United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-450/4-85-001
January 1985

Air

EPA

Dispersion of Airborne Particulates In Surface Coal Mines

Data Analysis

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DISPERSION OF AIRBORNE PARTICULATES IN SURFACE COAL MINES

Data Analysis

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Contract No. 68-02-3514

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Office of Air and Radiation
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1.0 SUMMARY AND PURPOSE

During the summer of 1983, Air Sciences, Inc. conducted a data collection field study at four Western surface coal mines to characterize the air flow within the mine pits. Smoke puffs were released at the bottom of the pits, the motion of the smoke puffs was videotaped, and meteorological data were collected both in and out of the mine pits during the smoke releases. The field study was designed to allow visualization of airflow within the mine pits.

TRC Environmental Consultants, Inc. contracted with EPA, OAQPS, to reduce, quantify, interpret, and analyze the field data. The purpose of TRC's work, which is described in this report, was three-fold:

- Reduce and translate the field data into a computer compatible data base. This involved data averaging, computing some meteorological parameters (e.g., stability classes), and data editing.
- Analyze and interpret the field data to investigate relationships between in-pit and out-of-pit parameters, as well as other calculated parameters such as escape fraction. This was accomplished by deriving several representative parameters (exit times, net exit velocities, escape fractions), and analyzing statistical relationships.
- Perform a literature survey to identify previous investigations that relate in-pit and out-of-pit emissions, and recommend future studies that will better characterize pit retention. Results of the literature survey, and recommendations for future work, are included in this report.

The data reduction effort, discussed in Section 4.0, utilized standard National Climatic Data Center (NCDC) and EPA methods and conventions to compute mean wind directions, wind speeds, and stability classes for each smoke release episode. Additionally, data obtained from the VCR videotapes were combined with pit geometry data to calculate average smoke puff exit velocities for each release episode.

The smoke puff observations by themselves do not provide a quantitative measure of particle pit retention. However, two independent techniques -- one based on a simple settling model, the other based on a particle deposition model -- were used in conjunction with assumed particle size distributions and relevant field data to infer values of escape fraction.

The analysis of the reduced and edited data base yielded several findings:

- Computed escape velocities and escape fractions are lowest during early morning, stable atmospheres, and during light wind speeds. This finding is in agreement with observed flow patterns in the mine pits, as the released smoke tracer was frequently observed to have stagnated within the mine pits during these conditions. Conversely, the greatest ventilation rates were observed during high wind speeds and near neutral atmospheres. It should be noted that the nature of the field study -- visual observations of smoke puffs -- precludes observations at night when stable atmospheres are most likely to occur. Hence the results of these investigations are biased toward non-stable, daytime conditions.

- The computed escape velocity was found to be positively correlated with measured wind speed, temperature, and wind direction, and negatively correlated with stability category, and the width of the mine pit. However, when these parameters were used in linear, multivariate regression analysis, only 32% of the variation in escape velocity values could be accounted for. The linear model could not be improved through the use of in-pit measurements rather than out-of-pit measurements, or by stratifying the data by mine, by stability class, or wind speed category. It is concluded that some processes or variables, not accounted for in this analysis, must act in conjunction with the above meteorological parameters to determine the escape velocity

- In-pit winds are significantly different from out-of pit winds. The in-pit wind direction differs from the out-of-pit wind direction by about 60°. Further, no correlation between the in-pit versus out-of-pit wind direction was found using linear regression techniques, hence the in-pit wind direction can not accurately be predicted from a knowledge of the out-of-pit wind direction. In-pit wind speeds are, on the average, 25% smaller than out-of-pit wind speeds. Linear regression analysis did identify a significant positive correlation between in-pit and out-of-pit wind speeds.

- The value of escape fraction (that portion of the dust emitted in the pit that leaves the pit) inferred from both the settling and the deposition models is greater for unstable and neutral conditions than for stable conditions, as shown in Table 1.1. This suggests that stable atmospheres may suppress vertical motion causing particulate matter to be retained in the mine pits. This finding is in keeping with conventional understanding of atmospheric motion, and agrees with the Winges model of pit retention which exhibits a decrease in escape fraction with increasing stability.

TABLE 1.1
ESCAPE FRACTION SHOWN BY STABILITY

PARTICLE SIZE DISTRIBUTION	STABILITY(1)	SETTLING MODEL	DEPOSITION MODEL	WINGES EQUATION	FABRICK EQUATION
UNIVERSAL	UNSTABLE	1.00	0.93	0.99	0.58
	NEUTRAL	1.00	0.81	0.92	0.88
	STABLE	1.00	0.58	0.58	0.68
EDS	UNSTABLE	0.81	0.59	0.90	0.11
	NEUTRAL	0.90	0.36	0.59	0.32
	STABLE	0.70	0.21	0.20	0.14

1. "A" stability class used for unstable; "D" used for neutral; "F" used for stable.

- Reasonably good agreement is indicated between the escape fractions inferred from the settling and deposition models and those predicted by the equation proposed by Winges when the data are grouped by stability class. Relatively poor agreement is indicated between escape fractions predicted by the Fabrick equation and those inferred from the settling and deposition models when the data are grouped by stability class.

- The magnitudes of escape fraction inferred from the settling model and from the deposition model differ considerably, as shown in Table 1.1. Because the field data provide no direct measure of escape fraction, it is not possible to assess the accuracy of either the settling or deposition models as means of computing escape fraction.

- Categorization of smoke release flows into characteristic patterns indicates that the smoke puffs disperse within the pit before exiting during stable, low wind speed conditions. This finding is as expected.

The literature search indicates that there are very few field studies that have looked at pit retention or the relationship between in-pit and out-of-pit concentrations. There are, however, several models that treat pit retention and dispersion in pits, ranging in complexity from the simple Winges and Fabrick algorithms to sophisticated numerical models that could be used to simulate pit dispersion.

Because the few field studies that have attempted to quantify surface mine pit effects to date have only inferred values of escape fraction, there is a need to measure surface mine pit effects directly. Several direct measurement investigations are proposed in this report. Additional effort in deriving and validating simple escape fraction algorithms that can be incorporated into regulatory dispersion models is needed.

2.0 BACKGROUND AND LITERATURE SURVEY

Most air quality dispersion models which are used to predict particulate concentrations in the vicinity of surface mines simulate emissions as if they were released at grade level. However, many different dust-producing operations at open pit mines occur inside the pit, sometimes at depths of many hundreds of feet below grade. It is reasonable to suspect that only a fraction of the fugitive dust generated at the pit floor escapes to the surface where it then may be transported to the mine boundaries. This tendency for particulate matter to remain inside the pit has been called pit retention.

There are probably two separate mechanisms that cause particulate matter to be retained in a mine pit. The first is a de-coupling of the wind field in the pit from the wind field at the surface, inhibiting or suppressing the vertical transport of particulate from the bottom of the pit to the surface. This suppression of vertical mixing is obvious to anyone who has viewed a deep surface mine pit on a calm morning before sunrise. A shroud of diesel exhaust often hangs in the pit, undisturbed by air movement at the surface. This pit retention mechanism would be expected to be most pronounced during stable, low wind speed conditions, such as occur at night. The other mechanism by which particulate is retained is through deposition and settling at the mine pit surface and along the pit walls. Both mechanisms occur simultaneously, and they are linked. When the air in the pit is very stable, for example, the residence time of a parcel of air in the pit increases, and the deposition and settling processes have a longer time to act on airborne particulate.

Pit retention is a phenomenon that one would intuitively expect to occur at a surface mine. Similarly, one would expect that the presence of the mine pit itself would disturb the airflow over and inside the pit, so that the "plume" of dust might not have the familiar Gaussian distribution imposed by many dispersion models, or might have a significantly different trajectory which would alter plume location. This altered plume shape or location, while technically different than pit retention, is certainly a related issue. The reason that these surface mine phenomena -- pit retention and plume perturbation -- are of interest is because most air quality models neglect them.

Although both pit retention and plume perturbation will influence particulate concentrations downwind of a surface mine, the nature of the influence is different. Pit retention, which removes particulate from the air before it leaves the mine pit, will always decrease downwind ambient concentrations. If an otherwise accurate model simulation of a mine ignores the influence of pit retention, and if there is indeed some retention of particulate in the pit of the mine, then the model will overpredict downwind concentrations. The error will be systematic and persistent. That is, even in predicting long term (annual average) concentrations when the random emission factor and modeling errors cancel out, the error due to neglect of pit retention will still be present and will produce modeled concentrations larger than those that would actually occur. On the other hand, model errors caused by alteration of the plume shape or location (plume perturbation) due to the presence of the pit could conceivably cause overpredictions or underpredictions, depending upon how the pit is simulated. If the pit is simulated as a very large area source, but the dust from the pit exits in a narrow and coherent plume, then the maximum concentration at the top edge of the pit could be underpredicted. Conversely, if the pit dust completely disperses in the pit before exiting, a model that treats the pit as a small, discrete area source may overpredict concentrations near the pit. However, the effect of poor approximation of the mine pit source would be expected to diminish with increasing time and with increasing distance from the pit. Over long time intervals the plume of dust from the pit certainly approaches the assumed Gaussian shape, and at large distances from the pit, the plume perturbation caused by the pit might be expected to be insignificant.

The remainder of this section of the report examines previous, and in one case proposed, investigations concerning pit retention and pit airflow. A distinction is made between experimental studies of pit retention (of which there are very few), and models of surface mine pits (of which there are several). The discussion in this section is based on a literature review of meteorological and air quality journals, as well as the authors' discussions with investigators working with surface mine pits.

2.1 EXPERIMENTAL STUDIES

Although field studies in the vicinity of surface mines have undoubtedly been influenced by pit retention, very few studies have specifically addressed pit retention. Furthermore, the recent interest in plume model validation typified by EPA and EPRI funded investigations (Bowne, 1982; Lavery, 1982), has been confined to more conventional stack releases, and to date there have been no rigorous validations of models applied at surface mines. There are two reported studies in which the investigators detected discrepencies between measured and modeled concentrations at surface mines, and attributed the discrepencies to pit retention (Cole and Fabrick, 1984):

- WYOMING EMISSION FACTOR STUDY. In a year-long emission factor development study conducted at two surface coal mines in Wyoming, Shearer, et al (1981) derived site specific particulate emission factors. These factors were then used in conjunction with mine operational data to estimate the total particulate emission rate from the pits. Independently, a modified PAL model (modified to account for deposition over flat terrain) was used to backcalculate from TSP concentrations measured at the edge of the pit to compute "effective" emission rates from the pits. The two pit emission rates differed by a factor of three, and Shearer, et al hypothesized that only one-third of the particulate emitted in the pit was escaping. It should be noted that the Wyoming study was not designed to isolate the effects of pit retention, and the factor of three difference in predicted emission rates could have been caused by phenomena other than pit retention.

- BERKELEY PIT STUDY. Cole and Kunasz (1982) used a hybrid receptor model to estimate effective particulate emissions at Anaconda's 550 meter deep copper pit in Butte, Montana. The receptor model indicated that emissions from the pit, as detected by hi-vol samplers at the pit perimeter, were 59 grams per second. A conventional emissions inventory identified pit emissions at 125 grams per second. The authors hypothesized that only one-half of the particulate matter emitted in the pit escaped to the surface. As with the Wyoming emission factor study, the Berkeley Pit investigation was not designed to look at pit retention, and it is possible that the difference in calculated emission factors could have been caused by emission factor errors or errors in the receptor model.

The only field study that specifically examines pit retention and flow fields at a surface mine appears to be the EPA funded work performed by Air Sciences, Inc. (Hittman and Air Sciences, 1983), which provided the data analyzed in this present report. The Air Sciences data collection effort is outlined in Section 3.0 of this report.

A number of studies in air pollution literature have looked at transport and dispersion over features similar to surface mine pits, namely, urban street canyons. The street canyon is like a mine pit in that both configurations involve the release of pollutants at the bottom of a cavity, and both must account for wind flow circulation within the cavity. The particulate retention in a pit is slightly more involved than the dispersion of gases in a street canyon because of additional effects of particulate settling and deposition. A recent street canyon study includes: comparison of an extensive date base of measured CO concentrations against predicted CO concentrations from the Intersection Midblock Model (IMM) showing that the model underpredicts frequently and severely (Zamurs and Piracci, 1982).

The wind tunnel offers a logical and convenient means of studying flow over cavities. There has been only one reported wind tunnel study that specifically looked at street canyons (Wedding, et al, 1977), and unfortunately, that study considered shallow canyons, and did not incorporate the findings into a dispersion modeling framework. A very ambitious wind tunnel study has been proposed for funding by the Federal Highway Administration (FHWA) in 1985. The FHWA wind tunnel study, which will consider street canyons and deep cuts, could have direct applicability to the surface mine pits. The goal of the 20 month effort will be to develop new, simplified algorithms that can be incorporated into existing Gaussian highway models to better predict pollutant concentrations. The FHWA study will investigate neutral and stable atmospheres, will consider various wind directions and surrounding roughness lengths, and will consider canyon width-to-depth ratios that range from 6:1 to 1:6.

2.2 SURFACE MINE MODELS

There are two simple models which attempt to simulate pit retention by deriving mass escape fractions:

- FABRICK EQUATION. Beginning with the helical flow street canyon equations used in the APRAC-1A model, Fabrick (1982) derived a pit retention equation that depends on pit width and surface wind speed. The Fabrick equation, discussed in detail in Section 4.5.6 of this report, predicted an escape fraction of 0.16 for the Wyoming data discussed previously (Cole, and Fabrick, 1984).

- WINGES EQUATION. The ERTEC Mining Air Quality Model includes a simple algorithm to account for bulk pit retention (Winges 1981). The equation, which is discussed in detail in Section 4.5.7 of this report, is a function of deposition-settling velocity, pit depth, and vertical diffusivity. In an application of the Winges equation to the Wyoming emission factor study mentioned previously, the Winges equation predicted an overall escape fraction of 0.50, as compared to the 0.33 escape fraction hypothesized from the Wyoming data (Cole and Fabrick, 1984).

In the field of fluid mechanics, study of flow over cavities is a mature discipline. Analytical solutions to the Navier-Stokes equations of fluid motion are available if a number of simplifying assumptions are made (two-dimensional, laminar flow, incompressible, constant diffusivity, flat plate driven). As the simplifying assumptions are discarded, the simulation of cavity flow becomes more complicated, and the Navier-Stokes equations can be solved only with numerical analysis. A very recent investigation of cavity flow was directed specifically at surface mine pits:

- HERWEHE MODEL. The Bureau of Mines funded development of a computer simulation modeling scheme applicable to shallow surface mines (Herwehe, 1984). The resulting modeling scheme simulates the transport, diffusion, and dry deposition of fugitive dust emitted from an idealized open-pit surface mine through the development of two 2-dimensional finite-element models: a planetary boundary layer model and an advection-diffusion model. The boundary layer model is used to generate quasi-steady-state atmospheric flow fields and diffusion quantities to be used as input data to the advection-diffusion model, which simulates the ultimate fate of the non-reactive particulate matter. Synoptic wind conditions, surface roughness, complex nonhorizontal terrain, atmospheric stability, a variety of pollutant sources, particulate terminal settling and deposition velocities, and particulate accumulation on the lower surface are all factors accounted for in these two models. The Herwehe model accounts for varying diffusivity with pit depth. However, the model is hydrostatic (assumes constant pressure with pit depth), and as a consequence would not be applicable to stable atmospheres nor to pit walls with slopes greater than about 35 degrees from horizontal (Herwehe, 1984 a).

The hydrostatic assumption in the Herwehe model may severely limit its applicability to surface mine pits. Other non-hydrostatic models, not specifically structured to simulate surface mines, could be modified to accomodate mine pits. Over the last eight years a series of Finite Element Models (FEM) have been developed that could be modified for use with surface mine pits:

- FEM. The 3-dimensional Galerkin Finite Element Model (FEM) was developed by Lawrence Livermore Laboratory to simulate complex terrains (Gresho, et al, 1976). The model has been applied to flow over ridges, regional geostrophic flow, and heavy gas flow. The FEM is non-hydrostatic, transient, and accepts non-constant diffusivities. Finite element modeling can very easily accomodate terrain features, such as a mine pit, and with much less difficulty than finite difference models. The major drawback to the FEM model is the large computer expense in running the model.

While numerical models such as Herwehe's or FEM provide scientifically rigorous solutions to specific pit simulations, their use in regulatory applications is limited because they have not been validated with field data. Also, a good deal of effort is needed to prepare the numerical models for any given simulation, and it is not a trivial matter to apply the same model to a pit with an even slightly different geometry.

A brief bibliography of references that examine surface pit mine modeling, pit retention, street canyons, flow over cavities, and related issues is included in Appendix 1.

3.0 DESCRIPTION OF FIELD WORK

From June 28, 1983 through August 6, 1983, Air Sciences, Inc. conducted smoke release measurements at four mines in Colorado, Wyoming, and Montana. The smoke release field study, performed for the Industrial Environmental Research Laboratory of EPA, is detailed in Studies Related to Retention of Airborne Particulates in Coal Mine Pits -- Data Collection Phase (Hittman and Air Sciences, 1983), and is briefly summarized in this section.

The smoke release program was designed to provide data concerning air motion within surface coal mine pits. At each of the four mines shown in Table 3.1 smoke generators at the bottom of the pits were used to release discrete 10 second puffs of diesel fuel smoke. An observer positioned at the top of the pit recorded each smoke release on a video cassette recorder (VCR). VCR recording began with the smoke release from the generator, and was terminated when the smoke puff left the pit, or when the smoke in the pit became so disperse that it was no longer visible. Roughly 800 such smoke release experiments, or episodes, were conducted at the four mines.

TABLE 3.1
STUDY MINES AND LOCATIONS

MINE	LOCATION
Colorado Yampa Coal Company	Steamboat Springs, CO
Caballo, Carter Mining Company	Gillette, WY
Spring Creek Mining Company	Decker, MT
Rosebud Coal Company	Hanna, WY

Meteorological data were measured both in- and out- of the pits during the smoke release experiments, and were recorded at one-minute intervals along with date and time on cassette tape. The meteorological parameters are indicated in Table 3.2

TABLE 3.2
METEOROLOGICAL MEASUREMENTS

OUT OF PIT 6 m. ABOVE GROUND	INSIDE PIT 3 m. ABOVE GROUND
WIND SPEED WIND DIRECTION TEMPERATURE VERTICAL WIND SPEED STD. DEV. OF HORIZONTAL WIND DIRECTION STD. DEV. OF VERTICAL WIND SPEED	WIND SPEED WIND DIRECTION STD. DEV. OF HORIZONTAL WIND DIRECTION TEMPERATURE

At the conclusion of each smoke release episode an observer located outside the pit filled out a field data log, recording start time of release, elapsed time until plume exit, distance to point of plume exit, direction to exit, and in-pit temperature. In addition, he estimated and recorded cloud cover and made a subjective assessment of smoke dispersion.

These data -- the VCR cassettes, meteorological data tapes, and field logs -- form the experimental data base that is analyzed in this report.

4.0 DATA REDUCTION

A major task in the analysis of the data collected by Air Sciences, Inc. was the reduction of data into parameters, averages, distributions, and expressions which allowed subsequent examination of air flow, meteorology, and pit retention. This section explains which data were reduced, what methods and conventions were used, and how the data were processed. A brief overview of the data reduction effort precedes the discussion, with a description of VCR observations, meteorological data, and special calculated parameters following.

4.1 DATA FEDUCTION OVERVIEW

The data reduction effort began with the quantification of data from the VCR cassettes. Video cassette recordings of the smoke release episodes were analyzed to determine smoke puff exit times, and to categorize the smoke flow into characteristic patterns. Additionally, mine identification and episode case numbers were obtained from the VCR cassettes to allow synchronizing of data.

Meteorological data gathered in the pit and out of the pit were recorded on magnetic tape during the smoke release episodes. Generally, these data consisted of one-minute averages of meteorological parameters.

Field logs, containing observations made on site, were also recorded on magnetic tape. The observations included a qualitative estimate of initial dispersion, time and angle of initial smoke puff exit, and episode case number.

Data from all three sources (VCR cassettes, meteorological data tapes, and field logs) were merged into a single computer compatible data file. Data were checked for consistent time synchronization, and anomalous or clearly erroneous data were discarded. The data base was edited to remove illegal, spurious characters which had been introduced during data transcription from cassette to magnetic tape.

The next step in the data reduction effort was to summarize data corresponding to discrete smoke release "episodes." Each episode was an individual smoke release experiment, that began with the smoke release from the generators at the bottom of the pit, and ended when the smoke puff exited the pit, or when the smoke puff became too dispersed to be visible. The duration of the smoke release episodes ranged from about 30 seconds to more than 5 minutes, but the average episode lasted about two minutes. Time dependent data, such as wind speed and wind direction for example, were averaged over the duration of the smoke release episode. Other parameters, such as mean exit velocity and escape fractions, were computed for each smoke release episode. The summarized data were written on a magnetic tape, structured so that each smoke release episode was contained in one data record. The data values in each smoke release episode record are shown in Figure 4.1, and the derivation of each value is described in more detail in sections 4.2 through 4.4 of this report. A FORTRAN program developed by TRC was used to summarize the data which then were the basis for all subsequent statistical analyses.

4.2 VCR OBSERVATIONS

As a preliminary step the videotapes were previewed in order to facilitate extraction of data that would be used in the analysis. It was seen from the previewing of the videotapes that some information still existed in audio/visual form which would have to be translated to digital form for use in the analysis. The name of the mine, the episode number (called "case number" by Air Sciences), and many observations about weather or operation of the smoke generators, were announced verbally on the VCR soundtrack. Furthermore, it became evident that the behavior of the smoke releases could be grouped into distinguishable patterns. The puff behavior in the pit appeared from this previewing effort to take one of two forms - either it stayed in the pit, or was ventilated out of the pit. In some cases it was not possible to determine what the behavior was. When the puff stayed in the pit it did so because it was recirculated back into the pit by an active circulation pattern, or it simply did not move a significant distance and dispersed to the point of losing visual definition while still within the confines of the pit.

FIGURE 4.1
DESCRIPTION OF VARIABLES REDUCED
FROM SMOKE RELEASE EXPERIMENTS

VARIABLE	DESCRIPTION	VARIABLE	DESCRIPTION
MINE	MINE ID number	WDINN	AWDIN normalized with respect to pit long axis.
JDAY	Julian day of experiment	AWSOUT	Average out-of-pit wind speed (MPH)
NTIME	Time of day (hr-minute)	AWSIN	Average in-pit wind speed (MPH)
IDNUM	Experiment case number	ATOUT	Average out-of-pit temperature (F)
IRES1	Time in seconds of initial puff exit	ATIN	Average in-pit temperature (F)
IRES2	Time in seconds of exit of entire puff	NACOV	Average cloud cover (tenths)
NDUR	Internal program counter-number of 1-minute met. observations required to describe experiment	ISGOUT	Out-of-pit stability based on sigma-theta (invalid)
AWDOUT	Average out-of-pit wind direction for duration of experiment	ISGIN	In-pit stability based on sigma-theta (invalid)
AWDIN	Average in-pit wind direction for duration of experiment	IPG	Stability based on Pasquill-Gifford
WDOUTN	AWDOUT normalized with respect to pit long axis	IVRT	Stability based on sigma-w (invalid)
FRAC 1	Escape fraction based on VEL1 and universal size distribution	AVRT	Average measured vertical velocity (invalid)
FRAC 3	Escape fraction based on VEL2 and universal size distribution	VEL1	Escape velocity based on IRES1 (cm/sec)
FRAC5	Escape fraction based on Winges equations and universal size distribution	VEL2	Escape velocity based on IRES2 (cm/sec)
		FRAC2	Escape fraction based on VEL1 and EDS size distribution
		FRAC4	Escape fraction based on VEL2 and EDS size distribution
		FRAC6	Escape fraction based on Winges equations and EDS size distribution

FIGURE 4.1 (continued)

VARIABLE	DESCRIPTION	VARIABLE	DESCRIPTION
FRAC7	Escape fraction based on Fabrick equations and universal size distribution	FRAC8	Escape fraction based on Fabrick equations and EDS size distribution
		PITA	Pit angle measured from North
WIDTH	Pit width (meters)	DEPTH	Pit depth (meters)
ITYPE	Observed flow pattern category		

When the puff left the pit it appeared to do so under three different regimes. In some cases there appeared to be a very local and subtle circulation pattern caused by the sun heating the pit wall directly adjacent to the puff and in turn circulating the puff up the wall and out of the pit by a thermally driven circulation. In other cases the ambient wind was sufficiently strong to advect the puff out of the pit. A third behavior was seen where the puff simply lifted gradually from its point of formation as if by thermal buoyancy. In some cases, however, it was not possible to determine the behavior of the puff. During some smoke releases the puff became too diffuse and lost visual definition which made it impossible to determine if or when it left the pit. In other cases the Test Director erroneously terminated the tape record of the experiment before it was possible to determine if the puff had left the pit. A separate category to allow for these occurrences was devised.

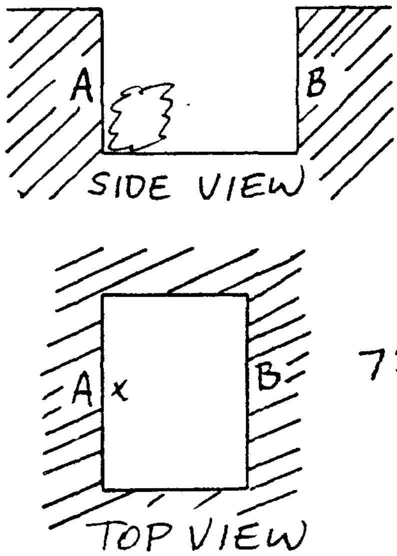
From these initial observations it was seen that determination of smoke plume dimensions and smoke opacity could not be determined as had been anticipated. There were several reasons for this. The smoke puff was not often contained in a steady-state coherent plume that could be assigned dimensions because the air motion in the pit was at times extremely chaotic. Furthermore, the single camera viewing point located at the top of the pit provided only a 2-dimensional view from the side, and there were no scale features in the visual recording with which to judge distances. Smoke opacity was also very difficult to judge because of the rapid movement of the smoke plume and because of the varied color of the background. Even if it had been possible to estimate opacity, this information alone, without optical path length (i.e., plume width), would not have been sufficient to characterize particulate concentrations.

In order to convert the audio/visual data into digital information that could be analyzed, a data coding form was devised. The form was designed in a way to allow the analyst to note the puff behavior in numerical code form and thus translate the audio/visual data to digital characters. Factors noted on the form included experiment identification, characteristic puff pattern (in several optional forms), duration of the experiment and some general observations which seemed to be important and might be amenable to further analytical treatment. A sample form is shown in Figure 4.2. The numerals appearing under the headings "Question" and "Card Column" are solely for use in keypunching the data. The elapsed time in Item 5 of the form is, in most instances, the time from initial release of the smoke puff until the end of the puff exited the pit. This time was determined by the VCR analyst using a stopwatch.

When the smoke puff dispersed in the pit so completely that it was no longer visible, the elapsed time was defined as the time from initial puff release until the plume could no longer be seen. Defining elapsed time in this manner introduces a bias in the measurement since the parcel of air in which the smoke puff dispersed, in some cases, probably remained in the pit even though it could not be seen. However, it was not possible to determine how much longer the puff remained in the pit (because the puff could not be seen), nor was it considered prudent to discard these episodes from the data base (because this would completely ignore the longest duration smoke puff retention episodes). The effect of this bias is to yield smaller smoke puff retention times than would actually have been measured had the smoke puff been visible, and for this reason the elapsed time associated with smoke release episodes that dispersed completely within the pit must be considered a lower bound. Of the roughly 800 individual smoke release episodes, smoke puffs from 248 of them dispersed completely within the pit. While this represents only a fraction of the total smoke release episodes, the bias is nevertheless important because it is these long duration retention episodes that probably account for the majority of pit retention.

The VCR data digitizing effort involved viewing the roughly 40 hours of videotape while filling out the coding forms. One form was completed for each smoke release episode, and then the data from the forms were keypunched and merged into the reduced data base. The roughly 800 coding forms have been bound in a separate volume.

COAL MINE VIDEOTAPE CODING FORM
Figure 4.2



7:02:40

1. Mine Identification

   1. Yampa
   2. Caballo
   3. Spring Creek
   4. Rosebud

2. Case Number

3. Characteristic Pattern

   A. Plume Stays in Pit

      1. Recirculation evident
      2. Disperses in pit
      3. Other (explain) ______________________

   B. Plume Exits Pit

      1. Thermally driven up side wall
      2. Advected out side wall
      3. Exits center of pit
      4. Other (explain) ______________________

   C. Don't know

      1. Sample invalid
      2. Tape ends
      3. Puff too diffuse
      4. Other (explain) ______________________

4. General Observations

____

5. Elapsed Time (seconds)

____

Question	Card Column	
1	1	3
2	2	
	3	7
	4	3
3A	5	2
3B	6	
3C	7	
4	8	
	9	
	10	
5	11	1
	12	8
	13	6

4.3 FIELD OBSERVER LOGS

The Air Sciences, Inc. field observer logs were available on magnetic tape. These data included smoke release episode number (case number), mine name, date, release time of smoke puff, and duration of puff. In addition, the observer estimated the qualitative degree of dispersion of the smoke plume (digitized from 1 to 5), distance that the plume was in contact with the side wall prior to exit, compass direction to exit location, cloud cover and ceiling, and in-pit temperature.

These data were merged with the VCR and meteorological data to make up the digital data base.

4.4 METEOROLOGICAL DATA

Meteorological data collected in and out of the mine pits were averaged over the smoke puff episode in order to yield measurements of meteorological parameters that influenced each smoke puff experiment. The methods used to average wind speed, wind direction, Pasquill-Gifford stability class, sigma theta stability class, and sigma w stability class are discussed in the following sections.

4.4.1 WIND SPEED AND WIND DIRECTION

Individual one-minute wind speed values both in and out of the mine pits were scalar averaged to yield mean wind speeds. That is, the sum of individual wind speeds was divided by the total number of valid observations.

Individual one-minute wind directions both in and out of the mine pits were unit vector averaged to yield resultant wind direction. Resultant wind direction, WD_r, was given by:

$$WD_r = \text{arctangent } (X/Y)$$

where

$$X = \sum \text{sine } (WD_i)$$

$$Y = \sum \text{cosine } (WD_i)$$

WD_i is individual wind direction

4.4.2 PASQUILL-GIFFORD STABILITY CLASS

The Pasquill-Gifford stability class was determined from cloud cover and ceiling appearing in the field observer's logs, combined with average wind speed during the smoke release episode. The procedures used to compute P-G stability class were those used by the National Climatic Data Center (NCDC) in deriving STAR data distributions.

4.4.3 SIGMA THETA

Values of sigma theta, that is, the standard deviation of horizontal wind direction, were measured simultaneously inside and outside the mine pits. Air Sciences programmed its Campbell Scientific CR-21 data logger to print out sigma theta values once per minute, with a polling interval of 10 seconds and an averaging time of one minute (Cole, 1984). The sampling time for the data logger is equal to the print out time. Clearly this choice of time parameters was prompted by a desire to increase data resolution, and is appropriate since some of the smoke releases were visible for only a minute or so. However, the short (one minute) averaging time and the inability of the data logger to accumulate sigma theta values longer than the print out time means that some data manipulation is required to convert the one minute sigma thetas to the fifteen minute sigma thetas needed to calculate atmospheric stability class (Irwin, 1980). The sequence of consecutive one-minute sigma theta values corresponding to each smoke puff episode were converted to representative fifteen-minute sigma theta values using a method described by Hanna (Hanna, et al, 1982). Next, the fifteen-minute sigma theta values were categorized into alphabetic stability classes using procedures outlined by Irwin (1980).

Examination of alphabetic stability classes determined in this manner revealed that the vast majority of the stabilities were class "D", both in- and out-of the pit. The Pasquill-Gifford stability distribution indicated that only 10 percent of the episode hours were class "D", which is a much more reasonable distribution for summer daylight hours. Given the low confidence in the accuracy and representativeness of the sigma theta measurements, stability classes determined by the sigma theta measurements were not used in this study.

4.4.4 SIGMA-W

Values of the standard deviation of vertical wind speed, sigma w, were recorded by Air Sciences, Inc. at the out-of-pit sensor. It was hoped that these measurements could be used as an indication of atmospheric stability class by relating sigma w to sigma phi in the manner recommended by the AMS (AMS,1977). However, TRC was notified by Air Sciences, Inc. that the sigma w data were suspect and probably in error (Cole,1984). The error was attributed to a faulty calibration of the vertical wind speed instrument that was discovered by Air Sciences only after the data collection effort was finished. Air Sciences did not know the direction nor magnitude of the calibration error. The sigma w data were not used in this study.

4.5 CALCULATED PARAMETERS

Several parameters used in this evaluation of mine pit data were calculated from direct measurements of observed values, from average meteorological conditions, from approximations of actual pit geometry, or from combinations of other measurements. These calculated parameters include:

- Pit dimensions. Obviously the geometry of the four mine pits is somewhat complicated, yet the Fabrick and Winges escape fraction equations require that the pits be assigned discrete widths, lengths, and depths. Hence the mine pits have been "idealized" by approximating their shapes with specific dimensions.

- Effective pit width. The path length from one edge of the pit to the other, defined by the out-of-pit wind direction. This effective pit width is used in Fabrick's escape fraction expression.

- Wind direction and pit orientation. In an effort to discriminate out-of-pit wind directions with respect to the long-axis orientation of the mine pits, wind directions were categorized as "parallel" or "cross-wind" using a calculated variable "TACK".

- Smoke puff escape velocity. The pit depth divided by the time required for the smoke puff to exit the pit. This is a measure of net upward vertical velocity.

- Smoke puff escape fraction determined by settling. The smoke puff escape velocity minus settling/deposition velocity, weighted according to particle size distribution. This escape fraction is dependent upon assumed particle size distributions.

- Smoke puff escape fraction determined by deposition. The mass fraction of particulate matter that remains in the dust plume at the point of exit from the pit as determined by the Van der Hoven source depletion/deposition model (Van der Hoven, 1968). This escape fraction is dependent upon assumed particle size distributions.

- Fabrick escape fraction. The mass fraction of particulate that escapes the mine pit as determined by Fabrick's equation. This escape fraction is dependent upon an assumed particle size distribution, wind speed, and pit width.

- Winges escape fraction. The mass fraction of particulate that escapes the mine pit as determined by Winges' equation. This escape fraction is dependent upon an assumed particle size distribution, pit depth, and stability class.

Each of these calculated parameters is discussed in the following sections.

4.5.1 PIT GEOMETRY

In order to assign discrete values of pit depth, length, and width for use in subsequent computations, it was necessary to use an idealized geometry of each pit. Idealized pit dimensions are those identified in the final report of the data collection phase of the pit retention study (Hittman and Air Sciences, 1983), summarized in Table 4.1. Tests were conducted in two different pits, or trenches, of the Yampa Mine, so that two different geometries result.

TABLE 4.1
PIT GEOMETRY

MINE	LENGTH (m.)	WIDTH (m.)	DEPTH (m.)	ORIENTATION TO NORTH[a] (deg)
1. YAMPA 6/28-6/30	600	22	19.0	35
2. YAMPA 6/30-7/2	600	40	20.5	55
3. CABALLO	850	408	33.0	90
4. SPRING CREEK	1130	40	45.0	110
5. ROSEBUD	400	40	40.0	130

a. Angle measured between North and long axis of rectangular pit.

As seen from Table 4.1, each of the pits approximates a rectangle, with a length to width ratio ranging from 2 to 28.

4.5.2 EFFECTIVE PIT WIDTH

The effective pit width, that is, the path length from one side of the pit to the other (measured parallel to the wind direction), is a function of the actual pit width, pit length, and wind direction. If the wind direction is perpendicular to the long axis of the pit then the effective pit width is equal to the pit length. An approximation to the effective pit width, W_e is given by:

$$W_e = W/\sin(\text{theta}) \qquad \text{Equation 1.}$$

Subject to $W_e < L$

Where
W is actual pit width
L is actual pit length
theta is the angle between the out-of-pit wind direction and the long axis of the pit.

Equation 1 is an approximation that introduces a maximum error in W_e of about 10 percent within a wind direction band of $\pm$ 3 degrees at the Caballo Mine. At all other mines, and at all other wind directions, the error introduced by the approximation will be less than 6 percent.

4.5.3 WIND DIRECTION AND PIT ORIENTATION

To examine the influence that out-of-pit wind direction and pit orientation have on dependent variables, all wind direction/pit orientations were divided into "parallel" or "crosswind" categories. When the out-of-pit wind direction was equal to the long axis orientation of the pit $\pm$ 45 degrees, the wind orientation was deemed parallel; when the wind direction was perpendicular to the long axis of the pit, $\pm$ 45 degrees, the wind orientation was deemed crosswind.

4.5.4 SMOKE PUFF ESCAPE VELOCITY

For each smoke release episode, two different (but related) smoke puff exit times were determined from the VCR recordings and the field logs: the initial exit time and, where appropriate, the final exit time. Dividing the pit depths by each of these exit times yields a measure of maximum and minimum escape velocity for the smoke puff.

One correction was made to the computation of escape velocity to account for the initial plume rise from the smoke generator. The pit depths were decreased by three meters, in accordance with Air Sciences' observations (Hittman and Air Sciences, 1983):

> "...The (smoke) generators, which imparted an initial horizontal exit velocity of 3 meters per second to the smoke, were generally oriented with smoke exiting downwind. Although entrainment was rapid, under calm and stable atmospheric conditions the plume rose to about 3 meters above ground before stabilizing..."

The exit velocities computed from pit depth and exit time represent an average upward velocity of the air in which the smoke puff is dispersed. The smoke acts like a tracer to allow the observer to see the motion of a parcel of air in the mine pit. Because the settling velocity of oil smoke is very small (see below), the smoke probably works well as a tracer.

As discussed in section 4.2 of this report, smoke release episodes in which the smoke puff dispersed completely within the pit before exiting were assigned exit times equal to the time duration from puff release until the puff was no longer visible. This procedure yields artificially small exit times, and artificially large exit velocities, for episodes in which the smoke puff dispersed within the pit so completely that it was not visible.

4.5.5 SMOKE PUFF ESCAPE FRACTION DETERMINED BY SETTLING

The vertical velocities computed by dividing the depth of each pit by the elapsed time between smoke puff release and smoke puff exit represent an escape velocity for smoke particles. That is, the computed vertical velocity is characteristic of oil smoke particles, which are perhaps 0.03 to 1.0 microns in diameter, and have a maximum gravitational settling velocity of 0.01 centimeters per second (Lapple, 1961). Real particulate matter found in surface coal mine pits certainly has a mass mean diameter much larger than smoke particles, and has an appreciably larger settling velocity. The difference in the observed behavior of the smoke puffs and the hypothesized behavior of actual coal mine dust, then, could be attributed to the settling, or deposition, of the coal mine dust. Subtracting the downward settling velocity of coal mine dust from the upward escape velocity of the smoke puffs will yield a net vertical velocity that should better characterize real coal mine dust. Furthermore, if the net vertical velocity is upward then the dust particle will be expected to escape from the mine pit, and if the net vertical velocity is downward then the particle will be retained in the mine pit.

When this reasoning is applied to a distribution of particle sizes it provides a simple means of assessing an overall escape fraction for the particle size distribution in question. This is accomplished by dividing the particle size distribution into categories, and computing the settling velocity for each of the size categories. Next, each settling velocity is subtracted from the smoke puff exit velocity, and those particle size categories which exhibit a net upward velocity are assumed to have escaped from the pit. Summing the mass fractions of each size category that escapes from the pit yields an overall escape fraction.

Clearly this computation depends upon the initial particle size distribution that is assumed to characterize real coal mine dust. In this computation, and throughout the remainder of this investigation, two separate particle size distributions are adopted:

- UNIVERSAL SIZE DISTRIBUTION. The so-called "universal" particle size distribution is one that was chosen in a previous EPA study of western surface coal mines (PEDCO & TRC, 1982) to represent a composite, or average, western surface mine. The universal size distribution considers only particles equal to, or smaller than, 30 microns in aerodynamic diameter. The universal particle size distribution is shown in Table 4.2, with mass fraction expressed cumulatively. Table 4.2 shows both deposition and settling velocities, indicating that deposition velocity is greater than settling velocity for all particle sizes in the universal particle size distribution.

- EDS SIZE DISTRIBUTION. As part of a privately funded Emission Development Study (EDS) for surface coal mines in the Powder River Basin, particle size distribution was determined from optical microscopic examination of millipore filters (Shearer, et al, 1981). The EDS study considered all particles in the visible size spectrum, from about 2 microns physical diameter to greater than 130 microns. The EDS particle size distribution is shown in Table 4.3, with mass fraction expressed cumulatively.

For each of the particle size distributions, equivalent deposition and settling velocities were estimated. Deposition velocities associated with each size category were taken from curves presented by Hanna, et al, (1982), with assumed surface roughness length (z_o) of 1.0 centimeter, and particle density of 1.0 grams/cm^3. These values are approximate choices of roughness length and particle density that could be expected to occur at surface mines (see Hogstrom, 1978). Settling velocities were calculated from Stokes' equation, with appropriate corrections for particle density and shape factor (Hanna, et al, 1982). These deposition velocities and settling velocities are shown in Tables 4.2 and 4.3 for the universal and EDS particle size distributions. In each case it is assumed that the larger of the two velocities, deposition velocity or gravitational settling velocity, is the dominant removal mechanism for any given particle size category. For every

TABLE 4.2
UNIVERSAL PARTICLE SIZE DISTRIBUTION -- CUMULATIVE

DIAMETER[a] microns	MEAN RADIUS cm.	CUMULATIVE[b] MASS FRACTION	STOKES SETTLING[c] VEL, cm/sec.	DEPOSITION[d] VEL, cm/sec.	LARGER OF SETTLING AND DEPOSITION, cm/sec.
2.5	1.25×10^{-4}	.021	0.0186	0.23	0.23
5.0	2.5×10^{-4}	.094	0.0744	0.70	0.70
10.0	5.0×10^{-4}	.270	0.2975	1.30	1.30
15.0	7.5×10^{-4}	.418	0.6694	2.00	2.00
20.0	1.0×10^{-3}	.533	1.9000	2.30	2.30
30.0	1.5×10^{-3}	1.000	2.6776	3.30	3.30

(a) Aerodynamic Diam (density = 1.0 g/cc)
(b) From PEDCO and TRC, 1982, p.16
(c) From Stokes Law, Hanna et al, 1982, p.67
(d) From Hanna et al, 1982, Fig. 10.4, p.70; z_o= 1 cm, density = 1.0 g/cc

TABLE 4.3
EDS PARTICLE SIZE DISTRIBUTION -- CUMULATIVE

DIAMETER(a) microns	MEAN RADIUS, cm.	CUMULATIVE (b) MASS FRACTION	STOKES SETTLING(c)(e) VELOCITY cm/sec.	DEPOSITION(d) VELOCITY cm/sec.	LARGER OF SETTLING AND DEP, cm/sec.
10	5.0×10^{-4}	.017	0.3504	1.40	1.4000
20	1.0×10^{-3}	.060	1.4017	2.50	2.5000
30	1.5×10^{-3}	.134	3.1537	4.00	4.0000
40	2.0×10^{-3}	.218	5.6066	5.00	5.6066
50	2.5×10^{-3}	.326	8.7602		8.7602
60	3.0×10^{-3}	.420	12.6147		12.6147
70	3.5×10^{-3}	.524	17.1700		17.1700
80	4.0×10^{-3}	.623	22.4261		22.4261
90	4.5×10^{-3}	.710	28.3830		28.3830
100	5.0×10^{-3}	.804	35.0408		35.0408
110	5.5×10^{-3}	.896	42.3994		42.3994
120	6.0×10^{-3}	.968	50.4587		50.4587
130	6.5×10^{-3}	.999	59.2129		59.2129

(a) Physical Diameter density = 1.0 g/cc
(b) From Shearer, et al, 1981, p.83
(c) From Stoke's Law, Hanna, et al, 1982, p.67, density = 1.51 g/sec
(d) From Table 10.4, Hanna, et al, p.70, z_0= 1cm
(e) Corrected α=1.28, p.68 of Hanna, et al, 1982

particle size category in the 0-30 micron universal distribution, the deposition velocity exceeds the settling velocity (see Table 4.2), whereas in the EDS distribution, which includes a much larger range of particle sizes, gravitational settling is the dominant means of particle removal for particles larger than about 40 microns physical diameter. This conclusion is consistent with experimental data which suggest that for particles smaller than 40 microns in size, deposition dominates, whereas for particles larger than 40 microns, gravitational settling dominates (Hanna, et al, 1982).

Both Tables 4.2 and 4.3 express removal velocity (either deposition or settling) and cumulative mass fraction as a function of particle size, so it is a simple matter to plot mass fraction versus removal velocity. Figure 4.3 (applicable to the universal distribution), and Figure 4.4 (applicable to the EDS distribution) show the graphs of particle mass fraction and removal velocity. In Figure 4.3 curves of mass fraction versus removal velocity are shown for both particle settling and particle deposition merely to illustrate that deposition velocities exceed settling velocities for all particle sizes in the universal particle size distribution. Each of these graphs, Figures 4.3 and 4.4, indicates what fraction of the total mass of particles exhibit removal velocities smaller than specified values. For example, Figure 4.3 shows that, for the universal particle size distribution, 86 percent of the total mass of particles have a removal velocity less than 3.0 cm/sec. If the escape velocity at a mine pit were exactly 3.0 cm/sec, then Figure 4.3 suggests that 86 percent of the total mass of the universal particle size distribution would escape. Figure 4.4 shows that, for the EDS particle size distribution, 13 percent of the total mass fraction of particles have a removal velocity less than 3.0 cm/sec. If the escape velocity at a mine pit were exactly 3.0 cm/sec, then Figure 4.4 suggests that 13 percent of the total mass of the EDS particle size distribution would escape. Figures 4.3 and 4.4 can be used to infer escape fractions in the following manner:

FIGURE 4.3
REMOVAL VELOCITY VERSUS MASS FRACTION
UNIVERSAL DISTRIBUTION

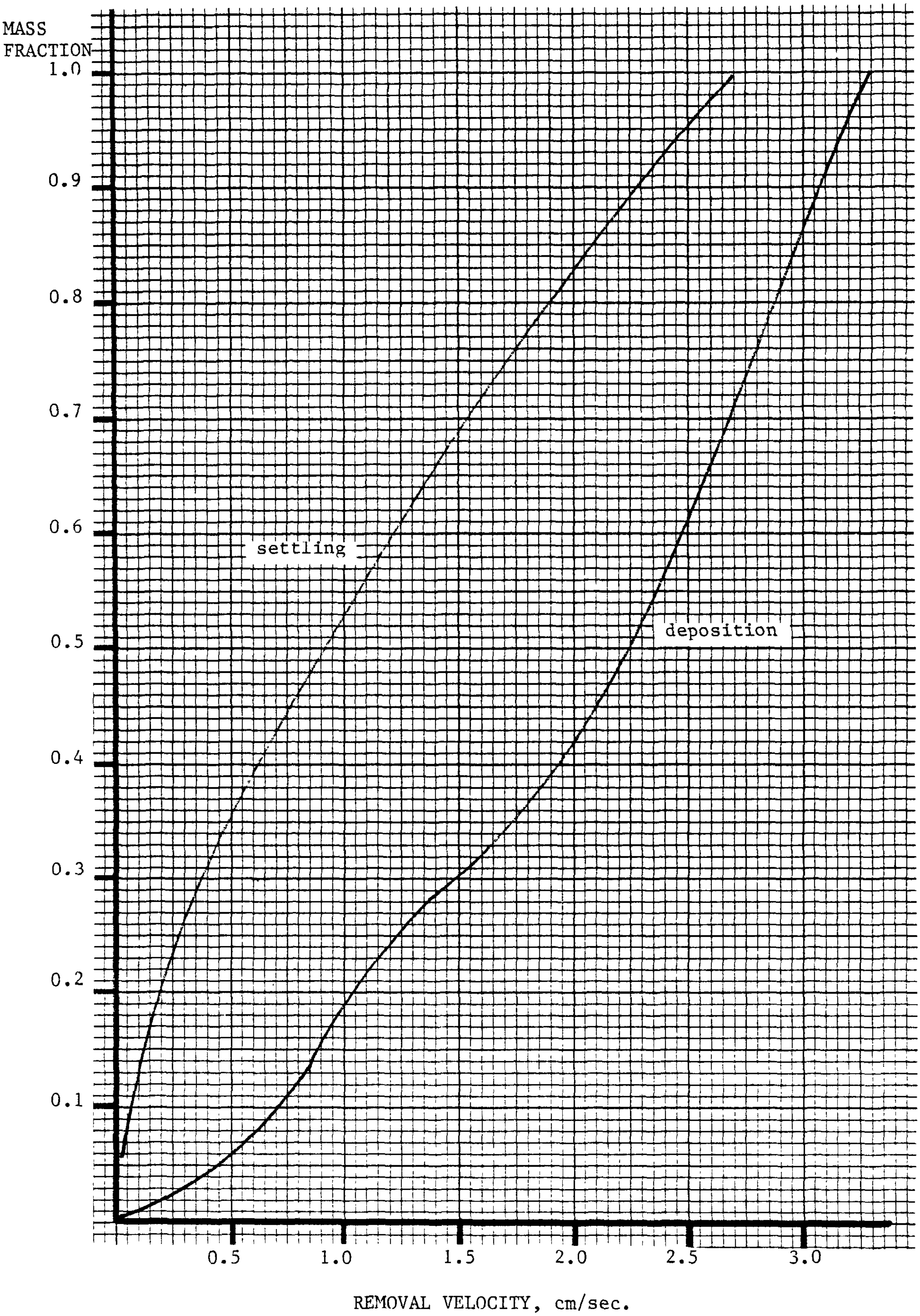
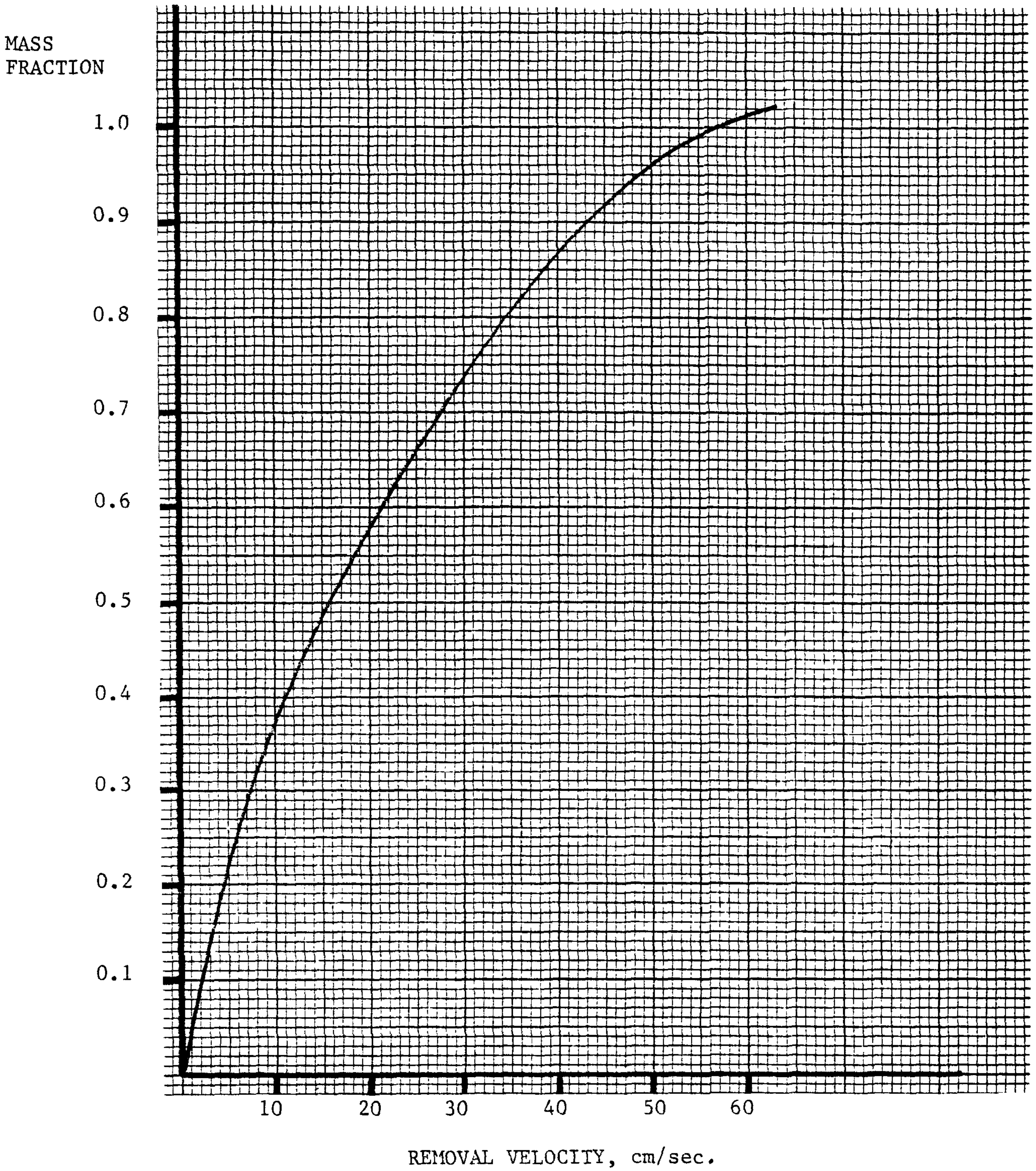


FIGURE 4.4
REMOVAL VELOCITY VERSUS MASS FRACTION
EDS PARTICLE DISTRIBUTION



1. Choose a particle size distribution, either universal (0-30 microns) or EDS (0-130 microns), of interest.

2. Calculate escape velocity for a given smoke puff episode by dividing pit depth by smoke puff exit time, as discussed in section 4.5.4.

3. Enter Figure 4.3 for universal distribution, or Figure 4.4 for EDS distribution, with escape velocity along the horizontal axis. Find mass fraction along the vertical axis of the Figures. The mass fraction is the amount of particulate that escapes.

In practice it would have been too time consuming to enter the graphs in Figures 4.3 and 4.4 manually for each of the roughly 800 smoke release episodes. To expedite the computation of escape fraction, the curves in the Figures were approximated with analytical expressions (curve fits), and computer programmed to calculate two escape fractions -- one corresponding to the universal size distribution and the other corresponding to the EDS distribution -- for each of the 800 smoke release episodes. The escape fractions were stored on magnetic tape for subsequent analysis. The results of this analysis are discussed in Section 5 of this report.

It is important to understand that the computation of escape fraction in the manner described in this subsection is an oversimplification of the actual pit retention phenomenon. The computation of escape fraction outlined in this subsection balances upward escape velocity, determined from the smoke puff behavior, against downward deposition and settling velocities, without regard to the exact details of smoke plume trajectory or plume-ground interaction. It is reasonable to expect that this simplification may tend to overestimate the true escape fraction, because the actual deposition process is strongly dependent upon the plume-terrain interaction when the plume is very close to the pit floor and the pit walls. It may be that some of the particulate matter released in the pit of a surface mine is removed by deposition at the pit floor even when the net escape velocity (the upward exit velocity minus the downward deposition or settling velocity) is directed upwards. The magnitude of the overestimation of the escape fraction will be greatest for small particles whose deposition velocities are consistently lower than the upward exit velocity. Furthermore, as has been explained in section 4.5.4, there is a bias in the computation of escape velocity for some of the smoke release episodes which yields artificially large exit velocities, and correspondingly large escape fractions.

Because of the uncertainty and known biases in this method of inferring escape fraction from the field data, a second, independent means of estimating escape fraction was adopted. This second means of computing escape fraction is discussed in the next subsection.

4.5.6 SMOKE PUFF ESCAPE FRACTION DETERMINED BY DEPOSITION

The previously discussed method of inferring escape fraction balances upward escape velocity against downward particle removal velocity, and in so doing ignores the plume-terrain interaction which influences particle deposition. A simple model that accounts for both settling and deposition is the so-called source depletion model (Van der Hoven, 1968), which is given by

$$Q_x/Q_o = \left[\exp \int_o^x \frac{dx}{\sigma_z \exp\,(h^2/2\sigma_z^2)} \right]^{-(2/\pi)^{1/2}(V_d/u)} \qquad \text{Equation 2}$$

where

- Q_x/Q_o is the ratio of apparent emission rate at distance x, divided by true emission rate at the source.
- σ_z is the standard deviation of vertical concentration, m.
- h is the separation distance between the dust plume and the ground, m.
- V_d is the larger of deposition or settling velocity, m/s.
- u is wind speed, m/s

The value of Q_x/Q_o is, of course, equal to escape fraction.

A simple FORTRAN computer program was written to solve Equation 2 by stepwise numerical integration for both the universal and the FDS distributions. The forward step size used in the integration was set to five meters, and the plume-terrain separation distance, h, was arbitrarily set to one meter to simulate ground level sources within the mine pit. Values of wind speed, effective pit width, and stability class determined from the field data were substituted into equation 2. The wind speed for each episode was set equal to the horizontal wind speed measured inside the pit, and the values of sigma-z were computed using the Martin (1976) curve fits to the familiar Turner dispersion coefficients (Turner, 1970). The limit of integration, x, was set equal to the effective pit width defined by the in-pit wind direction.

Equation 2 was solved for each particle size category (weighted by mass fraction) for the universal and the EDS particle size distributions. This computation was repeated for each of the roughly 800 smoke release episodes, and the resulting escape fractions were stored on magnetic tape for subsequent analysis. The results of this analysis are discussed in Section 5 of this report.

There are several potential sources of error inherent in the use of Equation 2 to infer escape fractions. The most important of these is the specification of deposition velocity, which can vary by an order of magnitude for small particles depending upon ground cover, roughness height, and other parameters (Hanna, et al, 1982). Additionally, the source depletion model imposes a Gaussian distribution in the vertical, and assumes that the particulate concentration is depleted uniformly throughout the entire vertical extent of the plume. The effect that these assumptions have on predicted surface mine pit escape fractions is not known.

4.5.7 FABRICK ESCAPE FRACTION

Fabrick (1982) derived a mine pit escape fraction equation that depends upon the width of the pit, the wind speed at the top of the pit, and a particle size distribution:

$$\epsilon = 1 - V_d \left[C/u \left(\frac{1}{2} + \ln \frac{w}{4} \right) \right] \qquad \text{Equation 3}$$

where ϵ is escape fraction

u is wind speed, m/s

w is pit width, m

V_d is the larger of deposition or settling velocity, m/s

C is an empirical dimensionless constant with a value of 7.

The Fabrick escape fraction was evaluated for both the universal and the EDS particle size distributions for each of about 800 individual smoke release episodes by substituting into Equation 3 values of effective pit width and out-of-pit wind speed from the field data, and the larger of deposition and settling velocity. The particle size distributions were subdivided into discrete size categories so that individual escape fractions could be computed for each size catogory. Multiplying these individual escape fractions by the mass fraction for each size category, and then summing the product over the entire particle size distribution, yielded escape fractions for each particle size distribution. These computations were performed in a subroutine of the data reduction computer program. The universal and the EDS particle size distributions are shown in Tables 4.5 and 4.6. Note that the distributions appearing in Tables 4.2 and 4.3 are identical to the distributions shown in Tables 4.5 and 4.6, although the former distributions (Tables 4.2 and 4.3) are expressed cumulatively with particle size, whereas the latter distributions (Tables 4.5 and 4.6) are expressed by particle size category.

4.5.8 WINGES ESCAPE FRACTION

Winges (1981) developed an equation to calculate the particulate escape fraction from surface mine pits. The escape fraction is given by:

$$\epsilon = \frac{1}{1 + \left(\frac{V_d}{K_z}\right) H} \qquad \text{Equation 4}$$

where ϵ is the escape fraction

V_d is the larger of deposition or settling velocity, m/s

K_z is vertical diffusivity, m^2/sec

H is pit depth, m.

TABLE 4.5
UNIVERSAL PARTICLE SIZE DISTRIBUTION -- CATEGORIZED

DIAMETER (a) RANGE (microns)	MASS (a) FRACTION	MID-POINT DIAMETER (microns)	DEPOSITION (b) VELOCITY (cm/sec.)
0-2.5	0.021	1.25	0.070
2.5-5.0	0.073	3.75	0.600
5.0-10.0	0.176	7.50	1.100
10.0-15.0	0.148	12.50	1.400
15.0-20.0	0.115	17.50	2.000
20.0-30.0	0.467	25.00	2.700

a. PEDCo & TRC, 1982, p.16
b. Hanna, et al, 1982, Fig. 10.4, p.70 @ z_o = 1 cm., density = 1.0 g/cc

The Winges equation was also evaluated for both the universal and the EDS particle size distributions for each individual smoke release episode. Values of stability class and pit depth were determined from the field data. Values of vertical diffusivity corresponding to stability class were those presented by Draxler (1977), shown in Table 4.7.

TABLE 4.7
VERTICAL DIFFUSIVITY, m^2/sec

P-G STABILITY	A	B	C	D	E	F
K_z	50	30	15	7	3	1

TABLE 4.6
EDS PARTICLE SIZE DISTRIBUTION -- CATEGORIZED

DIAMETER[a] RANGE (microns)	MASS[b] FRACTION	MID-POINT DIAM (microns)	MID-POINT RADIUS (cm)	SETTLING[c](e) VELOCITY (cm/s)	DEPOSITION[d] VELOCITY (cm/s)	MAX. OF SETTLING AND DEPOSITION (cm/sec)
0-10	0.017	5	2.5×10^{-4}	0.087	0.650	0.650
10-20	0.043	15	7.5×10^{-4}	0.789	2.000	2.000
20-30	0.074	25	1.25×10^{-3}	2.190	2.500	2.500
30-40	0.084	35	1.75×10^{-3}	4.292	4.000	4.292
40-50	0.108	45	2.25×10^{-3}	7.096	6.500	7.096
50-60	0.094	55	2.75×10^{-3}	10.600		10.600
60-70	0.104	65	3.75×10^{-3}	14.804		14.804
70-80	0.099	75	3.75×10^{-3}	19.711		19.711
80-90	0.087	85	4.25×10^{-3}	25.317		25.317
90-100	0.094	95	4.75×10^{-3}	31.624		31.624
100-110	0.092	105	5.25×10^{-3}	38.633		38.633
110-120	0.072	115	5.75×10^{-3}	46.341		46.341
120-130	0.030	125	6.25×10^{-3}	54.751		54.751

(a) Physical diam , density = 1.51
(b) From Shearer, et al, 1981, p.83
(c) From Stokes' law, Hanna et al, 1982, p.67, density = 1.51
(d) From Table 10.4, Hanna et al, p.70, z_o = 1 cm
(e) Corrected for α = 1.28, p.68 of Hanna, et al, 1982

5.0 DATA ANALYSIS

The substantial data base collected both during the original smoke release experiments and from analysis of the video tape recordings of those experiments provided the basis for the statistical comparisons described in this section. The data consist of meteorological data, collected both in and out of the four mine pits, escape times of the smoke puffs within each of the pits, and discrete categories which describe the movements, or flow patterns, of the puffs within those pits.

Several different types of comparisons are provided from analysis of these data. Out-of-pit meteorological data were correlated with the meteorological measurements performed at the same time within the mine pits. In addition, the out-of-pit meteorological data were compared to the flow pattern categories, to determine the relationships between the observed puff movements and conditions occurring outside of the pit. The escape velocities of the smoke puffs described in Section 4.5.4 were then correlated with the meteorological measurements to determine if a predictive method could be developed. Finally, escape fractions were computed and compared to escape fractions predicted by existing equations.

The statistical tests or methods used to facilitate the above-described comparisons varied depending on the type of data being used. Single variable, linear regression analysis and direct comparisons of mean values were performed on the meteorological measurements from in and out of the mine pits to determine not only relationships between the two data sets, but also to ascertain if in-pit conditions could be predicted from knowledge of out-of-pit conditions. Comparisons of flow patterns to meteorological measurements were facilitated through the use of frequency distributions, given the fact that these patterns are described by discrete, and arbitrarily defined, categories. Finally, the escape velocities developed from the smoke release observations were compared to meteorological measurements using both a comparison of mean values, and through multi-variate linear regression techniques. A predictive equation which relates the escape velocity to each observed meteorological parameter was developed and tested using these techniques.

The "Statistical Analysis System" (SAS) computer package was employed for all statistical comparisons described in this section. It provides means for not only analysis but for data programming, storage and retrieval, and file manipulation.

5.1 COMPARISON OF IN-PIT VERSUS OUT-OF-PIT METEOROLOGY

A comparison of mean values of meteorological parameters measured both in and out of the mine pits is presented in Table 5.1. The means were computed for all data combined, for each mine individually, for each stability class, and for each wind speed category.

Variations in wind direction between the inside and outside of the pit have been quantified by taking the difference between the two values (wind direction (in) - wind direction (out), not to exceed 180^{o}) for each smoke release experiment. From Table 5.1, in-pit wind directions varied from those measured out-of-pit by almost 60^{o} for all data combined. Measurements performed at the Rosebud Mine varied the most -- about 87^{o}, while those from Carter's Caballo Mine varied the least -- 36^{o}. Trends in wind direction differences between the inside and outside of the mine pits are not discernible when compared by Pasquill-Gifford stability categories. However, when viewed by wind speed categories, a very marked pattern emerges. Consistently greater differences between in-pit wind directions and out-of-pit wind directions occurred during light wind speeds. In fact, such variations are two to almost four times greater during the lightest wind speeds (less than 4 mph) than during the high speed categories (greater than 12 mph). This result is not unexpected as wind directions are typically more variable during light winds versus high winds, so comparisons of measured directions from two different locations, even in close proximity, are usually not favorable. However, these results do indicate that wind directions within a mine pit probably cannot be well represented by measurements performed outside of the pit. This finding will be explored further later in this section.

TABLE 5.1
COMPARISON OF MEAN VALUES
IN-PIT VERSUS OUT-OF-PIT METEOROLOGY

							DATA BASE									
		MINE ID[a]					P-G STABILITY[b]					NCDC WIND SPEED CATEGORY[c]				
PARAMETER	ALL	1	2	3	4	5	1	2	3	4	6	1	2	3	4	5
Difference in Wind Direction (degrees)	58	62	64	36	55	87	51	67	49	55	71	78	60	50	40	19
Windspeed-In (mph)	6.0	5.3	8.3	6.4	4.5	6.8	4.2	4.9	7.0	8.0	2.6	2.9	5.0	7.0	9.9	12.8
Windspeed-Out (mph)	7.8	5.5	10.5	9.6	6.0	8.5	3.5	5.0	9.9	12.6	4.0	2.9	5.7	9.5	15.2	19.8

[a]MINE ID

1. YAMPA
2. YAMPA
3. CABALLO
4. SPRING CREEK
5. ROSEBUD

[c]NATIONAL CLIMATIC DATA CENTER (NCDC) WIND SPEED CATEGORIES

1. 0-4.03 MPH
2. 4.04-7.49 MPH
3. 7.50-12.09 MPH
4. 12.10-18.99 MPH
5. 19.00-24.18 MPH
6. 24.19 MPH (no occurrences)

[b] Throughout Section 5 the following convention is used to identify P-G stability classes: 1=A, 2=B, 3=C, etc. Means were not computed for P-G Category 5 since only 8 such occurrences were observed in the entire data base.

Average wind speeds occurring inside and outside the mine pits are also listed in Table 5.1. Averages were computed for all data combined, as well as for each mine, stability class, and wind speed category. Since the categorization of wind speeds was accomplished using out-of-pit wind speeds, the mean out-of-pit values listed by category represent essentially the midpoints of those categories. However, comparing these means to those occurring within the pit is nevertheless instructive.

From Table 5.1, it is evident that in-pit wind speeds are consistently less than those occurring out-of-pit at the same times. This is true regardless of which mine is analyzed, and is essentially true for all stability categories as well. The one exception to this observation is during the most unstable -- Class A -- conditions, where only 15 observations were available for analysis. The largest differences between wind speeds measured in and out of the mine pits occurred under the highest wind speed categories.

Measurements of sigma-theta atmospheric stability both in and out of the mine pits were performed during the original smoke release experiments. Comparisons of such measurements would be useful, however, examination of the data revealed that the vast majority of the stabilities were class "D", both in and out of the pit. The Pasquill-Gifford stability distribution indicates that only 10 percent of the episode hours were class "D", which is a much more reasonable distribution for summer daylight hours. Given the low confidence in the accuracy and representativeness of the sigma-theta measurements, comparisons of in-pit versus out-of- pit stability categories thus determined are not provided.

Linear regression analysis was employed to determine if in-pit meteorological conditions could be accurately predicted from observations performed outside the pit. Regression analysis essentially determines the "best fit" of a linear expression of the form:

$$y = b_o + b_1 X$$

where y is the dependent variable (or in-pit measurement), X is the independent variable (or out-of-pit measurement), b_o is the y-intercept of the "best-fit" line determined using the least-squares method, and b_1 is slope of the best fit line.

A correlation or relationship between the dependent (y) and independent (X) variables is indicated if the slope of the "best-fit" line is not equal to infinity or zero. A measure of the "goodness-of-fit" of the linear expression, or model, to the observed data is described by the variation of the actual measurements from the "modeled" values. This variation is usually expressed in terms of the r^2 parameter -- a dimensionless number which ranges in value between 0 and 1. The larger the value of r^2, the better the model's fit.

Linear regression analysis was applied to determine whether or not the wind direction within a mine pit could be determined from a knowledge of the wind direction outside of the pit. Because of the discontinuity represented by north winds (0^o versus 360^o), out-of-pit wind directions (WD) were expressed in terms of the long axis of the pit by defining a variable called "TACK" constrained to values between 0 and 90 degrees:

- $0 < WD < 90$; TACK = WD
- $90 < WD < 180$; TACK = 180-WD
- $180 < WD < 270$; TACK = WD-180
- $270 < WD < 360$; TACK = 360-WD

The variable TACK then represents the relation of the wind direction to the long axis of the pit. A value of TACK equal to 0 represents a wind parallel to the long axis of the wind, while a value of 90^o represents a wind perpendicular to the pit's long axis, or a crosswind. To avoid the northwind discontinuity in the in-pit wind directions, the variable TACK was correlated with the difference (ΔWD) between the in-pit wind direction and the out-of-pit wind direction as used previously in Table 5.1. The results of the regression analysis:

$$y = b_o + b_1 X$$

where $y = \Delta WD$

and $X = TACK$

are shown in Table 5.2 The model was evaluated for all data combined, for each mine individually, and for each stability class. The Student's - T test was applied to evaluate whether the slope, b_1, of the best-fit line is different from zero (ie., whether y is a function of X). The parameter listed as PR T in Table 5.2 evaluates whether or not the computed slope, b_1, is statistically different from zero; values of PR T that approach zero indicate good correlation between y and X, whereas values that approach unity represent poor correlation.

TABLE 5.2
RESULTS OF REGRESSION ANALYSIS FOR WIND DIRECTION

MODEL PARAMETER	DATA BASE										
		MINE					P-G STABILITY				
	ALL	1	2	3	4	5	1	2	3	4	6
b_o	62.3	46.6	14.2	68.3	106.7	44.7	36.5	69.1	57.5	27.7	108.9
b_1	0.1	0.4	1.3	-0.5	-0.9	0.9	0.5	-0.1	-0.2	0.5	-0.7
PR T	.2248	.0091	.0001	.0017	.0001	.0001	.1340	.7055	.1193	.0081	.0528
r^2	.002	.063	.441	.050	.216	.284	.164	.001	.007	.091	.063

The results in Table 5.2 indicate that the out-of-pit crosswind angle, TACK, is a poor predictor of WD, the difference between in- and out-of-pit wind directions. In other words, the out-of-pit wind direction is a poor predictor of the in-pit wind direction. For all data combined, the slope of the regression line can be considered different from zero only at a confidence level of about 78% (from PR T, 1.0 - .2248 = .7752). Hence variations in out-of-pit wind directions characterize less than 1% of the variation of observed in-pit variations (from r^2, .002 x 100 = 0.2%). The regression model is improved somewhat when the data are separated for each mine, but even at Mine 2 (Yampa, location 2), only 44% of the variability of in-pit wind directions can be explained. Stratification of the data by stability class does not improve the fit of the model either. From this analysis, it can be concluded that in-pit wind directions can not be adequately predicted from knowledge of out-of-pit wind directions.

A single variable linear regression analysis was performed to determine if in-pit wind speeds are related to wind speeds measured out-of-pit. For this test, the out-of-pit speed was used as the independent variable -- X, while the in-pit wind speed was used as the dependent variable -- y. The results of this investigation appear in Table 5.3.

TABLE 5.3
RESULTS OF REGRESSION ANALYSIS FOR WIND SPEED

MODEL PARAMETER	DATA BASE										
		MINE					P-G STABILITY				
	ALL	1	2	3	4	5	1	2	3	4	6
b_o	1.5	2.0	3.6	-0.1	2.2	-0.5	0.9	1.1	1.2	-0.4	1.1
b_1	0.6	0.6	0.4	0.7	0.4	0.9	1.0	0.8	0.6	0.7	0.4
PR>T	.0001	.0001	.0001	.0001	.0001	.0001	.0008	.0001	.0001	.0001	.0003
r^2	.61	.55	.58	.73	.34	.75	.60	.56	.53	.63	.19

The results listed in Table 5.3 indicate that the out-of-pit wind speed is a reasonably good predictor of the in-pit wind speed. For all data combined, the small value of PR>T indicates that the dependent variable is strongly correlated with the independent variable. Further, the r^2 value of 0.61 indicates that 61% of the variation of the in-pit wind speed is explained by the regression model. Stratification of the data by mine, and by stability class yielded essentially similar results. An interesting exception occurs when the wind speeds are analyzed during stable atmospheres (P-G class 6). For these conditions, even though a strong correlation is indicated by the Student's T test, only 19% of the variation of the in-pit wind speed can be explained by the model. It is not clear why the model's performance is reduced during these conditions, but it is proposed that conditions within the mine pit are sometimes decoupled from the atmosphere above during stable conditions.

5.2 COMPARISON OF OBSERVED FLOW PATTERNS AND METEOROLOGICAL CONDITIONS

The videotape recordings of the actual smoke release experiments were reviewed to determine not only the smoke puff escape time from which escape velocities were computed, but also to determine the characteristic patterns of the puff's transport and dispersion within the mine pits. The categorization of the observed flow patterns was accomplished through the use of the coding forms described in Section 4.0 of this report.

The discrete categories obtained from analysis of the data contained on the coding forms are as follows:

TABLE 5.4
CATEGORIZATION SCHEME USED TO DESCRIBE PUFF BEHAVIOR

PUFF REMAINS IN PIT	PUFF EXITS PIT	DON'T KNOW
100-recirculation evident	10-puff thermally up sidewall	1-invalid sample
200-puff disperses in pit	20-puff mechanically driven up sidewall	2-videotape ended prematurely
	30-puff exits at center of pit	3-puff too diffuse

Definitions for each of the above categories were provided in Section 4.0. It should be noted however that two of the categories do not appear in the analysis. Samples considered by the observer to be invalid (Category 1), 43 out of the original 811 puff releases, were extracted from the data base before analysis. Also, puffs considered to have escaped the pit by thermal processes (Category 10) were combined with those driven mechanically up the side wall (Category 20) as the two categories were virtually indistinguishable. Undoubtedly both processes must occur within mine pits, however, it was found to be impossible to distinguish between them from the available visual record.

Data which are comprised of discrete, arbitrarily defined categories, such as the flow patterns described above, do not lend themselves to the types of statistical analysis used for other parameters. It is meaningless to compute an "average" flow pattern, just as it is impossible to state that a flow pattern is proportional to (or correlated with) another parameter. However, it is instructive to identify the categories which occur most frequently, and to examine the frequency of occurrence as a function of meteorological conditions. For this reason, the comparison of observed flow patterns to measured meteorological conditions is comprised of comparisons of the frequency of occurrence of specified flow patterns for given meteorological parameters. These frequencies, expressed as percentage of all occurrences of a given meteorological condition, are listed in Tables 5.5a through 5.5c, along with total count of occurrences. Every vertical column of frequencies in Table 5.5 sums to 100 percent, so that each individual entry in the Table represents the frequency of occurrence of a specified flow category observed during a specified meteorological condition. For example, of all the smoke release episodes during which the P-G stability class category was 1 (left most vertical column of values under heading P-G STABILITY 1), 27 percent of the episodes exhibited puff dispersion while the puff remained in the pit. Similarly, of all the smoke release episodes during which the out-of-pit wind direction was cross-wind to the long axis of the pit (right most vertical column of Table 5.5c), 5 percent of the episodes exhibited puff recirculation.

From Table 5.5, the observed flow patterns appear to relate better to atmospheric stability categories than to either the wind speed categories, or to wind directions. For example, during the most unstable conditions -- P-G Class 1 -- 53% of the smoke puffs were observed to exit the mine pit, while only 27% remained in the pit. In contrast, during stable conditions -- P-G Class 6 -- only 16% of the observed puffs exited the pit while 58% remained in the pit. However, the distribution of flow patterns remains reasonably constant for different wind speeds, and for different wind directions, at least in terms of the primary categories (ie., "plume remains in pit" versus "plume exits pit").

Other observations are possible from examination of the sub-categories of flow patterns. Recirculation of smoke puffs were observed more frequently during neutral atmospheres (P-G Class 4), and during the highest wind speeds (wind speed Category 5) than during other stability and wind speed categories. Evidently the recirculation patterns observed in the mine pits were most frequently associated with aerodynamic wake effects (ie., smoke puffs trapped within an aerodynamic cavity formed alongside the upwind sidewall). Another anticipated recirculation pattern, cellular circulation structures caused during light winds by differential surface heating or cooling, were also observed but much less frequently.

TABLE 5.5a
PERCENT FREQUENCY OF OCCURRENCE AND TOTAL NUMBER OF OCCURRENCES (in parentheses) OF OBSERVED FLOW PATTERNS FOR GIVEN METEOROLOGICAL CONDITIONS

FLOW CATEGORY	P-G STABILITY 1	2	3	4	6
PUFF REMAINS IN PIT					
100-RECIRCULATION	0 (0)	5 (13)	2 (8)	11 (8)	4 (2)
200-DISPERSED	27 (4)	25 (65)	32 (109)	33 (25)	54 (35)
CAT. TOTAL	27 (4)	30 (78)	34 (117)	44 (33)	58 (37)
PUFF EXITS PIT					
20-EXITS SIDE WALL	20 (3)	22 (57)	23 (79)	18 (14)	12 (8)
30-EXITS CENTER	33 (5)	11 (29)	2 (8)	0 (0)	4 (2)
CAT. TOTAL	53 (8)	33 (86)	25 (87)	18 (14)	16 (10)
DON'T KNOW					
2-TAPE ENDED	0 (0)	3 (7)	3 (11)	0 (0)	0 (0)
3-TOO DIFFUSE	20 (3)	35 (92)	37 (127)	38 (29)	26 (17)
CAT. TOTAL	20 (3)	38 (99)	40 (138)	38 (29)	26 (17)
Column total	100 (15)	100 (263)	100 (342)	100 (76)	100 (64)

(760 Valid P-G Stability Class Observations)

TABLE 5.5b
PERCENT FREQUENCY OF OCCURRENCE AND TOTAL NUMBER
OF OCCURRENCES (in parentheses) OF OBSERVED FLOW
PATTERNS FOR GIVEN METEOROLOGICAL CONDITIONS

FLOW CATEGORY	WIND SPEED CATEGORY 1	2	3	4	5
PUFF REMAINS IN PIT					
100-RECIRCULATION	2 (4)	5 (9)	2 (5)	9 (10)	7 (1)
200-DISPERSED	39 (76)	29 (54)	30 (77)	26 (30)	17 (1)
CAT. TOTAL	41 (80)	34 (63)	32 (82)	35 (40)	34 (2)
PUFF EXITS PIT					
20-EXITS SIDE WALL	18 (35)	23 (42)	23 (59)	22 (26)	33 (2)
30-EXITS CENTER	9 (18)	10 (19)	3 (8)	0 (0)	0 (0)
CAT. TOTAL	27 (53)	33 (61)	26 (67)	22 (26)	33 (2)
DON'T KNOW					
2-TAPE ENDED	4 (8)	3 (6)	1 (3)	3 (3)	0 (0)
3-TOO DIFFUSE	28 (55)	32 (59)	42 (109)	41 (47)	33 (2)
CAT. TOTAL	32 (63)	35 (65)	43 (112)	44 (50)	33 (2)
Column total	100 (196)	100 (189)	100 (261)	100 (116)	100 (6)

(768 Valid Wind Speed Observations)

TABLE 5.5c
PERCENT FREQUENCY OF OCCURRENCE AND TOTAL NUMBER OF OCCURRENCES (in parentheses) OF OBSERVED FLOW PATTERNS FOR GIVEN METEOROLOGICAL CONDITIONS

FLOW CATEGORY	OUT OF PIT WIND DIRECTION PARALLEL	CROSS-WIND
PUFF REMAINS IN PIT		
100-RECIRCULATION	3 (8)	5 (24)
200-DISPERSED	32 (90)	30 (146)
CAT. TOTAL	35 (98)	35 (170)
PUFF EXITS PIT		
20-EXITS SIDE WALL	22 (62)	21 (102)
30-EXITS CENTER	9 (25)	3 (15)
CAT. TOTAL	31 (87)	24 (117)
DON'T KNOW		
2-TAPE ENDED	2 (6)	3 (15)
3-TOO DIFFUSE	32 (90)	38 (185)
CAT. TOTAL	34 (96)	41 (200)
Column total	100 (281)	100 (487)

(768 Valid Wind Direction Observations)

To summarize the findings of this investigation of characteristic flow patterns it was determined that:

- smoke puffs remained in mine pits more often during stable atmospheres than during unstable atmospheres;
- smoke puffs remained in mine pits more often during light wind speeds than during high wind speeds;
- recirculating puffs are mostly associated with "downwash" cavities formed alongside the sidewalls during high winds;
- puff exits at the center of the pit (as opposed to exits along sidewalls) are most frequently associated with very unstable atmospheres and light wind speeds;
- circulation patterns exhibit a greater association with stability categories than with wind speed categories or with wind directions.

5.3 COMPARISON OF ESCAPE VELOCITY TO METEOROLOGICAL CONDITIONS

The videotape recordings of each smoke puff release were analyzed to determine the amount of time, termed retention time, required for the smoke puff to escape the pit. Given the depth of the pit and the retention time, the upward escape velocity was computed for each observation. This velocity was then compared to coincident meteorological conditions measured both in and out of the mine pit. The techniques used to make these comparisons are similar to those described previously in this section -- namely, comparison of mean values, and regression analysis.

Average escape velocities were computed for all data combined, as well as for each mine individually, each stability category, and each wind speed category. These results are presented in Table 5.6.

TABLE 5.6
AVERAGE ESCAPE VELOCITY AS A FUNCTION
OF METEOROLOGICAL PARAMETERS [(a)]

DATA BASE	ESCAPE VELOCITY	DATA BASE	ESCAPE VELOCITY	DATA BASE	ESCAPE VELOCITY
ALL	53.4	STAB= 1	39.6	WS. CAT.= 1	34.3
MINE= 1	40.3	STAB= 2	48.4	WS. CAT.= 2	47.2
MINE= 2	50.6	STAB= 3	61.5	WS. CAT.= 3	65.3
MINE= 3	59.5	STAB= 4	54.2	WS. CAT.= 4	67.5
MINE= 4	49.0	STAB= 6	30.6	WS. CAT.= 5	74.2
MINE= 5	65.9				

(a) velocity expressed in cm/sec.

From Table 5.6 it is seen that the computed escape velocity varies for each mine, stability category, and wind speed. The average escape velocity was found to be much higher for Mine 5 (Rosebud) and Mine 3 (Caballo) than for the other mines tested. From the configuration of the mines tested it is unclear why the escape velocity for Mine 5 (Rosebud) should be higher than for the other mines. The Rosebud mine pit is about as wide as it is deep, as are the Yampa (at Location 1), and the Spring Creek mines (see Table 4.4). If the mine configuration were the only factor affecting the escape velocity, then the values from these three mines should be roughly the same. Evidently the mine configuration is only one of the factors which determine the escape velocity.

The distributions of escape velocities as functions of stability class and wind speed are more in line with expected results. Average escape velocities were found to be highest during neutral and near neutral atmospheric stabilities (P-G Classes 3-4), and lowest under stable conditions. Consistent with these results, higher escape velocities occurred during high wind speeds, than during low wind speeds.

It is likely that the out-of-pit wind speeds are, in fact, the most significant factor in determining the escape velocity. The stability categories are themselves a function of wind speed. Both the most stable and the most unstable categories occur during light wind speeds, while near-neutral conditions are associated with high wind speeds. Since the escape velocities during the most unstable categories (P-G Class 1) are less than during neutral conditions, even though unstable atmospheres enhance vertical movements, it is likely that the magnitude of the wind speed is more important in determining the escape velocity than is the thermal stratification described by the stability category.

The importance of mine configuration and meteorological conditions in determining the escape velocity can be quantified more readily using regression analysis. It is apparent that this velocity is controlled by a variety of factors, so the most appropriate analysis tool for evaluating these effects simultaneously is linear, multi-variate regression analysis. This sophisticated statistical approach is available on the SAS computer package.

A linear model constructed using a multivariate regression approach takes the form:

$$y = b_o + b_1X_1 + b_2X_2 + b_3X_3 \ldots b_nX_n$$

where y is the dependent variable, b_o is the intercept of the best fit "line", and b_1 through b_n are regression parameters, equivalent to the slope of the line in single variable regressions, for independent variables X_1 through X_n. Interpretation of the results of multivariate regressions is similar to that described previously for single variable linear regressions. The regression parameters, b_1 through b_n, should be significantly different from zero, as indicated by the Student's-T test, for significant correlation, and the r^2 value, a measure the model's "fit", should approach unity for a good-performing regression model.

Two basic models were tested using multivariate regression techniques. The first was based on meteorological measurements performed outside of the mine pit, and the second was based on in-pit measurements. Table 5.7 describes the variables used in each of the models, while Table 5.8 lists the results of the regression analysis.

TABLE 5.7
PARAMETERS USED IN MULTIVARIATE REGRESSION ANALYSIS

	DEPENDENT	INDEPENDENT				
MODEL	Y	X_1	X_2	X_3	X_4	X_5
1	ESCAPE VELOCITY	WIND SPEED (out)	TEMPERATURE (out)	TACK	P-G STABILITY	WIDTH
2	ESCAPE VELOCITY	WIND SPEED (in)	TEMPERATURE (in)	TACK	P-G STABILITY	WIDTH

The reader is reminded that the variable TACK represents the angle of the wind direction with respect to the long axis of the mine pit. Angles approaching zero represent winds that are parallel to the long axis of the pit, while angles approaching 90° represent crosswinds perpendicular to the long axis.

TABLE 5.8
RESULTS OF MULTIVARIATE REGRESSION ANALYSIS

MODEL	NO. SAMPLES	b_o	b_1 PR>T	b_2 PR>T	b_3 PR>T	b_4 PR>T	b_5 PR>T	r^2
1	634	3.41	2.88 .0001	0.48 .0001	0.11 .0001	-3.49 .0001	-0.01 .0154	0.32
2	543	-6.27	3.94 .0001	0.47 .0001	0.10 .0002	-0.94 .0949	-0.01 .2040	0.32

The results indicate that neither of the models tested can adequately predict the escape velocities computed from the smoke release experiments. Regardless of whether in-pit or out-of-pit meteorological parameters are employed, only 32% of the variability of the escape velocity can be explained by the models. This is not to say that the independent parameters tested are not correlated with the escape velocity. In fact, significant correlations were found between the escape velocity and the measured wind speed, both in and out of pit, the temperature, both in and out of pit, the angle of the wind

TACK, and P-G stability category (a negative, but still significant correlation). The weakest correlation between the escape velocity and one of the independent variables was demonstrated for the mine width. When out-of-pit measurements are used, the width was found to be significantly, but negatively, correlated with the escape velocity at the 98% confidence level. However, when in-pit measurements are used, the confidence level for significance drops to 80%. Given the fact that all the independent variables tested demonstrate some degree of correlation with the escape velocity, and yet the model only accounts for 32% of the variation of the velocity, clearly some, as yet unaccounted for, factors or variables must influence the escape velocity.

In an effort to improve the performance of the model, several iterations of the multivariate regression techniques were performed. The above two models were modified, by eliminating the variable WIDTH from the analysis, without a meaningful improvement in the results. The same two models were also evaluated by restricting the data base to data from each mine, and each stability class, again without improvement. The results of each of these investigations is included as Volume 2 of this report.

In summary, the escape velocity has been found to be positively correlated with wind speed, temperature, and wind direction, and negatively correlated with stability category and the width of the pit. However, these parameters, when used in a linear regression model, do not provide very good predictions of the escape velocity. Only 32% of the variability of the escape velocity can be explained by these parameters. Certainly other processes must act, in conjunction with the variables tested here, to determine the escape velocity.

Perhaps it is not surprising that a regression model, relying on wind speed, wind direction, and stability class data collected at just two locations at a surface mine would have little success in predicting airflow parameters in the pit. Atmospheric modeling is one of the most challenging simulations performed today, and even very elaborate numerical models which use complete descriptions of the upwind flow field (velocity, temperature, diffusivity, vorticity), and exact representations of the terrain features, have difficulty predicting characteristics of flow fields.

5.4 COMPARISON OF ESCAPE FRACTION AND METEOROLOGY

Escape fractions were computed from four different methods in this study:

- SMOKE PUFF EXIT VELOCITY (SETTLING). Escape fractions were determined for each of the roughly 800 smoke release episodes by calculating the puff exit velocity for each episode, and then entering the curves shown in Figures 4.3 and 4.4 to find the escape fraction corresponding to the universal and the EDS particle size distributions, respectively. This effort, which was computerized, yielded roughly 1600 escape fractions (800 for the universal distribution and 800 for the EDS distribution). These escape fractions were written on magnetic tape for subsequent statistical analysis.

- SOURCE DEPLETION (DEPOSITION). Escape fractions were determined for each of the roughly 800 smoke release episodes by computing the escape fraction directly from the familiar source depletion equation. This effort, which was computerized, yielded roughly 1600 escape fractions (800 for the universal distribution and 800 for the EDS distribution). These escape fractions were written on magnetic tape for subsequent statistical analysis.

- FABRICK EQUATION. Values of wind speed, effective pit width, and deposition (or settling) velocity were entered into the Fabrick escape fraction equation (section 4.5.7) for each smoke release episode and for both the universal and the EDS size distributions. The individual values of escape fraction determined by the Fabrick equation were written on magnetic tape for subsequent statistical analysis.

- WINGES EQUATION. Values of pit depth, vertical diffusivity, and deposition or settling velocity were entered into the Winges equation (section 4.5.8) for each smoke release episode and for both the universal and the EDS size distributions. The individual values of escape fraction determined by the Winges equation were written on magnetic tape for subsequent statistical analysis.

The values of escape fraction inferred from the smoke puff exit velocity, inferred from the source depletion equation, calculated from the Fabrick equation, and calculated from the Winges equation, are shown in Table 5.9, grouped by stability class.

TABLE 5.9
ESCAPE FRACTION BY STABILITY CLASS

DISTRIBUTION	P-G STABILITY	EXIT VELOCITY (SETTLING)	SOURCE DEPLETION (DEPOSITION)	WINGES	FABRICK
UNIVERSAL	1	1.00	0.93	0.99	0.58
	2	1.00	0.88	0.98	0.72
	3	1.00	0.86	0.96	0.85
	4	1.00	0.81	0.92	0.88
	6	1.00	0.58	0.58	0.68
EDS	1	0.81	0.59	0.90	0.11
	2	0.85	0.46	0.84	0.17
	3	0.93	0.43	0.73	0.28
	4	0.90	0.36	0.59	0.32
	6	0.70	0.21	0.20	0.14

From Table 5.9, it is seen that escape fractions for the 0-30 micron particles that make up the universal particle size distribution are larger than those associated with the 0-130 micron EDS distribution. This is true for all four escape fraction computation methods, and reflects the fact that deposition velocity and settling velocity are parameters that appear in the computation of all four escape fractions. Intuitively it seems reasonable that a greater fraction of the large EDS distribution particles would be retained in the pit than would the smaller diameter universal distribution particles.

The escape fractions inferred from field data by both the exit velocity (settling) and the source depletion (deposition) methods clearly show that less particulate escapes from the pit during stable ("F" class) conditions than during other stability classes. This finding suggests that the very stable atmosphere suppresses vertical motion, causing more particulate to be retained in the pit. The Winges escape fractions agree well with the escape fraction inferred from the source depletion calculations, and are also much smaller during stable conditions than during unstable and neutral conditions, which reflects the presence of vertical diffusivity (K_z) in the Winges equation. The Fabrick escape fractions do not exhibit the characteristic decrease in magnitude with "F" stability. This is to be expected, since the Fabrick escape fraction equation is not a function of stability class or vertical diffusivity.

An evaluation of the variations in escape fraction with wind speed category, shown in Table 5.10, exhibits the same trend as the variation in escape velocity discussed earlier. The magnitudes of escape fraction increase with increasing wind speed, for all four escape fraction techniques. However,

TABLE 5.10
ESCAPE FRACTION BY WIND SPEED CLASS

DISTRIBUTION	WS CLASS	EXIT VELOCITY (SETTLING)	SOURCE DEPLETION (DEPOSITION)	WINGES	FABRICK
UNIVERSAL	1	1.00	0.78	0.90	0.60
	2	1.00	0.84	0.91	0.81
	3	1.00	0.86	0.95	0.87
	4	1.00	0.88	0.95	0.92
	5	1.00	0.88	0.96	0.93
EDS	1	0.75	0.35	0.70	0.10
	2	0.85	0.46	0.70	0.20
	3	0.96	0.43	0.73	0.28
	4	0.96	0.43	0.69	0.38
	5	0.99	0.43	0.76	0.43

escape fractions determined by the Fabrick equation exhibit slightly better agreement with escape fractions inferred by the settling and deposition models than do the escape fractions determined by Winges equation. The reason for this may be that the Winges equation does not include wind speed as an explicit parameter, as does the Fabrick equation. Inclusion of wind speed directly into the Winges equation may improve its ability to match the trends observed in the escape fractions inferred from the settling and deposition models.

The differences between escape fractions inferred by the exit velocity (settling) method and the source depletion (deposition) method raises an obvious question: "Which method is correct?" Unfortunately, no answer is possible because the field test was not designed to measure escape fraction directly, nor do the data lend themselves to straightforward computation of escape fraction. Both the exit velocity and the source depletion methods used to infer escape fractions incorporate numerous assumptions (see Sections 4.5.5 and 4.5.6 of this report), the validity of which cannot be checked with the available data. However, it should be remembered that there is some reason to suspect that the escape fractions inferred from the smoke puff exit velocity may be too large, especially for small diameter particles. The reasons for this are that the computation of exit velocity for some of the smoke puff episodes probably overestimates that velocity (see Sections 4.2 and 4.5.4), and that the exit velocity method does not take into account the plume-terrain interaction that governs particle deposition (see Section 4.5.5).

The grouping of escape fractions by mine is not very instructive. There is no apparent trend or pattern discernible for any of the escape fractions.

6.0 SUMMARY OF FINDINGS

Data from over 800 smoke release experiments were analysed to describe the removal mechanisms and dispersion affecting particulate emissions occurring within surface mine pits. An escape velocity, essentially the net upward velocity within each pit, was computed from the observed retention time of the tracers and the depth of each pit. This upward velocity, when compared to the downward settling and deposition velocity for different size particles, was the basis for the calculation of an escape fraction -- the percentage of particulate emissions expected to escape the mine pit. Independently, the source depletion equation was used, in conjunction with wind measurements made in the mine pits, to compute escape fraction. These computed escape fractions were then compared to escape fractions computed using methodologies proposed by Fabrick (1982) and Winges (1981). In addition, meteorological measurements performed inside the mine pits were compared to simultaneous out of pit measurements. Finally, observed movements of the smoke tracer plumes were categorized and then compared to the meteorological conditions occurring at the same time.

The following conclusions are presented from the findings of these analyses:

- Computed escape velocities and escape fractions are lowest during night-time, stable atmospheres, and during light wind speeds. This finding is in agreement with observed flow patterns in the mine pits, as the released smoke tracer was frequently observed to have stagnated within the mine pits during these conditions. Conversely, the greatest ventilation rates were observed during high wind speeds and near neutral atmospheres.

- The computed escape velocity was found to be positively correlated with measured wind speed, temperature, and wind direction, and negatively correlated with stability category, and the width of the mine pit. However, when these parameters were used in linear, multivariate regression analysis, only 32% of the variation in escape velocity values could be accounted for. The linear model could not be improved upon through the use of in-pit measurements rather than out-of-pit measurements, or by stratifying the data by mine, by stability class, or wind speed category. It is concluded that some processes or variables, not accounted for in this analysis, must act in conjunction with the above meteorological parameters to determine the escape velocity.

- In-pit winds are significantly different from out-of-pit winds. The in-pit wind direction differs from the out-of-pit wind direction by about 60°. Further, no correlation between the in-pit versus out-of-pit wind direction was found using linear regression techniques, hence the in-pit wind direction can not accurately be predicted from a knowledge of the out-of-pit direction. In-pit wind speeds are, on the average, 25% smaller than out-of-pit wind speeds. Linear regression analysis did identify a significant positive correlation between in-pit and out-of-pit wind speeds.

7.0 RECOMMENDATIONS FOR FUTURE WORK

It appears that there are two data needs that must be addressed in the future to gain a better understanding of the pit retention phenomenon. First, there is clearly a need to quantify the magnitude of pit retention with direct measurements of concentration, or particle flux, so that a data base suitable for evaluating the performance of pit retention algorithms will be available. This direct measurement would also provide an estimate of the range of pit retention escape fractions, and should give EPA hard data with which to answer policy questions:

- Does the magnitude of pit retention warrant corrections to existing models?
- Will pit retention affect PM-10 concentrations?
- Is the fluctuation in escape fractions within the error band ("noise") of particulate emission factors?

At the same time, there is a need to continue to identify and quantify the parameters that influence pit dispersion. Without an understanding of the dispersion, transport, and removal mechanisms that affect surface mine pits, there is little hope of simulating them.

With these needs in mind, the authors offer a series of recommendations for future study:

- MODEL COMPARISON. A very simple and inexpensive investigation can be performed to determine a "ballpark" magnitude of pit retention. Using existing hi-vol data and meteorological data already collected in the vicinity of surface mines, a comparison can be made of actual measured concentrations just downwind of a pit ($C_{measured}$), and modeled concentrations determined from the ISCST model ($C_{modeled}$), which idealizes the terrain as flat and unaffected by the presence of the pit. Emission rates would be estimated from AP-42, Supplement 14 fugitive dust factors, and a representative background concentration (perhaps from an upwind hi-vol) would be subtracted from the measured concentrations. Any departure in the value of ($C_{measured}$/$C_{modeled}$) from 1.0 would be due to errors in the emission factors, or to errors in the model. If a long time period is considered -- perhaps by examining annual average concentrations -- then random errors in the model and emission factors will cancel out. Differences in the value of ($C_{measured}$/$C_{modeled}$) from unity would be due to systematic errors, such as pit retention or plume perturbation caused by the pit. In the absence of systematic errors in the emission factors or in idealizing the dust plume, the ratio of ($C_{measured}$/$C_{modeled}$) would be just equal to the escape fraction for the particle size distribution collected by the hi-vols. This approach would be a "first-cut" at estimating the magnitude of pit retention. Of course, it would offer no insight into the physical mechanisms that control dispersion from the pit. A study of this sort, using existing data, would cost from $10,000 to $20,000.

o PARTICULATE MEASUREMENT PROGRAM. A logical extension of the MODFL COMPARISON investigation just described would be to measure particulate concentrations at the downwind edge of a mine pit, while measurements of meteorological variables are being made. As before, the ratio of measured and modeled concentrations would provide a measure of pit retention. However, the availability of detailed meteorological data, especially stability class, will allow an examination of relationships between pit escape fraction and meteorology.

The length of each test, or episode, must be at least 15 minutes, which is the minimum time needed to approach Guassian distributions and therefore derive pit retention algorithms for the existing Gaussian models. The maximum time duration for each test will be dictated by how much particulate matter must be collected by the samplers to provide reliable concentrations. Use of filter samplers suspended from a tethered balloon, and use of a quartz crystal microbalance, as suggested by Air Sciences (Hittman and Air Sciences, 1983), should be considered. The cost for these tests would be between $100,000 and $150,000.

• PARTICULATE TRACER RELEASE. Both of the studies suggested above are unable to differentiate between systematic errors in emission factors and the effect of pit retention. If, for example, the ratio of $C_{measured}/C_{modeled}$ is found to be 0.80, it is not certain whether the escape fraction of particulate is .80, or whether the emission factors are consistently low by 20 percent. This problem can be overcome by controlling the emission rate by using a tracer.

The portion of the mine dust particulate matter that is retained in the pit can be determined by employing a particulate tracer material that matches the settling velocities of the mine particulate. This tracer material would be emitted continuously for a short time, on the order of an hour, at a controlled rate from a simulated source in the pit. Measurements of the particle budget outside the pit would in turn establish the fraction that escaped from the pit to the ambient atmosphere. The difference between the escaped fraction and the emitted material would then represent the portion retained, or the pit retention fraction.

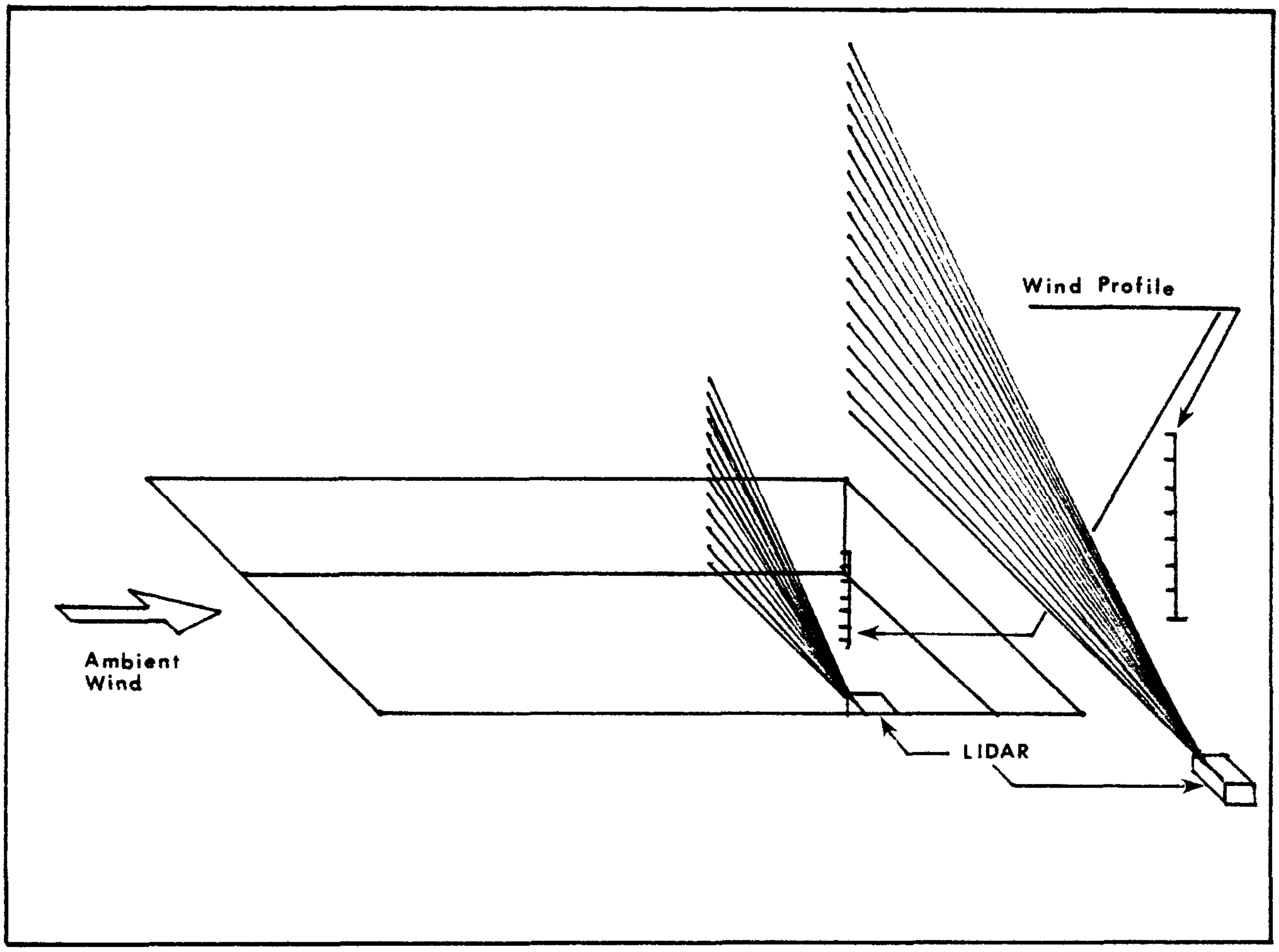
The mass flux of particulate tracer material downwind of the pit would be determined by measuring the concentration field. The methodology to measure this field of concentrations includes the use of several towers tall enough to encompass the vertical extent of the tracer plume, a broad enough array of towers to encompass the plume laterally, and with enough measurement points to enable rigorous reconstruction of vertical profiles of the tracer plume. With these concentration measurement points in a crosswind vertical array a specific cross sectional area is represented by each measurement point. A budget of particles observed can then be determined from a cross wind vertical integration of all these cross sectional areas.

Requirements:

- Tracer material in size range to match dust particulate settling rate.
- Assay of bulk tracer material to determine mean mass diameter and particle size distribution by percent of particles in size categories.
- Assay of observed concentration times with particle size distribution by percent in particle size categories at each sampler location.

FIGURE 7.1

PARTICLE LIDAR EXPERIMENT



The following observations and measurements would be made:

PHYSICAL FACTORS		ENVIRONMENTAL FACTORS	
DETERMINE	MEASURE	DETERMINE	MEASURE
Pit parameters	Length Width Depth Orientation	Atmospheric Stability out of pit Average wind speed	Cloud cover Time of day Wind speed (out of pit)
Tracer Source location	Location Dissemination rate	Stability out of pit	Statistics of wind speed variability Wind direction (out of pit) Statistics of wind direction variability
		Stability in pit	Wind speed (in pit) Statistics of wind speed variability Wind direction (in pit) Statistics of wind direction variability
		Vertical profile of Wind speed	Wind speed at several height on one tower
		Concentration field (tracer)	Concentration at several heights on each tower Time on-off each sampler

The tracer material to be employed is a broad-band particle size fluorescent particle material. This material can readily be distinguished from dust when assayed under ultraviolet radiation. The bulk fluorescent particle material (FP) would have to be obtained in a size range and width of size ranges to duplicate a typical range of dust settling rates. That is, since the FP material is normally of specific density in a different range than dust, it would be necessary to match the dust and FP by equivalent settling rates. Dust from mines can be expected to be in the specific density range near 2.0 while the most commonly used FP is specific density 4.0. If the dust size range can be expected to vary from 2 to 100 microns then FP in the range from 1 to 50 microns could be employed so long as the particle shape factor is roughly equivalent. There is however, some anticipation that FP material cannot be obtained in a size range extending as large as 50 microns. A size range up to 20 um is more likely. Alternately fluorescent dyed glass beads of sizes 50 to 100 microns with a specific density of 2.0 could be combined with the FP to fill out the full size range of concern.

The specific information that would be derived from such an experiment would include the following:

- Escape fraction and retained fraction in each particle size category by in-pit and out-of-pit stability class, wind speed class, pit parameter.
- Lateral and vertical plume dimension at the location of exit from pit, categorized by in-pit and out-of-pit stability class, wind speed class, and pit parameters.

The relative cost of performing particulate tracer experiments would be considerably higher than the previous experiment discussed. Particulate tracer work is quite labor intensive, in addition to the field measurement area. Due to the high cost of the manual optical assay techniques the overall cost of such a program probably would exceed $300,000.

- PARTICULATE FLUX MEASUREMENT

The final level of complexity and rigor suggested here involves making Lidar measurements of the actual dust source in the pit and companion Lidar measurements of the dust plume shortly after it has exited from the pit. Several types of Lidar devices are sensitive to dust particles. That is, they can detect the presence of dust particles and in turn can determine relative concentrations of dust particles. The CO_2 Lidar is probably the most sensitive to dust and has the added advantage of being "Eye Safe" beyond a few feet range. The Lidar devices have been developed to the point they are range gated and thus can give mean concentrations for increments of range. This means that one can obtain an along-path concentration profile for each firing of the Lidar beam. The range gating yields a concentration profile, along path, integrated based on mean concentrations for every 3 meters of Lidar beam range.

The approach to be employed with this device would be to locate one Lidar in the pit to measure a crosswind vertical profile of the concentration of dust generated by the activities of the mining operation. A second Lidar would be located to the side of the pit so it could do a cross wind profile just downwind of the pit. This second Lidar would be located so as to scan directly cross wind at a constant azimuth angle starting with a horizontal position and make successive firings at successively increased elevation angles. This would yield a crosswind vertical profile of dust concentration. Concurrent measurements of wind profiles both in-pit and out-of-pit would be needed to enable calculations of out-of-pit dust particle budgets which would be compared to the in-pit budgets to determine pit retention. A schematic of the experimental configuration is shown in Figure 7.1

The following observations and measurements would be made:

PHYSICAL FACTORS		ENVIRONMENTAL FACTORS	
DETERMINE	MEASURE	DETERMINE	MEASURE
Pit parameters	Length Width Depth Orientation	Atmospheric Stability out of pit Average wind speed	Cloud Cover Time of day Wind speed (out of pit)
Dust Sources	Locations Activity level	Stability out of pit	Statistics of wind speed variability Wind direction (out of pit) Statistics of wind direction variability
		Stability in pit	Wind speed (in pit) Statistics of wind speed variability Wind direction (in pit) Statistics of wind direction variability
		Vertical profile of Wind speed (out of pit)	Wind speed at several height on one tower
		Dust profile (in pit)	Lidar profile
		Dust profile (out of pit)	Lidar profile

The cost of conducting a Lidar field measurement program would be relatively high, most probably on the same order as the tracer experiment, that is, about $300,000.

The advantage in employing Lidar measurements is that they would provide a direct measurement of the dust behavior itself, rather than a measurement of a simulant as a tracer study would. The disadvantage is that there would be no information generated about particle size distributions unless extra observations were incorporated for that specific purpose.

- FEDERAL HIGHWAY ADMINISTRATION STUDY

As explained in Section 2.0, BACKGROUND AND LITERATURE SURVEY, the Federal Highway Administration will fund a 20 month long wind tunnel study of airflow and dispersion in street canyons and deep cuts. One purpose of the study will be to develop algorithms that can be used to improve predictions of CO concentrations in existing Gaussian models. EPA may choose to monitor this study since it will likely offer some insight into mine pit flows. Or, EPA may even consider funding an expansion of the FHWA study to include investigation of surface mine pits.

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APPENDIX 1

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report summarizes the results of an effort to better understand the dispersion and transport of particulate matter released within surface coal mine pits Data previously collected at four surface coal mines were used in this investigation. This report describes the analysis and interpretation of those data, examines the relationship between meteorology and smoke puff behavior, and compares mine pit escap fraction (that portion of the dust emitted in the pit that leaves the pit) with those predicted by existing equations.

Two independent techniques were used in conjunction with assumed particle size distributions and the onsite data, to infer values of escape fraction. These values were then used to determine the predictive ability of two widely used model algorithm The report contains numerous tabulations and discusses the relative merits of each method.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Coal Mining Emissions Particulates - Escape Fraction Meteorology		-

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