appendix B of ISPDAV) controls the amount of look-back time in the puff code. To implement the steady-state plume model, we set NMAX = 1 hr. That is, by restricting the look-back time to 1 hr we can calculate hourly concentrations in the standard way with the assumption that meteorological and emission data remain constant for 1-hr intervals, and that steady-state conditions are established by the end of each hour.

The original puff-model code, as described in Ref. 1, calculated concentrations over a receptor grid whose vertices coincided with the area-source grid. To save computer time and to concentrate on the detailed calculations at particular TAM stations, suitable changes were made in subroutines ISPDAV and ADAT2 (which reads in data cards specifying the receptor grid) so that the code would calculate concentrations at the exact location of one TAM station at a time using the wind measured at that TAM station.

9.2 Function ITRAN (Entry TRAN)

A statement in entry PUFF of the form

$$CHI = EMIS(JSUB(M-N+1),K,J)*TRAN(N,M,K,J,NTRAN)*0.381\ E-4$$

calculates the concentration CHI (ppm) at hour M due to a steady emission EMIS (lb/hr) between the hours M - N and M - N + 1 from stack K at plant J. In the steady-state plume model, N = 1. Entry TRAN of function ITRAN thus calculates the normalized ($\bar{X}/Q$) concentration at a single receptor due to a given point source. ITRAN is linked to ISPDAV by common statements which transmit the source and receptor coordinates and all pertinent meteorological variables. In addition, if the source is actually a virtual source

located upwind of a physical stack or area source, the time increments TX, TY, and TZ (hr) as determined by solving the equations

$$\sigma_{x0} = \sigma_x(TX), \sigma_{y0} = \sigma_y(TY), \text{ and } \sigma_{z0} = \sigma_z(TZ)$$

are also specified. These equations are solved for values of the time increments associated with pseudoupwind point sources in subroutine PSEUDO which is called by ISPDAV before ITRAN is called.

Function ITRAN (entered via TRAN) performs the following major calculations:

(1) Calculates the location of the virtual sources simulating reflection from the ground and the lid with the following restrictions:

a. If the physical stack penetrates the lid, the lid is set equal to 10,000 ft (effectively infinite) and the stability classes set = 5 (very stable).

b. If the physical stack is below the lid but the effective stack height is above the lid, then proceed as in a) except stability class = 4.

c. If effective stack height is below lid and receptor is above, ignore source (TRAN = 0.0).

(2) Calculates downwind (DW) and crosswind (CW) distance using CRDNTP.

(3) Calculates the normalized concentration χ/Q at a receptor due to a single point source. First the wind speed is compared with a critical value WJWG. If $WS < WJWG$, then the "calm algorithm" is used. Otherwise, the plume expression is used. If $WS > WJWG$ but $DW < 0$ (source is downwind of receptor), the source is ignored and $TRAN = 0.0$.

Evaluation of the plume expression proceeds as follows:

First, the sum of three terms, namely the source term (χ_1), the first virtual image below ground (χ_2), and the first virtual image above lid (χ_3), are compared with a parameter EPS (= 0.001 ppm). If $\chi_1 + \chi_2 + \chi_3 < EPS$, the source is ignored and $TRAN = 0.0$. If the sum exceeds EPS, then higher-order multiple images are calculated by standard Gaussian exponential factors; i.e., given $X_3 = [\text{concentration at receptor from a source image located } Z_3 \text{ miles above the receptor}]$, then the concentration X_4 due to the image located Z_4 miles above the receptor is given by

$$X_4 = X_3 \exp \frac{Z_3^2 + Z_4^2}{2\sigma_z^2}$$

All the image terms (up to nine terms) are then summed to obtain the total concentration returned as $TRAN = ADD\ 1 + ADD\ 2 + \dots + ADD\ 9$ where, ADD 1, ADD 2, etc., represent the normalized concentrations from the various image terms.

9.3 Input Data

The kinds and methods of handling of input data in the plume model code are identical to the puff-mode code of Ref. 1. Consequently, such items will be discussed only briefly here. The FORTRAN computational sub-routines, of which the principal one is ISPDV, are linked to the Master File of the APICS data management system by the PL/1 routine APDATA. The Master File contains historical meteorological data and annual emission data for the major point sources. The annual major point-source emission data is processed by PLANTSIM, which returns hourly emission rates for the historic period of interest (specified by input data cards). APDATA returns meteorological and point-source emissions data hour by hour to ISPDV via entry PUFF. Additional data not stored in the APICS system are the following:

(1) Additional point-source annual emission rates are stored in data statements in ISPDV. These data are processed within ISPDV to produce emissions hour by hour.

(2) Area-source annual emission rates are stored on input data cards, which are read in via ADAT2 and passed to ISPDV, where they are processed to obtain hour-by-hour emission rates.

(3) ADAT2 also reads a number of other bits of information from data cards including:

- (a) Date limits.
- (b) Choice of which TAM stations winds are to be used.
- (c) Choice of TAM station at which calculations will be carried out.
- (d) Specification of area and receptor grids and overlay area source grid.

Note: In the current program we have used the code to calculate concentrations at the exact location of a particular TAM station rather than over an array of uniformly spaced grid points.

Hence, the number of receptor grid points is set equal to one in ADAT2, and the location of that single receptor is specified within ISPDV. Consequently, ADAT2 reads in the number of the TAM station of interest, passes this number to ISPDV, which in turn selects the corresponding coordinates from DATA statements XTAM, YTAM, and ZTAM.

9.4 Example Problem

To illustrate the use of the plume computer code (see Appendix B for listing), an example problem is given in Appendix C. For this example, we have selected the calculation of the SO_2 concentrations at TAM 5 for February 17, 1967, which is one of the historic days used extensively in the present report for illustrating the effect of the "calm algorithm" and for comparing results of the puff and plume models. The necessary input data for this calculation not specific to February 17, 1967, can be found in Ref. 1. The remaining data are included in Appendix C.

10. SUMMARY OF RESULTS AND RECOMMENDATIONS FOR FURTHER INVESTIGATION

Since discussions of the results presented in this report have already been given in the relevant sections, we will only briefly summarize those results here. Furthermore, since these results suggest areas in which future work is necessary, we have included several specific recommendations for future research.

The initial milestone of the program was the development of a simple steady-state dispersion model based on the standard Gaussian plume expression which was to be used for comparison with the Argonne Integrated-puff Model. To specifically investigate the need for the sophistication of the puff kernel, the plume model was set up in such a way that it would share as many components in common with the original puff computer code as possible. After a number of calculations were performed with the plume code, it became clear that at very low wind speeds (calm periods) the model predicted unrealistically high SO_2 concentrations. Consequently, to carry out a more realistic comparison between the puff and the plume models, especially on a short-term basis, it was necessary to develop a special low-wind-speed function called the calm algorithm. Comparisons carried out between the puff and plume model, augmented with the calm algorithm, showed remarkably good agreement for both long- and short-term analyses. For example, means calculated for periods ranging from 2 days to 1 month showed relatively little difference for the two models. However, in certain cases, the fit to the data indicated by such quantities as the relative standard deviation of the differences between hourly calculated and observed concentrations was somewhat better for the puff than the plume model. The general conclusion we have drawn from this relatively close agreement between the two models is that, for an urban source-emission inventory such as exists in Chicago, the precision of the model is not limited by the sophistication of the transport function, but rather by the combination of the remaining components of the model, which include a number of computational routines as well as the input-data base, i.e., the emission inventory, source-simulation routines, and meteorological data.

To better understand why the puff and plume models produced such remarkably similar results when applied to the Chicago source-emission inventory, we carried out a detailed analytical and numerical analysis of the relationship between puff and plume expressions under special circumstances, which included the restriction to a single source-receptor pair.

The results of the numerical experiments, which consisted of evaluating the integrated puff and plume expressions under a variety of input conditions, showed that, provided sufficient time was allowed for the attainment of steady-state conditions (a time interval greater than the transit time), the two expressions produced essentially identical results.

By carrying out a Taylor expansion of the puff kernel about the delay time equal to the transit time, we were able to obtain an approximate analytical integration of the puff kernel and to show that at least the form of the plume expression, including the $1/u$ dependence as well as the correct dependence of the dispersion coefficients on the transit time, could be derived. The general conclusion of these studies is that one can expect the puff and plume models to yield nearly the same results provided that certain conditions are satisfied.

Before specifying those conditions, we point out that it is assumed that the input parameters are constant for the duration of a basic time step and that both models use the same time step. As to the conditions, first, hour-by-hour calculations will be quite similar, provided the transit time for most of the significant sources affecting a receptor are less than the time step. Otherwise, the plume model will violate the causality condition and overpredict compared to the puff model. Second, if the transit times from significant sources to the receptor is approximately equal to or greater than the time step, then even though hourly concentrations predicted by the two models differ, averages over two or more consecutive hours may be reasonably close, provided the input conditions remain constant for several hours, since the integrated puff will approach steady-state conditions as the exposure time increases. On the other hand, if transit times are of the order or greater than the time step and if the input conditions are quite variable hour to hour, then the plume model will consistently overpredict the puff model.

In regard to the use of the calm algorithm, there is a basic inconsistency in that whereas the wind speed is assumed to be zero, the plume-rise formula used is not valid for wind speeds < 4 mph. One should probably make use of one of the more recent plume-rise formulas designed for calm periods, such as given by Briggs.²³

The use of the travel-time-dependent dispersion coefficients of Turner⁹ in both models has been described in detail, but the relationship between these coefficients and actual dispersion in the real atmosphere in the urban boundary layer is not at all understood. This topic clearly deserves further investigation.

Several conclusions can be drawn from the results of the sensitivity analysis of the plume model to the meteorological input data. With respect to the replacement of the TAM measured winds with the Midway measured winds, it was found that there was relatively little difference for the long term (monthly statistics). On the other hand, short-term results were considerably better when the TAM winds were used. With respect to the effect of making changes in the TAM measured wind directions of $\pm 15^\circ$, during certain periods of 2-4 days it was actually possible to improve the results.

This was found to be connected with the existence of real nonuniformities in the Chicago wind field. The nature of these nonuniformities needs further investigation, and the fact that they can have a significant effect on the dispersion-model calculation indicates that they should be taken into account in at least an approximate way.

The effect of the lid height was examined by varying hourly values by a preset amount. A realistic assessment of the magnitude of the change in lid height to be used for the sensitivity analysis was obtained by performing a series of comparisons of different techniques for estimating the lid height based on remote and local radiosonde measurements.¹⁸ It was found that errors of 25-50% could be expected on the basis of these studies. Systematic errors of $\pm 50\%$ in the lid height were introduced into the input data, and the means of hourly concentrations calculated over 2- and 4-day periods varied by about 15% and in one case by as much as 27%. Provided such errors in the concentration are tolerable, then the corresponding errors in the lid height are acceptable. On the other hand, if it is desired to improve the dispersion-model calculation, then one should attempt to attain somewhat better estimates of the lid height. This should include a prescription for estimating hourly values of the lid height based upon local soundings. Such effects as the urban heat island and mechanisms that suppress the ordinary diurnal heating pattern should be better understood and taken into account in estimating the hourly lid height. Finally, although time did not permit, it would have been interesting to examine the effect of using a much cruder estimate of the lid height, based on some sort of simple diurnal pattern, or simply a single daily value or perhaps even an annual average value such as is currently used in the AQDM³⁰ (Air Quality Display Model).

A copy of the plume-model computer code is included in this report along with an example problem. Since this code has been demonstrated to be a reliable tool for prediction of air-pollutant concentration but is presently not in its most efficient state, it would seem worthwhile to develop a more user-oriented version of the code. Such a code could find a multitude of uses, including serving as a reference for comparison with other dispersion models.

Some effort was expended in attempting to speed up the puff-model computer code, and it was found that, by restricting the "look-back" time in the case of the area sources to 1 hr one could substantially reduce computer time. Other suggestions for reducing computer run time are provided in Appendix A.

APPENDIX A

Reduction of Computer Run-time Requirements of Puff Model

In an attempt to reduce the computer run-time requirements of the puff model, it was found that the run time for a particular hour was inversely proportional to the wind speed. This resulted from two effects. First, the number of sources making a significant contribution to the concentration at a given receptor increased. Second, the look-back time was automatically increased for lower wind speeds to allow for increased travel times and concentration buildup phenomena. This, in turn, increased the number of integrations required. Furthermore, whereas the increase of the look-back time (greater than 1 hr) was necessary to properly account for the contributions of the major point sources when $u \leq 5$ mph, an increase was not necessary for the area sources. Hence, a substantial amount of computer time could be saved by limiting the look-back time for the area sources to 1 hr. In addition, the mesh size needed to obtain a given accuracy for the numerical integration of the puff kernel was inversely proportional to the wind speed. That is, the greater the wind speed, the more integration points were required and therefore the more time required to perform an integration. This resulted from the fact that as the wind speed increases, the integrand (puff kernel) approaches a "Dirac Delta" function. Although it was not tried, a more careful treatment of the choice of integration limits guided by the peaked behavior of the integrand could substantially reduce the increase in integration time caused by the finer mesh size. On the other hand, for the low-wind-speed cases, some computer run time could be saved by using a numerical integration routine such as a "Gauss Quadrature," which achieves the same accuracy as the original "INTEG1" subroutine (which is a variable-mesh Simpson's Rule method) with far fewer integration points.

Furthermore, it has been suggested by Hanna³¹ that a much simpler treatment of the area sources could be used. However, the treatment he suggests substantially overpredicts when compared with the puff model, and it is not clear under what circumstances such a simplified treatment would be valid.

APPENDIX B

Listings of Steady-state Plume-model Computer Routines

This appendix contains listings of the following six computer routines used in the steady-state plume model:

ADAT2
ISPDAV
ITRAN
CRDNTP
SIGY
SIGZ

These routines are modified or corrected versions of the routines used in the original puff-model code, except for CRDNTP, which is a new routine. The remaining routines used in the steady-state plume model code are identical to those used in the original integrated puff-model code and are given in Ref. 1.

1. Subroutine ADAT2

```

SUBROUTINE ADAT2
C  ZERO QTOT ARRAY
  DIMENSION TITLE(20)
  COMMON/ASGRID/NSGRID,XSGRID(100),YSGRID(100)
  COMMON/QHWWW/PCTHW,DCAVG
C  DCAVG IS AVG NUMBER OF DEG.DAYS/YEAR(7000 IN CHICAGO).
C  PCTHW IS FRACTION OF ANNUAL FUEL USED FOR HOT WATER
C  CHICAGO HOT WATER REQ. =20 PCT OF ANNUAL FUEL
  COMMON/NUMBPT/NPOW,NIND
C  POINT SOURCES SHOULD BE LISTED WITH POW PLANTS J=1,NPOW,
C  INDUSTRY FROM J=NPOW+1 TO NIND, FOLLOWED BY RES/COML.
  COMMON/METREF/ZWS
C  ZWS IS HEIGHT(FT)OF AEROVANE
  COMMON/RGR/XRORIG,YRORIG,NWEST,NSTH,DRGRID,ZREC
  COMMON/AREAS/QTOT(3,1004),HAVG(3),DGRID,XSORIG,YSORIG,
2  NSXMAX,NSYMAX,EMAX(5,3)
  COMMON/MINQ/EMINPT
C  THE AREA SOURCE GRID COORDINATE SYSTEM HAS BEEN FORMED WITH +X
C  WEST AND +Y SOUTH.
C  THE GRID SYSTEM ORIGIN XSORIG,YSORIG NEED NOT BE 0,0.
C  DGRID IS THE GRID SPACING IN MILES.
C  NSXMAX AND NSYMAX DEFINE MAX GRID COORDINATES. THE COORDINATES
C  OF THE LOWER LEFT CORNER OF GRID SQUARE NX,NY ARE
C  (XSORIG+NX*DGRID),(YSORIG+NY*DGRID).
C  ORIGIN OF GRID SYSTEM SHOULD BE LOCATED SO THAT WHOLE
C  REGION LIES IN THIRD QUADRANT (HERE +X,+Y).
C  EACH AREA OF SIZE DGRID**2 MUST BE ASSIGNED A POLLUTANT
C  EMISSION RATE (LB/YR) FOR THREE TYPES OF EMISSIONS.
C  LOW PRESSURE SPACE HEATERS,HIGH RISE SPACE HEATERS AND
C  INDUSTRIAL. COMMERCIAL EMISSIONS CAN BE INCLUDED IN
C  EITHER OF THE FIRST TWO CATEGORIES.QTOT(NCL,NAREA)IS THE ARRAYNAME
C  A SINGLE STACK HEIGHT IS INPUT FOR EACH CLASS OF AREA SOURCES
  NSGRID=88
  DGRID=1
  XSORIG=-2.
  YSORIG=-12.
  NSXMAX=20

```



```

      NSYMAX=50
      DO 2 I=1,1000
      DO 2 NCL=1,3
2     QTOT(NCL,I)=0.
C     READ IN EMISSION DATA BASED ON JJR GRID
C     DATA DECK MUST BE FOLLOWED BY A CARD WITH 99999. PUNCH IN COLMS. 1-6
      K=0
      L=1
      M=4
3     K=K+1
      READ 15,TITLE
      GO TO (10,11,12,13,17),K
10    READ 5, ((QTOT(I,NA),I=1,3),NA=L,M)
      IF(QTOT(1,L).GT.10000.) GO TO 20
      L=L+4
      M=M+4
      GO TO 10
20    CONTINUE
      GO TO 3
11    READ 450,(XSGRID(IX),YSGRID(IX),IX=1,16 )
      GOTO3
12    READ 450,(XSGRID(IX),YSGRID(IX),IX=17,48)
      GOTO3
13    READ 450,(XSGRID(IX),YSGRID(IX),IX=49,88)
      GOTO3
17    READ 16,((EMAX(I,J),I=1,3),J=1,3)
30    CONTINUE
      5 FORMAT(12F6.0)
      15 FORMAT(20A4)
      16 FORMAT(3F8.0)
450   FORMAT(12F6.1)
      DO 40 J=1,1000
      DO 40 I=1,3
40    QTOT(I,J)=QTOT(I,J)*1.E4
C     QTOT(I,J) HAS UNIT LBS/YR.
      PCTHW=.2
      DDAVG=7000.
      NPOW=24
      NIND=72
      ZREC=75.
      EMINPT=10.
      HAVG(1)=100.
      HAVG(2)=200.
      HAVG(3)=150.
C     DEFINE 6X11 RECEPTOR GRID FOR TEST PROBLEM.
      XRORIG=3.
      YRORIG=-7.
      NWEST=0
      NSTH=0
      DRGRID=2.
      RETURN
      END

```

2. Subroutine ISPDAV

```

      SUBROUTINE ISPDAV(EMIS,HEFF)
C     THIS VERSION USED FOR STEADY STATE PLUME MODEL
C
C11111
      REAL*8 S NAMES(1)
      COMMON/KTROUB/KTRO
      DIMENSION KTAM(8) , JSSAVE(12)
      COMMON/MXC/MX
      DIMENSION A(12,8),B(12,8),C(12,8),WABAR(12,8)
      REAL*4 EMIS(12,4,1),HEFF(12,4,1)

```

```

    DIMENSION WD(8),WS(8)
    REAL*4 XS(1),YS(1),ZS(4,1),QSO2(1),QHEAT(1),
    1 SO2VAL(1),WDA(1),WSA(1),PERCENT(4,1) ,SOBS(1)

```

C

```

    COMMON/TIME/ MMAX,NMAX,M,N
    COMMON/KERNEL/X,Y,Z,U(24),V(24),W(24),JS(24),HMX(24),WSBAR(24),WZ
    COMMON/RISE/ZSS
    COMMON/POUT/I
    COMMON/XTRAN/KSTAB
    COMMON/SUEDO/TX,TY,TZ,DX,DY,DZ
    COMMON/HALF/THALF
    DIMENSION TEM(12)
    DIMENSION KSTAP(6,100)
    DIMENSION TXX(6,6),TZZ(6,6,3),DXX(6,6),DYY(6,6),
    2 EMIT(6,3,1000)
    DIMENSION PP(7),USAVE(24),VSAVE(24)
    DIMENSION NDW(12,4,100)
    DIMENSION WSSAVE(24)
    DATA PP/.2,.2,.2,.3,.4,.5,.5/
    DATA KPS/1/
    DATA NCLID/1/

```

C

C

```

    DIMENSION NTMP(4,8),NHRP(4),MPU(4),PREC(4,8) , OBSC(4,8)
    DATA NCOUNT/1/
    DIMENSIONXPT(30),YPT(30),ZPT(30),QPTOT(30),
    XQPHR(12,30),HEFPT(12,30),NPAT(30),NS(30),HKEE(12),
    XEKEE(12),SPCT(30)
    DATA NPTS/28/
    DATA NS/1,1,1,1,1,0,0,1,0,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,0,4,4,8,
    X1/
    DATA NPAT/3,3,3,3,3,2,2,1,2,1,1,1,1,2,1,1,1,1,2,2,2,2,2,2,1,1,1,
    X1/
    DIMENSION IIND(100)
    DATA IIND/2,2,2,2,2,3,3,2,3,2,2,2,2,3,2,2,2,2,3,3,3,3,3,3,1,1,1,
    X 1/
    DATA XPT/9.8,11.0,5.5,9.8,8.0,5.6,10.3,18.,6.0,15.1,6.7,7.2,8.8,
    X8.8,7.0,15.5,16.2,16.7,9.2,6.0,4.2,5.0,3.5,5.4,15.2,29.2,30.4,
    X11.7/
    DATA YPT/0.8,-6.0,12.0,-2.0,5.1,0.3,-0.5,-2.0,4.5,7.0,4.5,2.8,2.7
    X,2.8,17.4,5.2,5.9,6.0,0.7,0.3,-0.8,0.1,6.4,-0.5,-35.2,16.0,24.8
    X,-16.6/
    DATA ZPT/242.,285.,265.,240.,217.,110.,150.,150.,150.,150.,150.,
    X150.,150.,150.,150.,150.,150.,150.,150.,150.,150.,85.,160.,380.,
    X1400.,450.,500.,247./
    DATA SPCT/2.2,2.2,2.2,2.2,2.2,3.4,2.4,2.2,2.9,2.7,3.2,3.2,3.2,
    X2.7,2.5,2.5,2.5,2.5,3.1,3.2,2.7,2.0,2.5,1.4,2.9,3.2,3.5,
    X1.2/

```

C

```

    QPTOT UNITS ARE M LBS.SO2/YR.
    DATA QPTOT/2.34,2.42,2.10,2.02,1.89,8.00,2.73,4.12,4.26,31.89,4.59
    X,1.88,2.59,2.38,4.78,1.74,4.78,4.32,2.78,3.53,2.06,2.04,3.80,.42,
    X232.,397.,560.,1.01/

```

C

```

    ADDITIONAL POINT SOURCES INCLUDE:

```

C

```

    PUMPING STATIONS(CENTRAL PK.,MAYFAIR,ROSELAND,SPRINGFIELD,WESTERN AVE.),
    C UNION STATION POWER PLANT,CHICAGO-NORTHWESTERN RR,INTERNATIONAL HARVESTER,
    C PRODUCE TERMINAL,CORN PRODUCTS,SWIFT,DIAMOND GLUE,CELOTEX,MUN.HEATING PL.,
    C WYMAN GORDON,REYNOLDS, STANDARD LIME,ELECTROMOTIVE DIV.,SEARS ROEBUCK,
    C UNIV.OF ILL.,NO.WESTERN UNIV.,GOLDBLATT BROS.,UNIV.OF CHICAGO,
    C MERCHANDISE MART.,POWER PLANTS(WAUKEGAN,WILL COUNTY,JOILET).

```

C

```

    WINETKA POWER PLANT ADDED

```

C

```

    EACH ADDITIONAL POINT SOURCE IS IDENTIFIED BY A

```

C

```

    PATTERN OF EMISSION. 1=UNIFORM, 2=TEMP DEPENDENT, 3=PUMPING STA.

```

C

```

    EACH ADDITIONAL POINT SOURCE MUST BE

```

C

```

    IDENTIFIED BY A CLASSIFICATION NUMBER.

```

C

```

    1=UTILITY, 2=INDUSTRY, 3=RES/COML.

```

```

    DIMENSION NOSTK(50)

```

```

    DATA NOSTMX/9/

```

```

DATA NOSTK/25,28,30,31,40,41,43,45,50/
C
DATA VPPP/0/, NPRINT/1/
C RESULTS FOR GRID PRINTED EVERY NPRINT HOURS.
COMMON/AREAS/QTOT(3,1004),HAVG(3),DGRID,XSORIG,YSORIG,
2 NSXMAX,NSYMAX,EMAX(5,3)
COMMON/QHWWW/PCTHW,DCAVG
COMMON/NUMBPT/NPOW,NIND
COMMON /SO2DAT/RECDAT(4,500)
COMMON/RGR/XRORIG,YRORIG,NWEST,NSTH,DRGRID,ZREC
COMMON/MINQ/EMINPT
COMMON/ASGRID/NSGRID,XSGRID(100),YSGRID(100)
DIMENSIONCOUP(100,3,6)
DIMENSION VQ(6,3)
COMMON/METREF/ZWS
C ZWS IS HEIGHT(FT)OF AEROVANE
C
DATA VALOP,NRTAM/1.,1/
C IF VALOP.GT.0 THEN SO2VAL=RECDAT(4,NRTAM) IS RETURNED TO
C APDATA FOR EVENTUAL PRINTOUT ALONGSIDE SO2 DATA FROM
C TAM STATION SPECIFIED AS OUTSTATION ON INPUT CARDS
DIMENSION XTAM(8),YTAM(8),ZTAM(8)
DATA XTAM/13.2,7.0,5.1,3.0,7.4,5.8,11.9,10.5/
DATA YTAM/-7.1,-5.1,0.5,6.9,6.8,13.1,-0.2,9.2/
DATA ZTAM/60.0,80.0,180.0,70.0,75.0,60.0,75.0,40.0/
DATA PNCHOP/1/
DATA ADJWD/0.0/
DATA FROG/1.0/
COMMON /WAYNE/ WJWG
DATA ADJHL/1.0/
DATA ADJWS/1.0/
C IF PNCHOP.GT.0, SO2VAL AND SOBS ARE PUNCHED ON CARDS FOR
C USE WITH STATISTICS CODES.
C INITIALIZATION OF STORAGE IN TRAN.
CALL ITRAN(EMIS,HEFF)
NMAX=1
C NMAX MUST BE .LE.6 HOURS
C SET NMAX=1 FOR STEADY STATE PLUME MODEL
CALL ADAT2
C ADAT2 READS IN RECEPTOR AND AREA SOURCE DATA.
NTEST=1
IF(NTEST.GT.0 )
1 PRINT 401,QTOT(1,50),QTOT(3,300),HAVG(2),DGRID,XSORIG,
2 YSORIG,NSXMAX,NSYMAX,EMAX(2,2)
401 FORMAT(10X,6E10.2,2I10,E10.2)
IF(NTEST.GT.0 )
1 PRINT 402,XSGRID(20),YSGRID(20),ZWS
402 FORMAT(10X,3E10.2 //)
LLL=1
RETURN
C CODE COORDINATES,PLUS FOR X LEFT AND Y DOWN
C22222 ENTRY PUFF(NR,TEMP,WSA,WDA,STAB,HLID,NSRC,XS,YS,ZS,
1 PERCENT,QSO2,QHEAT,
2 SO2VAL,MM,KTAM,SOBS,SNAMES)
C SOBS IS THE ACTUAL OBSERVED SO2. USED HERE ONLY IN PUNCHED
C OUTPUT FOR STATISTICAL COMPARISON WITH CALCULATED VALUES
KTRO=0
C UNITS ARE F,DEG,MPH,,FT,,MI,MI,FT,FRACTION,LB/HR,TH/HR,,MI,MI,FT,,
C*****
C ONLY ONE AEROVANE READING IS USED PER PROBLEM.
C THIS IS SPECIFIED BY RECEPTOR CARD IN DATA DECK.
C$$$$$
C ZERO THE EMIT ARRAY
DO 2 I=1,6
DO 2 I=1,3
DO 2 K=1,1000

```

```

2  EMIT(L,I,K)=0.
   I=1
   IRR=1
   WS(I)=WSA(IRR)*ADJWS
   WD(I)=WDA(IRR)+ADJWD
   IF(WS(I).LT..01)          WS(I)=.1
3  CONTINUE
   HLID=HLID*ADJHL
   M=MM
   MX=MINO(NMAX,M)
   JSM=JSUB(M)
   IRR=0

C
   TEM(JSM      )=TEMP
   WZ=1.
   HR=NR
   IR=0
   TX=0.
   TY=0.
   TZ=0.
   DX=0.
   DY=0.
   DZ=0.
   I=1
   WDRAD=WD(I)*.01745
   A(JSM,I)=WS(I)*SIN(WDRAD)
   B(JSM,I)=WS(I)*COS(WDRAD)
   C(JSM,I)=0.
5  WABAR(JSM,I)=WS(I)
   JSTAB=STAB
   JS(JSM      )=JSTAB

C   CORRECTION FOR MISSING MIXING HT IN MASTER FILE.
   IF(M.EQ.1.AND.(HLID.GT.10000..OR.HLID.LT.0.))HLID=9999.
   IF(M.GT.1.AND.(HLID.GT.10000..OR.HLID.LT.0.))HLID=HMIX(JSUB(M-1))
   HMIX(JSM      )=HLID

C33333
C   THIS VERSION CALCULATES CONCENTRATIONS AT THE EXACT LOCATION OF
C   THE TAM STATION. ONLY ONE RECEPTOR POINT CAN BE CONSIDERED AT A TIME.
DO 6450 ITAMS=1,8
6450 IF(KTAM(ITAMS).EQ.1) GO TO 6451
6451 NNTAM=ITAMS
   IXR=XTAM(NNTAM)+0.5
   IYR=YTAM(NNTAM)
   XRORIG=IXR
   YRORIG=IYR
   DXR=XTAM(NNTAM)-XRORIG
   DYR=YTAM(NNTAM)-YRORIG
   ZREC=ZTAM(NNTAM)
   ZWS=ZREC
DO 8 J=1,NSRC
   IF(MM.EQ.5) PRINT 681,SNAME(J),J,NR,XS(J),YS(J)
681  FORMAT(3X,A8,2X,'NSRC,HOUR,X,Y = ',2I3,2X,2E12.5)
DO 8 K=1,4
   IRR=0
   ZSS=ZS(K,J)
   EMIS(JSM,K,J)=QSO2(J)*PERCENT(K,J)
   WSSSS=WS(1)+.1
   KSTAB=0
   DHMIN=PRISE(WSSSS,5,QHEAT(J)*PERCENT(K,J))
   IF(HLID.LT.ZSS)KSTAB=1
C IF KSTAB.GT. 0 ,WE HAVE CASE OF STACK ABOVE LID OR PENETRATION
C   INTO LID.  USE JSTAB=5 FOR PRISE AND SIGMAS.
C   UNTIL LID RISES TO HEFF. THEN TREAT AS A PLUME
C   REFLECTED AS USUAL.
   IF(HLID.LT.(ZSS+DHMIN).AND.KSTAB.EQ.0)KSTAB=2
   HEFF(JSM,K,J)=ZSS+DHMIN
   IF(KSTAB.GT.0)GO TO 7

```

```

      HEFF(JSM,K,J)= ZSS + AMIN1(PRISE(WSSSS,JSTAB,QHEAT(J)*PERCENT(K,J)
1    ) , HLID-ZSS)
      GO TO 98
7    CONTINUE
98   NDW(JSM,K,J)=0.
      WDW=15.1
C     DOWNWASH ASSUMPTION FOR TAM WINDS GT WDW
      IF(WSSSS.LT.WDW) GO TO 8
      NDW(JSM,K,J)=1
      HEFF(JSM,K,J)=ZSS
8    CONTINUE
      IF(WSSSS.LE.6.) GO TO 501
      IF(NOSTMX.EQ.0) GO TO 501
C     TABULATED STACK HEIGHTS ARE OFTEN SIMPLY BUILDING HEIGHTS WHERE
C     EMISSIONS ARE FROM STUBBY STACKS. FOR THESE CASES WHEN WS.GT.
C     6 MPH, CONSIDER DOWNWASH.
      J=1
      NC=1
      NOS=NOSTK(1)
503  IF(J.EQ.NOS) GO TO 502
      J=J+1
      GO TO 503
502  DO 504 K=1,4
      NDW(JSM,K,J)=1
504  HEFF(JSM,K,J)=ZS(K,J)
      NC=NC+1
      IF(NC.GT.NOSTMX) GO TO 501
      NOS=NOSTK(NC)
      J=J+1
      GO TO 503
501  CONTINUE
C44444
C     RECEPTOR GRID DEFINED BY XRORIG,YRORIG,NWEST,NSTH
      I=1
C     CALCULATE POINT SOURCE CONTRIBUTION AT EACH DOSE POINT
C     IN RECEPTOR GRID. AREA SOURCES EVALUATED MORE EFFICIENTLY.
C     POWER PLANTS TREATED SIMILAR TO INDUSTRIAL POINT SOURCES.
C     RECDAT(1,NR)-POWER PLANTS, (2,NR)-INDUSTRY,(3,NR)-RES/COML
C     (4,NR)-TOTAL POLLUTANT CONCENTRATION AT POINT NR
      NRMAX=(INWEST+1)*(NSTH+1)
C     NRMAX MUST BE .LE. 500
      NRWEST=NWEST
      NRSTH=NSTH
      DO 21 NRCP=1,NRMAX
      IWST=NXF(NRCP,NRWEST+1)
      ISTH=NYF(NRCP,NRWEST+1)
      CALL RGRID(IWST,ISTH,XRG,YRG)
      IF(NTST.GT.0.AND.NRCP.LE.2)PRINT 403,XRG,YRG,ZREC
403  FORMAT(10X,'XRG,YRG',ZREC=' ',3E10.2)
C     XRG,YRG ARE COORDS. OF DOSE POINT NUMBER NRCP
      DO 88 JJJJ=1,4
C     ZERO THE CONCENTRATION ARRAY FOR HOUR M AT DOSE POINT NRCP
88   RECDAT(JJJJ,NRCP)=0.
      ZT=ZREC
C     UNIFORM HEIGHT FOR ALL RECEPTOR POINTS IN GRID
      Z=ZT/5280.
      NLIM=NMAX
C     IF(WSSSS.GT.6.) NLIM=4
C     IF(WSSSS.GT.10.) NLIM=2
C     NLIM=MINO(NLIM,M)
      NLIMA=NLIM
      DO 20 N=1,NLIM
      JJX=JSUB(M-N+1)
      JJJ=JS(JJX)
C     POINT SOURCES      INITIAL DIMENSIONS SIGX=SIGY=100 FT,SIGZ=100 FT
      DSS=100.*2.4/5280.
      CALL PSEUDO(DSS,0.,0.,TX,TY,TZ,DX,DY,JJJ,100.,0)

```

```

TX1=TX
TZ1=TZ
C BUILDINGS WITHOUT STACKS OR STACKS IN DOWNWASH
C APPROXIMATED BY INITIAL DIMENSIONS SIGX=SIGY=750 FT,SIGZ=150
DSS=750.*2.4/5280.
CALLPSEUDO( DSS,0.,0.,TX,TY,TZ,DX,DY,JJJ,150.,0)
TX2=TX
TZ2=TZ
THALF=100.
C THALF IN HOURS
C SO2 HALF LIFE HERE ONLY A CRUDE FCT. OF TEMP.
L=N
DO9NT=1,L
IF (TEM(JSUB(M-NT+1)).GT.60.) THALF=4.
9 CONTINUE
C
XSAVE=-1.
YSAVE=-1.
KSTABB=-1
DO 20 J=1,NSRC
KM=4
CHT=0.
DO 10 K=1,KM
IF (EMIS(JJX,K,J).LE.EMINPT) GO TO 10
C EMISSIONS IN LB/HR. PROGRAM CONSIDERS EACH STACK SEPARATELY AND
C UP TO 6 STACKS PER PLANT. EMISSIONS LESS THAN EMINPT ARE
C DISREGARDED. FOR TWO FOR MORE STACKS PER PLANT,
C CALCULATIONAL SHORTCUTS ARE AVAILABLE. NTRAN IS A FLAG FOR THIS
NTRAN=0
IF (NDW(JJX,K,J).GT.0) GO TO 1001
TX=TX1
TY=TX
TZ=TZ1
GO TO 1002
1001 TX=TX2
TY=TX
TZ=TZ2
1002 CONTINUE
99 CONTINUE
X=XRG-(XS(J)-A(JJX,1)*TX)+DXR
Y=YRG+(YS(J)+B(JJX,1)*TY)+DYR
C NOTE PLANTSIM STORES +Y UP
C COORD SYSTEM IS +X(LEFT), +Y(DOWN)
C CONSIDERS UP TO 6 STACKS PER PLANT
KSTAB=0
IF (ZS(K,J).GE.HMIX(JJX)) KSTAB=1
IF (KSTAB.EQ.0.AND.HEFF(JJX,K,J).GT.HMIX(JJX)) KSTAB=2
IF (XSAVE.EQ.X.AND.YSAVE.EQ.Y.AND.KSTABB.EQ.KSTAB) NTRAN=1
IF (NTRAN.EQ.1) GO TO 11
KSTABB=KSTAB
XSAVE=X
YSAVE=Y
IF (ZT.LT.1.) ZT=1.
C ZT IN FEET
WZ=1.
HEF=HEFF(JSUB(M-N+1),K,J)
IF (KSTAB.GE.1) JJJ=5
IF (HEF.GT.ZWS ) WZ=((HEF )/ZWS )**PP( JJJ
IF (WZ.GT.3.) WZ=3.
C WIND PROFILE LAW
DO12IW=1,MX
WSBAR(IW)=WABAR(IW,I)*WZ
U(IW)=A(IW,I)*WZ
W(IW)=C(IW,I)
JSSAVE(IW)=JS(IW)
12 V(IW)=B(IW,I)*WZ
WJWG=FROG*WZ

```

```

11  CONTINUE
    X=XRG-(XS(J)-U(JJX)*TX)+DXR
    Y=YRG+(YS(J)+V(JJX)*TY)+DYR
    CHI=CHI+EMIS(JSUB(M-N+1),K,J)*TRAN(N,M,K,J,NTRAN)*.38122E-4
10  CONTINUE
    IXPT=1
    IF(J.GT.NPOW)IXPT=2
    IF(J.GT.NIND)IXPT=3
    RECDAT(IXPT,NRCP)=RECDAT(IXPT,NRCP)+CHI
    RECDAT(4,NRCP)=RECDAT(4,NRCP)+CHI
20  CONTINUE
21  CONTINUE
    IF(NTST.LT.1)GO TO 405
    PRINT 404
404  FORMAT(15X,'PROUT FOR PLANTSIM SOURCES ONLY')
    CALL PROUT(MM,RECDAT,NWEST,NSTH)
405  CONTINUE
C
C    ADDITIONAL POINT SOURCES
    JSM=JSUB(M)
    DO201IW=1,MX
    HKEE(IW)=HEFF(IW,1,1)
201  EKEE(IW)=EMIS(IW,1,1)
C    ESTIMATE HOURLY EMISSIONS
    DO220J=1,NPTS
    NPATTJ=NPAT(J)
    GOTO(209,211,213),NPATTJ
209  QPHR(JSM,J)=QPTOT(J)/8760.
    QPHR(JSM,J)=QPHR(JSM,J)*1.E6
    GOTO220
211  TE=0.
    IF(TEMP.LT.65.)TE=1.
    QPHR(JSM,J)=QPTOT(J)*(.2/8760.+ .8*TE*(65.-TEMP)/1.68E5)
    QPHR(JSM,J)=QPHR(JSM,J)*1.E6
    GOTO220
213  TPUMP=.429
    IF(HR.GT.6.9.AND.HR.LT.23.1)TPUMP=1.29
C    PUMPING STATION PATTERN
    QPHR(JSM,J)=QPTOT(J)*TPUMP/8760.
    QPHR(JSM,J)=QPHR(JSM,J)*1.E6
    GOTO220
220  CONTINUE
C    EMISSIONS FOR ADDITIONAL SCS. STORED AS M LBS SO2/YR
C    ESTIMATE PLUME RISE IF NS=0, ASSUME EMISSION AT
C    XBUILDING HEIGHT. ASSUME PLUME RISE PROP. TO 1/(NS**.5)
    DO225J=1,NPTS
    ZSS=ZPT(J)
    KSTAB=0
    DH=0.
    IF(NS(J).EQ.0.OR.WSSSS.GT.WDW)GOTO224
    DN=NS(J)
    QHEATT=QPHR(JSM,J)*.12/(.02*SPCT(J)*SQRT(DN))
C    ALLOW FOR 20 PERCENT GREATER PLUME RISE FROM STACK INTERACTION
    IF(DN.GT.1.1)QHEATT=1.4*QHEATT
    IF(HLID.LT.ZPT(J))KSTAB=1
    DHMIN=PRISE(WSSSS,5,QHEATT)
    IF(KSTAB.EQ.0.AND.(DHMIN+ZPT(J)).GT.HLID)KSTAB=2
    IF(KSTAB.GE.1)GOTO222
    DH=AMIN1(PRISE(WSSSS,JSTAB,QHEATT),HLID-ZPT(J))
    GOTO224
222  DH=DHMIN
224  HEFPT(JSM,J)=ZPT(J)+DH
    KSTAP(JSM,J)=KSTAB
225  CONTINUE
    IR=0
    I=1
    IR=IR+1

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Z=ZREC/5280.
DO270J=1,NPTS
C   SOME ADDITIONAL POINT SOURCES ARE 20 MILES FROM CITY.
NLIMA=MINO(NMAX,M)
DO270N=1,NLIMA
JJJ=JS(JSUB(M-N+1))
JSN=JSUB(M-N+1)
HEFF(JSN,1,1)=HEFPT(JSN,J)
EMIS(JSN,1,1)=QPHR(JSN,J)
IF(EMIS(JSN,1,1).LT.EMINPT) GO TO 270
KSTAB=KSTAP(JSN,J)
IIN=IIND(J)
IF(KSTAB.GT.0) JJJ=5
HEF=HEFF(JSN,1,1)
WZ=1.
IF(HEF.GT.ZWS) WZ=(HEF/ZWS)**PP(JJJ)
IF(WZ.GT.3.)WZ=3.
DO205IW=1,MX
U(IW)=A(IW,I) *WZ
V(IW)=B(IW,I) *WZ
W(IW)=C(IW,I) *WZ
205 WSBAR(IW)=WABAR(IW,I) * WZ
W.IWG=FRNG*WZ
IF(WSSSS.GT.WDW.OR.NS(J).EQ.0) GO TO 230
DSS=100.*2.4/5280.
CALL PSEUDO( DSS,0.,0.,TX,TY,TZ,DX,DY,JJJ,100.,0)
GO TO 231
230 CONTINUE
DSS=750.*2.4/5280.
C   DOWNWASH OR BUILDINGS WITHOUT STACKS DX=DY= 750. FT DZ=150.FT
CALL PSEUDO( DSS,0.,0.,TX,TY,TZ,DX,DY,JJJ,150.,0)
KSTAB=KSTAP(JSN,J)
231 CONTINUE
DO 269 NRCP=1,NRMAX
IWST=NXF(NRCP,NRWEST+1)
ISTH=NYF(NRCP,NRWEST+1)
CALL RGRID(IWST,ISTH,XRG,YRG)
X=XRG-(XPT(J)-TX*U(JSN)) +DXR
Y=YRG-(YPT(J)-TY*V(JSN)) +DYR
CO=.381E-4
CHI=EMIS(JSN,1,1)*CO*TRAN(N,M,1,1,0)
RECDAT(IIN,NRCP)=RECDAT(IIN,NRCP)+CHI
RECDAT(4,NRCP)=RECDAT(4,NRCP)+CHI
269 CONTINUE
270 CONTINUE
IF(NTEST.LT.1) GO TO 289
PRINT 406
406 FORMAT(10X,'PROUT FOR ALL POINT SOURCES')
CALL PROUT(MM,RECDAT,NWEST,NSTH)
289 CONTINUE
DO291IW=1,MX
HEFF(IW,1,1)=HKEE(IW)
FMIS(IW,1,1)=FKEE(IW)
291 JS(IW)=JSSAVE(IW)
C55555
C   EVALUATE AREA SOURCE CONTRIBUTIONS
C   ADJUST NIGHTTIME STABILITY FOR CITY ROUGHNESS
IF(HLID.GT.100..AND.WSSSS.GT.6.)GO TO 90
GO TO 95
90 IF(JSTAB.EQ.5) JSTAB=4
DO 91 J=1,MX
JSSAVE(J)=JS(J)
91 IF(JS(J).EQ.5)JS(J)=4
95 CONTINUE
C   PRORATE ANNUAL SOURCES
NSMAX=NSXMAX*NSYMAX
DO 1000J=1,NSMAX

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DO 100 NCL=1,3
IF(QTOT(NCL,J).LT..01) GO TO 100
GO TO (101,102,106),NCL
101 CONTINUE
C   LOW RISE ANNUAL FUEL USE -HOURLY PRORATION
C   SOURCES ON AT 6 AM, OFF AT 10 PM AND IDLE IN BETWEEN
TON=5.9
C   HOUR 0 IS MIDNIGHT
TOFF=22.1
IF(TEMP.LT.5.0) TON=3.9
C   FIRE BOILERS EARLY WHEN TEMP.LE. 5 DEG.F
TE=1.0
IF(HR.GT.TON.AND.HR.LT.(TON+2.1)) TE=1.5
C   JANITOR FUNCTION FOR LOW RISE RESIDENTIAL BUILDINGS
TONOFF=TOFF-TON+1.
GO TO 105
102 CONTINUE
C   HIGH RISE- TWENTY-FOUR HOUR SOURCE
TON=-.001
TOFF=24.001
TE=1.0
TONOFF=24.
105 CONTINUE
QIND=0.
QHT=0.
IF(TEMP.GE.65.)TE=0.
C PCTHW IS FRACTION OF ANNUAL FUEL USE FOR HOT WATER.
QHW= QTOT(NCL,J)*PCTHW/(24.*365.)
FR=1.-PCTHW
IF(NCL.EQ.1.AND.(HR.GT.TOFF.OR.HR.LT.TON)) TE=0.
QHT=QTOT(NCL,J)*FR*TE*(65.-TEMP)/(DDAVG*TONOFF)
GO TO 107
106 QHW=0.
QHT=0.
QIND=QTOT(NCL,J)/(24.*365.)
107 EMIT(JSUB(M),NCL,J)=QHW+QHT+QIND
100 CONTINUE
1000 CONTINUE
C66666
C
C   EACH AREA SOURCE HAS HOURLY SO2 IN 3 CLASSES.
C   DEPENDING ON NSIDE, THE COORD OF UPWIND PSEUDO PT SOURCE
C   IS KNOWN.
C   EACH MUST BE EVAL.BY TRAN.FIRST EVAL. LOW RISE AND IF
C   POSSIBLE USE EXPONENTIAL CORRECTIONS FOR OTHER CLASSES.
C   NSIDE NOW LIMITED TO 1,2,4,8,AND 16 MILES.
C
JSU=JSUB(M)
I=1
DS=.5
DO 110 IS=1,5
DS=2.*DS
DO 110 NCL=1,3
CALL PSEUDO(DS,A(JSU,I),B(JSU,I),TXX(JSU,IS),TY,
2 TZZ(JSU,IS,NCL),DXX(JSU,IS), DYY(JSU,IS),JSTAB,HAVG(NCL),NCL)
110 CONTINUE
C   DISTINCTION BETWEEN TZZ(.,NCL) VALUES IMPORTANT ONLY FOR
C   AREAS ADJACENT TO RECEPTOR POINT.
NLIMA=NLIM
DO 111 IW=1,MX
U(IW)=A(IW,I)
V(IW)=B(IW,I)
W(IW)=C(IW,I)
111 WSBAR(IW)=WABAR(IW,I)
WJWG=FRQG
C
C   A STANDARD RECEPTOR-ORIENTED SOURCE GRID SYSTEM WITH

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C   GRID SQUARES NUMBERED SEQUENTIALLY FROM 1-NSGRID IS DEFINED.
C   THE COORDINATES OF LOWER LEFT CORNER OF EACH SQUARE RELATIVE TO
C   THE REFERENCE RECEPTOR AT 0.0 ARE INPUTS.
C   PLACED SYMMETRICALLY ABOUT RECEPTOR, THE FIRST 16 SQUARES
C   ARE OF SIDE LENGTH DGRID, SQUARES 17-48 OF SIDE
C   LENGTH 2*DGRID, ETC.
C   WIND SPEED AND DIRECTION
C   ARE REPRESENTED BY SINGLE HOURLY-CONSTANT
C   FUNCTIONS OF TIME.
C   COUPLING COEFFICIENTS COUP(JSUB(M-N+1),NSQ,NCL) BETWEEN RECEPTOR
C   AND EACH GRID SQUARE ARE CALCULATED BASE ON A
C   REFERENCE EMISSION FOR EACH SIZE GRID SQUARE.
C       RESULTS ARE TRANSLATED AND ACTUAL
C   EMISSIONS USED TO CALCULATE CONCENTRATIONS AT EACH
C   POINT OF THE CITY GRID.
C
C   EVALUATE COUPLING COEFFICIENTS FOR SQUARES ADJACENT TO RECEPTOR.
C   FOR THESE SQUARES, A DISTINCT SIGZO
C   AND COUPLING COEF. SET IS USED FOR EACH SOURCE CLASS.
C   COEFS. FOR AREAS FURTHER OUT ARE NOT SENSITIVE TO THIS
C   DISTINCTION.
C
C   FOR EACH SIZE AREA(E.G. 1X1, 2X2, 4X4) AND EACH SOURCE
C   CLASS THERE IS A
C   MAXIMUM AVG. EMISSION RATE(LB/HR)
C   THESE VALUES ARE INPUTS. COUPLING COEFFICIENTS
C   ARE EVALUATED FOR THESE EMISSION MAXIMA (TO TEST FOR
C   SIGNIFICANCE).
C
C   DO 31 N=1,NLIMA
C   JSM=JSUB(M-N+1)
C   EMSAV=EMIS(JSM,1,1)
C   HKEEP=HEFF(JSM,1,1)
C   ONLY ONE LID HEIGHT CONSIDERED FOR WHOLE CITY
C   AREA SOURCE REFERENCE GRID. X AND Y VALUES IN MILES.
C   DO30NSG=1,NSGRID
C   NSIDE=1
C   IF(NSG.GT.16)NSIDE=2
C   IF(NSG.GT.48)NSIDE=3
C   IF(NSG.GT.88)NSIDE=4
C   RSIDE=NSIDE
C   IF(NSIDE.GT.2) RSIDE=4.
C   IF(NSIDE.GT.3) RSIDE=8.
C   RECEPTOR AT 0,0
C   X=-XSGRID(NSG)+DXX(JSM,NSIDE)+RSIDE/2. +DXR
C   Y=-YSGRID(NSG)+DYY(JSM,NSIDE)+RSIDE/2. +DYR
C   Z=ZREC/5280.
C
C   TX=TX(X(JSM,NSIDE)
C   TY=TX
C   DOWNWASH RULES. WS.GE.WSCRIT, THEN HEFF=HAVG
C   WS.LT.WSCRIT, THEN HEFF=HAVG+PRI
C   NCL=1
C   PRI=0.
C   ZSS=HAVG(1)
C   WSCRIT=6.
C   DH=ZSS
113 IF(WSBAR(JSM).LT.WSCRIT)PRI=DH
C   KSTAB=0
C   HLI=HMIX(JSM)
C   IF(HLI.LT.ZSS)KSTAB=1
C   HEFF(JSM,1,1)=ZSS+AMIN1(PRI,HLI-ZSS)
C   HEFF IN FEET.
116 CONTINUE
C   GOTO(117,118,119),NCL
117 CONTINUE
C   LOW RISE SPACE HEATERS

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TZ=TZZ(JSM,NSIDE,NCL)
EMIS(JSM,1,1)=EMAX(NSIDE,NCL)
COUP(NSG,NCL,JSM)=EMAX(NSIDE,NCL)*TRAN(N,M,1,1,0)*.381E-4
KSTABB=KSTAB
C LOW RISE DONE. HIGH RISE CHECK IF KSTAB IS SAME FOR
C THIS CASE AND IF NSG.GT.4. IF SO CAN SIMPLIFY CALCULATION
C IN SUBROUTINE TRAN.
C
NCL=2
WSCRIT=6.
PRI=0.
ZSS=HAVG(2)
DH=ZSS/2
GOTO 113
118 CONTINUE
NTRAN=0
IF(KSTAB.EQ.KSTABB)NTRAN=1
IF(NSG.LE.4)NTRAN=0
TZ=TZZ(JSM,NSIDE,NCL)
EMIS(JSM,1,1)=EMAX(NSIDE,NCL)
COUP(NSG,NCL,JSM)=EMAX(NSIDE,NCL)*TRAN(N,M,1,1,NTRAN)*.381E-4
KSTABB=KSTAB
C INDUSTRY
NCL=3
WSCRIT=15.
PRI=0.
ZSS=HAVG(3)
DH=ZSS
GO TO 113
119 CONTINUE
NTRAN=0
IF(KSTABB.EQ.KSTAB)NTRAN=1
IF(NSG.LE.4)NTRAN=0
TZ=TZZ(JSM,NSIDE,NCL)
EMIS(JSM,1,1)=EMAX(NSIDE,NCL)
COUP(NSG,NCL,JSM)=EMAX(NSIDE,NCL)*TRAN(N,M,1,1,NTRAN)*.381E-4
30 CONTINUE
IF(NTEST.LT.1.OR.LLL.GT.2) GO TO 1112
NT=NSGRID
LLL=LLL+2
1112 CONTINUE
C77777
C THE ARRAY OF COUPLING COEFFICIENTS FOR HOUR M AND CLASSES 1-3
C HAS BEEN FORMED. NOW PLACE ORIGIN OF GRID ON EACH POINT OF
C RECEPTOR GRID: EVALUATE ACTUAL AREA SOURCES. EVALUATE POLLUTANT
C CONCENTRATION.
C
EMIS(JSM,1,1)=EMSAV
31 HEFF(JSM,1,1)=HKEEP
DO 50 NRCP=1,NRMAX
IWST=NXF(NRCP,NRWEST+1)
ISTH=NYF(NRCP,NRWEST+1)
CALLRGRID(IWST,ISTH,XRG,YRG)
DO49NSG=1,NSGRID
XALL=XRG+XSGRID(NSG)
YALL=YRG+YSGRID(NSG)
IAX=(XALL-XSORIG+.1)/DGRID
IAY=(YALL-YSORIG+.1)/DGRID
NX=1
IF(NSG.GT.16)NX=2
IF(NSG.GT.48)NX=4
IF(NSG.GT.88)NX=8
NSIDE=NX
IF(NSG.GT.48)NSIDE=3
IF(NSG.GT.88)NSIDE=4
C IF GO UP TO LARGER AREAS, MUST MODIFY CODE HERE.
DO 35 NCL=1,3

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DO 35 N=1,NLIMA
JSM=JSUB(M-N+1)
35 VQ(JSM,NCL)=0
DO 45 NSIX=1,NX
DO 45 NSIY=1,NX
IAXX=IAX-(NSIX-1)
IAYY=IAY-(NSIY-1)
IF(IAXX.LT.1.OR.IAXX.GT.NSXMAX.OR.
2 IAYY.LT.1.OR.IAYY.GT.NSYMAX) GO TO 45
NAREA=NSXMAX*(IAYY-1)+IAXX
DO 44 NCL=1,3
DO 44 N=1,NLIMA
JSM=JSUB(M-N+1)
44 VQ(JSM,NCL)=VQ(JSM,NCL)+EMIT(JSM,NCL,NAREA)
45 CONTINUE
IF(NTTEST.LT.1.OR.LLL.GT.2) GO TO 1115
1115 CONTINUE
CHI1=0
CHI2=0
CHI3=0
DO 47 N=1,NLIMA
JSM=JSUB(M-N+1)
CHI1=CHI1+COUP(NSG,1,JSM)*VQ(JSM,1)/EMAX(NSIDE,1)
CHI2=CHI2+COUP(NSG,2,JSM)*VQ(JSM,2)/EMAX(NSIDE,2)
47 CHI3=CHI3+COUP(NSG,3,JSM)*VQ(JSM,3)/EMAX(NSIDE,3)
RECDAT(3,NRCP)=RECDAT(3,NRCP)+CHI1+CHI2
RECDAT(2,NRCP)=RECDAT(2,NRCP)+CHI3
49 RECDAT(4,NRCP)=RECDAT(4,NRCP)+CHI1+CHI2+CHI3
50 CONTINUE
C88888
C POLLUTANT CONCENTRATIONS CALCULATED FOR EACH POINT ON RECEPTOR
C GRID. CONTRIBUTIONS FROM MAJOR SOURCE CLASSES IS KNOWN.
IR=1
C I=NNTAM
C PRINT469,M,I,RECDAT(4,NRTAM),HLID
C 469 FORMAT(10X,'SO2 AT HOUR M=',I5,10X,'FOR TAM',I4,10X,'=',E12.3,
C X 10X,'HLID=',E10.2)
NPPP=NPPP+1
IF(NPPP.LT.NPRINT) GO TO 6666
NPPP=0
C IN ORDER TO USE SUBROUTINE PROUT TO PRINT CONCENTRATIONS
C IN GRID FORMAT, MUST LIMIT NRWEST+1 .LE.12
CALL PROUT(MM,RECDAT,NWEST,NSTH)
IJOHN=5
C PUNCH 1919,NNTAM,NR,MM,(RECDAT(I,1),I=1,4),IJOHN
6666 CONTINUE
C PUNCHED OUTPUT . ONE TAM STATION AT A TIME. FOUR HOURS PER CARD
IF(VALOP.GT.0) SO2VAL(1)=RECDAT(4,NRTAM)
IF(PNCHOP.EQ.0) GO TO 513
NHRP(NCOUNT)=NR
C I=NNTAM
NTMP(NCOUNT,IR)=I
PREC(NCOUNT,IR)=SO2VAL(1)
OBSC(NCOUNT,IR)=AMINI(9.999,SOBS(IR))
295 MPU(NCOUNT)=M
NCOUNT=NCOUNT+1
IF(NCOUNT.LT.5) RETURN
NCOUNT=1
DO 298 IR=1,1
PUNCH 470,(NTMP(NC,IR),NHRP(NC),MPU(NC),PREC(NC,IR),OBSC(NC,IR),
X NC=1,4)
298 CONTINUE
470 FORMAT(4(I1,I3,I4,2F5.3,2X))
513 CONTINUE
293 CONTINUE
1919 FORMAT(I1,2X,I3,2X,I4,4(2X,F6.3),35X,I1)
RETURN
END

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3. Function ITRAN

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      FUNCTION ITRAN(EMIS,HEFF)
C      THIS VERSION USED FOR STEADY STATE PLUME MODEL
C
C      COMMON/KTROUB/KTRO
C      CUT OFF ON N
C
C      REAL*4 EMIS(12,4,1),HEFF(12,4,1)
C
C      COMMON/MXC/MX
C      COMMON/KERNEL/X,Y,Z,U(24),V(24),W(24),JS(24),HMX(24),WSBAR(24),WZ
C
C      COMMON/SUEDO/TX,TY,TZ,DX,DY,DZ
C      COMMON/XTRAN/KSTAB
C      IF(KSTAB.GT.0)HAVE PLUME INITIALLY ABOVE LID.
C      COMMON/POUT/I
C      DIMENSION JSSS(24)
C      DATA NCUT/4/
C      DATA KPR/1/
C      DATA K1/0/,KMAX/100/
C
C      COMMON/WDUN/WSAVE
C      COMMON /WAYNE/ WJWG
C      ITRAN=0
C      ADD1=0.
C      QSS=0.
C      CHIMAX=0.
C      E5=0.
C      EPS=.0001
C      EPS=.001
C      RETURN
C
C      ENTRY TRAN(N,M,K,J,NTRAN)
C11111
C      TIN=TLEFT(YYYY)
C      IF(NTRAN.EQ.0) USE KERN TO EVALUATE POINT OR AREA SOURCE.
C      OTHERWISE USE PREVIOUS AREA SOURCE CALC. WITH NEW HEFF
C      MULTIPLE IMAGES
C      Z AND ZKEEP IN MILES
C      JSUBX=JSUB(M-N+1)
C      DO 510 IK=1,MX
510  JSSS(IK)=JS(IK)
C      NOW CAN PLAY AROUND WITH THE JS ARRAY
C
C      WSAVE=WSBAR(JSUB(M))
C      KFUME=10
C      ZKEEP=Z
C      IF (NTRAN.EQ.0) GO TO 1001
C      IF(DW.LT.0.0) GO TO 16
C      TEST=CHIMAX*E5*EMIS(JSUBX,K,J)/QSS
C      IF(NTRAN.EQ.1.AND.TEST.LT.EPS) GO TO 76
C      IF(NZERO.EQ.1) NTRAN=0
C      IF(NTRAN.GT.0) GO TO 1
1001 CONTINUE
C      NCALM=0
C      NZERO=0
C      QSS=EMIS(JSUBX,K,J)
C      ADD1=0.
C      ADD2=0.
C      ADD3=0.
1  CONTINUE
C      ADD4=0.
C      ADD5=0.
C      ADD6=0.
C      ADD7=0.
C      ADD8=0.
C      ADD9=0.

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      Z1=HEFF(JSUBX ,K ,J)/5280.-ZKEEP
      Z2=HEFF(JSUBX , K ,J)/5280.+ZKEEP
C
C
      MN=M
      NT=0
      ZSS=HEFF(JSUBX,K ,J)
      IF(KSTAB.GT.0)GO TO 121
      JIK=JSUB(M)
      IF(JS(JIK).EQ.5)JS(JIK)=4
      HLID=HMIX(JSUB(M))
      GO TO 140
121 JSSS=4
      IF(KSTAB.EQ.2) GO TO 130
      JSSS=5
130 JS(JSUB(M))=JSSS
      HLID=1.E4
140 Z3=(2.*HLID -HEFF(JSUBX ,K ,J))/5280.-ZKEEP
C      IF PLUME BELOW LID AND RECEPTOR ABOVE,CHI=0.AND GO TO 61
      IF(5280.*ZKEEP.GT.HLID.AND.KSTAB.EQ.0)GOTO61
      HLI=HLID/5280.
      IF(NTRAN.GT.0) GO TO 998
      ZA=Z1
      ZB=Z2
      ZC=Z3
      TY=TX
      XPP=0.
      YPP=0.
      XK=X
      YK=Y
      X=X-TX*U(JSUBX )
      Y=Y-TY*V(JSUBX )
      JLIM=M+1
6 CONTINUE
7 CONTINUE
      XP=XPP+U(JSUBX )
      YP=YPP+V(JSUBX )
      UU=U(JSUBX)
      VV=V(JSUBX)
C      CW=CROSSWIND DISTANCE AND DW=DOWNWIND DISTANCE IF POSITIVE.
      CALL CRDNTPT(X,Y,UU,VV,CW,DW)
C      TEST FOR CALM CONDITION. IF U<WJWG USE CALM ALGORITHM
      IF(WSAVE .LE. WJWG) GO TO 9596
      IF(DW)16,17,17
16 CONTINUE
      GO TO 76
17 CONTINUE
      X=XK
      Y=YK
      NDTL=0
      DMIN=CW
      TMIN=DW/WSAVE
305 CONTINUE
      JSTAB=JS(JSUB(M))
      IF(TMIN.LE..001) TMIN=.01
      T=TMIN
      SY=SIGY(JSTAB,T+TY)
      SZ=SIGZ(JSTAB,T+TZ)
      E1=.0000001
      E2=.0000001
      E3=.0000001
      EXPZ1=(-.5*(Z1/SZ)*(Z1/SZ))
      EXPZ2=(-.5*(Z2/SZ)*(Z2/SZ))
      EXPZ3=(-.5*(Z3/SZ)*(Z3/SZ))
      IF(EXPZ1.GT.-20.) E1=EXP(EXPZ1)
      IF(EXPZ2.GT.-20.) E2=EXP(EXPZ2)
      IF(EXPZ3.GT.-20.) E3=EXP(EXPZ3)
      IF(M.LT.3) PRINT 33333

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33333 FORMAT(1X,'RETURNED FROM SIGY CK.#1')
DENOM=6.284*WSAVE*SY*SZ
CHIMAX=EMIS(JSUBX ,K ,J)*(E1+E2+E3)*.38122E-4/DENOM
E4=DMIN/SY
EXPZ4=-0.5*E4*E4
E5=0.0000001
IF(EXPZ4.GT.-20.) E5=EXP(EXPZ4)
CHIME5=CHIMAX*E5
IF(CHIME5.LT.EPS)NZERO=1
IF(NZERO.EQ.1) GO TO 61
IF(KPR.GT.KMAX) GO TO 311
KPR=KPR+1
GO TO 311

      PRINT 404,M,N,I,HLID ,KFUME,NTRAN
404 FORMAT(3X,'IN TRAN. M,N,I=',3I5,5X,'HLID=',E12.3,
X 3X,'KFUME=',I4,3X,'NTRAN=',I3)
      PRINT 999,N,M,Z1,Z2,Z3,WSAVE,X,T,JSTAB,SY,SZ
999 FORMAT(3HON=I5,3H M=I5,4H Z1=E10.1,4H Z2=E10.1,4H Z3=E10.1/
17H WSAVE=F10.1,3H X=F10.1,3H T=F10.2/
27H JSTAB=I5,4H SY=E15.5,4H SZ=E15.5)
      PRINT 410,CHIME5,QSS,E1,E2,E3
410 FORMAT(10X,'CHIMAX*E5=',E10.2,5X,'QSS=',E12.2,5X,'E1,E2,E3=',
X 3E10.2)
      PRINT 413,KSTAB,U(1),V(1),X,Y,TX
413 FORMAT(10X,'KSTAB,U,V,X,Y,TX=',I5,5E10.2)
      PRINT 401,DMIN,TMIN,E5,DL,DT
401 FORMAT(5X,'IN TRAN. DMIN,TMIN,E5,DL,DT=',5E12.2)
C33333
311 CONTINUE
ADD1=E1*E5/DENOM
ADD2=ADD1*E2/E1
ADD3=ADD1*E3/E1
998 CONTINUE
60 CONTINUE
HLI=HLID/5280.
IF(WSAVE .LE. WJWG) GO TO 9596
IF(NCALM.EQ.1) GO TO 9596
SYY=SIGY(JSTAB,TMIN+TY)
SZZ=SIGZ(JSTAB,TMIN+TZ)
SZQ=SZZ*SZZ
IF(KPR.LT.KMAX)PRINT 407,Z1,ZA,Z2,ZB,Z3,ZC,ADD1,ADD2,ADD3,SZZ
407 FORMAT(3X,10E12.2)
IF(NTRAN.EQ.0) GO TO 660
EXPO=-.5*(Z1*Z1-ZA*ZA)/SZQ
IF(EXPO.LE.-20) EXPO=-10.
ADDA=ADD1
ADD1=ADD1*EXP(EXPO)
EXPO=-.5*(Z2*Z2-ZB*ZB)/SZQ
IF(EXPO.LE.-20) EXPO=-10.
ADDB=ADD2
ADD2=ADD2*EXP(EXPO)
EXPO=-.5*(Z3*Z3-ZC*ZC)/SZQ
IF(EXPO.LE.-20) EXPO=-10.
ADDC=ADD3
IF(ADDC.LT.1.E-4) GO TO 660
ADD3=ADD3*EXP(EXPO)
KU=KMAX
IF(KPR.LE.KU)PRINT 408,ADD1,ADD2,ADD3
408 FORMAT(75X,3E12.2 /)
660 CONTINUE
C44444
IF(ADD3.LT.1.E-5) GO TO 61
ZLBG=Z3+2.*ZKEEP
ZGAL=Z2+2.*(HLI-ZKEEP)
ZL3=ZLBG+2*HLI-2.*ZKEEP
G3=ZGAL+2.*ZKEEP
ZL4=G3+2.*(HLI-ZKEEP)

```

```

G4=ZL3+2.*ZKEEP
IF(ADD3.LE..00001) GO TO 61
EXPO= .5*(Z3*Z3- ZLBG**2)/SZQ
IF(EXPO.LE.-20.) GO TO 61
ADD4=ADD3*EXP(EXPO)
EXPO= .5*(Z3*Z3- ZGAL**2)/SZQ
IF(EXPO.LE.-20.) GO TO 61
ADD5=ADD3*EXP(EXPO)
EXPO= .5*(Z3*Z3- ZL3 **2)/SZQ
IF(EXPO.LE.-20.) GO TO 61
ADD6=ADD3*EXP(EXPO)
EXPO= .5*(Z3*Z3- G3**2)/SZQ
IF(EXPO.LE.-20.) GO TO 61
ADD7=ADD3*EXP(EXPO)
EXPO= .5*(Z3*Z3- ZL4**2)/SZQ
IF(EXPO.LE.-20.) GO TO 61
ADD8=ADD3*EXP(EXPO)
EXPO= .5*(Z3*Z3- G4**2)/SZQ
IF(EXPO.LE.-20.) GO TO 61
ADD9=ADD3*EXP(EXPO)
61 CONTINUE
TRAN=ADD1+ADD2+ADD3+ADD4+ADD5+ADD6+ADD7+ADD8+ADD9
IF(CHTMAX*E5.LT.EPS) GO TO 70
IF(ADD3.LT.1.E-5) GO TO 70
C
IF(KPR.GT.KU) GO TO 70
PRINT 409,ADD4,ADD5,ADD6,ADD7,ADD8,ADD9
409 FORMAT(3X,6E12.2)
70 CONTINUE
700 CONTINUE
DO 71 IK=1,MX
71 JS(IK)=JSSS(IK)
C
JS ARRAY AS BEFORE.
Z=ZKEEP
IF(NTRAN.EQ.0) GO TO 75
ADD1=ADDA
ADD2=ADDB
ADD3=ADDC
75 CONTINUE
RETURN
76 TRAN=0.
ADDA=ADD1
ADDB=ADD2
ADDC=ADD3
GO TO 700
9596 JSTAB=JS(JSUB(M))
C. CALM ALGORITHM
T=1.
DW=ABS(DW)
TMIN=DW/WSAVE
CONST=6.2831**1.5
E5=1.
RR=CW*CW+DW*DW
ZS1=Z1*Z1
ZS2=Z2*Z2
ZS3=Z3*Z3
SY=SIGY(JSTAB,T)
SZ=SIGZ(JSTAB,T)
ALPSQ=SY*SY
GAMSQ=SZ*SZ
TAU=2.
EE1=0.0000001
EE2=0.0000001
EE3=0.0000001
PXZ1=-(RR/(2.*ALPSQ)+ZS1/(2.*GAMSQ))/(TAU*TAU)
PXZ2=-(RR/(2.*ALPSQ)+ZS2/(2.*GAMSQ))/(TAU*TAU)
PXZ3=-(RR/(2.*ALPSQ)+ZS3/(2.*GAMSQ))/(TAU*TAU)

```



```

IF(PXEZ1 .GT. -20.) EE1=EXP(PXEZ1)
IF( PXEZ2 .GT. -20.) EE2=EXP(PXEZ2)
IF( PXEZ3 .GT. -20.) EE3=EXP(PXEZ3)
CALM1=1./((CONST*ALPSQ*SZ*(RR/ALPSQ+ZS1/GAMSQ))
CALM2=1./((CONST*ALPSQ*SZ*(RR/ALPSQ+ZS2/GAMSQ))
CALM3=1./((CONST*ALPSQ*SZ*(RR/ALPSQ+ZS3/GAMSQ))
CALM1=CALM1*EE1
CALM2=CALM2*EE2
CALM3=CALM3*EE3
CALM=CALM1+CALM2+CALM3
CAM=1./((HLI*SQRT(RR)*SY*5.013)
ERO=SQRT(RR)/(1.41*SY)
ERO=ERO/TAU
CAM=CAM*(1.-ERF(ERO))
PRINT 9666,CALM1,CALM2,CALM3,CAM
9666 FORMAT(' CALM1,CALM2,CALM3,CAM',4E12.3)
IF((CALM3/CALM1) .GT. .25) CALM=CAM
IF((CALM3/CALM1) .GT. .25) PRINT 9396
9396 FORMAT(' POOR CONVERGENCE')
CHIMAX=EMIS(JSUBX,K,J)*CALM
IF(CHIMAX .LT. EPS) NZERO=1
TRAN=CALM
IF(CHIMAX .LT. EPS) TRAN=0.0
IF(NZERO.LT.1)NCALM=1
GO TO 70
END

```

4. Subroutine CRDNTF

```

SUBROUTINE CRDNTF(X,Y,U,V,CW,DW)
ARG=ABS(U/V)
T=ATAN(ARG)
C DETERMINE QUADRANT
IF(U)10,11,11
10 IF(V)12,13,13
11 IF(V)14,15,15
12 T=T+3.14159
GO TO 15
13 T=6.28318-T
GO TO 15
14 T=3.14159-T
15 CONTINUE
SI=1.5*3.14159-T
XRR=-X-.001
YRR=-Y
H=SQRT (XRR**2+YRR**2)
ARG= ABS(YRR/XRR)
PHI= ATAN(ARG)
IF(XRR)1,2,2
1 IF(YRR)3,4,4
2 IF(YRR)5,6,6
5 PHI=-PHI
GO TO 6
4 PHI=3.1416-PHI
GO TO 6
3 PHI=3.1416+PHI
6 CONTINUE
C
THETA=PHI-SI
DW=H*COS(THETA)
CW=ABS(H*SIN(THETA))
RETURN
END

```

5. Function SIGY

```

FUNCTION SIGY(J,THOUR)
C
COMMON/WDUN/WSAVE
DIMENSION A(7),B(7)
DIMENSION C(5),D(5)
C
DATA C/155.,100.,68.,50.,34./, D/.91,.92,.93,.90;.93/
DATA A/2.1511,1.5454,1.0606,.68465,.59366,.59366,.59366/
DATA B/.87326,.88261,.89031,.88866,.89138,.89138,.89138/
DATA CONV/.000621371/
C J=1,2,3,4,5 ARE CLASSES B,C,D,E,F
C XX AND SIGXY ARE IN MILES
TSEC=THOUR*3600.
C
SIGY=(A(J)*TSEC**B(J))*CONV
C WSAVE IS MEAN WIND SPEED UP TO TIME T.
XX=WSAVE*THOUR*1.609
JJ=MAX0(J-1,1)
SIGXY=C(JJ)*(XX**D(JJ))*0.000889
C .000889=(1/1609.)*(6**.2)
SIGY=AMAX1(SIGY,SIGXY)
C
C DISPERSION COEFFICIENTS BASED ON TURNER WORKBOOK.
C WHERE THE SIGMAS GIVEN IN THE WORKBOOK FOR
C TEN MINUTE SAMPLINGS ARE SCALED TO 1 HOUR
C AVERAGES BY A FACTOR OF 1.43
RETURN
END

```

6. Function SIGZ

```

FUNCTION SIGZ(J,THOUR)
C
COMMON/WDUN/WSAVE
C DISPERSION COEF. BASED ON TURNERS WORKBOOK
C J=1,2,3,4,5 ARE CLASSES B,C,D,E,F
C X AND SIGZ ARE IN MILES
DIMENSION C(3,5),D(3,5)
REAL TIME(7),A(7,6),B(7,6)
C
DATA TIME/0.,300.,1000.,3000.,10000.,30000.,172000./
DATA A/.17122,.27668,.41219,.51921,.50963,.47639,.52140,
1 .11062,.39953,.41219,.57145,.76485,.71936,.88886,
2 .01338,.16640,.41219,1.0813,1.9467,2.3901,1.8877,
3 .01338,.16640,.41219,2.2830,2.9850,3.8684,6.7452,
3 .01338,.16640,.41219,2.3333,5.7990,16.897,20.673,
3 .01338,.16640,.41219,5.6801,14.599,64.577,54.149/
DATA B/1.2098,1.0572,.92365,.84130,.79689,.76308,.69839,
1 1.2864,.99275,.92365,.82449,.72571,.69082,.60486,
2 1.5922,1.1195,.92365,.73217,.59047,.51700,.49583,
3 1.5922,1.1195,.92365,.63883,.53708,.45686,.33677,
4 1.5922,1.1195,.92365,.63646,.46497,.29621,.21517,
5 1.5922,1.1195,.92365,.55016,.37541,.16667,.12177/
DATA C/110.,110.,110.,60.,60.,60.,33.,33.,40.,21.5,21.5,36.,14.,
114.,23.5/
DATA D/1.,1.09,1.09,.92,.92,.92,.80,.61,.53,.70,.56,.35,.78,.53,

```

```

1.30/
DATA CONV/.000621371/
DATA KPR/0/
C
TSEC=THOUR*3600.
DO 10 N=2,7
IF (TSEC.LE.TIME(N))GO TO 20
10 CONTINUE
IF (N.GT.7) N=7
C TIME OF TRAVEL SHOULD BE LESS THAN 172.E03 SEC APPROX. 2 DAYS
20 CONTINUE
N=N-1
KMAX=0
IF (KPR.GT.KMAX) GO TO 1
KPR=KPR+1
TIN=TLEFT(YYYY)
SIGZ=(A(J,N)*TSEC**B(J,N))*CONV
TIN=(TIN-TLEFT(YYYY))/100.
PRINT 401,TIN
401 FORMAT(10X,'IN SIGZ.TIN=', E12.2)
RETURN
1 CONTINUE
SIGZ=(A(J,N)*TSEC**B(J,N))*CONV
C TURNER TEST EQUATION
C SIGZ=(1.17518*TSEC**.72012)*CONV
XX=WSAVE*THOUR*1.609
I=1
IF (XX.GT.1.) I=2
IF (XX.GT.10.) I=3
JJ=MAX0(J-1,1)
C
C
SIGTZ=(C(I,JJ)*XX**D(I,JJ))*0.000889
.000889=(1/1609*(60/10)**.2
C SIGZ=AMAX1(SIGZ,SIGTZ)
RETURN
END

```

APPENDIX C

Example Computation of Hourly SO₂ Concentrations at TAM 5
for February 17, 1967, Using the Plume Code

This appendix describes the calculation of hourly SO₂ concentrations at TAM 5 using the steady-state plume-model code (see Appendix B for computer program listings) with the calm algorithm operative whenever $WS \leq 1$ mph. The calculations refer to the exact location of the TAM 5 aerovane using the winds measured at that location.

This appendix is divided into two parts. The first (Tables C.1-C.3) describes the input data necessary to carry out the computation. Some of these data are tabulated in Ref. 1 and will not be repeated here. The remaining data are included in this report. The second part (Table C.4) is a tabulation of the results. These results are a portion of the results obtained for the historical episode of February 16-18, 1967, which were displayed graphically and analyzed statistically in the text. (See Figs. 8 and 10 and Table 4.1.)

1. Input Dataa. Emission Data(1) Power Plants

Annual emission rates (p. 62 of Ref. 1).

Stack parameters (Table C.2).

Hourly emission rates (Table C.1).

(2) Major Point Sources

Annual emission rates (Table 7.3 of Ref. 1).

Stack parameters (Table 7.3 of Ref. 1).

Hourly emission rates (Table C.1).

(3) Additional Point Sources

Annual emission rates (Table 7.4 of Ref. 1).

Stack parameters (Table 7.4 of Ref. 1).

Hourly emission rates (calculated in ISPDV).

(4) Area Sources

Annual emission rates (Figs. 7.2 and B.3 of Ref. 1).

Stack parameters (Table 1.4 of Ref. 1).

Hourly emission rates (calculated in "ISPDV").

The coordinates of the various sources referred to in the tables are with respect to the coordinate system given in Fig. 7.1 of Ref. 1.

b. Meteorological Data

The meteorological data are shown in Table C.3.

c. Receptor (TAM 5) Coordinates

Coordinates for the TAM 5 receptor are given in Table C.2.

2. Results

The results are shown in Table C.4. There are two columns labeled TAM 5 SO_2 . The first column is the observed, and the second the calculated, concentrations.

TABLE C.1. PLANTSIM Output. Hourly emissions of SO₂ (in lb/hr)
and heat emissions (in therms/hr) for February 17, 1967.

PLANTSIM ALL SOURCES '67 FEB 16-18
DATE:67/02/17

HOUR	CECO__1 Q_SO2	CECO__1 Q_HEAT	CECO__2 Q_SO2	CECO__2 Q_HEAT	FISK__1 C_SO2	FISK__1 Q_HEAT	FISK__2 Q_SO2	FISK__2 Q_HEAT	FISK__3 Q_SO2	FISK__3 Q_HEAT
1	119.232	38.880	119.232	38.880	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	91.885	29.962	91.885	29.962	0.0	0.0	0.0	0.0	0.0	0.0
4	91.885	29.962	91.885	29.962	0.0	0.0	0.0	0.0	0.0	0.0
5	91.885	29.962	91.885	29.962	0.0	0.0	0.0	0.0	0.0	0.0
6	91.885	29.962	91.885	29.962	105.420	34.376	105.420	34.376	105.420	34.376
7	283.314	92.385	283.314	92.385	1561.521	509.192	1561.521	509.192	1561.521	509.192
8	1623.315	529.342	1623.315	529.342	1504.643	490.645	1504.643	490.645	1504.643	490.645
9	3264.135	1064.392	3264.135	1064.392	1641.152	535.158	1641.152	535.158	1641.152	535.158
10	3209.439	1046.557	3209.439	1046.557	1868.667	609.348	1868.667	609.348	1868.667	609.348
11	3291.480	1073.310	3291.480	1073.310	1925.547	627.896	1925.547	627.896	1925.547	627.896
12	3182.094	1037.640	3182.094	1037.640	1538.770	501.773	1538.770	501.773	1538.770	501.773
13	3100.051	1010.887	3100.051	1010.887	1698.030	553.706	1698.030	553.706	1698.030	553.706
14	3646.990	1189.237	3646.990	1189.237	1675.278	546.287	1675.278	546.287	1675.278	546.287
15	3318.828	1082.227	3318.828	1082.227	1663.903	542.577	1663.903	542.577	1663.903	542.577
16	3264.135	1064.392	3264.135	1064.392	1584.272	516.611	1584.272	516.611	1584.272	516.611
17	3811.074	1242.742	3811.074	1242.742	1584.272	516.611	1584.272	516.611	1584.272	516.611
18	4002.502	1305.164	4002.502	1305.164	1811.789	590.801	1811.789	590.801	1811.789	590.801
19	4358.012	1421.092	4358.012	1421.092	1518.400	527.740	1518.400	527.740	1518.400	527.740
20	4303.316	1403.257	4303.316	1403.257	1584.272	516.611	1584.272	516.611	1584.272	516.611
21	4002.502	1305.164	4002.502	1305.164	1518.400	527.740	1518.400	527.740	1518.400	527.740
22	4084.543	1331.917	4084.543	1331.917	1518.400	527.740	1518.400	527.740	1518.400	527.740
23	1541.274	502.590	1541.274	502.590	1015.483	331.136	1015.483	331.136	1015.483	331.136
24	91.885	29.962	91.885	29.962	1015.483	331.136	1015.483	331.136	1015.483	331.136
HOUR	FISK__4 Q_SO2	FISK__4 Q_HEAT	FISK__5 Q_SO2	FISK__5 Q_HEAT	CRAWF__1 Q_SO2	CRAWF__1 Q_HEAT	CRAWF__2 Q_SO2	CRAWF__2 Q_HEAT	CRAWF__3 Q_SO2	CRAWF__3 Q_HEAT
1	0.0	0.0	12338.828	4136.574	7177.012	2340.332	12713.836	4145.816	0.0	0.0
2	0.0	0.0	12682.688	4135.660	7058.043	2301.537	9557.586	3129.650	0.0	0.0
3	0.0	0.0	11121.262	3626.501	5590.750	1823.072	12000.480	3913.202	0.0	0.0
4	0.0	0.0	12916.898	4212.031	7097.699	2314.469	12150.660	3962.174	0.0	0.0
5	0.0	0.0	12448.465	4059.286	6185.598	2017.044	12000.480	3913.202	0.0	0.0
6	105.420	34.376	13346.285	4352.051	8842.590	2883.455	13201.922	4304.977	0.0	0.0
7	1561.521	509.192	13073.039	4262.949	7335.641	2392.058	11850.301	3864.229	0.0	0.0
8	1504.643	490.645	12750.758	4161.117	8683.965	2831.729	13427.191	4378.434	0.0	0.0
9	1641.152	535.158	13151.109	4268.406	8168.426	2663.619	13229.469	4317.219	3558.372	1160.339
10	1868.667	609.348	13151.109	4268.406	9477.094	3090.359	13539.832	4415.164	5487.609	1789.439
11	1925.547	627.896	13151.109	4268.406	9199.500	2999.838	13389.645	4356.191	5358.992	1747.499
12	1538.770	501.773	12955.934	4224.762	9239.156	3012.770	13389.645	4356.191	5294.684	1726.529
13	1698.030	553.706	13453.391	4390.238	8683.965	2831.729	13352.098	4353.949	5166.070	1684.589
14	1675.278	546.287	13190.145	4301.137	9159.844	2986.907	13502.285	4432.918	5230.379	1705.559
15	1663.903	542.577	12955.934	4224.762	9080.531	2951.044	13464.738	4330.676	4780.219	1558.769
16	1584.272	516.611	12838.828	4186.574	7692.547	2508.441	13089.281	4268.246	4458.680	1453.919
17	1584.272	516.611	13346.285	4352.051	7611.520	2547.236	13239.469	4317.219	4008.530	1307.130
18	1811.789	590.801	13424.355	4377.508	9218.469	3038.633	13652.461	4451.891	4330.066	1411.979
19	1618.400	527.740	13034.004	4250.219	8763.277	2857.592	13277.016	4329.461	4072.836	1328.099
20	1584.272	516.611	12994.969	4237.492	9120.188	2973.976	13539.832	4415.164	4587.297	1495.859
21	1618.400	527.740	12502.426	4402.969	9199.500	2999.838	7382.422	2407.313	4072.836	1328.099
22	1618.400	527.740	13385.320	4364.781	9080.531	2961.044	2651.730	864.695	1822.055	594.149
23	1015.483	331.136	13346.285	4352.051	9080.531	2961.044	0.0	0.0	0.0	0.0
24	1015.483	331.136	13229.180	4313.863	9120.188	2973.976	0.0	0.0	0.0	0.0

TABLE C.1 (Contd.)

PLANTSIM ALL SOURCES *67 FEB 16-18
DATE:67/02/17

HOUR	RIDGL_1 Q_SO2	RIDGL_1 Q_HEAT	RIDGL_2 Q_SO2	RIDGL_2 Q_HEAT	RIDGL_3 Q_SO2	RIDGL_3 Q_HEAT	RIDGL_4 Q_SO2	RIDGL_4 Q_HEAT	RIDGL_5 Q_SO2	RIDGL_5 Q_HEAT
1	2576.630	840.206	2576.630	840.206	2576.630	840.206	2576.630	840.206	5859.207	1910.612
2	2770.577	903.449	2770.577	903.449	2770.577	903.449	2770.577	903.449	5902.258	1924.651
3	2398.092	781.987	2398.092	781.987	2398.092	781.987	2398.092	781.987	5213.434	1700.035
4	2135.261	696.281	2135.261	696.281	2135.261	696.281	2135.261	696.281	5643.949	1840.420
5	2407.177	784.950	2407.177	784.950	2407.177	784.950	2407.177	784.950	5816.156	1896.574
6	2963.835	966.468	2963.835	966.468	2963.835	966.468	2963.835	966.468	5902.258	1924.651
7	2763.390	901.106	2763.390	901.106	2763.390	901.106	2763.390	901.106	5988.359	1952.728
8	3832.314	1249.668	3832.314	1249.668	3832.314	1249.668	3832.314	1249.668	5988.359	1952.728
9	3490.649	1138.256	3490.649	1138.256	3490.649	1138.256	3490.649	1138.256	5988.359	1952.728
10	3951.052	1288.387	3951.052	1288.387	3951.052	1288.387	3951.052	1288.387	5945.309	1938.689
11	3903.786	1272.975	3903.786	1272.975	3903.786	1272.975	3903.786	1272.975	6160.566	2008.882
12	3999.179	1304.081	3999.179	1304.081	3999.179	1304.081	3999.179	1304.081	6074.465	1980.805
13	3939.379	1284.581	3939.379	1284.581	3939.379	1284.581	3939.379	1284.581	5945.309	1938.689
14	3831.739	1249.481	3831.739	1249.481	3831.739	1249.481	3831.739	1249.481	6074.465	1980.805
15	3843.412	1253.287	3843.412	1253.287	3843.412	1253.287	3843.412	1253.287	5988.359	1952.728
16	3123.915	1018.668	3123.915	1018.668	3123.915	1018.668	3123.915	1018.668	6031.414	1966.766
17	3478.114	1134.168	3478.114	1134.168	3478.114	1134.168	3478.114	1134.168	6031.414	1966.766
18	4105.957	1338.899	4105.957	1338.899	4105.957	1338.899	4105.957	1338.899	6504.977	2121.189
19	4106.242	1338.993	4106.242	1338.993	4106.242	1338.993	4106.242	1338.993	6332.770	2065.035
20	3870.781	1262.212	3870.781	1262.212	3870.781	1262.212	3870.781	1262.212	6160.566	2008.882
21	3894.126	1269.825	3894.126	1269.825	3894.126	1269.825	3894.126	1269.825	6160.566	2008.882
22	3905.799	1273.631	3905.799	1273.631	3905.799	1273.631	3905.799	1273.631	6117.516	1994.843
23	3882.167	1265.925	3882.167	1265.925	3882.167	1265.925	3882.167	1265.925	6117.516	1994.843
24	3479.553	1134.637	3479.553	1134.637	3479.553	1134.637	3479.553	1134.637	5730.055	1868.497
HOUR	RIDGL_6 Q_SO2	RIDGL_6 Q_HEAT	CALUM_1 Q_SO2	CALUM_1 Q_HEAT	CALUM_2 Q_SO2	CALUM_2 Q_HEAT	STATE_1 Q_SO2	STATE_1 Q_HEAT	STATE_2 Q_SO2	STATE_2 Q_HEAT
1	0.0	0.0	1295.036	422.295	1295.036	422.295	0.0	0.0	0.0	0.0
2	0.0	0.0	1072.511	349.732	1072.511	349.732	0.0	0.0	0.0	0.0
3	2034.315	663.364	1097.236	357.795	1097.236	357.795	0.0	0.0	0.0	0.0
4	3083.888	1005.616	1146.686	373.920	1146.686	373.920	0.0	0.0	0.0	0.0
5	3696.136	1205.263	1047.786	341.670	1047.786	341.670	0.0	0.0	0.0	0.0
6	4045.956	1319.347	1171.412	381.982	1171.412	381.982	0.0	0.0	0.0	0.0
7	4133.457	1347.868	2086.234	680.295	2086.234	680.295	1556.630	461.452	1556.630	461.452
8	5139.297	1675.859	2654.910	865.732	2654.910	865.732	3551.760	1052.894	3551.760	1052.894
9	5576.621	1818.464	2630.186	857.670	2630.186	857.670	3253.980	964.619	3253.980	964.619
10	6451.262	2103.674	2605.459	849.607	2605.459	849.607	4028.211	1194.135	4028.211	1194.135
11	6188.871	2018.111	2704.359	881.857	2704.359	881.857	3819.764	1132.342	3819.764	1132.342
12	6232.602	2032.372	2729.086	889.920	2729.086	889.920	2449.973	726.277	2449.973	726.277
13	6232.602	2032.372	2729.086	889.920	2729.086	889.920	2152.191	638.002	2152.191	638.002
14	6145.137	2003.851	2654.910	865.732	2654.910	865.732	2479.750	735.104	2479.750	735.104
15	6101.406	1989.590	2729.086	889.920	2729.086	889.920	1645.964	487.935	1645.964	487.935
16	5532.887	1804.204	2729.086	889.920	2729.086	889.920	1526.853	452.625	1526.853	452.625
17	5620.352	1832.725	2704.359	881.857	2704.359	881.857	1675.742	496.762	1675.742	496.762
18	6713.656	2189.237	3495.559	1139.857	3495.559	1139.857	4474.879	1326.547	4474.879	1326.547
19	6669.926	2174.977	3668.635	1196.294	3668.635	1196.294	4861.996	1441.304	4861.996	1441.304
20	5970.211	1946.809	3643.910	1188.232	3643.910	1188.232	3373.092	999.929	3373.092	999.929
21	5882.746	1918.287	3643.910	1188.232	3643.910	1188.232	2837.086	841.034	2837.086	841.034
22	5970.211	1946.809	3693.359	1204.357	3693.359	1204.357	2241.525	664.485	2241.525	664.485
23	5882.746	1918.287	3248.311	1059.232	3248.311	1059.232	0.0	0.0	0.0	0.0
24	5882.746	1918.287	973.611	317.482	973.611	317.482	0.0	0.0	0.0	0.0

TABLE C.1 (Contd.)

PLANTSIM ALL SOURCES *67 FEB 16-18
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HOUR	STATE_3 Q_SO2	STATE_3 Q_HEAT	STATE_4 Q_SO2	STATE_4 Q_HEAT	STATE_5 Q_SO2	STATE_5 Q_HEAT	STATE_6 Q_SO2	STATE_6 Q_HEAT	MARBHEAD Q_SO2	MARBHEAD Q_HEAT
1	2567.287	761.054	2567.287	761.054	9136.547	2708.465	15643.875	4637.516	385.618	377.235
2	2567.287	761.054	2567.287	761.054	9300.613	2757.101	15729.238	4662.820	385.594	377.212
3	2567.287	761.054	2567.287	761.054	9095.531	2696.306	15601.195	4624.863	385.594	377.212
4	2567.287	761.054	2567.287	761.054	9218.582	2732.783	11162.371	3309.006	385.594	377.212
5	2567.287	761.054	2567.287	761.054	9177.563	2720.624	14235.410	4219.984	385.594	377.212
6	2567.287	761.054	2567.287	761.054	9751.793	2890.850	15729.238	4662.820	385.642	377.258
7	2670.916	791.774	2670.916	791.774	9546.715	2830.055	15729.238	4662.820	385.665	377.281
8	3422.225	1014.494	3422.225	1014.494	9628.746	2854.373	15729.238	4662.820	385.642	377.258
9	2567.287	761.054	2567.287	761.054	9628.746	2854.373	15729.238	4662.820	385.642	377.258
10	3422.225	1014.494	3422.225	1014.494	9792.809	2903.009	15601.195	4624.863	385.594	377.212
11	3448.133	1022.174	3448.133	1022.174	9628.746	2854.373	15643.875	4637.516	385.547	377.166
12	3474.039	1029.854	3474.039	1029.854	9341.629	2769.260	15857.281	4700.777	385.476	377.097
13	3085.432	914.654	3085.432	914.654	9792.809	2903.009	15515.832	4599.559	385.453	377.073
14	3344.502	991.454	3344.502	991.454	9528.746	2854.373	15857.281	4700.777	385.429	377.051
15	2670.916	791.774	2670.916	791.774	9874.840	2927.327	15643.875	4637.516	385.406	377.027
16	2567.287	761.054	2567.287	761.054	9259.598	2744.942	15430.473	4574.254	385.382	377.004
17	2904.082	860.895	2904.082	860.895	9628.746	2854.373	15430.473	4574.254	385.382	377.004
18	3474.039	1029.854	3474.039	1029.854	9546.715	2830.055	15515.832	4599.559	385.382	377.004
19	3007.709	891.615	3007.709	891.615	9095.531	2696.306	15643.875	4637.516	385.406	377.027
20	3137.246	930.014	3137.246	930.014	9464.680	2805.737	15643.875	4637.516	385.406	377.027
21	2929.988	868.574	2929.988	868.574	9628.746	2854.373	15729.238	4662.820	385.406	377.027
22	2981.803	883.935	2981.803	883.935	9464.680	2805.737	15729.238	4662.820	385.406	377.027
23	2670.916	791.774	2670.916	791.774	9628.746	2854.373	15814.602	4688.125	385.382	377.004
24	2670.916	791.774	2670.916	791.774	9013.500	2671.988	15430.473	4574.254	385.382	377.004
HOUR	CAMPBELL Q_SO2	CAMPBELL Q_HEAT	PROC_GAM Q_SO2	PROC_GAM Q_HEAT	SHER_WM Q_SO2	SHER_WM Q_HEAT	INTRLAK1 Q_SO2	INTRLAK1 Q_HEAT	INT_HARI Q_SO2	INT_HARI Q_HEAT
1	1063.779	358.846	483.105	175.038	803.324	280.665	484.864	182.432	539.659	175.976
2	1060.358	357.692	481.832	174.577	803.324	280.665	484.864	182.432	538.244	175.514
3	1060.358	357.692	481.832	174.577	803.324	280.665	484.864	182.432	538.244	175.514
4	1060.358	357.692	481.832	174.577	803.324	280.665	484.864	182.432	538.244	175.514
5	1060.358	357.692	481.832	174.577	803.324	280.665	484.864	182.432	538.244	175.514
6	1067.199	360.000	484.379	175.500	803.324	280.665	484.864	182.432	541.074	176.437
7	1070.619	361.154	485.653	175.961	803.324	280.665	484.864	182.432	542.490	176.899
8	1067.199	360.000	484.379	175.500	803.324	280.665	484.864	182.432	541.074	176.437
9	1454.058	490.500	556.830	201.750	803.324	280.665	484.864	182.432	795.224	259.312
10	1447.217	488.192	554.282	200.827	803.324	280.665	484.864	182.432	792.393	258.389
11	1440.376	485.884	551.734	199.904	803.324	280.665	484.864	182.432	789.563	257.466
12	1430.114	482.423	547.912	198.519	803.324	280.665	484.864	182.432	785.317	256.082
13	1426.694	481.269	546.639	198.058	803.324	280.665	484.864	182.432	783.901	255.620
14	1423.274	480.115	545.365	197.596	803.324	280.665	484.864	182.432	782.486	255.159
15	1419.853	478.561	544.091	197.135	803.324	280.665	484.864	182.432	781.070	254.697
16	1416.432	477.807	542.817	196.673	803.324	280.665	484.864	182.432	779.655	254.235
17	1416.432	477.807	542.817	196.673	803.324	280.665	484.864	182.432	675.005	220.110
18	1416.432	477.807	542.817	196.673	803.324	280.665	484.864	182.432	675.005	220.110
19	1419.853	478.561	544.091	197.135	803.324	280.665	484.864	182.432	676.420	220.572
20	1419.853	478.561	544.091	197.135	803.324	280.665	484.864	182.432	676.420	220.572
21	1419.853	478.561	544.091	197.135	803.324	280.665	484.864	182.432	676.420	220.572
22	1419.853	478.561	544.091	197.135	803.324	280.665	484.864	182.432	676.420	220.572
23	1416.432	477.807	542.817	196.673	803.324	280.665	484.864	182.432	675.005	220.110
24	1416.432	477.807	542.817	196.673	803.324	280.665	484.864	182.432	675.005	220.110

TABLE C.1 (Contd.)

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HOUR	CON_1 CO Q_SO2	CON_1 CO Q_HEAT	US_STEEL Q_SO2	US_STEEL Q_HEAT	INT_HAR2 Q_SO2	INT_HAR2 Q_HEAT	CEN_SOYA Q_SO2	CEN_SOYA Q_HEAT	DARLING1 Q_SO2	DARLING1 Q_HEAT
1	177.904	79.108	406.255	931.540	117.440	117.000	446.270	145.523	390.067	128.192
2	177.697	79.015	406.255	931.540	117.440	117.000	445.421	145.246	383.045	125.885
3	177.697	79.015	406.255	931.540	117.440	117.000	445.421	145.246	383.045	125.885
4	177.697	79.015	406.255	931.540	117.440	117.000	445.421	145.246	383.045	125.885
5	177.697	79.015	406.255	931.540	117.440	117.000	445.421	145.246	383.045	125.885
6	178.112	79.200	406.255	931.540	117.440	117.000	447.120	145.800	397.089	130.500
7	178.319	79.292	406.255	931.540	117.440	117.000	447.969	146.077	404.111	132.808
8	178.112	79.200	406.255	931.540	117.440	117.000	447.120	145.800	397.089	130.500
9	288.622	128.340	406.255	931.540	178.870	178.200	778.319	253.800	517.859	170.190
10	288.207	128.155	406.255	931.540	178.870	178.200	776.621	253.246	503.815	165.575
11	287.792	127.971	406.255	931.540	178.870	178.200	774.922	252.692	489.771	160.959
12	287.169	127.694	406.255	931.540	178.870	178.200	772.375	251.861	468.705	154.036
13	286.961	127.601	406.255	931.540	178.870	178.200	771.525	251.584	461.693	151.728
14	286.754	127.509	406.255	931.540	178.870	178.200	770.676	251.308	454.661	149.421
15	286.546	127.417	406.255	931.540	178.870	178.200	769.827	251.031	447.640	147.113
16	286.338	127.325	406.255	931.540	178.870	178.200	768.977	250.754	440.618	144.805
17	286.338	127.325	406.255	931.540	153.575	153.000	603.378	196.754	440.618	144.805
18	286.338	127.325	406.255	931.540	153.575	153.000	603.378	196.754	440.618	144.805
19	286.546	127.417	406.255	931.540	153.575	153.000	604.227	197.031	447.640	147.113
20	286.546	127.417	406.255	931.540	153.575	153.000	604.227	197.031	447.640	147.113
21	286.546	127.417	406.255	931.540	153.575	153.000	604.227	197.031	447.640	147.113
22	286.546	127.417	406.255	931.540	153.575	153.000	604.227	197.031	447.640	147.113
23	286.338	127.325	406.255	931.540	153.575	153.000	603.378	196.754	440.618	144.805
24	286.338	127.325	406.255	931.540	153.575	153.000	603.378	196.754	440.618	144.805
HOUR	INTRLAK2 Q_SO2	INTRLAK2 Q_HEAT	REP_STL Q_SO2	REP_STL Q_HEAT	CRANE Q_SO2	CRANE Q_HEAT	ARMOUR Q_SO2	ARMOUR Q_HEAT	CHI_MSD Q_SO2	CHI_MSD Q_HEAT
1	227.933	86.605	295.394	508.003	221.303	70.966	0.0	0.877	3320.457	1178.792
2	227.933	86.605	295.394	508.003	219.144	70.273	0.0	0.854	3320.457	1178.792
3	227.933	86.605	295.394	508.003	219.144	70.273	0.0	0.854	3320.457	1178.792
4	227.933	86.605	295.394	508.003	219.144	70.273	0.0	0.854	3320.457	1178.792
5	227.933	86.605	295.394	508.003	219.144	70.273	0.0	0.854	3320.457	1178.792
6	227.933	86.605	295.394	508.003	223.462	71.658	0.0	0.900	3320.457	1178.792
7	227.933	86.605	295.394	508.003	225.620	72.350	0.0	0.923	3320.457	1178.792
8	227.933	86.605	295.394	508.003	223.462	71.658	0.0	0.900	3320.457	1178.792
9	227.933	86.605	295.394	508.003	773.553	248.057	0.0	0.900	3320.457	1178.792
10	227.933	86.605	295.394	508.003	769.235	246.672	0.0	0.854	3320.457	1178.792
11	227.933	86.605	295.394	508.003	764.918	245.288	0.0	0.808	3320.457	1178.792
12	227.933	86.605	295.394	508.003	758.441	243.211	0.0	0.738	3320.457	1178.792
13	227.933	86.605	295.394	508.003	756.282	242.519	0.0	0.715	3320.457	1178.792
14	227.933	86.605	295.394	508.003	754.123	241.826	0.0	0.692	3320.457	1178.792
15	227.933	86.605	295.394	508.003	751.964	241.134	0.0	0.669	3320.457	1178.792
16	227.933	86.605	295.394	508.003	749.805	240.442	0.0	0.646	3320.457	1178.792
17	227.933	86.605	295.394	508.003	290.235	93.070	0.0	0.646	3320.457	1178.792
18	227.933	86.605	295.394	508.003	290.235	93.070	0.0	0.646	3320.457	1178.792
19	227.933	86.605	295.394	508.003	292.394	93.763	0.0	0.669	3320.457	1178.792
20	227.933	86.605	295.394	508.003	292.394	93.763	0.0	0.669	3320.457	1178.792
21	227.933	86.605	295.394	508.003	292.394	93.763	0.0	0.669	3320.457	1178.792
22	227.933	86.605	295.394	508.003	292.394	93.763	0.0	0.669	3320.457	1178.792
23	227.933	86.605	295.394	508.003	290.235	93.070	0.0	0.646	3320.457	1178.792
24	227.933	86.605	295.394	508.003	290.235	93.070	0.0	0.646	3320.457	1178.792

TABLE C.1 (Contd.)

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HOURL	INT_HAR3 Q_SO2	INT_HAR3 Q_HEAT	GLIDDEN Q_SO2	GLIDDEN Q_HEAT	WRIGLEY Q_SO2	WRIGLEY Q_HEAT	DARLING2 Q_SO2	DARLING2 Q_HEAT	CONT_2 Q_SO2	CONT_2 Q_HEAT
1	401.714	163.742	101.274	44.755	141.233	97.154	446.580	151.829	198.401	71.885
2	396.052	161.435	100.882	44.582	138.549	95.308	441.149	149.983	198.083	71.769
3	396.052	161.435	100.882	44.582	138.549	95.308	441.149	149.983	198.083	71.769
4	396.052	161.435	100.882	44.582	138.549	95.308	441.149	149.983	198.083	71.769
5	396.052	161.435	100.882	44.582	138.549	95.308	441.149	149.983	198.083	71.769
6	407.375	166.050	101.665	44.928	143.917	99.000	452.010	153.675	198.720	72.000
7	413.037	168.358	102.057	45.101	146.600	100.846	457.440	155.521	199.038	72.115
8	407.375	166.050	101.665	44.928	143.917	99.000	452.010	153.675	198.720	72.000
9	504.969	205.830	166.458	73.561	167.467	115.200	644.197	219.015	198.720	72.000
10	493.646	201.215	165.675	73.215	162.099	111.508	633.337	215.323	198.083	71.769
11	482.323	196.599	164.892	72.869	156.731	107.815	622.476	211.630	197.446	71.538
12	465.338	189.676	163.717	72.350	148.680	102.277	606.186	206.092	196.490	71.192
13	459.677	187.368	163.325	72.177	145.996	100.431	600.756	204.246	196.172	71.077
14	454.015	185.061	162.934	72.004	143.313	98.585	595.326	202.400	195.854	70.961
15	448.354	182.753	162.542	71.831	140.629	96.738	589.895	200.553	195.535	70.846
16	442.692	180.445	162.150	71.658	137.945	94.892	584.465	198.707	195.217	70.731
17	402.507	164.065	162.150	71.658	137.945	94.892	501.475	170.492	195.217	70.731
18	402.507	164.065	162.150	71.658	137.945	94.892	501.475	170.492	195.217	70.731
19	408.168	166.373	162.542	71.831	140.629	96.738	506.905	172.338	195.535	70.846
20	408.168	166.373	162.542	71.831	140.629	96.738	506.905	172.338	195.535	70.846
21	408.168	166.373	162.542	71.831	140.629	96.738	506.905	172.338	195.535	70.846
22	408.168	166.373	162.542	71.831	140.629	96.738	506.905	172.338	195.535	70.846
23	402.507	164.065	162.150	71.658	137.945	94.892	501.475	170.492	195.217	70.731
24	402.507	164.065	162.150	71.658	137.945	94.892	501.475	170.492	195.217	70.731

HOURL	BIRD_SON Q_SO2	BIRD_SON Q_HEAT	EJ_BRACH Q_SO2	EJ_BRACH Q_HEAT	ILL_MEAT Q_SO2	ILL_MEAT Q_HEAT	AM_CANCO Q_SO2	AM_CANCO Q_HEAT	TRIBUNE Q_SO2	TRIBUNE Q_HEAT
1	108.385	42.412	355.522	135.212	78.160	34.081	456.706	154.061	81.995	51.277
2	108.385	42.412	349.455	132.905	78.160	34.081	449.181	151.523	80.519	50.354
3	108.385	42.412	349.455	132.905	78.160	34.081	449.181	151.523	80.519	50.354
4	108.385	42.412	349.455	132.905	78.160	34.081	449.181	151.523	80.519	50.354
5	108.385	42.412	349.455	132.905	78.160	34.081	449.181	151.523	80.519	50.354
6	108.385	42.412	361.590	137.520	78.160	34.081	464.231	156.600	83.472	52.200
7	108.385	42.412	367.658	139.828	78.160	34.081	471.757	159.138	84.948	53.123
8	108.385	42.412	361.590	137.520	78.160	34.081	464.231	156.600	83.472	52.200
9	108.385	42.412	361.590	137.520	0.0	0.0	716.090	241.560	100.310	62.730
10	108.385	42.412	349.455	132.905	0.0	0.0	701.040	236.483	97.358	60.884
11	108.385	42.412	337.319	128.289	0.0	0.0	685.990	231.406	94.406	59.038
12	108.385	42.412	319.116	121.366	0.0	0.0	663.415	223.791	89.977	56.268
13	108.385	42.412	313.048	119.058	0.0	0.0	655.889	221.252	88.501	55.345
14	108.385	42.412	306.980	116.751	0.0	0.0	648.364	218.714	87.025	54.422
15	108.385	42.412	300.913	114.443	0.0	0.0	640.839	216.175	85.549	53.499
16	108.385	42.412	294.845	112.135	0.0	0.0	633.314	213.637	84.073	52.576
17	108.385	42.412	294.845	112.135	0.0	0.0	488.175	164.677	84.073	52.576
18	108.385	42.412	294.845	112.135	0.0	0.0	488.175	164.677	84.073	52.576
19	108.385	42.412	300.913	114.443	0.0	0.0	495.700	167.215	85.549	53.499
20	108.385	42.412	300.913	114.443	0.0	0.0	495.700	167.215	85.549	53.499
21	108.385	42.412	300.913	114.443	0.0	0.0	495.700	167.215	85.549	53.499
22	108.385	42.412	300.913	114.443	0.0	0.0	495.700	167.215	85.549	53.499
23	108.385	42.412	294.845	112.135	0.0	0.0	488.175	164.677	84.073	52.576
24	108.385	42.412	294.845	112.135	0.0	0.0	488.175	164.677	84.073	52.576

TABLE C.1 (Contd.)

PLANTSIM ALL SOURCES *67 FEB 16-18
DATE:67/02/17

HOUR	GEN_ELEC Q_SO2	GEN_ELEC Q_HEAT	HORWEEN Q_SO2	HORWEEN Q_HEAT	JO_WESTN Q_SO2	JO_WESTN Q_HEAT	US_STEE2 Q_SO2	US_STEE2 Q_HEAT	AVEY_COR Q_SO2	AVEY_COR Q_HEAT
1	712.336	232.284	79.101	31.115	394.449	148.413	334.139	766.180	19.318	10.499
2	712.336	232.284	78.807	30.999	385.250	144.952	333.606	764.958	19.318	10.499
3	712.336	232.284	78.807	30.999	385.250	144.952	333.606	764.958	19.318	10.499
4	712.336	232.284	78.807	30.999	385.250	144.952	333.606	764.958	19.318	10.499
5	712.336	232.284	78.807	30.999	385.250	144.952	333.606	764.958	19.318	10.499
6	712.336	232.284	79.394	31.230	403.649	151.875	334.673	767.404	19.318	10.499
7	712.336	232.284	79.687	31.345	412.849	155.336	335.206	768.627	19.318	10.499
8	712.336	232.284	79.394	31.230	403.649	151.875	334.673	767.404	19.318	10.499
9	712.336	232.284	79.394	31.230	536.405	201.825	334.673	767.404	19.318	10.499
10	712.336	232.284	78.807	30.999	518.005	194.902	333.606	764.958	19.318	10.499
11	712.336	232.284	78.221	30.768	499.605	187.979	332.540	762.511	19.318	10.499
12	712.336	232.284	77.341	30.422	472.005	177.594	330.939	758.842	19.318	10.499
13	712.336	232.284	77.047	30.307	462.805	174.133	330.406	757.619	19.318	10.499
14	712.336	232.284	76.754	30.192	453.605	170.671	329.872	756.396	19.318	10.499
15	712.336	232.284	76.461	30.076	444.405	167.210	329.339	755.173	19.318	10.499
16	712.336	232.284	76.167	29.961	435.205	163.748	328.805	753.949	19.318	10.499
17	712.336	232.284	76.167	29.961	365.240	137.423	328.805	753.949	19.318	10.499
18	712.336	232.284	76.167	29.961	365.240	137.423	328.805	753.949	19.318	10.499
19	712.336	232.284	76.461	30.076	374.439	140.885	329.339	755.173	19.318	10.499
20	712.336	232.284	76.461	30.076	374.439	140.885	329.339	755.173	19.318	10.499
21	712.336	232.284	76.461	30.076	374.439	140.885	329.339	755.173	19.318	10.499
22	712.336	232.284	76.461	30.076	374.439	140.885	329.339	755.173	19.318	10.499
23	712.336	232.284	76.167	29.961	365.240	137.423	328.805	753.949	19.318	10.499
24	712.336	232.284	76.167	29.961	365.240	137.423	328.805	753.949	19.318	10.499
HOUR	HAM_WHSE Q_SO2	HAM_WHSE Q_HEAT	GT_LAKEC Q_SO2	GT_LAKEC Q_HEAT	WESSON Q_SO2	WESSON Q_HEAT	RHEEM Q_SO2	RHEEM Q_HEAT	ROCK_OLA Q_SO2	ROCK_OLA Q_HEAT
1	89.105	58.393	169.598	116.666	32.541	44.769	173.807	108.692	86.973	38.674
2	86.992	57.009	169.537	116.624	32.373	44.538	170.117	106.385	86.662	38.536
3	86.992	57.009	169.537	116.624	32.373	44.538	170.117	106.385	86.662	38.536
4	86.992	57.009	169.537	116.624	32.373	44.538	170.117	106.385	86.662	38.536
5	86.992	57.009	169.537	116.624	32.373	44.538	170.117	106.385	86.662	38.536
6	91.218	59.778	169.658	116.707	32.708	45.000	177.497	111.000	87.285	38.812
7	93.331	61.163	169.718	116.749	32.876	45.231	181.187	113.308	87.596	38.951
8	91.218	59.778	169.658	116.707	32.708	45.000	177.497	111.000	87.285	38.812
9	95.626	62.667	169.658	116.707	67.597	93.000	191.409	119.700	87.285	38.812
10	91.401	59.898	169.537	116.624	67.262	92.538	184.029	115.085	86.662	38.536
11	87.175	57.128	169.416	116.541	66.926	92.077	176.648	110.469	86.039	38.259
12	80.836	52.975	169.235	116.417	66.423	91.385	165.578	103.546	85.105	37.843
13	78.724	51.590	169.175	116.375	66.255	91.154	161.888	101.238	84.794	37.705
14	76.611	50.205	169.115	116.334	66.088	90.923	158.197	98.931	84.482	37.566
15	74.498	48.821	169.054	116.292	65.920	90.692	154.507	96.623	84.171	37.428
16	72.385	47.436	168.994	116.250	65.752	90.461	150.817	94.315	83.860	37.289
17	67.977	44.547	168.994	116.250	48.308	66.461	150.817	94.315	83.860	37.289
18	67.977	44.547	168.994	116.250	48.308	66.461	150.817	94.315	83.860	37.289
19	70.089	45.932	169.054	116.292	48.475	66.692	154.507	96.623	84.171	37.428
20	70.089	45.932	169.054	116.292	48.475	66.692	154.507	96.623	84.171	37.428
21	70.089	45.932	169.054	116.292	48.475	66.692	154.507	96.623	84.171	37.428
22	70.089	45.932	169.054	116.292	48.475	66.692	154.507	96.623	84.171	37.428
23	67.977	44.547	168.994	116.250	48.308	66.461	150.817	94.315	83.860	37.289
24	67.977	44.547	168.994	116.250	48.308	66.461	150.817	94.315	83.860	37.289

TABLE C.1 (Contd.)

PLANTSIM ALL SOURCES *67 FEB 16-18
DATE:67/02/17

HOURL	PET_MUL Q_S02	PET_MUL Q_HEAT	NAT_BIS C_S02	NAT_BIS Q_HEAT	W_FELT Q_S02	W_FELT Q_HEAT	SUP_TAN Q_S02	SUP_TAN Q_HEAT	ST_BRDS Q_S02	ST_BRDS Q_HEAT
1	287.767	97.823	269.956	185.702	72.180	41.377	5.020	3.069	356.944	134.728
2	281.657	95.746	266.601	183.395	72.139	41.354	4.888	2.988	353.887	133.574
3	281.657	95.746	266.601	183.395	72.139	41.354	4.888	2.988	353.887	133.574
4	281.657	95.746	266.601	183.395	72.139	41.354	4.888	2.988	353.887	133.574
5	281.657	95.746	266.601	183.395	72.139	41.354	4.888	2.988	353.887	133.574
6	293.876	99.900	273.311	188.010	72.220	41.400	5.152	3.150	360.001	135.882
7	299.986	101.977	276.665	190.318	72.260	41.423	5.284	3.231	363.058	137.036
8	293.876	99.900	273.311	188.010	72.220	41.400	5.152	3.150	360.001	135.882
9	405.073	137.700	273.311	188.010	107.545	61.650	124.163	75.915	360.001	135.882
10	392.854	133.546	266.601	183.395	107.464	61.604	123.899	75.753	353.887	133.574
11	380.634	129.392	259.892	178.779	107.384	61.558	123.634	75.592	347.773	131.267
12	362.305	123.161	249.828	171.856	107.263	61.488	123.238	75.350	338.602	127.805
13	356.196	121.085	246.473	169.548	107.223	61.465	123.106	75.269	335.545	126.651
14	350.086	119.008	243.118	167.241	107.183	61.442	122.974	75.188	332.488	125.497
15	343.976	116.931	239.764	164.933	107.142	61.419	122.842	75.107	329.431	124.343
16	337.866	114.854	236.409	162.625	107.102	61.396	122.710	75.026	326.374	123.190
17	282.268	95.954	236.409	162.625	117.699	67.471	75.827	46.361	326.374	123.190
18	282.268	95.954	236.409	162.625	117.699	67.471	75.827	46.361	326.374	123.190
19	288.378	98.031	239.764	164.933	117.740	67.494	75.959	46.442	329.431	124.343
20	288.378	98.031	239.764	164.933	117.740	67.494	75.959	46.442	329.431	124.343
21	288.378	98.031	239.764	164.933	117.740	67.494	75.959	46.442	329.431	124.343
22	288.378	98.031	239.764	164.933	117.740	67.494	75.959	46.442	329.431	124.343
23	282.268	95.954	236.409	162.625	117.699	67.471	75.827	46.361	326.374	123.190
24	282.268	95.954	236.409	162.625	117.699	67.471	75.827	46.361	326.374	123.190
HOURL	WF_HALL Q_S02	WF_HALL Q_HEAT	GEN_REND C_S02	GEN_REND Q_HEAT	GOR_BAKE Q_S02	GOR_BAKE Q_HEAT	CUNEO Q_S02	CUNEO Q_HEAT	H_BUTTON Q_S02	H_BUTTON Q_HEAT
1	290.510	222.046	94.265	51.876	15.920	18.252	59.576	31.525	117.493	47.442
2	289.000	220.892	94.265	51.876	15.920	18.252	59.249	31.352	114.401	46.193
3	289.000	220.892	94.265	51.876	15.920	18.252	59.249	31.352	114.401	46.193
4	289.000	220.892	94.265	51.876	15.920	18.252	59.249	31.352	114.401	46.193
5	289.000	220.892	94.265	51.876	15.920	18.252	59.249	31.352	114.401	46.193
6	292.020	223.200	94.265	51.876	15.920	18.252	59.903	31.698	120.585	48.690
7	293.529	224.354	94.265	51.876	15.920	18.252	60.230	31.871	123.677	49.938
8	292.020	223.200	94.265	51.876	15.920	18.252	59.903	31.698	120.585	48.690
9	292.020	223.200	233.307	128.393	39.401	45.174	59.903	31.698	120.585	48.690
10	289.000	220.892	233.307	128.393	39.401	45.174	59.249	31.352	114.401	46.193
11	285.981	218.584	233.307	128.393	39.401	45.174	58.595	31.006	108.217	43.696
12	281.452	215.123	233.307	128.393	39.401	45.174	57.614	30.486	98.942	39.951
13	279.943	213.969	233.307	128.393	39.401	45.174	57.287	30.313	95.850	38.702
14	278.433	212.815	233.307	128.393	39.401	45.174	56.959	30.140	92.758	37.454
15	276.923	211.661	233.307	128.393	39.401	45.174	56.632	29.967	89.666	36.205
16	275.414	210.508	233.307	128.393	39.401	45.174	56.305	29.794	86.574	34.957
17	275.414	210.508	233.307	128.393	39.401	45.174	56.305	29.794	86.574	34.957
18	275.414	210.508	233.307	128.393	39.401	45.174	56.305	29.794	86.574	34.957
19	276.923	211.661	233.307	128.393	39.401	45.174	56.632	29.967	89.666	36.205
20	276.923	211.661	233.307	128.393	39.401	45.174	56.632	29.967	89.666	36.205
21	276.923	211.661	233.307	128.393	39.401	45.174	56.632	29.967	89.666	36.205
22	276.923	211.661	233.307	128.393	39.401	45.174	56.632	29.967	89.666	36.205
23	275.414	210.508	233.307	128.393	39.401	45.174	56.305	29.794	86.574	34.957
24	275.414	210.508	233.307	128.393	39.401	45.174	56.305	29.794	86.574	34.957

TABLE C.1 (Contd.)

PLANTSIM ALL SCURCES *67 FEB 16-18
DATE:67/02/17

HOUR	AM_OIL Q_SO2	AM_OIL Q_HEAT	CHGO_RAW C_SO2	CHGO_RAW Q_HEAT	LIN_BELT Q_SO2	LIN_BELT Q_HEAT	SQ_DINGE Q_SO2	SQ_DINGE Q_HEAT	W_ELEC Q_SO2	W_ELEC Q_HEAT
1	19.887	10.523	54.504	53.319	6.072	2.376	5.216	3.508	420.812	197.000
2	19.363	10.246	54.268	53.088	6.072	2.376	5.079	3.415	420.812	197.000
3	19.363	10.246	54.268	53.088	6.072	2.376	5.079	3.415	420.812	197.000
4	19.363	10.246	54.268	53.088	6.072	2.376	5.079	3.415	420.812	197.000
5	19.363	10.246	54.268	53.088	6.072	2.376	5.079	3.415	420.812	197.000
6	20.410	10.800	54.740	53.550	6.072	2.376	5.353	3.600	420.812	197.000
7	20.933	11.077	54.976	53.781	6.072	2.376	5.491	3.692	420.812	197.000
8	20.410	10.800	54.740	53.550	6.072	2.376	5.353	3.600	420.812	197.000
9	20.410	10.800	54.740	53.550	4.554	1.782	33.458	22.500	420.812	197.000
10	19.363	10.246	54.268	53.088	4.554	1.782	33.184	22.315	420.812	197.000
11	18.317	9.692	53.796	52.627	4.554	1.782	32.909	22.131	420.812	197.000
12	16.747	8.862	53.089	51.935	4.554	1.782	32.497	21.854	420.812	197.000
13	16.223	8.585	52.853	51.704	4.554	1.782	32.360	21.762	420.812	197.000
14	15.700	8.308	52.617	51.473	4.554	1.782	32.223	21.669	420.812	197.000
15	15.177	8.031	52.381	51.242	4.554	1.782	32.086	21.577	420.812	197.000
16	14.653	7.754	52.145	51.011	4.554	1.782	31.948	21.485	420.812	197.000
17	14.653	7.754	52.145	51.011	4.554	1.782	31.948	21.485	420.812	197.000
18	14.653	7.754	52.145	51.011	4.554	1.782	31.948	21.485	420.812	197.000
19	15.177	8.031	52.381	51.242	4.554	1.782	32.086	21.577	420.812	197.000
20	15.177	8.031	52.381	51.242	4.554	1.782	32.086	21.577	420.812	197.000
21	15.177	8.031	52.381	51.242	4.554	1.782	32.086	21.577	420.812	197.000
22	15.177	8.031	52.381	51.242	4.554	1.782	32.086	21.577	420.812	197.000
23	14.653	7.754	52.145	51.011	4.554	1.782	31.948	21.485	420.812	197.000
24	14.653	7.754	52.145	51.011	4.554	1.782	31.948	21.485	420.812	197.000

HOUR	INGERSOL Q_SO2	INGERSOL Q_HEAT
1	112.463	91.016
2	112.463	91.016
3	112.463	91.016
4	112.463	91.016
5	112.463	91.016
6	112.463	91.016
7	112.463	91.016
8	112.463	91.016
9	112.463	91.016
10	112.463	91.016
11	112.463	91.016
12	112.463	91.016
13	112.463	91.016
14	112.463	91.016
15	112.463	91.016
16	112.463	91.016
17	112.463	91.016
18	112.463	91.016
19	112.463	91.016
20	112.463	91.016
21	112.463	91.016
22	112.463	91.016
23	112.463	91.016
24	112.463	91.016

TABLE C.2. Stack Coordinates and Physical Parameters

Name	X, mi	Y, mi	Stack No.	Height	Inside Diameter, ft
CECO-NW	8.5	-4.2	1	303.83	14.
			2	303.83	14.
Fisk	6.4	+1.9	1	291.	11.
			2	291.	11.
			3	291.	11.
			4	291.	11.
			5	450.	14.
Crawford	9.9	+3.5	1	346.	-
			2	378.	-
			3	378.	-
Ridgeland	13.0	+4.5	1	213.	8.
			2	213.	8.
			3	213.	8.
			4	213.	8.
			5	213.	9.83
			6	213.	9.83
Calumet	1.0	+11.6	1	302.5	9.
			2	302.5	9.
Stateline	0.0	+11.9	1	301.	18.
			2	301.	18.
			3	301.	18.
			4	301.	18.
			5	400.	16.5
			6	396.5	13.5
TAM 5	7.4	+6.8	Height of aerovane is 75 ft.		

TABLE C.3. Meteorological Data for February 16-18, 1967.
The columns labeled Turner and Norco represent the Turner
stability class⁸ and mixing height¹⁷ (in ft), respectively.

		MIDWAY TEMP	MIDWAY WIND_DIR	MIDWAY WIND_VEL	TURNER TURNER_C	NORCO MIX_HT
67/02/16	0	15.000	310.000	20.000	4.000	*****
67/02/16	1	14.000	310.000	15.000	4.000	*****
67/02/16	2	13.000	310.000	15.000	4.000	778.000
67/02/16	3	12.000	310.000	15.000	4.000	1249.000
67/02/16	4	11.000	300.000	17.000	4.000	1548.000
67/02/16	5	10.000	300.000	13.000	4.000	1671.000
67/02/16	6	8.000	300.000	12.000	4.000	1696.000
67/02/16	7	7.000	310.000	10.000	4.000	1566.000
67/02/16	8	7.000	300.000	10.000	4.000	1456.000
67/02/16	9	9.000	310.000	10.000	4.000	1629.000
67/02/16	10	10.000	290.000	4.000	3.000	1669.000
67/02/16	11	13.000	240.000	3.000	2.000	1989.000
67/02/16	12	14.000	260.000	4.000	2.000	2073.000
67/02/16	13	16.000	200.000	6.000	3.000	2267.000
67/02/16	14	17.000	240.000	4.000	3.000	2347.000
67/02/16	15	17.000	270.000	6.000	3.000	2311.000
67/02/16	16	17.000	0.0	0.0	3.000	2275.000
67/02/16	17	17.000	0.0	0.0	5.000	2240.000
67/02/16	18	16.000	0.0	0.0	5.000	2091.000
67/02/16	19	16.000	260.000	4.000	5.000	1929.000
67/02/16	20	16.000	300.000	4.000	5.000	1791.000
67/02/16	21	16.000	0.0	0.0	5.000	1703.000
67/02/16	22	17.000	320.000	2.000	5.000	1846.000
67/02/16	23	17.000	280.000	3.000	5.000	1772.000
67/02/17	0	17.000	280.000	3.000	4.000	1718.000
67/02/17	1	18.000	210.000	5.000	4.000	1816.000
67/02/17	2	18.000	180.000	5.000	5.000	1765.000
67/02/17	3	18.000	190.000	5.000	5.000	1724.000
67/02/17	4	18.000	190.000	3.000	5.000	1690.000
67/02/17	5	16.000	0.0	0.0	5.000	1291.000
67/02/17	6	15.000	300.000	3.000	5.000	951.000
67/02/17	7	16.000	310.000	5.000	4.000	1053.000
67/02/17	8	16.000	330.000	5.000	4.000	807.000
67/02/17	9	18.000	0.0	0.0	4.000	1223.000
67/02/17	10	20.000	180.000	4.000	4.000	1577.000
67/02/17	11	23.000	130.000	8.000	4.000	1893.000
67/02/17	12	24.000	120.000	7.000	2.000	1974.000
67/02/17	13	25.000	140.000	5.000	3.000	2072.000
67/02/17	14	26.000	100.000	4.000	3.000	2190.000
67/02/17	15	27.000	90.000	4.000	4.000	2298.000
67/02/17	16	27.000	90.000	7.000	4.000	2265.000
67/02/17	17	27.000	70.000	9.000	4.000	2231.000
67/02/17	18	26.000	80.000	7.000	4.000	1908.000
67/02/17	19	26.000	70.000	7.000	4.000	1838.000
67/02/17	20	26.000	140.000	5.000	4.000	1777.000
67/02/17	21	26.000	130.000	6.000	4.000	1712.000
67/02/17	22	27.000	100.000	4.000	4.000	1976.000
67/02/17	23	27.000	190.000	4.000	4.000	1910.000
67/02/18	0	28.000	230.000	5.000	4.000	2151.000
67/02/18	1	28.000	0.0	0.0	4.000	2104.000
67/02/18	2	27.000	140.000	5.000	5.000	1769.000
67/02/18	3	25.000	170.000	5.000	5.000	1149.000
67/02/18	4	24.000	0.0	0.0	5.000	921.000
67/02/18	5	23.000	0.0	0.0	4.000	763.000
67/02/18	6	23.000	140.000	3.000	5.000	761.000
67/02/18	7	24.000	160.000	3.000	4.000	822.000
67/02/18	8	25.000	140.000	9.000	4.000	894.000
67/02/18	9	25.000	140.000	10.000	4.000	805.000
67/02/18	10	26.000	180.000	12.000	4.000	892.000
67/02/18	11	27.000	170.000	11.000	4.000	991.000
67/02/18	12	28.000	170.000	12.000	4.000	1186.000
67/02/18	13	29.000	180.000	10.000	4.000	1460.000
67/02/18	14	29.000	170.000	8.000	4.000	1302.000
67/02/18	15	29.000	130.000	9.000	4.000	1117.000
67/02/18	16	30.000	140.000	8.000	4.000	1400.000
67/02/18	17	30.000	160.000	9.000	4.000	1208.000
67/02/18	18	30.000	150.000	8.000	4.000	914.000
67/02/18	19	31.000	190.000	10.000	4.000	1417.000
67/02/18	20	32.000	220.000	6.000	4.000	1783.000
67/02/18	21	32.000	220.000	6.000	4.000	1661.000
67/02/18	22	32.000	220.000	8.000	4.000	1582.000
67/02/18	23	30.000	220.000	6.000	5.000	749.000

TABLE C.4. Results of Sample Computations of SO₂ Concentrations at TAM 5 for February 16-18, 1967. Only the last four columns are of interest. Of the two columns labeled TAM 5 SO₂, the first is the observed and the second the calculated concentrations.

		TAM_7 SO2	TAM_8 SO2	TAM_5 WIND_VEL	TAM_5 WIND_DIR	TAM_5 SO2	TAM_5 SO2
67/02/16	0	0.010	0.050	18.200	281.000	0.060	0.048
67/02/16	1	0.020	0.020	15.000	280.000	0.070	0.045
67/02/16	2	0.020	0.030	14.200	283.000	0.050	0.069
67/02/16	3	0.020	0.030	14.100	279.000	0.050	0.052
67/02/16	4	0.020	0.030	13.100	285.000	0.040	0.082
67/02/16	5	0.060	0.030	11.000	287.000	0.030	0.149
67/02/16	6	0.090	0.050	9.100	287.000	0.050	0.167
67/02/16	7	0.090	0.070	8.600	292.000	0.080	0.243
67/02/16	8	0.090	0.050	6.400	290.000	0.090	0.253
67/02/16	9	0.080	0.070	5.100	288.000	0.110	0.213
67/02/16	10	0.080	0.070	2.100	273.000	0.130	0.244
67/02/16	11	0.070	0.070	2.500	227.000	0.170	0.057
67/02/16	12	0.090	0.050	4.000	213.000	0.190	0.028
67/02/16	13	0.080	0.030	5.500	222.000	0.150	0.042
67/02/16	14	0.080	0.050	4.600	220.000	0.080	0.038
67/02/16	15	0.070	0.080	4.000	241.000	0.060	0.045
67/02/16	16	0.070	0.070	3.100	239.000	0.060	0.054
67/02/16	17	0.080	0.040	1.900	224.000	0.070	0.083
67/02/16	18	0.110	0.040	2.100	223.000	0.090	0.077
67/02/16	19	0.110	0.050	3.100	226.000	0.090	0.080
67/02/16	20	0.110	0.050	2.000	258.000	0.090	0.113
67/02/16	21	0.120	0.050	0.900	280.000	0.110	0.091
67/02/16	22	0.140	0.120	0.700	258.000	0.150	0.056
67/02/16	23	0.200	0.090	1.800	221.000	0.140	0.048
67/02/17	0	0.250	0.120	1.900	180.000	0.120	0.049
67/02/17	1	0.260	0.130	3.000	180.000	0.110	0.033
67/02/17	2	0.260	0.150	2.100	156.000	0.110	0.065
67/02/17	3	0.210	0.130	0.800	190.000	0.110	0.046
67/02/17	4	0.190	0.120	0.0	0.0	0.110	0.071
67/02/17	5	0.220	0.120	0.0	0.0	0.120	0.142
67/02/17	6	0.270	0.250	0.900	292.000	0.140	0.168
67/02/17	7	0.260	0.300	0.0	0.0	0.360	0.146
67/02/17	8	0.260	0.310	2.100	352.000	0.560	0.785
67/02/17	9	0.310	0.170	6.700	69.000	0.290	0.106
67/02/17	10	0.200	0.140	7.500	56.000	0.060	0.091
67/02/17	11	0.070	0.100	8.500	58.000	0.030	0.080
67/02/17	12	0.090	0.090	6.700	61.000	0.060	0.052
67/02/17	13	0.140	0.190	3.700	49.000	0.070	0.103
67/02/17	14	0.200	0.180	4.600	34.000	0.150	0.111
67/02/17	15	0.270	0.180	5.100	50.000	0.100	0.092
67/02/17	16	0.280	0.190	4.100	39.000	0.100	0.133
67/02/17	17	0.170	0.160	4.800	44.000	0.060	0.108
67/02/17	18	0.200	0.160	4.400	57.000	0.080	0.096
67/02/17	19	0.130	0.130	4.800	63.000	0.070	0.091
67/02/17	20	0.140	0.020	5.500	63.000	0.090	0.085
67/02/17	21	0.180	0.120	3.100	97.000	0.150	0.123
67/02/17	22	0.220	0.090	3.100	82.000	0.150	0.058
67/02/17	23	0.210	0.060	3.600	155.000	0.090	0.039
67/02/18	0	0.220	0.100	3.300	194.000	0.040	0.018
67/02/18	1	0.100	0.030	0.0	0.0	0.030	0.046
67/02/18	2	0.150	0.060	1.000	161.000	0.030	0.031
67/02/18	3	0.130	0.070	1.500	195.000	0.030	0.048
67/02/18	4	0.120	0.090	0.0	0.0	0.050	0.083

TABLE C.4 (Contd.)

DMR7

TAM_5 FEB 16-18, 1967

	TAM_7 SO2	TAM_8 SO2	TAM_5 WIND_VEL	TAM_5 WIND_DIR	TAM_5 SO2	TAM_5 SO2
67/02/18 5	0.180	0.090	0.500	191.000	0.040	0.156
67/02/18 6	0.200	0.110	2.300	147.000	0.090	0.273
67/02/18 7	0.200	0.110	3.500	146.000	0.120	0.138
67/02/18 8	0.180	0.100	5.900	142.000	0.100	0.087
67/02/18 9	0.150	0.050	8.000	137.000	0.040	0.091
67/02/18 10	0.150	0.060	9.000	139.000	0.030	0.069
67/02/18 11	0.100	0.070	8.300	145.000	0.030	0.063
67/02/18 12	0.080	0.070	8.600	142.000	0.030	0.058
67/02/18 13	0.070	0.060	7.000	146.000	0.030	0.059
67/02/18 14	0.100	0.020	5.100	156.000	0.030	0.069
67/02/18 15	0.130	0.020	4.900	130.000	0.040	0.289
67/02/18 16	0.190	0.040	5.200	127.000	0.100	0.321
67/02/18 17	0.130	0.040	6.700	141.000	0.100	0.066
67/02/18 18	0.160	0.060	6.000	154.000	0.050	0.079
67/02/18 19	0.270	0.050	6.500	186.000	0.030	0.030
67/02/18 20	0.140	0.100	6.600	210.000	0.020	0.026
67/02/18 21	0.140	0.080	5.300	214.000	0.030	0.027
67/02/18 22	0.130	0.070	4.400	203.000	0.040	0.014
67/02/18 23	0.120	0.070	4.400	210.000	0.040	0.021

APPENDIX D

Definitions of Quantities Used in Analysis of Results

Both the puff and the plume models calculate the SO_2 concentrations on an hourly basis. However, to show the effects of averaging over n consecutive hourly concentrations, we analyze the results in terms of the averaging intervals $n = 1, 6$, and 24 hr. These averaged concentrations are in turn averaged over short- or long-term periods where appropriate. The following quantities are used in the analysis:

$\chi_{ei}(\chi_{oi})$ = estimated (observed) SO_2 concentration at the i th hour.

$\mu_{ej}^{(n)}$ = n -hour average estimated concentration for the j th n -hour consecutive interval.

$\mu_{oj}^{(n)}$ = n -hour average observed concentration for the j th n -hour consecutive interval.

$$= \frac{1}{n} \sum_{i=k}^{nj} \chi_i, \quad \text{where } k = n(j-1) + 1.$$

$\sigma_{oe}^{(n)}$ = standard deviation of the differences between the n -hour average observed and corresponding n -hour average calculated concentrations

$$= \frac{1}{\sqrt{N-1}} \left\{ \sum_{j=1}^N [d_j^{(n)}]^2 - \frac{1}{N} \left[\sum_{j=1}^N d_j^{(n)} \right]^2 \right\}^{1/2},$$

where

$$d_j^{(n)} = \mu_{oj}^{(n)} - \mu_{ej}^{(n)},$$

and

$$n = 1, 6, \text{ and } 24 \text{ hr.}$$

If we are working with a total of M hr of historical air-quality data, then $N = M/n$. In addition, we define the overall averages of calculated and observed concentrations

$$\mu_e = \frac{1}{N} \sum_{j=1}^N \mu_{ej}^{(n)}, \quad \mu_o = \frac{1}{N} \sum_{j=1}^N \mu_{oj}^{(n)}$$

which are independent of n (provided $N = M/n$ is used). A reasonably good measure of the spread of the differences $d_j^{(n)}$ is the relative standard deviation given by $\sigma_{oe}^{(n)}/\mu_o$.

The percentile distributions of the differences is described adequately by the following quantities:

50% = percent of the calculated results within 50% of the observed results.

F2 = percent of the calculated results within a factor of 2 of the observed results.

PN025 = percent of the differences within 0.025 ppm.

PN050 = percent of the differences within 0.050 ppm.

PN1 = percent of the differences within 0.100 ppm.

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