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IMPROVED ALGORITHMS FOR ESTIMATING THE EFFECTS OF POLLUTION IMPACTS FROM AREA AND OPEN PIT SOURCES

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INTRODUCTION

The increasing environmental concern over hazardous emissions from landfills, landfarms, settling ponds, agricultural fields, surface mines, and surface impoundments has renewed interest in improving concentration estimates downwind from area sources. Simplistic and numerically efficient methods (for estimating area source impacts) are the virtual point source approach (Turner, 1970) as used in the models LONGZ (Bjorklund and Bowers, 1979) and VALLEY (Burt, 1977), and the finite line source approach as used in ISCST (Bowers et al., 1979). The virtual point source and finite line segment algorithms are most appropriate for estimating concentrations at downwind distances significantly larger than the side width of the area source (Hwang, 1986 and Weber, 1982). However, these constructs fail for concentration estimates within or near the area source. Thistle and Londergan (1989) showed that these algorithms behaved in a manner inconsistent with mathematical and physical principles. They demonstrated that models that use numerical techniques to approximate the Gaussian point source dispersion function over the area source are more realistic although computationally intensive. One of the models that they found to be mathematically and physically consistent was PAL (Petersen and Rumsey, 1987).

Shortly after the Thistle and Londergan study, the Office of Air Quality Planning and Standards in the U.S. Environmental Protection Agency (EPA) decided to update the area source algorithm in ISC2 (U.S. EPA, 1992) using the approach contained in PAL. At about the same time the Office of Research and Development in EPA was involved in a project to improve the computational efficiency of the area source algorithm in PAL. It is this more efficient version of the PAL area source algorithm that has been implemented in ISC2 and will be described in this paper. In addition, the improved area source algorithm is utilized in a new approach to modeling open-pit sources.

Title II, Part B, Section 234 of the Clean Air Act Amendments of 1990 provide for a reexamination of the current Environmental Protection Agency's methods for modeling fugitive particulate (PM_{10}) from open-pit surface coal mines. ISC2 is specifically named as the method that needs further study.

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To address the requirements of the Act, an open pit algorithm has been developed. Wind tunnel experimentation (Thompson, 1993, 1994a and Perry et al., 1994) suggests that the emissions within the pit are not uniformly released from the pit opening. Rather, they show a tendency to be emitted primarily from an upwind sub-area of the pit opening due to the general recirculation flow within the pit. The algorithm uses the pit depth and dimensions, height of emissions above the pit floor, and the wind direction to 1) estimate the fraction of particulate that leaves the pit (escape fraction) and 2) to calculate the sub-area dimensions. The new integrated area-source algorithm is used to model emissions from this sub-area. Initial vertical dispersion due to turbulence in the pit is also considered. Although the development work for the area source and open pit algorithms was done with ISC2, both are incorporated in ISC3. In this paper we will refer to the model incorporating these algorithms as ISC3.

NEW AREA-SOURCE ALGORITHM

Based on the results of an evaluation of area source algorithms performed for EPA (Thistle and Londergan, 1989), the finite line segment algorithm used in the ISCST model gives physically unrealistic results for receptors located near the edges and corners of the area. This is not so much a deficiency in the algorithm as it is a problem in application. The finite line segment was developed as a simple approximation to the contribution at a receptor from an area source. Conceptually, it is an improvement over the virtual point source approach without the expense of numerically approximating the point source function over an area source. It was never the intent of the developers that the area source algorithm would be applied for nearby receptors. However, recent concern for environmental impacts from nearby area sources and advancements in high speed data processing for PC's make it reasonable to revisit the area source problem. This section provides a brief description of the integration technique used in ISC2.

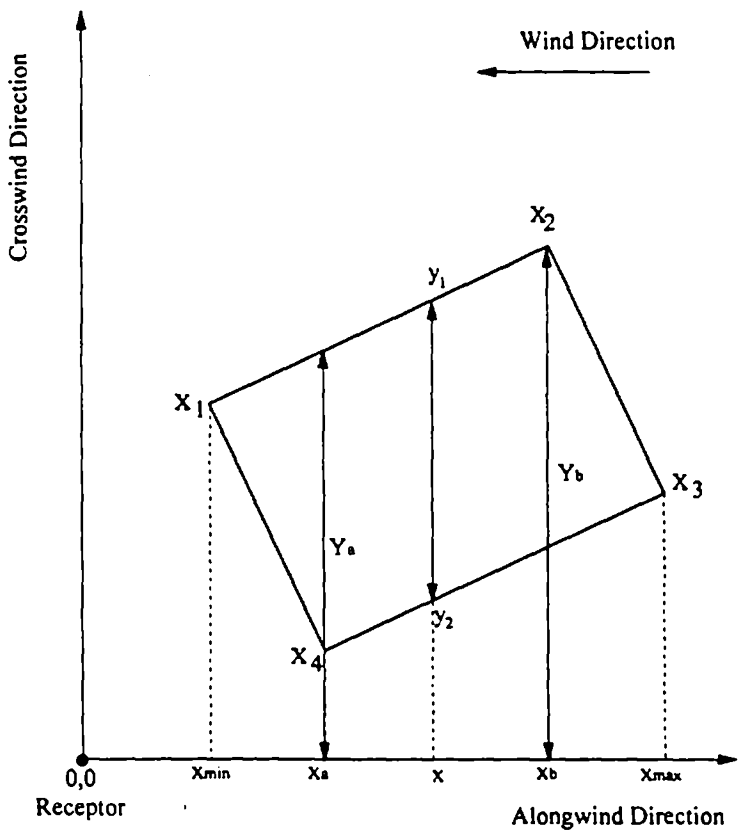

Figure 1. x_{min} and x_{max} are the distances to the closest and furthest vertices from the area source. y_1 and y_2 are the crosswind distances at an arbitrary distance x upwind.

The area source algorithms in PAL and ISC3 are functionally the same; the pollutant impact from an area source is approximated by a number of finite crosswind line sources. However, the integration techniques are different. To illustrate the integration technique we apply it for a rectangular area source. Let x be the upwind distance and y the crosswind distance. For a given source receptor pair, there is a x_{min} and a x_{max} (see Figure 1) which coincides with the x of a vertex. That is, a vertex is represented by (x_i, y_i) with $x_{n+1} = x_1$, for closure. If we let $f(x)$ be the dispersion from a point source at a distance x and let $y(x)$ be the crosswind distance to the i^{th} side, then the integration proceeds as follows: In Figure 1, x_{min}, x_a, x_b, and x_{max} are the upwind distances from the nearest to furthest vertex from a downwind receptor and the four vertices are X_1, X_2, X_3, and X_4. The concentration can be expressed as;

$$\chi = \int_{x_1}^{x_4} f(x)\, e(p_1)\, dx - \int_{x_1}^{x_2} f(x)\, e(p_2)\, dx + \int_{x_4}^{x_3} f(x)\, e(p_1)\, dx - \int_{x_2}^{x_3} f(x)\, e(p_2)\, dx$$

where; $p_1 = \frac{y_1}{\sigma_y}$ $p_2 = \frac{y_2}{\sigma_y}$,

and $e(p_1)$ and $e(p_2)$ are defined as follows,

$$e(p_1) = \int_{-\infty}^{p_1} \frac{1}{\sqrt{2\pi}} \exp\left[-0.5\, p^2\right] dp, \quad and\ e(p_2) = \int_{-\infty}^{p_2} \frac{1}{\sqrt{2\pi}} \exp\left[-0.5\, p^2\right] dp$$

The integrals from $-\infty$ to p_1 and $-\infty$ to p_2 are the cumulative distribution of the standardized normal distribution and can be determined from tables. Each side of the area source can now be integrated independently. Figure 2 provides a simplified graphical representation of the integration by sides. In the actual integration only those portion of the sides that contribute to the concentration at the receptor are included, that is $|y(x)/\sigma_y(x)| \leq 4.0$. This criteria is a function of source-receptor geometry, wind direction, and atmospheric stability. $f(x)$ has the following forms: For stable conditions or unlimited mixing:

$$f(x) = \frac{Q}{\sqrt{2\pi}\, u\, \sigma_y\, \sigma_z} \left(\exp\left[\frac{-0.5(z-H)^2}{\sigma_z^2}\right] + \exp\left[\frac{-0.5(z+H)^2}{\sigma_z^2}\right] \right)$$

In unstable or neutral conditions and if σ_z is greater than 1.6 times the mixing height, L, the distribution below the mixing height is uniform with height.

$$f(x) = \frac{Q}{\sqrt{2\pi}\, u\, \sigma_y\, L}$$

In all other unstable or neutral conditions, that is if σ_z is less than 1.6 time L:

$$f(x) = \frac{Q}{\sqrt{2\pi}\, u\, \sigma_y \sigma_z} \sum_{N=-\infty}^{\infty} \left(\exp\left[\frac{-0.5(z-H+2NL)^2}{\sigma_z^2}\right] + \exp\left[\frac{-0.5(z+H+2NL)^2}{\sigma_z^2}\right] \right)$$

This infinite series converges rapidly, and evaluation with the integer, N, varying from -4 to +4 is usually sufficient.

AREA REPRESENTATION ALGORITHM FOR OPEN PIT MINING

The method for modeling particulate impacts from open-pit, surface coal-mine activities is based on the analysis by Perry et al. (1994) and Thompson (1994a, 1994b) of two wind-tunnel studies recently performed at the EPA Fluid Modeling Facility in which the impacts of emissions

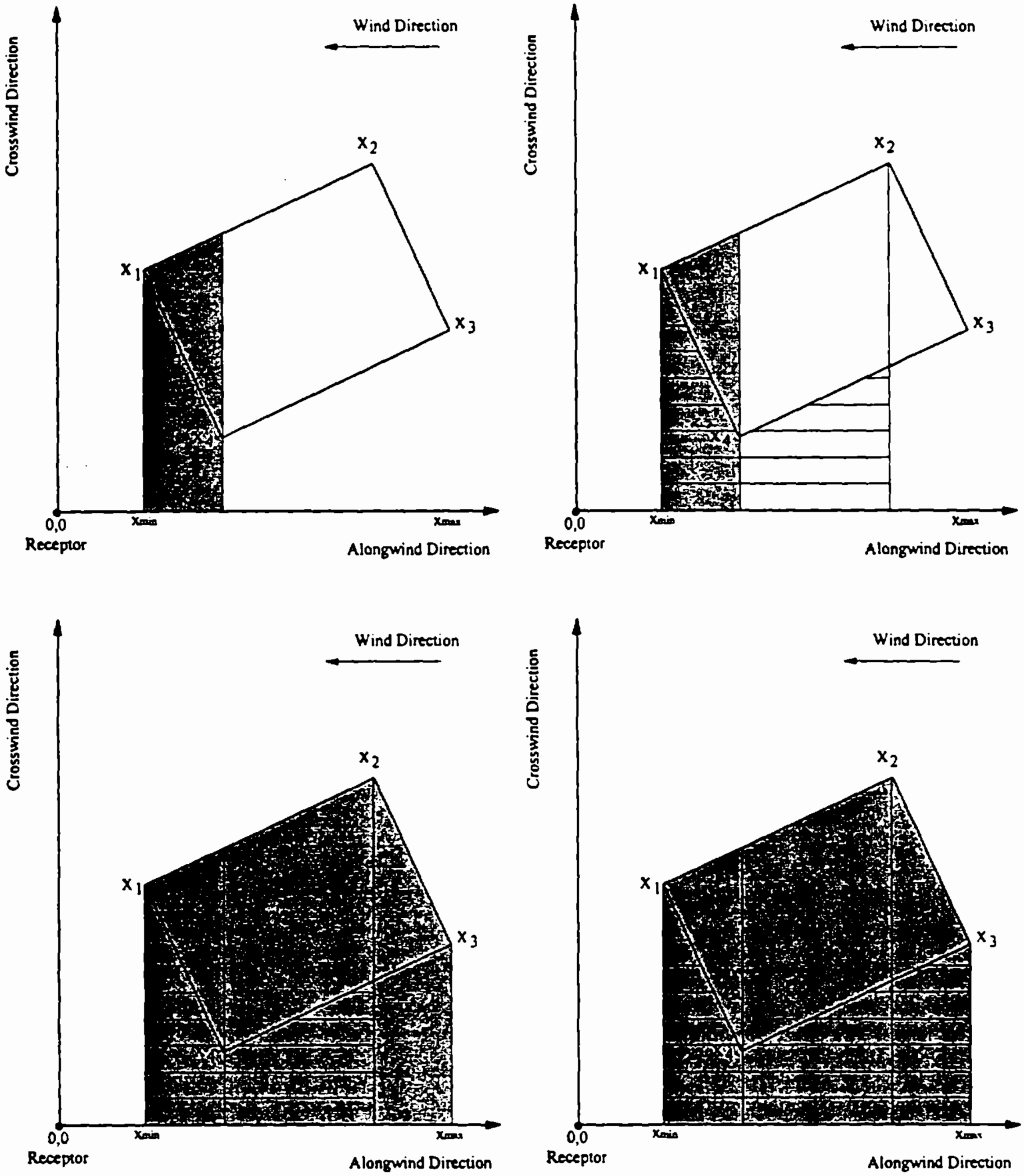

Figure 2 Graphical representation of the integration by sides. The shaded areas represent a positive contribution. The horizontal-line pattern represents a negative contribution. The positive and negative contribution cancel everywhere except the area source.

from a variety of scale model open pits were examined. Perry et al. concluded that, due to recirculations within the pit, particles that escape show a tendency to be emitted toward the upwind portion of the pit opening. The pit-mining algorithms determine the escape fraction (for each particle size group); and establish the location and size of the sub-area from which the escaped particulate is modeled with ISC3. It is important to preface that the open-pit algorithms are designed only for the modeling of impacts outside of the pit caused by emissions within the pit, that mines are assumed generally rectangular in shape, and that the emissions within the pit are assumed to be at least somewhat scattered.

ISC3 first estimates the escape fraction as a function of incident wind speed and the particle size distribution of material released within the pit (Thompson, 1994b). The computation of escape fraction is particularly important for modeling large particles susceptible to gravitational settling and less important for PM_{10} analyses where the vast majority of material escapes. As implemented in ISC3, for each of up to 20 particle size categories, an escape fraction (ε) is computed as:

$$\varepsilon_i = 1.0 \; / \; \left(1 + \frac{v_i}{\alpha \, U_r}\right)$$

where

v_i	is the settling velocity,
U_r	is the approach wind speed at a height of 10m,
α	is the proportionality constant in the relationship between flux from the pit and the product of U_r and concentration in the pit (Thompson, 1994a).

v_i is already computed in ISC3 (as is done in ISC2) for each size category. Thompson (1994a) used laboratory measurements of pollutant residence times in a variety of pit shapes and determined that a single value of α = 0.029 worked well for all pits studied.

The adjusted emission rate (q_i) for each particle size category is then computed as:

$$q_i = \varepsilon_i \bullet f_i \bullet q$$

where q is the total emission rate (for all particles) within the pit, f_i is the original mass fraction for the i-th size category, and ε_i is calculated from the above equation. The adjusted total emission rate, for all particles escaping the pit, is the sum of the q_i. In summary, the amount of particulate that leaves the open pit mine and is available to impact air quality downwind is a function of the total emissions within the pit, wind speed, and the particle size distribution of emitted material.

Secondly, ISC3 computes the location and size of a sub-area of the actual pit opening from which the pit emissions will be modeled. This sub-area source is assumed to be at surface level. Given an arbitrary rectangular-shaped pit with an arbitrary wind direction as shown in Figure 3, ISC3 determines the sub-area source in the following way. Based on the wind direction and pit orientation, the model determines the upwind sides of the pit; in the case of Figure 3, the upwind sides are 1 and 2. The model then computes the along wind length of the pit (l). l varies between the lengths of the two sides of the rectangular pit as follows:

$$l = L \bullet (1 - \theta / 90) + W \bullet (\theta / 90)$$

where θ is the wind direction relative to the long axis of the pit (therefore θ varies between 0° and 90°). l is the scaling factor that is used to normalize the depth of the pit.

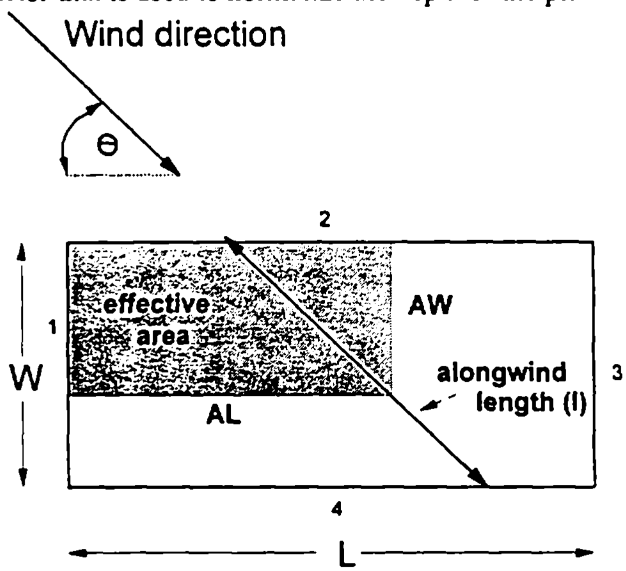

Figure 3. The effective area for a wind direction of about 45 degrees from the long axis of the pit. AL and AW (and thus the area) vary with wind direction.

The model user must specify the average height (H) of emissions from the floor of the pit and the pit volume (V). With these, ISC3 calculates the effective pit depth (d_e) and the relative pit depth (d_r) as:

$$d_e = V / (L \cdot W)$$
$$d_r = (d_e - H) / l$$

Based on observations and measurements in the wind tunnel study, it was clear that the emissions within the pit are not uniformly released from the pit opening. Rather, the emissions showed a tendency (based on smoke releases) to be emitted primarily from an upwind sub-area (or effective area, A_e) of the pit opening and the sub-area size and location depended on the relative pit depth and the wind direction. The wind tunnel data indicate that if $d_r \geq 0.2$, then the effective area is about 8% of the total opening of the mine (i.e. A_e=0.08). If $d_r < 0.2$, then the fractional area increases as:

$$A_e = (1.0 - 1.7\, d_r^{1/3})^{1/2}$$

When $d_r = 0$, the effective area is equal to the total area of the mine opening (i.e. A_e=1.0).

The specific dimensions of this assumed rectangular sub-area are calculated as a function of θ such that (see Figure 3):

$$AW = A_e^{(1-\cos^2\theta)} \cdot W$$

and,

$$AL = A_e^{(\cos^2\theta)} \cdot L$$

W is defined as the short dimension of the pit and L is the long dimension; AW is the dimension of the effective area aligned with the short side of the pit and AL is the dimension of the effective area aligned with the long side of the pit. In the way of a few examples, if $A_e = 0.36$ at $\theta = 45°$, then AW = 0.6·W and AL = 0.6·L; at the extreme of $\theta = 0°$ (wind along the long axis of the pit), AW = W and AL = A_e·L; at $\theta = 90°$ (wind along the short axis of the pit), AW = A_e·W and AL = L.

The emission rate, q_e, for the effective area is such that;

$$q_e = q_a / A_e$$

where q_a is the emission rate per unit area from the pit if the emissions were uniformly released from the actual pit opening (with an area of L·W).

The model includes some initial vertical dispersion to simulate the high level of turbulence and initial mixing in the mine. Using the pit depth, d_e, as the representative dimension over which the pollutant is vertically mixed, ISC3 calculates an initial vertical dispersion value, σ_{zo}, equal to d_e/4.3 (Turner, 1970). 4.3·σ_{zo} represents about 90% of a Gaussian plume (in the vertical). For example, when d_e = 45m, σ_{zo} = 10.5m. Thus, the ISC3 model includes the pit-induced initial dispersion with the ambient dispersion as:

$$\sigma_z(x) = \left(\sigma_{zo}^2 + \sigma_z^2(x)\right)^{1/2}$$

For modeling impacts close to the pit (small x), the initial dispersion value can be particularly important.

In summary, ISC3 models the emissions from a rectangular mine as a sub-area source on the upwind edge of the rectangular pit. The size of the sub-area is a function of the relative pit depth (which is in turn a function of the actual pit depth, alongwind pit dimension, height of the emissions above the pit floor, and wind direction). The total emissions from the sub-area are equal to the total emissions (adjusted for escape fraction) from within the pit. Initial vertical dispersion as a function of the actual pit depth is modeled. The required inputs for simulating open pit sources are: the wind speed, wind direction, location and dimensions of the rectangular pit opening, pit volume, total emissions within the pit, height of emissions above the pit floor, and mass fraction and settling velocities of up to 20 particle sizes.

An example comparison of the ISC3 model with wind tunnel data is shown in Figure 4. This is a case that represents emissions that are spread throughout the floor of the pit (as may be expected in an actual mining operation with activities related to drilling, blasting, shoveling, loading, and transporting coal and topsoil throughout the pit). This example involves a pit with full scale dimensions of 225 m in the along flow direction and 450 m in the cross flow direction (the wind is perpendicular to the long dimension of the pit, i.e. θ = 90 degrees). The pit is 45 m deep and the emissions are from the pit floor (H = 0). Therefore the effective pit depth, d_e , is simply 45 m and the relative pit depth, d_r , is equal to 45/225 = 0.2. With this relative depth, the effective area for emissions, A_e , equals 0.08 (8 %), and the dimensions of the area are 18 m in the alongwind direction and 450 m in the crosswind directions. In addition, the pit-induced initial dispersion is equal to 45 m/ 4.3 = 10.5 m.

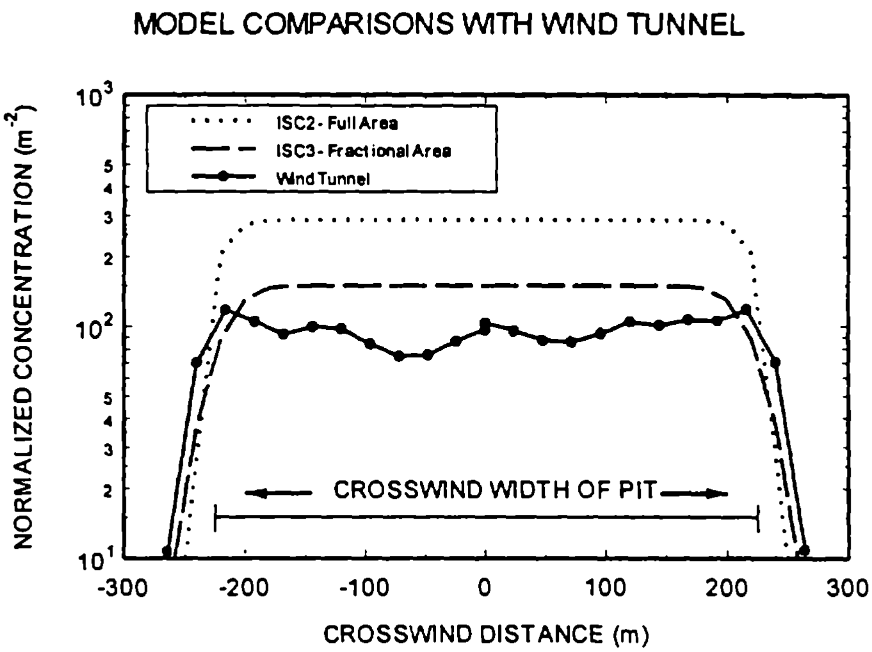

Figure 4. Horizontal concentration distributions at the downwind edge of a 225m X 450m pit with effective depth of 45m and source at the pit floor. ISC2 Full Area is the distribution from the ISC2 model and ISC2 Partial Area is from ISC3.

The concentration distribution at the downwind edge of the pit for the wind tunnel measurements and two modeling scenarios are shown in Figure 4. The results labeled FULL-AREA are those provided by the ISC2 model. The results labeled FRACTIONAL AREA are those provided by ISC3. For ISC2 where it is assumed that the entire opening of the rectangular pit acts as a surface level area source with emissions uniform over that area, the modeled distribution is nearly three times larger than that observed.

In contrast, the ISC3 model is releasing the same total emissions over a much smaller area on the upwind edge of the actual pit opening (only covering 8% of the pit opening); the plume is initially dispersion by pit generated turbulence. ISC3 is showing a slight tendency to overpredicting the distribution particularly near the center of the pit. However, it is clear that the modified area-source approach is a great improvement over that of ISC2 for impacts at the downwind edge of the pit where concentrations are expected to be highest. For large downwind distance (many times the dimensions of the pit), the ISC2 and ISC3 approaches are not expected to give very different results.

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DISCLAIMER

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

Bjorklund J.R. and Bowers J.F., 1979, User's instructions for the Shortz and Longz computer programs (Volume I), TR-79-131-01, H.E. Cramer Company, Inc., University of Utah Research Park, POB 8049, Salt Lake City, Utah.

Bowers, J.F., Bjorklund J.R., and Cheney C.S., 1979, User's guide for the Industrial Source Complex (ISC) dispersion models, Volume I -User Instructions, EPA-450/4-79-030, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Burt E.W., 1977, Valley model user's guide, EPA-450-2-77-018, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Hwang S.T., 1986, Methods for estimating onsite ambient air concentrations, ACS Annual Meeting Anaheim, California.

Perry S.G., Thompson R.S., and Petersen W.B., 1994, Considerations for modeling small-particulate impacts from surface coal mining operations based on wind-tunnel simulations, Eight Joint AMS/AWMA Conference on Applications of Air Pollution Meteorology, Jan. 23-28, 1994, Nashville, Tennessee, American Meteorological Society, Boston, Massachusetts.

Petersen W.B. and Rumsey E.D., 1987, User's guide for PAL 2.0 - A Gaussian-plume algorithm for point, area, and line sources, EPA-600-8-87-009, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Thistle H. and Londergan R.J., 1989, Review and evaluation of area source dispersion algorithms for emission sources at superfund sited, EPA-450-4-89-020, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Thompson, R. S., 1993, Wind tunnel simulations of dispersion from surface coal mines. Internal Data Report, Fluid Modeling Facility, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Thompson, R. S., 1994a, Residence time of contaminants released in surface coal mines - a wind-tunnel study. Eighth Joint AMS/AWMA Conference on Applications of Air Pollution Meteorology, Jan. 23-28, 1994, Nashville, Tennessee, American Meteorological Society, Boston, Massachusetts.

Thompson, R. S., 1994b, Personal Communication.

Turner D. B., Workbook of atmospheric dispersion estimates, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, pp 84.

U.S. Environmental Protection Agency, 1992, User's guide for the Industrial Source Complex (ISC2) dispersion models, Volume I -User Instructions, EPA-450-4-92-008a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Weber E., 1982, Air Pollution Assessment Methodology and Modeling, Plenum Press, New York.

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16. ABSTRACT

The increasing environmental concern over hazardous emissions from landfills, landfills, settling ponds, agricultural fields, surface mines, and surface impoundments has renewed interest in improving concentration estimates downwind from area sources. Simplistic and numerically efficient methods (for estimating area source impacts) are the virtual point source approach (Turner, 1970) as used in the models LONGZ (Bjorklund and Bowers, 1979) and VALLEY (Burt, 1977), and the finite line source approach as used in ISCST (Bowers et al., 1979). The virtual point source and finite line segment algorithms are most appropriate for estimating concentrations at downwind distances significantly larger than the side width of the area source (Hwang, 1986 and Weber, 1982). However, these constructs fail for concentration estimates within or near the area source. Thistle and Londergan (1989) showed that these algorithms behaved in a manner inconsistent with mathematical and physical principles.

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