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CONSIDERATIONS FOR MODELING SMALL-PARTICULATE IMPACTS FROM SURFACE COAL-MINING OPERATIONS BASED ON WIND-TUNNEL SIMULATIONS

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1. INTRODUCTION

The Clean Air Act Amendments of 1990 provide for a reexamination of the current Environmental Protection Agency's (USEPA) methods for modeling fugitive particulate (PM10) from open-pit, surface coal mines. The Industrial Source Complex Model (ISCST2) is specifically named as the method that needs further study. Title II, Part B, Section 234 of the Amendments states that "... the Administrator shall analyze the accuracy of such model and emission factors and make revisions as may be necessary to eliminate any significant over-predictions of air quality effect of fugitive particulate emissions from such sources."

So the problem is two-fold: reassessment of emission factors used by the model and examination of model reliability. The emission work (which includes a study of both in-mine emissions and those from associated activities away from the pits) is being performed in a separate study at an actual operating

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mine in Wyoming. Additional emission work is being performed by Thompson (1993b) with a wind tunnel study of pollutant residence time in the pits.

The initial EPA effort to assess the ISCST2 model for mining applications is described in this paper. A related wind-tunnel study (Thompson, 1993a) yielded a data base to assist in the modeling study and to provide a better understanding of fine particulate impacts downwind of a variety of mine shapes and sizes. It is important to point out that there are many activities (e.g. hauling, crushing, loading of coal) in the vicinity of a surface coal mine that contribute to emissions of particulate into the atmosphere. The modeling and wind-tunnel studies described here were confined to an examination of the impacts downwind of the pit from those activities that typically occur **within** a mining pit.

An analysis of the sensitivity of near-field downwind surface concentrations to mining pit and source geometry has highlighted some of the important parameters to consider in any modeling analysis. The ISCST2 model is currently in use for modeling such sources. A recent improvement to the manner in which ISCST2 handles area sources is described here and estimates from this version of the model are compared with the wind tunnel simulations for a case where emissions are released from many locations within the mine.

2. SURFACE COAL MINE OPERATIONS

Although open-pit surface coal mines come in many shapes and sizes, the operations necessary to extract the coal are common to most mines. Typically the coal is in a 10 to 20 meter layer that is buried below tens of meters of overburden. The primary extraction activities within the borders of the pit include: the removal and storage of topsoil; the drilling, blasting, and removal of overburden; the drilling, blasting and loading of coal; the hauling of the coal out of the pit; and the reclamation of the pit area. Each of these activities produce airborne fugitive dust that potentially can escape from the pit and influence air quality downwind.

An established mine operation with the constant removal and backfill of overburden generally has a pit with a large flat bottom and stair-stepped walls. The coal-hauling trucks travel up and down gently sloping exit roads into and out of the pit. The mining process yields a constantly changing mine shape and location which is important to consider in modeling long-term average impacts.

3. WIND-TUNNEL STUDY OF OPEN-PIT COAL MINES

As part of the effort to assess the current modeling methods for surface coal mines, a wind-tunnel study (Thompson, 1993a) was designed and conducted to produce a data base useful for examining model performance and for providing a better understanding of the fate of airborne material released from open pits. This study, separate from that for determining residence times (Thompson, 1993b), involved the measurement of **steady-state**, tracer-gas concentration fields downwind of model mines of various shapes, sizes and orientations with low-momemtum, point-source releases of a neutrally buoyant tracer gas from various locations in the pit.

Fluid modeling of dust particles (with proper consideration of settling and deposition) at the reduced scale of a wind tunnel is not practical. However, the emphasis of the surface coal mining problem is on the small end of the particulate distribution (PM10, $\leq 10\mu m$) and on near-field concentration estimates. For particles of this small size and for the generally high levels of turbulence in the mining pit, turbulent transport will easily dominate (in relation to settling) particle motions. Therefore, relevant information about the behavior of PM10 can be obtained from a laboratory study using a neutrally buoyant gaseous tracer.

All of the experimental measurements were made in the EPA Meteorological Wind Tunnel with a neutrally buoyant boundary layer. A detailed description of the wind tunnel is found in Snyder (1979). The model mining pits were located in the floor of the 3.7m wide by 2.1m high by 18.3m long test section. All dimensions were scaled to a ratio of 300 to 1 allowing for model mines (representing dimensions typical of actual operations) to fit into the tunnel test section. The freestream windspeed for the experiments was 2 ms^{-1}.

All of the model pits were rectangular, with dimensions ranging in length from 225m to 600m (full scale), in width from 45m to 450m, and in depth from 30m to 75m. With only a few exceptions, the pits contained steps (typically found in actual mines) along the walls that were each scaled to 15m high and 15m wide (the number of steps depended on the depth of the model mine). Figure 1 illustrates the geometry of 13 (of a total of 26) experimental pits discussed in this paper showing the size and shape of each pit, the location of the tracer source, and an indication of the presence or absence of steps. This set of cases (where all but one has dimensions of 225m X 450m) was intended to test the sensitivity of the downwind concentration to: pit depth, crosswind dimension, and the location of the source (horizontally and vertically) within the pit. In addition, the importance of the presence of the steps was tested.

Ethane gas (with a molecular weight very near to that of dry air) was used as the tracer. The gas was emitted through a 10-mm diameter, perforated hollow plastic sphere. Generally the source was located on the floor of the mine but several experiments were run with the source located on the steps of the side walls.

Steady-state concentrations were measured using flame ionization detectors with intake ports near the surface in intervals of 24m (full scale) horizontally across the flow at both the downwind edge of the pit and at one kilometer downwind from the pit. Concentrations were also measured at the center of the downwind edge of the pit (and at one kilometer downwind) in intervals of 9m vertically. All steady-state concentrations were corrected for background tracer and normalized to full scale as $10^6CU/Q$ (where U is the wind speed at 10m, full scale, and Q is the emission rate).

To examine the flow within the pit, velocity measurements were made in and around the model for Case 4. The measurements were made with a pulsed-wire anemometer along the centerline (in the flow direction) of the model pit. Figure 2 shows the vector velocities plotted along with calculated streamlines indicating a recirculating flow with a reverse flow in the lower half of the pit. This has significant implications to the fate of pollutants released near the floor of the mine.

4. SENSITIVITY OF CONCENTRATIONS TO SOURCE/PIT GEOMETRY

One of the major objectives of the wind-tunnel study was to provide a basis for better understanding the release of material from the modeled pits and the sensitivity of the downwind concentrations to a wide range of parameters related to pit geometry and source location. For this paper, we limited our analysis to five areas including sensitivity to: the depth of the pit, the crosswind dimension of the pit, the presence of sidewall steps in the pit, the height of the release above the pit floor, and the lateral location of the source within the pit. By examining these parameters, we hope to better define the extent to which we need to describe the mining operation for modeling purposes.

The sensitivity analysis involves combinations of the thirteen individual cases displayed in Figure 1. They will be referenced by the case numbers shown in the lower left-hand corner of each pit in that figure. In addition, the analysis here is limited to the surface-level horizontal distribution of concentration along the downwind edge of the pit. To aid in the visual comparisons, each of the measured distributions has been associated with a smooth Gaussian fit since horizontal distributions in the wind tunnel are generally very nearly Gaussian.

4.1 *Sensitivity to pit depth*

Four cases (4, 10, 11, 12) were used to examine the sensitivity of the downwind concentration to the depth of the model pit. In each case the pit dimensions (in full scale equivalent) are 225m alongwind and 450m crosswind. The pit depth ranges from 30m to 75m. Typical surface mining pits fall within this range. Normalizing the depths by the alongwind pit dimension yields relative depths, D, of between 0.13 and 0.33. In all four cases, the source is located on the floor of the pit and is centered on the upwind edge; sidewall "steps" are present.

The comparison of the distributions of concentration along the downwind edge of the pits is shown in Figure 3a. The deepest pit ($D = 0.33$) displays the lowest peak concentration and a narrow Gaussian distribution. The peak concentration increases monitonically with decreasing depth. However, there is very little significant difference between the distributions for $D \geq 0.2$. Only when the depth of the pit decreases to 13% ($D = 0.13$) of the crosswind dimension does the peak concentration increase dramatically. This is better displayed in figure 3b in a plot of the centerline surface concentration as a function of pit depth. Notice that the concentration in all cases has been normalized by the concentration for $D = 0.2$ (that of case 4) in this figure.

It appears that as the pit becomes very shallow, the recirculating flow (shown in figure 2) becomes shallower and thus less important in determining the movement of pollutants from the bottom of the pit. Instead, the pollutant more quickly mixes into the region of the flow above the recirculating area where it is swiftly advected to the downwind edge thus resulting in a higher peak concentration. Therefore, pit depth is an important consideration in modeling surface mining whenever the pit is fairly shallow.

4.2 *Sensitivity to Crosswind Dimension of Pit*

Only two cases are used in this comparison, cases 1 and 4. Case 1 has a crosswind to alongwind ratio of 1.0 (both dimensions are 225m) and the depth to alongwind ratio, D, equal to 0.2. Case 4 has a ratio of 2.0 (225m X 450m) with $D = 0.2$. The sources are on the pit floor and centered on the upwind edge. Figure 4 shows the comparison of the measured downwind distributions. We see that, for the narrower pit, the plume from the point source appears to sense the presence of the sides of the pit with the result being elevated surface concentrations at all lateral locations. The peak concentration is about 15% larger for the narrow pit. Clearly, the ratio of pit width to alongwind dimension can be important for modeling individual point emissions in a mining pit. Although not displayed in figure 4, the actual wind-tunnel measurements for the narrow pit have closer to a top-hat distribution rather than a Gaussian one. However, the conclusions about the sensitivity are the same; the peak concentration is higher and the distribution is broader for the narrower pit.

4.3 *Sensitivity to Sidewall Steps*

In researching actual surface coal-mining operations, Thompson (1993a) found that typical mining pits have stair-step walls due to the manner in which the coal is removed. Scaled steps were therefore included in the wind-tunnel models. The steps were removed in a few cases in order to determine their importance to downwind concentrations. Cases 4 and 9 are used in this comparison. They are identical in size and depth (225m X 450m, D = 0.2) and both have the source on the pit floor and centered on the upwind edge.

Figure 5 shows that there is very little difference between the two cases, with the presence of steps yielding a slightly higher peak concentration. This is most likely attributable to the fact that the total volume of the pit is increased by about 20% when the steps are removed, accounting for a bit more mixing in the pit before the plume reaches the downwind edge. However, it appears that including the steps is of little importance to modeling these sources.

4.4 *Sensitivity to Height of the Source*

After glancing at the flow structure displayed in figure 2, it is obvious that the downwind concentrations will be influenced by the source height above the floor of the pit. This is born out in our analyses of six cases relative to this issue. The first three, cases 4, 22, and 25 have identical pit dimensions (225m X 450m, D = 0.2) with the sources centered on the upwind edge. Case 4 has the source on the pit floor (h = 0), case 25 has h = 15m (source is on the lower step), and case 22 has h = 30m (source is on the upper step). The concentration distributions are shown in figure 6a.

As somewhat expected, the peak downwind concentration increases as the source is elevated higher in the pit. Locating the source higher in the pit places it closer to the area of the flow that can more quickly advect the plume to the receptor (an effect similar to that seen in Section 4.1 when decreasing the pit depth). It is interesting to note that a larger increase in peak concentration occurs between h of 0 and 15m than between 15m and 30m. In any event, height of the source is an important modeling consideration when the source is on the upwind edge.

Three additional cases were considered which are analogous to cases 4, 22, and 25 except that the sources were centered on the downwind edge of the pit. Cases 6, 23, and 26 also have dimensions of 225m X 450m with D = 0.2. Case 6 has h = 0.0, case 26 has h = 15m (lower step), and case 23 has h = 30m (upper step). As with those on the upwind edge, figure 6b shows an increase in peak downwind concentration as the source is placed higher in the pit. However, there is one significant difference with the source on the upper step. Because of its proximity to the upper edge (lip) of the pit, much of the material is quickly mixed up and is advected a very short distance to the receptor locations. This results in a very large peak concentration at the downwind edge. For sources lower in the pit, a much larger amount of released material appears to be mixed through the recirculating flow before escaping the pit and impacting the receptor. Therefore, height of the source in the pit can be an even more important modeling consideration when the source is on the downwind edge.

4.5 *Sensitivity to Lateral Location in the Pit*

The analysis of the sensitivity of the downwind concentrations to lateral position of the source yielded mostly predictable results. Cases 4, 5, and 24 were included here. Again, all pits were 225m X 450m with D = 0.2. The sources were all on the floor of the pits. The only difference exists in the location of the source. In case 4 the source is centered on the upwind edge; in case 24 it is halfway between the center and the side; and in case 5 it is centered on the side wall.

The comparison of the downwind concentration distributions is found in figure 7. As expected, the peak of the distribution is shifted laterally with the sources. However, as the sidewall comes into play in cases 24 and 5, the peak concentration increases somewhat over that for the centered source location. As mentioned in section 4.2, the measured distributions are not well represented by a Gaussian fit when the sidewalls of the pit come into play. In case 5 (along the side wall), the distribution drops off dramatically at the pit edge. In spite of this, the fitted Gaussian shape correctly indicates the location of the maximum and the approximate spread of the distribution. Clearly lateral source location is important if modeling individual sources within the pit.

5. THE INDUSTRIAL SOURCE COMPLEX MODEL (ISCST2)

ISCST2 (USEPA, 1992a) is based on the steady-state, straight-line, Gaussian plume equation with the ability to handle a wide variety of source types that might be present in a typical industrial complex. It can model emissions from stacks or other point sources as well as line, area, and volume type sources. The area-source algorithms are the most likely candidates for simulating particulate escaping from the top of an open-pit mine.

The ability to make realistic estimates of air quality impacts from area sources has been problematic when the receptors of interest are located within or nearby the area source itself. Previous model evaluation studies (USEPA, 1989) have pointed out the deficiencies of the area source algorithms contained in ISCST2. The previous ISCST2 algorithm was based on a finite line segment approach that is computationally efficient but fails to adequately treat the effects of source receptor geometry near the source. Because of this shortcoming a new algorithm was recently incorporated into the ISCST2 code and made available to the public on the EPA bulletin board for testing. This new algorithm is based on the integrated line source approach found in the PAL model (Petersen and Rumsey, 1987).

The new area source algorithm (to be described in Section 5.2) was evaluated using wind tunnel data of Snyder (1991). This comparison (USEPA, 1992b) showed that the model performed very well over a wide range of source orientations and receptor downwind distances. Therefore, we applied ISCST2 with the new area source algorithm in this analysis (Section 6).

The wind tunnel boundary layer is characterized by neutral stability. However, the dispersion parameters in the wind tunnel do not correspond precisely with the Pasquill-Gifford dispersion parameters (Turner, 1970) for stability class D. During the fluid modeling study, the lateral and vertical dispersion parameters as a function of downwind distance were determined by measuring the concentration distributions downwind of a surface level point release. Comparison with the Pasquill-Gifford curves for stability classes C and D shows that the turbulence levels in the wind tunnel fall generally between class C and D, with a tendency toward D-stability for downwind distances beyond about 300 to 500m. Power law fits to the wind tunnel data yield the following relationships:

$$\sigma_y = 0.560x^{0.689} \tag{1}$$

$$\sigma_z = 0.267x^{0.706} \tag{2}$$

where x is in meters. These relationships were programmed into the ISCST2 model for use when performing model comparisons with wind-tunnel results.

5.2 *New Area Source Algorithm*

In the upgraded algorithm the emissions from area sources are simulated as a number of finite crosswind line sources. The ground-level concentration at a receptor located downwind of all or a portion of the source area is given by a double integral in the upwind (x) and crosswind (y) directions as:

$$\chi = \frac{Q}{2\pi u}\int_x \frac{V}{\sigma_y \sigma_z}\left(\int_y \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right]dy\right)dx \qquad (3)$$

where:

Q = area source emission rate,
u = wind speed,
V = Gaussian vertical dispersion term.

In equation 3, the integral in the lateral direction (contribution of any single finite crosswind line source) is solved analytically. The integral in the longitudinal direction (i.e. the summation of the contributions from the finite crosswind line sources in the upwind direction) is approximated with a Romberg integration technique (Press, et al, 1986). The technique treats the sequence I_k (successive refinements of the extended trapezoidal rule solution to the integral) as a polynomial in k. Whereas the Simpson's rule method is a special case of the Romberg technique for $k = 2$, ISCST2 has been programmed with $k = 5$ in solving the integral.

This new approach in ISCST2 for handling area sources is essentially equivalent to, but much more efficient than, the method used in PAL. Unlike the previous method in ISCST2 for handling area sources, this approach has no difficulty making valid estimates at receptors very near to as well as within the area source.

6. MODEL COMPARISON TO WIND TUNNEL

The purpose of this work is to assess the ISCST2 model for estimating PM10 impacts downwind of operations in a surface coal mine pit. Actual mining operations are not characterized by individual point sources; instead they consist of a variety of sources in a variety of locations throughout the pit (see

Section 2). In addition, modelers are interested in impacts over a 24-hr period or longer so the contributing sources can be widely spread within the pit over that time. Therefore it is less important for the model to simulate individual point sources and more important to simulate multiple sources.

Our initial look at the performance of the model will be taken by combining four of the individual wind-tunnel cases to make the equivalent of a case with sources spread throughout the floor of the pit (as may be expected in an actual pit operation). Four cases (4, 5, 6, and 24) with the same pit dimensions (225m X 450m; D = 0.2) were chosen for this example. Combining case 4, 5, 6, and 24 with a mirror image (reflected about an alongwind line through the center of the pit) of cases 5 and 24 yields a concentration field equivalent to a wind-tunnel case with six separate point sources on the pit floor. The wind-tunnel horizontal distributions can be flipped this way since the flow in the tunnel is symmetrical (on average) about the centerline of the pit. The combined case has the equivalent of three sources along the upwind edge, one each centered on the side walls, and one source centered on the downwind edge.

The combination of the six concentration distributions at the downwind edge of the pit is shown in figure 8. Also in figure 8 are the results of two attempts at modeling this combined case with the modified ISCST2 model. For the first case (noted as FULL AREA), we simply assumed that the entire opening of the rectangular pit acts as a surface level area source with emissions uniform over that area. Obviously, this is a poor representation of the emissions from the pit since the modeled peak concentration is nearly three times larger than that observed. The reason for the poor agreement can be seen in the flow features of figure 2. The recirculation in the pit has the effect of mixing and transporting much of the emissions from these floor-level sources toward the upwind side of the pit before mixing them up and out. The resulting flux of material across the opening of the pit would appear to be skewed (larger) toward the upwind edge. This, in fact, is exactly what was observed with smoke releases in the same cases.

Therefore, an alternative approach is to model the area source as uniformly emitting in the lateral over the actual width of the pit but to define the alongwind dimension as a fraction of that for the actual pit. Based on observations from smoke releases in the tunnel model, we chose a fraction of one-eighth for this comparison. Thus the modeled area source is 28m X 450m and is aligned with the upwind side of the actual pit. The model results for this case are also shown in figure 8 (noted as PARTIAL AREA). The model is still slightly overpredicting the peak of the distribution but this is somewhat due to the fact that the actual emissions from the pit are not uniform but instead the combination of six point releases. However, it is clear that the emissions from the pit are larger near the upwind edge and are similar to those of a modified area source. Obviously this initial modeled case does not suffer from all of the sensitivities mentioned in Section 4. When mining activity is grouped into specific areas of the mine for extended periods, much consideration must be given to the previously discussed analyses.

7. SUMMARY

As part of EPA's effort to assess the ISCST2 model for applications to surface coal mining, a wind-tunnel study was performed to both highlight the important parameters to consider for modeling and to provide some results for comparison with the model. The sensitivity analyses indicated that important features are the pit depth, the crosswind dimension, and the height and location of the source. The presence of steps along the sidewalls was found to be of little significance. The comparison of the combination case with the ISCST2 model indicates that the open pit acts as a modified area source where the emissions are greatest near the upwind side of the actual pit.

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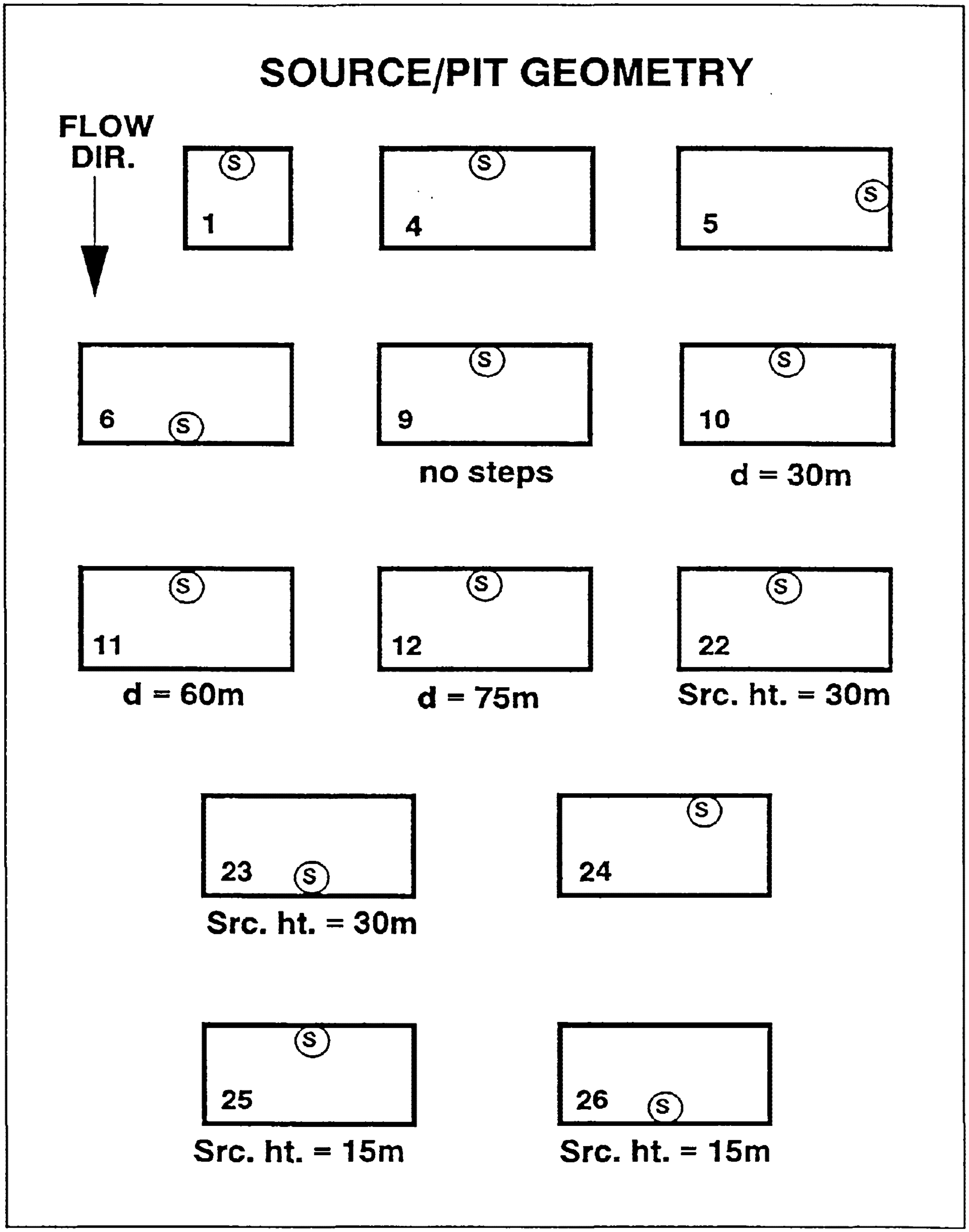

Figure 1. Geometry of the 13 model mines used in this paper; unless otherwise noted, mine depth, d, is 15cm (45m full scale), steps are present, and source is on mine floor; circled s is source location.

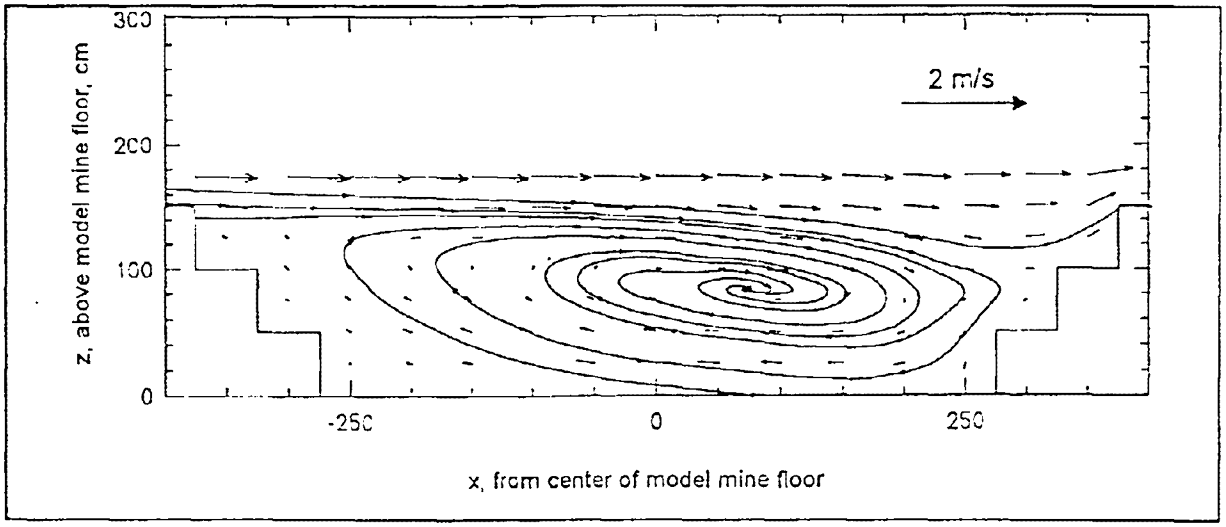

Figure 2. Centerplane velocity vectors and streamlines for Case 4 as computed from pulsed-wire anemometer data within and above the mining pit.

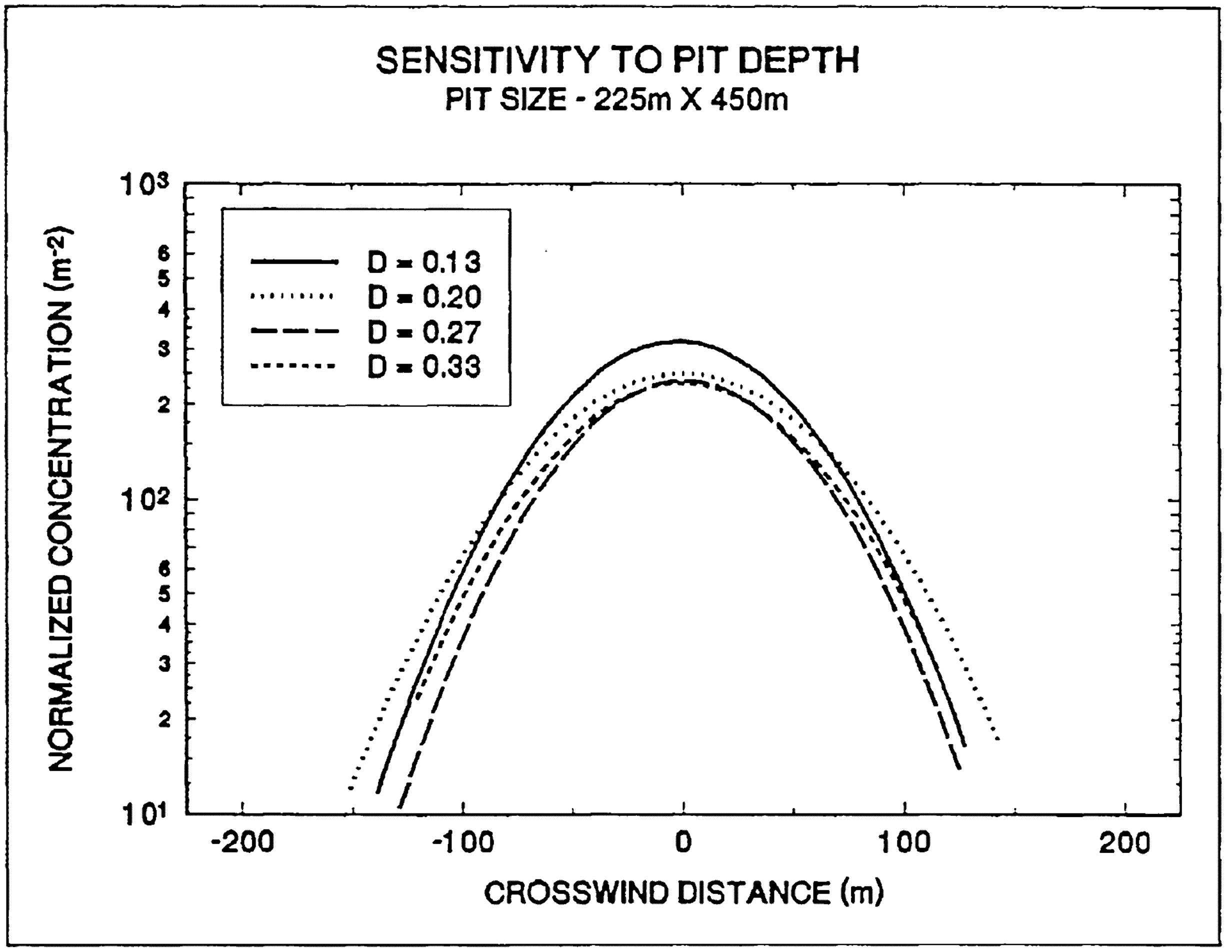

Figure 3a. Horizontal concentration distributions at downwind edge of pit (near-surface); source centered on upwind edge at floor; cases 4, 10, 11, and 12.

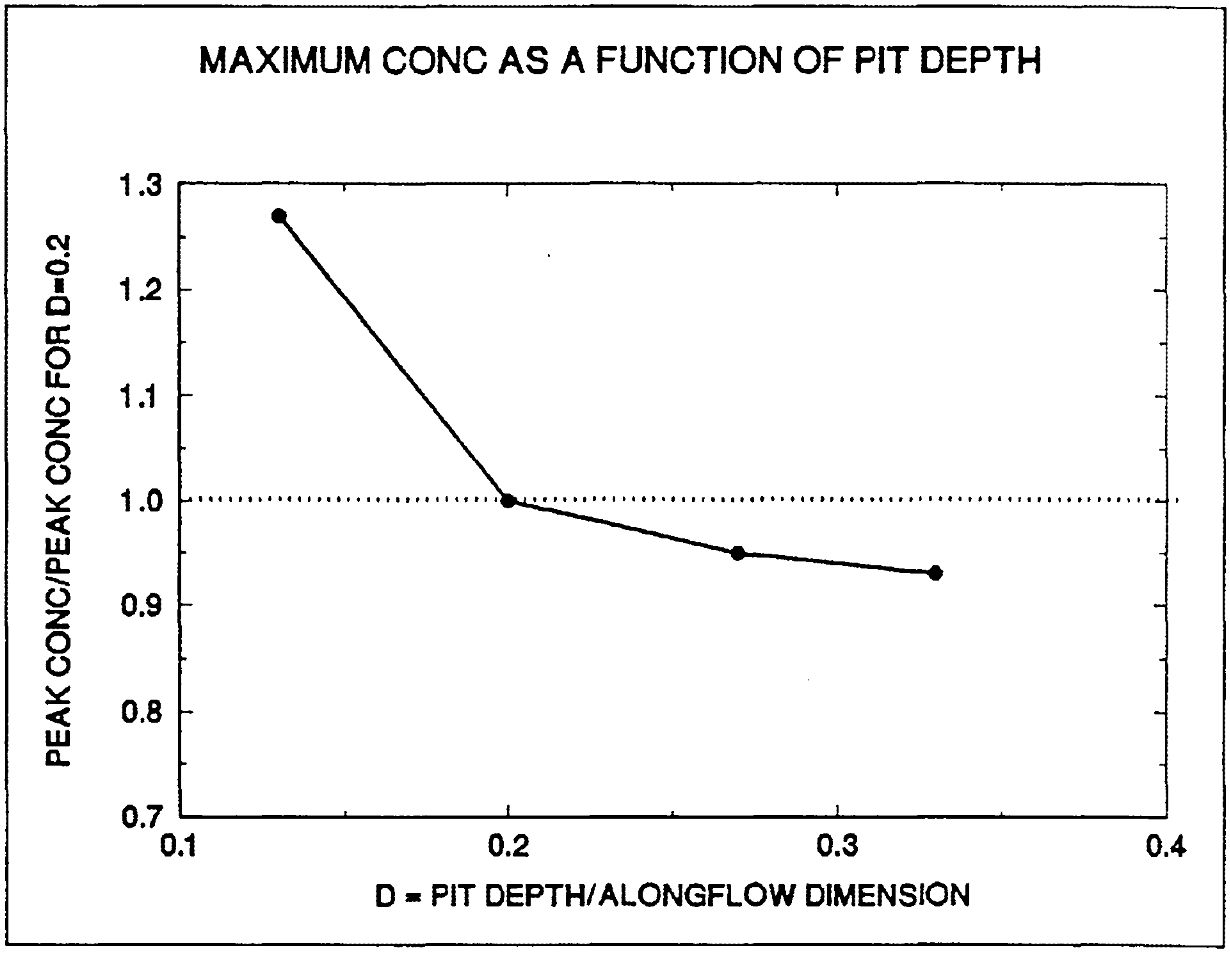

Figure 3b. Centerline (maximum) concentration for the four distributions of figure 3a as a function of normalized pit depth. Concentrations normalized by maximum for case with D = 0.2.

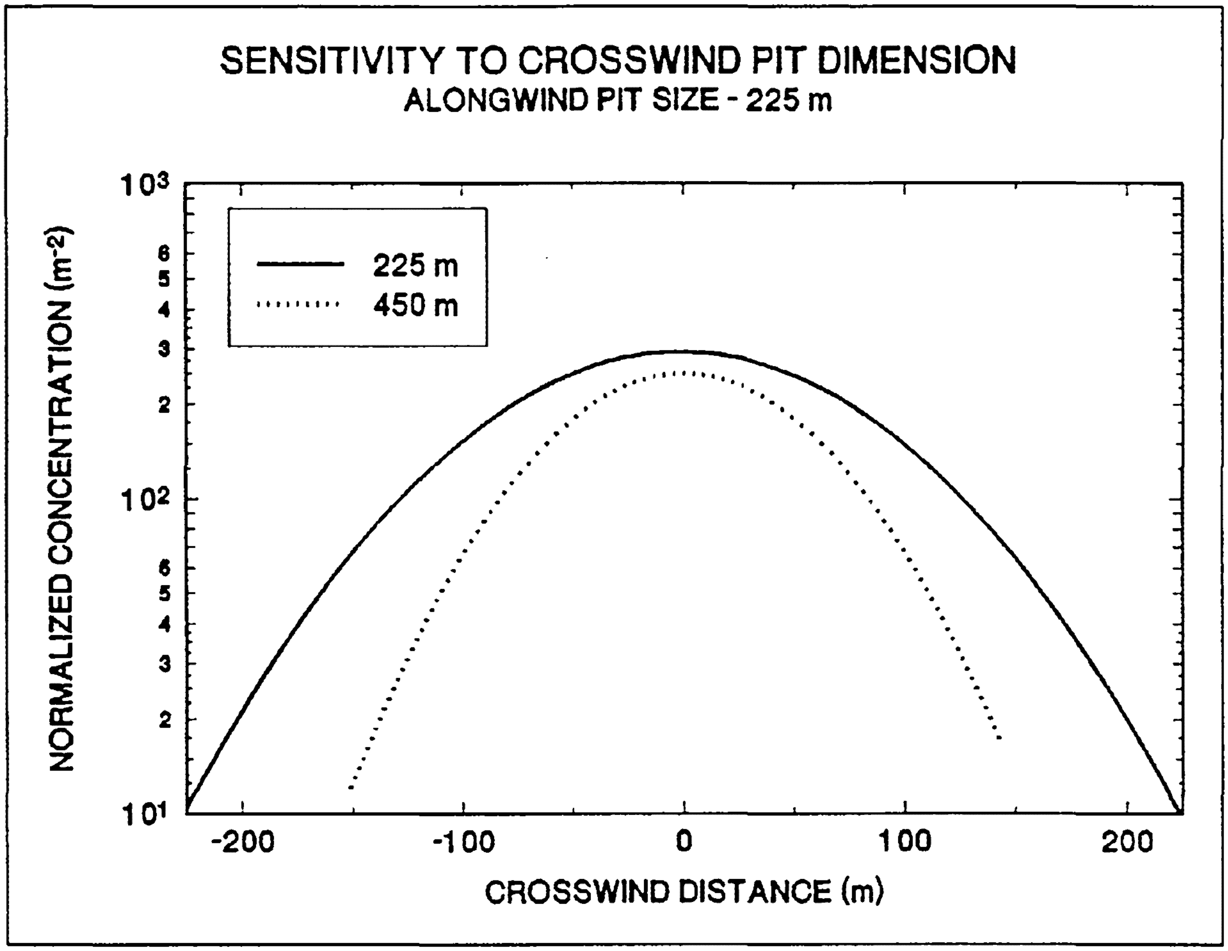

Figure 4. Horizontal concentration distributions at downwind edge of pit (near-surface); source centered on upwind edge at floor; cases 1 and 4.

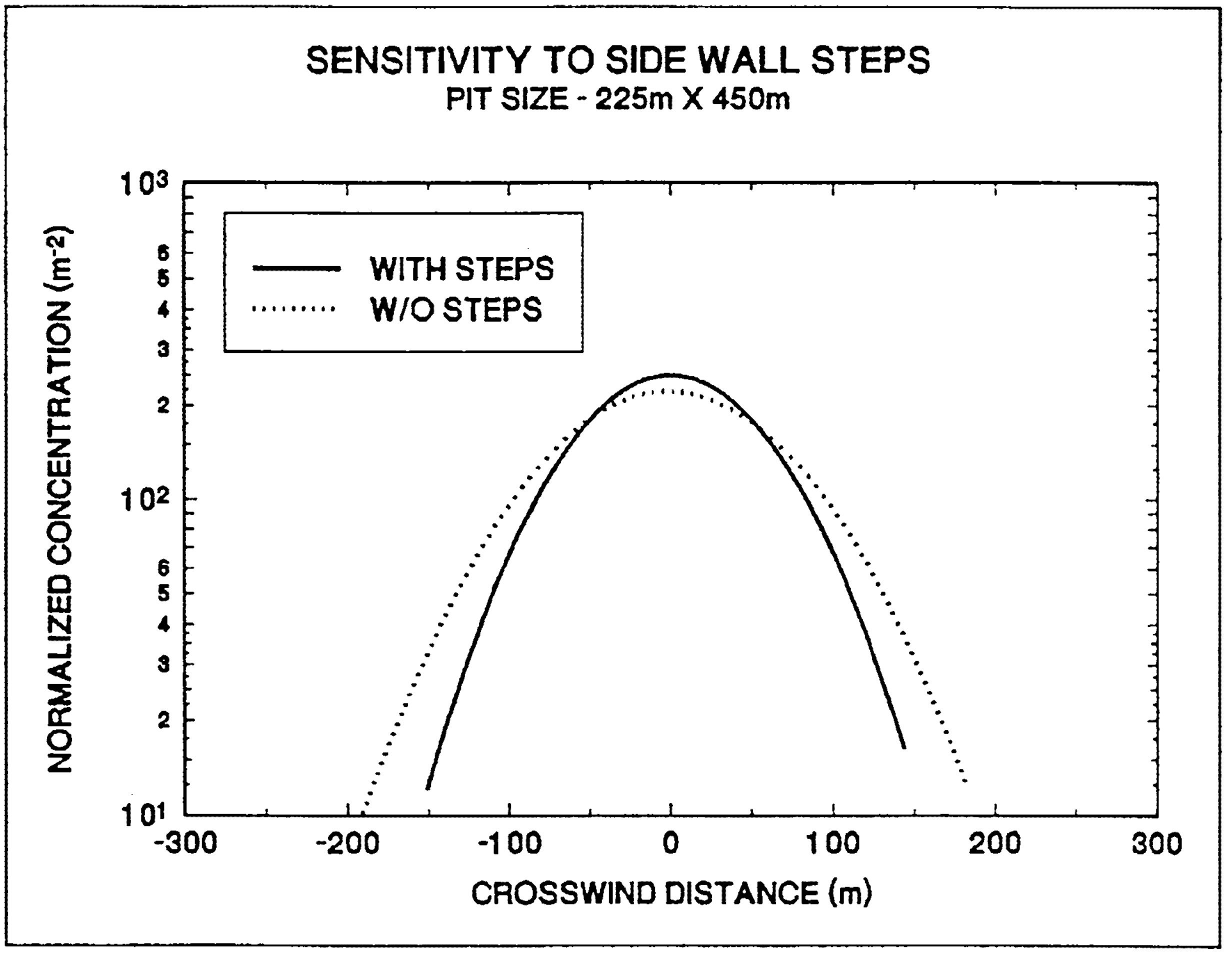

Figure 5. Horizontal concentration distributions at downwind edge of pit (near-surface); source centered on upwind edge at floor; cases 4 and 9.

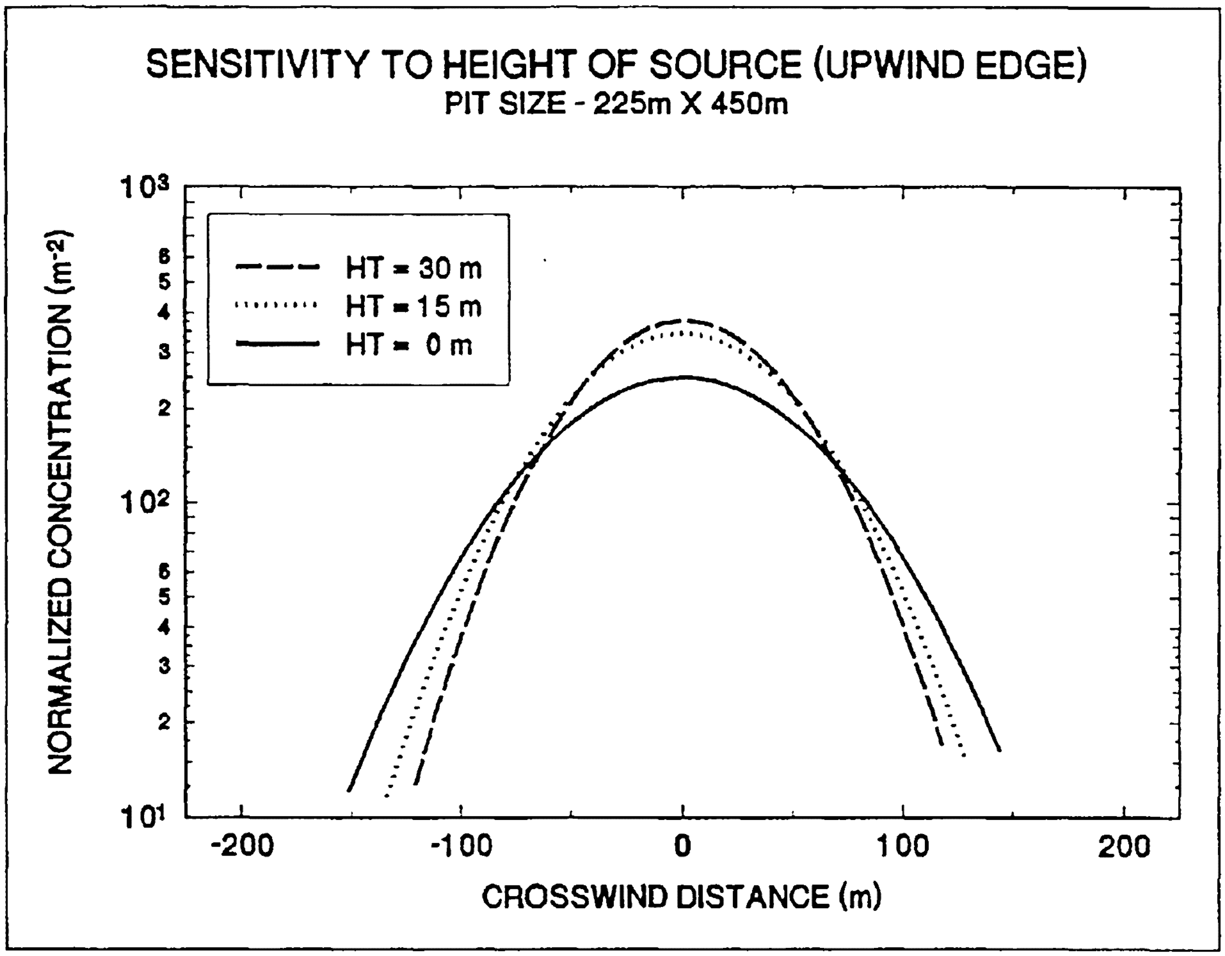

Figure 6a. Horizontal concentration distribution at downwind edge of pit; sources centered on upwind edge at various heights; cases 4, 22, and 25.

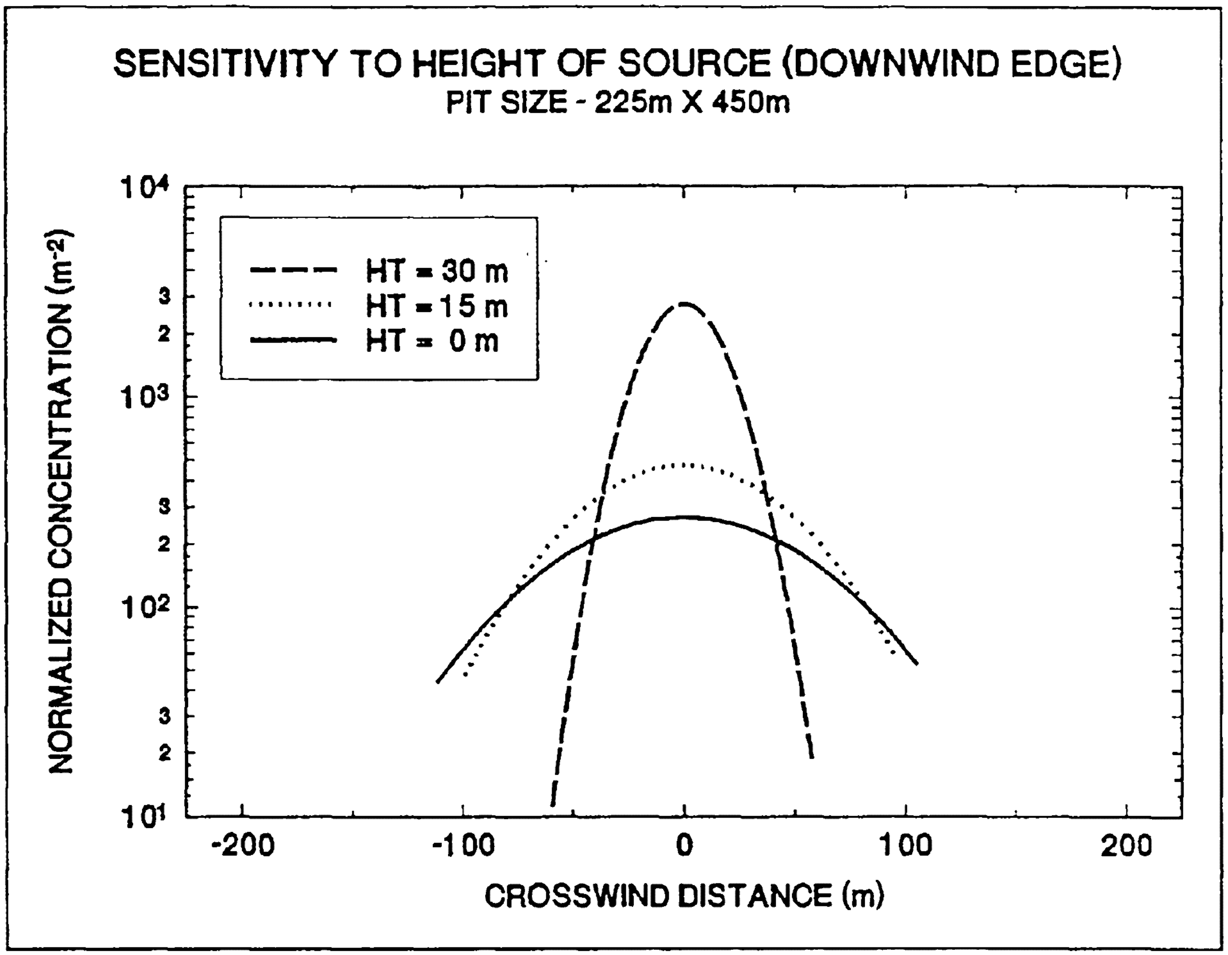

***Figure 6b**. Horizontal concentration distributions at downwind edge of pit; sources centered on downwind edge at various heights; cases 6, 23, and 26.*

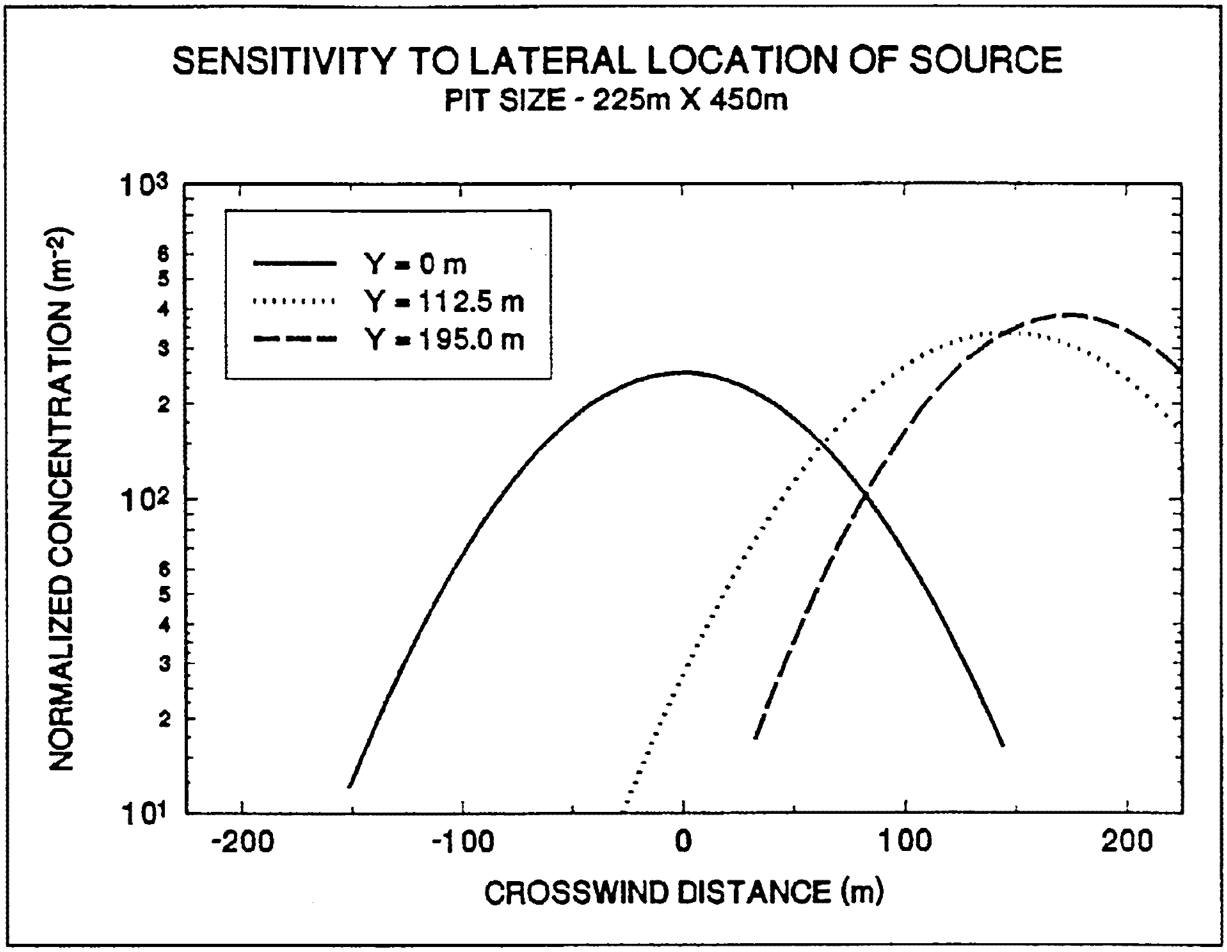

Figure 7. Horizontal concentration distributions at the downwind edge of the pit; sources at pit floor at various lateral locations; cases 4, 5, and 24.

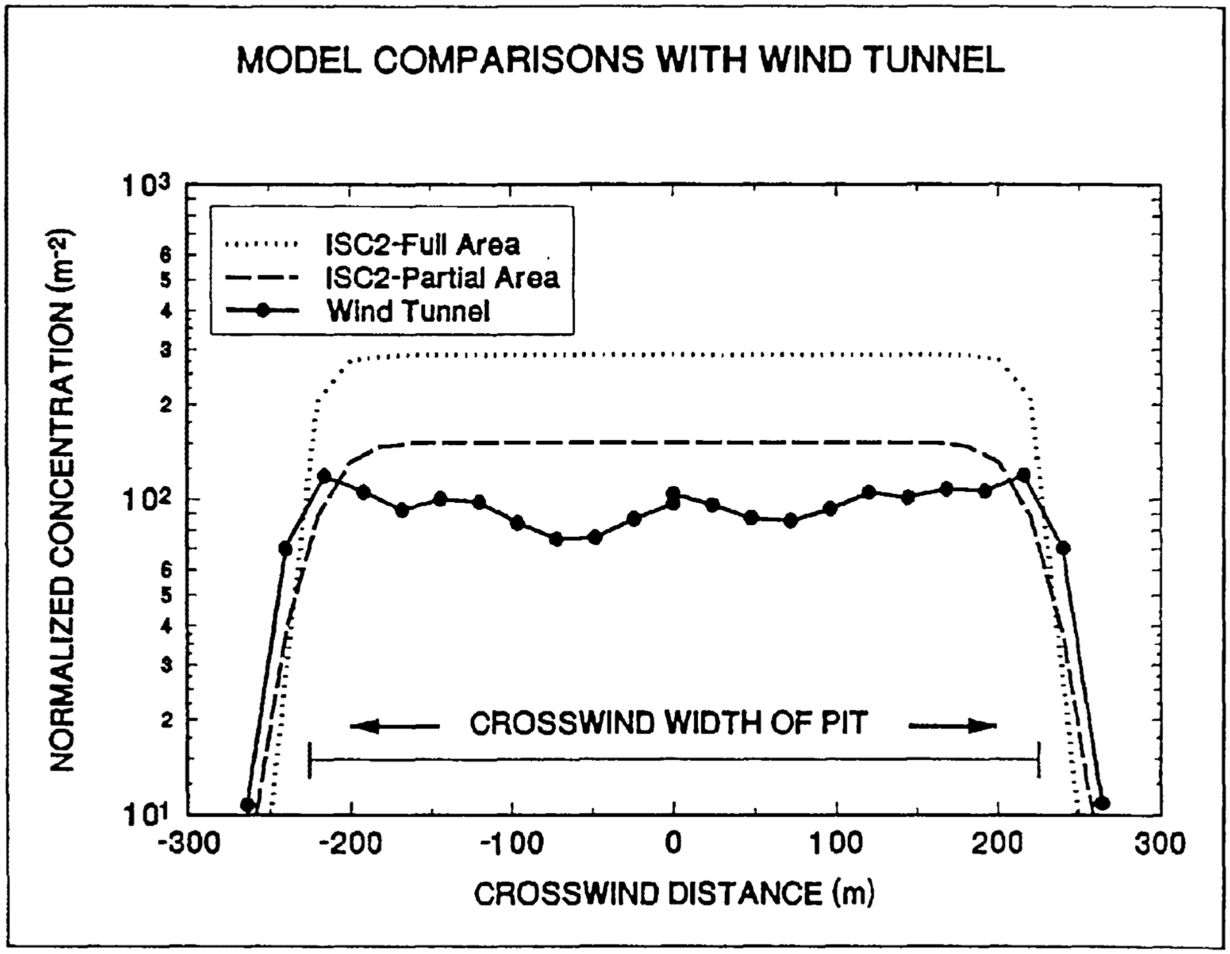

Figure 8. Horizontal concentration distributions at the downwind edge of a 225m X 450m pit with D = 0.20; wind tunnel data is a combination of cases 4, 5, 6, 24, 5-flipped, and 24-flipped.

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16. ABSTRACT

As part of EPA's effort to assess the ISCST2 model for applications to surface coal mining, a wind-tunnel study was performed to both highlight the important parameters to consider for modeling and to provide some results for comparison with the model. Sensitivity analyses indicated that important modeling features are the pit depth, the crosswind dimension, and the height and location of the source. The presence of steps along the sidewalls was found to be of little significance. The comparison of the combination case with the ISCST2 model indicates that open pits act as modified area sources where the emissions are greatest near the upwind side of any actual pit.

17. KEY WORDS AND DOCUMENT ANALYSIS

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