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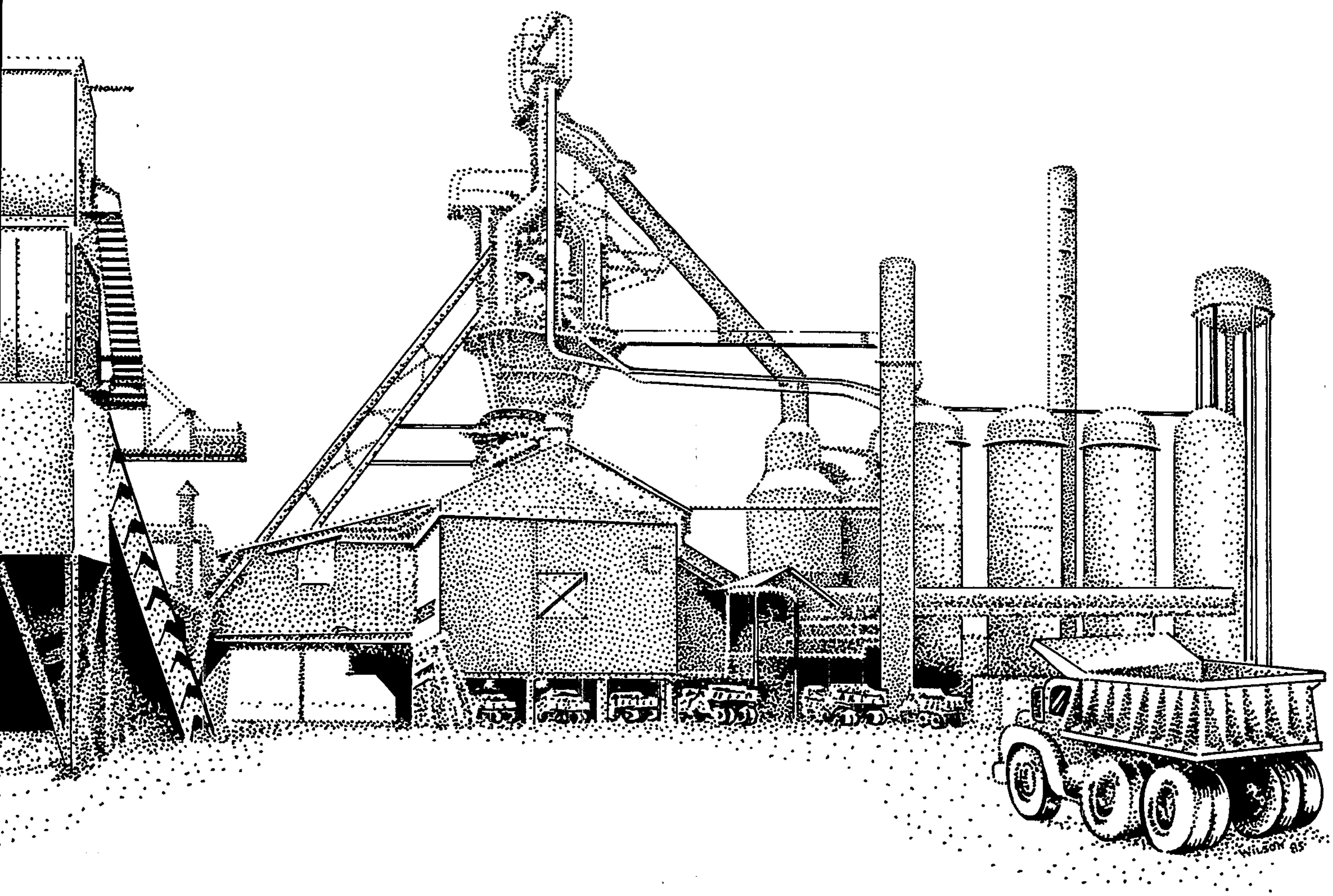
User's Guide:

Fugitive Dust Control Demonstration Studies



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USER'S GUIDE

FUGITIVE DUST CONTROL DEMONSTRATION STUDIES

U.S. ENVIRONMENTAL PROTECTION AGENCY

Office of Research and Development
Center for Environmental Research Information
and
Office of Air Quality Planning & Standards

CENTER FOR ENVIRONMENTAL RESEARCH INFORMATION
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 45268

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FOREWORD

Under certain circumstances, sources of air pollution may be able to meet their obligations under the Clean Air Act by the use of the bubble concept in which emission points can be controlled to a greater or lesser degree than otherwise required, as long as the total plant emissions are within established limits. Strict controls can often be applied to non-process fugitive (also called nontraditional) particulate to emissions to allow a lesser degree of control for stacks and vents under a bubble proposal.

State and local agency officials are responsible for determining the validity of bubble proposals. Thus, these officials must be in a position to determine if claimed reductions in fugitive emissions from such sources as roadways and storage piles can be substantiated for the control methods proposed. There are many studies available to the official that discuss the effectiveness of various control techniques for nontraditional particulate emissions.

This User's Guide provides state and local agency officials and those responsible for conducting fugitive particulate demonstration studies insight into the validity of recent studies. It also stresses the considerations of importance when planning this type of study. From the data presently available, it was not possible to develop quantitative emission factors or control efficiencies for the various control alternatives.

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Chapter 1

INTRODUCTION

The Clean Air Act Amendments of 1977 require states to submit to the U.S. Environmental Protection Agency (EPA) a revised State Implementation Plan (SIP) describing the state's plan for expeditious attainment of the National Ambient Air Quality Standard (NAAQS) for all areas within the state. The specific EPA requirements for the revised SIPs (published in the Federal Register, April 4, 1979 and in subsequent EPA documents) include requirements for addressing several classes of particulates, especially in nonattainment areas: stack emissions, process fugitive dust, and nontraditional fugitive dust (or nontraditional particulate matter). Nontraditional fugitive dust includes urban fugitive dust, dust reentrained from road surfaces, and dust created by construction activities.

For those areas which have not attained the NAAQS for particulates and in which fugitive dust contributes to the violation of the particulate NAAQS, the SIP must adopt the requirement that reasonably available control technology (RACT) be used to control traditional sources of fugitive dust (process fugitive dust); in addition the SIP must contain a schedule for the study and eventual adoption of controls for nontraditional sources of particulates. Many such "RACT-plus" studies have been conducted across the country to demonstrate the effectiveness of proposed technologies in controlling these nontraditional sources.

Because of the large number of nonattainment areas requiring demonstration studies and considering the cost of these studies, EPA commissioned a workbook to provide guidance in designing and executing a proper study [1]. The Workbook was published in March 1981. The guidelines set forth in the Workbook are to ensure that defensible results are obtained from the study, and that the results can be exchanged among jurisdictions, thus minimizing duplication of effort. The Workbook stresses two critical guidelines that must be followed for any demonstration study to be successful: (1) The study design must ensure that the amount and type of data generated will be sufficient to realize the objectives of the study; and (2) The data must be subjected to the proper, rigorous statistical analysis.

In addition to the Workbook, EPA has also recently sponsored or partially funded a number of these demonstration studies to evaluate the effectiveness of a wide variety of nontraditional particulate control systems. These studies were conducted in Denver, Colorado; Minneapolis, Minnesota; and Portland, Oregon.

Of the studies reviewed, many were found to be deficient in their analyses when compared to the Workbook guidelines. Generally speaking, in the studies with valid analyses, control techniques that were evaluated were not highly effective. Further, many of the studies neglected the critical time factor; that is, the study analyzed the immediate effect of the control but failed to analyze the decay in effectiveness over time.

The objectives of this User's Guide are to:

- Verify that the Workbook is a firm foundation to build a demonstration study upon

- Discuss the study variables that must be taken into account in the study design

- Summarize the major fugitive particulate studies that have been done to date

- Make state and local agency personnel aware that control efficiencies reported in some studies may be unduly optimistic.

This Guide is therefore of particular value to those designing and implementing future studies as well as to state and local agency personnel reviewing permit applications in which the control of nontraditional particulate sources is an integral part.

Chapter 2 of this Guide reviews the Workbook's guidelines on the design and implementation of demonstration studies. The guidelines include a consideration of:

- Study design
- Sampling and analysis
- Statistical analysis of results
- Development of control efficiencies
- Optional investigations
- Usefulness to state and local agencies.

The review of case histories is found in Chapter 3, which provides detailed descriptions of the three recent EPA-funded demonstration studies and brief descriptions of a number of earlier studies.

Chapter 2

GUIDELINES FOR CONDUCTING FUGITIVE DUST CONTROL DEMONSTRATION STUDIES

The proper design, implementation, and interpretation of the results of a demonstration study are essential to the defensibility and usefulness of its findings. This section summarizes the guidelines set forth in Workbook: Demonstration Studies for Control of Nontraditional Particulate Sources [1]. These guidelines serve as a yardstick against which the project descriptions contained in the case histories are measured. The Workbook was thoroughly reviewed and found to provide excellent guidance for a demonstration study which, when rigorously followed, should yield defensible results.

2.1 STUDY DESIGN

The design of a demonstration study is critical to the study's ability to produce clear, valid, and defensible results which can be applied to circumstances outside the the study itself. The study design must begin with the objectives of the study, such as "to determine the effectiveness of various wet suppression chemicals for controlling emissions from unpaved roads." Second, the availability of data related to this objective must be ascertained in order to see whether the demonstration study is warranted. A study is warranted only when the data needed are not available or are unusable. For example, all available data on a particular type of control may reflect the short-term effectiveness of a technique, whereas long-term effectiveness data are needed.

Once the objectives have been defined and a determination has been made that the study is warranted, the next step is to decide which of the two approaches described below is most appropriate for determining the effect of the control method under study. The "source-oriented" approach measures the emission rates from a source before and after controls are applied. This approach is better suited for essentially uniform emissions from isolated sources. The advantage of this approach is that the results can be converted directly to emission factors. The disadvantage of this approach is that areawide results must be extrapolated by a dispersion model which will require extensive data. The "receptor-oriented" approach determines the ambient concentrations in the vicinity of the source. This approach is well suited for averaging widely variable emissions from a large area of sources such as a network of urban streets. The advantage of this approach is that the results do not have to be extrapolated through modeling but rather apply directly to the areas in which monitors are located. However, the number and location of monitors used are critical elements in the study design if the test results are to be used to predict area wide effects. Most nontraditional particulate studies will probably be receptor oriented since they involve impacts in a large area.

The next step is to select one of three types of study designs described below on the basis of implementability and usefulness for subsequent analysis. This step must be closely integrated with the selection of the statistical analysis technique which will be used later; these techniques are described below. If the type of design is ill-chosen or cannot be followed meticulously throughout the course of the study, the statistical analysis of field data may be hampered or even invalidated.

A Type 1 design consists of a single study area sampled during an uncontrolled period and during a controlled period. This design assumes that all parameters other than the control parameter remain constant from the first to the second period. Therefore, this design is only effective if the other variables (such as weather and site activities) can be shown through statistical analysis to not influence the results.

A Type 2 design consists of simultaneously sampling two study areas, one with and one without controls. In this manner, the variables that can affect the uncontrolled and controlled emissions (other than the control itself) will be nearly identical.

A Type 3 design consists of two study periods: during the first period one study area is controlled while the other area is not controlled; during the second period, the roles are reversed. Although more expensive to conduct, a Type 3 design is usually preferable to Type 2, and is called for if source activities vary widely or if for other reasons, such as an expectation of seasonal effects, the study areas cannot be considered identical. The greatest disadvantage of this type is the possibility that the effect of controls in one area might be carried over into the first part of the second period when that area is said to be uncontrolled.

Another step in the planning stage is to detail the specifications for applying the controls, including the area to be administered, and the frequency, methods, and rates of application. These specifications must include incidental instructions that may apply, such as a prohibition of parking during street-cleaning.

2.2 SAMPLING AND ANALYSIS

The success of the study is dependent on the coordination of all parties involved to ensure that the sampling program is carried out in accordance with the study design. It is particularly important that those responsible for implementing the source controls do so at the agreed-upon time. A Type 1 or 3 study may be irreparably damaged if sampling during the control period cannot be completed because of a failure to completely implement controls during the scheduled sampling period.

A primary requirement for the study is that enough samples are taken to demonstrate statistically that the control method does or does not bring about the desired effect. If too few samples are taken, results will be inconclusive. The Workbook provides detailed instructions for calculating the minimum number of samples. The design must also allow for the loss of samples which will be dropped due to errors.

The frequency of sampling generally represents a compromise between the time period available for the study and the resources and level of effort that can be committed to the project. For source-oriented studies, any convenient sampling period is selected, provided it is representative. For receptor-oriented studies, daily sampling is preferable, especially in tracking the effect of variables whose effects may be transitory, such as the application of chemical dust suppressants. The sampling periods selected are normally 24 hours in length to correspond with daily cycles of weather, vehicle traffic, and so on.

Determining the number of sampling sites is generally a site-specific consideration. Source-oriented studies can use a single monitoring site. However, at least two monitoring sites are recommended for each study area for a receptor-oriented study: normally one monitoring site is located near the source (or sources) to measure the impact of the control method in a small area, and an additional monitoring site is located up to several hundred meters from the source to measure the impact in a larger area. A background site located upwind from the source is also advisable when studying ambient impacts that are expected to be small. The actual location of the instruments should follow guidelines such as those found in the Workbook and similar references. These guidelines address concerns such as height above the ground, distance from buildings, and distance from trees.

The standard sampling instrument for a receptor-oriented study is the high volume sampler, or hi-vol, which measures total suspended particulates (TSP, less than 30 microns in diameter). If an important parameter in the study is the proportion of particulate matter between specific size ranges, such as inhalable particulates (IP, less than 15 microns in diameter) or fine particulates (FP, less than 2.5 microns in diameter) options are available. If two size fractions are required, a dichotomous sampler can be used; if more fractions are desired, a cascade impactor with several stages can be used in conjunction with a hi-vol. It should be mentioned that cascade impactors suffer from the problem of "particle bounce" in which large particles migrate to lower stages of the instrument, thereby significantly biasing the results toward the small particle size.

The specifications for every demonstration study must explicitly delineate detailed quality assurance procedures. A quality assurance checklist such as that published in the Workbook must be strictly observed during the sampling and analysis phase of the study.

2.3 STATISTICAL ANALYSIS OF RESULTS

Four methods of statistical analysis have been or could be used to interpret the results of demonstration studies when a controlled source is compared to an uncontrolled source. These analyses include the paired t-test, analysis of variance, analysis of covariance, and multiple linear regression analysis. The paired t-test compares the averages of the controlled source data with the averages of the uncontrolled source data and analyzes the differences to determine whether or not the control method has caused a real difference. Analysis of variance compares the magnitude of two or more sample variances to determine whether they are different at a predetermined level of significance, for example, with 90 percent confidence. Analysis of covariance is an extension of analysis of variance; variations attributable to measured variables (covariates) other than the control variable are subtracted out before testing for significance. This allows conclusions to be drawn concerning the effect of the controls as well as of each of the covariates. Multiple linear regression analysis derives an equation relating an effect (such as a concentration) to a series of independent variables. The results of this analysis indicate which, if any, of the independent variables are correlated to the effect. The reader is referred to the Workbook for more detailed discussion of these methods of statistical analysis.

The following is a summary of these methods and their suitability to the three types of demonstration studies:

Technique	Study Design Applicability	Requirements	Limitations
Paired t-test	Type 2	Paired data	Only two data sets can be compared
Analysis of variance	Types 1, 2, 3	Sampling must be done for combinations of variables	Period of time required cannot be determined because variables are not controllable
Analysis of covariance	Types 1, 2, 3	All independent variables of interest (covariates) must be measured	More difficult to use for Types 1 and 2 than for Type 3
Multiple linear regression	Types 1, 2, 3	All independent variables of interest must be measured	

It is apparent from the above table that the statistical analysis method selected for a demonstration study is highly dependent on the type of study design as well as on the number of variables the designer is able and willing to measure. Obviously, the study design and corresponding statistical analysis method must be selected together in order to meet the study objectives in the most cost-effective manner.

Once selected, the statistical analysis method must be rigorously followed and the results compiled in a well-documented fashion. Furthermore, each method requires assumption of a confidence level; for example, a finding of effectiveness of a control method at a 95 percent confidence level is a stronger endorsement of the method than a similar effectiveness at an 80 percent confidence level. The confidence level must be clearly delineated when reporting the results in order for the reader to judge the impact of the findings and conclusions, as well as to be able to compare findings among similar studies, and to decide whether the results can confidently be extrapolated to a full-scale implementation of the control method.

2.4 DEVELOPMENT OF EMISSION FACTORS AND CONTROL EFFICIENCIES

The results of a demonstration study are usually expressed in the following form: It can be said, with a certain confidence level, that the effect of a control system lies between A and B, where A and B are reductions in ambient particulate concentrations from the level when the source was uncontrolled. The study may go on to provide emission factors or emission factor algorithms relating emissions to variables such as traffic density or days since precipitation. In order to be useful, emission factors developed in this manner must be firmly grounded in the results of the study and must not merely represent a restatement of previously developed equations that are not completely verified by the present study.

The result that is probably most useful to the permitting process is the development of control efficiencies. These should be based strictly on the effects data described above and again, they should not be influenced by previous work or unwarranted assumptions. Furthermore, any limitations on the application of the developed control efficiencies must be clearly stated. For example, a control efficiency for the use of a chemical dust suppressant on unpaved roads applies only at the application doses and frequencies employed in the demonstration study and only for that particular suppressant.

2.5 OPTIONAL INVESTIGATIONS

Optional investigations are defined here as activities other than general particle size analyses (TSP, IP, and FP) that may be conducted for reasons specific to the demonstration study. One such study might be an elemental analysis of samples to provide corroborating data for other similar studies or to identify and remove interferences from the study. For example, a significant portion of collected particulate matter in an urban location may comprise nonsoil elements, or one or more soil elements may be present in suspiciously high concentrations. Either of these phenomena may be traceable to an overwhelming background source, the contribution of which, if quantifiable, could be subtracted from the data in question to provide a clearer estimation of the effectiveness of control.

Chapter 3

CASE HISTORIES

This chapter presents case histories of demonstration studies designed to evaluate the effectiveness of control techniques for particulates. These case histories are intended to illustrate the application of the study guidelines presented in the previous section to actual demonstration studies. The design, implementation, and conclusions drawn from each of the cases are presented and critiqued, with the hope that this information will assist others in the design of similar studies. The case histories are divided into detailed accounts of recent EPA-sponsored studies in Denver, Minneapolis, and Portland, Oregon, and less detailed accounts of earlier studies.

3.1 RECENT EPA DEMONSTRATION STUDIES

For each of these case histories, an account is provided of the circumstances prompting the study, the reasons for the choice of particular study design, the implementation of the study, and the conclusions drawn from the results. The methods and procedures employed in each study are then compared with the criteria and guidelines established in the Workbook. In these studies many results could not be substantiated due to such factors as the inability to carry out a study as designed, the effect of interferences, and less than adequate statistical analysis of sampling results. State and local agency personnel should be aware of these deficiencies both in reviewing compliance plans based on these studies and in designing future studies.

3.1.1 Denver, Colorado

The Denver study [2] was conducted for the Colorado Division of Air Pollution Control during the winter of 1980-81. The study actually consisted of two independent studies designed to address the hypotheses that (1) ambient concentrations of particulate matter can be reduced by substituting road salt for sand; and (2) ambient concentrations of particulate matter can be reduced by later cleaning up the sand used on the snowy roads.

No large-scale demonstration studies of this type had been conducted previously despite the widely held belief that the use of sand for snow control may be detrimental to local air quality. The first hypothesis was tested in Lakewood, a suburban area near Denver; the second was tested in the City of Denver. Both the suburban and urban locations were primarily residential.

In both locations, concentrations of TSP, IP, and FP were measured at three distances: near-street (10 to 11 meters from the street); off-street (50 to 70 meters from the street); and neighborhood (greater than 200 meters from the street). The results of the studies indicated a slight improvement in air quality for TSP and FP at the near-street location when the sand was removed. Substituting salt for sand failed to show any improvement in air quality; in fact, a slight degradation of TSP air quality was observed at the near-street and off-street locations. These results are summarized below.

Control Method	Air Quality Improvement		
	TSP	IP	FP
Salt Substitution (Lakewood, CO)			
Near street	Negative	NSS*	NSS
Off-street	Negative	Not tested	Not tested
Neighborhood	NSS	Not tested	Not tested
Sand Removal (Denver, CO)			
Near street	Positive	NSS	Positive
Off-street	No conclusions possible		
Neighborhood	No conclusions possible		

*Not statistically significant

<u>Study Design</u>. Both portions of the study used the receptor-oriented approach, which was appropriate given that a wide variation in emission rates was anticipated. In order to partially overcome the limitations of this approach, monitors were located at the three distances from the streets described above, thus eliminating the temptation to assume that the particulate concentrations were consistent throughout the entire neighborhood.

The study design selected for the salt substitution case was Type 3. Two sites were monitored concurrently, one using salt and the other sand; the process was reversed for the second period. The sand removal study was also to have been a Type 3 design, but it was essentially reduced to a Type 2 design because street cleaning activities were not performed as planned. Meaningful results could have been obtained in the Type 2 design had the two areas been shown to be essentially identical in terms of meteorology, background concentrations, interferences, and so on. However, this was not found to be true.

The actual areas selected for the two studies appear to be appropriate. Each was primarily residential, which tends to minimize interferences from background sources. The paired sites were similar in terms of land use patterns and number of paved streets. Those sites in the salt substitute case differed somewhat in terrain; site A was a valley and site B a grassy hill. However, because a Type 3 design was used, this inconsistency would be inconsequential.

The concentration of TSP at each of the four monitoring stations was measured by a hi-vol sampler with a standard glass filter. A dichotomous sampler with a teflon filter was used to measure concentrations of IP and FP at the near-street monitoring stations only. For the sand removal study, a background monitoring station, consisting of a hi-vol sampler and a dichotomous sampler, was maintained in another part of downtown Denver. Sampling was conducted for 24-hour periods from mid-day to mid-day, allowing sample collection and restarting of monitors during normal working hours. The location and operation of monitors appear to be adequate. The duration of each portion of the study also appears to be adequate for generating enough data for a rigorous statistical analysis.

Sampling and Analysis. As mentioned previously, the sand removal study suffered from a lack of coordination which resulted in a Type 3 design actually being conducted as a Type 2 design. Other than this, the implementation of controls proceeded as planned. The sampling and analysis plan provided sufficient samples for statistical analysis of results, even though the study was terminated after five months instead of the six months which had been planned.

Extensive quality assurance procedures were established and followed. These covered equipment maintenance and calibration, sampling procedures, laboratory procedures for filter preparation and analysis, and data handling. Independent audits were performed to check hi-vol flowrates and filter weights, and to ensure the reproducibility of the hi-vol results. The audit of hi-vol filters essentially verified the procedures used; some problems with reweighing of dichotomous filters were reported even though a higher than normal reweighing tolerance was used. The report provides the proper caution concerning interpretation of these results in light of potentially large weighing errors.

Analysis of Results. For the salt substitution study the concentrations of TSP, IP, and FP for all sampling days were calculated directly from the laboratory results. For each site and period, the mean concentrations of all data were then calculated. The differences in ambient concentrations between each pair of sites were averaged for both periods and used in a multiple linear regression analysis. The regression analysis was used to determine the variables, other than salt substitution, that may have affected air quality.

For the sand removal case, the multiple linear regression technique could not be used because the expected Type 3 design turned out to be a Type 2 design. Instead, the paired t-test was used, requiring the calculation of mean values and standard deviations for two groups of data (with and without sand removal) as well as the average difference of paired data values. As mentioned previously, the Type 2 design is only valid if the two areas can be shown statistically to be identical. The paired t-test was thus first used for this purpose and revealed that the sites were identical only at the near-street locations. Therefore, no conclusions concerning the control method could be made concerning the other two distances. Although a somewhat standard 80 percent confidence level was used for discussing the significance of the salt substitute results, the sand removal results are presented in terms of a 95 percent confidence level. It is not clear why two different confidence levels were used.

In general, the study presents conclusions properly and does not extrapolate the results beyond the constraints of the study. The most useful conclusion is that neither control method was shown to provide a significant air quality benefit. Note on the summary table (p. 10) that 14 of the 18 cases cannot be discussed in terms of the effectiveness of the control. These cases are eliminated for one of three reasons: samples were not taken for that parameter (not tested); the type of study design implemented precluded conclusions from being drawn (no conclusion possible); or the results were not statistically significant.

<u>Emission Factors and Control Efficiencies</u>. The uncertain nature of the results prohibited the development of emission factors and control efficiencies.

<u>Optional Investigations</u>. Selected filters were further analyzed to define the nature of the particulate matter collected. Some hi-vol filter samples were ashed to determine percent volatile material, and some dichotomous filter samples were subjected to elemental analysis by X-ray fluorescence.

The presence of the ten elements for which the filters were analyzed has been explained in terms of their expected sources: soil, fuel combustion, automobile exhaust, and application of sand or salt. However, in general these ten elements represented only 10 to 25 percent of the total mass of the samples. Therefore, with no further analysis, no conclusions regarding interferences from unexpected elements are possible. A qualitative discussion of the variation of the ten elements across sites and time periods is presented, but does not achieve any specific objective. A brief discussion of volatile content is also provided.

<u>Usefulness to State and Local Agencies</u>. As mentioned earlier, neither control method was shown to be effective in improving ambient particulate air quality, given the limits of the test program. Therefore, one obvious use of the results is to encourage state and local officials to be skeptical of favorable claims made for these control methods applied in similar situations.

Future studies of this type would benefit from coordination and planning of the implementation of controls. No conclusions for the off-street and neighborhood locations were possible for the sand removal study because immediate cleanup of sand was not practiced. If a control measure is to be implemented by other than the study contractor, a firm commitment with the performing organization must be made before testing begins. In addition, the contractor's performance must be monitored throughout the study period.

The Denver sand removal study can be somewhat useful in providing background data on the uncontrolled levels of small particulate in anticipation of a size-specific standard such as the suggested PM-10 (particles less than 10 microns) standard. In both study areas at the near-street locations, concentrations of IP (less than 15 microns) and FP (less than 2.5 microns) were determined by dichotomous samplers, which would permit interpolation to the approximate fraction of PM-10. However, because of possible interferences, it is perhaps wise to view this interpolated PM-10 value as an order-of-magnitude estimate.

3.1.2 Minneapolis, Minnesota

The Minneapolis study [3] was conducted for the Minnesota Pollution Control Agency. Field measurements took place in the summer of 1982. The objectives of this study were to assess the impact of construction-related fugitive dust on ambient air quality in an urban area, and to assess the effectiveness of water spraying as a control method for this source. The study was needed because at the time, little data was available on fugitive dust from construction activities or on the effectiveness of water spraying as a control method. Concentrations of TSP and IP were measured upwind and downwind of the construction activity; concentrations of FP and PM-10 were interpolated from log-normal plots of the data. Because of problems encountered in executing the study, no firm quantitative conclusions were justified concerning the effectiveness of watering to control construction-related dust.

Study Design. A receptor-oriented approach was planned, in which monitors were placed at distances of 25 and 50 meters upwind and downwind (north to south orientation) of the road construction right-of-way. Monitors were deactivated during periods when the wind direction differed by more than 67.5 degrees from the north-to-south line.

The study was conceived as a Type 1 design with one area to be monitored during consecutive periods of no control followed by control. During the early stages of the road construction, water spraying of the dirt surface, though planned, was not conducted; a modest amount of watering was done later when the road had a gravel surface. The result was that the sampling data collected before and after the application were for two essentially different sites, thereby ruling out a meaningful statistical analysis of the effect of control. Therefore, the effect of water spraying could not be evaluated and an alternative analysis based partly on previous work was used.

The selection of the site appears to have been appropriate, as it consisted of the full range of activity from site clearing to paving with hot mix asphalt. The monitors were properly oriented, parallel to the prevailing wind direction. Particulate concentrations upwind and downwind were measured by hi-vol samplers fitted with a 15-micron selective inlet and a 5-stage cascade impactor. The TSP and IP concentrations were thus measured directly, while PM-10 and FP were determined by extrapolation or interpolation from the particle size curve developed by the cascade impactor results. Monitors in both directions were in areas with ground cover provided by crops and were mounted such that the inlets were two meters above the ground.

Sampling and Analysis. As discussed above, an insufficient number of samples were taken during watering to provide for a statistical analysis of the effectiveness of the control technique; furthermore, the samples taken for the controlled and uncontrolled conditions were for different surfaces (gravel and dirt). Part of the problem was the short duration of that part of the construction which was performed on dirt (approximately 35 days). This would have made it difficult to collect enough samples even if watering had been done for as much as half of this period.

The sampling and analysis procedures followed appear to have been adequate. Extensive field measurements of meteorological variables such as wind speed and direction, temperature, and humidity were taken, as well as other independent variables such as vehicle speed and number of passes. Samples of the actual working surface were collected for laboratory analysis.

Extensive and appropriate quality assurance procedures were followed covering equipment siting, operation and maintenace, instrument calibration, and laboratory procedures. Audits of unexposed and exposed filters were conducted.

Analysis of Results. The concentrations of TSP and several particle size fractions were directly calculated from the the hi-vol 15 micron inlet, and from the cascade impactor catches. The data were plotted on a log-normal distribution curve, from which the concentration of PM-10 and FP were then interpolated. During this procedure, an unexpectedly large amount of particulate matter bypassed the cascade impactor stages and was found on the backup filter (particle bounce). A calculation, presumably verified in previous work, was used to correct this problem.

A possible interference was noted in the presence of a significant amount of black particulate matter in the smaller size ranges. It was speculated that the source was diesel exhaust from heavy construction equipment. This speculation was not verified by laboratory analysis.

Meteorological and other independent variables were averaged and tabulated. Water application rates were highly variable in duration and intensity and were thus normalized and reported as liters per square meter per hour.

Originally, it was intended that an analysis of variance would be used to statistically analyze the effectiveness of the control. However, because of the problems in carrying out the original study design, this technique could not be used. Instead, a multiple linear regression analysis was used to attempt to relate ambient particulate concentrations to various independent variables.

A regression model was proposed which related concentration to three independent variables -- silt content (percent less than 200 mesh), traffic density, and surface moisture -- that were selected from a preliminary correlation analysis. However, it is not clear why vehicle weight was not included in this model, since this variable exhibited a greater correlation coefficient than did surface moisture.

The regression model was then run with traffic density data from the field and values for the two other variables from laboratory tests. The results were expressed as values for a coefficient and for individual exponents for each particle size (TSP, IP, and PM-10). Correlation coefficients were then calculated which revealed that a large percentage of the variation in concentrations was statistically related to the three variables. Surface moisture was found to be the least dominant variable, becoming even less important at greater distances (50 meters versus 25 meters).

<u>Emission Factors and Control Efficiencies</u>. Two approaches were used to analyze the effect of controls, focusing on the data for the 25-meter sampling distance. (Apparently because of alternate approaches used, the 50-meter data was not analyzed in this manner.) In the first approach, the regression analysis was used to calculate particulate concentrations near the gravel surface. This analysis was based on six data points for watering and one for no control. The resulting control efficiencies are on the order of 50 percent but are of limited use, as they are based on such a small sample size. Furthermore, no account was taken of the decay in effectiveness over time.

The second approach involved a laboratory experiment in which three representative samples from field sites were watered in an attempt to simulate the desired watering program that was not carried out. Two application rates were used: the field-measured normalized rate and a rate twice this amount. Gravimetric analysis of samples before and after watering yielded surface moisture values which were inserted along with the other variables into the regression equations to yield concentrations before and after watering and thus the control efficiency. The resulting control efficiencies ranged from 41 to 70 percent (again without regard to decay with time); however, because these results are based on a laboratory simulation, they cannot be applied directly to actual field situations.

The conclusions presented in this study must be tempered with an understanding of the actual conduct of the study in relation to the original study design. One might justifiably state that the study has established that road construction activity causes a "significant and measurable impact on the ambient air quality" in terms of fugitive dust. It is perhaps also fair to conclude that the regression model, complete with constants for each particle size distribution, reasonably relates this impact to surface silt content, surface moisture, and traffic density. However, the study's conclusion that approximately 50 percent control can be achieved by watering is not totally supported by the results of the study because one determination was based on very limited field data for a gravel surface and the other determination was based on a laboratory experiment that may or may not accurately reflect conditions for an actual dirt road in a construction area. The laboratory experiment is unreliable in that it represents a hybrid approach that sets out to calculate an ambient concentration from data derived partly from the field and partly from the laboratory. This conclusion also says nothing about decay in effectiveness with time.

The study's conclusion that watering is the only viable control strategy for fugitive dust emissions from construction activities is not warranted because this hypothesis was not tested by this study. Also, the study's conclusion concerning the black particulate matter found on filters is more of a hypothesis to be investigated at a later date, in that the association of the black particles with diesel exhaust is a supposition, rather than a conclusion supported by analysis.

Optional Investigations. Two optional investigations were conducted as part of the demonstration study. The first was an emissions inventory of the area around the monitoring site. The only apparent and direct result was that no other significant sources of fugitive dust were found within one kilometer of the construction site. The contribution of sources within ten kilometers of the construction site was estimated using previously developed emission factor algorithms for wind erosion, vehicular traffic, and material storage piles. These results were published in an appendix, but were not directly applied to the analysis.

The second optional investigation was a determination of mud or dirt carry-out, that is, reentrainment of dust carried onto paved roads by construction traffic. Samples were taken by portable vacuum cleaners at three nearby sites. Surface loadings for each sample were calculated, and each sample was analyzed in the laboratory for silt content. These results were presented but, again, were not directly applied to the analysis. Rather, they were collected as the first part of a more comprehensive study to have been completed later.

Usefulness to State and Local Agencies. A true Type 1 analysis was not achieved in the Minneapolis study primarily because of a failure to implement controls during the control period of the study. As a result, indirect analyses were used involving a laboratory analysis and the limited field data collected. The latter included only one sample for the control period and one other for a different surface from that tested under the uncontrolled scenario. Consequently, the conclusions drawn from this analysis must be considered tentative at best. It is particularly inadvisable to apply the conclusions to actual field sites because they are based on a hybrid (field/laboratory) experimental approach.

A problem raised by the study is that of interference by either a point source or a traditional fugitive source in the study area. It is important once a potential interference has been found that the source be identified and confirmed so that its contribution can be removed in the analysis of results. This should have been done once a significant amount of black particulate matter was noted on the sample filters. Speculation on the nature and source of potential interferences does not enhance the usefulness of the results.

The Minneapolis study could provide useful data on the distribution of PM-10 particulates from road construction under uncontrolled conditions. Although not measured directly, PM-10 values inferred from the test data should be relatively accurate because they are determined by extrapolation from a cascade impactor particle size distribution consisting of five particle sizes. The top size is 7 microns, which is relatively close to 10; furthermore, the extrapolation is done for large particle diameter rather than for the smaller particle sizes where there is greater uncertainty caused by the particle bounce problem.

3.1.3 Portland, Oregon

The Portland study [4] was conducted in 1981 under the direction of the Department of Public Works of the City of Portland, Oregon. The objective of this study was to determine the effectiveness of daily vacuum sweeping of the curb lane of city streets in controlling particulate concentrations. Concentrations of particulates greater and less than 2.5 microns were determined in the two study areas. The study was unable to demonstrate any relationship between vacuum sweeping and air quality.

Study Design. Previous studies investigating the effectiveness of vacuum sweeping in improving the particulate air quality were not conclusive because they usually relied on remote measurements of TSP and because they failed to account for independent variables relating to meteorology and traffic.

This study employed a receptor-oriented approach, which is appropriate for this type of study because emissions are distributed over a wide area and are expected to vary significantly. Dispersion modeling was to have been used to project the results to a wider area.

A Type 3 study design was used, in which two areas were monitored for two three-month periods, with street cleaning practiced in one area during the first period and in the other area during the second period. Two areas were selected after extensive review of candidates, including preliminary modeling studies. Each study period was to last three months, and was designed to provide enough data for subsequent statistical analysis.

Two monitoring sites were located in one study area and one in the other. A fourth site, the Continuous Air Monitoring Station (CAMS) operated by the Oregon Department of Environmental Quality, was selected as a regional trend site. Meteorological and traffic data were collected at this site on a routine basis. Each monitoring site was equipped with a hi-vol sampler, a low-vol sampler, and a dichotomous sampler with a 2.5 micron size cutoff. Sampling periods were 24 hours in duration and appear to have run from midnight to midnight. The study was conducted during the dry season of May through October.

Sampling and Analysis. In addition to collecting daily ambient air monitoring and meteorological data within each study area, hourly and daily traffic counts were recorded in each study area, as was vacuum sweeper performance (daily sweeper logs were maintained by the operators). Road dust samples were collected from curbs, medians, and traffic lanes to check the efficiency of street sweeping and to provide a basis for comparing the chemical analysis of filters collected from the monitoring sites.

Quality assurance procedures that were followed are not discussed in detail in the report but are extensively referenced to sources including the Quality Assurance Handbook published by the EPA Office of Research and Development. No major problems associated with precision and repeatability of instruments were reported. Some traffic count data was lost due to damage to the counting equipment by vacuum sweepers.

Analysis of Results. For each monitoring site, the concentrations of TSP, IP, and FP were calculated directly from the hi-vol, lo-vol, and dichotomous filter weights. Filter samples were also analyzed by X-ray fluorescence for 17 elements. The "geologic component" was determined for composite road dust samples as well as for lo-vol and the coarse portion of the dichotomous samples in an effort to correlate the two by a chemical mass balance technique. (The geologic component is that component associated with elements common to soil.) Interferences due to industrial emissions would be highlighted by a large non-geologic component.

Two additional data sets were generated. The first was a set including only "dry" days, defined as days greater than one since the last rainfall of 0.01 inch or more; the second was a set of all days in the period of June 25 to September 17.

The experimental values were normalized to the CAMS (background) value by dividing the sample values by the CAMS values for the same period. Hence, the results of each site were normalized to those of the regional trend site. Data from each of the three sites were then subjected to a linear regression analysis.

Emission Factors and Control Efficiencies. None of the three sites showed a statistically significant effect on particulate air quality from vacuum sweeping. In other words, given the number of samples used, any measured differences in air quality between the two areas can be attributed to random variations in the generation of particulate matter rather than to the effect of the controls. It is possible that larger sample sizes may have resulted in statistically significant differences; however, because the number of samples in all cases already exceeds 30 samples, it is more likely that, given the conditions of the experiment, vacuum sweeping had no significant effect on particulate air quality. The geologic mass data suggest that, for two of the sites, sweeping may actually increase the concentration of particulates in the ambient air.

Because the results of the study did not demonstrate a significant air quality improvement from sweeping, the planned use of chemical mass balance techniques to combine meteorologic and traffic variables to develop a dispersion model capable of predicting the area wide effect of sweeping was not conducted.

Generally speaking, the conclusions presented are well founded in the results of the study. A pertinent point is made that an earlier study citing beneficial results from sweeping was based on sweeping the traveled areas of the roadways in addition to the curb lanes; only the curb lanes were swept in this study. Perhaps the reentrainment of dust from the travel lanes of paved roads is a major source of nontraditional particulate emissions. Any further research on vacuum sweeping should give attention to this area of the road surface.

Optional Investigations. One of the optional investigations undertaken in the Portland study involved elemental analysis of samples by X-ray fluorescence. Although conducted primarily to support the chemical mass balance approach, this analysis was useful in identifying interferences. For example, geologic sources of particulates generally exhibit aluminum-to-silicon ratios of less than one. However, it was found that several samples from one of the sites in an industrial area showed much higher ratios (as high as 30). Although the interfering source of aluminum particulate was not found, all samples with ratios exceeding one were deleted from the data base.

In order to be able to rule out reentrainment caused by the vacuum sweeper itself as a significant source of particulate matter, a source sampling method (Oregon Method 8) was used to test sweeper emissions under isokinetic conditions. The results showed sweeper emissions to be on the order of 0.125 pound per hour, a relatively small amount.

Usefulness to State and Local Agencies. As a result of this study, state and local officials should approach claims made for vacuum sweeping of paved roads with caution. The results of this study firmly support the conclusion that daily vacuum sweeping (at least as practiced in Portland for this study) does not significantly improve the particulate ambient air quality. An important finding may be that no beneficial effect was observed from daily vacuum sweeping of curb lanes, as opposed to travel lanes. Further study of curb plus travel lanes is warranted.

Another important aspect of the study was the observation of an interference and its subsequent removal from the results. The removal would have been even more justifiable if the interfering source had been identified. The measurement of the mineral content of collected samples, as practiced in this study to reveal the interference, is highly desirable if not mandatory for a study of this nature. This type of analysis should be weighed heavily by state and local officials in the evaluation of demonstration studies referenced by permit applicants.

The investigation of the vacuum sweeper itself as a possible interference represents an appropriate optional investigation. State and local officials should scrutinize demonstration studies for this type of evaluation of whether the control method itself represents a potential interference.

3.2 OTHER STUDIES

Several additional case studies are presented in lesser detail than the foregoing major studies. The purpose is to further define the state of the art for state and local agency officials.

3.2.1 Philadelphia, Pennsylvania

The Philadelphia study [5] was an early (1977) study of nontraditional particulate emissions. A major portion of the study consisted of a literature search, an emission inventory, an analysis of previously collected ambient TSP concentration data, and an analysis of field samples for several metals and for TSP levels as a function of location, such as heavily traveled urban streets and major construction sites.

A receptor-oriented demonstration study of street washing in the downtown area was quite limited and was intended to be only a minor portion of the study. The application of controls consisted of intensive water flushing of all streets in a 10-block downtown area for three consecutive days between the hours of 7:00 AM and 6:30 PM. TSP levels were measured by hi-vol samplers, recorded, and plotted for the periods before, during, and after flushing. Traffic volume in the study area was also measured during this period.

Because the control period was only three days, and because no attempt was made to statistically remove other independent variables, the results of this demonstration study were not verifiable. The tentative conclusion reached was that street flushing under these conditions actually increased the TSP concentration immediately after flushing. In analyzing this apparently anomalous result, the researchers statistically compared TSP levels with traffic volume, and found a strong correlation between the two. The researchers speculated that the street flushing program was not effective because the violent flushing of traffic lanes toward curbs and the splashing of the as-yet undrained water by vehicles essentially redistribute previously concentrated particles and, after drying, the particles may become reentrained.

Because this study was conducted several years ago, guidelines for its design and conduct were not available. Therefore, this control technology can not be evaluated unless further studies are undertaken and reinforced with complete statistical analysis.

3.2.2 Bangor, Maine

This study [6], conducted for the City of Bangor, examined the effects of vacuum sweeping of urban streets on ambient TSP concentrations during the period 1980 to 1983. The study made use of existing daily TSP measurements determined by two hi-vol samples located in the downtown business district and presumably operated by the city. The data spanned four street-sweeping seasons (March through October of each year), the first two years representing the uncontrolled period. When the sweeping program was initiated, data were collected for the following two-year period. A total of 223 data points were available for the uncontrolled period, and 569 for the controlled period.

The study report concludes that the vacuum sweeping program resulted in a reduction in ambient TSP concentrations of 20 percent, and that the statistical analysis of the data supports this conclusion. However, it is difficult to evaluate this analysis because statistical parameters such as standard deviations are not presented. Furthermore, it does not appear that a statistical analysis of the independent variables was conducted to explain differences in air quality during the two periods. Independent variables such as meteorological conditions or construction activity may have accounted for some of the difference in TSP concentrations for the two data sets.

3.2.3 Kansas City, Kansas

The Kansas City study [7] was conducted to determine the effectiveness of twice-weekly sweeping and flushing of paved streets in an industrial area. The study was receptor-oriented, measuring ambient concentrations of TSP only. Measurements were made before and after controls were implemented in a single downtown area. A Type 1 design was used because an "identical" test area could not be found. Hence, the study was subject to greater possible uncertainties than one using a Type 2 or 3 design. The study concluded that, given the parameters of the experiment, there was no statistically significant reduction in TSP concentrations in the area due to regular cleaning of the streets. A multiple regression analysis revealed that the four independent variables thought to have a major influence on TSP concentration had, in fact, a relatively minor influence and that many other variables were involved.

3.2.4 Lincoln, Nebraska

The Lincoln study [8] was conducted by the Lincoln-Lancaster County Health Department. This was a receptor-oriented study in which concentrations of TSP and IP were measured before and after application of liquid calcium chloride to unpaved gravel and crushed rock roads. Calcium chloride is a soluble crystalline salt that is applied as an aqueous solution for dust control. A line source formula was then used to convert the measured ambient concentrations into emissions on a mass per-vehicle-mile basis. A single application of calcium chloride was not found to be effective for TSP, but to be effective in reducing the concentration of IP by 70 to 80 percent (this reduction decayed to below 50 percent after about two-and-a-half weeks). However, a 65 to 80 percent reduction in TSP concentrations was found when applications to the unpaved roads were repeated at three to four week intervals. The study appears to have been a well-designed Type 1 study in which independent variables not of interest were properly removed by statistical analysis. Furthermore, the conclusions appear to be backed by an adequate statistical analysis of the results.

3.2.5 Clark County, Nevada

The Clark County study [9] was conducted by the Clark County Department of Health. This study had three major objectives:

- To estimate the relative cost-effectiveness of magnesium chloride and Coherex for dust control (magnesium chloride is a relatively soluble crystalline compound employed as an aqueous solution; Coherex is a petroleum resin used diluted with water)
- To study the effectiveness of alternative housing construction practices in reducing ambient particulate levels
- To study the effectiveness of emulsified asphalt on road shoulders in reducing ambient particulate levels.

All portions of the study were receptor-oriented and measured only TSP. The chemical dust suppression and housing construction experiments were Type 2 designs, and the road shoulder experiment was a Type 1 design. Magnesium chloride was found to be significantly less expensive to apply than Coherex; however, no information was provided concerning the effectiveness of the suppressants. The effectiveness of the unspecified alternative construction practices could not be determined because the two study areas were too close to one another. The effectiveness of the road shoulder technique could not be determined because of proximity of the study area to construction activities.

3.2.6 Erie County, New York

The Erie County study [10] was conducted by the Erie County Division of Environmental Control to assess the effectiveness of several dust control strategies in an industrial area. Three techniques were assessed: watering of storage piles (actually, notation of the effect of rainfall), oiling of unpaved roads and parking lots, and regular vacuum sweeping of paved roads. TSP was the pollutant monitored in this receptor-oriented study. Several hi-vol samplers were located throughout the study area, with at least one sampler located at each specific test site. The study presented great potential for interference among experiments, as they were all located relatively close to one another. The following conclusions were offered concerning the control efficiencies of the methods tested:

- o Watering storage piles -- no conclusion possible
- o Oiling unpaved roads -- 40 to 60 percent reduction in TSP
- o Oiling parking lots -- 40 to 70 percent reduction in TSP
- o Vacuum sweeping paved roads -- 40 to 60 percent reduction in TSP.

Several factors cast doubt on the reliability of these conclusions. First, each test consisted of only a few measurements (generally three to seven). It does not appear that a rigorous statistical analysis of test results was conducted. Also, while the possibilities for interference among test areas were numerous, the investigation did not seek to quantify the extent of this interference. Finally, the long-term reduction in the effectiveness of oiling was not addressed.

3.2.7 Allegheny County, Pennsylvania

An exhaustive study of nontraditional particulate emissions at U.S. Steel's Allegheny County steel plants [11] was conducted as part of a consent decree with EPA. A number of control methods were tested by surface sampling of road dust as well as by the exposure profile technique. Exposure profiling is a technique employing isokinetic sampling of several points across a dust "plume" cross section. Statistical analysis was performed on both of these source-oriented results to obtain control efficiencies. Measurements were made of FP, IP and TSP.

A control efficiency of 90 to 95 percent was given for control of unpaved roads where the control of paving the road and following with daily vacuuming. Applying Coherex to unpaved roads also achieved 90 to 95 percent control in the short term. The effectiveness of a single application of Coherex decreased after approximately 20 days; on the other hand, its effectiveness was found to be cumulative with successive applications. However, Coherex is considered to be relatively expensive. For paved roads, the control efficiencies were as follows: 80 to 85 percent for daily vacuuming, and 60 to 70 percent for twice-weekly vacuuming of moderately dusted roads; and 40 to 50 percent for twice-daily vacuuming of heavily-dusted roads.

The general elements of the study design were essentially fixed by the consent decree; however, the specific aspects of the design appear to have been well formulated and executed. Of particular usefulness are the development of emission factor equations (through multiple linear regression analysis) for the various control techniques tested, and the comparison of the emission factors calculated from these equations with those calculated from the experimental data.

3.2.8 The Road Carpet Study

The Road Carpet Study [12] was performed for EPA's Industrial Environmental Research Laboratory (IERL). The study assessed the effectiveness of a fabric "road carpet" to control emissions from unpaved haul roads. Two Type 2 design tests were conducted using controlled and uncontrolled contiguous road segments. The roads consisted of a crushed marble road at a western U.S. site and a crushed shale road in the eastern U.S. Both tests employed hi-vol samplers and hi-vols equipped with size-selective inlets to measure the ambient concentration of TSP and IP. The results for individual tests of control efficiency were as follows:

		Control Efficiency (percent)	
Road type	Region	TSP	IP
Marble	West	30-70	30-50
Shale	East	50-55	65-75

A significant decay in the control effectiveness from these values over several months was also noted. The study apparently did not employ extensive statistical analysis to further analyze these results. The conclusions must therefore be tempered with the knowledge that relatively few tests were run and many must have been of short duration. (During one period, four tests were run in one day.) Further testing with a thorough statistical analysis of results is warranted before employing the results of this study.

3.2.9 The Iron and Steel Plant Studies

Two studies of several iron and steel plants have been conducted for EPA's IERL. The first steel plant study [13] used exposure profiling (a source-oriented technique) to measure the effectiveness of several control methods for open sources of dust. For each experiment in this study, a single area was tested both in the presence and absence of controls. The study concentrated more on the decay of control effectiveness over time than on a statistical proof of the initial effectiveness of each measure. The researchers apparently reasoned that the methods had been previously established as effective, at least over the short term. Hence, the purpose of the study was to demonstrate the change in effectiveness over time. The parameters measured were FP, IP, and TSP; the results may therefore be useful for comparison with a future PM-10 regulation.

The treatment of unpaved roads with Coherex was found to be over 90 percent effective in the short term, with a slow decay over time. The efficiency of treatment with water alone decayed from almost 100 percent to 60 percent in only five hours. The efficiency of both vacuum sweeping and water flushing of paved roads was found to decay rapidly from about 50 percent, while for flushing with broom sweeping the efficiency decayed rapidly from approximately 70 percent.

The decays in effectiveness were not quantified or discussed explicitly in the report, but they were obvious from the emission factors developed from the exposure profiling results. Conclusions for control of coal storage piles were tenuous at best due to numerous experimental difficulties, such as interference from precipitation and the contamination of filters by particles that were not airborne. The study appears to have been well designed and conducted; however, future work should concentrate on repeated testing of the decay in control effectiveness for a specific technique, with a thorough statistical analysis of the results.

The second or extended evaluation study [14] was also conducted for the IERL. The study was designed to provide further information on the effectiveness of dust suppressants on unpaved roads. Exposure profiling was used to measure emissions under controlled and uncontrolled conditions. The results were expressed in terms of decay rates or lifetime of effectiveness, the latter expressed in terms of the number of vehicle passes. Variations in vehicle weight, number of wheels and vehicle speed were statistically removed by a normalization procedure based on a previously developed algorithm relating the emission factor to these three independent variables. Effectiveness decay rates were determined by a regression analysis, and were plotted for each control method. The PM-10 fraction was measured in addition to TSP, IP and FP.

"Petro-Tac" (an emulsified asphalt) on an unpaved road was found to have an effective lifetime of about 100,000 vehicle passes for the control of TSP. Effective lifetime in this case was defined as the time required for the effectiveness of the control to decay essentially to zero. The control efficiency of spraying water was initially high but decayed at a rate of about 8 percent per hour. For Coherex, the results indicated a life of 7,500 vehicle passes for a single application and 45,000 for a repeat application. As with the earlier study of this type, the results are contingent upon the formulations and application rates used.

The study appears to have been well designed and conducted. A significant number of samples were taken, and the analysis of the data is comprehensive. Results were reported for IP, FP and PM-10 as well as for TSP, and the variations in decay as a function of particle size are discussed in detail. The information on effective lifetimes perhaps would have been better presented as the time required to decay to 75 percent or 50 percent effectiveness because, as a practical matter, a source would have to reapply the controls long before the effectiveness had decayed to zero.

Chapter 4

CONCLUSIONS

The Workbook: Demonstration Studies for Control of Nontraditional Particulate Sources contains explicit instructions for the design and execution of a conclusive and cost-effective demonstration study of control technologies. However, the studies reviewed here exhibited a variety of problems in study design and also in execution which resulted either in no conclusions concerning the control technologies tested or in conclusions that were difficult to support and not broadly applicable. The following studies were conducted appropriately without major deviations from good study procedures. These are Portland, Oregon; Lincoln, Nebraska; Kansas City, Kansas; Allegheny County, Pennsylvania; and the Iron and Steel Plant studies. However, the remaining studies suffered from inadequate designs, in some cases because the Workbook guidelines were not available. The following cautions and recommendations are offered to both study designers and those who must evaluate studies, particularly studies offered in support of bubble proposals or similar plans for particulate compliance:

- The Workbook has been assessed and found to be an excellent guidance document which, when carefully followed, will greatly enhance the likelihood of success of a demonstration study.
- A proper demonstration study is expensive to design and conduct; however, a study that is not done properly will produce results that cannot be applied in the field. Therefore, there must be a firm commitment to a complete and proper study and effective coordination and management of the study throughout.
- A demonstration study must be extremely well designed in order to produce usable results; furthermore, the execution of the study must rigorously follow the design. Cost-cutting ideas for fewer monitors, less frequent application of controls and so forth must be avoided so as not to invalidate the results and the subsequent statistical analysis.
- In order to be applicable in the field, results from a demonstration study must be statistically significant. The study design, therefore, must ensure that the statistical analysis selected is correct for the type of study and that a sufficient number of samples are taken. Careful coordination and control of the control/no control arrangements of the study are also required.

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