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EXHAUST STACK MONITORING ISSUES
AT THE WASTE ISOLATION PILOT PLANT

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NOTICE TO THE READER

The Environmental Evaluation Group (EEG) was assigned to the New Mexico Institute of Mining and Technology in October 1988 by the National Defense Authorization Act, Fiscal Year 1989, Public Law 100-456, Section 1433, and is no longer a part of the New Mexico Health and Environment Department, Environmental Improvement Division. Continued funding is being provided by the Department of Energy through Contract DE-AC04-79AL10752.

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FOREWORD

The purpose of the Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the potential radiation exposure to people from the proposed Federal Radioactive Waste Isolation Pilot Plant (WIPP) near Carlsbad, in order to protect the public health and safety and ensure that there is minimal environmental degradation. The EEG is part of the Environmental Improvement Division, a component of the New Mexico Health and Environment Department -- the agency charged with the primary responsibility for protecting the health of the citizens of New Mexico.

The Group is neither a proponent nor an opponent of WIPP.

Analyses are conducted of available data concerning the proposed site, the design of the repository, its planned operation, and its long-term stability. These analyses include assessments of reports issued by the U. S. Department of Energy (DOE) and its contractors, other Federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP.

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EXECUTIVE SUMMARY

The problems of obtaining valid, representative samples of, and continuously monitoring for, radioactive particulates in the discharge air from the underground disposal facilities at WIPP have been particularly challenging. The Environmental Evaluation Group (EEG) involvement in the attempted resolution of these problems has taken three forms:

1) EEG has undertaken detailed reviews and critiques of the concepts, bid specifications, and designs of the flow conditioning and isokinetic sample extraction equipment for WIPP. This is an ongoing process due to the fact that there appear to be serious problems with the presently installed systems. Chapter 1 of the report provides an overview of current EEG perspective on the major issues regarding these systems. The principal conclusions of the overview are that the present sampling locations are not optimum for the intended purpose; that the chosen probe design is not capable of meeting ANSI requirements for delivery of a representative sample to the detectors; and that the proposed test plan for the flow conditioning and monitoring system is seriously flawed.

2) Due to the highly technical nature of the problems of extractive stack sampling and monitoring, EEG early in the discussions called for a peer review of the WIPP proposed design concept by experts in the field. The peer review lead to recommendations which would enhance the chances of successful approaches being taken. Chapter 2 is a summary of the major findings and recommendations of the peer review conducted by EEG with participation by WIPP/DOE and outside experts. Among the major findings of the review are the judgement that the proposed flow conditioning concepts were likely to be an unworkable substitute for having adequate duct length between major disturbances in flow and the sampling or monitoring locations; that the use of probes of simpler design with large diameter inlet nozzles feeding short transmission lines would provide superior performance; and that conditions for monitoring discharge air would be far better ahead of the collar in the exhaust shaft than any location downstream, including the one selected by Bechtel.

3) Due to the unique role EEG must play in the review, oversight, and validation of DOE's own surveillance and monitoring activities on, and off-site at WIPP, DOE and the State of New Mexico formally agreed at the outset that EEG must be prepared, and be permitted to conduct reasonable monitoring of WIPP operations and environmental discharges. Currently there are both high and low volume air samples being collected in nearby towns, around the perimeter of the facility, and on-site itself.

Recognizing the difficulty and reliability of regional sample estimation of actual stack discharges, EEG has repeatedly requested support and permission from DOE to conduct in-stack sampling for discharge estimation purposes. Negotiations with WIPP/DOE have progressed to the point of a request by WIPP for a detailed conceptual design of a proposed state fixed air sampling system. With the technical assistance from Southern Research Institute, such a design has been prepared and presented.

Chapter 3 contains the detailed technical basis for a conceptual design, and a proposed sample extraction system for the stack discharge location. Thus the report's three chapters correspond to each of the three elements of EEG's response to problems of stack sampling and monitoring at WIPP.

RECOMMENDATIONS

In light of the technical critique of the present system and independent assessment of workable alternative approaches to monitoring and sampling of stack discharges, there are several recommendations to be made:

1) The sample extraction system (isokinetic probes) for both the Fixed Air Sampler (FAS) and the Continuous Air Monitors (CAMs) should be redesigned such that the full range of particle sizes which are considered significant in evaluation of human health and safety will be represented on the filter. Such a design criterion is only reasonable in the circumstances at WIPP since the physical characteristics of potential accident generated aerosols are unknown, but could well be in this range. Further, the greatest hazard potential of aerosols generated in TRU waste is from inhalation exposure.

2) Reliance on mechanical systems to provide conditions suitable for extractive sampling should be minimized or eliminated. A highly suitable environment for monitoring at Station A already exists in the shaft ahead of the collar. At Station B, and with the new southern extension, an unobstructed extension of the duct may be the only straightforward flow conditioning approach to take. It may be necessary to study the alternatives for Station B through the use of quarter-scale models and velocity mapping in these ducts in the absence of any flow conditioning apparatus.

3) An integrated approach to extractive sampling system design for the CAMs which takes into account both the needs of sample extraction and transport (i.e., suitable inlets, large diameter, short, and vertical transport lines, etc.), and the needs of the CAM detector (i.e., sample geometry, limited accumulation of nuisance salt dust, electrical and electronic needs, etc.) should be undertaken. The resultant CAM system might well follow the presently planned FAS approach with the detector placed directly under the stack as recommended by the peer review.

4) A thorough testing of whatever sample extraction system is chosen should be undertaken. Although the proposed ITRI testing protocol covers most of the needed tests to demonstrate system performance, the addition of tracer aerosols which would reveal the response time characteristics of the system should be made. As Schwendiman indicates (27), if one purpose of a monitoring system is to monitor during emergencies, not only must the dynamic range of the sensor in the monitoring instrumentation be addressed, but also the speed of response of the system to a step input. He recommends the use of a dispenser of dry, well characterized particles which could contain pigments, oxides, sulfides, carbonates, fluorescent/phosphorescent particles, or crystals as tracers. Analysis could then be both gravimetric and selective by simple, but precise chemical or optical methods.

5) In conjunction with any proposed tests of the ability of a sampling probe to extract and deliver a representative sample to a filter in a reasonable time, there must be developed a detailed set of performance and acceptance criteria. The present lack of such criteria in the Bechtel test plan should be remedied. A recommended addition would be that the sample extraction system be capable of delivering at least 50% of the 10 μm AED particles to the filter.

EXHAUST STACK MONITORING
ISSUES AT THE WASTE ISOLATION PILOT PLANT

OVERVIEW OF THE ISSUES

1.1 Introduction

The Department of Energy is constructing a waste disposal facility in New Mexico called the Waste Isolation Pilot Plant (WIPP), designed for the disposal of Department of Energy Transuranic (TRU) waste generated from defense program activities. These wastes, containing concentrations of plutonium in excess of 100 nanocuries per gram of waste, will be disposed in a deep geologic formation of bedded salt at a depth of 2100 feet. The authorized volume of waste to be disposed in this facility is 6.3 million cubic feet. Under provisions of an agreement between the State of New Mexico and the Department of Energy (DOE), the DOE has agreed to fund a State environmental surveillance program on and off site at WIPP, which will provide an independent evaluation and verification of the results of DOE's own environmental surveillance program. Both split samples and independently collected samples are involved in this joint effort. The State program is being carried out by the Environmental Evaluation Group (EEG) within the State of New Mexico Environmental Improvement Division.

A major component of the environmental surveillance program at WIPP is air monitoring. Discharges to the atmosphere constitute one of the major potential release pathways at WIPP due to the characteristics of the waste handling operations and the design of the exhaust air system from the underground disposal areas.

There are four surface locations where discharge air monitoring and sampling are planned by DOE: in the exhaust duct upstream of the Exhaust Filter Building (Station A), in the exhaust duct downstream of the Exhaust Filter Building (Station B), in the exhaust duct of the Waste Handling Building near the point of discharge (Station C), and in a recently added exhaust duct to the south of the exhaust shaft (Station D). (These locations are shown in Figures 1, 2, 3, and 4). It should be noted that the discharge air from the Waste Handling Building is 100% HEPA filtered and the corresponding stack monitoring system is situated in filtered air. In contrast, the air from the underground storage area is not normally filtered. Only in the event of a release of radioactivity which is detected, is exhaust air shunted through the Exhaust Filter Building. This is accomplished by closing the diversion valves in the main exhaust duct forcing the air to flow through the HEPA filters in the Exhaust Filter Building (see Fig. 1). Station A is part of the Effluent Monitoring Systems (EMS) which is designed to detect releases in discharge air and cause the air to be filtered if control limits are exceeded. The original design of the exhaust system at WIPP called for a single 10 ft. diameter duct connecting the exhaust shaft to the Exhaust Filter Building (Fig. 1). However, a 1987 change in ventilation design calls for an additional inlet air shaft and additional discharge fans which will nearly double the flow through the underground facility. As shown in Fig. 3, the discharge air 9was originally planned to exit the exhaust shaft through a 90° bend and immediately encounter the monitoring probes at Station A. The new design calls for replacing the 90° elbow with a plenum structure with flow being equally divided between two ducts (See Fig. 4).

Because the discharge air from the Waste Handling Building is continuously HEPA filtered, there is very much less concern for accidental releases to the environment by this discharge, and there is also much less chance of malfunction of the monitoring probes due to buildup of particles in nozzles and lines. (However, there is still a need for the same performance capabilities of this monitoring system). Hence the focus of the following discussion is on the Station A, Station B, and Station D systems monitoring the underground facility exhaust air.

Continuous air sampling in the WIPP underground exhaust air is planned for three purposes: a) the detection of a release of radioactivity in the exhaust air at Station A, which would result in the generation of a signal to cause diversion valves in the existing exhaust duct and in the new exhaust duct to the south to close, thereby forcing the airstream to flow through a HEPA filter bank before discharge to the environment, b) the continuous monitoring of radionuclide discharges at Station B with alarm capabilities but no connection to the diversion valve control, and c) the collection at Station B and the new station in the south duct of a representative sample of the radioactivity in the air being discharged to the environment (filtered or unfiltered). The system for continuous extraction of a sample for detection purposes will be referred to in this report as the Isokinetic Monitoring Probe (IMP) System which supplies a sample to the Continuous Air Monitors (CAM) containing radiation detectors. The system for obtaining a representative sample of particulate discharges will be referred to as the Fixed Air Sampling (FAS) system. In the present WIPP design, the FAS obtains sample aerosols from the same IMP Probe design as the CAMs. In the last chapter an alternative proposed design for an FAS probe is described, which is believed to be capable of much improved performance.

In the following sections a number of critical issues related to the specification and design of these systems will be briefly outlined to establish a context for the detailed review of the WIPP plans, procedures and equipment for stack monitoring and sampling and recommendations of EEG on this issue. Although some of the discussions refer to a 90° elbow in the exhaust duct and its effects on the velocity and particle profiles at Station A, this feature is no longer planned. However, the same sort of problems may well persist with the new plenum design.

Following the Chapter 1 overview, Chapter 2 is a detailed synopsis of the results of a Peer Review Meeting on the WIPP Stack Monitoring System held in Santa Fe, NM November 14, 1986. The agenda of the review included aerosol characterization, location of sampling stations, sample extraction

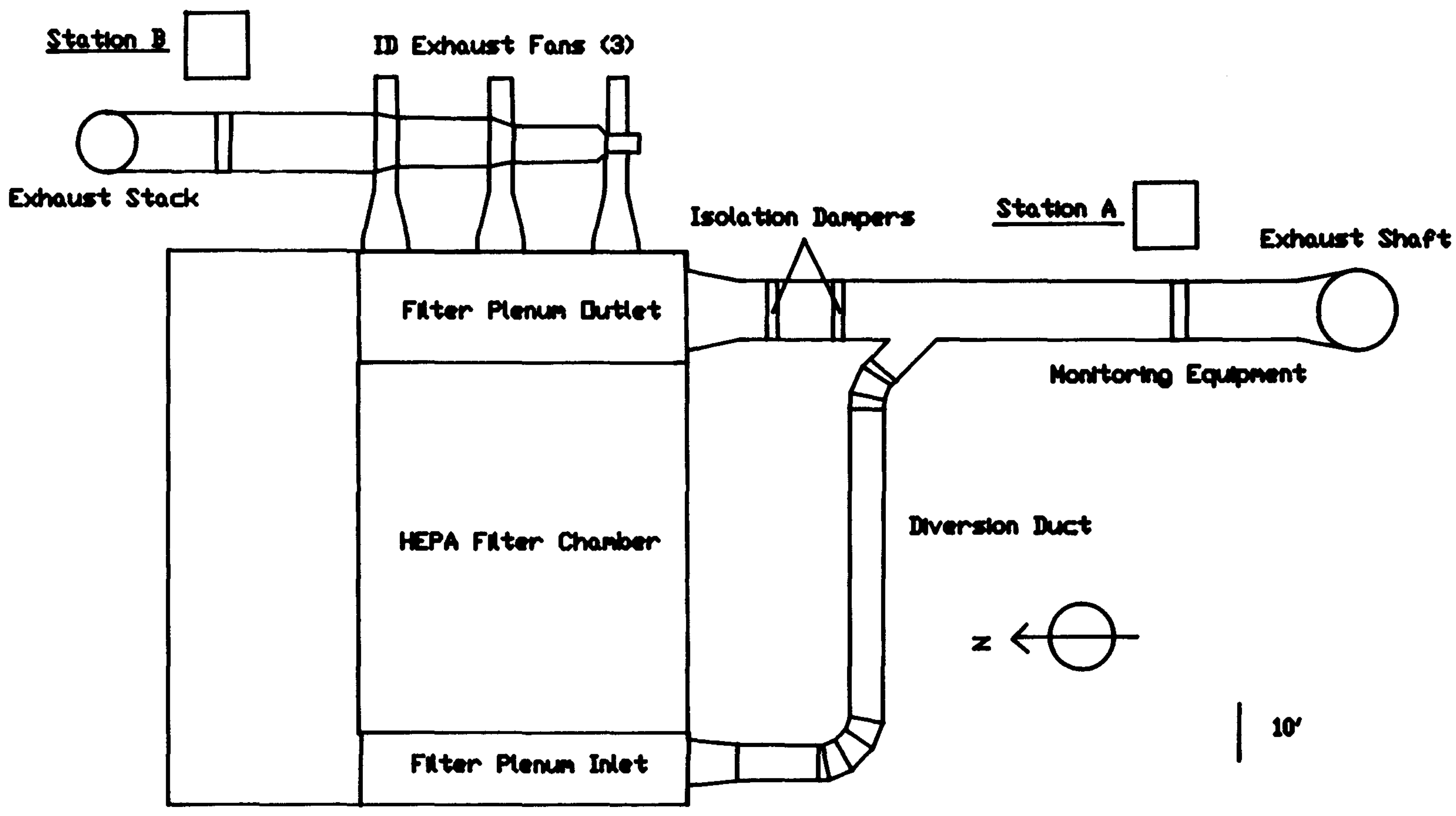
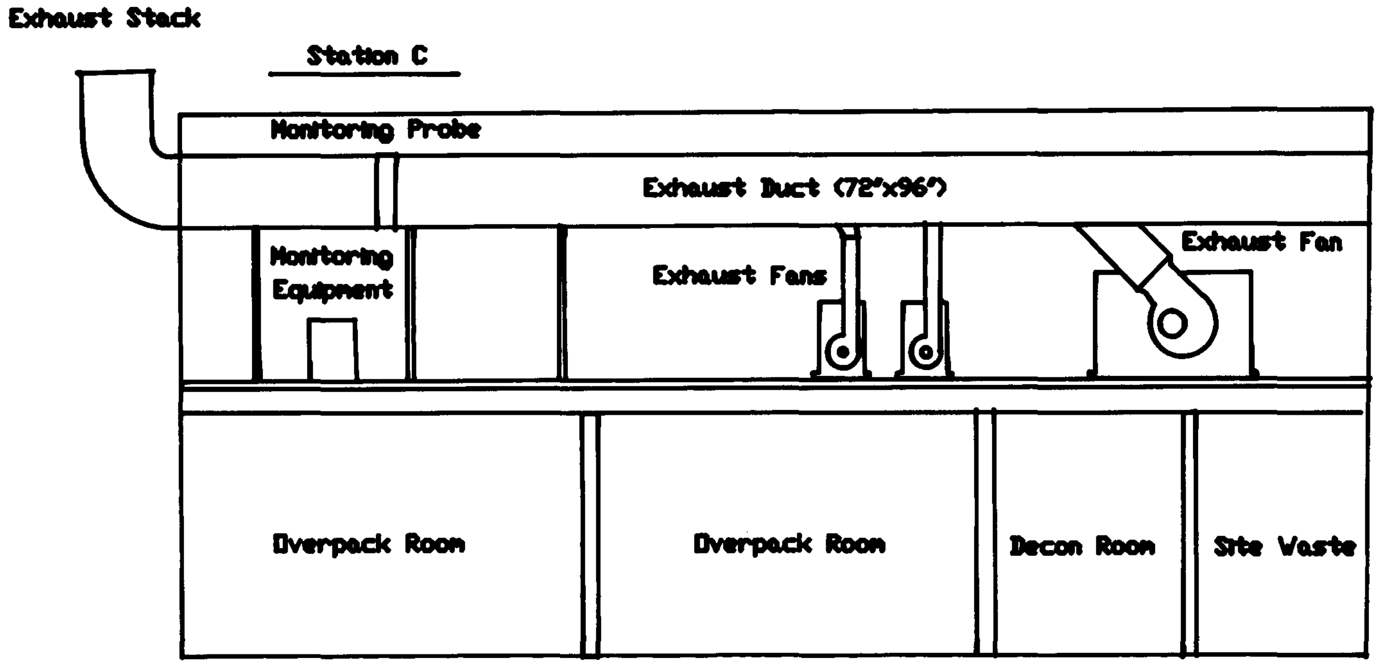


Fig.1 Exhaust Filter Building (Plan View)
Station A and Station B

Fig.2 Elevation Cross-Section of the Waste Handling Building Exhaust Stack and Station C



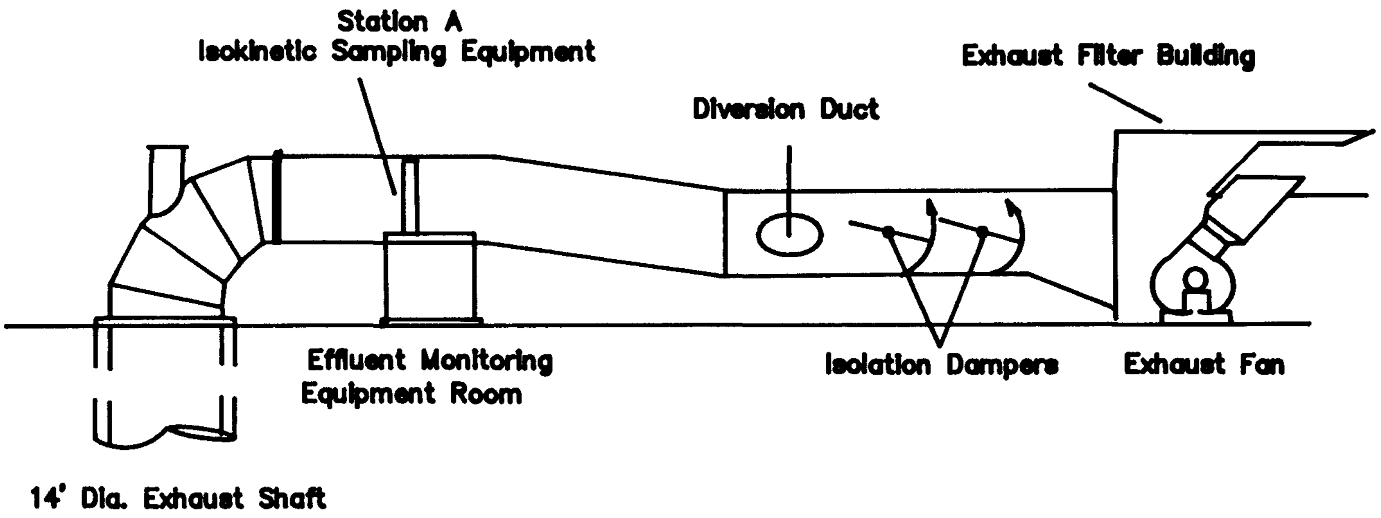


Fig. 3 Elevation View Station A,
Original 90–Degree Elbow, and Dampers

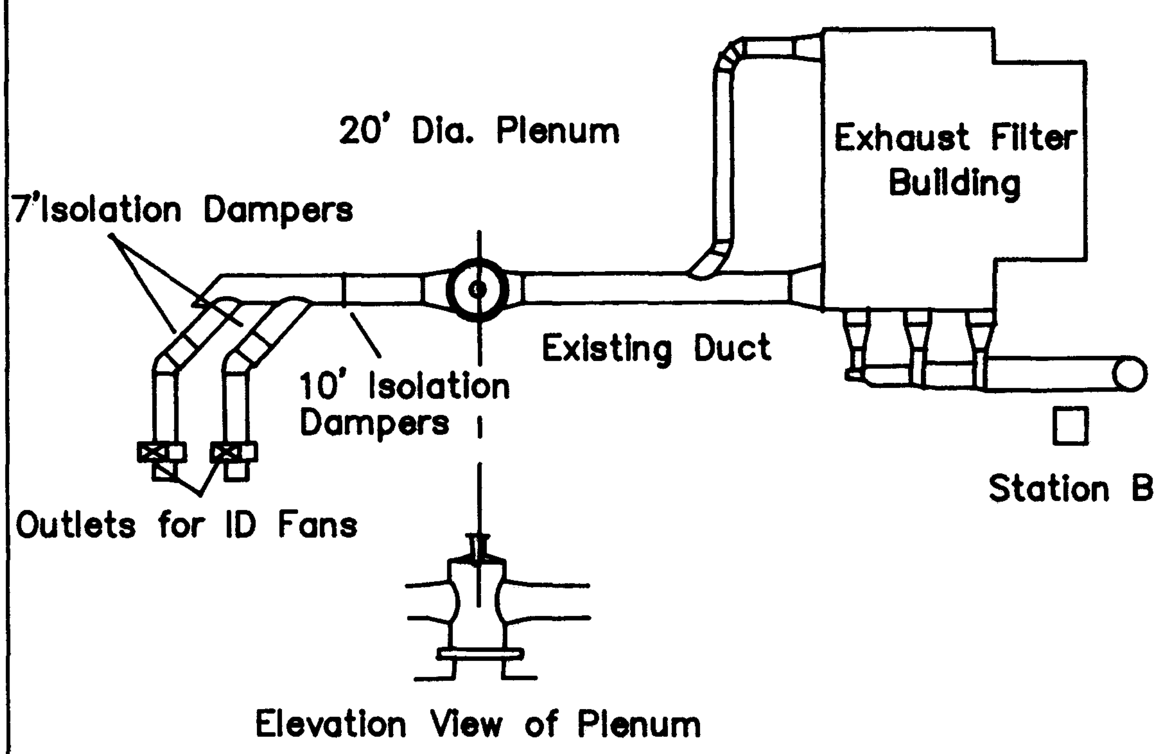


Fig. 4 Modified Exhaust System Plenum, South Duct, and Dampers

system design and transport line design. Chapter 3 presents a conceptual design of a separate FAS nozzle and transport line. The design implements all of the recommendations of the Peer Review for an FAS system and insures transmission of a truly representative sample.

1.2 Isokinetic Sampling Probe Performance Specification

In the current IMP design at WIPP, aerosol sample extraction from ducts is accomplished using small diameter multiple nozzle probes. The only performance specifications identified for such systems is a reference to ANSI Standards N13.1 (3) and N42.18 (4). The Bechtel design requirements include: a) the requirement that the filter and detector mechanism be attached to the IMP such that the sample filtration point is as close as possible to the sample extraction point(s); b) that the number of nozzles shall provide a representative sample within the constraints of sample flow rate and nozzle inside diameter, and c) that the sample probe shall be designed such that the full range of particulate sizes encountered in the duct shall be represented by the extracted sample (7).

While the requirement of "representativeness" of the sample is evident, no mention is made of what this means in terms of the expected performance of the probe and transport line expressed as the percentage of particles up to a specific size which would be expected to be delivered to the collection filter of the detection system or fixed air sampler. A requirement that the IMP and FAS systems be capable of delivering at least 50% the 10 micrometer aerodynamic diameter particulates, which defines the EPA inspirable particle size limit, would have greatly clarified the performance requirement, and is recommended by EEG. It might be thought that although transuranic aerosols in the size range of 10 micrometers aerodynamic equivalent diameter (AED) are indeed inspirable, they should be of lesser concern than smaller sizes since large particles are almost all deposited in the nasal passages when inhaled. Indeed, the inhalation dose commitment from large diameter, insoluble (class Y) aerosols is lower than for one micrometer particles. But for soluble (class W) forms of plutonium, and for americium generally, the inhalation dose commitment is actually larger from 10 micrometer AED particles. Hence, the stated probe performance specification is amply justified on health and safety grounds. Specification of particle size and quantity delivered to the filter would also provide a clear basis for performance testing of any chosen system. At present, no clear-cut performance test for particulate extraction and transport to a filter has been identified.

1.3 Isokinetic Sampling Probe Location

Bechtel specifications for the isokinetic sampling probe system call for the contractor to determine whether the probes for Station A are to be located ahead of, or downstream of, the bend in flow from the exhaust shaft to the duct. The locations of Station B and Station C were specified by Bechtel, including the length of duct between major disturbances in flow and the location of the probes. These specifications are central to the discussion of whether the ANSI N13.1 requirement (paragraph 4.2.1.2) that sample extraction not be allowed any closer than 5 stack diameters downstream from a major disturbance in flow has been met. Neither the contractor's current design nor the original Bechtel conceptual plan for Stations A, B, or C meet that requirement.

The Station A probe location was chosen by the WIPP contractor to be immediately downstream of the 90° elbow originally planned to couple the discharge from the underground shaft to the exhaust duct. As mentioned, the present exhaust stack design calls for the 90° elbow to be replaced by a plenum structure to be placed on top of the exhaust shaft in order to accommodate a larger flow through the underground facility (Fig. 4). The effects of the plenum on sampling conditions at Station A are unknown, but may be at least as severe as the bend in terms of velocity profile inhomogeneity and stability.

It is significant that as of mid-July 1987 no preoperational measurements had been made of velocity or particulate profiles at the proposed extraction locations in the above ground exhaust duct. A Bechtel test plan (to be discussed below) was announced for August 1987, but was postponed indefinitely due to apparently poor performance of the installed flow conditioning systems. As a result, no empirical data on expected conditions for sampling are available for inclusion in design and performance specifications. Data on velocity and aerosol profiles and behavior in the underground exhaust shaft portion of the facility exhaust have recently (March 1987) been collected by the Inhalation Toxicology Research Institute (ITRI) but were not reported prior to the development of Bechtel's test plan and acceptance criteria for the current IMP system. Preliminary indications are that the ITRI study confirms peer review predictions that the optimum location for extracting a representative sample of aerosols in discharge air upstream of the Exhaust Filter Building would be a point near the top of the exhaust shaft. Since a plenum structure is now being designed to replace the 90^{o} elbow (see Fig. 4), an excellent opportunity exists for redesign of an IMP system for Station A which takes advantage of the ideal sampling conditions in the exhaust shaft demonstrated by ITRI measurements.

It is also significant that no preinstallation performance tests have been performed on any of the components of the IMP system which has been delivered to the WIPP site. As of October 1987, it appears that no in place testing of the delivered system will be attempted due to the difficulties with the flow conditioning system installed. An independent consultant has been contracted by the WIPP Project Office to review the entire discharge monitoring system and make recommendations to resolve the current problems.

1.4 Sample Extraction Probe Design

The design of continuous sample extraction system for obtaining representative samples from a large diameter duct such as the exhaust duct at WIPP is very challenging, particularly due to the fact that the discharge contains so much salt dust. The transfer of stack sampling system technology developed for the large diameter ducts of nuclear power plants would appear to be inappropriate for WIPP inasmuch as the discharge airstream is HEPA filtered in those plants but is not at WIPP. Yet such an attempt appears to have been made by the current contractor with his proposed design. At an information exchange meeting on his system design (9), the contractor was asked what data are available that demonstrate the efficacy of the proposed flow conditioning apparatus and the use of a large number of small diameter nozzles for sample extraction. He claimed that while none of these components has been subjected to controlled tests, they have received de facto acceptance by the Nuclear Regulatory Commission (NRC) by virtue of unchallenged installation in a number of licensed nuclear power plants. When this claim was brought to the attention of NRC staff (9), their comment was that by virtue of the probe assembly placement in HEPA filtered air downstream of primary radiation detection systems within reactor containment structures, the performance testing and certification requirements for primary systems are not required. Hence it is, to say the least, strongly misleading to suggest that such a system has been "de facto accepted" by NRC, implying some sort of testing and endorsement of general suitability for nuclear installations.

Good extractive sampling probe design, as recommended in ANSI N13.1, emphasizes the importance of beginning the design process by making a judicious estimate of particles present or of interest. In the case of WIPP, the particles normally present are salt aerosols and diesel exhaust. The particles of interest are those potentially present as a result of accidental releases underground. In order for the monitoring systems to properly detect releases and to evaluate health hazards, they should deliver at least 50% of the 10 μm aerodynamic diameter particles to the CAM and FAS filters. This can only be achieved by avoiding small diameter nozzles, long transport lines, and abrupt changes in flow direction. The data in the Appendices of ANSI N13.1 emphasize another critical factor, that in order to adequately transport larger size particles (greater than a few microns), a large transport tube is needed.

None of these considerations seem to have factored into the design of the present system, which is characterized by numerous small diameter nozzles, numerous bends, long transport lines and small diameter tubing. The rationale behind this approach was stated to have been that re-entrainment effects would essentially limit sample losses and hence the need for careful consideration of transport line design was obviated. When the ANSI cautions were mentioned to the contractor (9), his response was that their data on deposition losses were valid only for clean probes under grab sample conditions. When operated as continuous probes, he claimed a different set of data would be obtained, and, therefore, the ANSI guidance was of limited scope and is outdated.

Although the particulate penetration studies planned for the WIPP sample probes have not been carried out as of October 1987, the empirical models discussed in Chapter 3 indicate that deposition losses would indeed be as severe as indicated in the ANSI standard.

Separate contracts were let for the sample extraction system and for the fixed and continuous radioactivity sampling and detection systems. As a result, the sample extraction contractor has designed a nozzle array, manifold portion of the transport line, and a stack velocity sensing system which must interface with another contractor's continuation of the same transport line. This includes a section of transport line containing a splitter block which feeds two radiation detectors, and associated pumps and controls valves. Aside from the obvious interface requirements such as that the transport line diameters are equal and that the extraction system be capable of handling the flow that the CAM pumps generate, no individual contractor apparently has had the full responsibility of meeting even the generalized performance requirements described earlier. For example, the transport line flow requirement for each CAM, which is based on considerations of collecting a sufficient sample for detection, while at the same time avoiding rapid plugging of the filter due to too high a sample rate, may not at all match the requirements for flow in the extraction nozzles and the transport line which will deliver an adequate quantity of a representative sample to the filter. Experimental findings discussed in Chapter 3 make it clear that flow rate in the transport line has a significant effect on loss of sample. At the same time, the rapid buildup of salt dust on the CAM filter operated at high sampling rates could seriously degrade CAM performance. Although the nozzle diameter of the proposed IMP systems was apparently designed to provide isokinetic sampling flow at the maximum combined alpha and beta CAM extraction rate, no consideration was apparently given to the consequences of flow conditions in the transport line for sample bias and loss in transport by either contractor.

The present isokinetic probe design is based on sensing stack velocity by means of pitot tubes with the delta-pressure signal being converted to a mass flow equivalent voltage signal passed on to the CAM system. These CAMs are designed with transport line flow control maintained by mass flow sensors (thermoanemometers). These mass flow control devices are positioned downstream of the filters, and upstream of an electrically operated flow control valve. Either a manually set or automatic set-point voltage (0-5 VDC) can be used to set a constant mass flow through the system regardless of pressure differential increase across the filter but which tracks the velocity of the stack flow. The uncertainties and inaccuracies in maintaining true isokinetic sampling conditions in the combined system are then a product of the errors associated with the pitot tubes themselves (i.e., effects of plugging with salt dust, response at low flow), the pressure transducer (i.e. temperature sensitivity, limits of response to pressure differentials), and flow controller and flow control valve (i.e., inherent "dead band" of response of the controller control valve-mass flow sensor loop, and calibration errors). The combined effects on representative sampling of these problems could be considerable, but are unknown. At the lowest duct flow (60K CFM) the velocity may be difficult to track using an array of self-averaging pitot tubes with good accuracy, and the extreme range of flow (60K-210K CFM) may not be accurately covered. If the set point derived from such a pitot system is erratic or unreliable, the entire sampling train will not function isokinetically. If the flow conditioning system used does not provide sufficiently flat and stable conditions, the use of an average velocity derived from a pitot tube array may lead to serious errors.

An alternative approach based on single point sampling with a large diameter nozzle and transport line incorporated in an FAS probe design with its own flow sensor, pump and control system independent of the CAMs is discussed in Chapter 3. If properly placed in the stack flow, well removed from major disturbances, it should deliver highly representative samples. A similar approach using large diameter inlet nozzles and transport tubes could considerably improve the performance of the CAM probes as well.

Besides concern for the proposed sample extraction air flow control system being capable of sampling isokinetically, there is concern for whether a sufficient quantity of a truly representative sample of particulates can penetrate the entirety of the nozzle and sample transport line system and be deposited on the filter at the detector. As previously mentioned, the State's position is that the sample extraction system should deliver at least 50% of 10 micrometer aerodynamic equivalent diameter (AED) particles to the filter in order to properly evaluate releases and health hazards. The results of calculations of the anticipated performance of the presently proposed system at WIPP (to be discussed below) suggest that it will not meet this requirement. Although the Bechtel bid specifications require that each bidder submit an estimate of the projected distortion of the representative sampling characteristics of their proposal sampling system for the record prior to installation (7), the State has been unable to obtain a copy of this submittal of the successful bidder from the WIPP Project Office. The reason alleged was that it contained proprietary information.

1.5 Modeling Sampling System Performance

The ideal means to assure that a given sampling system design will in fact meet minimum performance criteria under the range of sampling conditions expected at WIPP is to subject completed sampling trains to particle transmission testing under laboratory controlled conditions. The present monitoring system at WIPP was not tested in this way before installation. In order to estimate its expected performance characteristics in the absence of test results, conservative models of the principal mechanisms for sample distortion, including impaction in nozzles, inertial losses in bends, gravitational settling, and turbulent diffusion, have been developed for EEG by Southern Research Institute from a variety of sources in the contemporary research literature. These are described in detail in Chapter

3. The action of each of these mechanisms on particle deposition losses can be combined by the reasonable assumption that the effect on sample transmission are multiplicative (27).

As will be shown in detail in Chapter 3, each of these models of deposition due to a particular mechanism have a strong empirical basis. Losses from more than one mechanism have usually been controlled in given experimental investigations, but there are possible exceptions to be noted. For example, the model of Okazaki of deposition at nozzle entrances includes, in addition to the effects of disturbances in flow induced by the nozzle itself, deposition due to settling and turbulence in a 20 cm length of tubing downstream of the nozzle. The processes of turbulent deposition and gravitational settling may both be present in a given sampling system, and could be represented in the data. However, for electrically neutral aerosols larger than about 1 μm AED, the predominant deposition mechanism is due to particle inertia (turbulent deposition), provided the pipe is oriented vertically (16). In the WIPP case to be discussed below, a portion of the transport tube is inclined with respect to the vertical. In this situation there will be some tube flow/particle size combinations for which one or the other of gravitational or inertial effects dominate. Both effects have been modeled for the WIPP transport system. The dominant loss mechanism was selected to represent particle transmission through the tube for that case. In this way a conservative estimate of transmission losses were made in the absence of more specific experimental models of transport in inclined tubes.

The flow conditions of the WIPP stack are quite high and variable. The normal flow at 210,000 CFM corresponds to a stream velocity in the range of 1500 cm/sec, and the turn-down velocity of the discharge air when HEPA filtered is about 450 cm/sec. Much, but not all of the data and models in the literature have been developed from laboratory wind-tunnel and other experimental equipment operated at lower flows, which raises the question of the suitability of extrapolations to the conditions of sampling at WIPP. In the case of the model for deposition in inlets, the flows used were in th range 125 - 1000 cm/sec, which is comparable to the WIPP conditions.

Although minor extrapolation on the high velocity extreme is necessary, it is within a region where the model should still be applicable. The model for turbulent deposition was developed under flow conditions of about 500 cm/sec. which is well within the range of tube velocities studied. As will be shown in the discussion of this model in Chapter 3, the effect of higher flow rates in small diameter transport tubes is to decrease penetration by 10 μm or larger particles.

One effect which could cause an overestimate of deposition losses in nozzles and transport tubes by the proposed models of is particle bounce and re-entrainment. This phenomenon is of particular interest in the context of the sampling system for WIPP. As was noted in Section 1.4 it has been claimed by the WIPP sampling probe contractor (9) that during the process of continuous sampling of dry aerosols, such as the WIPP salt dust, a thin layer of deposited aerosols would be deposited, and then particle bounce and re-entrainment would occur such that further deposition by all the aerosol would be very significantly reduced or eliminated so that the length of transport lines should not be of concern.

An analysis of the probability of particle deposition in pipes from fluid streams has been made by Beal (6). Beal was able to demonstrate a significant correlation between sticking probability, p, and dimensionless stopping distance, S^+:

$$\begin{aligned} p &= 1, & S^+ &\leq 4.5 \\ p &= (4.5/S^+)^3, & S^+ &\geq 4.5 \end{aligned}$$

A number of cases have been simulated with deposition loss models incorporating the above model of Beal to investigate the probability of sticking under a range of flow conditions and particle sizes likely to be encountered in model applications. The results indicate that for particles smaller than 10 μm the probability for sticking is essentially unity. For larger particles, the probability of sticking significantly declines, mainly at high flow rates due to particle bounce. Based on these results, the hypothesis that there will be a significant reduction in deposition loss during continuous sampling for particle sizes of concern (0.01 μm - 10 μm) is very unlikely to be true for the WIPP aerosols, including accident generated aerosols. That is, it is reasonable to presume that particles once deposited will stick, and continue to stick as continuous sampling proceeds.

The several models of deposition loss in Chapter 3 have been assembled into a single computer model of sampling transport line penetration by aerosols as a function of transport line geometry, sample rate and particle size (see Appendix A for details). The most direct test of the validity of the proposed combined model is a comparison of model predictions with experimental data obtained under conditions approximating sampling probe configurations and size of interest. For the present application, the experimental data of Strom (30) on transmission efficiency of sampling lines were used. His experimental apparatus consisted of a circuit constructed of two horizontal tubes and two vertical tubes 16.8 mm ID connected by three bends of the same material with bend radius of 80 mm. Operating in a vertical plane, tritium labeled aerosol (DOP) was introduced in the lowest horizontal tube. The test aerosol then moved vertically, horizontally again, and then down vertically to a filter. The transmission efficiency of the model sampling line was measured for particles of diameters 2.1, 4.7, 8.0 and 15 μm AED at Reynolds numbers (Re) equal to 450 to 5600. Inlet and outlet aerosol concentrations were calculated from tritium measurements in collected samples. To generate predicted transmission efficiencies with the computer model, input parameters were adjusted to as closely match the conditions of the experiment as possible. However, inlet conditions were not unambiguously specified: "The output from the (aerosol) generator was mixed with room air, according to the required rate of flow through the model sampling line." (30) This was interpreted to mean that inlet flow was adjusted to match the mean velocity of the tube at the desired Reynolds number. The model parameters were similarly set. The results of simulations of the four particle sizes at the flow rates corresponding to the requisite Re values are shown in Figure 5. The dotted lines are model results, and the solid lines are estimated experimental results from the smoothed curves of Strom (30, Fig. 2).

Fig. 5 MODEL PREDICTIONS COMPARED WITH THE EXPERIMENTAL DATA OF STROM

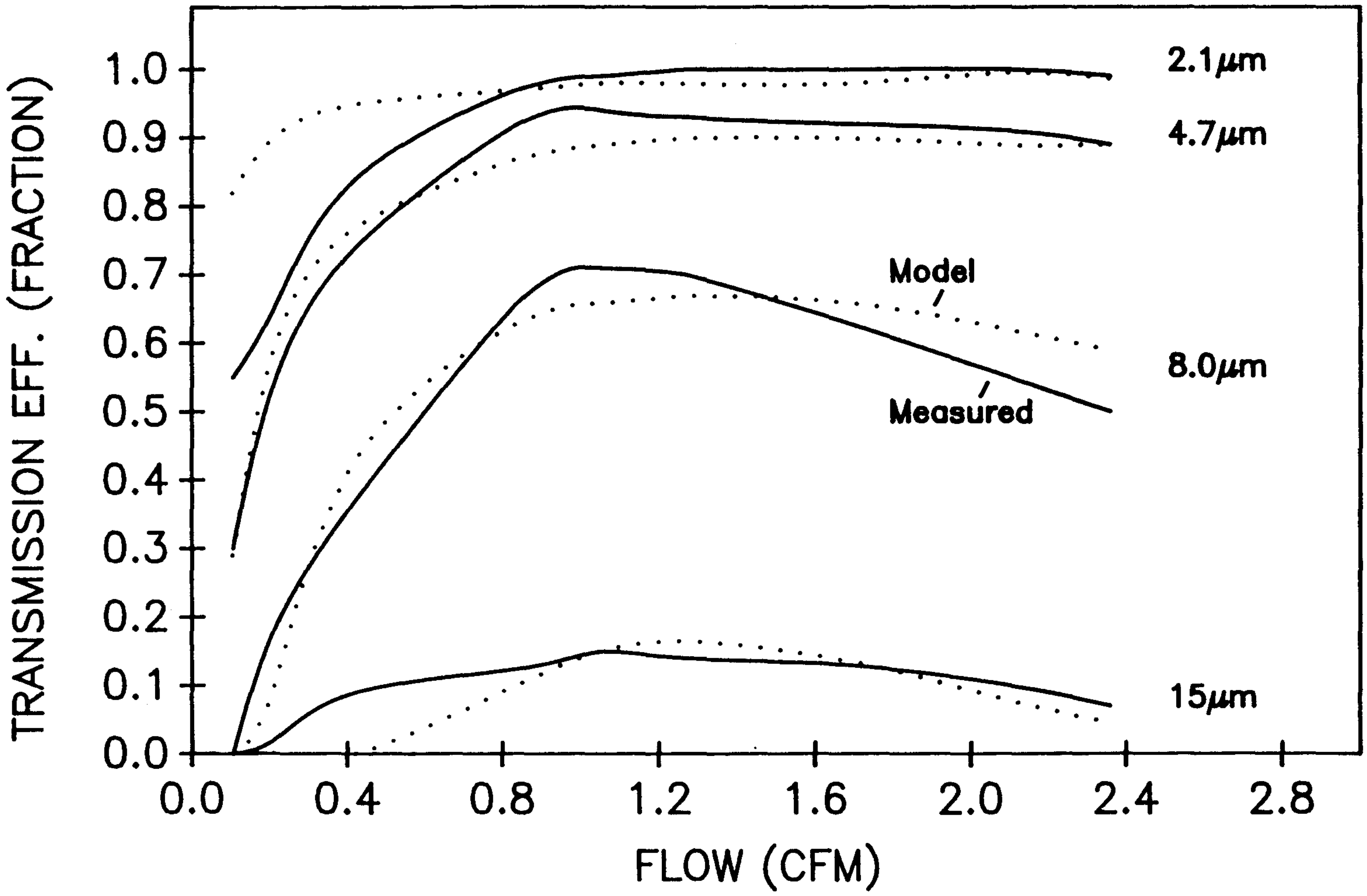
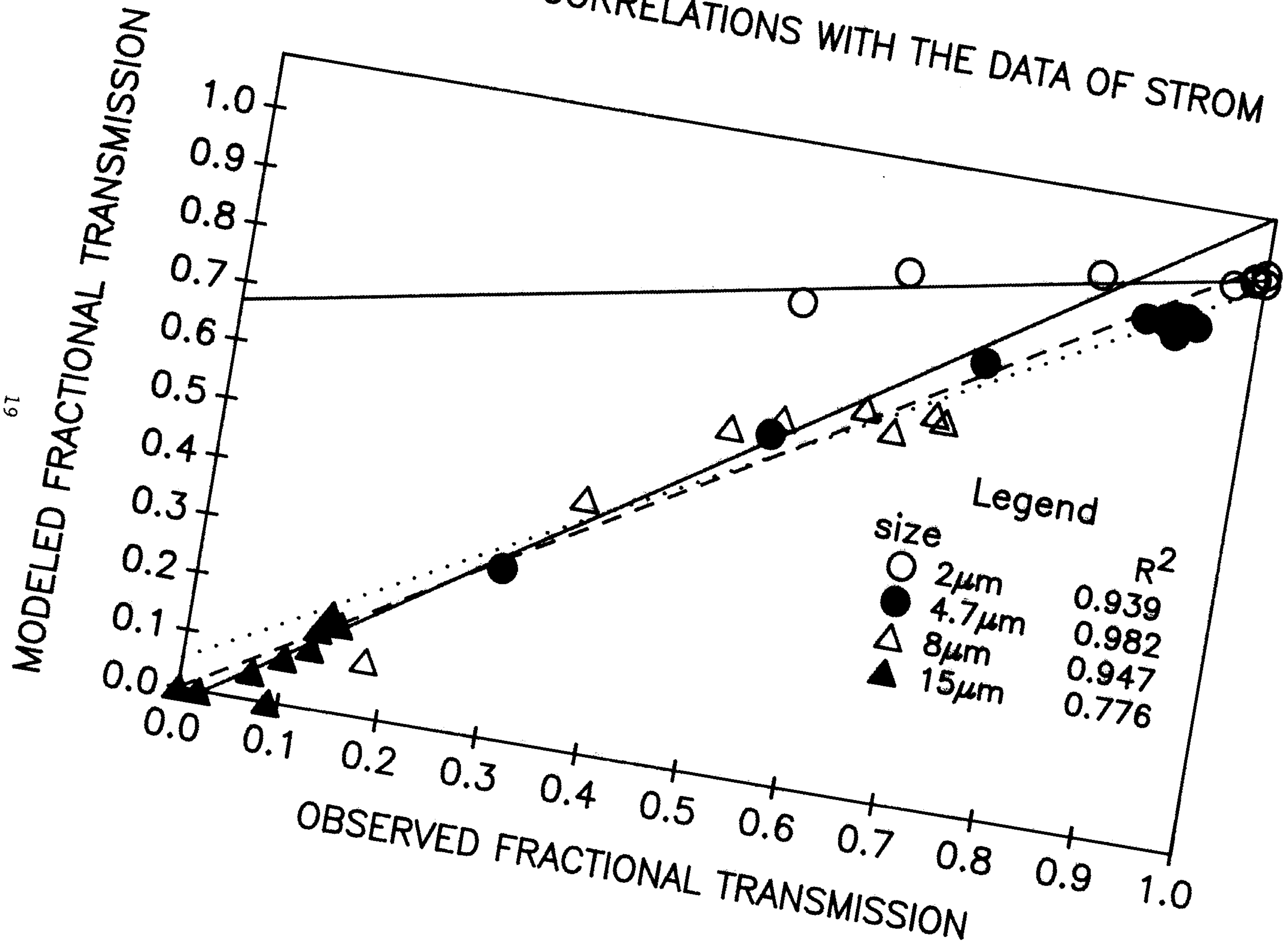


Fig. 6 MODEL CORRELATIONS WITH THE DATA OF STROM



Overall, the agreement between model predictions and the experimental data is excellent. A regression of each prediction against corresponding experimental result show excellent correlations (Figure 5). The largest discrepancy is observed with small particles at low flows (<0.5CFM, Re<1000). For the purposes of the present model applications, the validation against the data of Strom is quite adequate. As always, the best assurance of extractive system performance is laboratory and field testing with well characterized and labeled aerosols to demonstrate that adequate quantities of aerosols representative of those potentially released in an accident will reach the filter.

1.6 Expected Sample Distortion

As previously noted, there is a strong possibility that the presently installed sample extraction, transport, and collection system is not capable of providing a representative sample of accident generated aerosols, which should include at least 50% of the 10 micrometer AED particles. The expert discussions summarized in Chapter 2 emphasize the same point. The conceptual model of Chapter 3 as just described and validated can be used to test the hypothesis that the effective "cut" of a multi-nozzle, small nozzle diameter, relatively low sample rate system would be in the vicinity of a few micrometers, assuming that there is relatively little re-entrainment of particles up to 10 μm AED at the flows expected. The geometry of the sampling train system is as shown schematically in Figure 7. The array of 6 nozzles faces into the flow in the 10 ft. diameter duct. The collection manifold connects to approximately 18 ft. of 0.75 in. ID diagonal transport line and approximately 5 ft. of vertical transport line in the equipment building. Inside, the line passes through a splitter block and then a final bend as it enters the CAM housing. The flow again turns through 90^{o} as it enters the filter.

There are effectively four bends in addition to the one at the nozzle, (diagonal to vertical transition, two at the splitter block, and CAM). Assuming a nozzle diameter of about 1/4-inch and sampling rates of 6 CFM

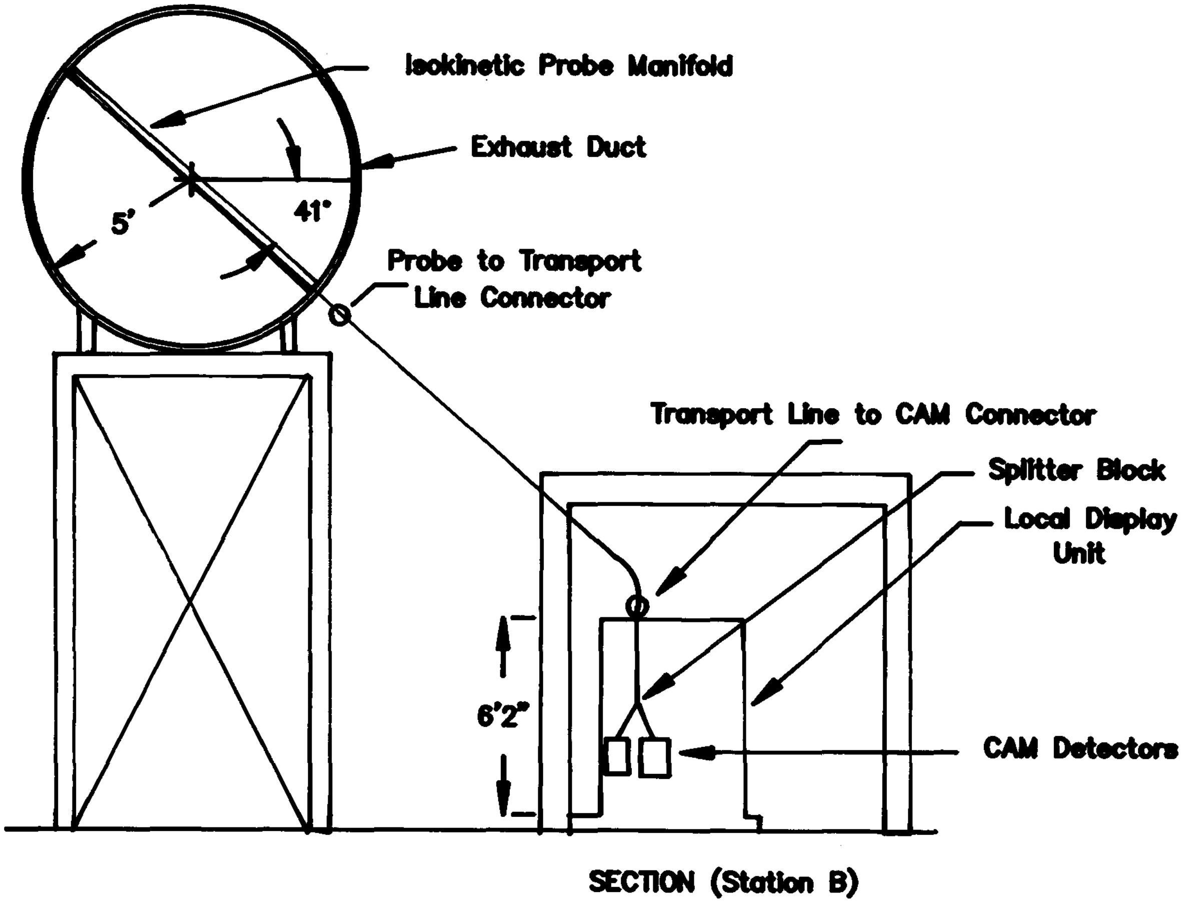


Fig. 7 Probe and Transport Line System at Station B

Fig. 8 AEROSOL PENETRATION OF WIPP MONITORING SYSTEM

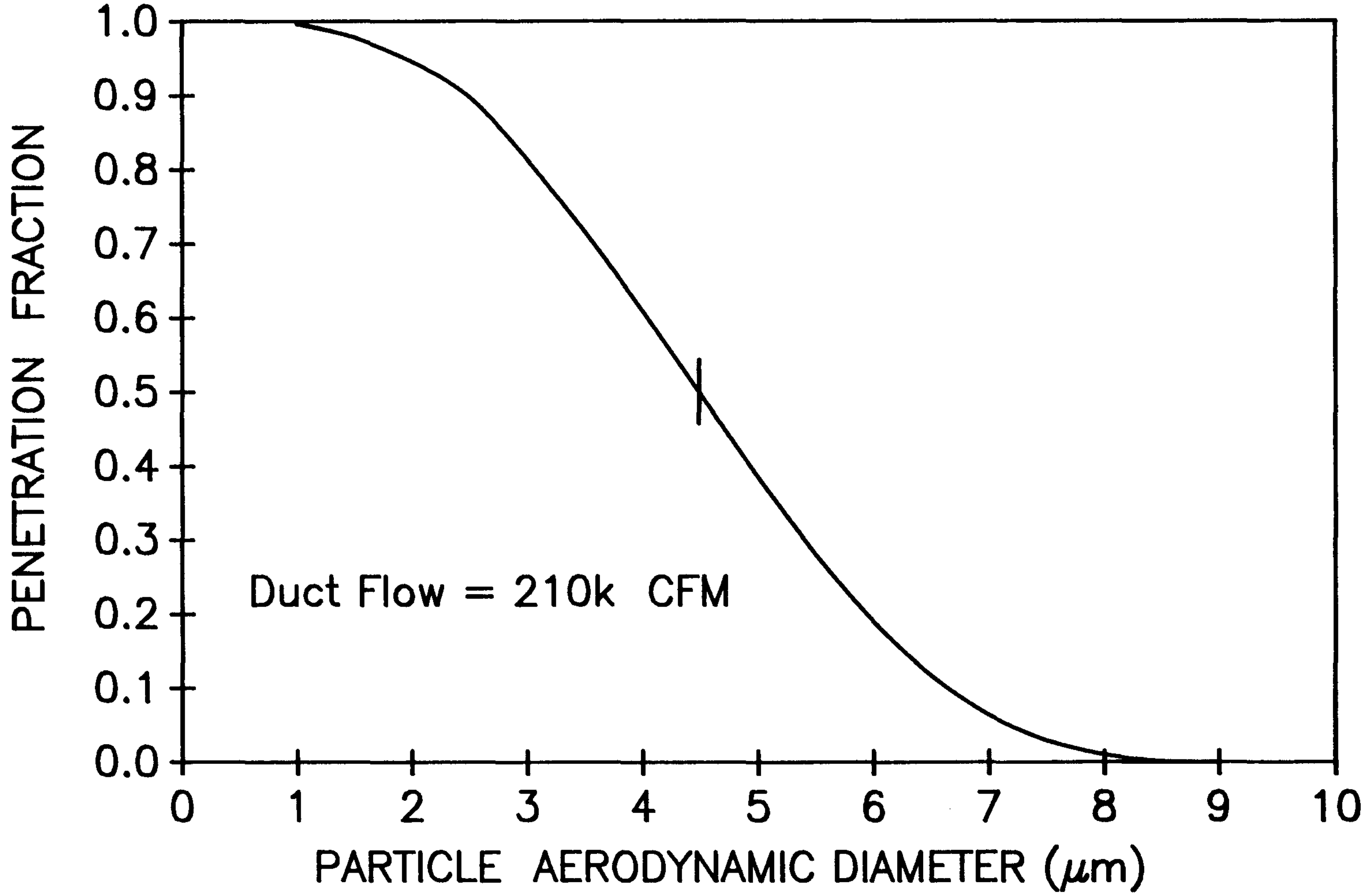
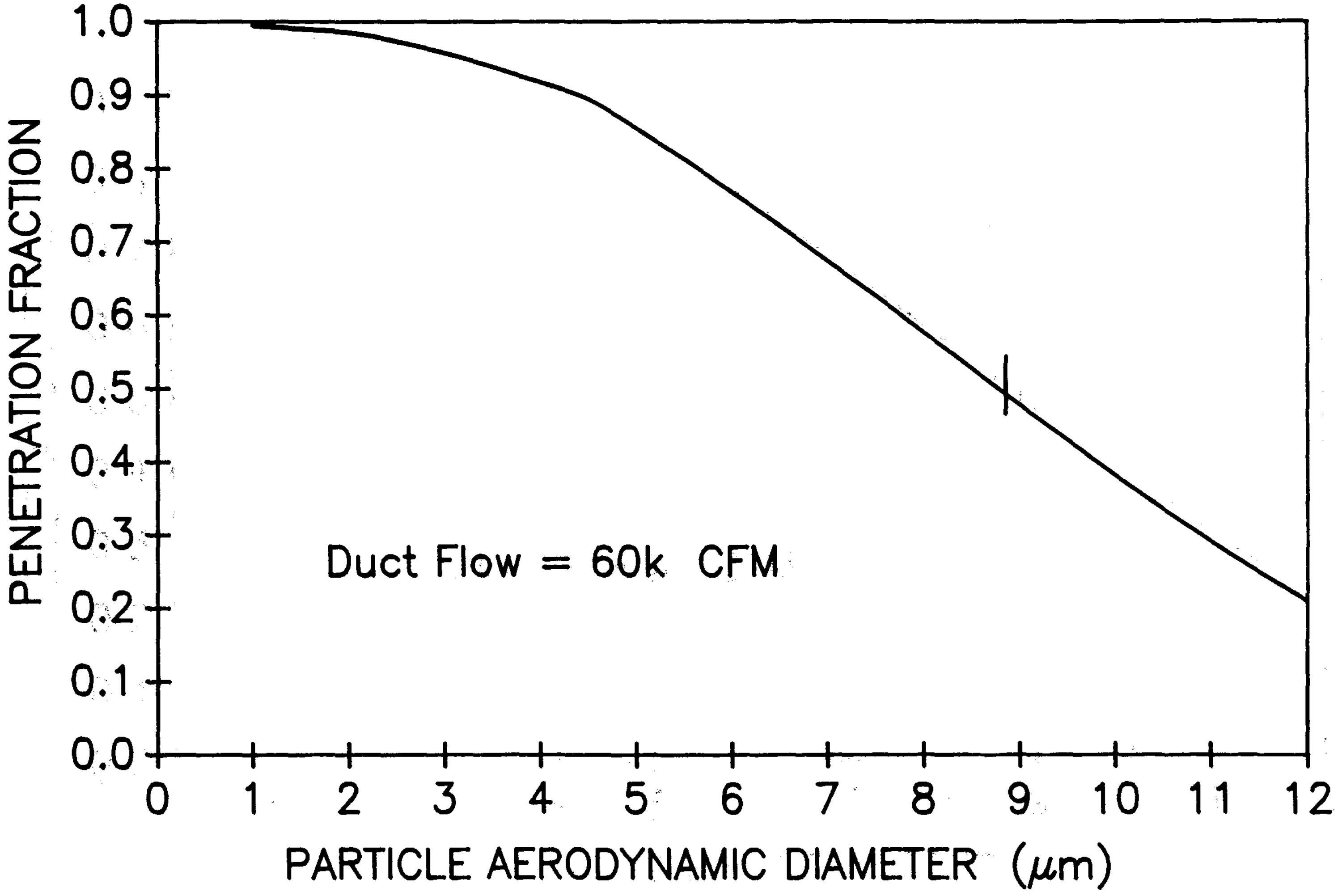


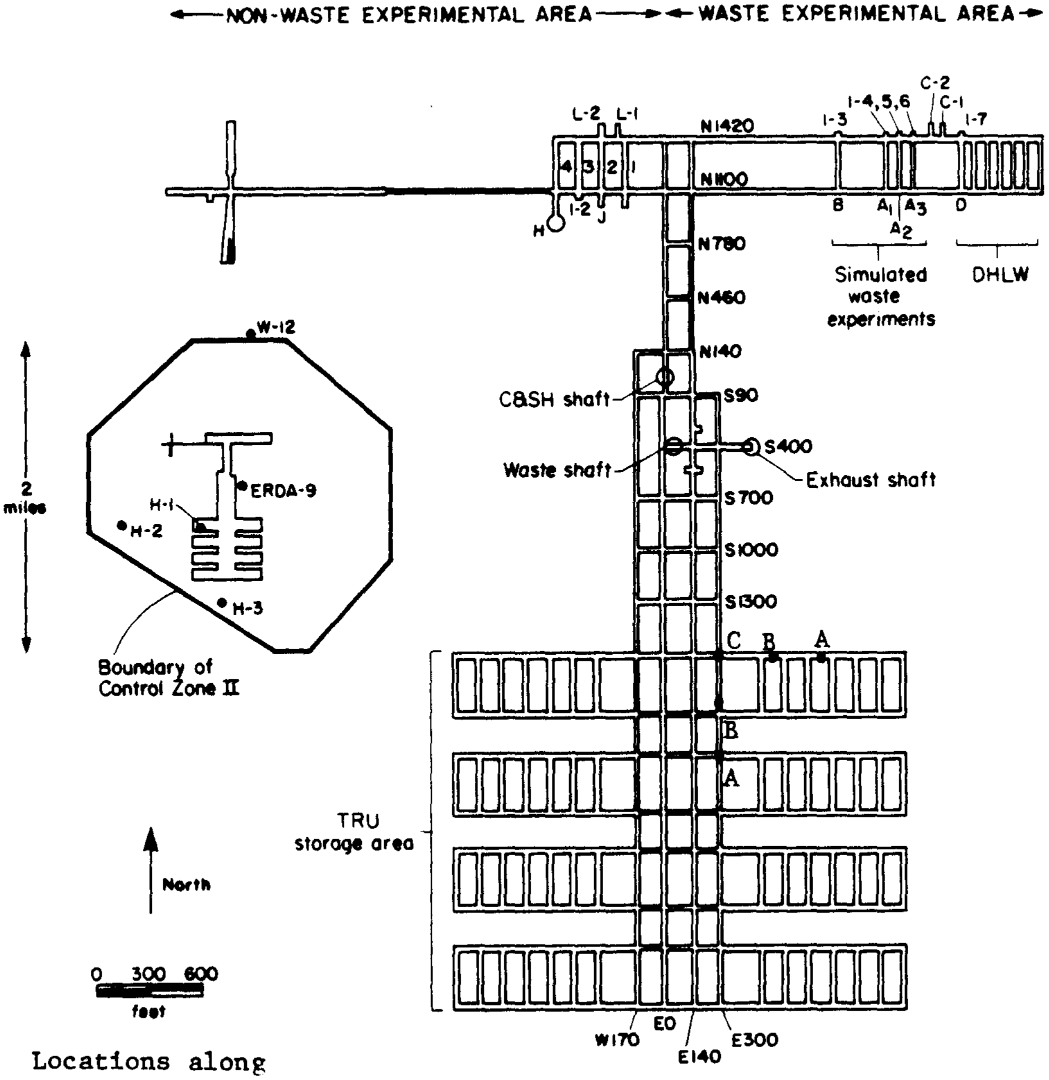
Fig. 9 AEROSOL PENETRATION OF WIPP MONITORING SYSTEM



and 1.8 CFM corresponding to the two flow conditions expected in the stack (210,000 CFM and 60,000 CFM), the modeling results are as shown in Figure 8 and Figure 9. At the high flow condition the 50% penetration efficiency point occurs at a particle aerodynamic diameter of 4.5 micrometers. With the lower flow condition it is about 8 μm AED. These modeling results predict substantial losses during aspiration and transport of relatively large particle sizes.

At either flow, a substantial distortion of the sample with respect to particle size could occur if particles above 5 μm are present. Could particles greater than about 5 μm AED generated in an accident situated in the waste storage areas reach the intake of the exhaust shaft? Some have expressed doubts that particles of that aerodynamic size range would penetrate very far in the WIPP drifts (see Chapter 2 discussion). In an effort to address this question a model of particle loss due to turbulent deposition in rectangular ducts was used to investigate potential particle transport in drifts. Figure 10 illustrates an approximate WIPP exhaust drift geometry which was used together with an estimate of flow rate derived from typical working face ventilation rates to predict transport of different sized particles. In Figure 11, the results of modeling are plotted as a family of curves representing the fraction of particles penetrating the exhaust drift (y-axis) as a function of distance along the drift from exhaust shaft to the source. These distances are shown relative to the underground layout. The model clearly predicts that substantial quantities of particles with aerodynamic diameters of 10μm and larger can be transported from the disposal area panels to the inlet of the exhaust shaft. Further, Stokes Law predicts that particles as large as 100 μm would be carried up the shaft even under the low flow condition (60,000 CFM). The recent decision to construct a new separate intake shaft, which will essentially double the earlier projected ventilation rate, will ensure that drift air flow rates will remain high and increase the likelihood that large particle transport will occur. Although there have not been a lot of data collected on particle transport, a 1983 study of transport in the partially completed underground facilities at WIPP (20) indicated that the aerosol size distribution of the salt dust component (0.5μm - 10μm) changed

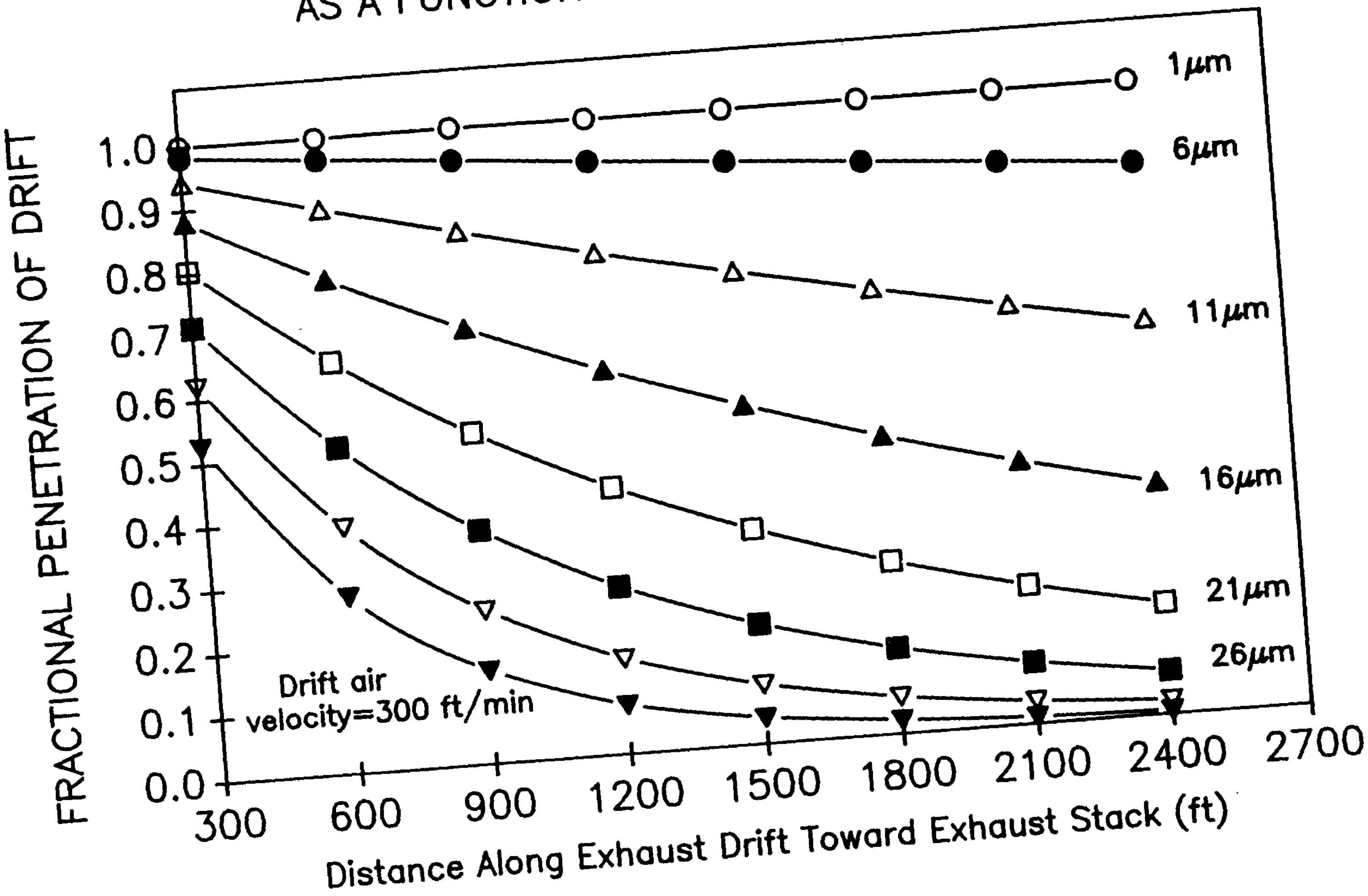
Fig. 10 WIPP Exhaust Drift Geometry for Particle Transport Calculations



Locations along exhaust drift:

A=300 ft.
B=600 ft.
C=900 ft.
D=2200 ft.

Fig. 11 AEROSOL PENETRATION OF EXHAUST DRIFT AS A FUNCTION OF AERODYNAMIC DIAMETER



relatively little in the E140 drift during transport over a distance of nearly 1000 ft. with the largest change occurring in the 5μm to 10μm region. These findings are consistent with the model predicted 11 μm particle penetration of 300-1300 ft compared with the 1 μm and 6 μm particle size penetration (top 3 curves) of Figure 7.

A recent study of the velocity and particle profiles near the top of the WIPP exhaust shaft by ITRI (21) has found, as exepected given the large diameter and high flow rate, that the velocity profile is quite flat across the shaft. Further, while the mass median diameter of the salt aerosol in the discharge air was found to be on the order of 5 μm, there were indeed significant quantities of salt particles found in the size range 10-12 μm AED. Unfortunately, measurments of particle size distributions were not made at the same time along the exhaust drift underground from the storage areas toward exhaust shaft, so confirmation of model predictions is not possible.

Thus there are substantial grounds for expecting that relatively large (but still inhalable) particles generated in an accidental release could indeed be transported through the exhaust drifts to the exhaust shaft and out to the exhaust stack. Air monitoring and sampling systems must therefore be designed to efficiently aspirate and transport aerosols through the 10 μm aerodynamic diameter range to detectors and sample filters. It would appear that the present systems at WIPP will not do that. It is highly recommended that whatever system is selected be subjected to careful, thorough, and appropriate testing prior to being placed into service.

1.7 Testing of Monitoring and Sampling Systems

No prior testing of individual components (e.g., nozzles, transport lines) or in-situ tests of completed assemblies have been identified or reported for the IMP system which has been delivered to WIPP by the contractor and installed in the exhaust stack. One approach to testing which was discussed and critiqued at the April 1987 Quarterly Review Meeting between WIPP/DOE and EEG (7) called for placing open faced filter sampling heads sampling isokinetically directly in the duct flow adjacent to individual IMP nozzles. The samples collected would be compared with the sample collected at the in-line filter at the CAM. Such a comparison of masses of salt aerosol collected could reveal what percentage of the salt dust mass in the air stream is represented by the sample at the CAM. Such a gravimetric determination would not, however, demonstrate that the sample at the CAM was representative of the aerosol particle size distribution in the stack and hence measure any distortion of the sample. A more complete and appropriate Bechtel test plan for the isokinetic sampling system (including both the flow conditioning and IMP subsystems) was prepared in June 1987 (8). A corresponding field sampling protocol which implements the tests prescribed in the test plan in revised form was prepared by the Inhalation Toxicology Research Institute (ITRI) in July 1987 (19).

In brief, the original Bechtel test plan called for the following tests, to be performed using whatever nuisance aerosols are generated by mining which may be present in the exhaust air at the time rather than appropriately prepared test aerosols.

1) Air velocity profiles: Four air velocity profiles are to be made by four 13-point traverses of the duct at a plane located between the probe nozzles and the air straighteners and as close to the nozzles as possible. Profiles are to be established at the maximum (210,000 CFM) and minimum (60,000 CFM) flow rates, and at two intermediate flow rates (70,000 CFM; 140,000 CFM).

2) Airborne mass and size distribution profiles: Particulate samples are to be taken at the same locations as air velocity measurements using cascade impactors capable of determining particle size between 0.1 μm and 10 μm AED.

3) Deposition losses: At each nozzle of the existing probe, test cascade impactors are to be installed such that the inlets are in the same plane as the probe. The inlet nozzles of the test impactors are to be of the same diameter as the probe nozzles. The flow in the test impactors are to be

the same as in the sampling probes. Impactors are also to be installed in successive tests at the outlet of the probe assembly and at the transport line to CAM connector.

The deposition loss tests are to be performed under maximum and minimum flow conditions for a duration of 4 weeks with filter analyses every 7 days.

Included in the test plan are two Reference Acceptance Criteria of section 5:

> "5.1 All velocity profiles shall be within 10% of average value under maximum flow conditions (210,000 CFM) over 60% of the cross-sectional area at the sampling plane, with the remaining air profiles not to exceed 30% of that area (sic)."
>
> "5.2 All particulate profiles shall be to the same tolerances as stated above for velocity profiles."

There are three major concerns with the above test plan and acceptance criteria. First, the analysis of deposition loss as proposed would not actually determine whether or not the existing sampling probes obtain a truly representative sample of the duct aerosols. The reason is that the nozzle diameter and flow rates are to be designed to match probe specifications rather than being designed to assure that the <u>reference</u> system at least is obtaining an accurate sample. Thus if the existing probes fail to collect a representative sample due to faulty nozzle design or sampling rate and the reference probes are forced to conform to that design, the proposed test would not detect it.

Second, by eliminating the use of selected labeled aerosols input to the duct, the test plan eliminates the possibility of insuring through response time measurements that an adequate quantity of particulates in all size ranges through the inspirable range (0.1 μm to 10 μm AED) penetrate through the sampling system as a coherent signal. Also, the possibility for tracking mass balance and the effects of re-entrainment through the entire probe assembly will not be possible. The use of labeled aerosols in such tests is a requirement of ANSI N42.18 (5.4.10).

Third, although in-line impactors are being planned at two critical junctions, both the splitter block and the final bend in the transport line at the CAM head itself could cause significant deposition losses and should be tested as well.

Finally, the reference acceptance criteria only address the performance of the flow conditioning portion of the installed isokinetic sampling system. Both the Bechtel bid specifications and the test plan make reference to ANSI N13.1 and ANSI 42.18 as generally applicable standards. Yet the requirement that the sampling system deliver a representative sample, unbiased with respect to physical or chemical properties contained in these standards, is not translated in any way into reference acceptance criteria. Thus fully half of the required test plan does not produce a result which can be compared against a single performance or acceptance criterion in Section 5 of the test plan.

The test protocol prepared by ITRI (the test contractor) meets several, but not all of these objections. ITRI cascade impactors to be used in the tests do apparently have nozzles which will properly sample aerosols up to 10 μm aerodynamic diameter and presumably would not be necked down to match the existing probe 0.25 inch diameter. Inlet velocities in the impactors adjacent to each sample nozzle will be isokinetic. Total flow in these test impactors will be adjusted to match the present system. Further, the ITRI proposed tests were to be conducted prior to attachment of the exhaust duct to the underground ventilation system. Hence, although only sampling conditions and equipment at Station B could be tested, at least then a selected independently generated aerosol could be used. However, ITRI did not include provisions for tests with a labeled aerosol, which should be used. Also the ITRI plan called for additional impactor samples to be collected after the splitter block and at the CAM head, so these potential sites of deposition would be tested, which resolves another issue with the Bechtel test plan.

As of August 7, 1987, the planned ITRI tests were indefinitely postponed due to the apparent inability of the installed flow conditioning equipment to produce even approximately flat velocity profiles in the sampling plane at Station B. Thus the ineffectiveness of the proposed flow conditioning apparatus predicted in the Peer Review Meeting on stack monitoring at WIPP (see Chapter 2) has been found to be the case at WIPP Station B. What alternatives, such as extension of the exhaust duct, will be pursued remains to be seen.

1.8 Plugging of Sampling Lines

The preceding discussion of sampling nozzles and transport lines has indicated that a substantial loss of particles aspirated from the discharge stream due to impaction and turbulent deposition can be anticipated. This is particularly true for larger sized particles, as was noted. In addition to the problem of sample distortion as a result of this process, another concern arises as a result of the deposition process.

If material from the aerosol sample readily deposits in nozzles, bends, splitter blocks, and transport lines during sampling a condition leading to eventual buildup and plugging could occur. Such would be the case if the WIPP aerosols readily adheres to the walls of pipes and nozzles and are readily cohesive to each other. WIPP aerosols have been characterized as being a mixture of salt dusts of varying size and diesel exhaust aerosols of relatively small size. The adhesive characteristics of this mixture on walls of sampling lines has not been investigated, although the buildup of deposited WIPP aerosols on the inlet of samplers under certain conditions has been reported (10). As was discussed above in Section 1.5, the studies of Beal and others suggest that with the exception of large particles at high flow rates, particles will stick in the transport tubes if deposited.

If the aerosols do indeed adhere to walls and themselves, then a simple model (34) can be used to estimate the time required to plug the present sampling nozzles and lines. The model predicts the integrated mass transported through a pipe prior to plugging at the point of greatest thickness of deposit.

$$m = kD^3$$

where m = mass transported prior to plugging (kg)

k = dimensional factor (kg m^{-3})

and D = pipe diameter (m)

The value of k found to fit a variety of test cases is $k = 30{,}000 \pm 20{,}000$ kg m^{-3}. Although this generalized value of k does not fit an extremely large range of pipe diameters, it does seem to be suitable for the range of diameters of interest (0.25" to 6"). Although the model is highly generalized (generalized from data for pipe bends, straight sections, different entrance conditions and aerosol conditions) it does provide some sort of indication of what might be expected if a tendency toward aerosol deposition is observed at WIPP. The results of calculations with this model shown in Table 1, are a function of mass loading of salt-dust/diesel aerosols, tube diameter, and flow rate through the tube.

These results clearly show the potential for rapid plugging of small diameter nozzles under Table 1 (below).

Provisions previously made to back-flush the sample lines with compressed gas starting just ahead of the splitter block have been eliminated at WIPP. It remains to be seen what other options will prove to be an effective maintenance strategy should the decision be made to continue to use the present small diameter probe systems.

The foregoing completes a general overview of the issues surrounding current plans for an isokinetic sampling system at WIPP. The development of this vital monitoring and control system is, of course, an ongoing process. Already, however, the predictions of the expert panel who reviewed the present plans have been found to be correct regarding the efficacy of the flow conditioning system at Station B. Hence the continuing relevancy of these early discussions summarized in Chapter 2. As planning continues for future tests of the probes themselves the conceptual approach of Chapter 3 will be particularly valuable.

Table 1. Potential Plugging of Sampling Tubes[1]

Tube Diameter (cm)	Flow Rate (CFM)	Mass Transported (kg)	Time to Plugging (days)
0.66(nozzle[2])	1.0	8.8 X 10^{-3}	52
1.9 cu (manifold[2])	6.0	1.5 X 10^{-1}	150
6.0 (FAS[3])	6.0	6.48	6620

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[1] Salt-dust loading assumed to be 4 mg/m^3, which is about twice the amount observed during construction at WIPP.

[2] Approximate values for current system.

[3] Proposed by EEG (see Chapter 3).

2. ENVIRONMENTAL EVALUATION GROUP PEER REVIEW MEETING ON THE WIPP STACK MONITORING SYSTEM

2.1 Background

The proposed stack effluent monitoring system at the Waste Isolation Pilot Plant (WIPP) has been under review by the State of New Mexico Environmental Evaluation Group since June 1986. The sampling conditions of three of the four stack discharge sampling stations (before, and after the Exhaust Filter Building, and in the exhaust stack to the north and to the south of the Waste Handling Building) are in some respects unusually severe and complex for nuclear facilities. Only the Waste Handling Building exhaust is normally and continuously HEPA filtered. The other three stations normally must be designed to continuously extract a representative sample of salt-dust-laden air and transport that sample to a remotely located Continuous Air Monitor (CAM) or fixed air sampler (FAS). Of these three stations, two are proposed to be located in a 10-foot diameter portion of the exhaust stack just downstream of a plenum structure previously described in Chapter 1. The potential for flow and particle profile distortions induced by abrupt transitions are well known. The other station is located immediately downstream of the exhaust fans, which also induce severe distortions in flow.

A meeting was held in July 1986 with the contractor for the isokinetic sampling system, Air Monitor Corporation (AMC), at which technical issues were raised regarding the proposed design (9). A number of the technical issues raised by EEG were brought to the attention of the State by Alfred C. Schmidt, P.E., of Schmidt Instrument Co., who had participated in the WIPP stack sampling probe contract bidding. Mr. Schmidt has on numerous occasions transmitted detailed objections to the proposed sampling system design to both the State of New Mexico (EEG) and WIPP/DOE. The EEG has undertaken to incorporate appropriate technical concerns raised by Mr. Schmidt in the ensuing discussions and correspondence with WIPP/DOE on this matter. Many of these issues were left unresolved at the conclusion of the meeting with AMC (9) because there was no evidence cited by them which would substantiate the performance claims for their design from the technical literature, or from results of performance testing. At the July meeting EEG called for a peer review of the AMC design. In August 1986 DOE decided to conduct a technical review themselves, and contracted with the Inhalation Toxicology Research Institute (ITRI) to conduct a review of portions of the Bechtel bid package and the AMC bid. A number of the same objections raised by EEG were also made by ITRI, particularly regarding loss of sample in long transport lines and the expected poor performance of the AMC flow conditioning system. A number of modifications to the AMC design were proposed by ITRI and accepted by AMC. Certain experimental tests and measurements in the WIPP exhaust shaft were proposed by ITRI. On October 29, 1986 a letter was sent by EEG to Mr. Cooper, WIPP Project Manager, outlining the continued objections of EEG to the proposed design even in modified form. Again a peer review by stack sampling experts was called for. In addition it was recommended that WIPP not proceed with the AMC contract in order to permit the measurements by ITRI to be completed and the recommendations of the peer review panel taken into account prior to continuation. The DOE agreed to participate in a peer review, but chose to continue with the AMC contract.

Three technical experts constituted the core of the peer review: George Newton (ITRI), Bill Farthing (Southern Research Institute), and Virgil Marple (University of Minnesota). Other participants* from EEG and WIPP/DOE contributed additional expertise and experience relevant to the discussions. All participants received a package of background materials prior to the meeting, including information on the bid specifications and the AMC design proposal, notes on the July meeting with AMC, and a list of issues and questions prepared by EEG.

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* The other participants included: Dick Figlick, WIPP Project Office (WPO), Dick Crawley, WIPP, Kayse Prince, Westinghouse/WIPP, Bob Adams, Martin Marietta/WIPP, Robert Neill, EEG, Jim Channell, EEG, John Rodgers, EEG.

The following section (2.2) summarizes the salient points of the Peer Review Meeting on WIPP Stack Monitoring held in Santa Fe, November 1986. The summary is based on a transcription of the record of the meeting (10).

2.2 Peer Review Meeting Synopsis

2.2.1 Aerosol Characterization and Transport

A fundamental question which must be answered as part of the basic design for stack monitoring at WIPP is: What is the largest particle size that the sampling system must deliver to the detector with at least 50% efficiency? The regulatory requirements in DOE Orders (35) pertinent to this facility, and relevant ANSI standards (3, 4) require that the system deliver a "representative" sample efficiently but do not provide specific performance requirements. A corollary question is, what particle size distribution should be used to characterize an underground accidental release?

The discussion of this question involved a review of early ITRI measurements of aerosol characteristics in the WIPP underground drifts and in the exhaust shaft effluent. George Newton (ITRI) was of the opinion that if a large particle size aerosol were released underground, "in just a few hundred meters of movement through those drifts, the aerosol, whatever it is, is going to be very quickly pushed toward 3 micrometers mass median aerodynamic diameter."

However, in contrast to that assurance, Virgil Marple noted that there was some mass of particles up to 10 micrometers reported by Newton in the sample taken at the top of the shaft. Newton agreed and then noted that not only that, but some mass didn't make it into the impactor sampler, and that the data represents only 3 measurements under very adverse conditions.

Furthermore, there was general agreement that whatever aerosol particle size distribution is present at the bottom of the vertical exhaust shaft is not going to change much during transport up the shaft. The implication is that any accidental release in the vicinity of the waste shaft or the first few panels of the storage area can contribute aerosols having a larger mass median aerodynamic diameter (MMAD) than was observed in the ITRI study.

With respect to the WIPP Safety Analysis Report (SAR) (36) assumptions of large deposition losses of aerosols released in drifts, there was concern that the assumptions used to arrive at the estimated losses are not obvious and may not be correct, depending on waste form and the conditions of the release (e.g. whether or not a plume of hot gases would rise to the ceiling). There was skepticism about the magnitude of wall losses as well.

With regard to the effects of the proposed AMC flow conditioning apparatus on the particle size distribution, there did not appear to be any strongly felt opinion that it would cause any significant effect, although particles would be removed from the airstream.

Recommendations:

The final recommendations on aerosol characterization were that further development and specification of the underground release scenarios, particularly fires, to enable better estimates of probable aerosol characteristics, losses to drift walls, and other surfaces during transit to the bottom of the exhaust shaft, would be highly desirable. The question of whether or not underground diesel fuel fires could occur was raised. Although a transport crash involving a diesel fire is considered to be an incredible accident in the WIPP Safety Analysis Report (36), there was some skepticism voiced as to whether or not such an accident really is beyond the realm of possibility.

2.2.2 Location of Sampling Stations

The question of the proper location of sampling stations involves the larger question of the proper configuration of the sampling station equipment in relation to disturbances in the stack or other conditions which might make extraction and transport of a representative sample difficult or impossible.

With respect to the location of Station A, a recurring question, first raised by Virgil Marple, was, "Why can't we go with a station ahead of the 90^{o} elbow?" He said, "You have got a half a mile of turbulent flow; you've got very good mixing, and if you would sample anywhere in that pipe say 6 inches off the wall you'd get a good representative sample". There was no disagreement that this would be the ideal location for Station A. But would the proposed AMC flow conditioning apparatus produce essentially equivalent conditions just downstream of the 90^{o} bend?

There were repeated opinions expressed by the experts that the mixer (turbulator) would not function to produce well mixed particle profiles. It was noted that because the curved vanes of this system put no energy into the flow (but rather absorb it) there is no way it could function as needed based simply on physical principles. Newton, Marple, and Farthing all agreed on this. With respect to the other component of the flow conditioning system, the honeycomb straightener, the major concern was that while it may do some good for awhile, over the long-term it could become a problem due to the salt crusting process observed by Newton and others. If an equalizer is installed that is susceptible to failure such as this is, it may unknowingly start to fail. If the equalizer were not designed into the system in the first place, inequalities in flow, particle distribution, etc. would have to be determined in advance and the sample extraction system designed accordingly.

Part of the difficulty with evaluating the efficacy of the honeycomb flow conditioning concept is that there appears to be little guidance in the literature or regulatory requirements for the accepted use of these devices.

There was interdependence of these discussions on Station A location with the question of whether or not flow conditioning could be relied upon. Thus an additional element entered the discussion: in-stack testing of the functioning of the AMC flow conditioning system.

Because the AMC system has been built (a stop-work order was not issued), the question was raised, "Even though the expectation is that the AMC system won't work, should it be tested in the stack to demonstrate that it won't work?" Three points of view on this question were advanced:
1) Accept the fact that a probably unworkable system was contracted for. Don't waste time and money testing it. Get on with designing a proper system located in the optimal sampling location ahead of the 90° bend. A danger in installing and testing the AMC system is that a kind of momentum for continuing with it is established. Marple, who most vigorously pressed these views said, "I still think there is a danger that once you put it in, it might be written into the whole system where it is real difficult to get it out." Farthing tended to agree with this concern. He said at another point, "...and there is a certain amount of money here now to do something with, and there is a tremendous amount of momentum in that kind of situation. That is, whatever is done at that time, is extremely hard to change down the road." Marple put his position generally on this point in this way: "I don't think there is anything wrong in saying, 'We made a mistake; we shouldn't have bought the thing; we just won't use it'." There was a lot of agreement on these points, particularly from Farthing and by EEG participants. 2) Another point of view was that although it appears, on the grounds of aerosol physics, that the flow conditioning concept of AMC will not work at the proposed locations, it should be tested anyway. No evidence of meaningful tests of the AMC system has been identified, even by AMC, although Prince did think some aerosol injection studies of similar systems (without the blades) had been done at a nuclear power plant. But it has been installed in a number of facilities and its performance should be known. Here is an opportunity to test it. Newton took the lead in championing this position. He said, "...I would like to get a little bit of information on its real capability. If we did it (the in-place testing) there and we found it doesn't do anything, it doesn't do what it is supposed to do, then I think we have a better case. If it doesn't do anything, we can then decide to take it out..." There was some (but not unanimous) agreement on this point of view, particularly by the WIPP participants. One line of objection to attempting a series of tests on the AMC system is that, a.) no apparent detailed performance specifications

have been prepared and agreed upon (the bid specifications make vague reference to collection and delivery of a "representative" sample), and b.) some of the failure modes such as plugging may take longer to be identified than a short-term acceptance test. Adams suggested that DOE is in a position to request a detailed acceptance plan from Bechtel, citing the requirement that the contractor will have to perform all necessary testing required to demonstrate the reliability and proper operation of the equipment. This leads to the third position.

3) The third position developed from the observation that the contractor has a contractual obligation to demonstrate that his equipment performs all functions as were claimed. As Adams put it, "...they can put it in, but if it doesn't work as they say it should, say for instance the turbulator bars mixing it all up, and then the equalizer creating the uniform velocity distribution, as well as taking out the turbulence...if they can show that, we'll pay for it. If they can't, don't pay for it." This is a more legalistic approach to the concern than technical. There was not a lot of discussion of this view. The WIPP participants seemed to favor this position.

Recommendations:

In terms of a final recommendation for the location of Station A, the first choice was sample extraction in the exhaust shaft below the collar and ahead of the 90^{o} bend. Various ideas were advanced about implementing the "ideal" Station A configuration. One suggestion proposed by Marple was, "...take this elbow out of here, and then put up a room up there so the air comes up and then it turns and goes straight out. Then a probe into the airstream ahead of the 90^{o} bend would be easier to implement." The second choice was a location downstream of the 90^{o} bend, but with greatly improved sample extraction design (a large diameter single probe with a short transmission line directly into the CAM head).

The discussion of the proper location for Station B was again convoluted with the discussion of the likelihood of the successful performance of the

AMC conditioning scheme. There was general agreement that flow there would be highly turbulent with vortices and eddies, and that some form of control was needed. But once again there were severe misgivings about relying on the AMC scheme, particularly the turbulator vanes: "We've already expressed our lack of confidence that that particular set of vanes would do anything significant..." (Farthing).

The final recommendation for Station B was that the horizontal duct be lengthened by several stack diameters. Then many of the potential problems with turning vanes, honeycomb straighteners, etc. would go away. Since, as Newton pointed out, the real cost of this option is not going to be in the cost of the length of the conduit (but would be adding support structures), the recommendation was to add length to achieve a total of 5 stack diameters. "So let's go ahead and go, so we have a total of 5 diameters downstream from the injection of the last pump..." (Marple).

For Station C (in the Waste Handling Building) the location proposed seemed appropriate to the reviewers. Here the sampler is in double HEPA filtered air, so the conditions for sampling are much less severe. The major issue in this case is whether or not the flow conditioning equipment is really needed under these conditions, not whether or not it would plug up and fail. The sense of the discussion was that it was not needed. But sampling has to be done for regulatory purposes so the focus of attention was on proper design and positioning of the sample probe.

Perhaps the best summary on the issues of whether or not the proposed AMC designed flow conditioning would work to permit proper isokinetic sampling in the present stack configuration came in answer to a summary question by Figlick:

"Let me just ask the question; there's been various accounts about the best way to do things and about the 1st choice and the 2nd choices. Just to summarize, our existing design: is there any strong feeling that what we have just won't work?" (Figlick)
"Yes, very strong!" (Farthing)

"I think we went through that this morning". (Marple)
"My feelings are, that it won't do what they claim it's going to do, but I have another question on whether it is really necessary to try to do what they claim it's going to do." (Newton)

2.2.3 Sample Extraction Systems

The principal concerns about the design of the sample extraction are whether isokinetic sample withdrawal is essential (or even desirable under WIPP conditions), whether multiple nozzle arrays are needed, whether small nozzle openings are acceptable, and what sort of velocity sensing is needed and appropriate under the conditions at WIPP.

On the question of whether sample extraction had to be isokinetic, opinion seemed to be that under the non-laminar flow conditions of the stack, anisokinetic sampling would not introduce large sampling errors (less than 10%). The proper focus of attention is on the particle size cut introduced by the size of the nozzle entrance, the diameter of the transport line, and the shape of bends in the probe array.

In the discussion of probe design, a number of problems were raised associated with utilizing a multiple nozzle array to obtain, in effect, an instantaneous traverse sample. A major concern had to do with the necessity to reduce inlet diameter to accommodate multiple nozzles. The original AMC design called for 12 nozzles, but after discussions with ITRI, a decision was made to reduce the number of nozzles to 6. Newton explained that the reason for recommending a reduction in the number of nozzles was to get a bigger nozzle inlet diameter. His reason for not reducing the number below 6 was "...a desire to at least attempt to satisfy the ANSI N13.1 requirement, because it's at 6 as a minimum number of probes for ducts over 50". But it was pointed out in the discussion that the ANSI guidance on number of probes is based on circumstances where the distribution of particles across the duct is unknown. ANSI guidance states that fewer withdrawal points may be used if careful studies show that uniformity of composition exists through portions or throughout the cross section of the duct. In the case of the WIPP duct, the fact that the

Reynolds number is greater than 10^6 suggests that the point-to-point departures from the average velocity would be rare in the flow ahead of the 90° elbow, and in the flow at Station B if an extension were added. Furthermore, as the ANSI guidance suggests, in some circumstances, impractical small probe entry nozzle diameters would result from using numerous probes. Such is the case at WIPP due to the potential for plugging with salt. As was concluded by the group, there is ample justification for considering a much smaller number of probes, perhaps only one if mapping demonstrates the suitability of a single probe.

Recommendations:

After much discussion, the conceptual design that was converged upon was a single probe with a large diameter nozzle entry if conditions warrant it. The concept included the idea, suggested by Marple, of using a thick-walled tube for the probe rather than a thin walled, tapered probe, which offers some advantages in this situation. For Station A, a large diameter probe extracting a sample straight from the shaft below the collar seemed best. A large diameter tube with a large radius bend feeding as directly as possible into a CAM or FAS was seen as a very reasonable approach for Stations B and C. Problems with the AMC design were thought to be that the diameter of the nozzle opening is too small, and particle collection would occur at the junctions of the probes with the manifold.

Marple recommended that whatever redesign was proposed ought to be tested: for example, the large diameter thick-walled probe is "...something you could test fairly easily without going to the site".

If it is assumed that a large diameter probe is placed such that it is extracting samples from highly turbulent flow which has been stabilized by long distance transport (e.g. ahead of the collar, and 5 stack diameters downstream from the fans), then precise location of the probe should not be very critical, according to the experts, nor should the position change drastically with discharge rate. "...I think all three of us would agree that most likely that flow is not going to shift...with changing [discharge] to ruin a single point measurement. It's something we observe, and should be verified in actual use." (Farthing)

The advantages of a single large diameter probe were summarized as follows: "We could size it so that it would minimize the probe transport losses. You'd know when it fails. It would be cheaper to replace. There will be fewer bends, because you could put it there and drop it straight down and the CAM head could be attached directly underneath." (Newton)

"The problem with the manifold that you're talking about (AMC) is these little tubes. You need a bend in these little tubes - or you are talking about one bend in a much bigger tube which is better." (Marple)

"And you've got a larger tip diameter for the same flow." (Rodgers) "Easier to maintain" (Channell) "In an isokinetic sampling, problems are less when you've got a large nozzle which means large flow rate. Your cut...your diameter...your right angle can be made larger and you don't have to worry about stagnant zones for sampling. And your wall losses, turbulent diffusion drops off too. The percent losses drops off as your tube diameter gets bigger" (Farthing).

In regard to multipoint velocity sampling as proposed by AMC, the consensus appeared to be that if a typical velocity was measured and used to set a sampling rate, the expected deviations from iso-mean velocity would not introduce large errors when sampling from a large diameter probe. Thus a big array of pitot tubes was seen to be unnecessary. However, since at Station B, it is essential to obtain a measure of the total flow as well as concentration of radioactivity, if any, there was a discussion of potential alternatives to the use of pitot tubes such as thermoanemometers for flow measurements.

One concept proposed was the possibility of monitoring the power demand on the fans and calibrating that against measured velocity traverses at Station B under different flow conditions. The problem with sensors in the flow is that they will get crusted with salt (or in the case of pitot tubes, plug up). An external indication would avoid that problem, but it was not decided whether or not it would be sensitive and accurate enough.

There was agreement that at least one continuous in-stack measure of velocity be made. "A single point possibly. Just to make sure that things are not wandering off into never-never land...so I think some kind of measurement is needed. Just this whole array (AMC pitot array) is not needed..." (Farthing). A final recommendation was not made on whether a rugged pitot system or rugged thermoanemometer would be most appropriate.

2.2.4 Sample Delivery Line

The original design of the sample extraction system necessitates having relatively long transport lines from the sample extraction system to the CAMs located in the instrument housing nearby. The problem this creates is that long runs and numerous bends greatly increase size-selective deposition loss. An AMC spokesman had earlier made the claim that under conditions of continuous sampling these deposition losses would not continue to be observed. Instead, a steady-state is reached between deposition and re-entrainment regardless of particle size and flow conditions. Hence long transport lines for continuous samplers are not a problem. The experience of all the reviewers did not support this view. Newton provided a succinct statement on the deposition process: "...the forces...on a particle deposit, the forces that hold it on there are more than the available energy to remove them, in most cases. There'll be a little bounce-off or a little re-entrainment, but you can't help that. But the net effect is going to be to slowly close up, and as it closes up, it (the airflow) is going to go faster. It's going to go faster and the deposition will increase." There were special circumstances (types of aerosols, transport lines, flow conditions) mentioned where plugging was not a problem. But for the WIPP salt aerosols, it seems very unlikely that deposition equilibrium would occur. The shortest possible transport line was unanimously recommended.

Large radius bends are usually recommended and an agreement has been reached between the contractor and WIPP/DOE to reduce the number of bends in the original design and make them all large radius bends. But the peer review group expressed some doubts about the real efficacy of this approach: "I think that referring to making gradual bends is not enough" (Farthing). "I don't know if a long bend is better than a short bend. In practical terms of mass transfer, the loss of particles is actually going to be about the same, just spread out over a larger area" (Newton).

Thus the recommendations of the group appeared to be that it would take a combination of a large diameter pipe, <u>and</u> a large radius bend, <u>and</u> proper attention to proper sampling rate to achieve conditions of best sampling: "that is...the particle's got a certain amount of momentum going in one direction, and you can't turn it unless you give it a certain amount of time to slow down without being able to come in contact with the walls. Because if the air takes these particles too close to a wall, and then it starts turning, then you're going to collect them on these. So the flow field is critical" (Farthing).

The recommended transport line concept at Station A is a short, straight line from a nozzle projecting into the flow ahead of the bend, directly into the CAM head. A possible complication of separating the CAM head from the rest of the sampling and data processing unit is an electronic noise consideration which could not be answered by the group. For Stations B and C, a large diameter, tube was the recommendation, again with as short a straight run into the CAM as possible (i.e. CAM head on the duct).

Prince pointed out that with respect to Stations B and C there are Fixed Air Sampler (FAS) heads which must be provided for as well as the CAMs, and these should be on or as near the ducts as possible: "The fixed filter will be used to demonstrate compliance with regulations. The CAMs associated with it are just the instruments for determining some upset condition, so from our standpoint, for compliance, its critical that the fixed filter is as near to the duct as possible" (Prince). The present design calls for a three-way "splitter block" in the transport line to accommodate the FAS as well as the two CAMs. Deposition losses are associated with such devices which must be considered in a final design. These blocks are located at the end of the transmission line near the CAM.

With regard to flow rate in the transmission line, the large diameter sampling nozzle and associated line helps reduce sampling losses: "The bigger the nozzle is, and the bigger the tubing is, without having to worry about settlement...the better." (Farthing) A problem arises, however, in matching optimum flow in the nozzle with the number of samples that must be collected. Each probe at Station B and Station C must supply 3 different systems: an alpha-CAM, a beta-CAM, and an FAS, each running at up to 2 CFM. Newton expressed concern about the proper operation of the CAMs at flow rates greater than 1 CFM due to dust loading, so there are operational factors which must be considered before a final design evaluation can be developed.

Generally, the participants indicated that optimal transport conditions could be obtained by adjustment of both transport line diameter and flow rate, adjusting conditions to minimize turbulent deposition. There was some concern that a design based simply on optimizing the flow Reynold's number may be too simplistic. A lot depends on whether the extraction and CAM systems can be configured with a short vertical transport line, or whether a long horizontal run is needed. It apparently will be difficult to eliminate significant losses if long lines are necessary. Farthing reported EPA's experiences in sampling particulates indicate that it is commonplace for up to 90% of a sample to be caught in the probe rather than making it to the filter.

Recommendations

The final recommendations on the design of transport lines emphasized the value of a simple, short, large diameter, straight, and vertical line into the CAM. Embellishments such as the use of cyclones to achieve 90° bends were discussed but not recommended. The use of exhaust gas recirculation to maintain constant transmission line flow was also discussed, but unless long horizontal runs are necessary it was not recommended.

Even the utility of isokinetic sampling was questioned. According to Newton, a good case for anisokinetic sampling being superior in some applications could be made. In fact, it seemed that since continuously monitoring flow to maintain isokinetic sampling conditions was not absolutely essential at least for Station A, the real need for monitoring flow remaining is to be able to calculate the total discharge of radioactivity if a release were to occur. Thus isokinetic sampling at Station B is necessary to assure as representative a sample of the discharge as possible and to be able to report total quantities discharged.

2.3 Conclusions

Based on the broadest perspective on these discussions it is clear that the participants concluded that it was a mistake to attempt to import techniques and hardware from the context of monitoring for releases in HEPA filtered air (i.e., multiple nozzles of small diameter, long transport lines, many bends, etc.) to the salt dust laden discharge air at WIPP.

Furthermore, based on the collective experience of the experts, there was an expectation that the AMC system will not function to mix and straighten air flow in the vicinity of the 90^{o} bends and downstream of the fans as claimed, particularly in the case of an aerosol containing significant quantities of larger sized particles.

The recommendations of the committee were for a very simplified sample extraction system which utilizes the inherently superior sampling conditions in the shaft below the 90^{o} bend for Station A, and the effects of an increased duct length 5 stack diameters beyond the Exhaust Filter Building to achieve representative sampling conditions at Station B, rather than flow conditioning at either station. Also, a simplified direct approach to sample nozzle design was recommended. Rather than a multiple nozzle rake, a large diameter single nozzle was recommended if stack measurements indicate a representative location can be identified, or as few a number as possible otherwise. And to achieve optimum sample transport it was recommended that the CAM head be positioned as closely as feasible to the sample extraction system. With this approach, a representative sample can be delivered with high reliability and without continual maintenance. Since anisokinetic sampling could potentially deliver equivalent or better performance over isokinetic sampling with elaborate systems of multiple pitot tube arrays and flow control, the design recommendation was to consider other sampling rate conditions at Station A. A velocity sensor is recommended to allow generation of accurate continuous flow (discharge) data and isokinetic sampling at Station B. It is not clear that the elaborate array of flow conditioning apparatus is really needed at Station C in HEPA filtered air.

3. CONCEPTUAL DESIGN OF A FIXED AIR SAMPLING SYSTEM

3.1 Introduction

As a result of the Santa Fe Peer Review meeting on isokinetic stack sampling at WIPP, a decision was made by EEG to attempt to develop a conceptual design for a sample extraction system suitable for the conditions at WIPP which would implement the principal recommendations of the peer review. A design basis for a fixed air sampling system at Station B was chosen as the most appropriate to focus on since the EEG has, from the outset of discussion on this issue, been urging WIPP/DOE to agree to the establishment of a State monitoring station in the exhaust stack near Station B. William Farthing of Southern Research Institute, a participant in the peer review, agreed to develop such a conceptual design under contract with EEG. The following sections are derived from the Farthing report (11).

3.2 Overview of Stack Sampling Issues

The rigorous approach for measurement of stack emission rate is to isokinetically sample many points of the sample plane. This, of course, requires measurement of gas velocity and flow control at each of the points. Because, in principle, particles enter the nozzles at the same rate as they would be emitted, the emission rate can then be obtained directly from the aspirated mass per unit sample time multiplied by the ratio of total duct area to the total nozzle area. These measurements are usually expressed as an average concentration and an average gas velocity, but the result is the same. Sampling at many points is desirable because the emission rate may vary across the sample plane and sampling isokinetically minimizes the disturbance of gas flow by the nozzles so that particles are not oversampled or undersampled due to their inertia. The rigorous approach is needed for sampling sites in general, but in practice there are other important considerations which, in specific applications, may conflict with the rigorous approach.

Recovery of the aerosol particles after aspiration through the nozzle(s) is a practical problem of major concern. This problem is readily solved if the filter(s) can be mounted in the duct or the probe(s) washed after the sampling run. These approaches are utilized in EPA's Methods 17 (in-stack filter) and 5 (out-of-stack filter with probe washing). In the latter, 90% of the sample is frequently deposited in the probe. The applicable ANSI guidelines for sampling (3) state that the deposition efficiency of any extractive system should be measured before its acceptance. Deposition occurs just past the nozzle entrance due to nonlinear and nonaxial flow similar to anisokinetic sampling. It occurs along straight transport lines due to settling, if horizontal, and both Brownian and turbulent diffusion. And finally, deposition occurs in bends due to particle inertia.

Upon deposition in a nozzle or transport line, whether or how long a particle remains on the surface varies unpredictably with composition, environment, and size. Some experience indicates that some types of particles bounce or are blown off of internal surfaces with high transport velocity. However, other experience has shown plugging at high velocity caused by deposition of other types of particles. At WIPP, the experience of Newton, et al. (20) and Rodgers (10) indicates that adhesion to surfaces will likely be a problem. In his sampling at the top of the exhaust shaft, Newton reported that salt deposits in his nozzle were severe. The most important aspect of re-entrainment or the absence of it in the FAS at WIPP is that the nature of the particles to be detected is unknown and cannot be measured or predicted because the number of possible scenarios for an accidental release are too large. Thus, confidence cannot be ascribed to a detection system which requires that particles are re-entrained after contacting internal surfaces of an extraction probe.

The instack filter is valuable because the transport line is eliminated. This approach is also feasible for multiple sample points. Of course, multiple filters must then be analyzed in the lab and the flowrate for each sampler must be high enough to provide the minimum required sensitivity.

Approaches employing a filter mounted out of the duct must either have low losses in the transport line or the transport line washed to recover this material. The wash liquid would then be evaporated leaving the material from the probe on a suitable substrate. This would probably require a series of washings to reduce the material to a sufficiently small substrate. Such handling and the fact that the total sample would be on two substrates, the original filter and the probe material, would effect detection sensitivity but the sample rate could be higher to compensate. This approach could also incorporate multiple sample points. However, it would require much labor over the long term.

Because in-duct filters and out-of-duct filters with high probe losses would possibly require substantially higher operation and maintenance costs, an out-of-duct approach with low probe losses is needed. Thus, the major problem addressed by the following discussion is design of the extraction system.

3.3 Approach to Conceptual Design of FAS

A conceptual design is developed in this report by first considering sampling error, including deposition in nozzles and transport lines, versus geometry and flowrate for a single sampling point. Next, the error associated with the number of sample points is considered. Finally a specific design is chosen within practical flowrate limits to optimize the overall system performance which is limited by the degree to which all sources of error are restricted. Although much research is needed, most aspects of the potential problems can be addressed quantitatively from information in the literature. Stratification can be considered in a qualitative manner at this time. Measurements at the site can provide satisfactory answers where information is lacking.

The following sections of first address anisokinetic sampling error and extraction losses versus probe geometry and flowrate for a single nozzle and probe. Procedures are given from the literature for calculations with any geometry. Results are given for an assumed geometry to illustrate magnitudes of errors. Then the question of stratification of particle concentration and velocity and the errors associated with them are addressed. The last section gives recommendations for the FAS.

Brownian diffusion is not directly addressed here except to note that it is minimized by the shortest transport line possible and the highest flowrate. The diameter of the transport line has no effect upon the transport efficiency with respect to Brownian diffusion (3). Losses due to Brownian diffusion will not be a problem in this application. For example with a tube length of 20 ft and flowrate of 5 CFM the transport efficiency of 0.001 μm particles would be almost 90%, increasing for large particles.

Effects of electrical charge are also not addressed although it is possible that some charge will reside on the particles. Losses caused by charge are minimized by minimizing the length of transport lines using metallic lines, and maximum transport velocity.

When quantitative methods of predicting particle deposition for a specific condition of interest are not available, a key parameter (used by Fuchs, (12) and most texts on aerosols) for estimating how aerosol particles will behave is the relaxation time, τ. It is useful when particles respond to the forces acting upon them faster than significant changes in the forces occur. Then such a particle is always approximately at its terminal velocity. When the gas velocity changes in the absence of external forces, the velocity of a particle relative to the local gas volume surrounding it is given by τa where a is the acceleration of the gas. For Stokes law behavior, τ is given by

$$\tau = D^2/18\mu \text{ (sec)},$$

where

D = particle aerodynamic diameter, cm, and
μ = viscosity of the gas, poise.

This expression ignores the slip correction factor because it is negligible for the larger sizes which are of interest in design of the sampling system. For 10 μm particles τ is 0.31 ms. Stokes law is valid for particle Reynolds numbers up to about 2, which corresponds to velocities of about 300 cm/s for a 10 μm particle relative to the gas surrounding it. However, an acceleration of 1000 g's would be required to cause a 10 μm particle to attain such a velocity relative to the gas, so Stokes law behavior can be assumed.

3.4 Anisokinetic Sampling

Anisokinetic sampling errors refer to differences between the concentration of particulate matter entering the nozzle inlet plane and the concentration upstream of the nozzle. They are due to nonuniform and nonaxial flow into the nozzle entrance. These flow conditions can be due to a mismatch in the average nozzle velocity from the stream velocity, which is corrected by adjusting the sample rate under ideal circumstances, to fluctuations associated with turbulence at high Reynolds number (Re), to disturbance in the stream due to bends, fans, etc., and to the disturbance caused by the nozzle itself. These latter mechanisms are not usually given consideration, but are relevant, nonetheless.

The aspiration coefficient of a nozzle, A (defined as the ratio of concentration of aerosol entering the nozzle, to concentration of aerosol in the gas upstream of the nozzle), has been studied extensively. The most general expression for A is:

$$A = 1 + (R \cos\theta - 1)B/(B+1) \qquad (1)$$

where R = the ratio of stream velocity, v, to average nozzle velocity, u, = v/u,

θ = angle of steam velocity with respect to nozzle axis,

B = a semi-empirical function of R, θ, and K,

K = Stokes number of a particle in the stream with respect to the nozzle,

= $\tau v/d$, and

d = nozzle diameter.

The most important characteristics of this expression are that sample error (given by the second term) is small when $R=1$ and $\theta=0$ or when B is small. Most sampling protocols attempt to adhere to the first criterion ($R=1$ and $\theta=0$) while ignoring the second. Somewhat different expressions for B have been obtained by several authors but all are linear with K. The most appropriate for the present problem is that by Vincent, et al. (31), who measured the variation of B as a function of θ and reviewed all previous contributions to the subject. They concluded that

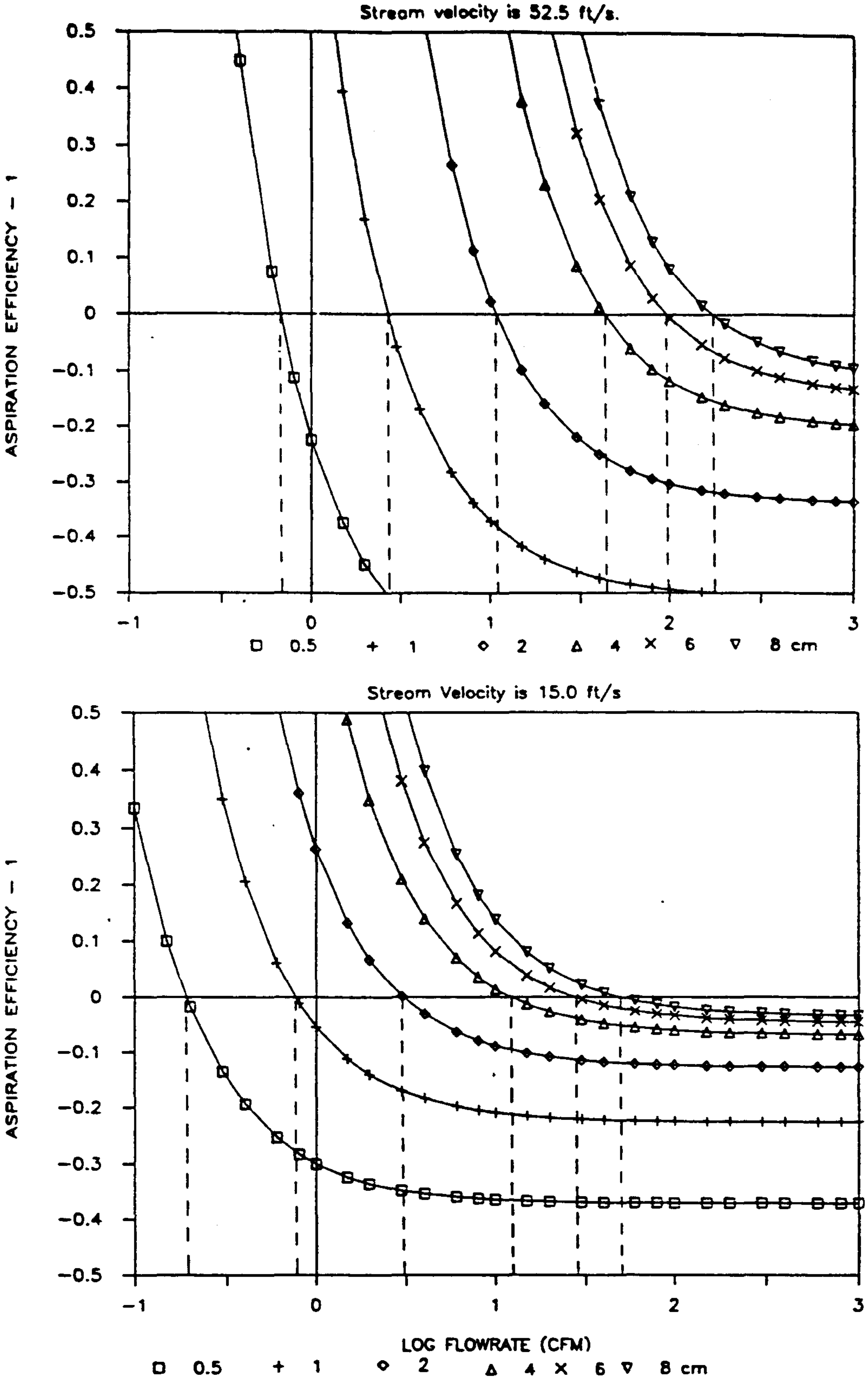
$$B = 2.1\ (\cos\theta + 4[R\sin\theta]^{1/2})K. \qquad (2)$$

Calculations were performed to explore the effects of anisokinetic sampling at WIPP. Because the gas velocity in the duct may be decreased from about 52.5 ft/s (for 210,000 cfm) to 15.0 ft/s (for 60,000 cfm), the sample rate must be decreased by a factor of 3.5 to maintain R approximately equal to 1. Decreasing the sample rate has the effect of decreasing the sensitivity or the response time of detection. Note that average velocities for these flowrates are 44.6 and 12.7 ft/s; higher velocities are considered to allow for the expected higher peak velocity.

A number of test cases exploring the consequences of stack velocity, angle of impact, nozzle opening diameter and sampling flowrate were studied. A single particle size of 10 μm was used in this (and succeeding cases) in part to limit the amount of data to be discussed and displayed, but also since a large particle size aerosol represents the most severe challenge to a sample extraction system and hence bounds the expected consequences of various design considerations.

An example of the results are given in Figure 12 where sampling error (a-1) is plotted as a function of sample rate, Q, for six nozzle sizes, 0.5 to 3 cm in diameter. Note that the plotting symbol for each nozzle size is given below each horizontal axis. In Figure 12 (θ equal to 0^{o}) the flowrate at which each of the curves crosses the horizontal line (A-1=0) corresponds to isokinetic sampling for that particular nozzle diameter. Vertical dashed lines indicate these flowrates. The slopes of these curves

Fig. 12 Anisokinetic Sampling Error versus Sample Flowrate



are important, the nearer to a zero slope the smaller the error that will result for a given value of R. Observation of the changes of the slopes with nozzle size reveals that the larger nozzles are more "forgiving", i.e., the error incurred for $R \neq 1$ is smaller for larger nozzles. As the flowrate is increased, the error goes from positive to negative and (as R goes to 0 approaches a constant given by $B(\theta)/(B(\theta)+1)$. Comparison of results from the high to low stream velocities reveals that low stream velocities are more "forgiving" than high velocities. Of course, since the high flow condition is the one corresponding to no filtration during a release episode, that is the one which must be of primary concern for design purposes.

To evaluate the possibility of one sample rate for both duct velocities note first that to keep anisokinetic sampling errors about the same magnitude for both duct velocities using the same sample flowrate, then the nozzle velocity must be nearer to the higher stream velocity, the one for which significant emissions would most likely occur if a release occurred.

The probability that particles of significant size will penetrate the control system utilizing HEPA filters is extremely small. Thus, sampling should be made most accurate at the higher flowrate. Consider, for example, a nozzle diameter of 2 cm and a sample flowrate of 10.8 cfm ($u = 52.5$ ft/s). At the high duct velocity no anisokinetic sampling error would be incurred, while at the low duct velocity this error would be -9 percent. The error would be -26 percent if the nozzle diameter were 0.5 cm and the sample rate were 0.7 cfm. ($R=1$ at 52.5 ft/s). Larger nozzle diameters, which require higher sample rates, would give less error.

If stable nonaxial flow in the duct (θ greater than 0°) is present, this could be taken into account by nozzle alignment. However, nonaxial flow, which is caused by flow disturbance, is accompanied by rapid variations in θ. It is, of course, such variations which led to the specification in ANSI 13.1 (1969) that any sampling location be five or more duct diameters from the nearest disturbance. Even with five duct diameters upstream of the FAS, the extent of such variations should be measured. The major effect of nonaxial flow is to shift error toward negative values. Thus considering the 2 cm nozzle with flowrate so that R equals 1 at the high duct velocity, sampling error (A-1) during high duct velocity would be -0.04 for θ equal to 20°, and -0.17 for θ equal to 40°. If the duct velocity were reduced to 15 ft/s while keeping the sample rate the same, the error becomes -0.18 for 20° and -0.22 for 40°. As with the zero angle case, larger nozzles give less error while smaller nozzles give more. These magnitudes of error for a 2 cm nozzle are undesirable but not intolerably high.

Whether or not the sample rate should be decreased with the duct velocity to maintain R approximately equal to 1 should be based upon the effect of decreasing the sample per unit time by a factor of 3.5 and the desired minimum sensitivity.

3.5 Probe Transport

Deposition in a sample probe can be quite high due to the inherent flow disturbance at the nozzle entrance, particle inertia in bends, and turbulent diffusion and settling if the transport line is horizontal. Methods for modeling these effects are described below. The severity of each acting alone is illustrated; then combined effects are illustrated.

3.5.1 Inlet

Deposition at the nozzle entrance occurs due to the inherent change in gas flow caused by the nozzle. This disturbance should be expected to be more substantial if sampling is not isokinetic due to curvature of flow lines entering the nozzle. The only practical model for calculating these losses is that given by Okazaki, et al. (22, 23). They concluded through curve fitting to empirical data (23) that the transport efficiency, E_i, for θ equal to 0 is given by

$$E_i = e^{-4.7G} \quad (3)$$

where $G = [ZK/Re^{1/2}]^{3/8}$

Z = gravitational deposition parameter = $L\tau g/ud$,

L = length of tube = 20 cm,

g = acceleration due to gravity, and

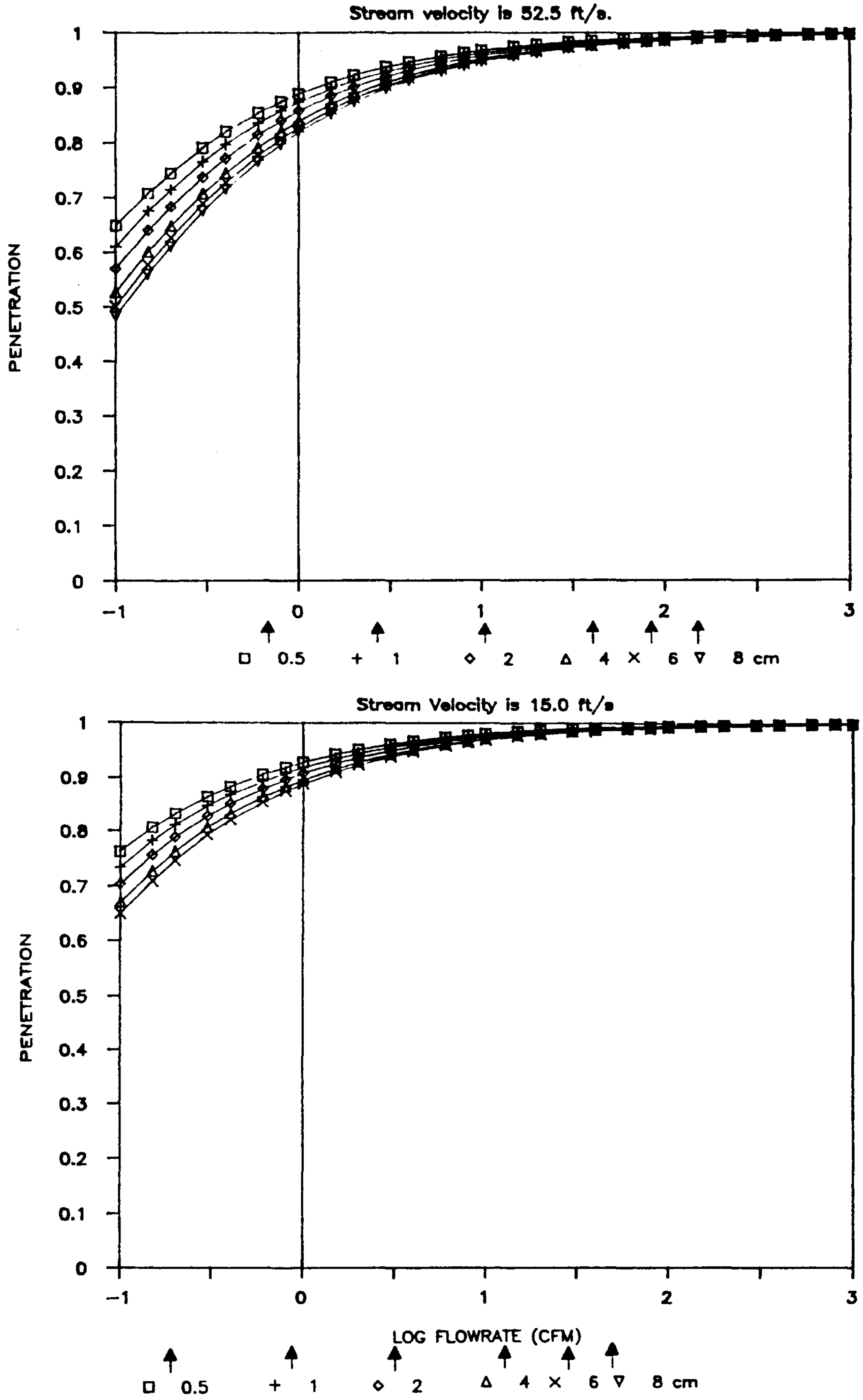
Re = Reynolds number of the tube.

Note that τ, u, K, and d are defined in the preceding sections. In the second paper by Okazaki, et al. (23), results of measurements in which θ was varied are given but these were not incorporated into E_i given above. Farthing found that their data were suitably characterized by replacing K, in the expression above for G, with $K=(1+14.8\sin^2\theta)$.

Due to their experimental procedure, this model includes the effect of additional mechanisms when sampling with nozzles followed by a 20 cm length of tubing in a horizontal orientation. Deposition due to settling and turbulence which are independent of the region adjacent to the entrance are included. Thus, even though Equation 3 suggests that log E_i is a linear function of nozzle length, L, it is not expected that transport efficiency will approach unity, simply by making L small. Without further analysis, including separate modeling or measurement of settling and turbulent deposition for Okazaki's conditions, which is beyond the scope of this current investigation, it is advised that Equation (3) be used only for L in the range of 10 cm to 20 cm. The results should be considered optimistic for L less than 20 cm.

Figure 13 illustrates transport efficiency calculated from Equation (3) as a function of sample flowrate for nozzle sizes ranging from 0.5 to 8 cm and θ equal to 0^o, i. e. the duct flow was assumed to be axial for this illustration. These results indicate that transport efficiency through the nozzle inlet and first 20 cm of transport tube is near 100% at flowrates near 10 cfm or above for all nozzle sizes studied. However at lower (more typical) flowrates, penetration drops significantly, to about 80% at 1 cfm and about 60% at 0.1 cfm.

Fig. 13 Penetration Through Nozzle Inlet versus Sample Flowrate



3.5.2 Bends

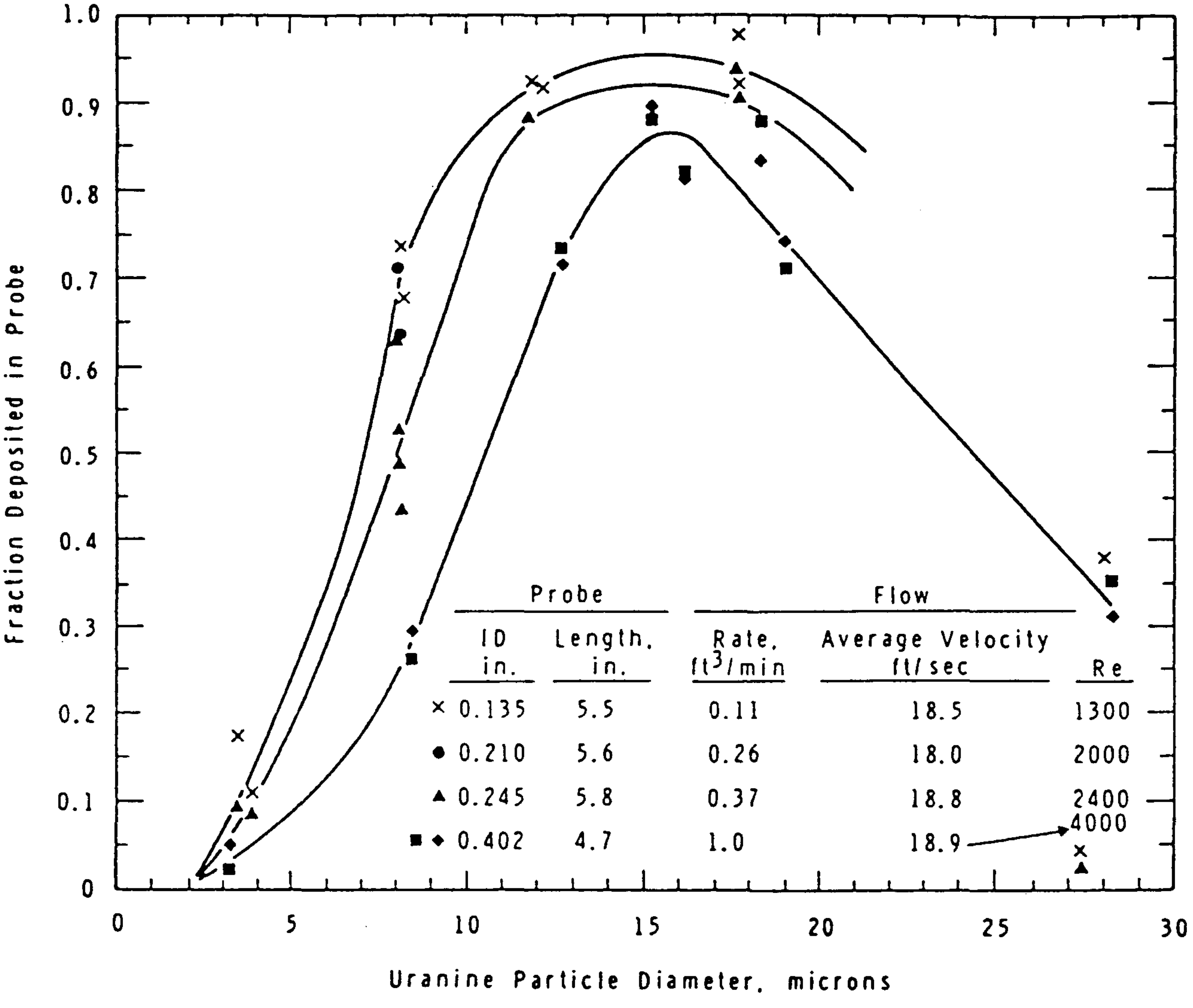
Expressions for deposition of aerosols in bends are infrequently given in the literature. Data are available but had to be put into a general form for use in the current situation. The acceleration given a particle when the gas, at velocity v_t, in which it is suspended goes into a turn with radius of curvature, r, is v_t^2/r. Ignoring variations of v_t with position, one concludes that the distance which the particle moves relative to the gas, $\tau v_t/d$ or K_t, is the important parameter in describing collection efficiency of the bend, E_b. In reality, v_t is not uniform across the flow. If the Reynolds number is high and the radius of curvature is small, then the gas velocity may be stratified toward the outside wall. To take such nonideal effects into account, a function of K_t was fit to the data of Sehmel (28). Sehmel's original presentation is given as Figure 14 where collection efficiency is plotted versus particle diameter. Figure 15 presents this data in terms of Stokes number K_t. Calculation of these efficiencies are also presented for the expression

$$E_b = 1.75(K_t - 0.01) \qquad (4)$$

It agrees well with the measurements at low values of E_b. Because most of the differences at high collection efficiency were probably due to re-entrainment (solid particles were used in these measurements) and a transport line with low E_b is sought here, this linear expression is satisfactory. A model which would include re-entrainment is not desired here because a transport line is sought in which no particles (or a small fraction) would deposit on the walls.

Figure 16 gives the calculated penetration through a bend versus flowrate for the tube sizes 0.5 cm to 8 cm. It is obvious that the appropriate choice of tubing size, depending on flowrate, is necessary to prevent deposition in the bend. For example, at 0.7 cfm (isokinetic flowrate with a 0.5 cm nozzle at 52.5 ft/s) the tubing inside diameter must be about 2 cm or greater to prevent significant deposition of 10 μm particles in the bend. Figure 16 indicates that size of the transport line should be increased between the nozzle entrance and a bend.

Fig. 14 Deposition Within a Curved Sampling Tube (after Sehmel, 1970)



Probe		Flow		
ID in.	Length, in.	Rate, ft^3/min	Average Velocity ft/sec	Re
× 0.135	5.5	0.11	18.5	1300
● 0.210	5.6	0.26	18.0	2000
▲ 0.245	5.8	0.37	18.8	2400
■ ◆ 0.402	4.7	1.0	18.9	4000

Fig. 15 Collection Efficiency versus Stokes Number (from Sehmel's data, 1970)

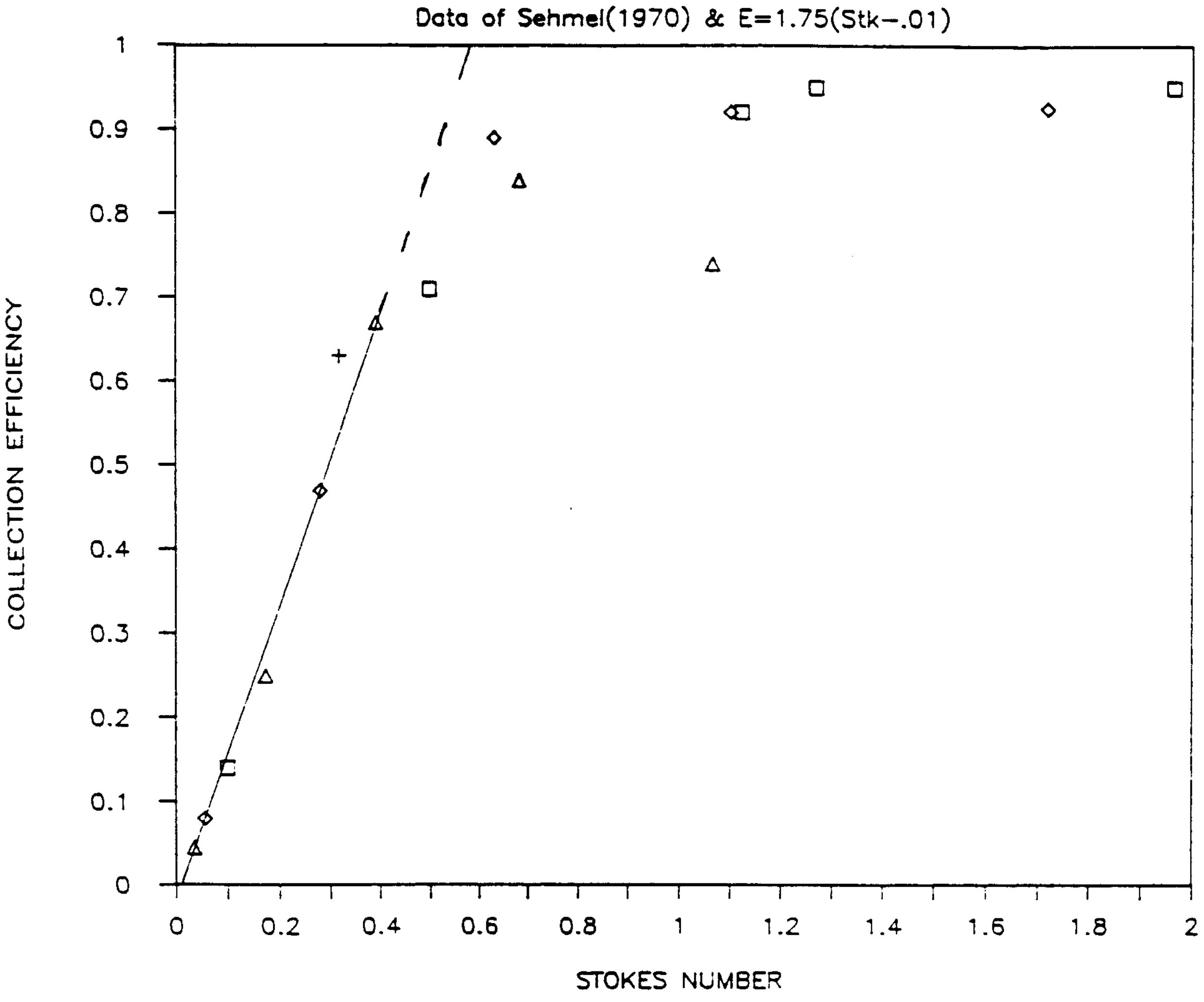
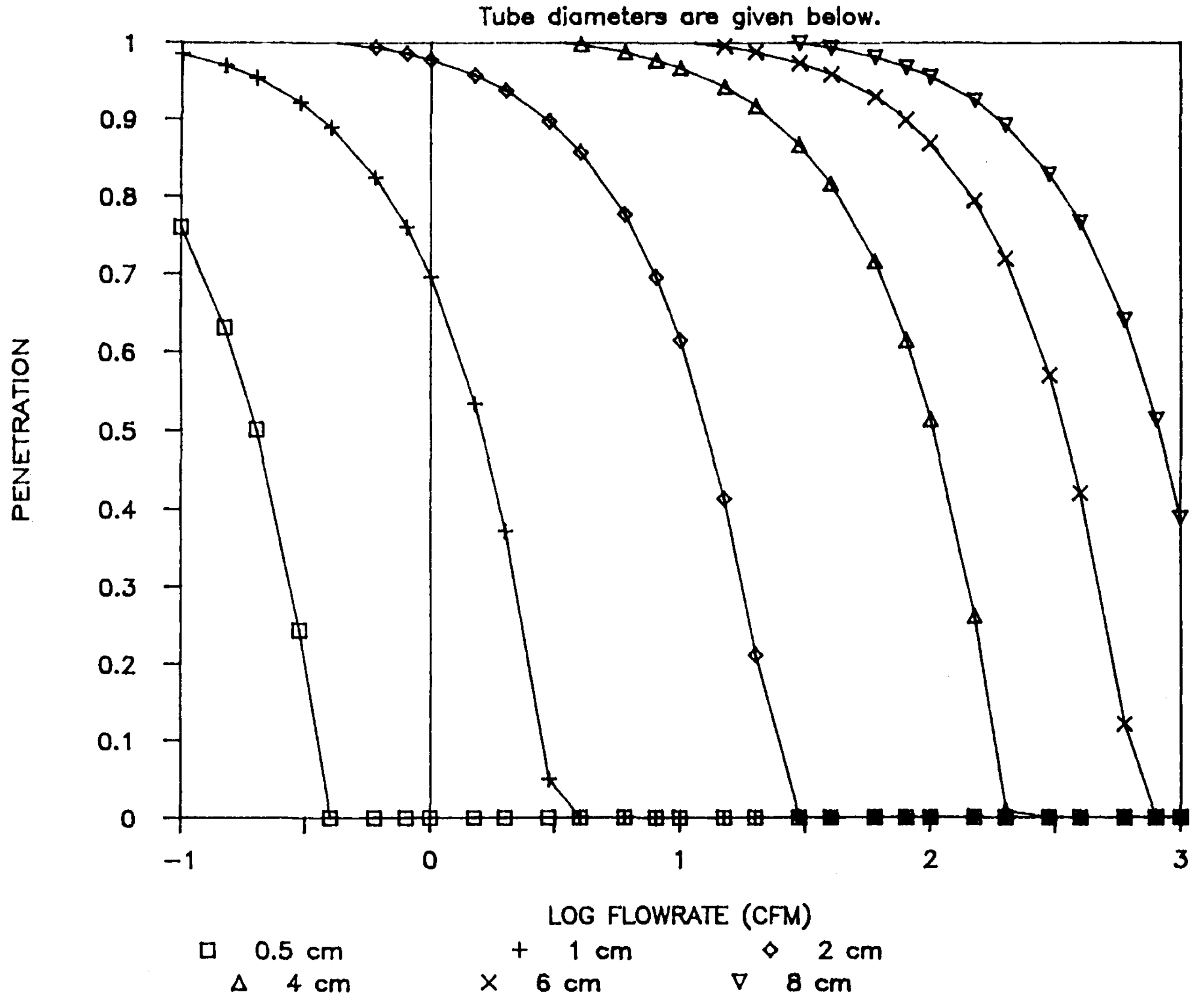


Fig. 16 Aerosol Penetration Through One Bend



3.5.3 Turbulent Diffusion

Liu and Agarwal (16), Liu and Ilori (17), and Agarwal (1) give a direct method for estimating the penetration, P, through a tube with average gas velocity v_t as

$$P = e^{-\pi d v_d L/Q} \tag{5}$$

where d = diameter of the tube, cm,

v_d = particle deposition velocity due to diffusion, cm/s,

L = length of tube, assumed to be 10 ft or 305 cm, and

Q = flowrate, cm^3/s.

The particle deposition velocity v_d is determined from empirical data expressed in terms of the dimensionless parameters v_+, and τ_+ where $v_d = v_+(f/2)^{1/2}v_t$, $\tau_+ = KfRe/2$, and f is the friction factor for the tube walls. Agarwal (1) gives v_+ versus τ_+ for various surfaces. For a smooth surface, for which f is given by the Blasius equation $[f = 0.3164/(4\ Re^{1/4})]^*$, it was found that v_+ is satisfactorily expressed by:

$$v_+ = 6.9\text{x}10^{-4}\tau_+^{\ 2} \text{ for } \tau_+ \leq 15 \tag{6}$$

and

$$v_+ = 0.16\tau_+^{\ -0.086} \text{ for } \tau_+ \geq 15 \tag{7}$$

Figure 17 illustrates deposition from turbulent diffusion for an assumed 10 ft straight transport tube and 10 μm aerodynamic diameter particles. The significance and character of deposition for this tube length and particle size is similar to that for deposition in bends. Increasing the diameter of flow (which includes reduction in flow velocity in the transport tube) increases penetration.

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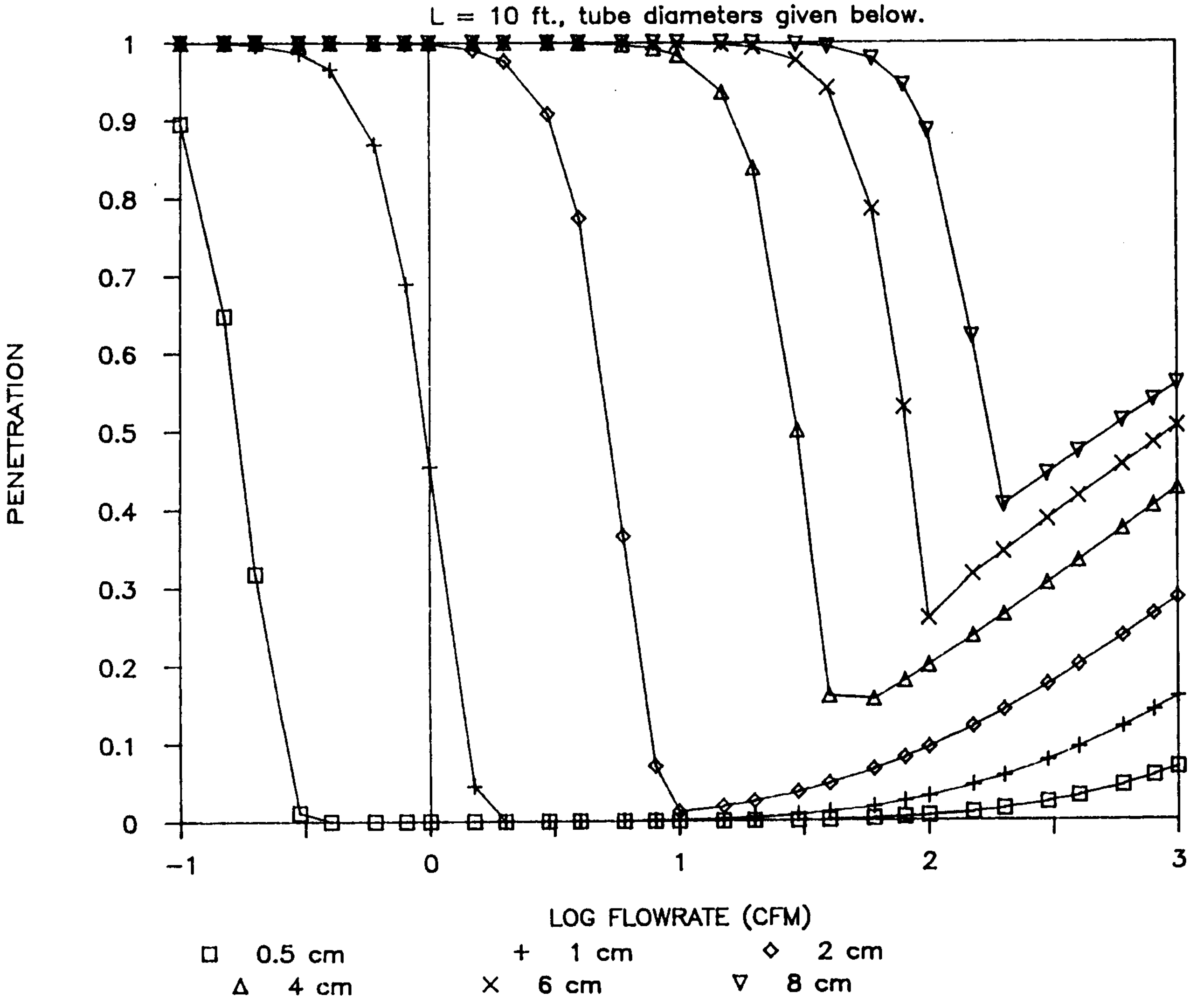
* The Blasius equation is sometimes represented without the factor of 4 in the denominator. For consistency in citation of the results of Agarwal his representation will be followed here.

Fig. 17 Deposition in a Tube from Turbulent Diffusion



3.6 Gravitational Settling

Natanson (18) and others have independently solved the problem of settling in a horizontal circular tube. The collection efficiency E_s, is given by

$$E_s = [2\varepsilon \sqrt{1-\varepsilon^{2/3}} - \varepsilon^{1/3} \sqrt{1-\varepsilon^{2/3}} + \arcsin \varepsilon^{1/3}]\,2/\pi \qquad (8)$$

where $\varepsilon = 3Z/4$ and Z is the gravitational deposition parameter defined at Eqn. (3). Smith, et al. (29) found close agreement between this expression and measured collection efficiency. E_s is a monotonically increasing function of the gravitational deposition parameter, Z. Values of E_s at selected values of Z are given in the following table:

Z	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
E_s	0.12	0.23	0.34	0.43	0.53	0.61	0.69	0.76	0.83	0.88

To keep the deposition fraction due to settling below 0.34 in a straight horizontal section of the probe, Z must be less than 0.3.

Figure 18 illustrates deposition due to settling for an assumed 10 ft straight, horizontal transport tube and 10 μm particles. The overall characteristic is that penetration improves as flow velocity in the tube increases, smaller tubes and/or higher flowrates. Comparison of the results in Figure 17 (for turbulent diffusion) with these results in Figure 18 shows that choosing small tubes or high flowrates to avoid settling losses can result in high deposition from turbulent diffusion. To avoid both causes of deposition, tube sizes of 2 cm or larger are necessary for 10 μm particles.

Since the main transport tube, running perpendicular to the duct axis, could be oriented vertically to eliminate deposition due to settling, the geometry is chosen. Settling is not considered further here. If a horizontal transport tube were necessary, for an unforeseen reason, the effects of settling illustrated in Figure 18 should be considered in the final design.

3.7 Penetration Through a Modeled Transport Line

A trial geometry was assumed, consisting of a horizontal tube 20 cm in length from the nozzle to a 90^o bend. Following this bend the sample gas was assumed to flow vertically down through a length of 10 ft. Initially the nozzle and tube diameters are assumed identical. Collection of droplets is modeled; i.e., the true collection efficiency will be less than calculated if re-entrainment occurs.

Figure 19 gives the results of calculations of penetration of 10 μm particles through the entire sample probe combining effects of the inlet, the bend, and turbulent diffusion as the product of penetrations. The same tube and nozzle diameters were assumed as those studied above for anisokinetic sampling and θ is 0^o. The independent variable is again flowrate, Q (in cfm).

In Figure 19, it is shown that for each condition penetration goes through a peak as flowrate is varied. The flowrate, where the peak is located, and the width of the peak vary with tube diameter. The reduction in penetration at the lower flowrates (left side of each curve) is controlled by deposition at the inlet (given by Okazaki's measurements). The penetration near the peak is controlled by a combination of losses at the inlet, and impaction in the bend, and turbulent diffusion. The penetration at the higher flowrates (right side of each curve) is controlled by impaction in the bend and turbulent diffusion.

Varying duct velocity from 52.5 ft/s (upper curves) to 15 ft/s (lower curves) gives an increase in penetration for the lower flowrates, but the change is not substantial. Increasing θ to 20^o and 40^o decreases the penetrations for lower flowrates.

Fig. 18 Deposition in a Tube from Gravitational Settling

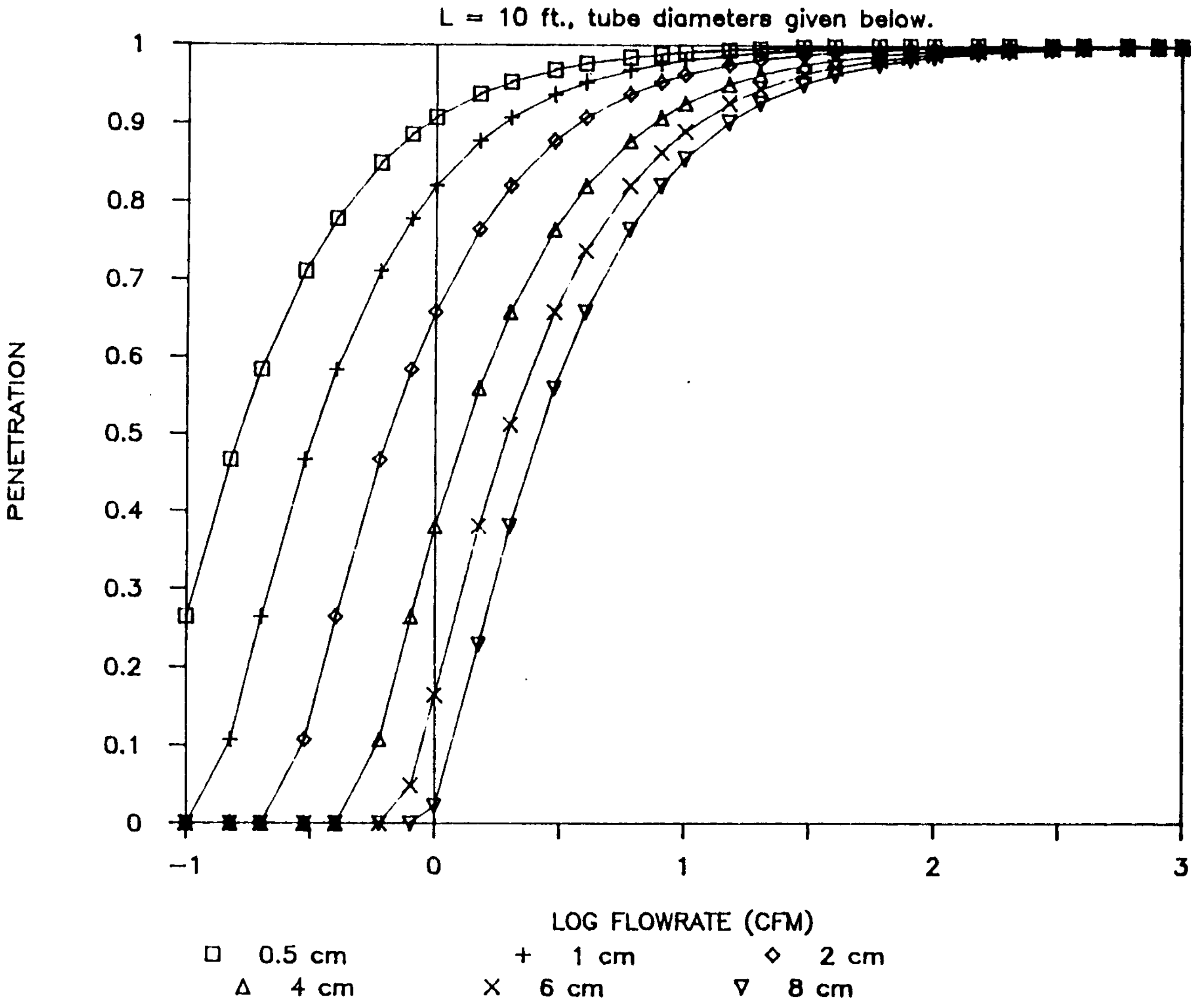
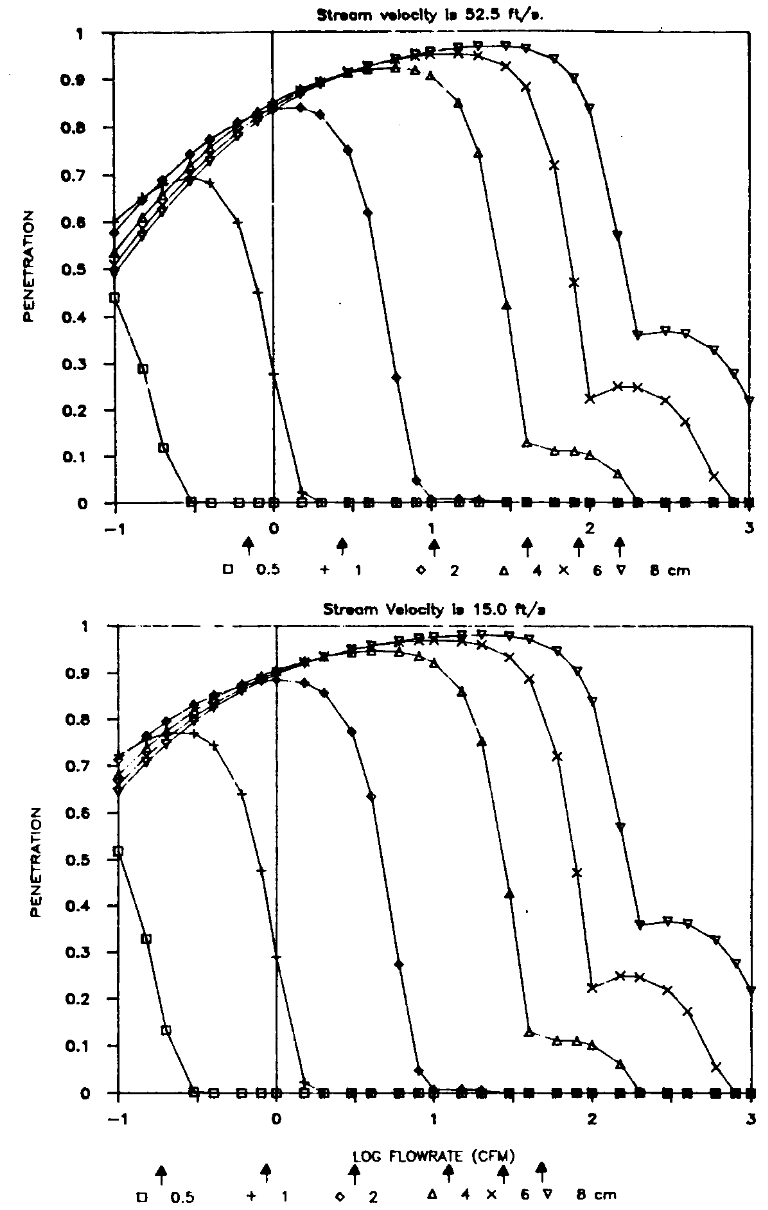


Fig. 19 Aerosol Penetration Through a Modeled Transport Line, Nozzle, and Tube of Equal Size



In Figure 19 arrows are drawn below the horizontal axes to indicate the flowrate for each tube diameter which would correspond to isokinetic sampling at the given duct velocity when the nozzle inlet diameter is the same as the tube diameter.

Considering first the higher duct velocity, one finds that penetration would be very low for all of the diameters considered. Turbulent diffusion would remove the 10 μm particles. The penetration increases as the tube diameter is increased, but it appears that a very large diameter and a very high flowrate would be necessary to obtain high penetration.

At the lower duct velocity, satisfactory penetrations are indicated when sampling isokinetically with the larger tubes. However, note that these results are for 10 μm particles; the right side of each curve would be shifted to the left for larger particles.

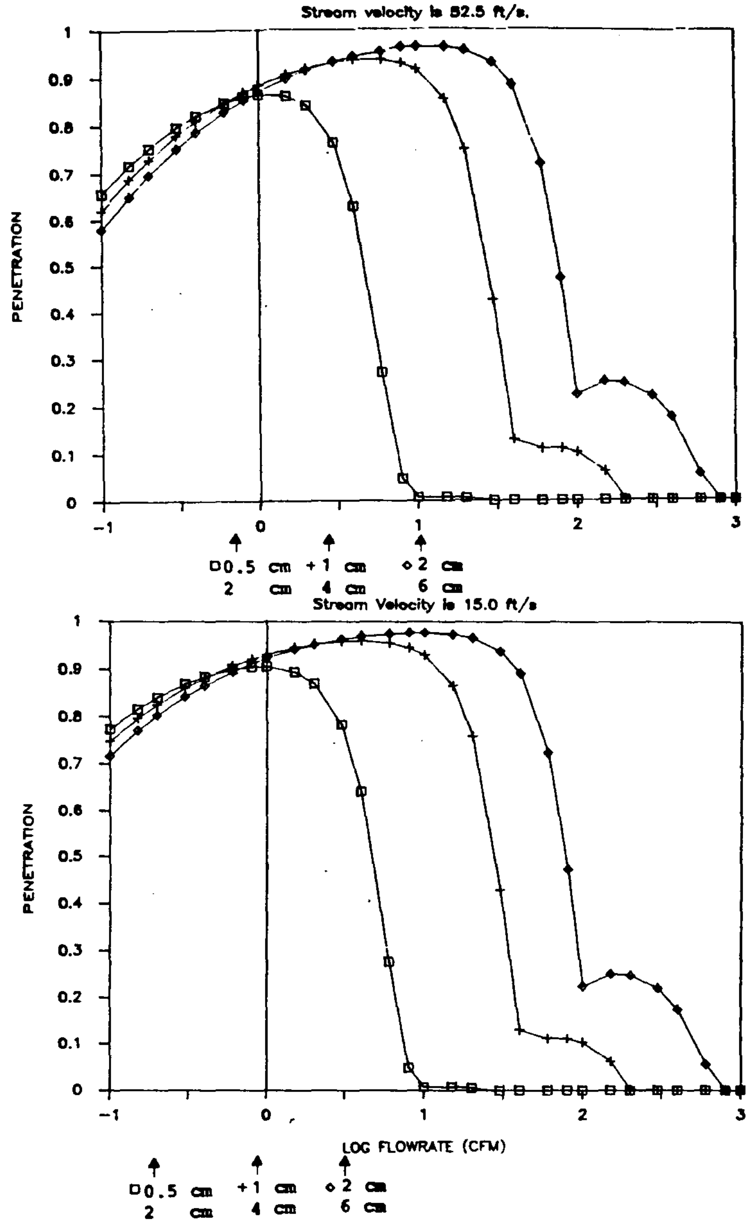
3.7.1 Penetration with Nozzle Diameter Smaller than Bend, and Transport Line

These results indicate that it is necessary for the sample flow to increase with (and decelerate) before passing through the bend and into the main transport tube. This type geometry was modeled for three combinations of inlet (nozzle) diameters and bend and transport line diameters, 0.5 to 2 cm, 1 to 4 cm, and 2 to 6 cm. These results are given in Figure 20 for 10 μm particles. These combinations of geometries for 10 μm particle (Figure 18) and the high duct velocity (52.5 ft/s) give penetrations of 85, 90, and 95% at isokinetic flowrates of 0.7, 2.7, and 10.6 cfm.

3.7.2 Transition from the Nozzle Inlet Diameter to a Larger Transport Tube Diameter

The apparent need for a nozzle diameter which is smaller than the transport tube diameter leads to another question. What should the geometry of the transform be? Current work at Southern Research Institute for EPA is related in which a nozzle inlet diameter of 1.8 in. must be transformed to

Fig. 20 Aerosol Penetration Through a Modeled Transport Line, Nozzle Smaller than Tube



1/2 in. Laboratory calibration has shown that when a straight diverging geometry (conical) is utilized the angle of divergence must be small to avoid losses in this section. Losses were found to be high (≃40%) for abrupt divergence of the nozzle wall, probably due to flow separation. This problem seems to be less severe for larger dimensions, but neither measurements nor theoretical calculations which directly address this phenomenon for the larger dimensions are available yet.

It is known, from venturi design, that flow separation will not occur if the divergence angle is 7° (total included angle) or less. Transforms with such a small angle are difficult to manufacture and inherently long. Since precise information is not available, the appropriate guideline for design purposes is to make the angle of divergency as small as practical considerations will permit.

3.8 Exhaust Duct Particulate and Velocity Stratification

Significant particulate and/or velocity stratification in the airstream of the exhaust duct downstream of the ID fans in the Exhaust Filter Building, if present, could cause additional complications for isokinetic sampling at Station B.

3.8.1 Sources of Particulate Stratification

Many examples of particulate stratification are given in the literature such as the ANSI/ASME sampling guide (5) and Hanson, et al. (13). All sources of particulate stratification can be categorized into 2 types, separation from gas flow caused by rapid changes in gas velocity or direction and various forms of localized injection, creation, or removal. Examples of the first type are cyclones, fans, and bends. Examples of the second type are malfunctioning of a small segment of a control device, combining of streams which differ in concentration, or re-entrainment of material deposited on surfaces.

3.8.1.1 Bends

Specific studies of the effects of elbows in the ductwork by Hanson, et al. (13) concluded that they generally do not cause significant concentration gradients. This can readily be understood from the relaxation time. The velocity of particles relative to gas in the bend is $\tau v^2/r$ where v is the local velocity of the gas and r the local radius of curvature of the bend. To simplify the discussion assume that the velocity is constant across the duct. Then the distance moved by the particle relative to the gas is $\tau v \delta\theta$ where $\delta\theta$ is the total angle of the bend. Thus, for a 90° bend and a gas velocity of 100 ft/s, the distance moved by 10 and 40 μm particles would be 0.6 and 9.3 in., respectively. In actual flow, particles near the wall would shift less due to the lower gas velocity. This analysis shows that for industrial size ducting significant stratification in bends occurs only for relatively large particles at high velocity.

3.8.1.2 Fans

At WIPP, high velocity and small flow cross sections will occur only in the centrifugal ID fans (see Fig. 21). At the fan inlets the ducting narrows to about 4 ft in diameter. The gas will turn and move spirally outward from the fan rotor. The acceleration of the gas in the fans will be $R(2\pi N)^2$, where N is the fan speed in rotations per second (rps) of the fan rotor and R is the distance of a gas volume (or particle) from the axis. Since N will be a constant, the radial velocity of a particle relative to its local gas volume in passing through the fan will increase linearly with R, $v_R = \tau(2\pi N)^2 R$. Integrating this leads to the expression

$$R/R_0 = e^{2\pi N \tau \delta\theta} \qquad (9)$$

for the radial position of a particle relative to that of its initial gas volume, R_0. To arrive at Equation (9), $2\pi Nt$, where t is the transit time through the fan, has been replaced by $\delta\theta$. The value of N can be estimated from a principle of fan design which says that for high efficiency, the inside of the rotor should move at about the velocity of the gas at the inlet to the fan (Jorgenson (14)). For 70,000 cfm and the fan inlet

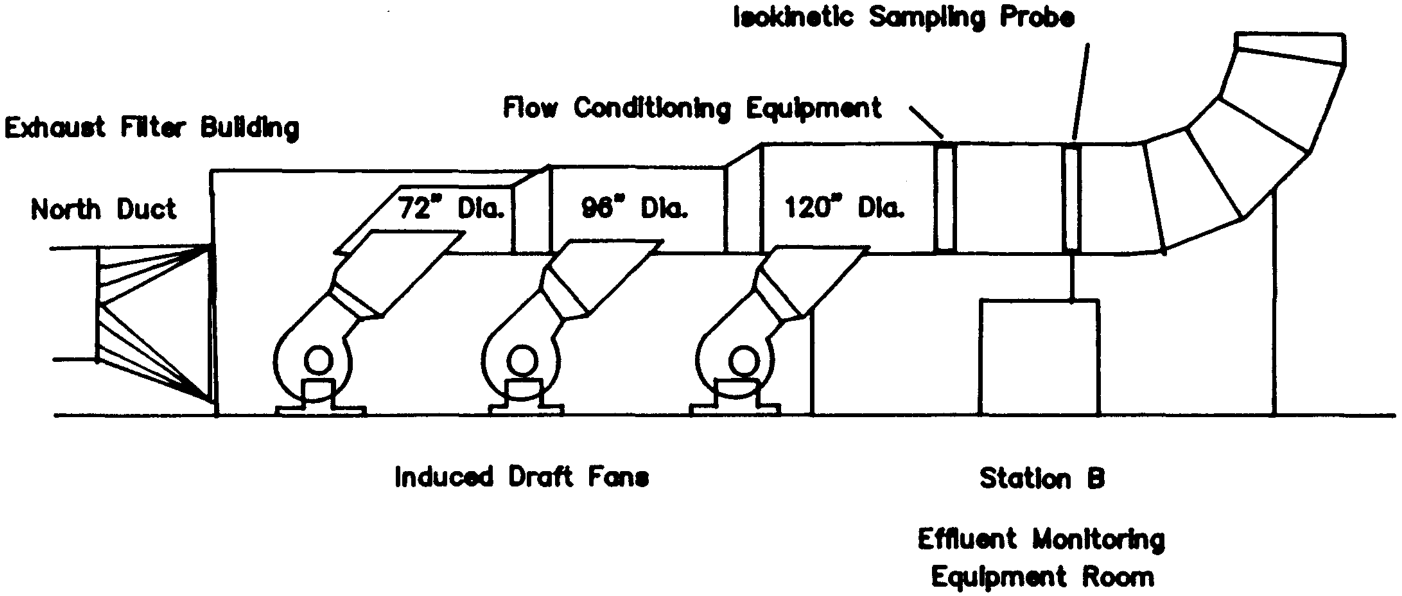


Fig. 21 Induced Draft Fans and Duct Near Station B

diameter of 4 ft, this means that N will be about 7 rps. Thus, R/R_0 for a 10 μm particle is estimated to be 1.05 assuming that a typical value of $\delta\theta$ is π. The ratio of inside to outside diameter for the fans is 1.5, so 10 μm particles will be shifted to the outside 0.92 $(=(1.5^2-1.05^2)/(1.5^2-1))$ of the flow. Table 1 gives corresponding values for 5, 10, 20, and 40 μm particles as a function of rotor speed. Some of these particles will impact upon the outside wall of the fan outlets. If these remain deposited then a buildup will occur which must be removed periodically. The values given in Table 1 are based upon no buildup. If the particles stick and are then blown off later the particulate mass will be shifted toward larger particle size.

Table 2. Stratification of Particles in Passing Through Centrifugal Fans (Ratio of inside diameter to outside diameter of rotor is 1.5)

Rotor Speed (rpm)	Particle Aerodynamic Diameter (micron)	Particle Relaxation Time (msec)	Shift of Particle (R/Rsub0)	Fraction of Flow with Particles
430	5	0.077	1.01	0.98
430	10	0.307	1.04	0.93
430	20	1.228	1.19	0.66
430	40	4.911	2.02	0.00
860	5	0.077	1.02	0.96
860	10	0.307	1.09	0.85
860	20	1.228	1.42	0.18
860	40	4.911	4.09	0.00
1750	5	0.077	1.05	0.93
1750	10	0.307	1.20	0.66
1750	20	1.228	2.05	0.00
1750	40	4.911	17.54	

3.8.1.3 Gravitational Settling and Turbulent Diffusion

Gravitational settling will cause a small portion of the particulate matter to deposit upon the bottom of the ducting. Under normal conditions (210,000 cfm), the residence time will be about 5 sec over the length of the ducting leading to the fans. Fuchs (12) analyzes settling including effects of diffusion. He shows that diffusion can be ignored at distances greater than $4D_d/g\tau$, where D_d is the diffusion coefficient (cm^2/s) and g is the gravitational acceleration. At the values of Re for the ducting at WIPP, turbulent diffusion dominates over Brownian diffusion. Using the method of Liu and Agarwal (16), Liu and Ilori (17), and Agarwal (1), D_d was estimated at .000035, .022, and 0.89 cm^2/s for the discharge ducting and 10, 20 and 40 μm particles, respectively. Using Fuchs's criterion, one finds that turbulent diffusion will not effect overall settling rates of particles in the exhaust ducting; i.e. the flow of particles toward the bottom of the ducting will be the same as for laminar flow conditions. It probably should be noted that settling will not establish a long range gradient in the presence of turbulence, but particles near the bottom settle out while diffusion assists in replenishing this region near the bottom. The expression for collection efficiency due to settling in a horizontal tube gives 1, 2, and 10 % for these particle sizes. It is expected that these particles will remain in the ducting leading up to the fans, probably in the exhaust plenum. After passing through the fans, settling will then occur in the discharge duct with efficiencies of 0.4, 2, and 6 %. It is possible that particles which have settled upon the bottom can be lofted if their cohesion is very low. In that instance, there will be a gradual movement of these particles toward the outlet. A probe would have to be very close to the bottom wall to sample these. At the lower flowrate, 60,000 cfm, when the gas would go through the filter building, the residence time will be increased and settling would increase accordingly in the discharge duct. However, lofting of any particles which penetrated the HEPA filter and settled to the bottom would also decrease.

Turbulent diffusion is another mechanism for deposition of particles upon the walls of the ducting. As above, these may or may not remain there. An important difference from the situation with settling is that the same mechanism which transported them to the wall will tend to remix re-entrained particles with bulk flow rather than permitting them to stay close to the wall. Regardless of the remixing, particles which are near the ducting wall upon entering the fans will exit the fans at different locations due directly to the geometry of flow through the fans. Thus stratification due to turbulent deposition followed by re-entrainment from the walls is relevant only in the discharge duct. The method of Liu and Agarwal (16), Liu and Ilori (17), and Agarwal (1) for estimating the penetration, P, through a pipe is described in a preceding section.

Values for v_d for the discharge duct at the higher flowrate by the method of these authors are 0.34, 4.2, and 4.2 cm/s for 10, 20, 40 μm particles, respectively. Thus, penetrations of 99, 86, and 86 % are expected. For the lower flowrate, corresponding values of v_d are .0018, .0255, and .3823 cm/sec which give penetration-values of 100, 100, and 95.4 %.

From the above estimates, it is concluded that settling and turbulent diffusion can produce some stratification if particles reaching the walls are re-entrained and not remixed with the flow. If complete re-entrainment occurred with no remixing, then, unless probes were near the wall at Station B, total errors of 1, 15, and 19 % could occur for 10, 20 and 40 μm particles during such conditions. Corresponding errors for the lower flowrate would be 1, 5, and 24 %. In terms of radioactive emissions this may still not be the final result. If the time for re-entrainment of particles is relatively long and the ducting is cleaned out immediately after an emission episode then these particles would not have the opportunity to be re-entrained. Regardless, it is believed that actual errors will be much smaller because of mixing.

3.8.1.4 Faulty Control Devices (Leaks)

Leaks at the isolation dampers or the HEPA filters are the only other potential sources of stratification at the WIPP exhaust ducting. These would represent localized sources of particulate matter. Particles passing through a leak at the isolation dampers would pass through the first induced draft fan. Particles passing through a leak in one of the HEPA filters would also pass preferentially through a particular fan depending upon its precise location.

3.8.1.5 Mixing

Turbulence will tend to counteract the viable sources of stratification discussed above, particle inertia and the induced draft fans, leaks in the isolation dampers and the HEPA filters, and re-entrainment of material deposited on walls by settling and turbulent diffusion. The most extensive mixing will occur in the discharge duct due to the disturbance caused by the fans. Injection of turbulent streams is widely used to promote mixing in industry (Ajinkya, 31).

Measurements of velocity profiles downstream of fans show that most of the flow exits toward the outer edge of the fan rotor. The exits of the fans perpendicular to the direction of flow have a depth of about 3 ft (in the direction along the fan axis) and a length of about 5 ft. Based on these dimensions the fan exhausts are compared to a jet with diameter of 3 ft and flowrate of 70,000 cfm, the normal condition, or 20,000 cfm injected into the duct at 40^{o}. These flowrates give velocities of 130 and 37 ft/s, respectively.

The horizontal discharge duct at the exit of first fan is 6 ft in diameter over a distance of 15 ft. (see Fig. 21). At the second fan this duct expands to 8 ft in diameter for 20 ft. Then at the third fan the diameter is 10 ft. The 3 ft diameter stream leaving the first fan will flow across the initial portion of the discharge duct and, upon impinging on the far side, begin to spread. If this stream remains close to the wall, then it will behave like a wall jet which spreads toward the stagnant region at an angle of 4^{o}, entraining gas from the stagnant region as it travels (Rajaratnam, 27). It will travel about 23 ft from the fan exit to where it will encounter the stream from the second fan, thus, spreading to about 5 ft at the second fan and its center velocity will have dropped to about 80 % of the original value.

The interaction of the streams from the first and second fans are characterized as a turbulent jet (from the second fan) in cross flow (from the first fan) by Pratte and Baines (27). Initially, in the potential zone, two attached vortices will form with one on each side of the entering jet. Beyond the potential zone, the two flows will mix rapidly due to entrainment of cross flow by the vortices. The jet flow will spread and entrain cross flow rapidly. The jet will bend over toward downstream and its mean velocity decrease rapidly. The vortices will dissipate slowly. For values of Re greater than several thousand, the behavior will be independent of Re.

The length of the potential core will typically be about 2 jet diameters when the ratio of jet velocity to cross flow velocity is near one. Wu (34) demonstrated that relations for the path and spreading given by Pratte and Baines can be corrected for change in the angle of injection by a transformation of coordinates. For the stream from the second fan the relation for the centerline path jet is

$$z/f = (x/f) + 0.26(x/f)^{3.57} \qquad (10)$$

where z is the number of initial jet diameters traveled downstream, x is the initial jet diameters traveled perpendicular to the downstream direction, and f is the ratio of initial jet velocity to cross flow velocity. The value of f for the second fan is estimated as 1.25 (=1/.08). This relation predicts that at the third fan, 20 ft downstream, the centerline of the jet will be 7.5 ft above the bottom of the duct and moving at an angle of 29°. The relation from Pratte and Baines (corrected according to Wu (24)) for width of the jet, h in jet diameters, is

$$h/f = 0.84(x/f)^{1.43} \qquad (11)$$

From this relation, h will be 8.4 ft for the stream originating from the second fan when it arrives at the third fan, which means that part of the jet will have impinged on the far wall. However, it appears reasonable to interpret this as meaning that the jet flow will still extend 4.7 ft (= 8-7.5+8.4/2) down from top of the duct. Rajaratnam gives a relation for the change in flowrate of the jet due to entrainment of cross flow as

$$Q/Q_0 = 0.54\ s^{1.22} \tag{11}$$

where Q_0 is the initial flowrate of the jet and s the distance (in jet diameters) along the centerline of the jet. For the jet from the second fan, s, will be about 8 before reaching the third fan, so the jet is predicted to increase by a factor of 7. Since there will not be that much flow available, this means that the flow from the first and second fans will have combined.

The ratio of velocities, f, for the third fan is estimated from the width of cross flow (from the first and second fans) given above, 4.7 ft. The cross flowrate will be twice that from the third fan through a factor of 2.5 ($=(4.7/3)^2$) more cross sectional area. Thus, again f is estimated at 1.25. The behavior of this jet is predicted to be like that from the second fan. In 20 ft the vortices produced by the interaction of the jet and the cross flow will have entrained the upstream flow. This indicates that mixing will be complete and any differences in the aerosols passing through the three fans will not lead to variation of concentration in the discharge duct. However, the double vortex produced by jets in cross flow is a cause for concern. The particles shifted to the outside of the fan exits by the induced angular momentum will be moved around the outside of each jet by the double vortex. This will reduce the possibility of shifting these larger particles toward the top of the duct. The concern is for the particles which will be separated from the bulk of the flow by the angular momentum in these vortices. This situation is similar to that in the fans, but the angular velocity cannot be predicted. It is believed that, overall, the vortices will provide a positive effect in moving particles away from the top of the duct.

3.8.2 Velocity Stratification and Angularity

Pratte and Baines (24) observed that in free flow the vortex structure dissipates very slowly. Impingement on the top of the duct, at about 20 ft will certainly increase this process. Experience indicates that after initially impinging on the top of the duct the jet may separate from this wall and its path vary with time and position downstream. Example data, such as that given by the ANSI/ASME sampling guide (5) and Hanson, et al. (13), indicate that 5 additional duct diameters downstream will reduce the variation of average axial velocity at the sample plane within 30%. However, without flow conditioning the vortex structure will persist to this point causing nonaxial flow. The honeycomb device, planned for installation by Air Monitoring Corporation will eliminate or reduce large vortices to small, less energetic ones. However, there is concern with problems associated with salt deposits. If it is installed, the best location will be well downstream of the fans to permit thorough mixing and dissipation of spatial variations of axial velocity, because these processes will be eliminated as well as flow rotation by the honeycomb. Honeycombs distribute flow if the pressure differential is substantial, which requires restriction of the cross sectional area of flow. This typically leads to high deposition. From discussions with engineers who specialize in design of ductwork for power plants, it was found that good design of flow conditioning devices requires construction of scaled models to test trial geometries, which are based on intuition and experience. In that application the goal is to maximize energy recovery which implies preventing flow disturbances. At the WIPP discharge duct, the disturbance occurring at the fan exits may be beneficial, so the optimum approach to flow conditioning for WIPP is different. The important point is that empirical testing specific to the ducting geometry is typically needed in design of flow conditioning.

3.8.3 Summary of Stratification

In summary, significant particulate stratification in the discharge duct is not expected. Variation in particulate concentration which could occur up to and in the fans will be eliminated due to the mixing caused by the disturbances in flow as the fans blow into the discharge duct. Velocity stratification and angularity will occur without flow conditioning equipment.

Particulate and velocity stratification should be measured at WIPP before construction of the sampling hardware, but a particulate sample obtained at one location is expected to be sufficient for a satisfactory determination of concentration. Measurement of total duct flowrate will require either measurements at multiple points or a technique based upon bulk flow. Even if multiple point measurements of velocity are performed with a pitot or thermal anemometer array, the bulk flow approach with the fans is recommended as an independent monitor of duct flowrate because it will be inexpensive.

3.9 Recommended Concepts for the FAS

Calculations of aerosol sampling and transport using available knowledge from the literature leads to several important conclusions. It is indicated by Figure 12 that isokinetic sampling is necessary when the duct flowrate is at the normal (high) level. Anisokinetic sampling at the lower duct flowrate may not cause large apparent errors (<10%) if the nozzle diameter were 2 cm or greater and if flow angularity is not severe. However, these restrictions are not necessary if sample flowrate is controlled based upon a monitor of duct flowrate (or velocity). Since flowrate control is a well-developed technology, it is recommended that sampling be isokinetic at all conditions, assuming the sensitivity of radiation detection at the lower sampling rate is sufficient.

It is indicated by Figure 16 that the initial portion of a sample stream should transform the sample flow from the diameter of the nozzle inlet to a substantially larger diameter before the sample passes through a bend. It is further indicated by Figures 13 and 19 that the nozzle inlet diameter should be as large as practical to avoid substantial deposition such as that observed by Okazaki (15, 16) and at Southern Research Institute in a current project.

For a limited flowrate of the total system, these requirements force a compromise between the size of nozzle inlets and the number of sample points in the duct. This compromise is necessary because with isokinetic sampling the total system flowrate is the product of number of sample points, nozzle inlet cross sectional area, and duct velocity. It is believed that a practical upper limit of 10 cfm should be assumed.

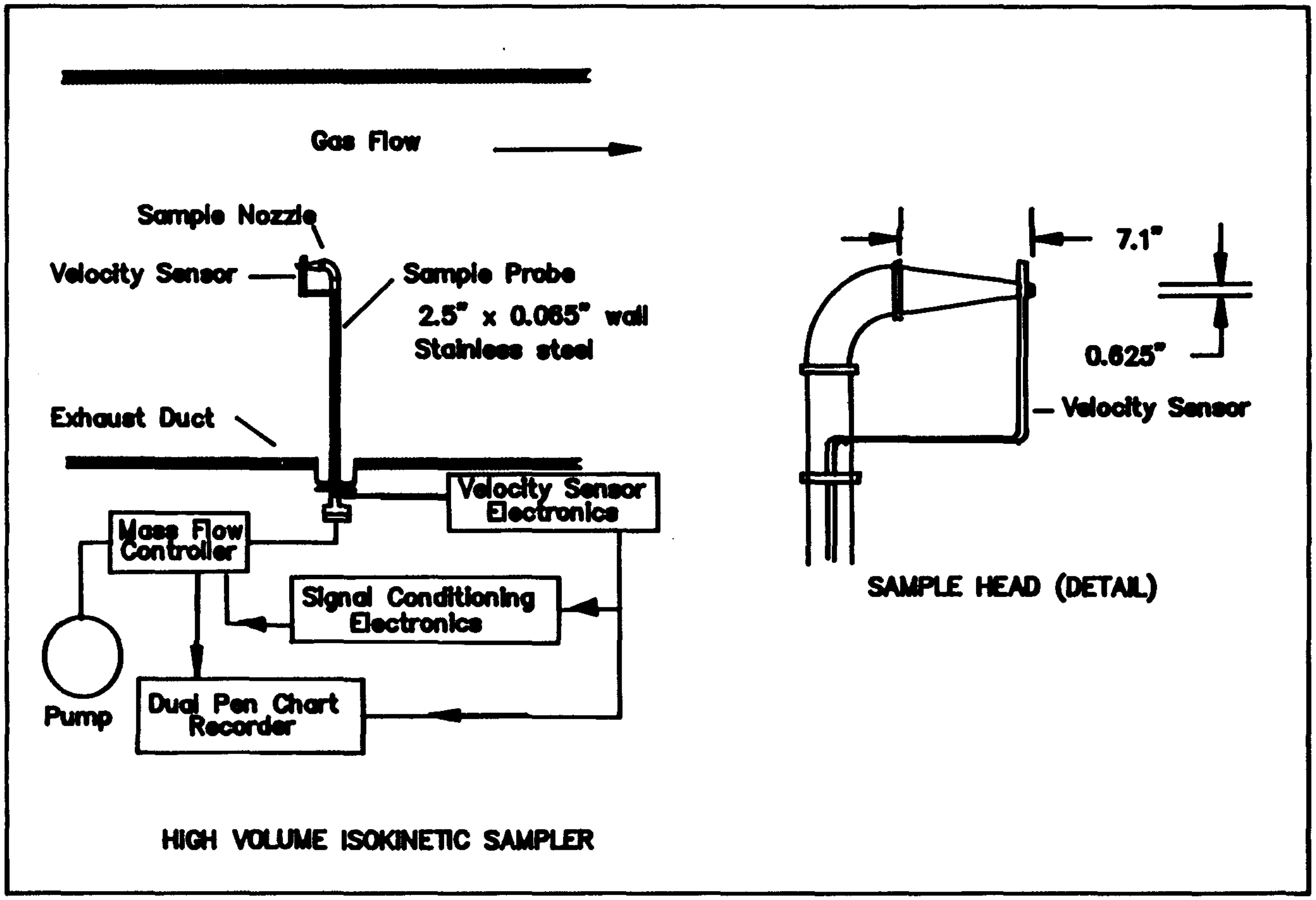
In the absence of particulate stratification, a single sample point with the largest nozzle consistent with the 10 cfm requirement is the optimum. Analysis of sources of stratification given above, based upon an extended discharge duct, indicate that particulate stratification will not be severe. Even with stratification it is believed that measurements would permit locating a sample point which would insure that errors due to stratification would be small (<20%). Thus, sampling at a single point is recommended with the qualification that potential stratification be empirically evaluated on site before construction and installation of the sampling system. An alternate geometry incorporating multiple sample points is discussed below if unacceptable errors due to particulate stratification would be incurred with one sample point.

3.9.1 FAS With One Sample Point

A concept for an automated, isokinetic sampler is given in Figure 22. The sample would be assembled using an electronic mass flow controller and a rugged thermal anemometer. The sample would be drawn through a 1.59 cm (0.625-in) sampling nozzle followed by a 7^{o} (half-angle) taper to a diameter of approximately 6 cm (2.4 in) for a total length of approximately 7 inches. Using a commercially available 90^{o} elbow and assembly flanges, the nozzle can be attached to the desired length of probe. The probe, which may be sectioned using the commercial flanges, would be fabricated from standard 2.5 inch stainless steel tubing (0.065-in wall). The sample would be collected on an out-of-stack, in-line filter. A commercial mass flow controller would be used to adjust and maintain the sample flow.

To insure isokinetic sampling the sample flow can be regulated according to the local duct velocity, as measured by a co-located thermal anemometer.

Fig. 22 Concept of a High Volume Isokinetic Sampling Train



The signal from the velocity sensor is relayed via a custom-designed signal conditioner. As a visual check of the duct velocity and sample flowrate relationship, the 0-5 Vdc output of both electronic components should be monitored with a dual pen chart recorder.

Modifications for Multiple Sample Points

If overall accuracy were found to be improved by measurements of stratification at the site, about three 1 cm nozzle-elbow units or six 0.7 cm nozzle-elbow units could be mounted on the main transport tube. A nozzle-elbow unit with 1 cm inlet diameter should transform to 4 cm before its elbow. Similarly, a nozzle-elbow unit with a 0.7 cm inlet should transform to 3 cm before its elbow.

4. DISCUSSION

4.1 Discussion

A system for the extraction of particulates from the stacks at WIPP for monitoring and representative sampling purposes has proven to be complex and difficult to design and implement, and still has not been successfully completed. Had there been an early study of the velocity and particulate profiles in the portion of the exhaust duct work around the Exhaust Filter Building before specifications and design concepts for isokinetic sampling were prepared, then possibly the present upsets over the apparent poor performance of the installed flow conditioning equipment and concerns about the probe design could have been avoided.

As matters stand, the course of the work on this vital system appears to have taken the form of trial and error on the part of the flow conditioning equipment contractor who has tried to find a "fix" that will work. And at the same time, ITRI has been attempting to fill in the gaps in our understanding of the behavior of air flow and particulates in the exhaust shaft, duct work, and hopefully in the near future, in the sampling lines as well. When the ITRI studies are completed, then a more systematic and effective probe location and design specification process can be undertaken, and the need and means for controlling the flow instabilities downstream from fans in the exhaust duct can be evaluated.

Although some of the guidance of the Peer Review group appears to have been applied to the present system (for example, more direct transport lines to the equipment rooms, and the use of a separate FAS probe with pump and filter holder mounted directly below the stack), much more could be done with the expert advice of this panel. This is particularly true of the group's concern about placing reliance on flow conditioning to create conditions suitable for extractive sampling.

The analytic tools of Chapter 3 could play a substantial role in the future evolution of the air sampling systems at WIPP were they to be used. Although it is imperative that any sample extraction system that is designed and built be subjected to laboratory and field testing to validate its performance, these analytic tools provide a valuable first look at expected performance, and as such, can help guide design choices which would otherwise be difficult to make.

A case in point regarding preliminary analysis of expected performance are the presently installed flow conditioning and sample extraction systems in the Exhaust Filter Building exhaust duct. Although there have been repeated requests for information regarding the expected performance of these systems, none has been forthcoming. The impression left is that neither experimental nor calculational methods have been used to determine expected performance of these devices and systems. Final resolution of the concerns raised in the peer review and elsewhere in this report await completion of WIPP site field tests, provided they are conducted appropriately, and the outcomes are judged against meaningful test performance criteria. The absence of test performance criteria for the particulate transport portion of the proposed Bechtel test plan is a disturbing exception to such expected criteria.

Overall, this report represents an update on portions of a similar Battelle Atmospheric Sciences Report of 1976 by Schwendiman which presents design criteria, test procedures, and design performance calculational methods analogous to what has been presented here (27). Had these specifications and evaluation methodologies been applied scrupulously to the design and specification of the WIPP monitoring system, a very different concept might well have emerged, one more in line with the recommendations of the peer review panel.

APPENDIX A

Appendix A

Modeling Particle Transport in Sampling Probes

A computer model which implements the mathematical models of particulate losses in sampling nozzles and lines described in Chapter 3 has been developed by EEG and is included here for reference. A number of assumptions must be understood about its intended use and limitations.

The geometry of a model probe is as shown in Figure A-1. The nozzle diameter can be equal to or smaller than the nozzle tube and bend diameter. The nozzle tube bend diameter can be smaller than the transport tube diameter as would be the case if a number of small nozzles feed into a large diameter sampling rake manifold. Note that a nominal 20 cm nozzle length before the bend is assumed for sample probes having a bend in the nozzle. This value reflects the empirical nature of the nozzle model.

The user is prompted for all necessary inputs which include, in addition to the nozzle and transport tube diameters, the length and angle of horizontal runs in the sampling line, the number of bends in the line and the number of nozzles in the whole sampling rake. The user must choose between high and low duct velocity.

Computation of the response of a given probe design can be done in one of two ways: 1) If it is assumed that sampling is adjusted to be isokinetic, then the results are computed as a function of particle size aerodynamic diameter from 1 μm to 45 μm in steps of 5 μm. This option is accessed by answering the question, "Is sampling rate assumed isokinetic for each nozzle at the chosen flow?" by "y". Finally the user specifies the angle of the nozzle with respect to flow. Answering "n" to the prompt on sampling rate leads to the alternative which is to compute results as a function of sampling rate, from 0.1 to 1000 CFM in logarithmic steps (i.e. powers of 10). The user must specify the maximum CFM of interest in this range, the particle size of interest in the calculation, and the angle of the probe in the flow.

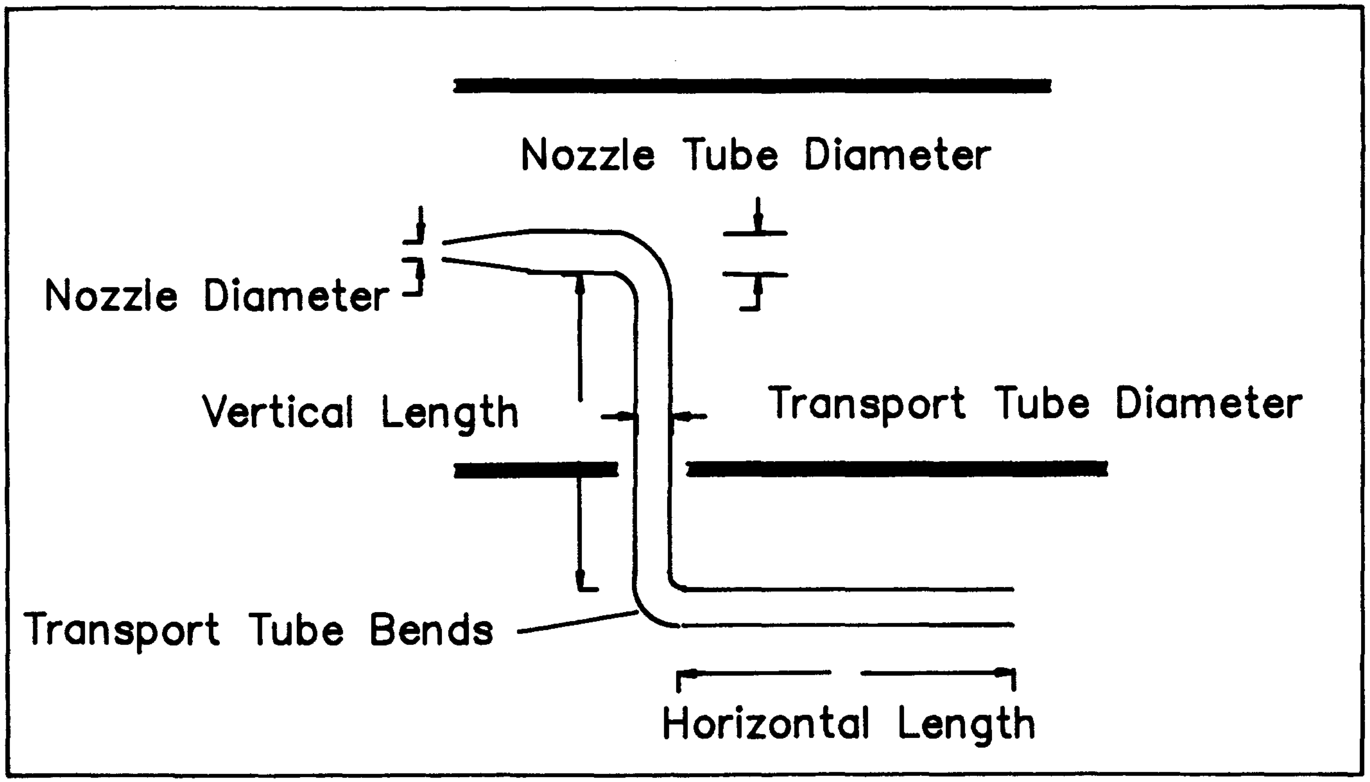
The output of the computation is available both as hard copy, and as a disc file on drive B called "noz.inp". The data is in the form of fractional penetration as affected by different removal mechanisms, and the total penetration. The order of output in the disc file is: CFM, particle diameter (cm), aspiration efficiency, inlet penetration, penetration of the nozzle bend, penetration of line bends, penetration of horizontal tubes, penetration of vertical tubes, total penetration (without aspiration effect), and total penetration including aspiration efficiency.

The total is calculated both with, and without the effect of aspiration efficiency (i.e.,whether or not the sample was collected isokinetically). Two interesting results can be observed from a comparison of these results. First, the anisokinetic sampling error can be gauged, and second, it can be seen that in fact sampling sub-isokinetically may actually improve sampling efficiency for larger size particles. The nozzle, if large enough, can act as a collector of larger particles which leave diverging streamlines and enter the system. Although this would not be a useful condition when a truly representative sample for the record is needed, there may be some real advantages for the probes feeding the CAM detectors where some (but not too much) additional large particles may be an advantage to offset the tendency for large particle loss in the transport line.

See Table A-1 for the program listing and Table A-2 for a sample input and output listing for a test case consisting of a six nozzle array feeding a slant transport line.

As is always the case, with empirically based models, there may be ranges of input conditions for which the assumptions of the models are not valid. The user should use the model with the limitations and understanding of the discussion of Chapter 3. Although every effort was made to eliminate coding errors, some may persist. Please notify EEG of any coding errors found.

Fig. A-1 Sampling System Model Geometry



```
55 REM                TABLE A-1  PROGRAM LISTING
6 REM
7 REM
8 REM
10 REM                Program     NOZZLE7
20 REM
30 REM        WIPP Sample Extraction Nozzle and Transport Line Model.
40 REM        Computes sample losses due to aspiration error, losses in
50 REM        bends, losses due to gravitational settling, and turbulent
60 REM        deposition.  The model system is assumed to consist of one
70 REM        or more nozzles facing into the flow in a large circular duct.
80 REM        Each nozzle feeds into a manifold/transport line exiting the
90 REM        duct.  Combined flow is transported through a series of near-
100 REM       horizontal and vertical transport tubes with several bends
110 REM       to the system FAS and CAMs.
120 REM
130 REM       The model is based on a Southern Research Institute report to
140 REM       the Environmental Evaluation Group, June 1987, written by
150 REM       William Farthing.   There is no warantee of the accuracy or
160 REM       suitability of these models for a particular purpose expressed
165 REM       or implied.   Any coding errors are the responsibility of EEG.
168 REM
170 REM       The Vectra BASIC (GW BASIC 3.2) program was written by John C.
180 REM       Rodgers, Environmental Evaluation Group, Santa Fe, June 1987.
190 REM
200 REM
210 REM    ***********************   VARIABLES   ****************************
220 REM
230 REM           MU= Viscosity of air, poise
240 REM           ND= Nozzle diameter ,cm
245 REM          NTD= Nozzle tube diameter, cm
250 REM           TD= Transport tube diameter, cm
260 REM            L= 20 cm, nominal nozzle length before the bend at manifold
270 REM          DIA= particle diameter, cm
280 REM          HORIZ = Length of horizontal run in transport link, FT (Note!)
290 REM          THETA =Actual Angle of horizontal run with respect to
300 REM          vertical, degrees.
310 REM          VLENGTH= Vertical length of transport line, FT (note!)
320 REM          NONOZ= Number of nozzles in sample extraction array
330 REM          DV= Duct velocity ft/sec: 52.5 ft/sec at 210,000 CFM (Hi flow),
340 REM              and 15 ft/sec at 60,000 CFM (Lo flow) to account for peaks,
350 REM          CFM= Cubic ft/min sampling rate PER NOZZLE
360 REM          PHI= Angle of nozzle axis with respect to principal stream flow,
370 REM          UN= Nozzle velocity, cm/sec
380 REM          UTB= Velocity in nozzle tube, cm/sec
390 REM          R= Ratio, duct velocity to nozzle velocity
400 REM          TAU= Particle settling time, sec
410 REM          KN= Stokes number, nozzle
415 REM          KNB= Stokes number, nozzle tube
420 REM          KT= Stokes number, tube
430 REM          RENN= Reynolds number, nozzle
440 REM          RENT= Reynolds number, tube
450 REM          VDEP= Deposition velocity in horizontal tube
460 REM          AE= Aspiration efficiency
465 REM          AP= Aspiration error
470 REM          EI= Inlet loss
480 REM          EB1= Bend loss in bend at the nozzle
490 REM          EB= Bend loss in bends in transport tubes
500 REM          BENDP1= Penetration of bend at nozzle
```

```
510 REM         BENDP= Penetration of bends in transportation tube
520 REM         FRF= Friction factor
530 REM         ESUBS= Model settling fraction in circular transport tubes
540 REM         TPLUS, VPLUS, Turbulent deposition parameters
550 REM         VDEP= Turbulent deposition fraction in vertical tubes
560 REM         TOT(CFM)= Total penetration of bends & line assumed mult. rule
570 REM         TDIF= Turbulent deposition in circular tube
580 REM
590 REM   **********************************************************************
600 REM
610 REM     ********* Initialize & Input data for run **************************
620 REM
625 DIM TOT(1000)
630 OPEN"o",#1,"B:\NOZ.INP"
640 MU=.000181:PI=3.1416:GRA=980.7:CFMAX=0!
650 L=20: REM    Nozzle length is nomally 20 cm
660 INPUT"Nozzle inside diameter (cm)";ND
670 INPUT"Nozzle Tube inside diameter (cm) ";NTD
675 INPUT"Manifold and/or Transport Tube inside diameter (cm) "; TD
680 INPUT"Horizontal run length (ft) ";HORIZ:HORIZ=HORIZ*12*2.54:IF HORIZ=0 THEN
 GOTO 710
690 INPUT"Angle of horizontal run (90 deg=perfectly horiz) ";THETA
700 THETA=THETA*PI/180
710 INPUT"Vertical run (ft) ";VLENGTH: VLENGTH=VLENGTH*12*2.54
720 INPUT"Number of bends in horizontal and vertical tube runs ";NBEND
730 INPUT"Number of nozzles";NONOZ
740 INPUT"Choose <h>igh duct velocity or <l>ow duct velocity ";CHO$
750 IF CHO$="h" THEN DV=52.5 ELSE DV=15!
760 DV=DV*30.48: REM  Convert to cm/s
770 INPUT" Is sampling rate assumed isokinetic for each nozzle at flow<y/n>?";AN
$:  IF AN$="y" THEN GOSUB 5000: GOTO 790
780 INPUT"Assumed maximum sampling rate is=";CFMAX
785 INPUT"Selected particle size for analysis at this flow (microns)= ";DIA:DIA=
DIA*.0001
790 INPUT"Angle of duct flow inpact on nozzle(s) ";PHI
795 GOSUB 7000: REM  Printout of the initialization parameter assumptions
800 REM  ******************* Begin penetration computations ********************
810 REM
815 IF CFMAX>0 THEN GOTO 822
820 FOR DIA=.0001  TO .0045 STEP .00005:GOTO 830
822 REM  For this option compute penetration as a function of CFM in duct
824 FOR N=-1 TO 3 STEP .25:IF 10^N >CFMAX THEN GOTO 990
826 CFM=10^N:LPRINT"................  CFM= ",CFM,"........................."
830 TAU = DIA^2/(18*MU)
840 GOSUB 4000: REM   Nozzle loss calculations
850 GOSUB 3000: REM Bend loss calculations
860 REM             For nozzle bend, assume tube is same diameter as nozzle
870  REM  Gravitational settling effects in horizontal tubes
880 GOSUB 3500: REM   Horizontal tube calculations
890  REM  Turbulent deposition in Vertical tubes
900 GOSUB 3800: REM    Vertical tube calculations
910 REM
920 REM      Total penetration of system based on multiplicative rule *********
930 REM
940 TOT(CFM)=   EI*BENDP1*(BENDP^(NBEND))*HORZP*TDIF
950 IF TOT(CFM)<=0 THEN TOT(CFM)=0
955 IF TOT(CFM)=0! THEN GOSUB 6000: GOTO 990
960 REM      Outputs
970 GOSUB 6000
```

```
972 IF CFMAX =0 THEN 980
974 NEXT N
976 GOTO 990
980 NEXT DIA
990 CLOSE#1
1000 END
3000 REM
3010 REM  ****************    Subroutine to compute losses in bends ***********
3020 REM
3030 REM      First bend is the bend at the nozzle
3035 IF NTD< TD THEN  UTB =CFM*471.95/(PI*(NTD/2)^2) ELSE UTB=CFM*471.95/(PI*(TD
/2)^2)
3037 IF NTD<TD THEN KNB=TAU*UTB/NTD ELSE KNB=TAU*UTB/TD
3040 EB1=1.75*(KNB-.01): IF EB1<=0 THEN EB1=0
3050 UT=CFM*NONOZ*471.95/(PI*(TD/2)^2) :REM    Velocity in tube
3060 REM  Velocity in tube=sum of all nozzle inputs
3070 KT=TAU*UT/TD: REM    Stokes number for the tube
3080 EB=1.75*(KT-.01): IF EB<=0 THEN EB=0
3090 BENDP1=1-EB1:IF BENDP1<=0 THEN BENDP1=0:  REM    Penetration of first bend
3100 BENDP =1-EB:IF BENDP <=0 THEN BENDP=0: REM    Penetration of all tube bends
3110 RETURN
3500 REM
3510 REM  ***************  Subroutine to compute losses in horiz. tubes *******
3520 REM
3530 ZT=HORIZ*TAU*GRA/(UT*TD)
3540 RENT=.0012*UT*TD/MU
3550 FRF=(.316/(4*(RENT^.25)))
3560 EPSIL=3*ZT/4
3570 IF (1-EPSIL^(2/3) ) <=0 THEN HORZP=0 :GOTO 3620
3580 A1=2*EPSIL*SQR(1-EPSIL^(2/3)):A2=EPSIL^(1/3)*SQR(1-EPSIL^(2/3)):A3=ATN(EPSI
L^(1/3)/SQR(1-EPSIL^(2/3)))
3590 ESUBS=2*(A1-A2+A3)/PI
3600 ESUBS=ESUBS*SIN(THETA):REM   Theta corrects for slant horizontal runs
3610 HORZP=1-ESUBS: REM  Penetration of horiz tube
3620 RETURN
3800 REM
3810 REM  ************  Deposition in Vertical tubes **********************
3820 REM
3830 TPLUS=KT*FRF*RENT/2:
3840 IF TPLUS<=15 THEN VPLUS=.00069*TPLUS^2 ELSE VPLUS=.16*(TPLUS^-.086)
3850 VDEP=VPLUS*SQR(FRF/2)*UT
3860 TDIF=EXP(-VDEP*PI*TD*VLENGTH/(UT*PI*(TD/2)^2)):IF TDIF<=0 THEN TDIF=0
3870 RETURN
4000 REM  ****************** Subroutine to compute nozzle losses  *************
4010 REM                          and aspiration and inlet losses
4020 UN=CFM*471.95/(PI*(ND/2)^2)
4030 R=DV/UN
4040 PHI=PHI*PI/180
4050 KN=TAU*DV/ND: REM   Stokes # for inlet
4060 B=2.1*KN*(COS(PHI)+4*SQR(R*SIN(PHI)))
4070 AP=(R*COS(PHI)-1)*(B/(B+1)): REM ap = aspiration error
4080 AE=1+AP: REM    AE  is  Aspiration efficiency
4090 RENN=.0012*UN*ND/MU:  REM   Nozzle reynolds number
4100 ZN=L*TAU*GRA/(UN*ND)
4110 GV=(ZN*KN/SQR(RENN))^.375 : REM  power of exponent is 3/8
4120 EI=EXP(-4.7*GV): IF EI<=0 THEN EI=0
4130 REM      EI is the inlet penetration
4140 RETURN
5000 REM ******************Subroutine to compute Isokinetic Sampling rate *****
```

```
5010 REM
5020 RA=(ND/2)/(2.54*12): CFM=RA^2*PI*(DV/30.48)*60
5030 PRINT"Sampling rate computed = ";CFM
5040 RETURN
6000  REM     ************   OUTPUTS ******************************************
6010 REM
6020 PRINT#1,USING"##.##^^^^ "; CFM,DIA,AE,EI,BENDP1,BENDP^NBEND,HORZP,TDIF,TOT(
CFM),TOT(CFM)*AE
6026 LPRINT,USING"\            \";"   dia    ","aspir ","inlet","noz bend "
6030 LPRINT,USING "##.##^^^^ ";DIA,AE,EI,BENDP1
6031 LPRINT,USING"\            \";"other bend", "horizontal","vert dif ","total","
tot*ae"
6032 LPRINT,USING"##.##^^^^ ";BENDP^NBEND,HORZP,TDIF,TOT(CFM),TOT(CFM)*AE
6035 LPRINT
6040 RETURN
7000 REM     *****************     Input Summary    **************************
7010 LPRINT " ----------------------- Parameter Data Summary ------------------
----------"
7020 LPRINT
7030 LPRINT "Nozzle inside diameter (cm):  ";ND
7040 LPRINT" Nozzle Tube inside diameter (cm):  ";NTD
7050 LPRINT" Manifold and/or Transport Tube inside diameter (cm): ";TD
7055 LPRINT "Horizontal (slant) run (ft):  ";HORIZ/(12*2.54)
7060 LPRINT" Angle of horizontal run (degrees):  ";THETA /(PI/180)
7070 LPRINT" Vertical run (ft):  ";VLENGTH/(12*2.54)
7080 LPRINT" Number of nozzles:  ";NONOZ
7085 LPRINT "Number of bends (excl. nozzle bend):  ";NBEND
7090 LPRINT" Duct velocity (ft/s):  ";DV/30.48
7100 IF CFMAX>0 THEN GOTO 7110:LPRINT" Sampling rate per nozzle:  ";CFM
7105 LPRINT " Sampling rate per nozzle (cfm):  ";CFM
7110 LPRINT" Angle of flow impact on nozzle (degrees):  ";PHI/(PI/180)
7200 LPRINT
7205 LPRINT " ------------------------------------------------------------------
----------"
7500 RETURN
```

TABLE A-2 SAMPLE INPUT/OUTPUT

```
 ---------------------- Parameter Data Summary -------------------------

Nozzle inside diameter (cm):   .635
 Nozzle Tube inside diameter (cm):   .635
 Manifold and/or Transport Tube inside diameter (cm):  1.9
Horizontal (slant) run (ft):   18
 Angle of horizontal run (degrees):   5
 Vertical run (ft):   5
 Number of nozzles:   6
Number of bends (excl. nozzle bend):   4
 Duct velocity (ft/s):   52.5
 Sampling rate per nozzle (cfm):   1.073789
 Angle of flow impact on nozzle (degrees):   0

 ---------------------------------------------------------------------------
                 dia      aspir      inlet      noz bend
              1.00E-04  1.00E+00  9.96E-01  1.00E+00
             other bend  horizontal  vert dif    total        tot*ae
              1.00E+00  1.00E+00  1.00E+00  9.96E-01  9.96E-01

                 dia      aspir      inlet      noz bend
              1.50E-04  1.00E+00  9.93E-01  9.87E-01
             other bend  horizontal  vert dif    total        tot*ae
              1.00E+00  1.00E+00  1.00E+00  9.80E-01  9.80E-01

                 dia      aspir      inlet      noz bend
              2.00E-04  1.00E+00  9.89E-01  9.63E-01
             other bend  horizontal  vert dif    total        tot*ae
              1.00E+00  1.00E+00  9.98E-01  9.51E-01  9.51E-01

                 dia      aspir      inlet      noz bend
              2.50E-04  1.00E+00  9.85E-01  9.33E-01
             other bend  horizontal  vert dif    total        tot*ae
              9.94E-01  9.99E-01  9.96E-01  9.10E-01  9.10E-01

                 dia      aspir      inlet      noz bend
              3.00E-04  1.00E+00  9.81E-01  8.96E-01
             other bend  horizontal  vert dif    total        tot*ae
              9.61E-01  9.99E-01  9.92E-01  8.37E-01  8.37E-01

                 dia      aspir      inlet      noz bend
              3.50E-04  1.00E+00  9.76E-01  8.52E-01
             other bend  horizontal  vert dif    total        tot*ae
              9.24E-01  9.99E-01  9.85E-01  7.55E-01  7.55E-01

                 dia      aspir      inlet      noz bend
              4.00E-04  1.00E+00  9.70E-01  8.01E-01
             other bend  horizontal  vert dif    total        tot*ae
              8.82E-01  9.99E-01  9.75E-01  6.67E-01  6.67E-01

                 dia      aspir      inlet      noz bend
              4.50E-04  1.00E+00  9.65E-01  7.43E-01
             other bend  horizontal  vert dif    total        tot*ae
```

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