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I am submitting herewith a thesis written by Chung-Tung Shen entitled "Evaluation of the Air Quality of a Residential Home." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

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**EVALUATION OF THE AIR QUALITY
OF A RESIDENTIAL HOME**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Chung-Tung Shen

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DEDICATION

This thesis is dedicated to my wife, Tsai-Hsia. She has, not only displayed continual support, encouragement, and understanding, but also undertaken the additional responsibility in guiding and supervising our two teenaged children, during the time taken away from our family activities to support my classroom and thesis requirements.

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ABSTRACT

The purpose of this study is to conduct a performance-based evaluation of the changing indoor air quality of a residential home under the condition of keeping a heating, ventilating, and air conditioning (HVAC) fan running continuously. To get a real world picture, the air samples were measured while the residential home was occupied by a family of four. However, the domestic activities were kept minimum during the period of data collection. An optical particle counter with multichannel analyzer was used for this study so that the concentration of particles in the particle size increments of interest could be measured simultaneously.

Two different types of the commercially available residential air filters were selected for this study. Two filters of each different type were used for the study of filtration efficiency. All four filters were tested to determine their initial (prior to dust loading) particle removal efficiencies in the range of 0.5 to 5.0 μm . The initial efficiencies of all filters were evaluated under normal air flow rate, as well as a higher air flow rate created by closing one of the three return air inlets in the residence. The measured efficiencies of the filters were studied to compare the consistency in filtration performance between two filters of the same type, the difference in performance between two different types of filters and under different flow rates.

Two filters of one type were also evaluated to determine their filtration efficiencies at the various stages after dust loading throughout the six weeks period of this study. The relationship between the efficiency and the associated parameters such as pressure drop and the increased weight of the filter was evaluated.

To evaluate the air quality, the sample data for the particle concentrations of indoor and outdoor air were measured on twelve days covering the whole period of six weeks. The results were plotted in various curves to visually evaluate the characteristics of the changing air quality with time, the effects by various incidental human activities noted, and the correlation between the indoor particle concentrations and the outdoor levels. The indoor particle concentrations prior to and during cooking were specifically measured in one case to evaluate the effect of cooking on the particle concentrations.

A deterministic model based on particle mass balance was utilized to evaluate the causes of, and ways to alter the indoor particle concentration levels. An experiment was also conducted to develop a basis for a cost effectiveness study of the case of keeping HVAC fan running continuously.

The observed results of this study indicate that the predominant particle distribution range of the subject residential home is in the category of "respirable particles" which are believed to be capable of causing reduction of lung function. It was concluded that keeping the HVAC fan continuously

turned on would be an effective option for improvement of indoor air quality. Realizing the limited scope of this study, related topics for further study are also recommended.

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CHAPTER 1

INTRODUCTION

The purpose of this study was to conduct a performance-based evaluation of the efficiency of the air filters, as well as the changing air quality of a residential home, under the condition of keeping the HVAC fan running continuously throughout the study period, as suggested above. This was compared to the air quality outside and to the air quality inside (when the HVAC fan was shut off for short periods of time) to see what the air quality would have been if the HVAC fan had not been running (i.e., no filtration).

Two different types of commercially available residential air filters were selected for this study. One type was chosen from a more expensive group in which the filters are claimed to be high efficiency mechanical filters with electrostatic properties. The other type was chosen from a lesser expensive group consisting of standard fiber glass filters. Two filters of each different type were used for the study of filtration efficiency.

All four filters were tested to determine their initial (as purchased and prior to dust loading) particle removal efficiencies in the range of 0.5 to 5.0 μm . The initial efficiencies of all filters were calculated under two different

flow rates. The measured efficiencies of the filters were studied to compare the consistency in performance between two filters of the same type, the difference in performance between two different types of filters and under different flow rates. Two of the filters (the more expensive type) were also measured to determine their filtration efficiencies at the various stages after dust loading throughout the six weeks period of this study. The particle removal efficiency performance of both filters at the different stages after dust loading were also evaluated.

Since most people spend most of their time indoors, a significant part of their exposure to particles occurs indoors. However, many studies (Wallace, 1996) showed high correlations of personal exposures with outdoor particle concentrations. Therefore, to understand the health effects of particles requires consideration of indoor air as well as outdoor air sources and concentrations.

To evaluate the air quality, the sample data for the particle concentrations of indoor and outdoor air were measured on twelve different days throughout the period of six weeks. The data of the indoor and outdoor particle concentrations measured were plotted in various curves to assist in the visual evaluation of the characteristics of the changing air quality with time, the effects by various human activities, and the correlation between the indoor particle concentrations and the outdoor levels.

It was noted in several cases during the sample collection that minor cooking activities were incidentally performed. The concentrations of fine particles (less than 1.5 μm) were found to contribute slightly but with little significance to overall indoor concentrations of particles. As indicated from all major studies of particle concentrations and sources in homes and buildings (Wallace, 1996), the single largest indoor source of fine particles is cigarette smoking. The second largest identified indoor source of particles, as determined by several studies, is cooking. Since the residential home of this study is a cigarette smoking free environment, the indoor particle concentrations prior to and during cooking were specifically measured in one case to further evaluate the effect of cooking on the particle concentrations.

To further understand and evaluate the causes of, and ways to alter the indoor particle concentration levels, a deterministic model based on particle mass balance was utilized. To develop a basis for determination of the cost effectiveness for keeping HVAC fan running continuously, an experiment was also conducted to estimate the energy (electricity) consumption by the operation of the fan alone so that additional cost could be estimated under this condition of continuous versus on-off operation.

Throughout this study, an optical particle counter with multichannel analyzer was used to simultaneously measure the concentration of particles in the particle size increments of interest.

The observed results of this study indicate that the predominant particle distribution range of the subject residential home is in the category of "respirable particles" which are believed to be capable of causing reduction of lung function. It confirms the findings of many similar studies which have been published. It was concluded that increasing the recirculation flow rate and/or filter efficiency may be a solution to the improvement of indoor air quality. It was also shown that keeping the HVAC fan continuously turned on would be an effective option for improvement of indoor air quality. Realizing the limited scope of this study, related topics for further study are also recommended.

CHAPTER 2

REVIEW OF LITERATURE

The results of numerous scientific investigations have shown that air inside office buildings and residences is contaminated by a large variety of hazardous contaminants, some of which are apparently in sufficient concentrations to adversely affect the health of those exposed. In addition to the recognition of the presence of hazardous contaminants and the likelihood of relatively long exposure durations indoors, there have been numerous reported outbreaks of building-related illnesses in offices and other public access buildings. There is no doubt that indoor air pollution can cause serious public health problems.

Numerous studies of particle concentrations and sources in homes and buildings have been performed (Wallace, 1996). All major studies found that an important indoor source of fine and coarse particles was cigarette smoking, with estimated increases in homes with smokers ranging from 25 to 45 $\mu\text{g}/\text{cubic meter}$ of fine particles under 2.5 μm in diameter. Several studies identified cooking as a second important source. Elemental emission profiles have been determined for both smoking and cooking, with potassium and chloride being major markers for smoking, and iron and calcium for cooking.

All of the major studies found a substantial portion of indoor particles to be due to unexplained indoor sources, suggesting a topic for future research.

Most studies showed poor correlations of personal exposures with outdoor concentrations. However, for those studies with seven or more repeated measurements, longitudinal regressions on exposures of individual subjects showed much improved correlations with outdoor particle concentrations. This new finding provides some support for the epidemiological findings of increased morbidity and mortality associated with higher outdoor particle concentrations.

Particles in the indoor environment are derived from various indoor and outdoor sources. Historically, much research has focused on the generation of airborne particles from combustion sources outdoors (e.g., sulfates and lead) or indoors (e.g., cigarette smoke) and the associated levels in indoor air, as measured by fixed or personal air samplers. Another potential source of indoor particles that has not received as much attention is soil that is tracked into homes by residents and resuspended into indoor air by walking, vacuuming, etc. This transport process is of potential concern because it brings soil-derived contaminants into the indoor environment where individuals can contact the contaminated dust/soil via incidental ingestion, dermal contact, and direct inhalation. These exposure mechanisms could be just as important as direct contacts with contaminated soil outdoors because

people spend most of their time indoors while at home.

A two-story, single-family, detached residence in Livermore, California, during the summer of 1993 was studied (Layton and Thatcher, 1995) to quantify the input parameters required to estimate the amount of particle penetration through the house shell.

Based on the findings of the studies, fine particles indoors (i.e., less than about 2 μm in diameter) should not be influenced strongly by indoor activities. And as a result, concentrations of fine particles indoors (and associated contaminant species) would be expected to have a higher correlation coefficient with outdoor levels than would coarse particles, which are more susceptible to resuspension indoors.

The analysis of the data collected as part of the Arnhem Lead Study (Layton and Thatcher, 1995) indicates that the movement of Pb-bearing soils into the houses by tracking, followed by resuspension by human activities such as walking and vacuuming accounts for a significant portion of the Pb in indoor particulate matter.

The relationship between contaminants in outdoor soil and the associated levels in the indoor environment requires additional studies to clarify the role of human factors (e.g., occupancy, cleaning frequencies, etc.) and housing factors (e.g., carpeted surfaces, type of vacuum cleaner, filtration by heating/cooling equipment etc.) in modifying indoor levels. Future studies

are needed that address specifically a set of parameters (such as the air exchange rate and deposition velocities for indoor particles, etc.) that are linked to models that describe the transport processes influencing the migration of soil contaminants to the indoor environment. (Layton and Thatcher, 1995)

Recent studies have generated renewed interest in the health effects of sub-micron particles. These same particles play a major role in soiling processes and also contribute to corrosion, current leakage and shorts in electronic equipment. The data collected for more than a year at a Burbank, CA location shows that the indoor concentration of sub-micron particles closely tracks the outdoor concentration, but the ratio of the indoor values to the outdoor values is not constant, and that most of the sub-micron particles found indoors have originated outdoors. This is consistent with the absence of indoor sources at the site. The outdoor concentration of sub-micron particles can vary by large amounts over time intervals as short as an hour. Consequently, there exists the opportunity to reduce the indoor concentration of sub-micron particles by limiting the amount of outdoor air during periods when the outdoor concentration of sub-micron particles is elevated. Particle counters can be used as feedback elements in the HVAC system to accomplish this task (Weschler et al., 1995).

In one of the major studies (New York State study), the results showed

that gas stoves, wood stoves, and fireplaces were found to have no noticeable impact on total concentrations of particles. In another major study, vacuuming, dusting, and sweeping were found to contribute slightly but with doubtful significance to indoor concentrations of particles under 10 μm in diameter. House volume had a significant but small effect on particle concentrations. Air exchange rates were also significant at times, but with different impacts depending on the relative indoor and outdoor concentrations - at high outdoor concentrations, increased air exchange resulted in increases in the indoor air particle levels (Wallace, 1995).

Carpet fresheners are a widely distributed commercial product that consist of a powder, usually corn starch or baking soda, to which a fragrance has been added. A paper details the results of a study (Steiber, 1995) in which two such products were applied to the carpet of a suburban home. The data indicates that room air concentrations of all particles, including those breathable fine particles at 0.35 μm and smaller, increased as much as 80% when the corn-starch-based freshener was applied. With the baking-soda-based freshener, total concentrations increased up to 150% while particle sizes 0.35 μm and smaller increased only about 45%. The corn-starch-based freshener increases persisted for approximately 24 hours while the baking-soda-based freshener increases did not return to background levels for nearly 48 hours.

Contaminated tap water is another source of potentially hazardous air pollutants (gases, not particles) in residential indoor air. The results of a study (Howard and Corsi, 1995) indicated that contaminants have been found to volatilize from the following household tap water sources: showers, wash basins, bathtubs, washing machines, dishwashers, and toilets. It was observed and concluded that more attention should be given to wash basins and tubs, whose numerous operating conditions yield a significant range of chemical stripping efficiencies. Significant gas-phase resistance can occur, even for relatively volatile contaminants, during some operating conditions. This observation has important implications on conventional protocols used to extrapolate radon data to other volatile contaminants in drinking water.

The public's increased awareness towards indoor air quality (IAQ) and its related issues, and their demand to be able to work in healthy environments, along with building owners' and managers' desires to keep energy consumption to a minimum, has fostered a growing need for economical and effective solutions.

The use of air cleaners has steadily moved from one of protecting equipment (such as the heat exchanger in a furnace) to one of protecting people from objectionable indoor aerosol particles (e.g., common dust and allergens). This shift has necessitated the development of new test methods for determining air cleaner filtration efficiency. Under a cooperative

agreement with the U.S. Environmental Protection Agency (EPA) and contracts with the American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE) and the Canadian Electrical Association (CEA), the Research Triangle Institute (RTI) has developed a test method for measuring the fractional aerosol filtration efficiency of air cleaners using an optical particle counter. In order to obtain sufficient particles for an accurate calculation, a minimum total of 500 particle counts in each channel was specifically specified. The method provides a reliable and accurate means of measuring air cleaner fractional efficiencies over the particle diameter size range of 0.01 to 10 μm .

Because the new method provides a more detailed assessment of an air cleaner's performance than the current efficiency and weight arrestance tests of ASHRAE 52.1-1992, use of the new method may lead to the development of improved air cleaners(Hanley et al., 1995).

The usage of air filtration has emerged as an important asset in the prevention and mitigation of indoor environmental problems. This importance is recognized by the revision draft of the ASHRAE Standard 62-1989-R which deals with filtration in a much stronger manner. The role of filtration is also affected by the methods of rating and selecting particulate filters. This technology is being revised by the new ASHRAE Standard 52.2P. This proposed Standard 52.2 provides the performance data of a

clean filter over an entire particle size distribution. It also provides an opportunity for classifying filters used for general ventilation, based on their life cycle loading performance (Burroughs, 1995).

Recently there has been increasing concern about the growth of viruses and bacteria on filter surfaces after capture. This would result in possible re-entrainment into the air. Even HEPA filters are of concern with the possible growth through the media to the exit side. While the filters can effectively remove a significant portion of the particles in the air, including bacteria and other organisms, the filters can also provide sites for growth of microorganisms, particularly in humid air streams. A study (Davis et al., 1995) was conducted to evaluate the effectiveness of biocide-loaded filters in removing bacteria from the air stream and preventing the growth of bacteria collected on the surfaces of the filter, as well as to determine if the filters actually affected the potential growth of bacteria passing through the filter media uncollected. The results indicated that, in seven out of the eight biocides tested, the removal efficiencies were found to be significantly greater for the filters with the biocide than those without biocide. In the case of the polymer-based biocide, there was some indication that the increased efficiency may have been due, in part, to bacteria which passed through the filter, but whose ability to form colony forming units (CFUs) had been inhibited. In the case of the topically applied biocides, the enhancement in

efficiency may have been due to the increased pressure drop and blocking of the pores, which were caused by the application of the biocide to the filters. Out of the fourteen biocides-loaded filters evaluated, eleven of them showed a zone of inhibition on at least some of the organisms, two of the biocides showed significant zones of inhibition for all of the microorganisms tested.

In a full assessment of IAQ concerns, it may be important to determine which types of particles are present in a building environment. Microscopy is the best way to characterize and identify the particle component of indoor or outdoor air. Once a particle pollutant is identified, the source of the pollution can be determined and exposure controlled.

Microscopical examination of dust samples collected in regard to IAQ concerns can often provide useful information about the source of contaminants (Hopen and Millette, 1995). The samples are analyzed by polarized light microscopy and in some cases by scanning electron microscopy.

Some IAQ problems are concentrated in certain areas where the air changes offered by an HVAC system are not adequate to solve the problem, even with high efficiency filters and outside air. One obvious example would be segregated smoking areas. Another might be areas where airborne transmission of viruses and bacteria can occur, such as transient centers plagued with highly infectious contaminants (such as tuberculosis) or waiting

rooms for doctors. A paper (Cheney and Topmiller, 1995) documents a case where a heavy tobacco smoke problem was solved with the use of an air moving system independent of the HVAC system. It contained high efficiency electrostatic precipitators(ESP) and activated carbon that developed an air pattern to sweep the smoke from the room. This resulted in a 94% reduction in the steady state concentration within the non-smoking area and a 78% reduction in the smoking area. An ASHRAE funded test at Research Triangle Institute (RTI) showed the ESP used in this system had a removal efficiency of 94% or higher on particulate sizes from 0.025 to 1.0 μm . Bioaerosols are in the same general size range as tobacco smoke and remains airborne for long periods of time. It seems logical to examine this characteristic and see if meaningful reductions in concentrations of bioaerosols might be accomplished. Therefore, it is possible to extrapolate the results on tobacco smoke to the control of many airborne diseases in places like doctors offices, hospital emergency rooms, and transient centers. The air pattern that can be established with high efficiency, self contained air cleaners has been shown to be superior to exhaust systems and HVAC systems in reducing the concentration of any submicron contaminant.

The effect of regular vacuuming in the control of fungal and bacterial contamination indoors was studied in 33 houses in the Lower Rio Grande Valley, TX. Sampling procedures were standardized based on preliminary

studies. In the top ten highly contaminated houses, regular vacuuming reduced the fungal population by 30% or more in six of the houses. In eight of the ten most contaminated houses, vacuuming reduced bacterial population by 40% or more. Non-carpet sources of bacterial and fungal spores, if any, must be identified for effective control strategy to maintain healthy indoor air (Skaria, 1995).

Indoor contaminants may be grouped into four categories: bioaerosols (microorganisms); respirable particulates; gaseous contaminants; and vaporous contaminants. While their concentrations may vary, all of these contaminants may exist regardless of types of building, HVAC systems and occupant activity. Whatever air cleaning systems are used, they must be capable of removing indoor contaminants that cause short- and long-term health effects. This means that they must remove and, more importantly, retain reasonable quantities of bioaerosols, respirable particulates, and gaseous and vaporous contaminants. Therefore, an IAQ filtration system must consist of at least four components: bioaerosol filter, respirable particulate filter, gas/vapor adsorber, and the housings for the assembly of these filters/adsorbers. When designed and applied properly, filtration systems can be a practical and effective means to control indoor contaminants. The filtration systems and the methodologies described in a paper (Liu and Huza, 1995) provide building engineers a framework of

filter/adsorber selection. Building engineers may use filtration systems to augment other control strategies (such as source management) to create an indoor environment that, at a minimum, provides acceptable indoor air quality and, at the maximum, increases worker's productivity and well-being (Liu and Huza, 1995).

CHAPTER 3

METHODOLOGY

The test site of this study is an all brick, two story with basement, residential home located about seventeen miles to the west of Knoxville, Tennessee. It is occupied by the author who has a typical family of four with a small house dog. The amount of soil being tracked into the house by the residents has been maintained minimum by keeping the shoes outside the house. It was constructed in early 1982 as a very "tight" building for conservation of energy. The finished area, including the basement, is estimated to be approximately 3900 square feet. The house was built with all electric appliances and a central air/heating system with a heat pump.

Two different types of commercially available residential air filters were selected for this study. One type was chosen from the most expensive group which are claimed to be the high efficiency mechanical filters with electrostatic properties by the manufacturer. It consists of a 0.2 cm layer of polypropylene mesh with 316 μm fiber diameter and a 1.6 cm layer of polyester with approximately 26 μm fiber diameter. The other type was chosen from the least expensive group and was a standard fiber glass filter (approximately 2.5 cm in thickness). The pictures of these two different types

of filters are shown in Figures 3-1 and 3-2. Two filters of each different type (one for the first floor and the other for the second floor) were used for the study of filtration efficiency. They were designated as Filters A and B (for the more expensive type), and C and D (for the lesser expensive type).

All four filters were tested to determine their initial (as purchased and prior to dust loading) particle removal efficiencies in the range of 0.5 to 5.0 μm . The initial efficiencies of all filters were calculated under the normal air flow of the house where all three return air inlets were kept open, as well as under a higher air flow (at the first floor return air vent). The higher air flow rate was accomplished by closing the return air inlet on the second floor to create a higher flow rate in the first floor return air inlet.

A. Sampling of Air Flow

As schematically demonstrated in Figure 3-3, there are three return air inlets in the HVAC system. Two of them were constructed to hold nominal 16 in. x 25 in. air filter, and are located on the first and second floors. The third one was built to hold a nominal 14 in. x 16 in. air filter, which is located on the basement floor.

Due to the availability of the size of the filters chosen, only the air filters installed in the return air inlets on the first and second floors were evaluated. The air filter in the return air inlet on the basement floor was left intact with the same type of standard fiber glass filter as Filters C and D throughout the

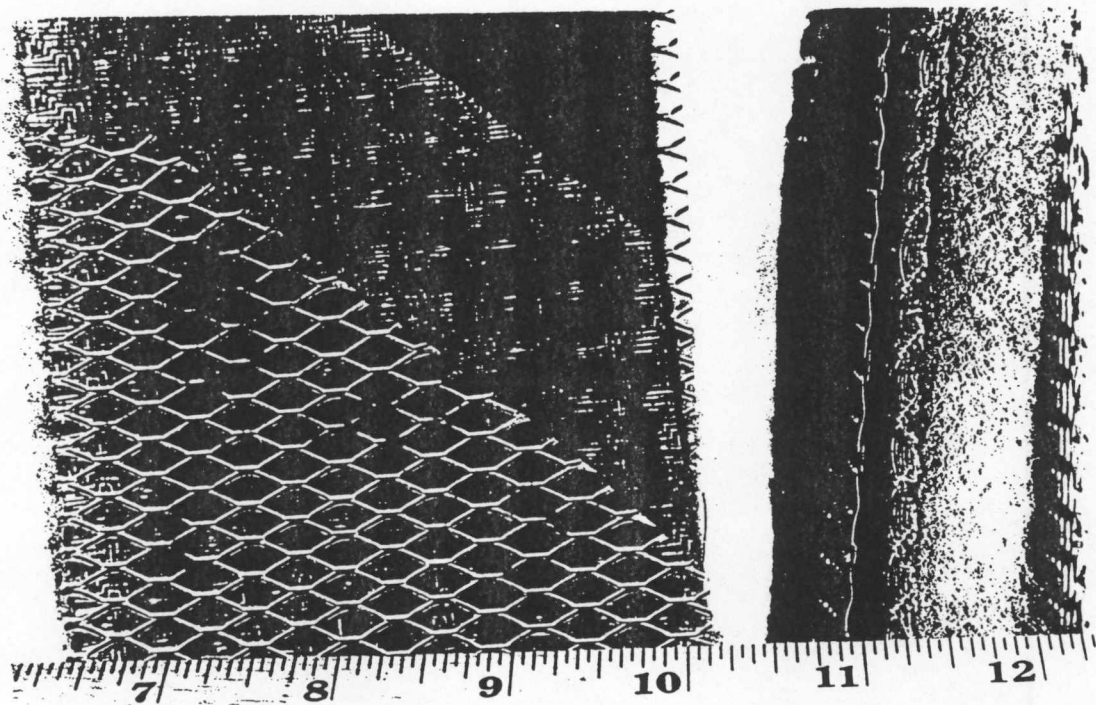


Figure 3 - 1. Picture of Filter A (or B)

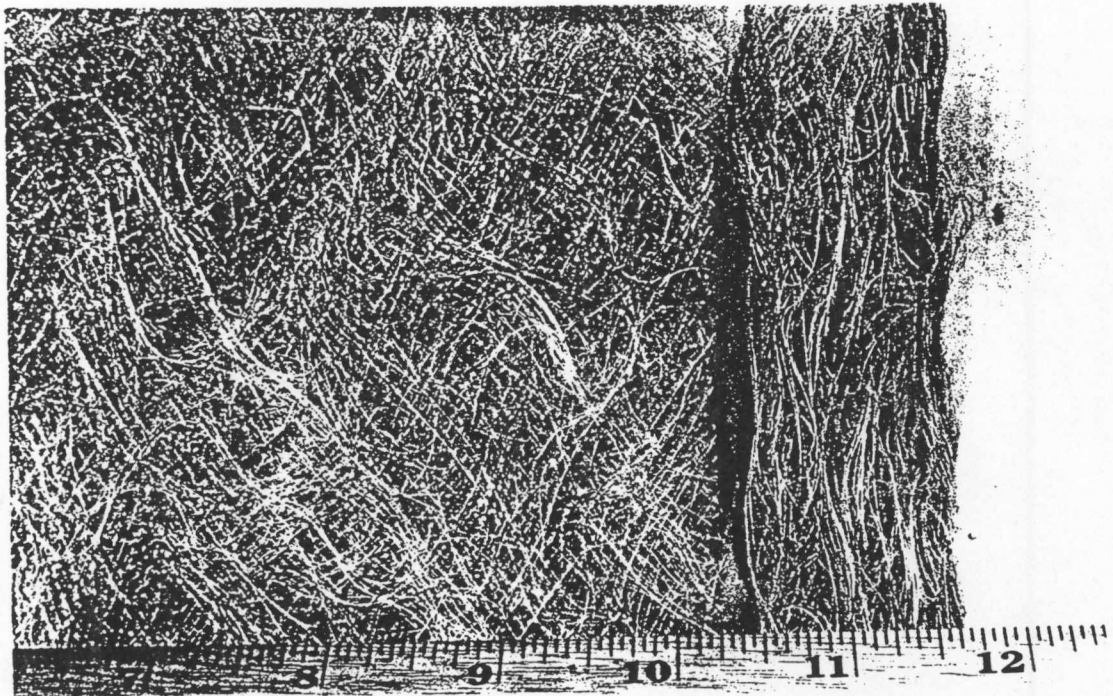


Figure 3 - 2. Picture of Filter C (or D)

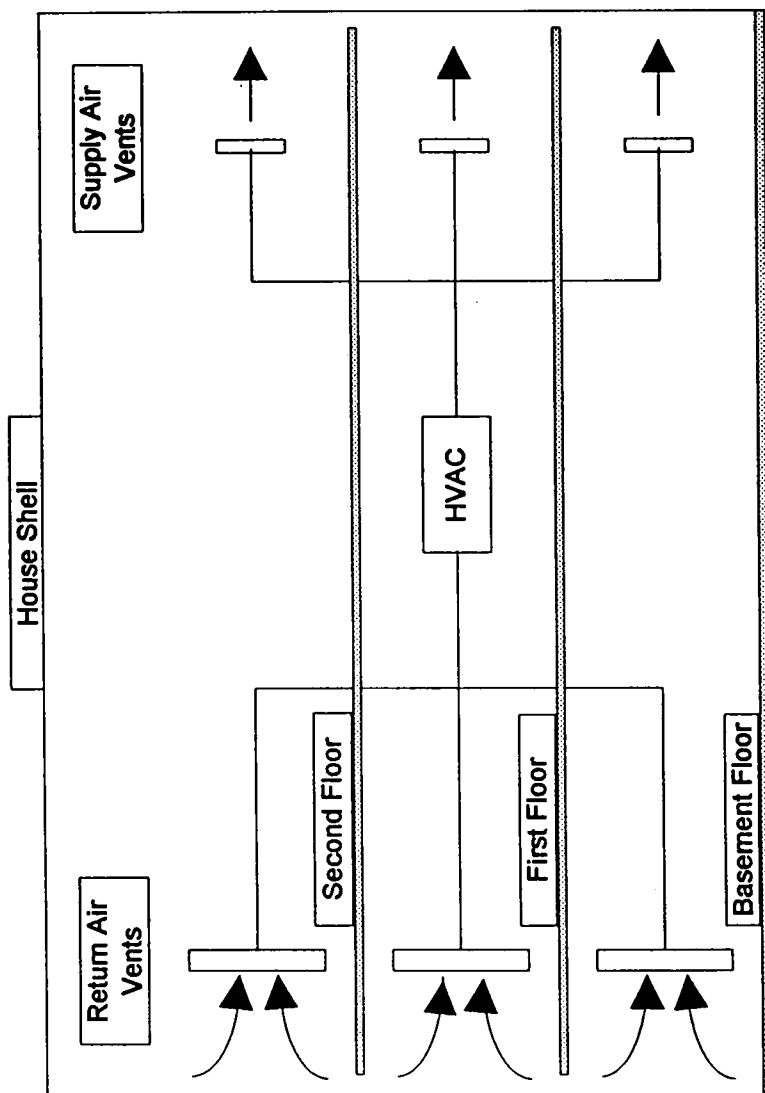


Figure 3 - 3. Schematic of HVAC system

period of this study. All air samples were taken from the test duct located at the return air inlet on the first floor.

The setup of the test duct is as shown schematically in Figure 3-4. Two probes are mounted at about the center (but not exactly at the same position to avoid the interference of air intakes) of the duct inlet with the upstream and downstream probes located in front of and behind the filter, respectively. They are used to extract a sample of the flow into an optical particle counter to measure the particle concentrations.

The particle counter used in this study is a Climet Model 7300 optical particle counter (OPC) capable of measuring particle sizes of 0.5 - 10.0 μm . Each particle which passes through the counter scatters the light at an intensity which is related to its particle size. The intensity is amplified and creates a voltage pulse ranging from approximately 50 mv to 10 volts for particles of 0.5 - 10.0 μm , respectively. In order to obtain simultaneous counts at each particle size of interest, the signal from the OPC is processed by a multichannel analyzer card (MCA) which processed the signal into 1024 channels in the 0 - 8 volt range. The card, a Nucleus Personal Computer Analyzer card (PCA-III) (Oxford Instruments, Oak Ridge, TN) is mounted in an IBM compatible 486 SX personal computer.

The software associated with the MCA allows the user to specify the region of interest (ROI) in which the counts are to be summed. In the case

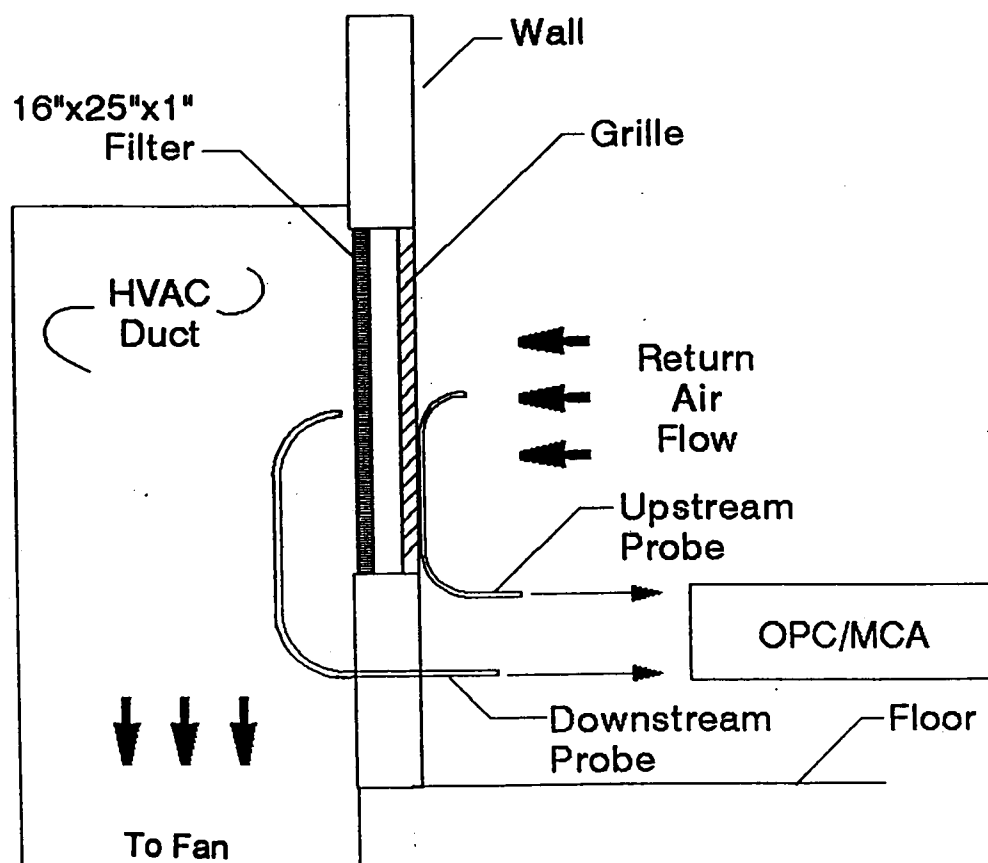


Figure 3 - 4. Schematic of IAQ test duct

for the calculation of filter efficiencies, the ROIs are set to sum the number of particles in a total of nine narrow ranges centered about 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, and 5.0 μm , respectively. In the case for measuring of air quality, the ROIs are set to sum the number of particles in a total of eight consecutive ranges of 0.5 - 0.7, 0.7 - 1.0, 1.0 - 1.5, 1.5 - 2.0, 2.0 - 2.5, 2.5 - 3.0, 3.0 - 4.0, and 4.0 - 5.0 μm .

The OPC/MCA was calibrated by generating monodispersed latex spheres of known size in an ASTM 1215 Test Stand. Sizes used in the calibration included 0.497, 0.624, 0.804, 1.07, 2.04, and 2.94 μm . Once the calibration curve was generated, the channels corresponding to each size of interest were interpolated from the curve.

B. Calculation of Filter Efficiencies

The average efficiency of the filter was reported in this study as the average of a series of calculated efficiencies. The number of calculated efficiencies required for use in determining an average efficiency was determined when a statistically convergent value was derived for the averaged efficiency of each particle size of interest. For the calculation of the initial efficiencies (prior to dust loading) of each of the four test filters (Filters A, B, C, and D) and the case where there was only a grille with no filter installed, 11 upstream and 10 downstream samples were taken sequentially (i.e., one upstream, one downstream, one upstream, one

downstream,....., until the last upstream sample was obtained). The sampling duration for each sample was 1 minute. There was a period of 1 minute between two consecutive sample collections to allow for adequate flushing of the OPC sampling cell. To minimize the effect of particle variability, the average of the counts obtained from two upstream samples and the downstream sample collected in between were used to compute each calculated efficiency. Thus, ten calculated efficiencies were used to obtain an average initial efficiency of the filter.

Filters A and B were actually installed in the two return air inlets for filtration of the indoor air during the six-week period of data collection. The average efficiencies of each of these two filters were also calculated at the end of the second week, fourth week, and sixth week after dust loading. Based on the experience from the calculation of the average initial efficiencies, the average efficiencies of each of these two filters were derived by the average of seven calculated efficiencies with 8 upstream and 7 downstream samples taken sequentially. Parameters such as humidity, temperature, pressure drop (Δp), flow rate of the air, and the weight of the filter were measured at the time the air sample data are collected.

C. Measurement of Air Quality

The sample data for the particle concentrations of indoor and outdoor air were collected on twelve different dates throughout a period of six weeks.

The particle counts were set to be summed in the eight consecutive size ranges as described in Section A above. Typically, the indoor particle concentrations data were collected continuously for a complete period of 140 minutes. The data collection began while the HVAC fan was continuously in operation. The fan was turned off at the end of the first 10 minutes and then was turned on again about 40 to 60 minutes after the data collection began. The system was turned off for this short period of time just to see if the concentrations in the area would begin to increase and reach a stable value without the fan in operation. This would provide immediate insight into the benefit of a continuous system versus one that might be operated in the normal cyclical mode. As for the outdoor particle concentrations, the data were typically collected continuously for 10 minutes on the same day right after indoor data were collected. While part of the intent of the exercise of shutting the fan off was to see if the indoor concentration would increase, reaching a stable value, it was later found that the time required to reach a stable value would have been considerably longer than this 40 to 60 minute period. This is discussed later in the discussion of the results.

The energy (electricity) consumption resulting from the operation of the HVAC fan was estimated through the reading of the electric meter for a fixed period of time during which the fan was running while all other electric appliances, including heating /cooling, in the residential home were turned

off. The electricity consumed was determined from the average of three readings and was estimated to be 0.7776 kilowatt-hours (kwh) per hour. The cost charged by the utility company was \$0.05475/kwh. Thus, the cost for the operation of HVAC fan alone can be calculated to be \$0.0426/hour (\$0.05475/kwh x 0.7776 kwh/hour) or approximately \$30/month.

D. Calculation of Infiltration Rate

A deterministic model based on particle mass balance was utilized to help understand and evaluate the causes of, and ways to alter the indoor particle concentration levels measured. A schematic of a ventilation system for time varying indoor-outdoor model is shown in Figure 3-5. Based on the air mass balance and the particle mass balance of this model, the time varying indoor particle concentration C_i may be derived (Wadden and Scheff, 1983) as follows:

$$C_i = \frac{k[q_0(1-F_0)+q_2]C_o+S}{k(q_0+q_1F_1+q_2)+E} (1 - e^{-[(k/V)(q_0+q_1F_1+q_2)+E]t}) + C_s e^{-[(k/V)(q_0+q_1F_1+q_2)+E]t}$$

where C_i is the indoor concentration at any time t , and C_o is the outdoor concentration (assumed to remain constant); t is time; C_s is the indoor concentration when $t=0$; q is volumetric flow rate for make-up air (q_0), recirculation (q_1), infiltration (q_2); F is filter efficiency for make-up (F_0) and recirculation air (F_1); V is room volume; S is indoor source emission rate; R is

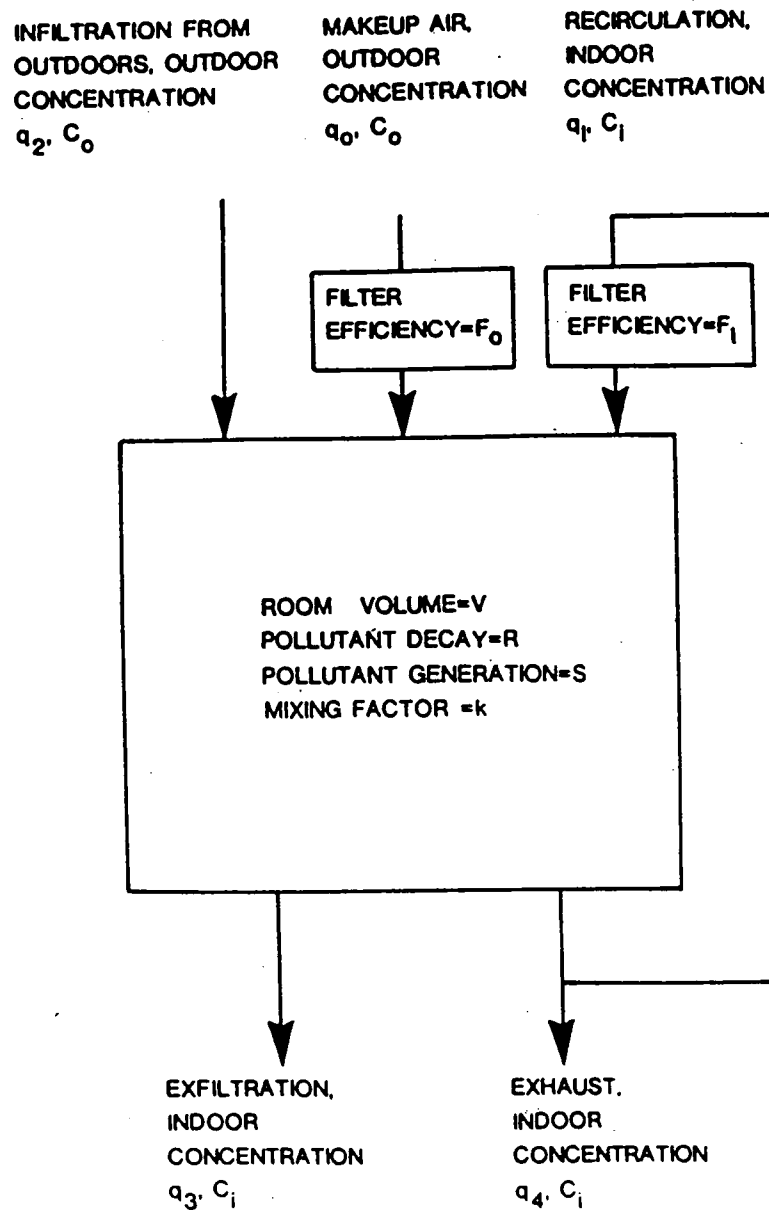


Figure 3 - 5. Schematic of a ventilation system for time varying indoor-outdoor model

indoor sink removal rate; E is a proportionality constant for the particular particle of interest, such that $R=E C_i$; and k, a factor which accounts for inefficiency of mixing, is the fraction of incoming air which completely mixes within the room volume.

Since there is no make-up air in the ventilation system of the subject residence, the term, q_0 , should be equal to zero. The indoor source emission rate and the indoor sink removal rate are assumed to be low enough to be negligible (i.e., $S=E=0$). With good mixing (using fan), the value of k was found to be close to unity (Waddon and Scheff, 1983). Therefore, steady-state values of indoor particle concentrations will result by letting t approach ∞ which, for the above equation, results in

$$C_i = \left(\frac{q_2}{q_1 F_1 + q_2} \right) C_o$$

or

$$q_2 = \left(\frac{C_i}{C_o - C_i} \right) q_1 F_1$$

Since no values of filtration velocities and filter efficiencies of the filter at the basement (designated as Filter E) were measured, the values measured

at Filters C and D were used for Filter E because of identical filter type. In addition, the values of filtration velocities for Filter E were also adjusted so that a consistent level of pressure drop among all three recirculation air inlets was maintained. Based on the values of filtration velocities, filter efficiencies, as well as the indoor and outdoor particle concentrations measured, the infiltration rate may be calculated.

To study the actual time required for the indoor particle concentrations of the subject residence to reach the steady-state values with fan on, the time varying term

$$\text{Exp}(-x) = e^{-[(k/V)(q_0 + q_1 F_1 + q_2) + E]t}$$

was calculated (where $k=1$, $V=8 \times 3900=31200$, and $q_0=E=0$) for various time and the results were plotted. The steady-state values of the indoor particle concentrations are reached when this term approaches zero.

CHAPTER 4

RESULTS AND DISCUSSION

A. Initial Efficiency

The average initial efficiencies were calculated under both normal air flow and a higher air flow, as defined in Chapter 3. It should be noted that the particle concentrations greater than 2.5 μm (i.e., 3.0, 4.0, and 5.0 μm), in this residential home, were insufficient (Most of them were less than 100 counts/cubic ft.) to provide an adequate basis for a meaningful calculation. While it would have been possible to sample for longer periods, it was felt that the time varying concentration of the particles would have caused additional error in the efficiency measurements. Thus it was not possible to accurately assess the efficiency of removing particles for particles greater than 2.5 μm . As a result, the discussion in this study will address only the particle sizes less than 3.0 μm in diameter. It should be noted that the predominant particle distribution range of this residential home happens to be right in the category of "respirable particles" which are capable of reaching the nonciliated portion of the lung to cause reduction in lung function as described in the study by Miller et al., 1979.

As shown in Table B-2, the initial filtration velocities of Filters A and B

were 216 fpm at normal air flow and 382 fpm at the high flow condition. For Filters C and D, which had a lesser pressure drop, the velocities were 355 and 479 fpm for the normal and high flow conditions, respectively. The higher air flow condition was created essentially to see if there was any appreciable increase or decrease in efficiency due to the possible use of a higher filtration velocity as could easily be the case in another home where velocities might be different. The filtration velocities measured at the surface of Filters C and D were approximately 65% and 30% higher than the values measured at the surface of Filters A and B under normal and higher air flows, respectively. That means approximately 30% to 65% more air flow would be recirculated through the filter if Filter C (or D) was used in stead of Filter A (or B). For the case with no filter installed, the efficiencies were calculated under normal air flow. No filtration velocity was measured. The purpose of performing this case was to determine the filtration efficiency contributed by the grille alone.

To demonstrate how the number of tests of efficiency was determined for use in determining the average efficiency of the filters, the sample data of 1.0 μm particles during the initial efficiency tests of Filter A at normal air flow was selected for illustration. As shown in Figure A-1, the maximum and minimum values of the average initial efficiencies for different number of randomly taken tests of efficiencies were calculated and plotted. It was seen that the

efficiency can be determined with reasonable accuracy by averaging approximately seven tests of efficiency. While ten calculated efficiencies were used to obtain an average initial efficiency for all filters (Filters A, B, C, and D), it was determined that seven calculated efficiencies were sufficient to obtain a reasonably accurate average efficiency for Filters A and B after dust loading.

The curves representing the relationship between the average initial efficiencies (convergent values) of all four filters including the case with the grille only (no filter installed) and the corresponding particle sizes, under normal air flow were shown in Figure A-2. The curves for the four filters under the higher air flow were shown in Figure A-3. These average initial efficiencies were also summarized in Table B-1. To make a convenient comparison, the efficiencies of each individual filter under normal and higher air flow were plotted against the corresponding particle sizes as shown in Figures A-4, A-5, A-6, and A-7 for Filters A, B, C, and D, respectively.

It should be noted, from Table B-1(a) and Figure A-2, that other than at particle sizes of 0.5 μm and 0.7 μm , the case with the grille alone provides no effect on filtration efficiency. Review of Figures A-2 and A-3 indicated that the efficiencies of Filters A and B were clearly higher than those of Filter C and D in the particle size range less than 3.0 μm under normal air flow, but not that much higher under the higher air flow. Review of Figures A-4

through A-5 also indicated that Filters A and B both showed decreased efficiencies as filtration velocity was increased (i.e., higher air flow). However, Filters C and D showed just the opposite effect as shown in Figures A-6 and A-7. This represents a significant difference between the media of the different filters which probably suggests the need for further study in future. It should be noted that the Filters A and B are manufactured with electrostatic properties which tend to increase in effectiveness as the filtration velocity is decreased (i.e., larger residence time), whereas Filters C and D are fibrous filters with inertial impaction as the primary removal mechanism. Inertial impaction tends to increase the efficiency with increased filtration velocity. This could be the reason for the difference noted above.

The average initial efficiencies of Filters A and B varied from 2-5% at a particle size of 0.5 μm to 37% at a particle size of 2.5 μm . As for Filters C and D, they varied from 1.3-1.9% at a particle size of 0.5 μm to 11.3-14% at a particle size of 2.0 μm , and 5% at a particle size of 2.5 μm . The unreasonably low efficiency at 2.5 μm was resulted from the negative efficiencies caused by insufficient particle counts at the time of the data collection, and was therefore not reliable. It was also noted from Figure A-2 that up to 2% of efficiency at a particle size of 0.5 μm may be provided by the grille alone, suggesting that Filters C and D provided no real removal at the smaller particle sizes.

B. Efficiency/Pressure Drop as Function of Dust Loading

Parameters such as humidity, temperature, pressure drop (Δp), filtration velocity, and the weight of the filter were measured at the time the air sample data were collected. The values of these parameters were summarized in Tables B-2 and B-3. Based on the data from Table B-3, the average indoor particle concentration removed by the Filters A and B were calculated and the results were included in Table B-3a. The average efficiencies of Filters A and B at the beginning (initial) and after dust loading were summarized in Table B-4. For visual evaluation of the changes in efficiencies during dust loading, the average efficiencies with corresponding particle sizes were plotted as shown in Figures A-8 and A-10 for Filters A and B, respectively. To compare the difference in efficiency performance of Filters A and B at each of the four different stages during dust loading, four plots were made as shown in Figure A-12.

Review of Tables B-3 and B-3a indicated that the humidity, temperature, and filtration velocity were at about the same levels for both Filters A and B. The pressure drop and the weight of both filters increased as the duration of dust loading increased. The average indoor particle concentration removed by the Filters A and B were calculated to be 4.25 and $7.33 \mu\text{g}/\text{m}^3$, respectively. The correlation between the pressure drop and the weight of dust loaded for Filters A and B was plotted as shown in Figure A-13. As

indicated from the figure, the values of these two parameters for both filters were consistently close throughout the six weeks period of dust loading. Study of Figures A-8 and A-10 indicated that the average efficiencies of both filters at the end of sixth week after dust loading increased to the highest levels (10.5-12.5% at a particle size of 1.0 μm and 45.2-50.7% at a particle size of 2.5 μm). However, there was no obvious increase or decrease in efficiency with dust loading at the end of second and fourth week. To further analyze the situation, the correlation between the efficiency and the weight of dust loaded were plotted in Figures A-9 and A-11 for Filters A and B, respectively. Review of Table B-3a and Figures A-9 through A-12 revealed that the average efficiencies of both filters at the end of second and fourth week after dust loading were at the same or lower than the initial levels at the particle size range of 1.0 - 2.5 μm . It was also noted, from Table B-3a, that the average indoor particle concentration removed by the Filters A and B for the second and third 2 weeks were, in general, less than the amount for the first 2 weeks after dust loading. This could be caused by a number of factors as follows.

1. Filters were removed every two weeks, although they were handled carefully. - So there probably was some dislodging of dust, although slight.
2. Particles on different days could have had different origin. - Thus

different densities and possibly different efficiencies as a result.

3. experimental error - Although counter is generally very stable.

Overall, factors 1 and 2 were probably the most likely cause for this variation.

A review of Figure A-12 demonstrated that the efficiency performance of both Filters A and B were, in general, consistently close at different stages of dust loading for the particle size ranges less than 3.0 μm in diameter. The negative efficiency observed at the second week should be disregarded as explained above.

C. Indoor Particle Concentration and Distribution

To facilitate the study of indoor particle concentration and distributions, a set of plots of the indoor air concentration curves, in logarithmic scale, on each of the twelve sample collection days was included in Figures A-14a through A-14l. To further study the characteristics of the changing air concentrations with time, a set of 12 plots of indoor changing air concentrations with time, together with corresponding plots of outdoor particle levels were included in Figure A-15, A-16, and A-17 for the particle size ranges of 0.5 - 0.7, 1.0 - 1.5, and 2.0 - 2.5 μm , respectively. A review of Figures A-14 through A-17 indicated the following:

1. As indicated in the figures A-14a through A-14l, the particle concentrations typically decreased with the increased particle size. It

may be observed as noted above, in general, that the concentrations of particles greater than 2.5 μm were insufficient to provide an adequate basis for any meaningful efficiency evaluation.

2. Activities such as cooking, walking, application of cleaner spray, operation of washer and dryer, etc. usually increase the fine particle (less than 1.5 μm) concentrations. However, cooking was observed to be the most significant attribute among all these activities. As noted during data collection, the incidental activity of minor cooking was occurring, prior to the data collection on 07/25/96 and 08/02/96, at the beginning of the data collection on 07/29/96, and in the later part of the data collection on 08/10/96 and 08/16/96; the activity of cleaning (application of cleaner spray) was occurring, prior to the data collection on 08/30/96; the washer and dryer was in operation at early stage of data collection on 08/19/96. The increased concentrations of particles were found to contribute slightly but with little significance to the overall indoor particle concentrations. This may be observed in every case as reflected on those plots in Figures A-14a through A-17.
3. Particle concentrations of outdoor air vary sharply with a wide range of activities and weather conditions. It was noticed that the particle counts were greatly reduced during or after raining (as reflected on the 07/29/96 and 07/20/96 plots, respectively) and sharply increased

when a neighbor was operating a lawn mower (as reflected on the 08/30/96 plot).

D. Effect of Cooking

To further evaluate the effect of cooking on the particle counts, the indoor air concentrations with time prior to and during cooking were depicted side by side for comparison in Figure A-18, A-19, and A-20 at the particle size ranges of 0.5 - 0.7, 1.0 - 1.5, and 2.0 - 2.5 μm , respectively. As evident from the figures in all three particle size ranges, the particle counts increased sharply immediately following the cooking activity. The particle concentrations increased from 270,000 counts/cubic ft. to 320,000 counts/cubic ft. at the size range of 0.5 - 0.7 μm ; from 8,300 counts/cubic ft. to 25,200 counts/cubic ft. at the size range of 1.0 - 1.5 μm ; and from 180 counts/cubic ft. to 1,160 counts/cubic ft. at the size range of 2.0 - 2.5 μm . To take an overview of the changing particle counts between the cases for prior to and during cooking, the six plots as shown in Figures A-18 through A-20 were plotted in the same scale and included in Figure A-21 for easy evaluation and comparison. It may be clearly observed, from Figure A-21, that the particles generated by cooking were predominantly in the size range less than 1.5 μm , although the greatest relative increase occurred in the larger sizes. i.e., The relative concentration increased by only 18% in the 0.5 - 0.7 μm range whereas the increase was 540% in the 2.0 - 2.5 μm range.

E. Comparison of Indoor/Outdoor Concentrations

The correlation between the indoor and outdoor particle concentrations (i.e., number of particles/cubic ft., taken at 6 minutes after beginning of data collection) at the particle sizes of 0.5 - 0.7, 0.7 - 1.0, 1.0 - 1.5, 1.5 - 2.0, and 2.0 - 2.5 μm for each of the twelve data collection days were plotted in Figures A-22a through A-22e. Based on these particle counts and an assumed particle density of 2.5 gram/cubic centimeter, the mass mean diameters of the indoor and outdoor particle distributions were calculated. The values of the associated particle distribution properties were included in Table B-5. The log-probability plot of the mass distributions of four indoor and four outdoor particle samples were shown in Figures A-23 and A-24, respectively. Comparisons of the particle concentrations, the mass mean diameters, and the standard deviations of the indoor and outdoor particle distributions were also shown in Figures A-25, A-26, A-27, respectively. Study of these figures indicated the following:

1. Even though the subject residential home was custom constructed as a very "tight" building, it was demonstrated, from the Figures A-15 through A-17, that the indoor particle concentrations - especially the fine particles (less than 2.0 μm in particle diameter), in general, increased as outdoor particle levels increased. Furthermore, the correlation between the indoor particle concentrations and the outdoor

levels was also substantiated by the least squares fit regression trend lines, as shown in Figures A-22a through A-22e, as well as the comparison demonstrated in Figure A-25. This confirms the results of the study by Laton and Thatcher, which concluded that the concentrations of fine particles indoor (and associated contaminant species) would be expected to have a higher correlation coefficient with the outdoor levels than would coarse particles, which are more susceptible to resuspension indoor.

2. The mass distributions of the selected particle samples were all plotted approximately in Figures A-23 and A-24 on log probability scale. These curves provide a basis for the calculation of the approximate mass mean diameter and the geometric standard deviation of the particle distribution. As indicated from Table B-5 and Figure A-26, the mass mean diameters ranged from 0.68 to 1.2 μm for indoor particles and 0.84 to 1.53 μm for outdoor particles. With the exception of the data collected on 08/10/96, the mass mean diameter of the outdoor particle sample was found to be higher than that of the indoor particle sample on the same day on each data collection day. The exception as shown on 08/10/96 could possibly be a result of the data interpolation.
3. A review of Figure A-25, Tables B-5, and B-5a revealed that,

throughout the six weeks of test period, the indoor particle concentrations ranged from 0.66 to 8.55 $\mu\text{g}/\text{cubic meter}$, and the outdoor particle concentrations ranged from 4.64 to 32.6 $\mu\text{g}/\text{cubic meter}$ for the particle size range of interest (0.5 to 5.0 μm). The outdoor particle concentrations were found to be higher than the indoor particle concentrations on each data collection day. The average ratio of outdoor and indoor particle concentrations was calculated to be 6.49, which means the indoor particle concentration is approximately 15% of the outdoor level. Further evaluation of the outdoor/indoor ratios at various particle size ranges, as shown in Table B-5a, indicated that the average ratio for the range of 0.5 to 0.7 μm was actually lower (3.71) than the overall average value of 6.49. This means that the indoor particle concentration at the small particle size range of 0.5 to 0.7 μm is approximately 27% of the outdoor level.

4. A study of Table B-5 and Figure A-27 indicated that the standard deviations of the outdoor particle distributions were, in most cases, greater than those of the indoor particle distributions. That means the indoor particle distributions are, in most cases, more concentrated around the mass mean diameter than are the outdoor particle distribution.

F. Evaluation through An Air Model

To further understand and evaluate the causes of, and ways to alter the indoor particle concentration levels, a deterministic model based on particle mass balance was utilized. Particle concentrations at 6 minutes after the beginning of data collection indoor, and at 6 minutes after the beginning of data collection outdoor on each data collection day were selected as the basis for calculation of infiltration rates of the subject residence.

Recirculation flow rates at all three return air inlets were calculated as summarized in Table B-6. Since there was no measured data available for the return air inlet at the basement, and the filter used was the same type as Filters C and D, the average values of the initial efficiencies of Filters C and D were assumed to be the efficiencies of the filter at the basement (Filter E). In addition, the measured filtration velocity of Filter C (or D - same value), as included in Table B-2 and adjusted by the ratio of pressure drop of Filter A and C, was assumed as the filtration velocity for Filter E. Based on the calculated results from Table B-6 and the selected indoor and outdoor particle concentrations measured, the infiltration rates for all particle sizes of interest on each of twelve data collection days and an average value of the infiltration rates on all data collection days (except the data on 08/02/96) for each particle size were calculated and summarized in Table B-7. The data calculated on 08/02/96 were excluded from the calculation of the average

value because of the unrealistic negative infiltration rate noted. Using the average values of infiltration rates as calculated from Table B-7, the percentage reduction (or increase) in indoor particle concentration with the corresponding hypothetical percentage increase (or reduction) in recirculation flow rate and/or filter efficiency may be determined. These results are summarized in Tables B-8a and B-8b and plotted in Figures A-28 and A-29.

To study the actual time required for the indoor particle concentrations of the subject residence to reach the steady-state values, on which the calculations of infiltration rates were based, the time varying term, $\text{Exp}(-x)$, as defined in Section D, Chapter 3, was calculated. The results were plotted in Figure A-30.

Review of Figures A-28 through A-30 and Tables B-6 through B-8b indicated the following:

1. As revealed from Figure A-30, the steady-state values of the indoor particle concentrations may be reached approximately 9 hours (at particle size range of 2.0 - 2.5 μm) to 23 hours (at particle size range of 0.5 - 0.7 μm) after the HVAC fan is placed into continuous operation, assuming no major particle-generating activities inside the house.
2. Other than reducing and/or eliminating the indoor particle generating

sources, the indoor air quality may be improved through increasing recirculation flow rate and/or filter efficiency. According to Figure A-28 for example, an increase of 25% in recirculation flow rate and 20% in filter efficiency (i.e., $1.25q_1 \times 1.20F_1 = 1.50q_1F_1$) may result in a reduction in indoor particle concentration by a range of 21% (at particle size range of 0.5 - 0.7 μm) to 32% (at particle size range of 2.0 - 2.5 μm). As a practical example, if the standard fiber glass filters like Filters C and D) are used to replace the expensive filters like Filters A and B, there will be an increase of 65% in recirculation flow rate (i.e., $354/215 = 1.65$, as reflected by the ratio of filtration velocities shown in Table B-2). Assuming a reduction of 40% in filter efficiency due to this replacement of the filter type, it will result in no change in indoor particle concentration level (i.e., $1.65q_1 \times 0.60F_1 = 1.0q_1F_1$). This means that installing the more expensive (more efficient) filters, in this case, would have no more reduction in indoor particle concentration than using the lesser expensive (less efficient) ones, since the latter had a lower pressure drop, and thus a higher flow rate.

3. As indicated from Table B-7, the calculated infiltration rates of the subject residence range from 0.125 air change per hour (ach) (based on the particle size range of 0.5 - 0.7 μm) to approximately 0.05 - 0.07

ach (based on the particle size range of 0.7 - 2.5 μm). The average infiltration rate was calculated to be 0.07 ach. It should be noted that this average value of infiltration rate may be underestimated. Due to the fact that more of the larger particles are likely to be removed in the process of infiltration, the actual infiltration rate of the residence should be close to 0.125 ach as associated with the small particle size range of 0.5 - 0.7 μm . In comparison with the typical value of 0.5 ach (Wadden and Scheff, 1983), the infiltration rate of the subject residence is very low.

4. To develop a basis for determination of the cost effectiveness for keeping the HVAC fan running continuously, an experiment was conducted to estimate the energy (electricity) consumption for the operation of the fan alone. The cost for running the fan was estimated to be \$0.0426/hour. If we assume that one third of the time is required for the fan to be in operation under normal condition controlled by setting of the thermostat, the additional cost for keeping the fan running continuously for one month may be calculated to be \$20.45 ($\$0.0426/\text{hour} \times 24 \text{ hour/day} \times 30 \text{ day/month} \times 2/3$). However, the saving of \$20.45 per month will actually reduce the recirculation flow by 67%. This, according to Figure A-29, will result in an increase of approximately 60% (at particle size range of 0.5 - 0.7 μm) to 180% (at

particle size range of 2.0 - 2.5 μm) in indoor particle concentration.

Based on the above analysis, it appears that keeping the HVAC fan continuously running probably is an effective option for improving indoor air quality.

CHAPTER 5

CONCLUSIONS

For a "tightly built", cigarette-smoking free, residential home with a limited amount of soil being tracked into the house by residents, the predominant particle size distribution appears to be essentially in the size range less than $2.5\text{ }\mu\text{m}$ in diameter, which happens to be in the range of "respirable particles" which are capable of reaching the nonciliated portion of the lung to cause a significant health problem. For the commercially available residential air filters tested, the efficiency increased as particle size was increased indicating that inertial impaction is the dominant mechanism at the flow rate of normal condition (which corresponds to a filtration velocity of around 220 ft/min.). The measured initial efficiencies at $0.5\text{ }\mu\text{m}$ range from less than 2% for the lesser expensive filters up to 2-5% for the more expensive ones. In the particle size range of $2.0 - 2.5\text{ }\mu\text{m}$, the initial efficiencies range from about 14% for the lesser expensive filters up to 37% for the more expensive filters. The efficiencies of the more expensive filters increased up to 51% for the particle size of $2.5\text{ }\mu\text{m}$ at the end of the sixth week after dust loading although the variation in weeks 2 and 4 suggest that there is no consistent increase and that the variation is caused by the

changing character and source of aerosol. While the filter may be highly efficient for the large particles, it is the filtration efficiencies at the size range of respirable particles that are important, if the predominant particle distribution of indoor air of the residential homes is typically in the same range as the one studied.

Activities such as cooking, walking, application of cleaner spray, operation of washer and dryer, etc. usually increase the concentrations of fine particles (less than $1.5\ \mu\text{m}$) indoor. However, in the cigarette-smoking free residential home studied, cooking was observed to be the most significant attribute among all these indoor human activities. This confirms the findings of many other studies.

The mass distributions of the randomly selected particle samples (four indoor and four outdoor samples) were found to be approximately log-normal in most cases. This is useful since its linearity lends itself to easy interpolation of important values, such as the mass mean diameter and standard deviation, especially when only limited experimental data on the particle-size distribution are available.

Even in a "tightly built" residential home, the concentrations of fine particles (less than $2.0\ \mu\text{m}$) indoor are highly influenced by the outdoor particle levels. Throughout the six weeks of test period, the indoor particle concentrations were found to range from 0.66 to $8.55\ \mu\text{g}/\text{cubic meter}$ as

compared to 4.64 to 32.6 $\mu\text{g}/\text{cubic meter}$ for the outdoor particle concentrations. The overall average indoor particle concentration was calculated to be about 15% of the outdoor level. It was noted that the average indoor particle concentration at the small particle size range of 0.5 to 0.7 μm is higher (27%) than the overall average of 15% of the outdoor level. The mass mean diameters were computed to range from 0.68 to 1.2 μm for indoor particle distributions as compared to 0.84 to 1.53 μm for outdoor particle distributions. The particle concentrations and the mass mean diameters for the outdoor samples were, in general, higher than those for the indoor samples on each data collection day. The particle concentrations of outdoor air may vary sharply with a wide range of outdoor activities and weather conditions. Therefore, the concentrations of fine particles indoor (and associated contaminant species) may also be affected indirectly by a wide range of outdoor activities and weather conditions. This finding may provide some support for the epidemiological findings of increased morbidity and mortality associated with higher outdoor particle concentrations.

The average infiltration rate of the subject residence was calculated to be 0.07 ach. However, the actual infiltration rate is likely to be close to 0.125 ach, which is considered very low in comparison with the typical value of 0.5 ach. The indoor particle counts usually are anticipated to start increasing

after the HVAC fan is turned off. However, due to the low infiltration rate, this phenomenon was not adequately observed. During the testing, the fan-off periods were only 40-60 minutes duration, whereas it would have taken 9-23 hours to reach a steady-state equilibrium concentration based on the above air infiltration rates.

Other than reducing and/or eliminating the indoor particles generating sources, the indoor air quality may be improved through increasing the recirculation flow rate and/or filter efficiencies at the predominant particle distribution range of the general residential homes. Therefore, keeping the HVAC fan continuously running may be an effective option to improve the indoor air quality.

While some filters may be efficient in particle removal, they may also have high pressure drop, resulting in decreased air flow circulation. The net result could be no improvement in indoor air quality. On the other hand, a lesser expensive (less efficient) filter with low pressure drop would have worked just as good as the more expensive (more efficient) filter with high pressure drop. It is apparent that proper selection of a filter on the basis of total performance (i.e., efficiency vs pressure drop) is critical to the improvement of indoor air quality.

CHAPTER 6

RECOMMENDATIONS FOR FUTURE STUDY

The scope of this study is limited to a single residential home. Even though certain results from this study, such as the predominant indoor particle distribution range, the performance-based efficiencies of the filters, the influence of outdoor particle concentrations to the indoor levels, and the effect of cooking to indoor air quality, qualitatively confirm the findings of other similar studies. A program may need to be developed to conduct a structured and systematic evaluations of a broad range of the residential homes of different categories and in different regions of the country so that "typical" results in various categories can be quantitatively derived to serve as the basis for the research and development of a better air filter for use in the residential homes to improve the indoor air quality and our health.

It is beyond the scope of this study to further analyze the specific "morphology" of the particle/aerosol type in the residential home. The concentration of particles will not necessarily be able to show us how hazardous it is to our health unless we know exactly what kind and how much of the hazardous material is in the air we breathe. More complete research and analyses in this area are needed to make data available for the

improvement of indoor air quality.

The residential air filters are typically installed without a positive edge seal other than the seal provided by the suction of the filter frame against the flange of the filter holder. The effect of edge leaks around the filters under initial condition (prior to dust loading) was evaluated in the study by Davis et al. The results of that study show that the efficiencies of the filters are not significantly affected by the manner in which the filters are installed (whether naturally sealed by the suction of the filter against a flange, or sealed by taping the edge of the filter to the housing) particularly in the case of low efficiency filters. Additional studies are needed to evaluate the importance of edge leakage around the filter under dust loading condition.

As indicated by many studies (Wallace), a substantial portion of indoor particles are found to be due to unknown indoor sources. Further research in this area is definitely needed before the indoor air quality can be effectively improved.

As a final note, the filters used in this study, although reasonably efficient when compared to other commercially available filters, did not provide very high efficiencies at the size range of "respirable particles", which are critical to our health. Further research in the development of a residential filter with improved efficiencies at this size range and increased filtration velocity is definitely needed for the protection of public health.

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APPENDICES

APPENDIX A

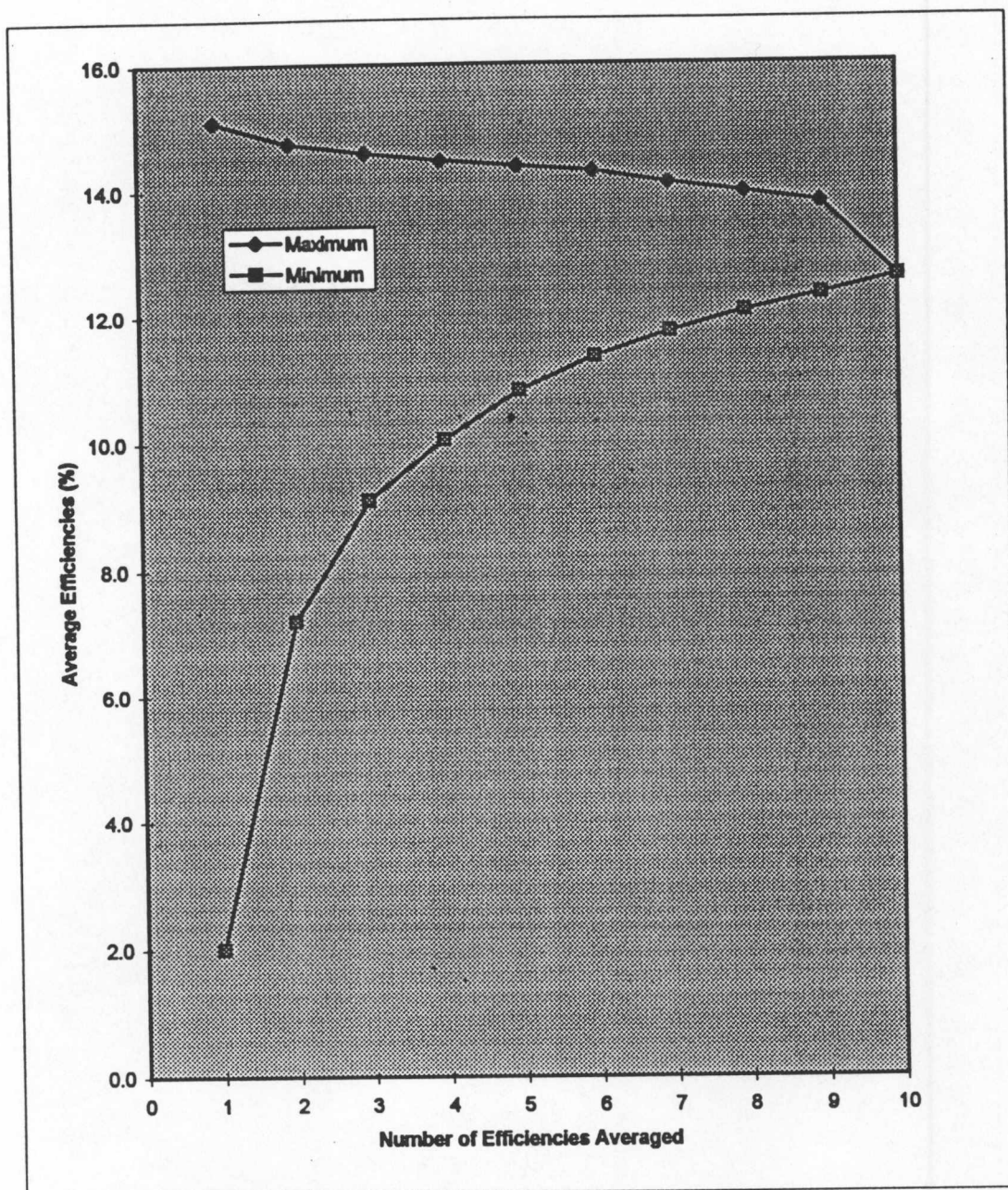


Figure A - 1. Maximum and minimum values of the average initial efficiencies under random sampling
Filter A - normal air flow
particle size 1.0 μm

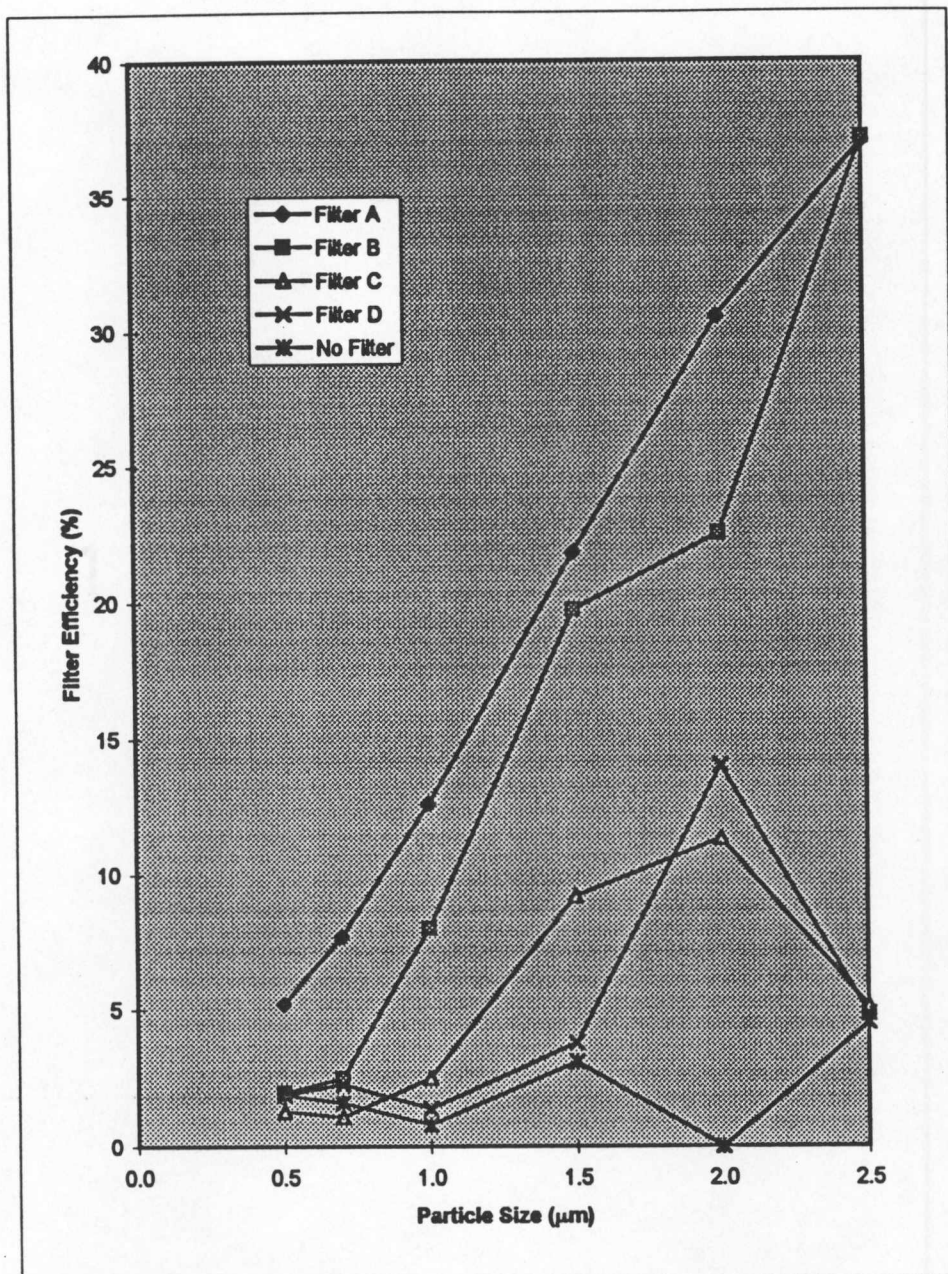


Figure A - 2. Average initial filter efficiencies under normal air flow

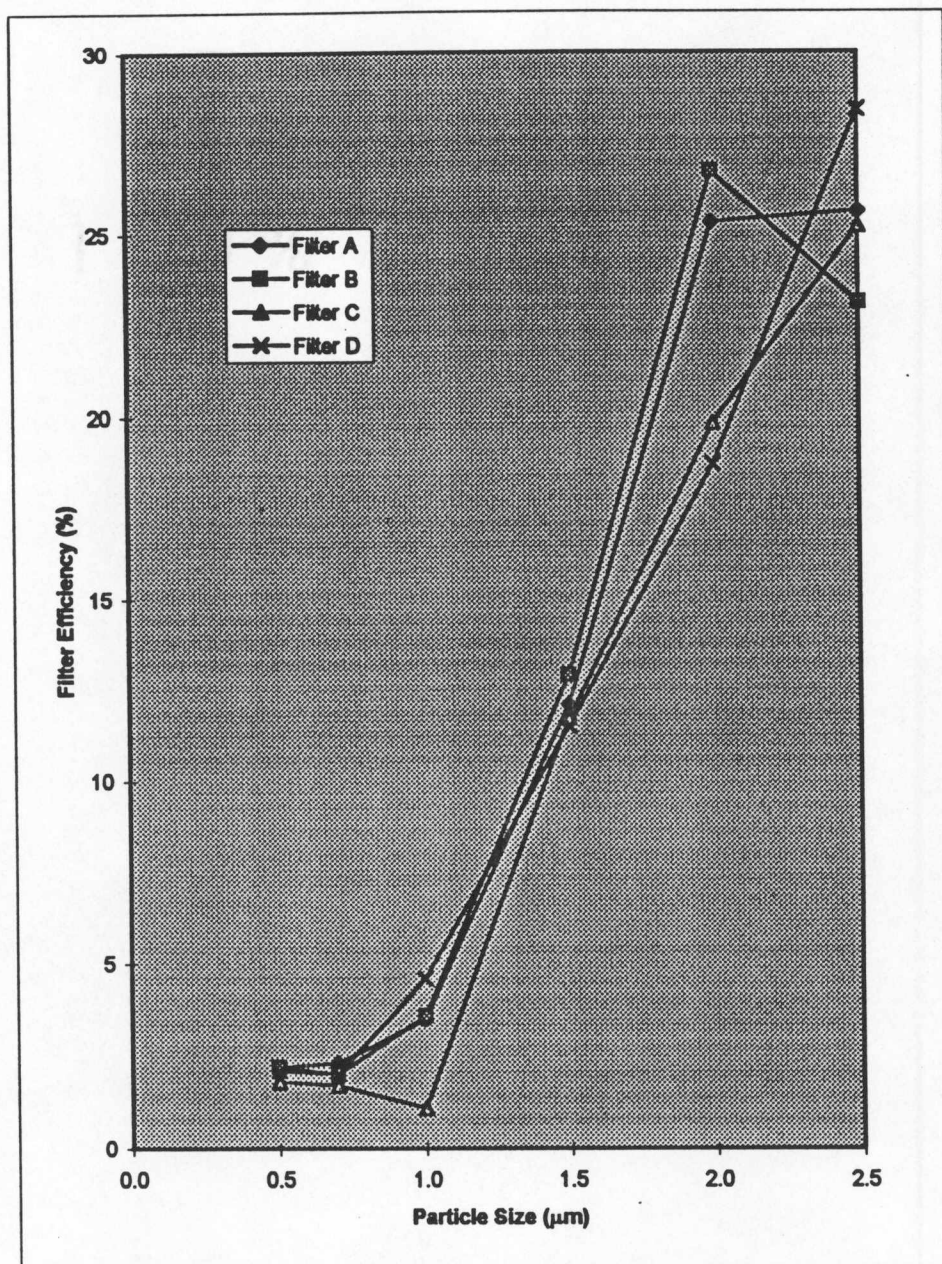


Figure A - 3. Average initial filter efficiencies under higher air flow

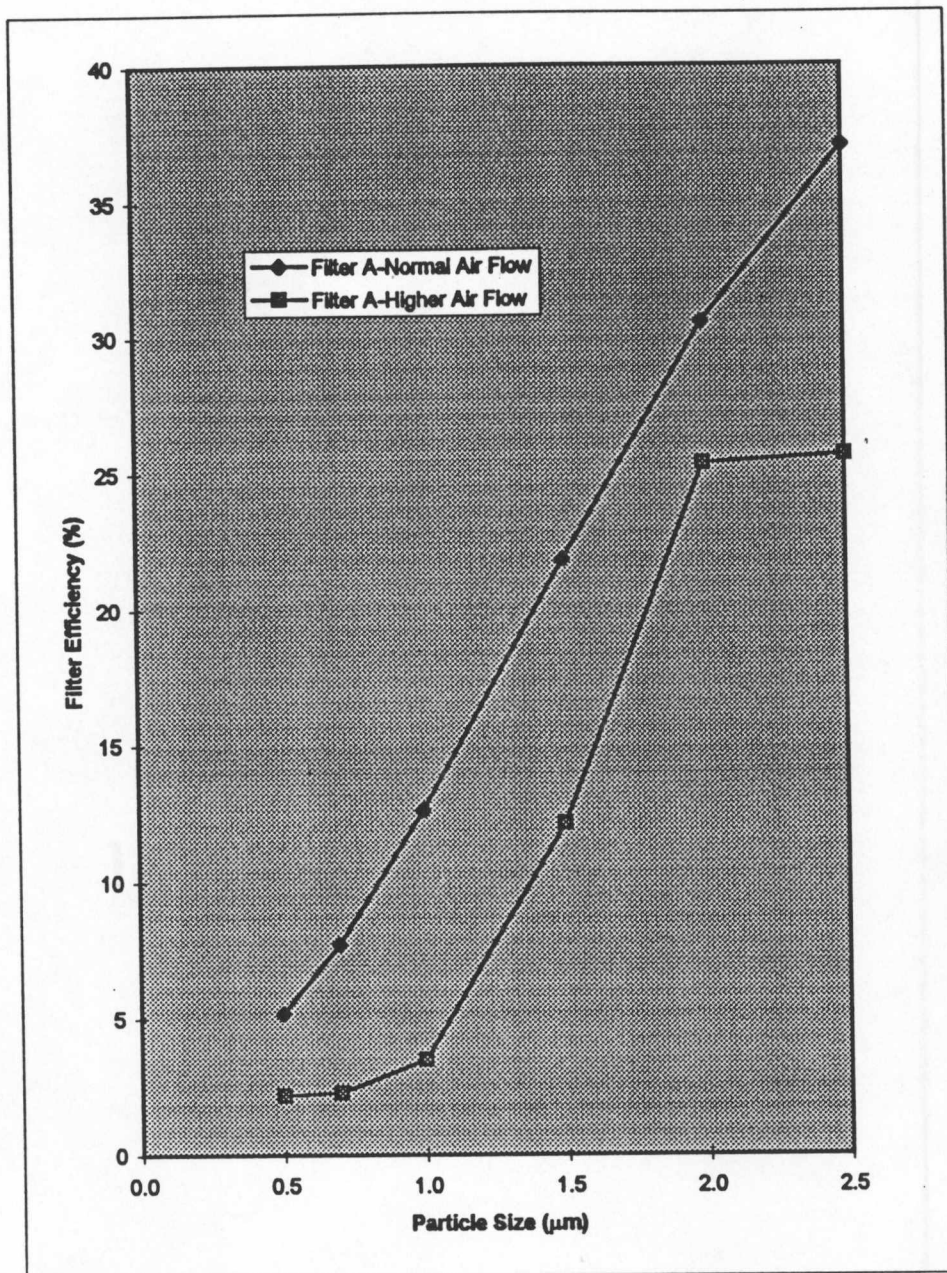


Figure A - 4. Average initial efficiencies of Filter A under normal and higher air flows

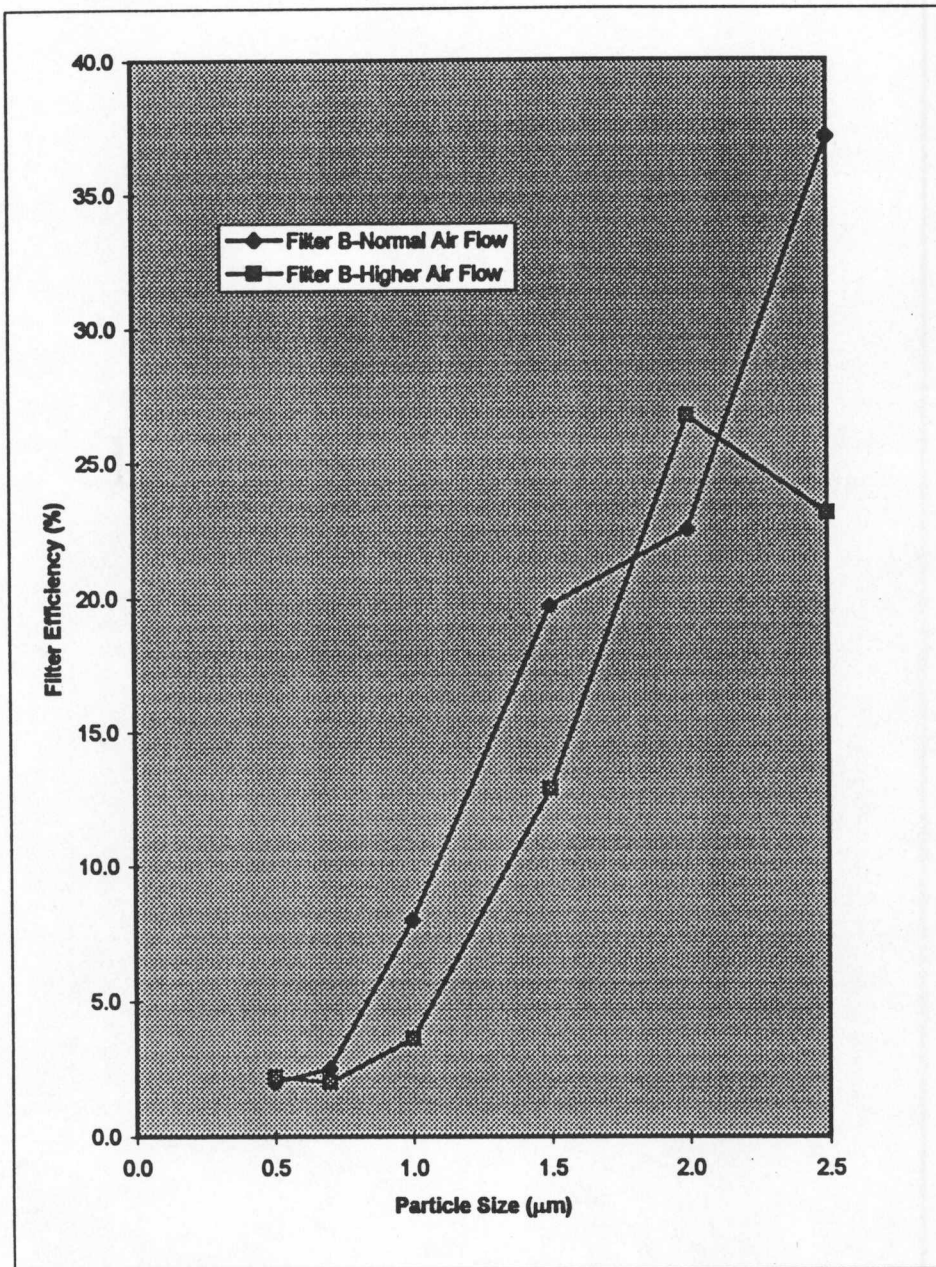


Figure A - 5. Average initial efficiencies of Filter B under normal and higher air flows

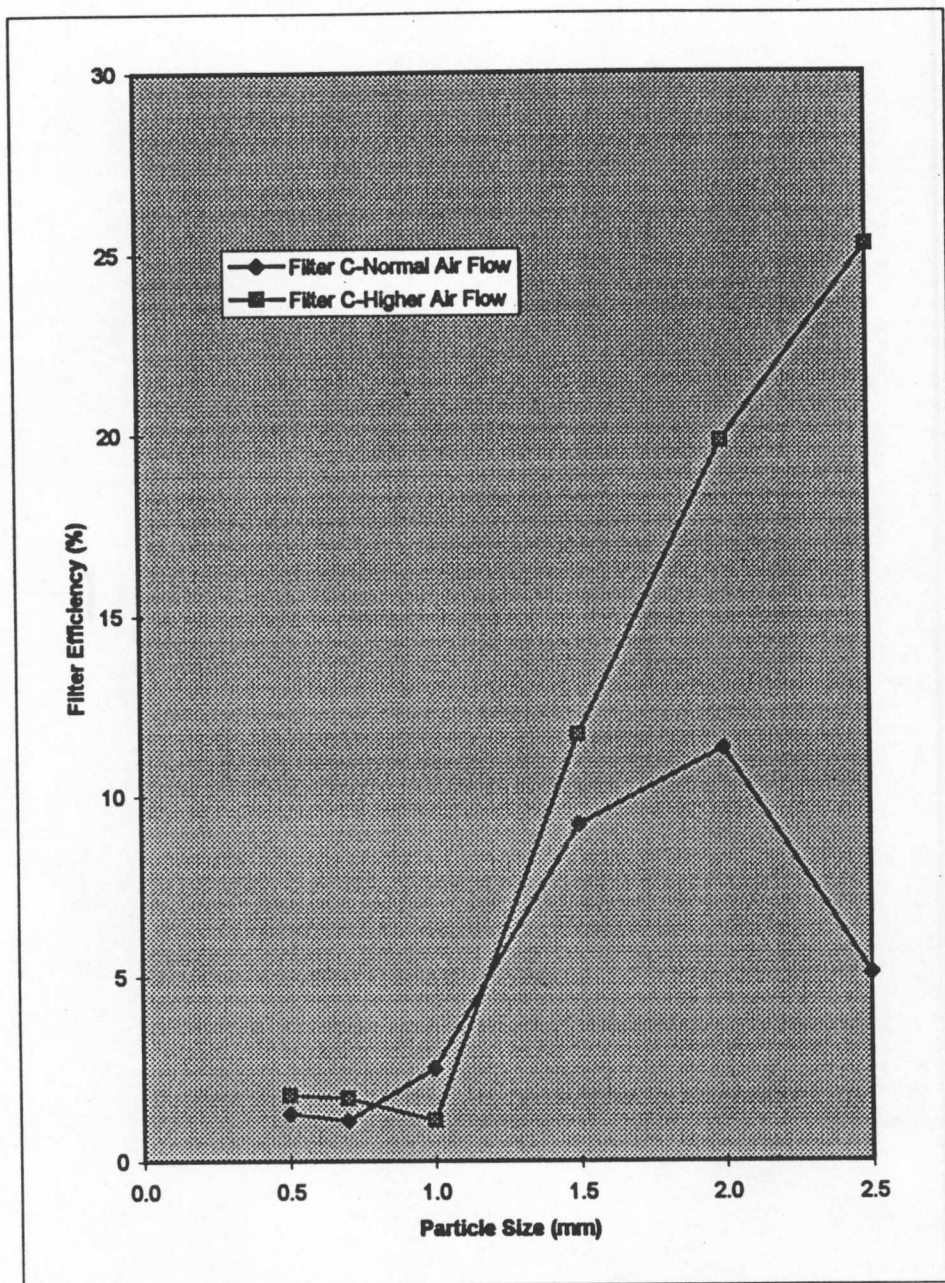


Figure A - 6. Average efficiencies of Filter C under normal and higher air flows

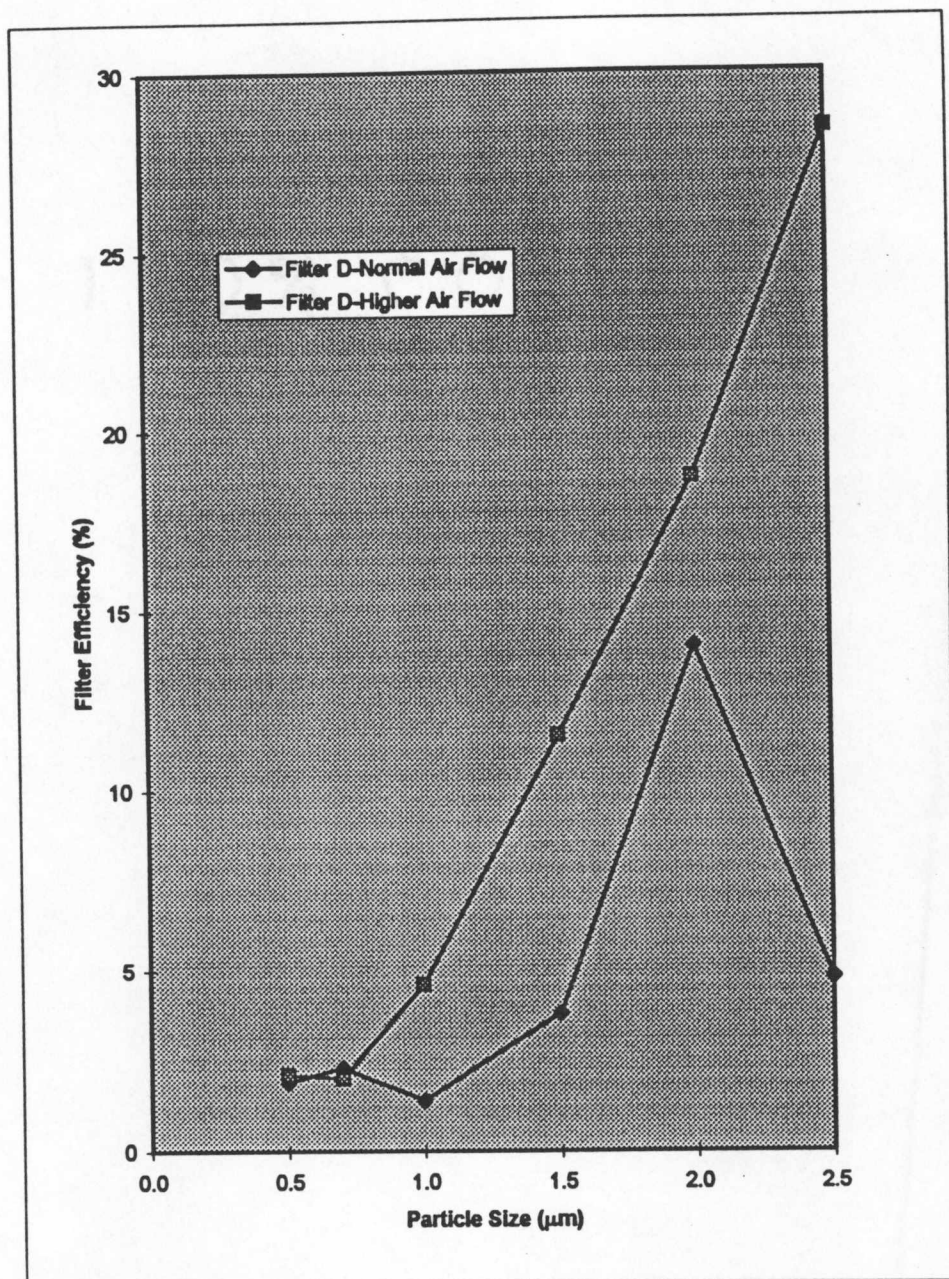


Figure A - 7. Average initial efficiencies of Filter D under normal and higher air flows

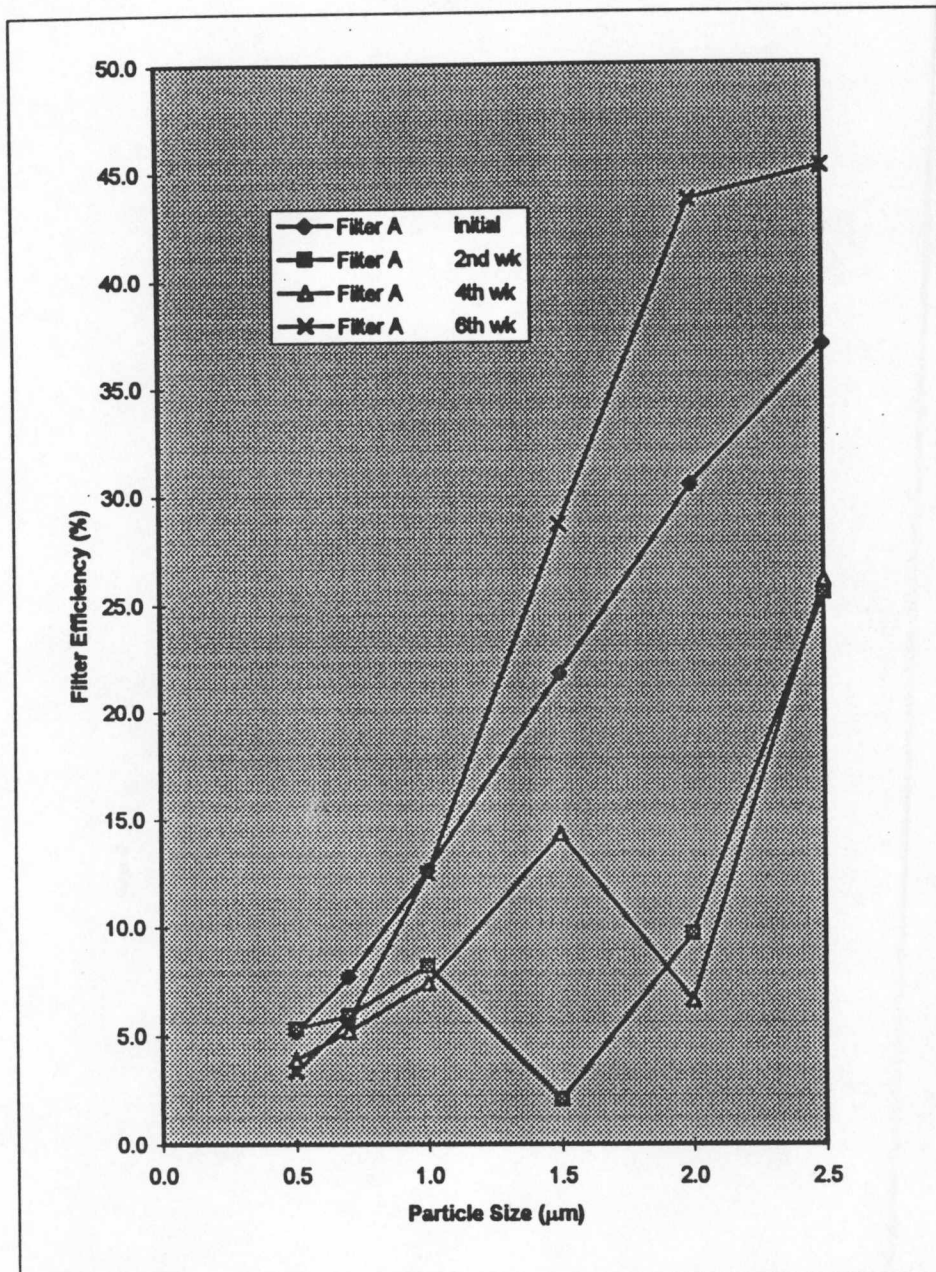


Figure A - 8. Average efficiencies of Filter A during dust loading

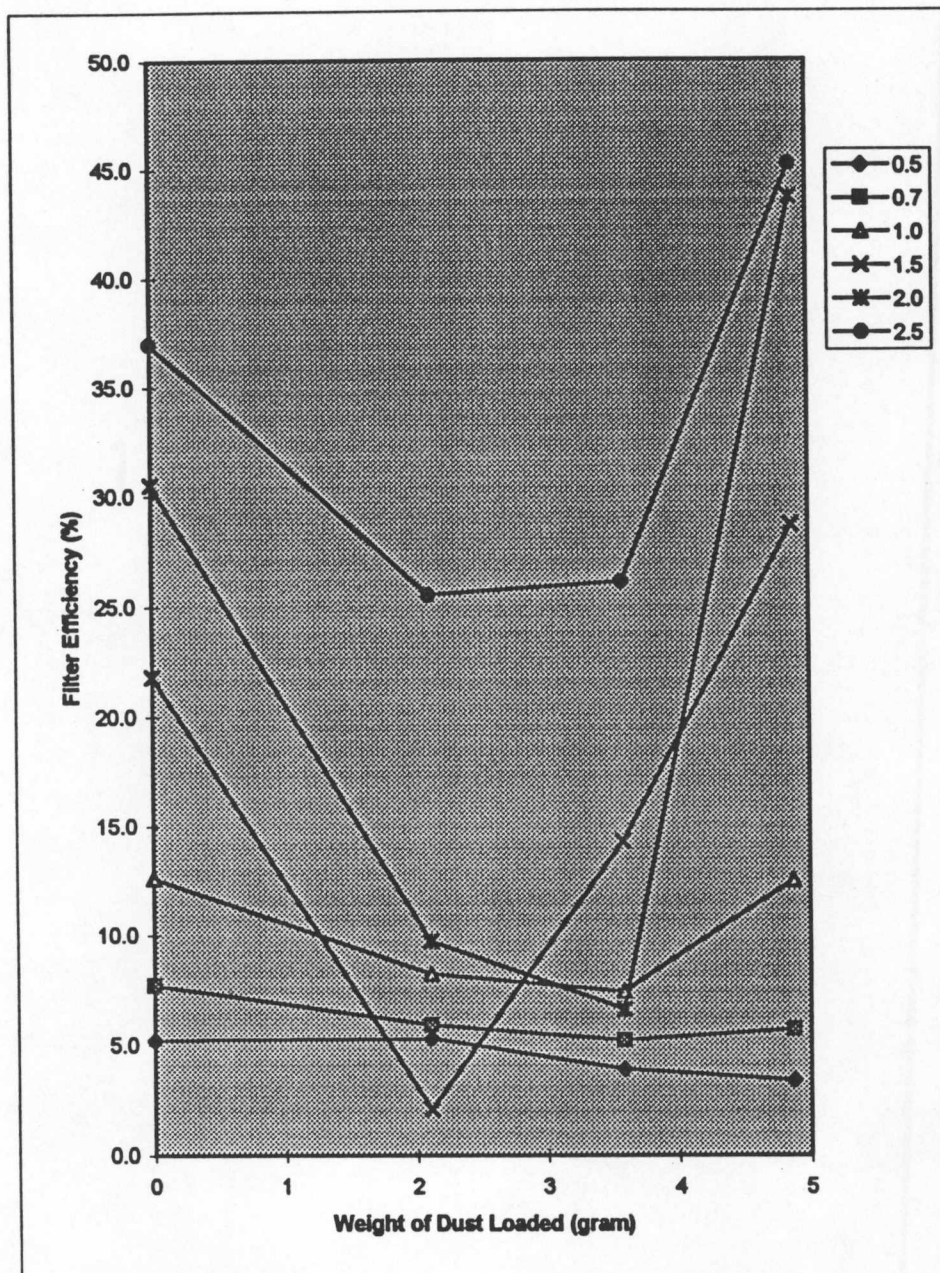


Figure A - 9. Correlation between the efficiency and the weight of dust loaded for Filter A

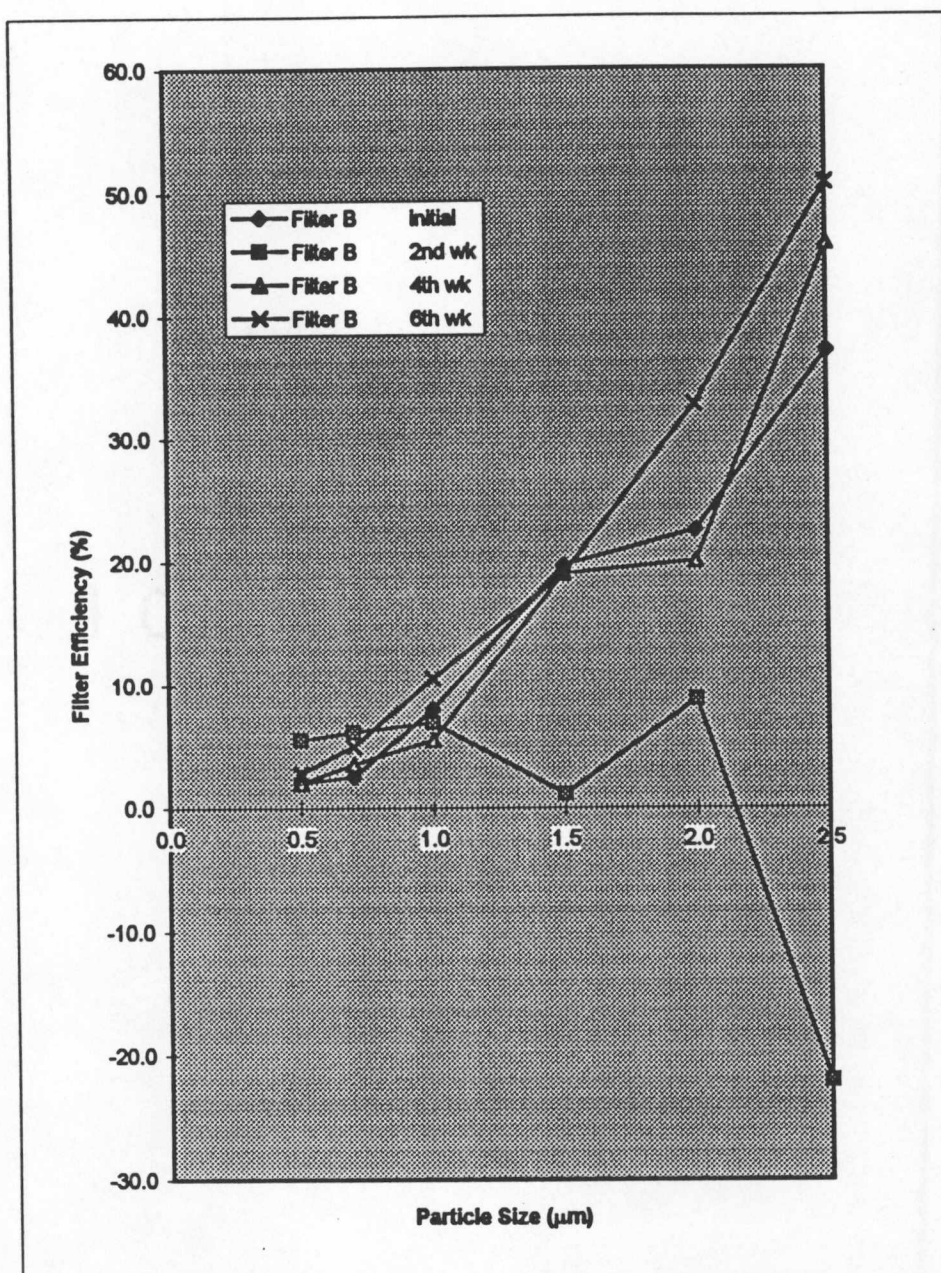


Figure A - 10. Average efficiencies of Filter B during dust loading

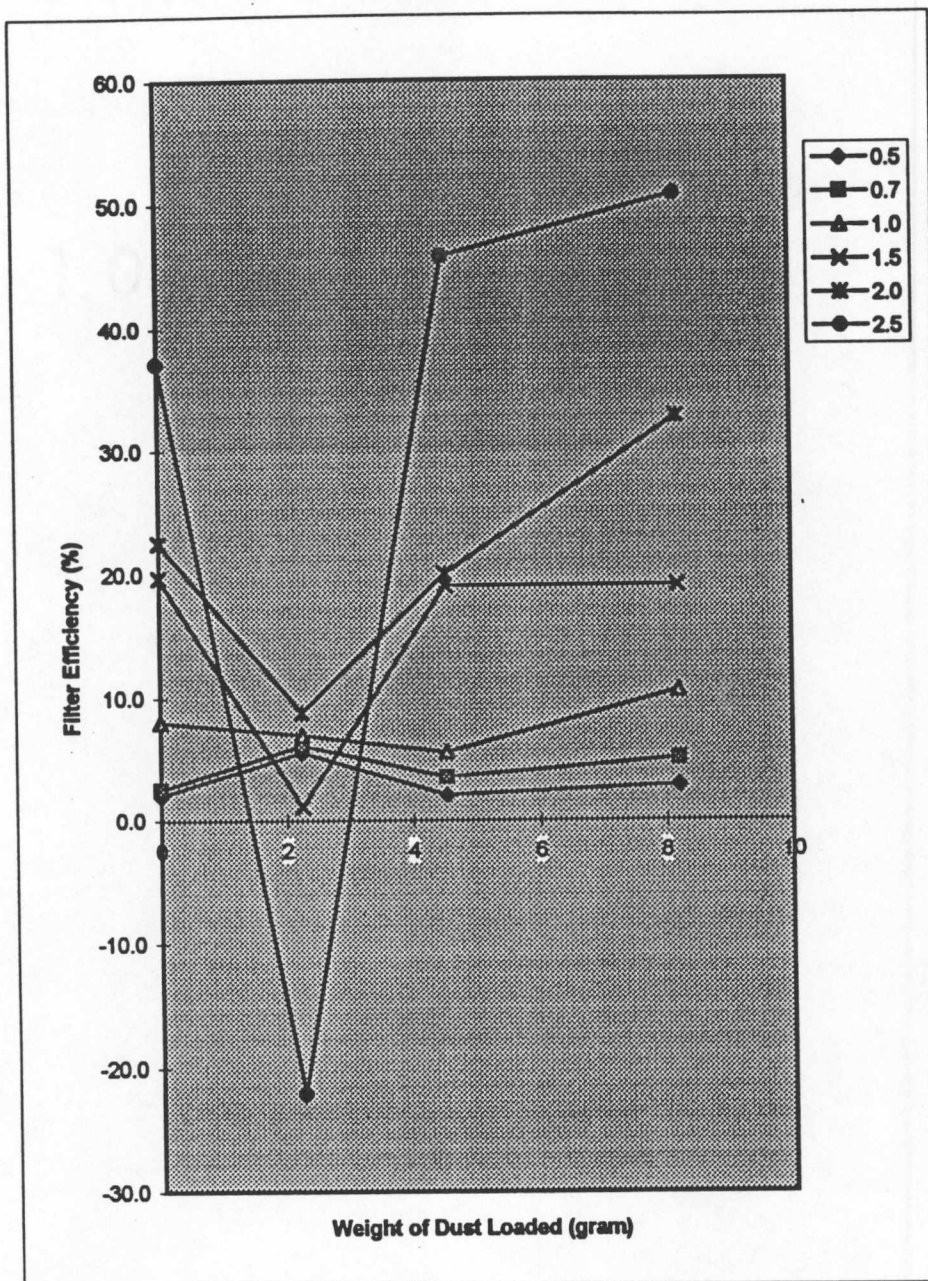


Figure A - 11. Correlation between the efficiency and the weight of dust loaded for Filter B

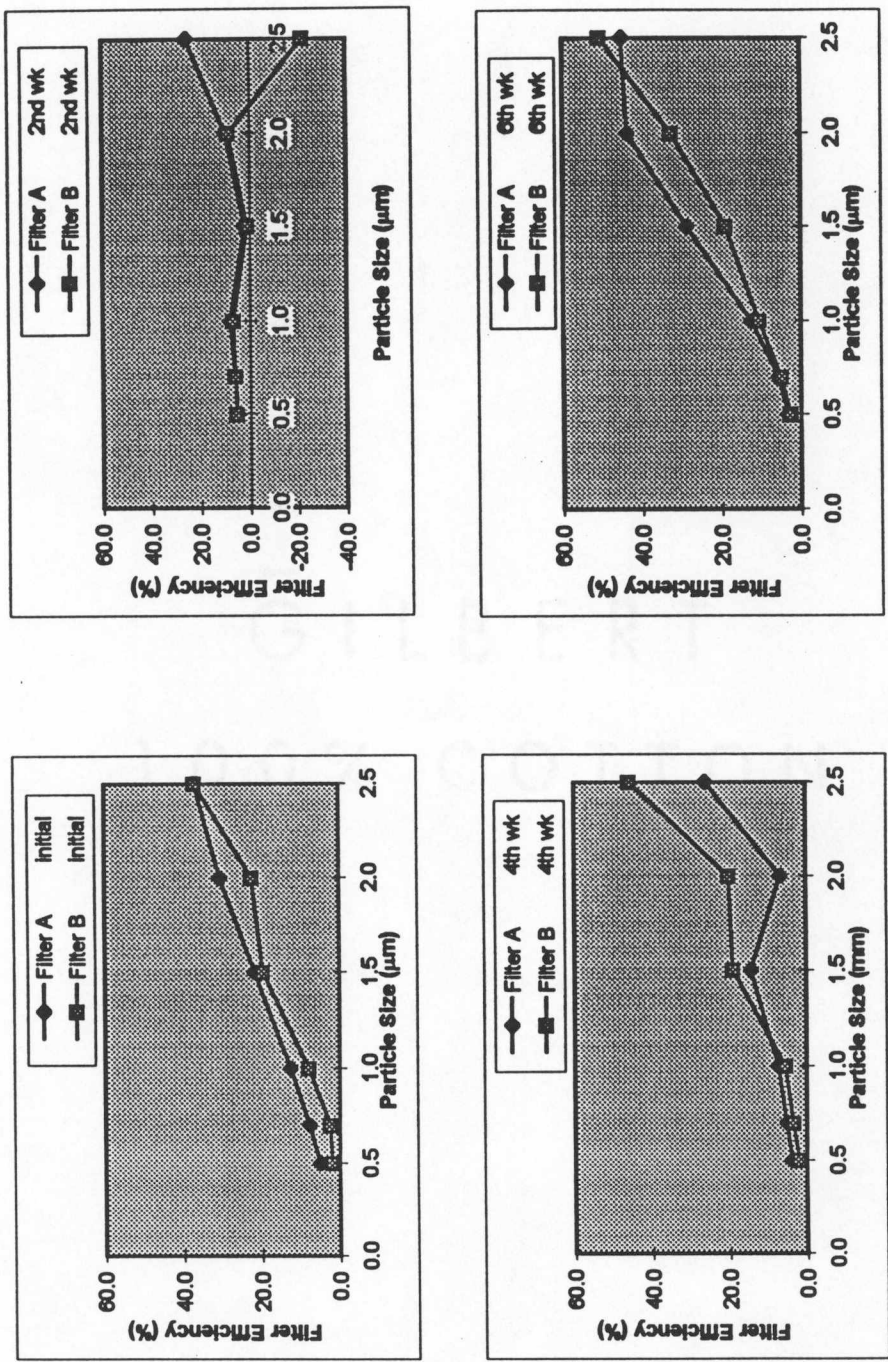


Figure A - 12. Comparison of average efficiencies of Filters A and B during dust loading

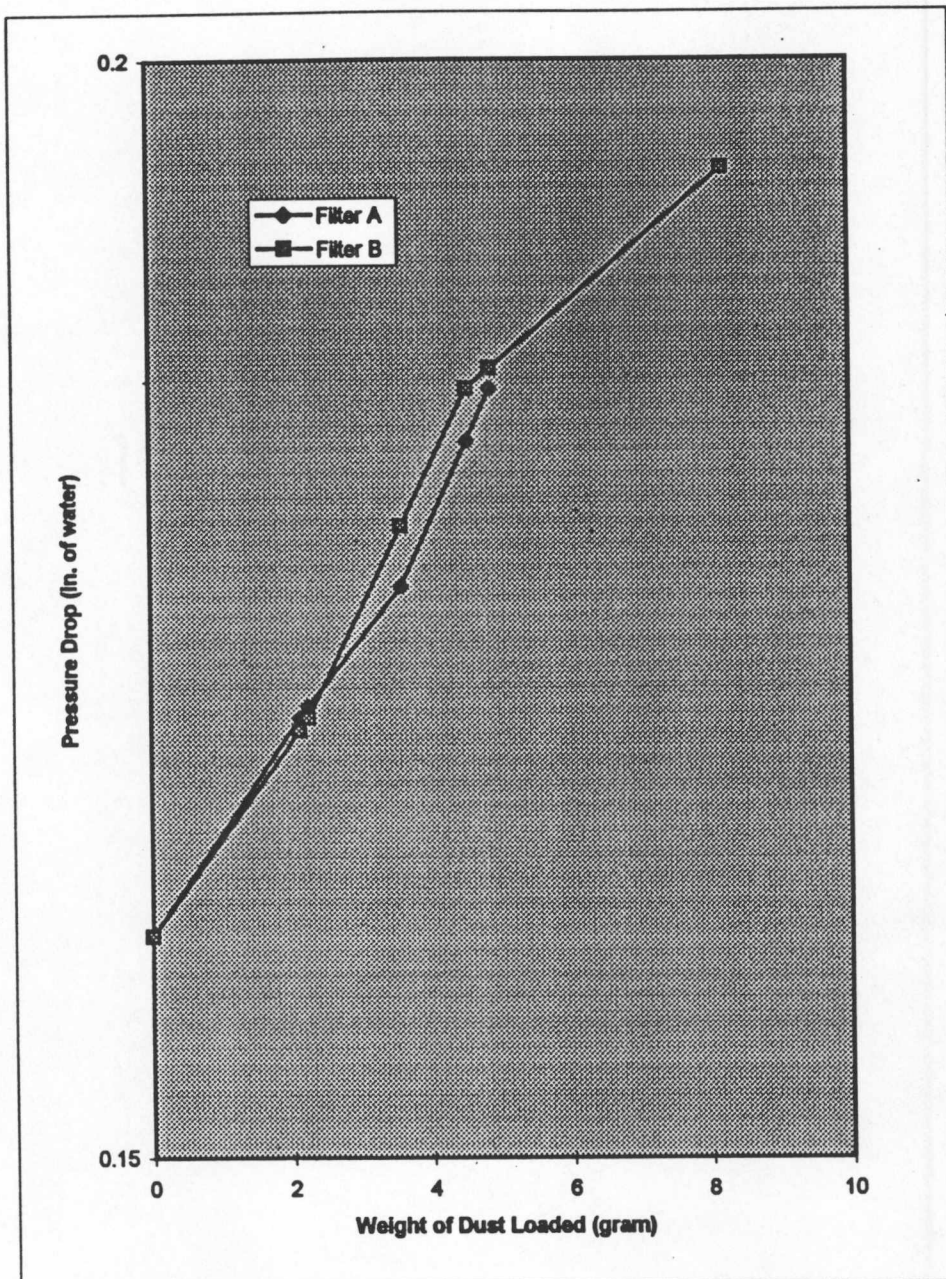
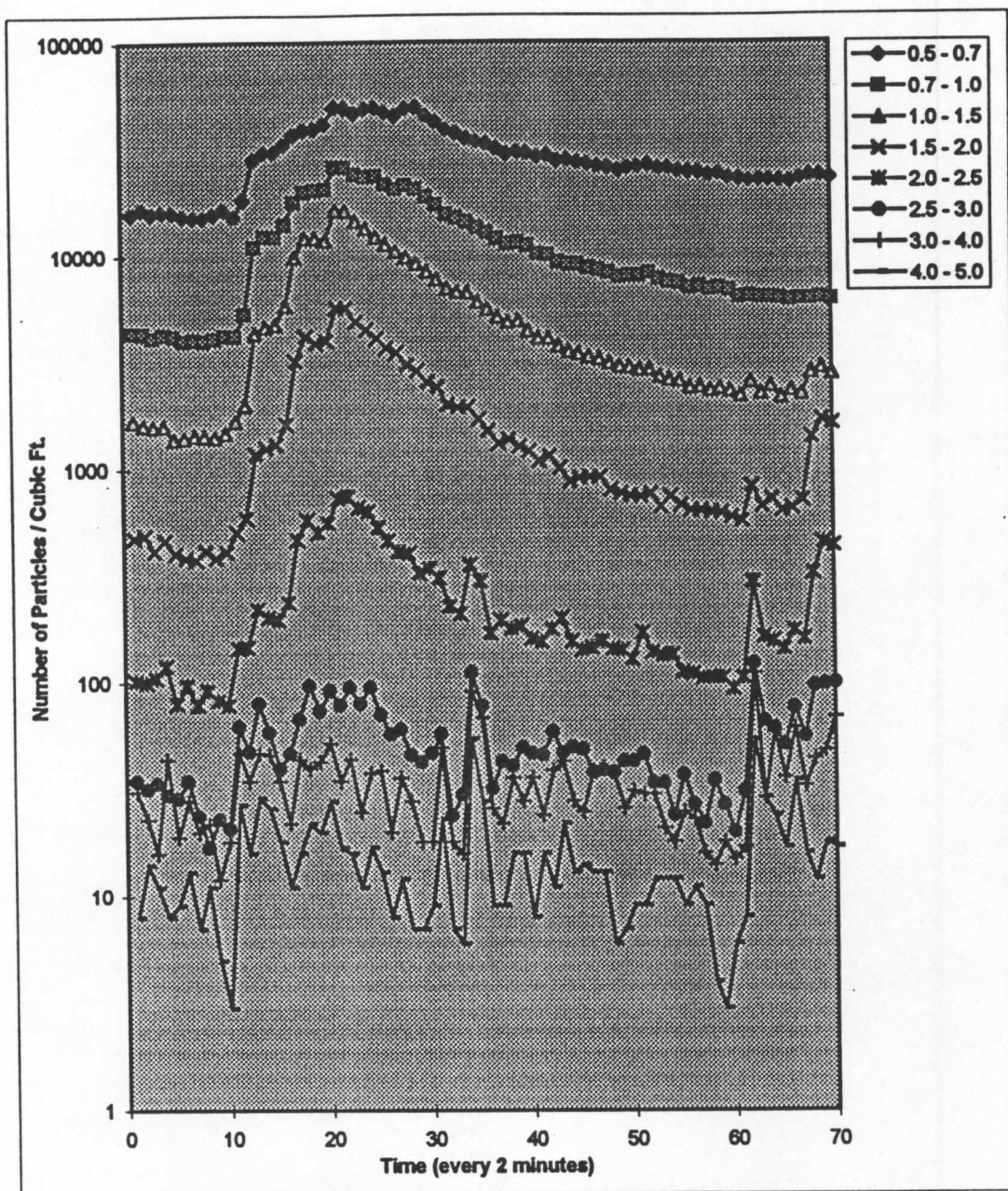
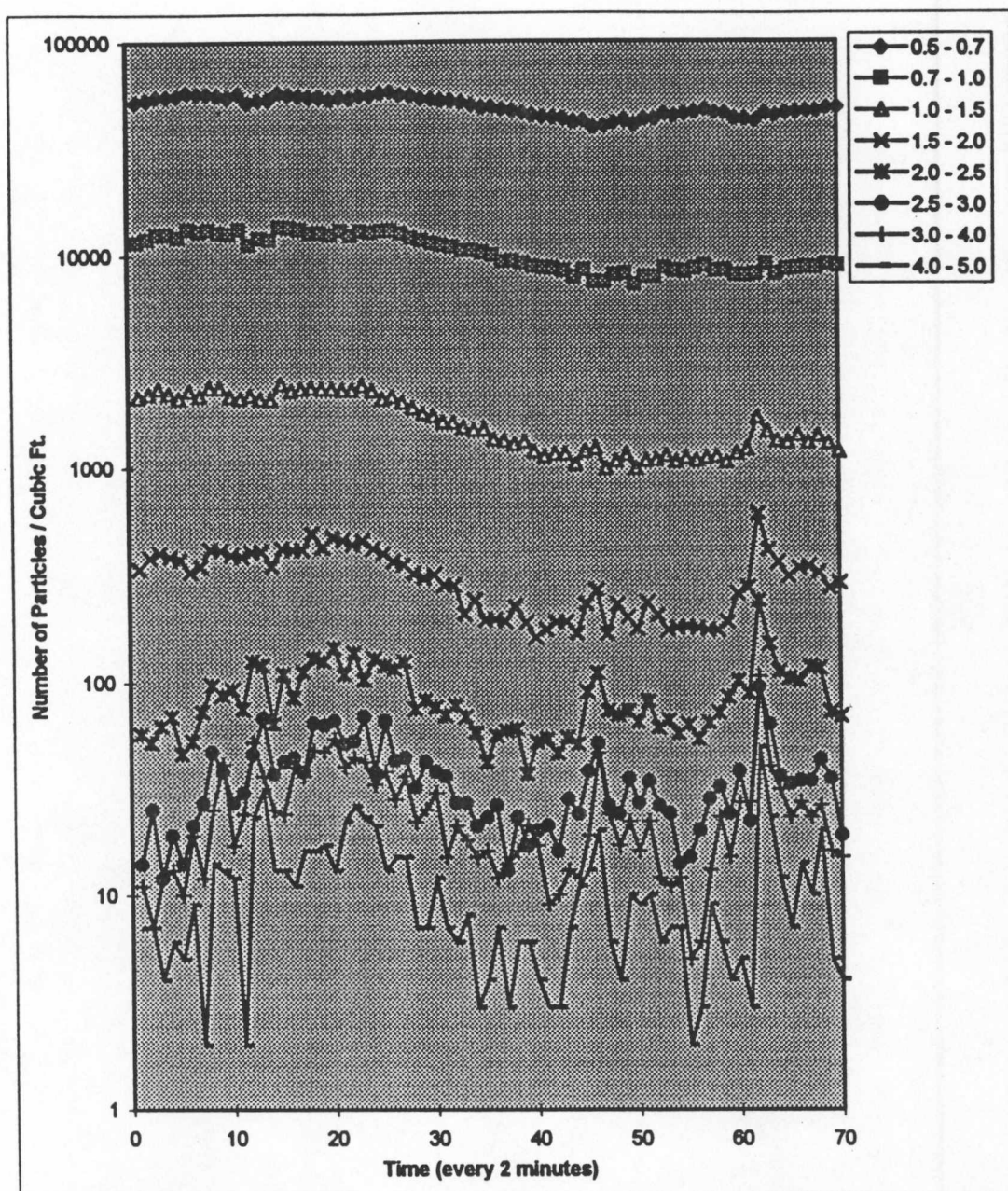


Figure A - 13. Correlation between the pressure drop and the weight of dust loaded for Filters A and B



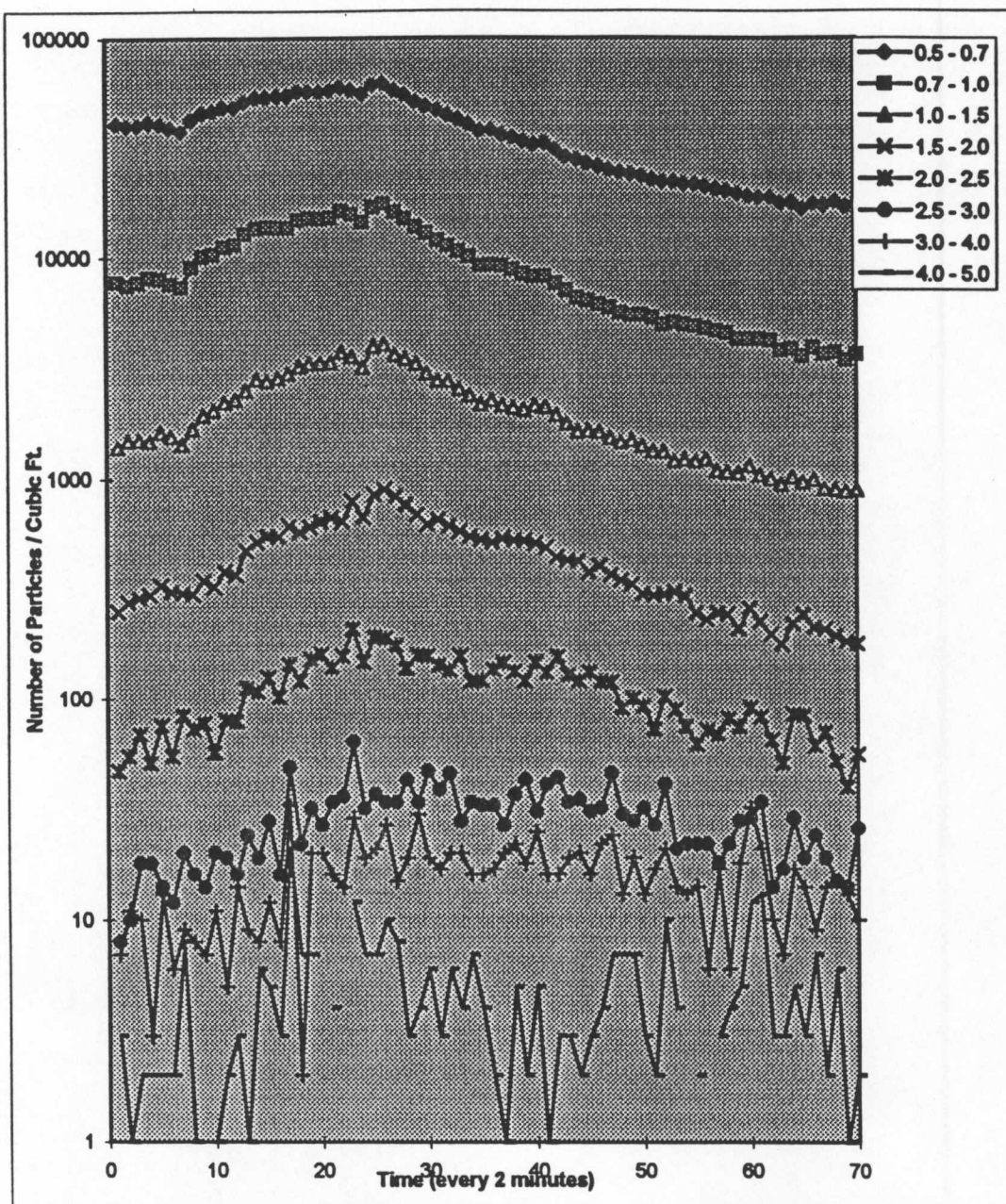
a. 07/20/96

Figure A - 14. Plot of indoor air concentration curves



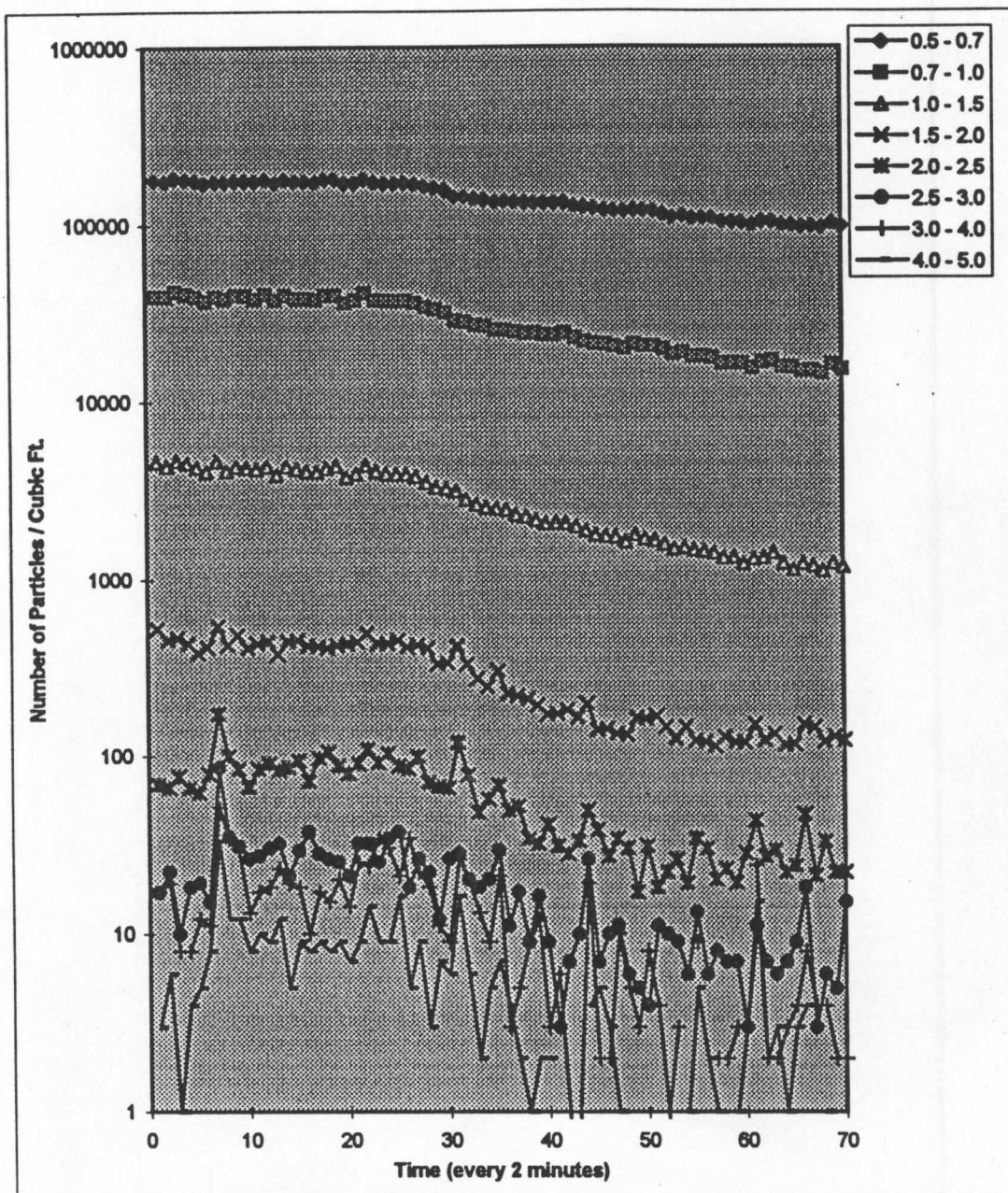
b. 07/25/96

Figure A - 14. (continued)



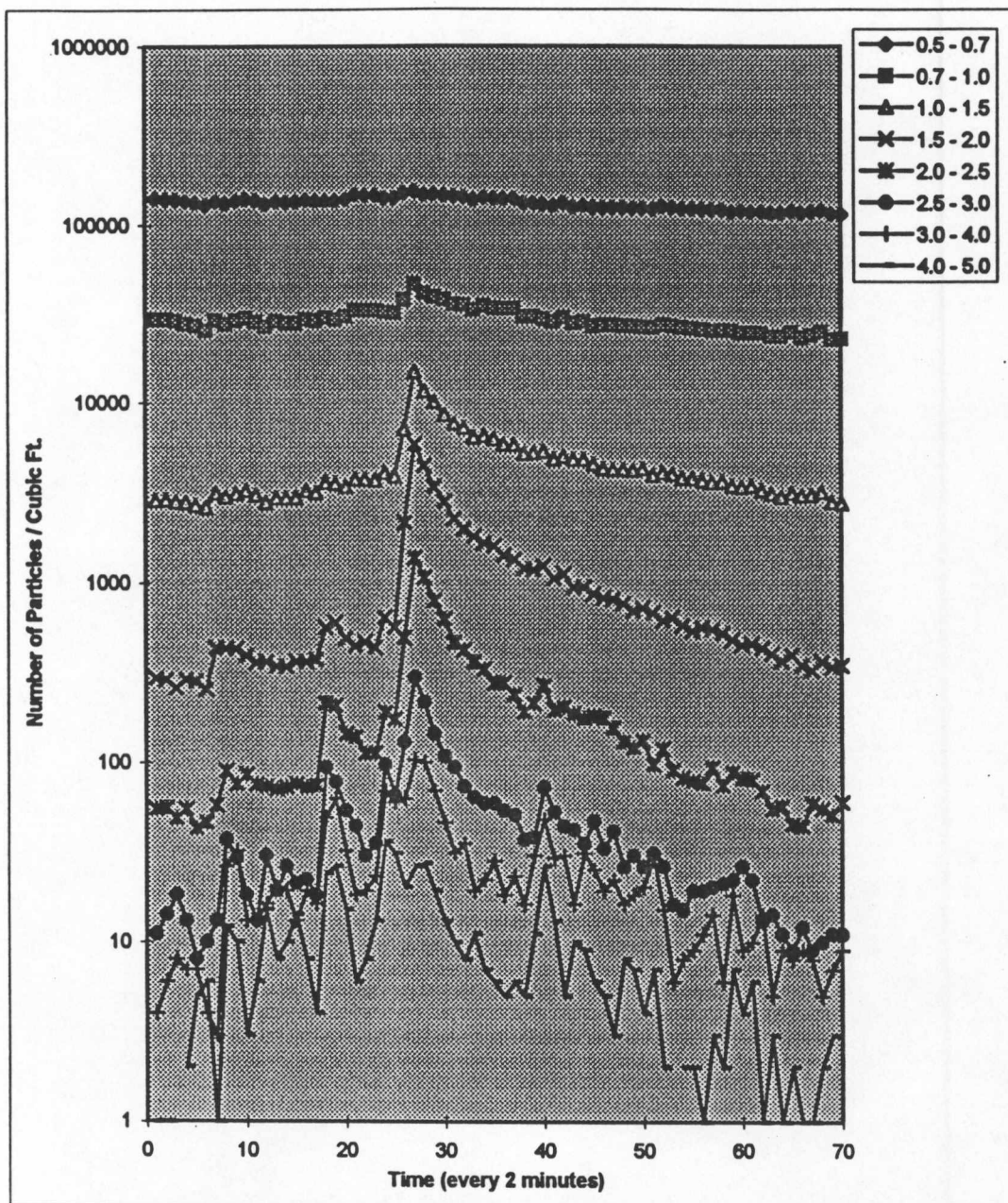
c. 07/29/96

Figure A - 14. (continued)



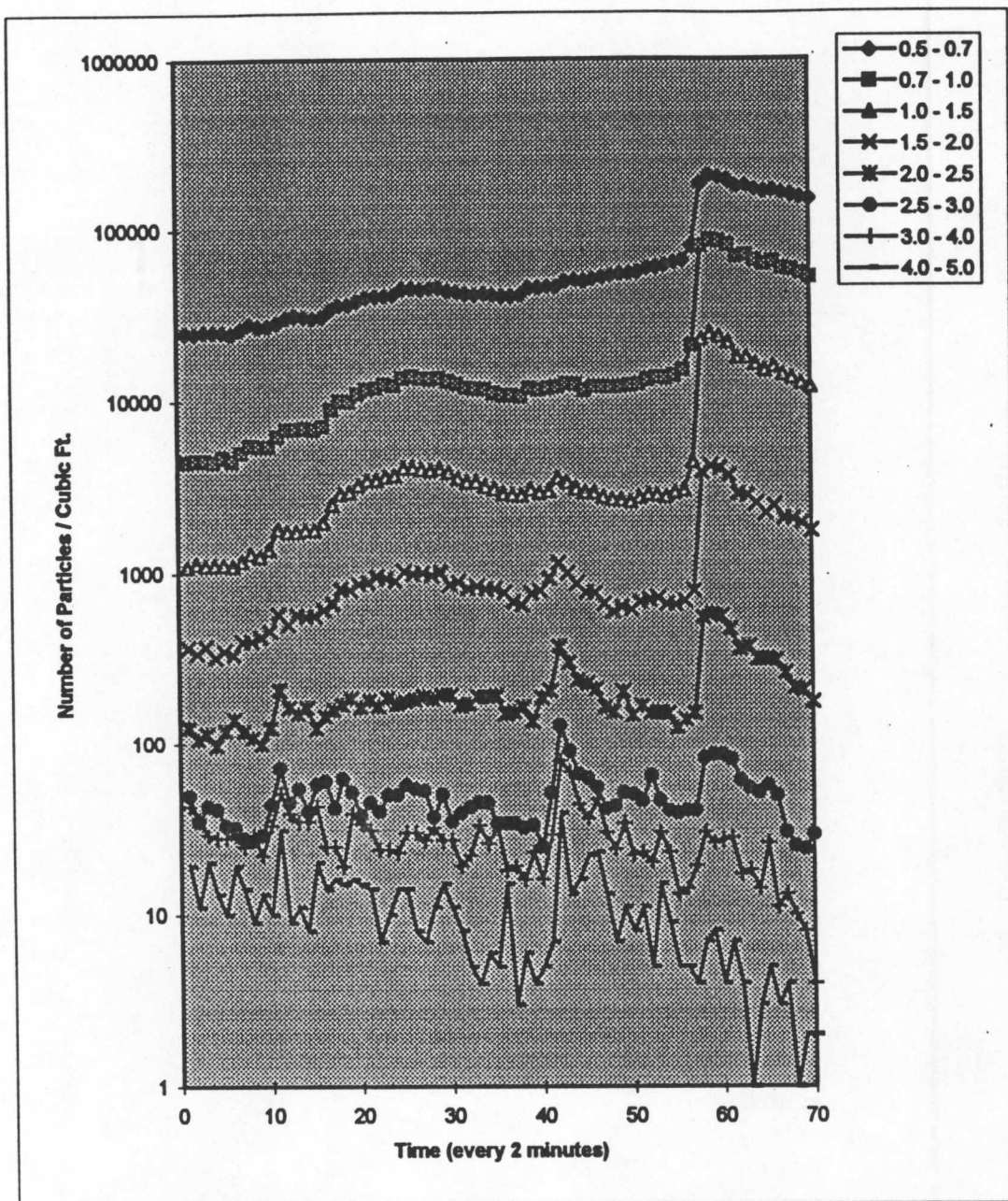
d. 08/02/96

Figure A - 14. (continued)



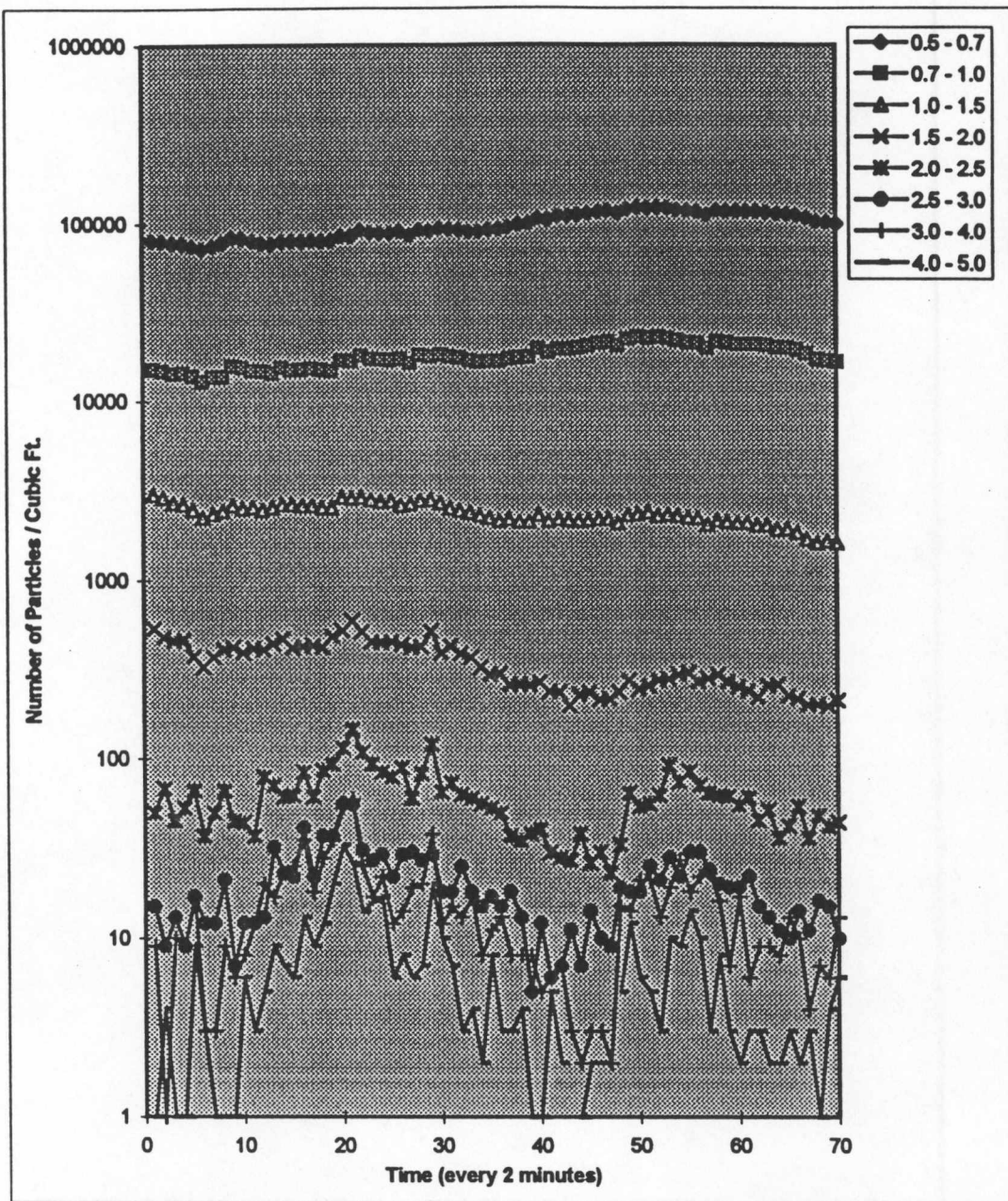
e. 08/06/96

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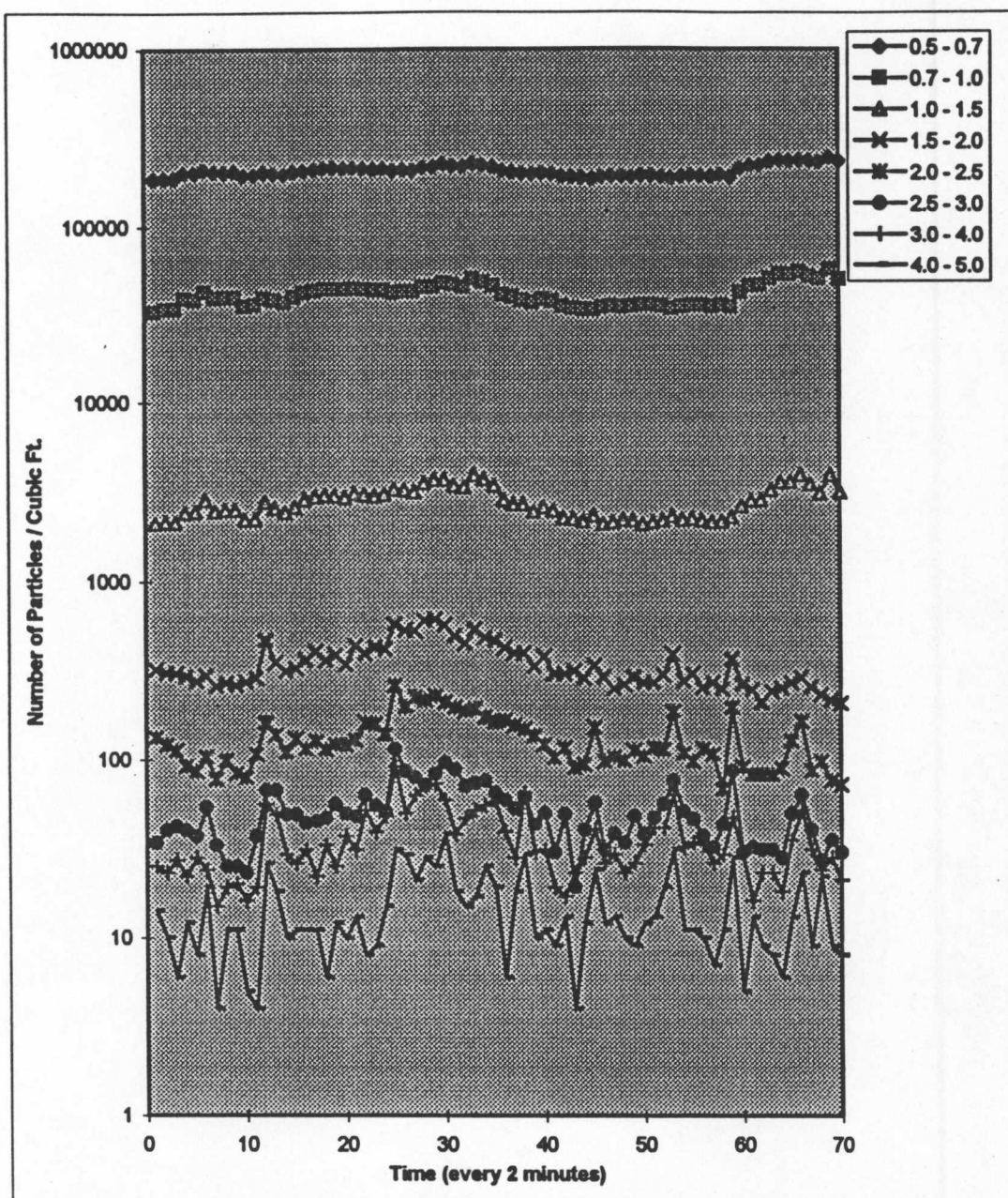
f. 08/10/96

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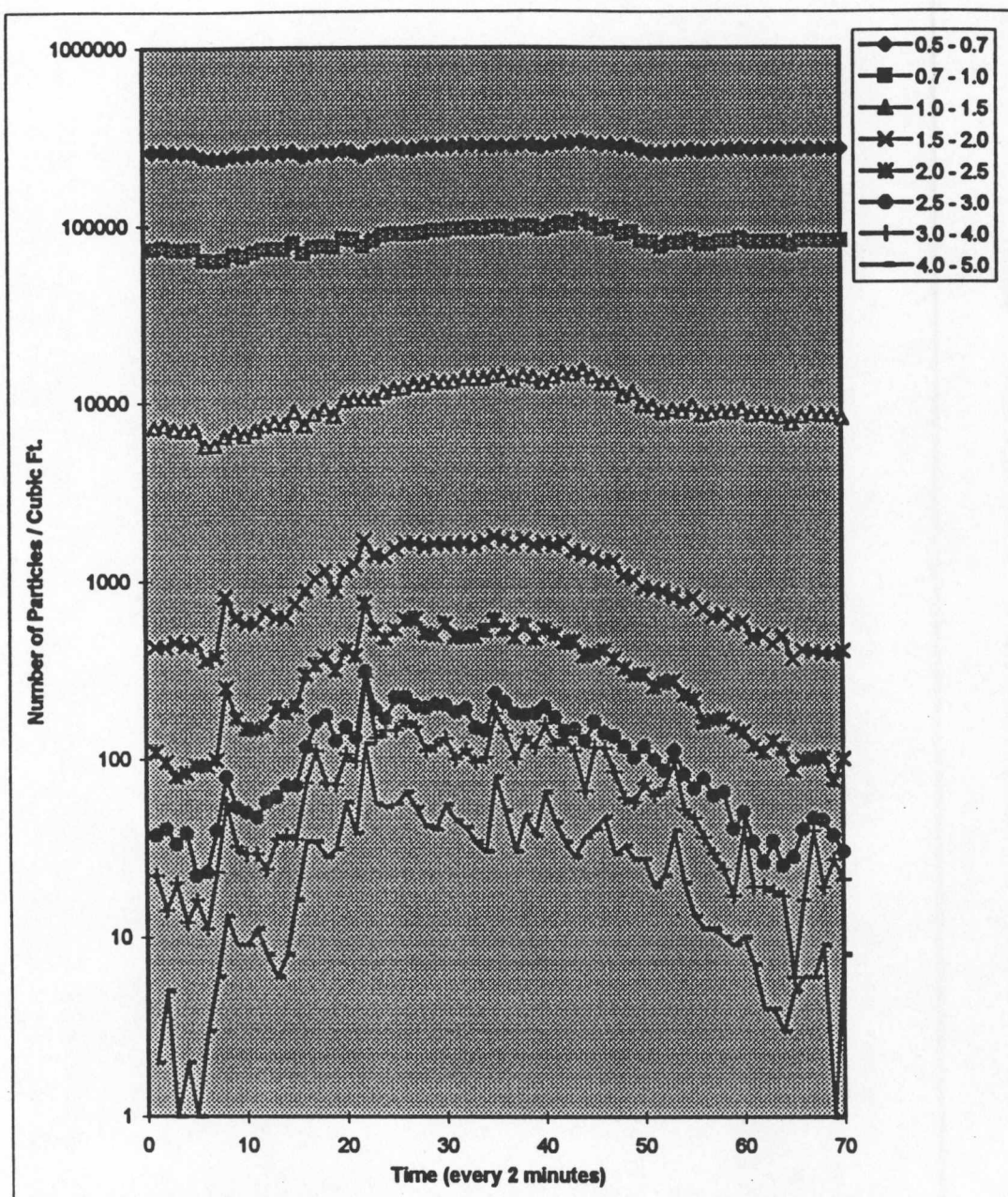
g. 08/14/96

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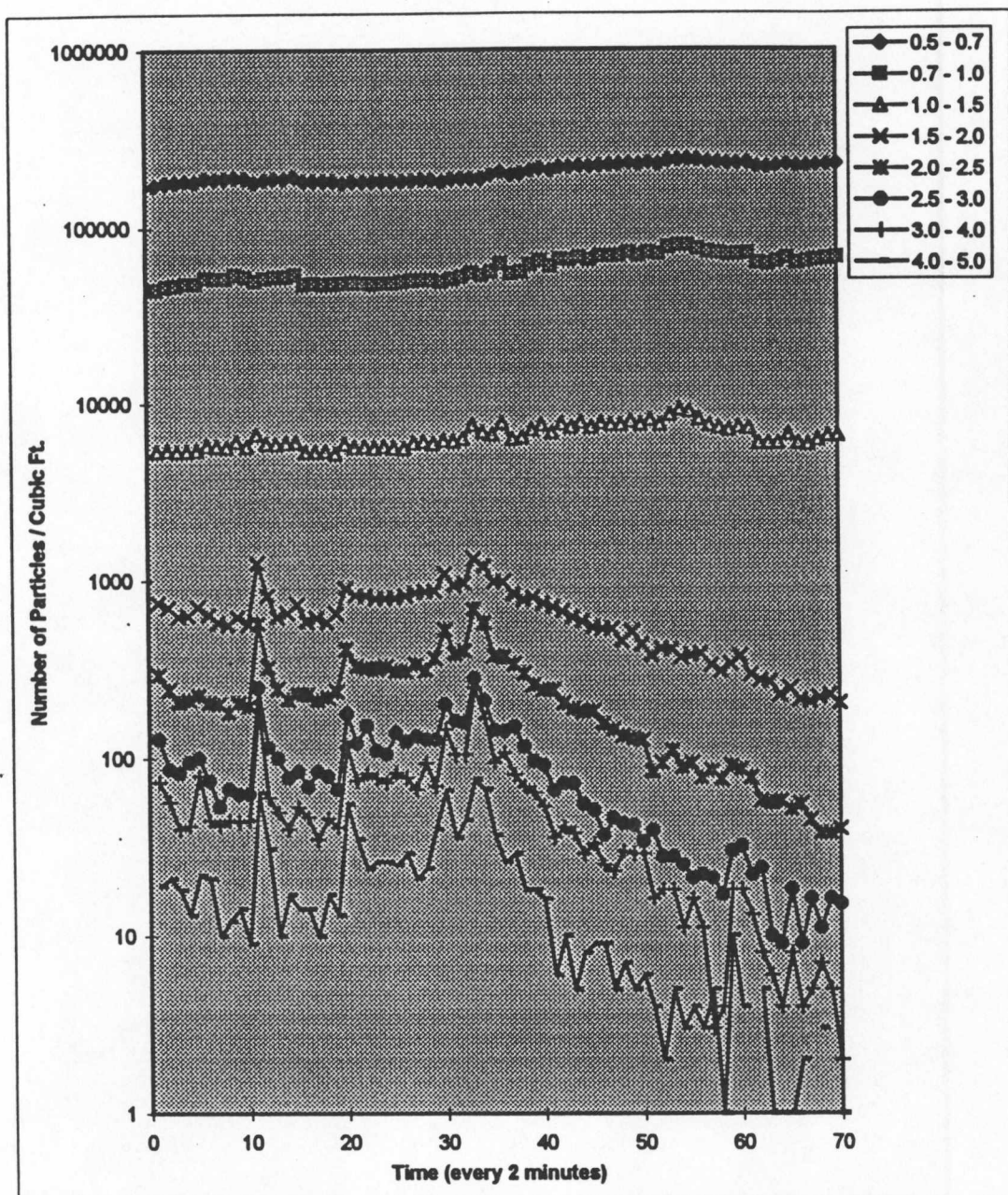
h. 08/16/96

Figure A - 14. (continued)



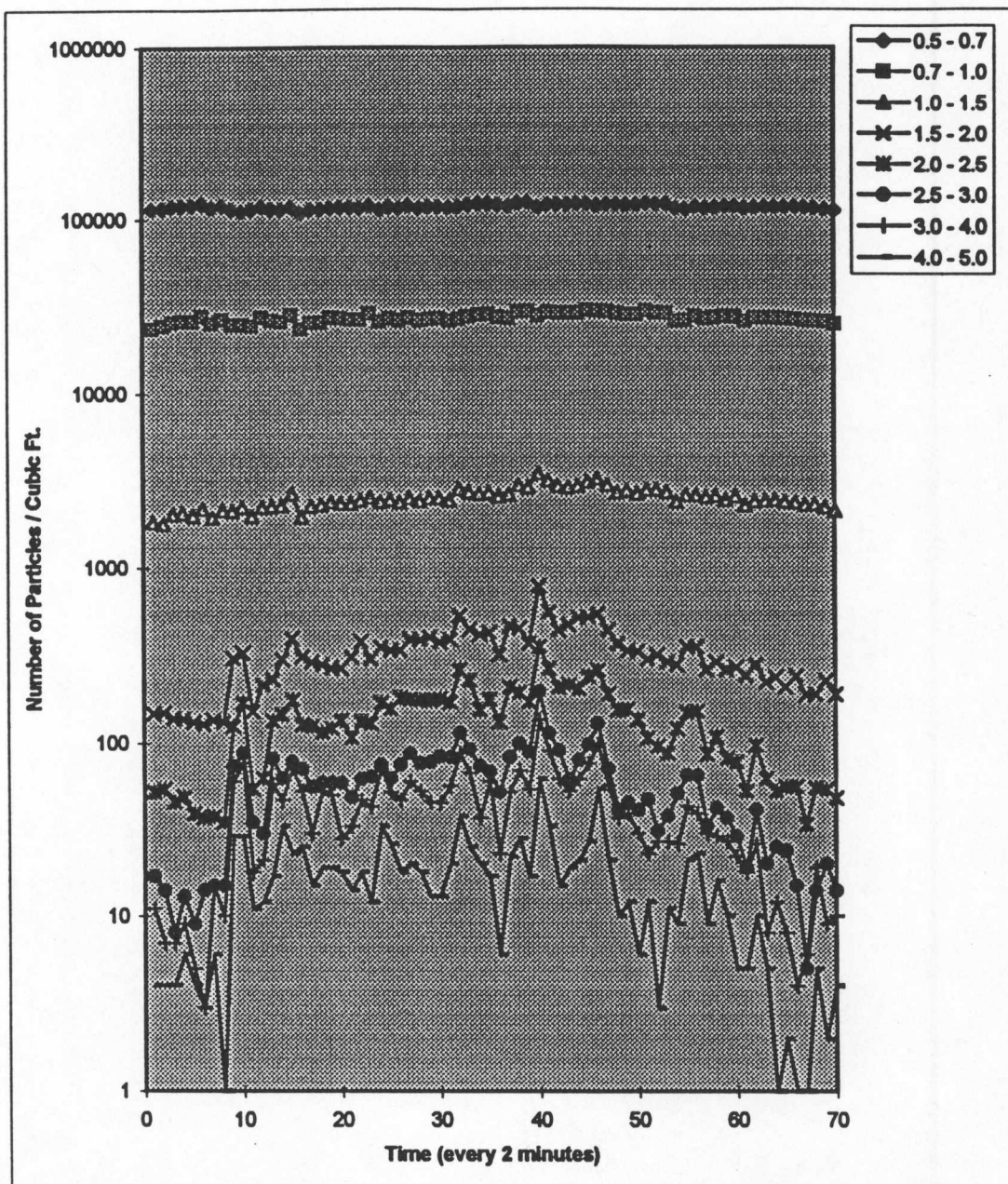
i. 08/19/96

Figure A - 14. (continued)



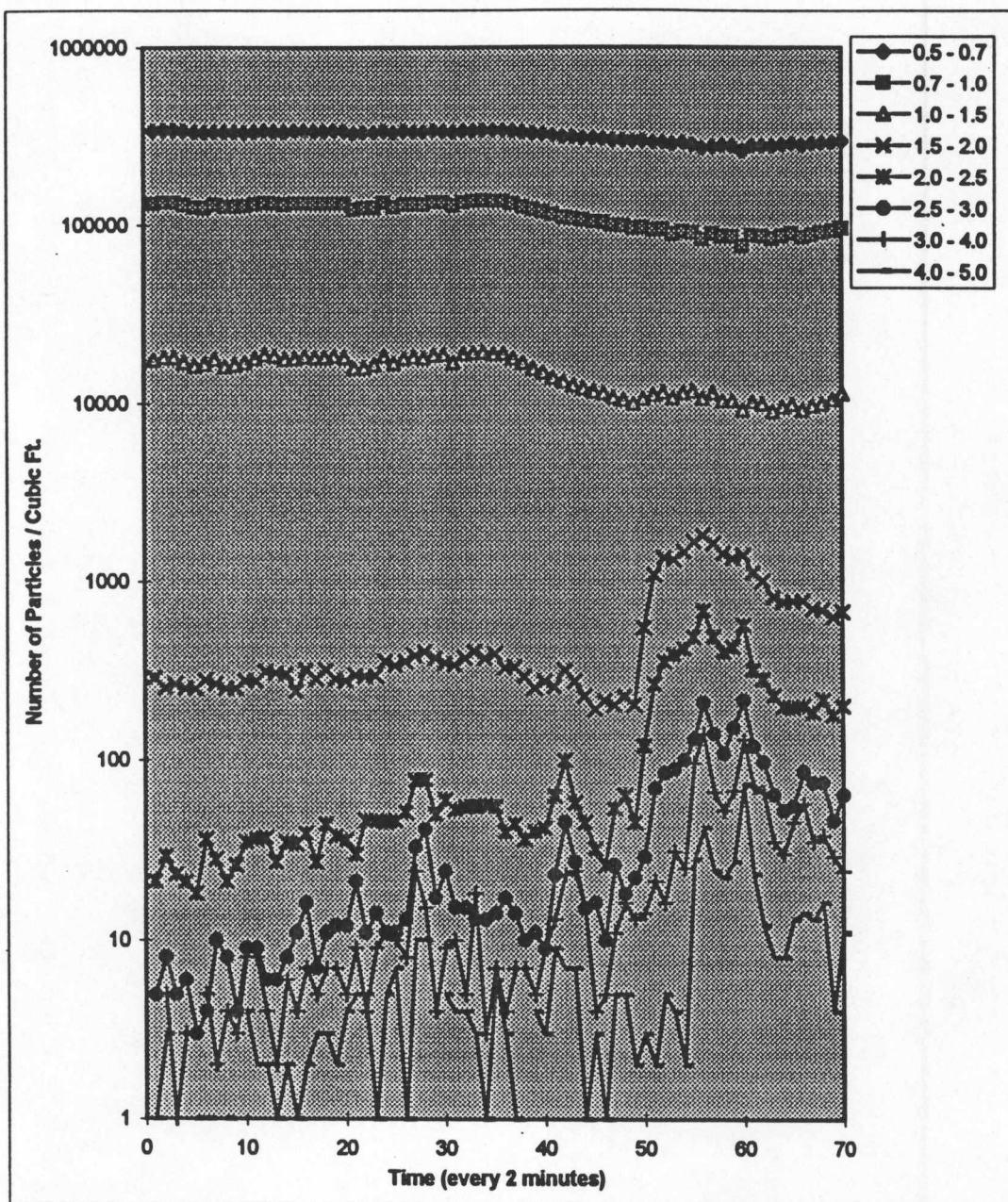
j. 08/23/96

Figure A - 14. (continued)



k. 08/27/96

Figure A - 14. (continued)



I. 08/30/96

Figure A - 14. (continued)

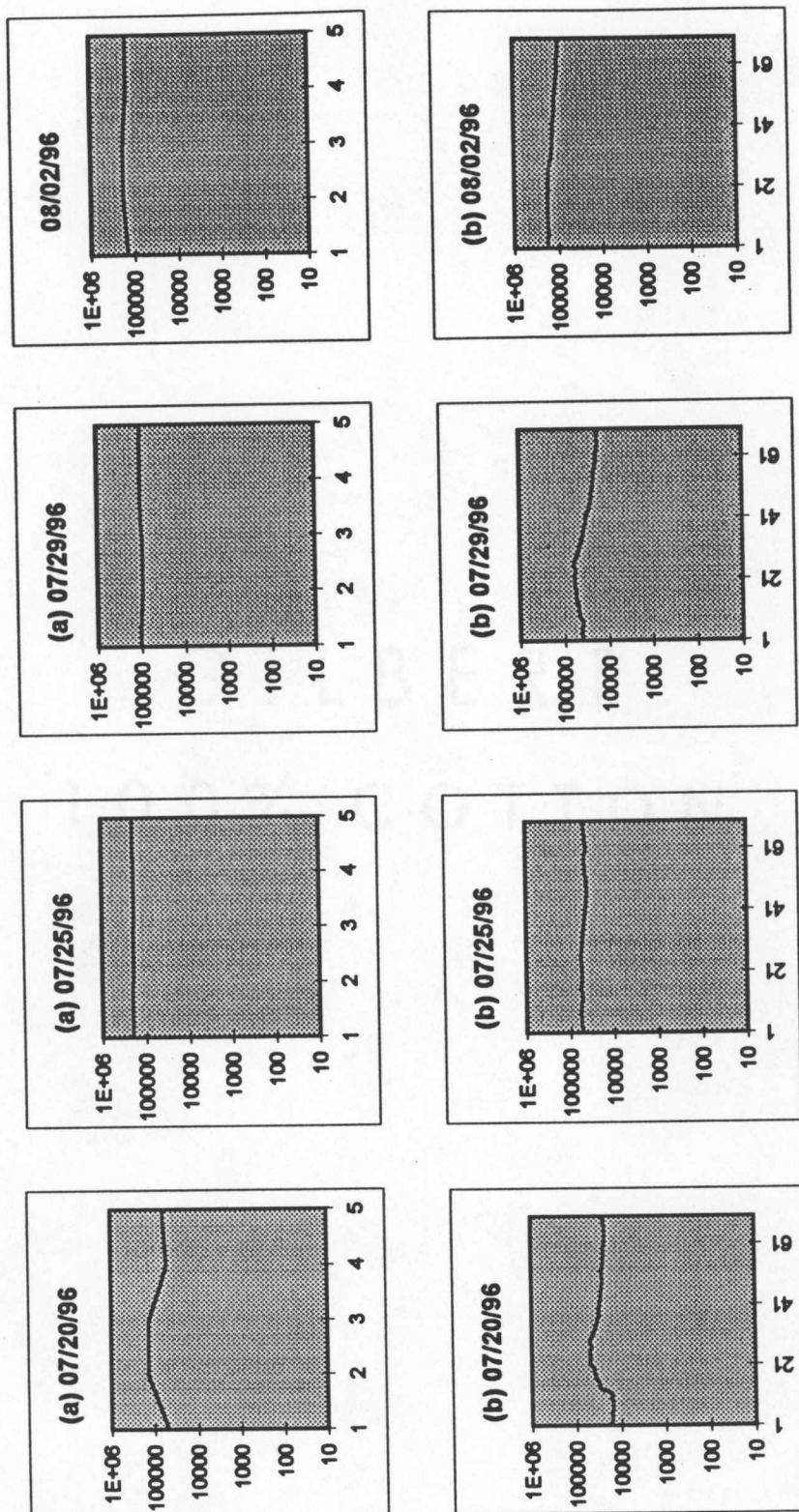


Figure A - 15. Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes)
 in uniform scale - particle size 0.5 - 0.7 um
 (a) outdoor (interval of 10 minutes)
 (b) indoor (interval of 140 minutes)

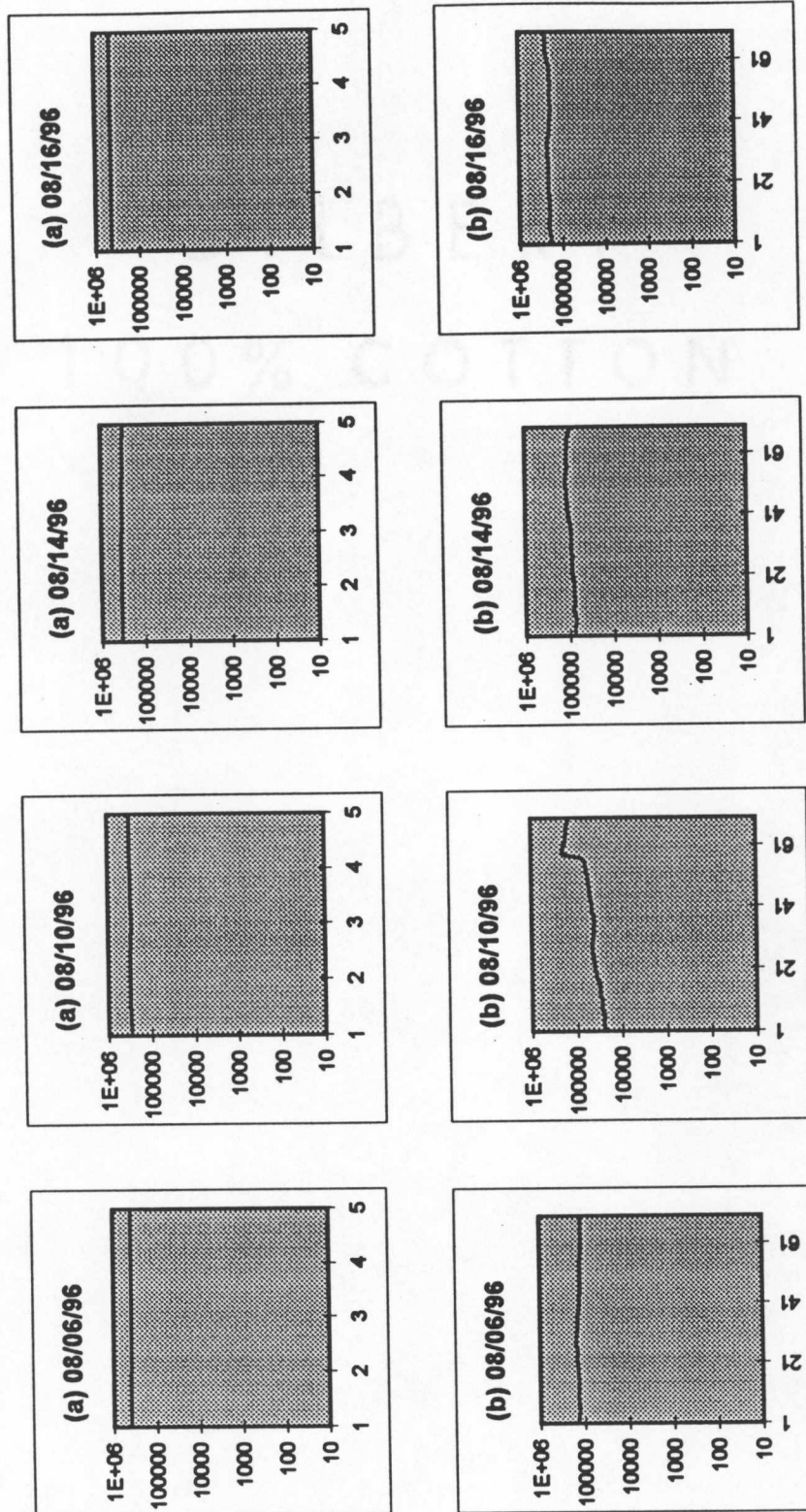


Figure A - 15. (continued) Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes) in uniform scale - particle size 0.5 - 0.7 μm

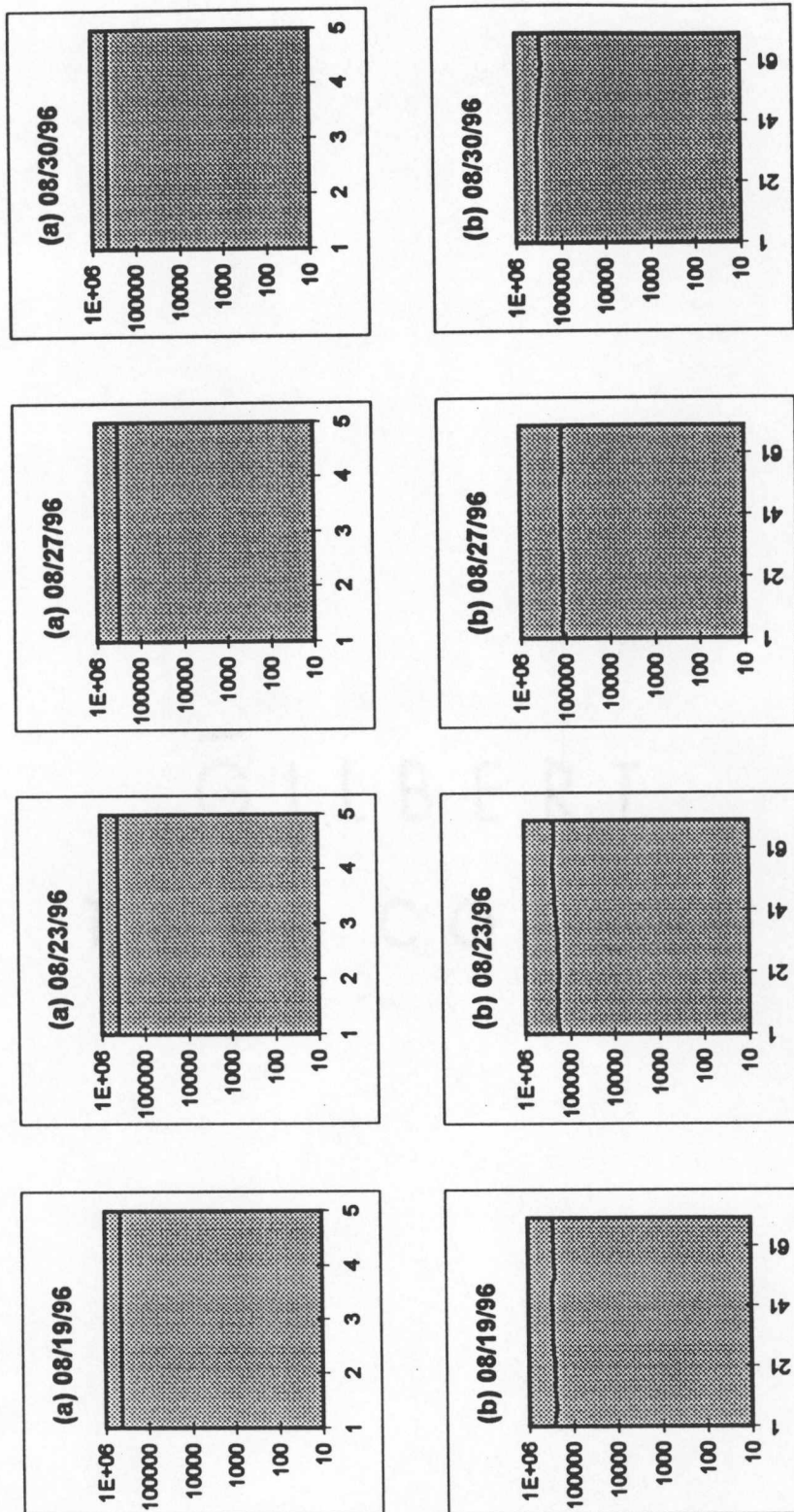


Figure A - 15. (continued) Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes) in uniform scale - particle size 0.5 - 0.7 um

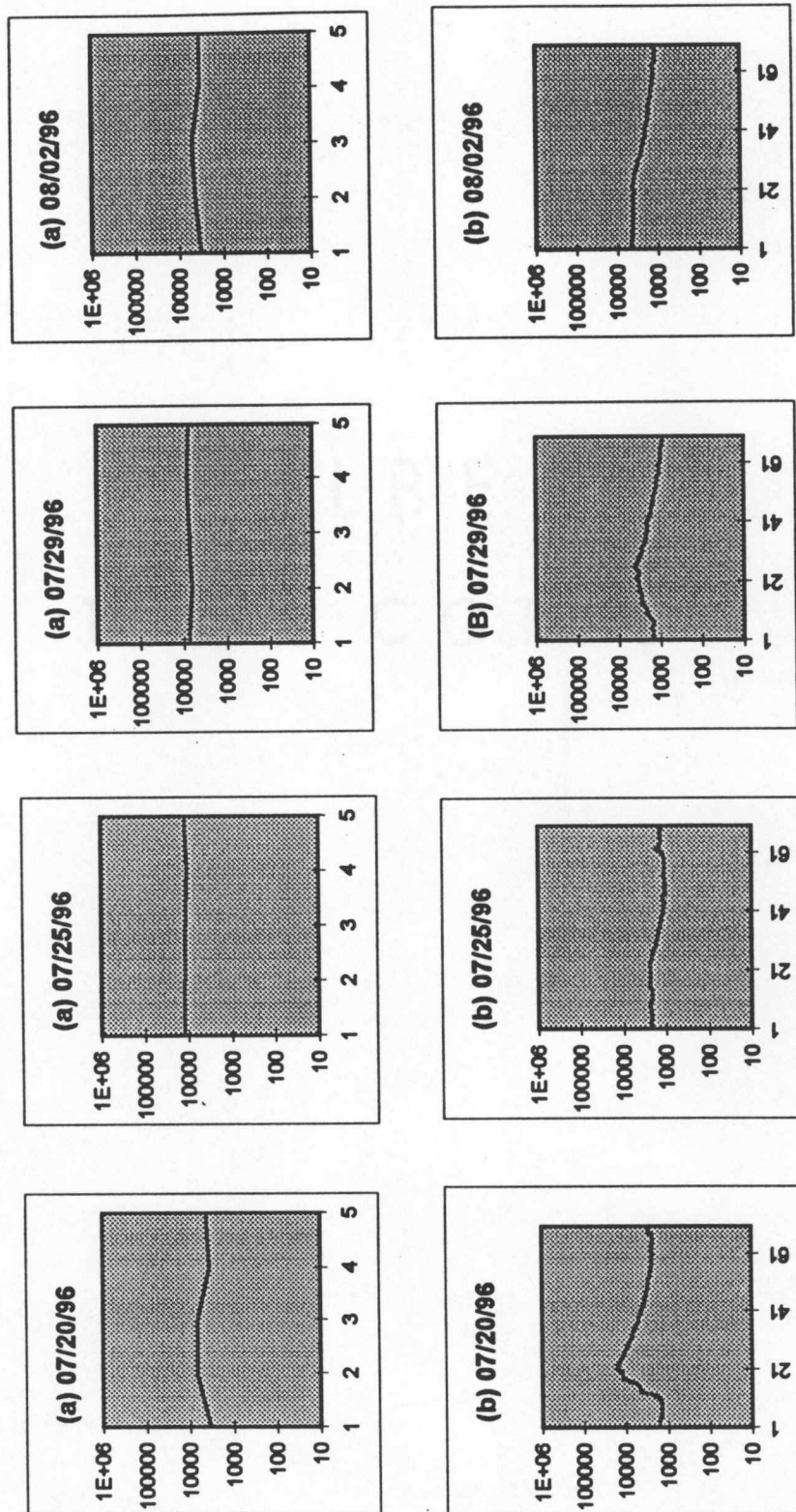


Figure A - 16. Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes)

In uniform scale - particle size 1.0 - 1.5 μ m

(a) outdoor (interval of 10 minutes)

(b) indoor (interval of 140 minutes)

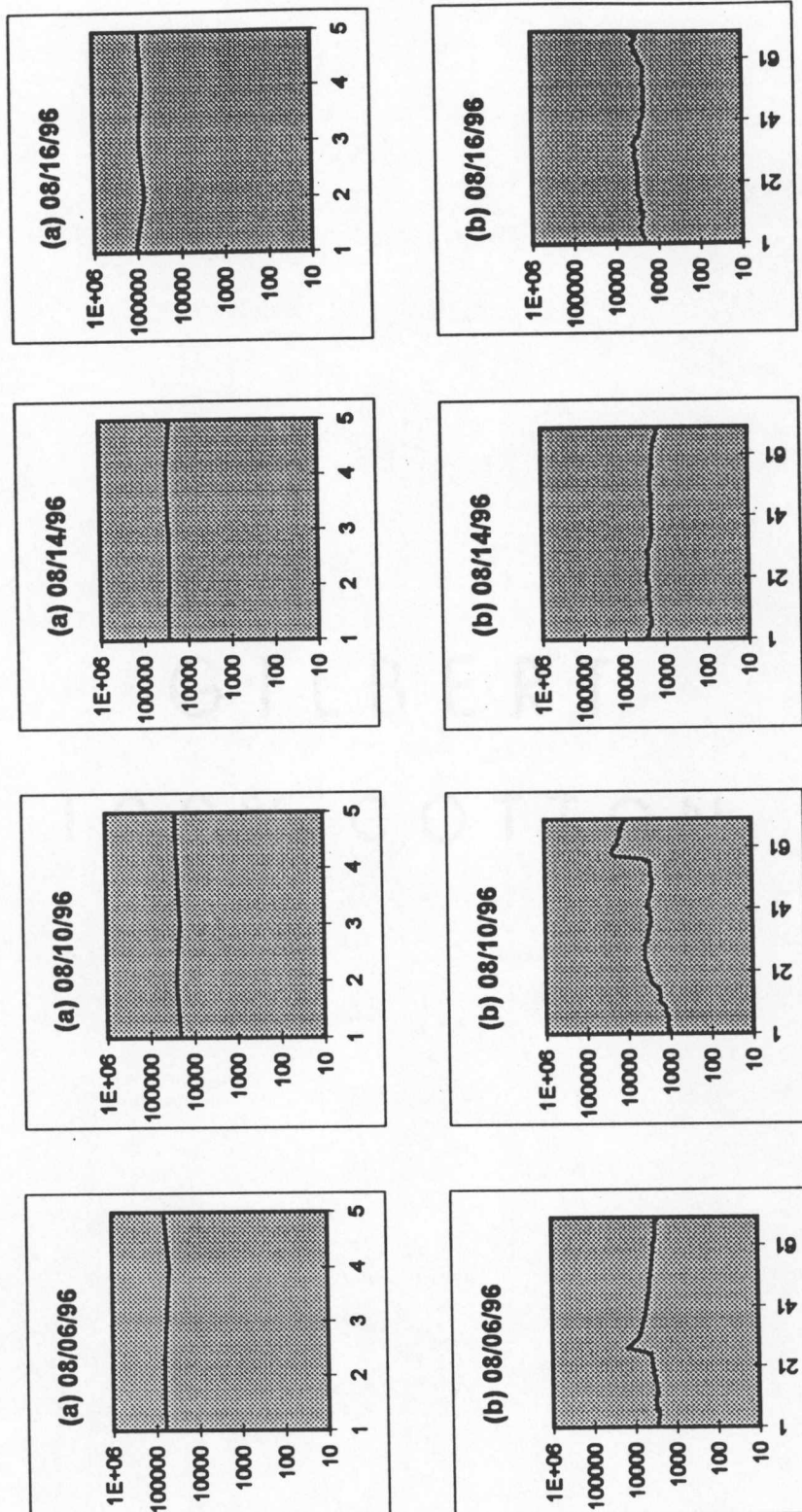


Figure A - 16. (continued) Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes) in uniform scale - particle size 1.0 - 1.5 um

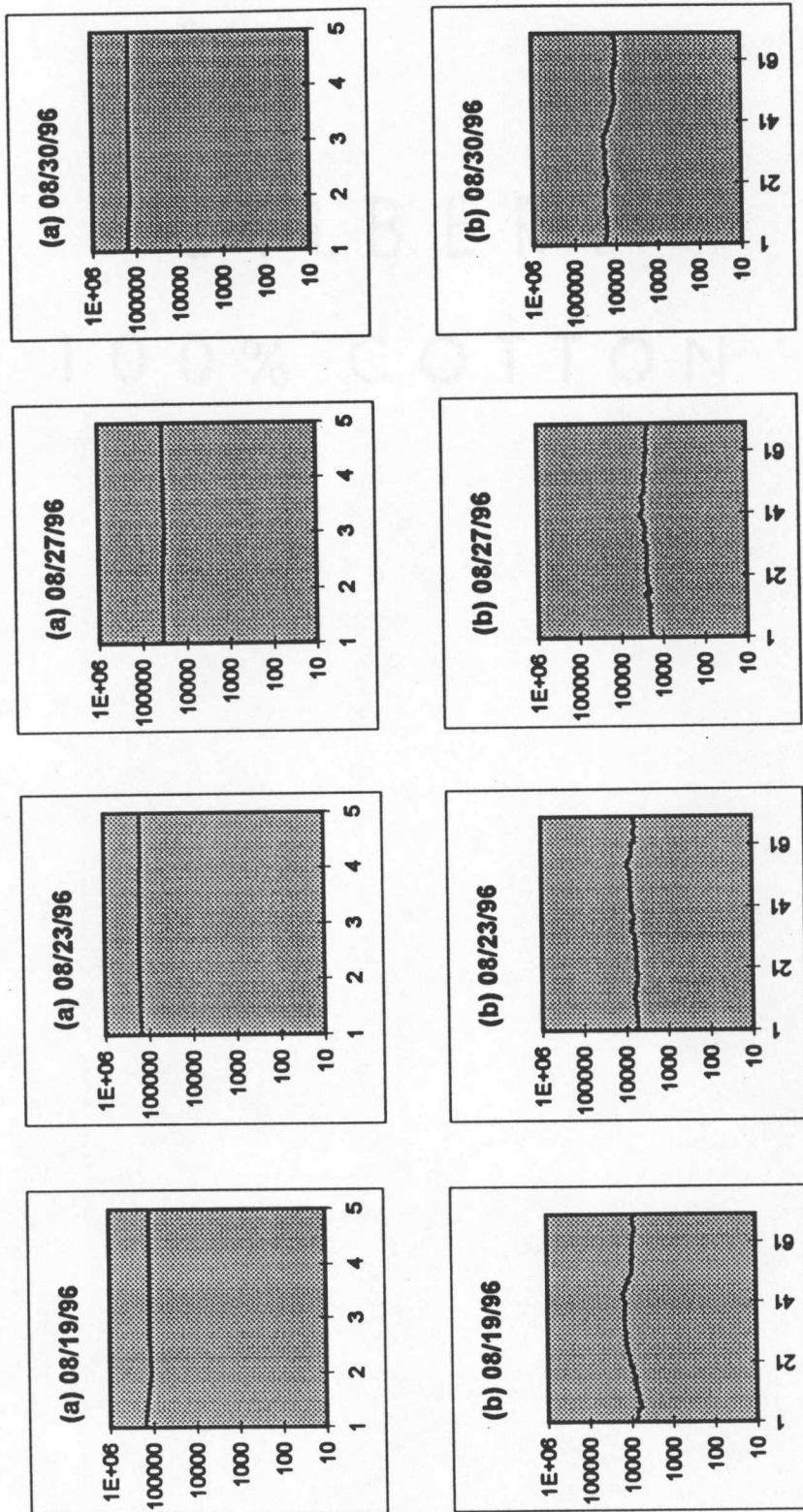


Figure A - 16. (continued) Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes) in uniform scale - particle size 1.0 - 1.5 um

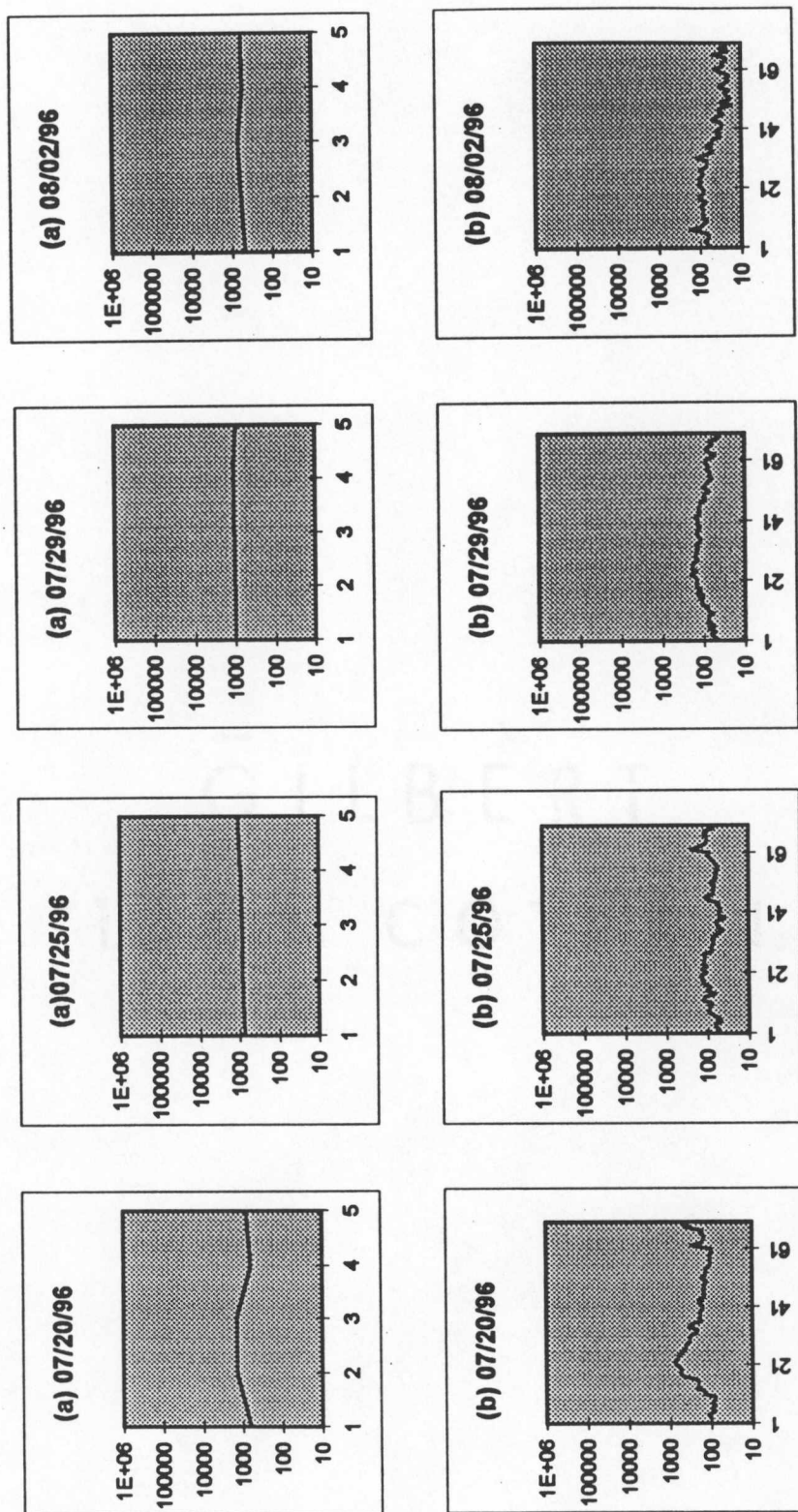


Figure A - 17. Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes)
in uniform scale - particle size 2.0 - 2.5 μm

(a) outdoor (interval of 10 minutes)

(b) indoor (interval of 140 minutes)

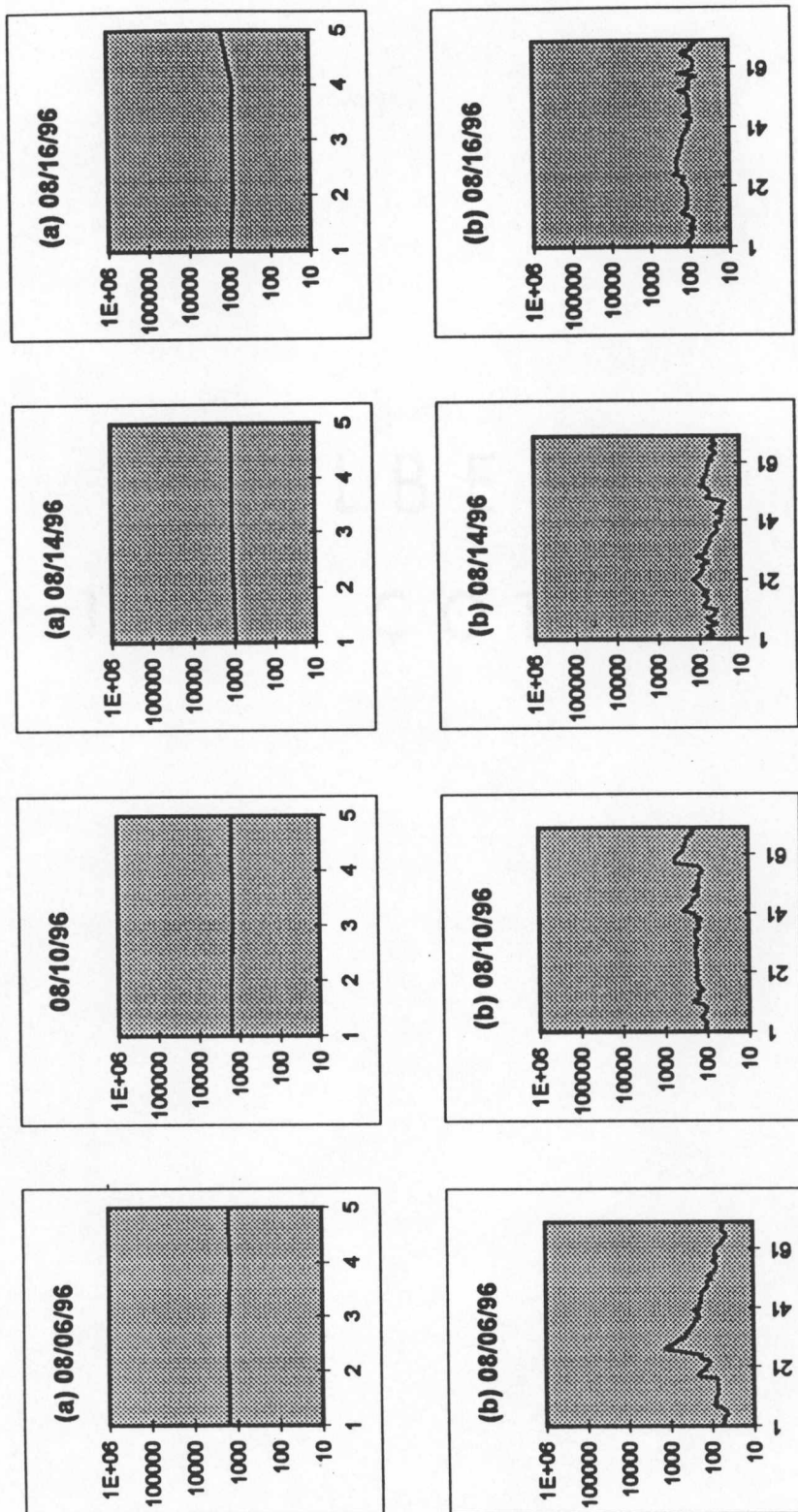


Figure A - 17. (continued) Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes) in uniform scale - particle size 2.0 - 2.5 um

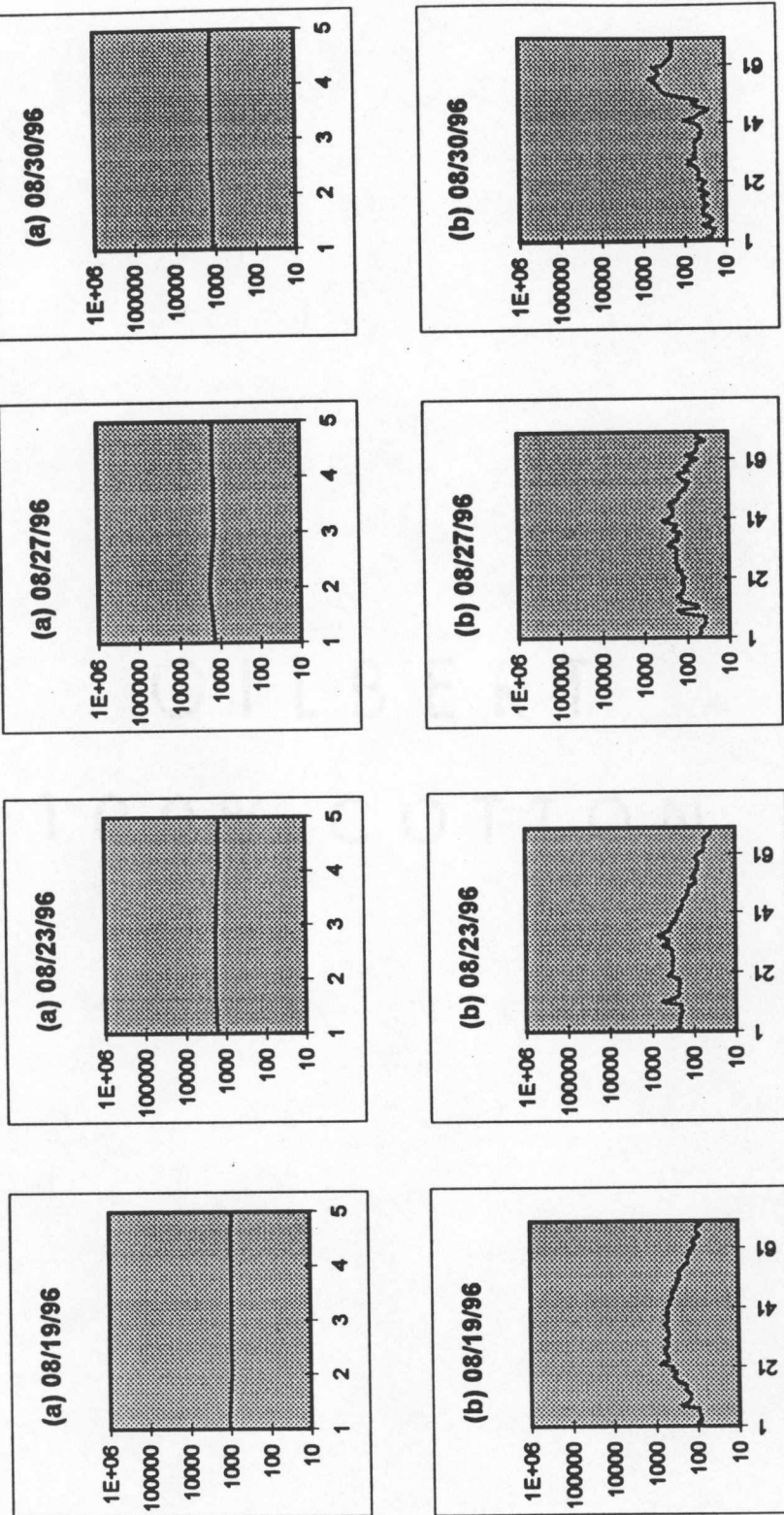


Figure A - 17. (continued) Plots of changing air concentrations (number of particles / cubic ft.) with time (every 2 minutes)
In uniform scale - particle size 2.0 - 2.5 μ m

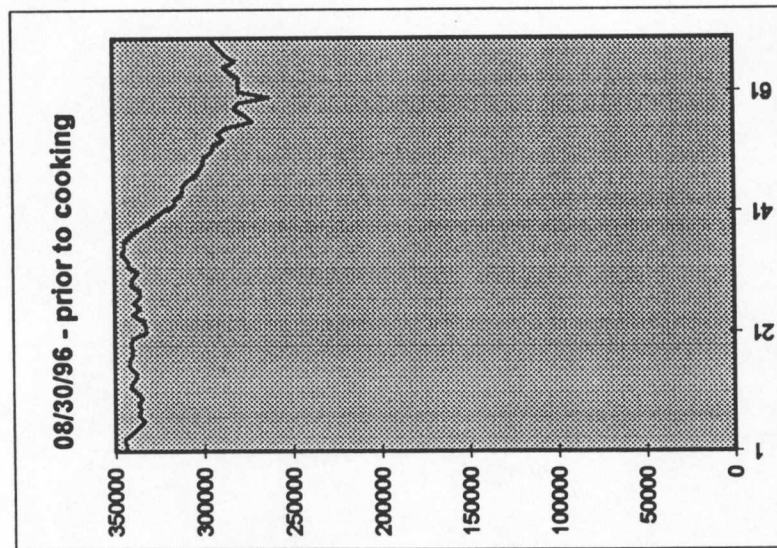
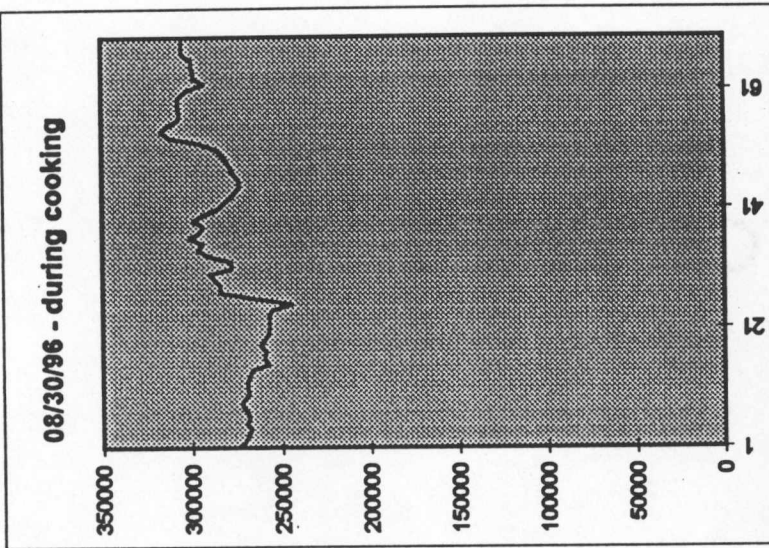


Figure A - 18. Plot of indoor air concentrations (number of particles / cubic ft.) with time (every 2 minutes)
prior to and during cooking
particle size 0.5 - 0.7um

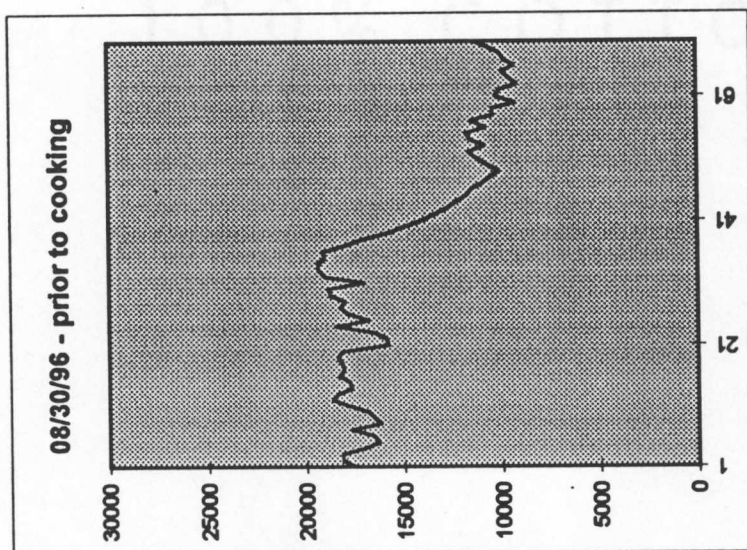
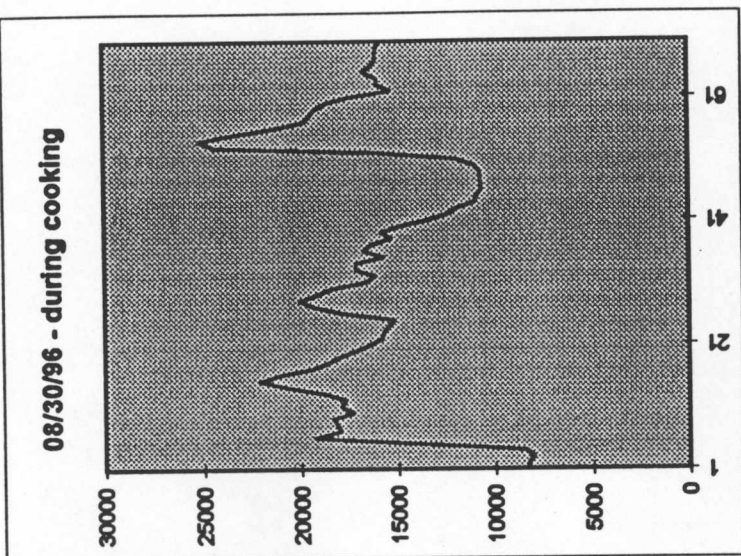


Figure A - 19. Plot of indoor air concentrations (number of particles / cubic ft.) with time (every 2 minutes)
prior to and during cooking
particle size 1.0 - 1.5 μm

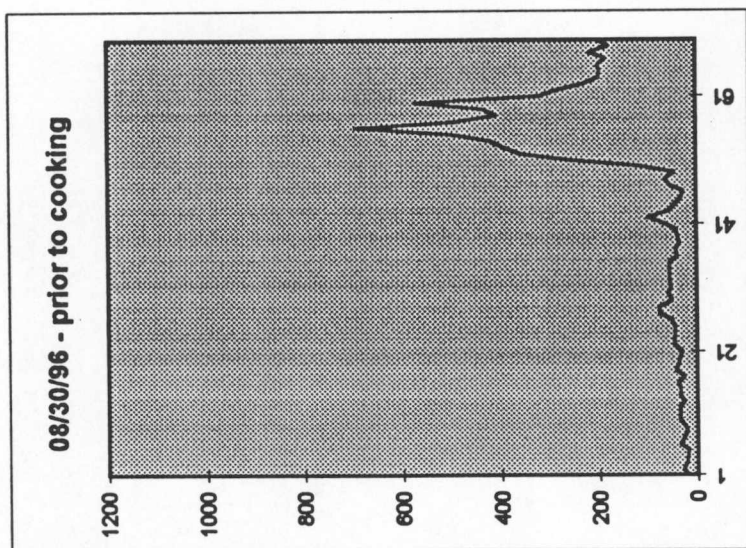
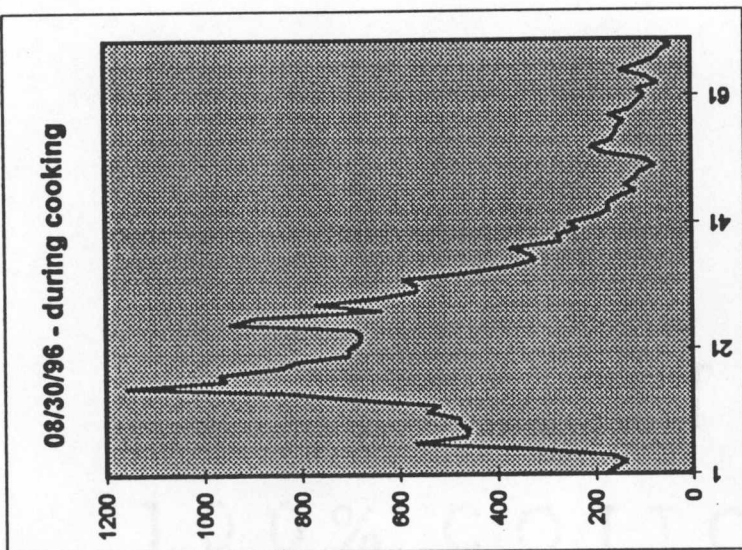


Figure A - 20. Plot of indoor air concentration (number of particles / cubic ft.) with time (every 2 minutes)
prior to and during cooking
particle size 2.0 - 2.5 μm

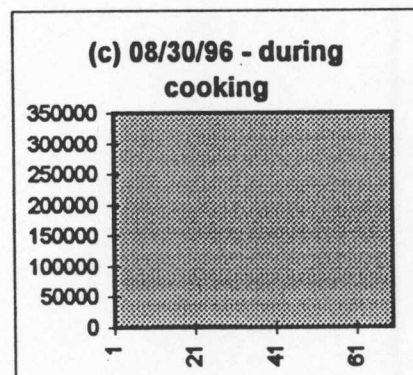
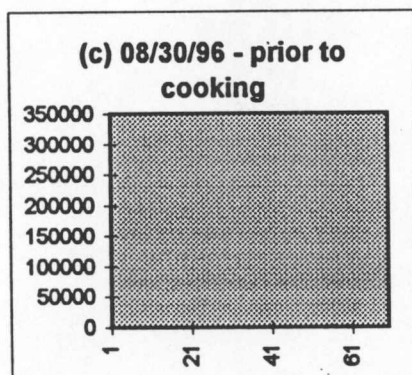
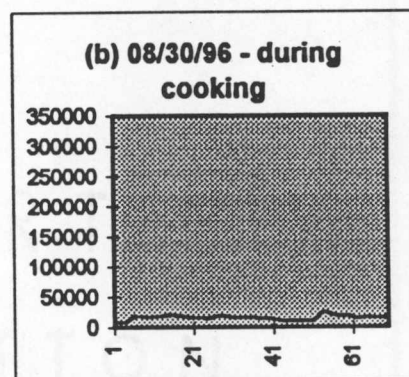
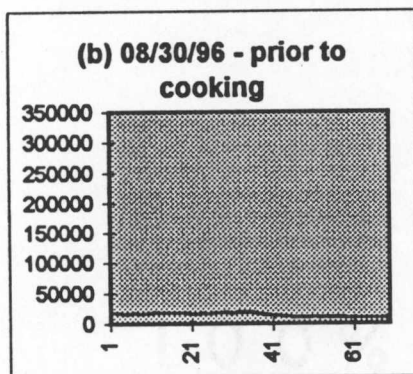
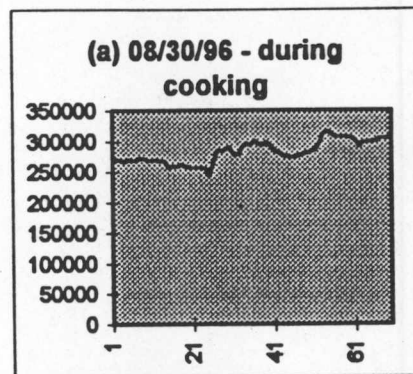
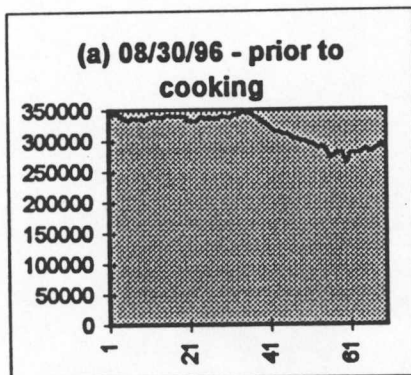
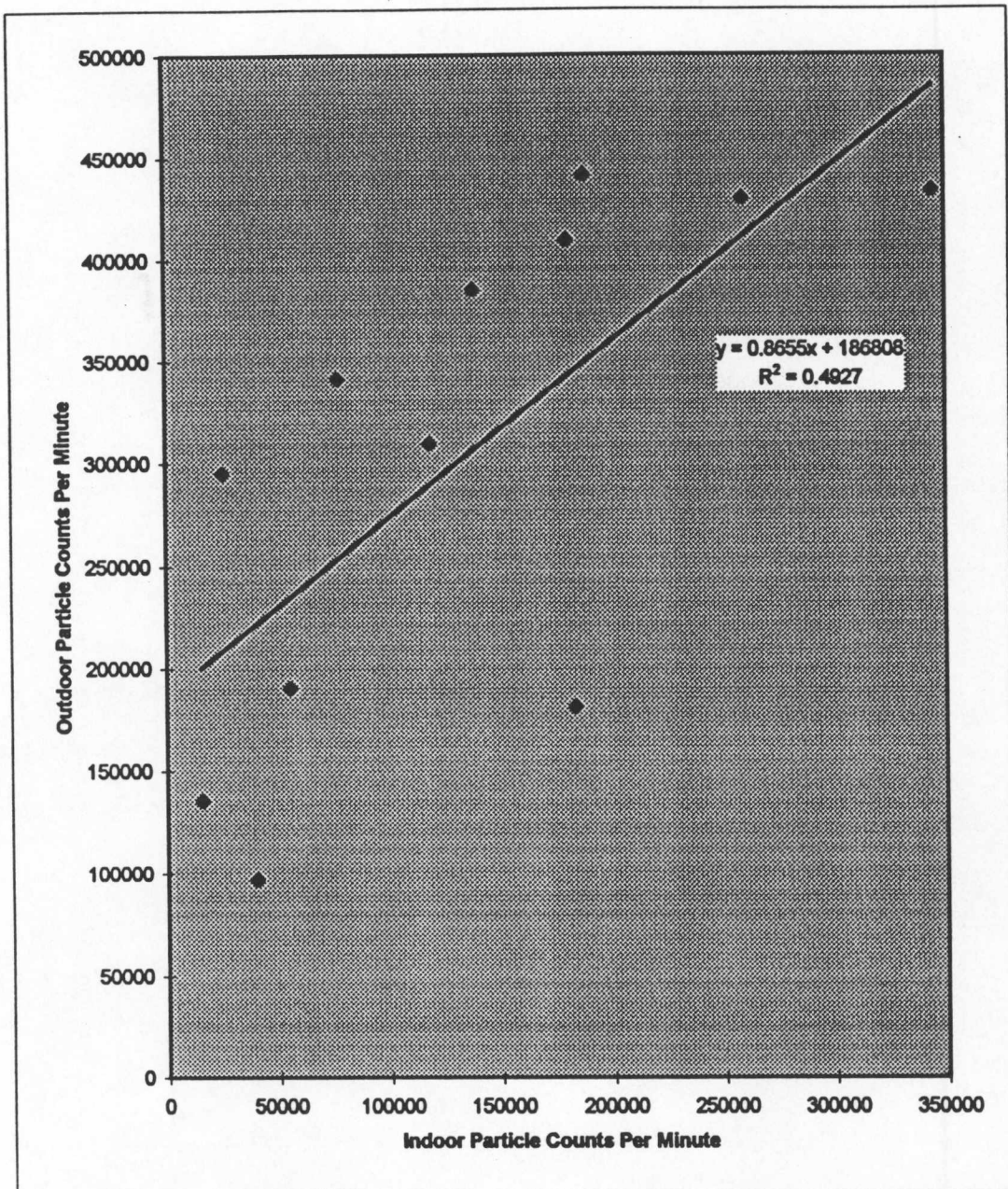


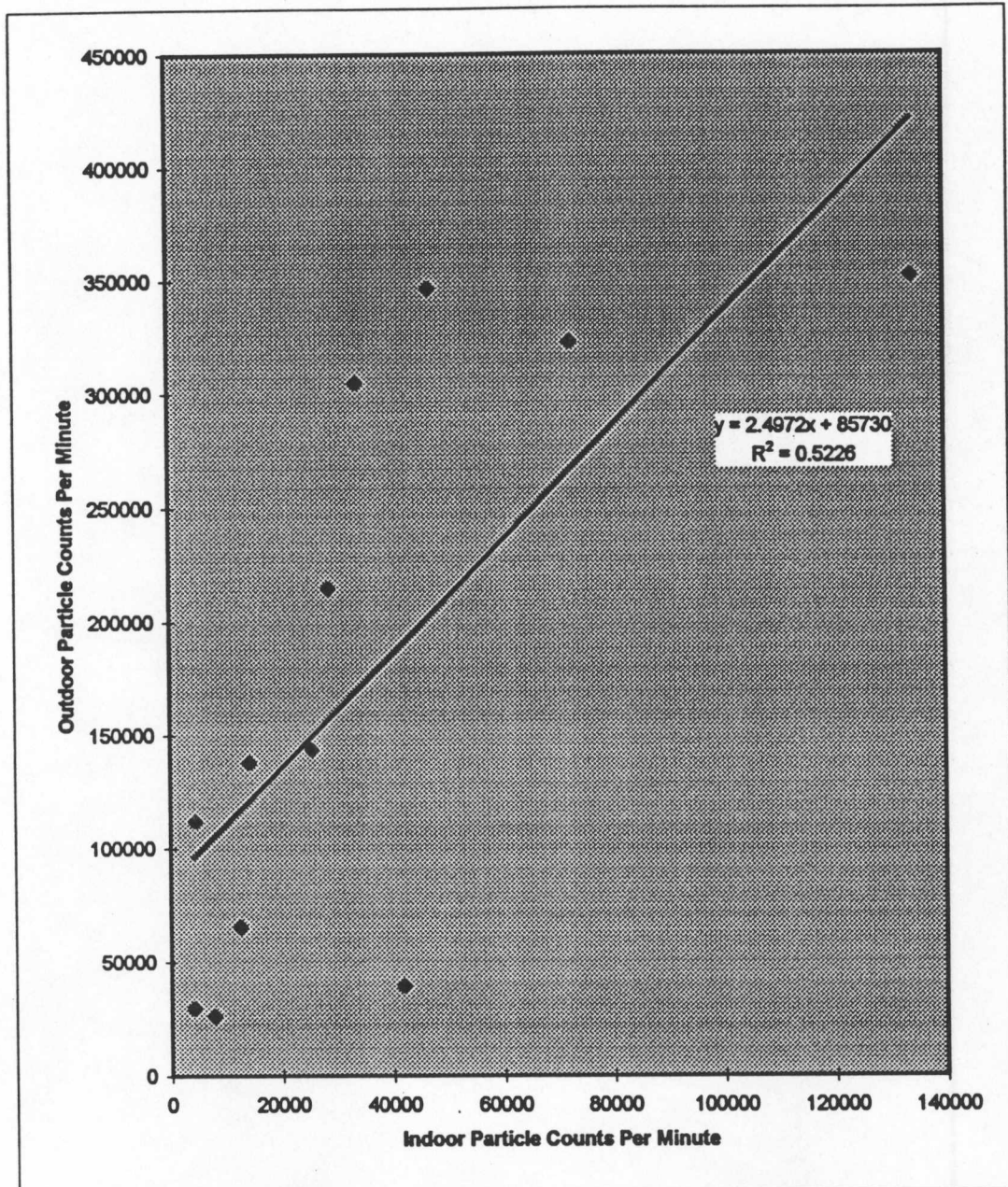
Figure A - 21. An overview of indoor air concentrations (number of particles / cubic ft.) with time (every 2 minutes) prior to and during cooking

- (a) particle size 0.5 - 0.7 μm
- (b) particle size 1.0 - 1.5 μm
- (c) particle size 2.0 - 2.5 μm



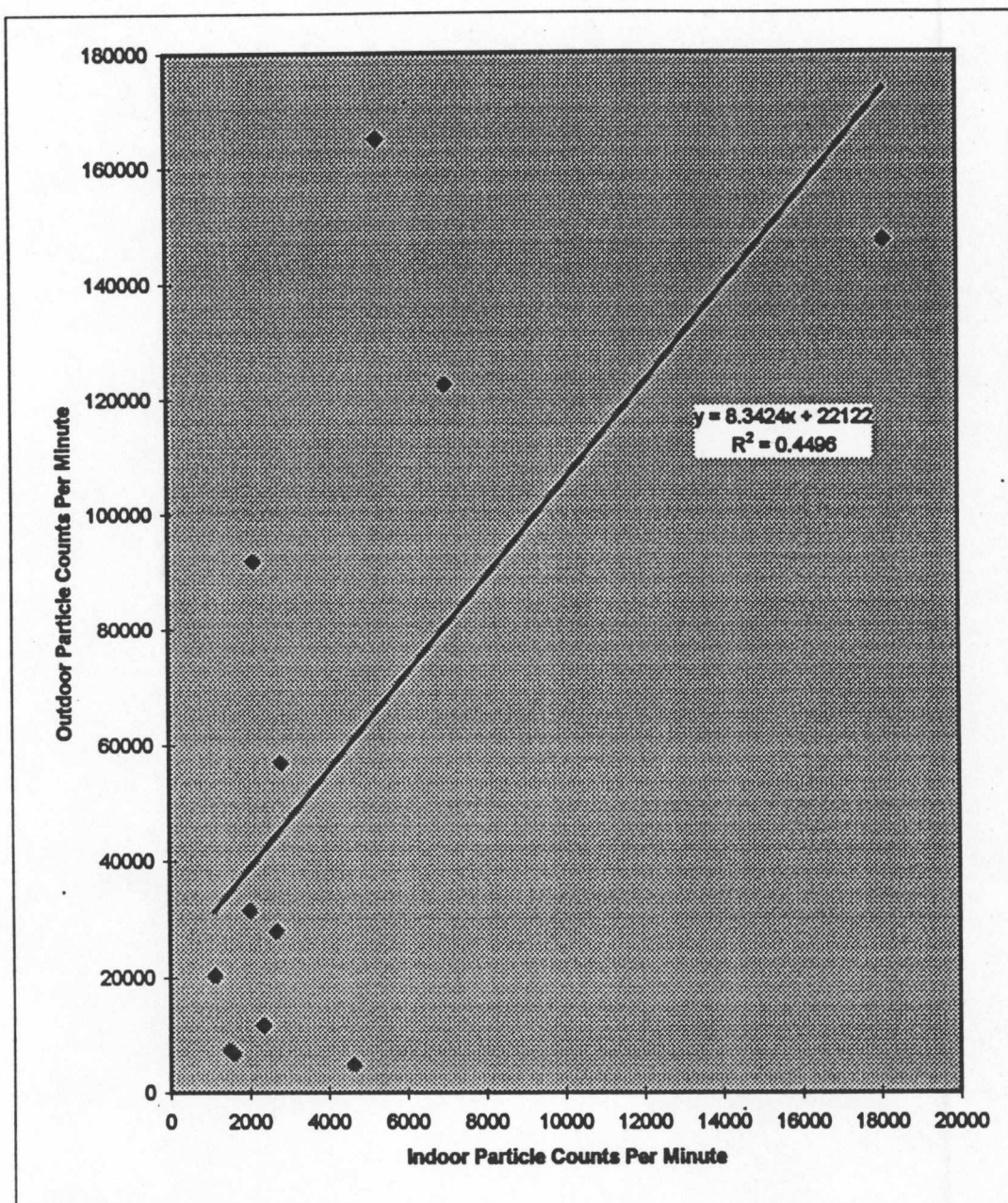
a. particle size 0.5 - 0.7 μm

Figure A - 22. Correlation between indoor particle counts and outdoor particle counts 6 minutes after beginning of data collection - indoor and outdoor



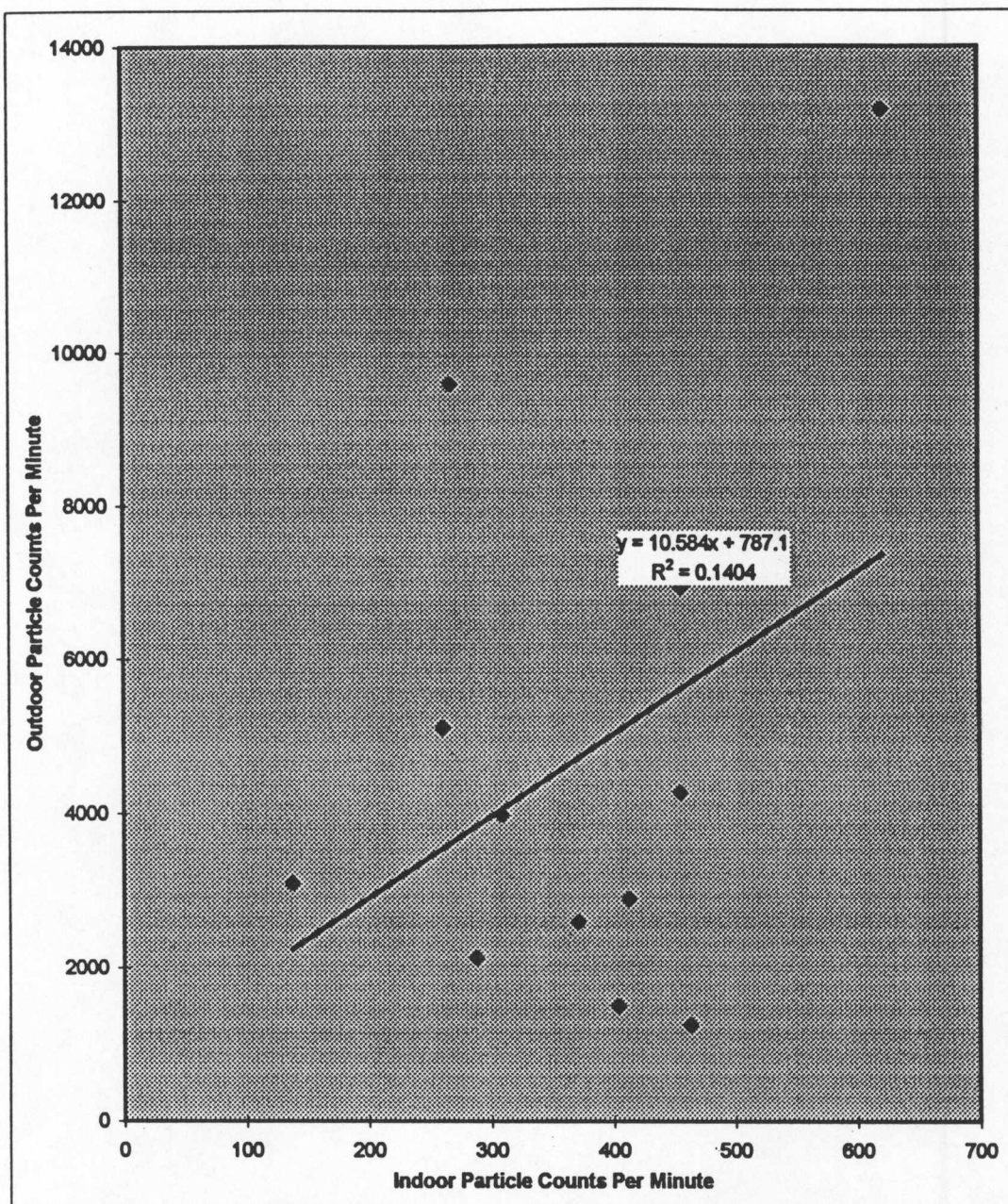
b. particle size 0.7 - 1.0 μm

Figure A - 22. (continued)



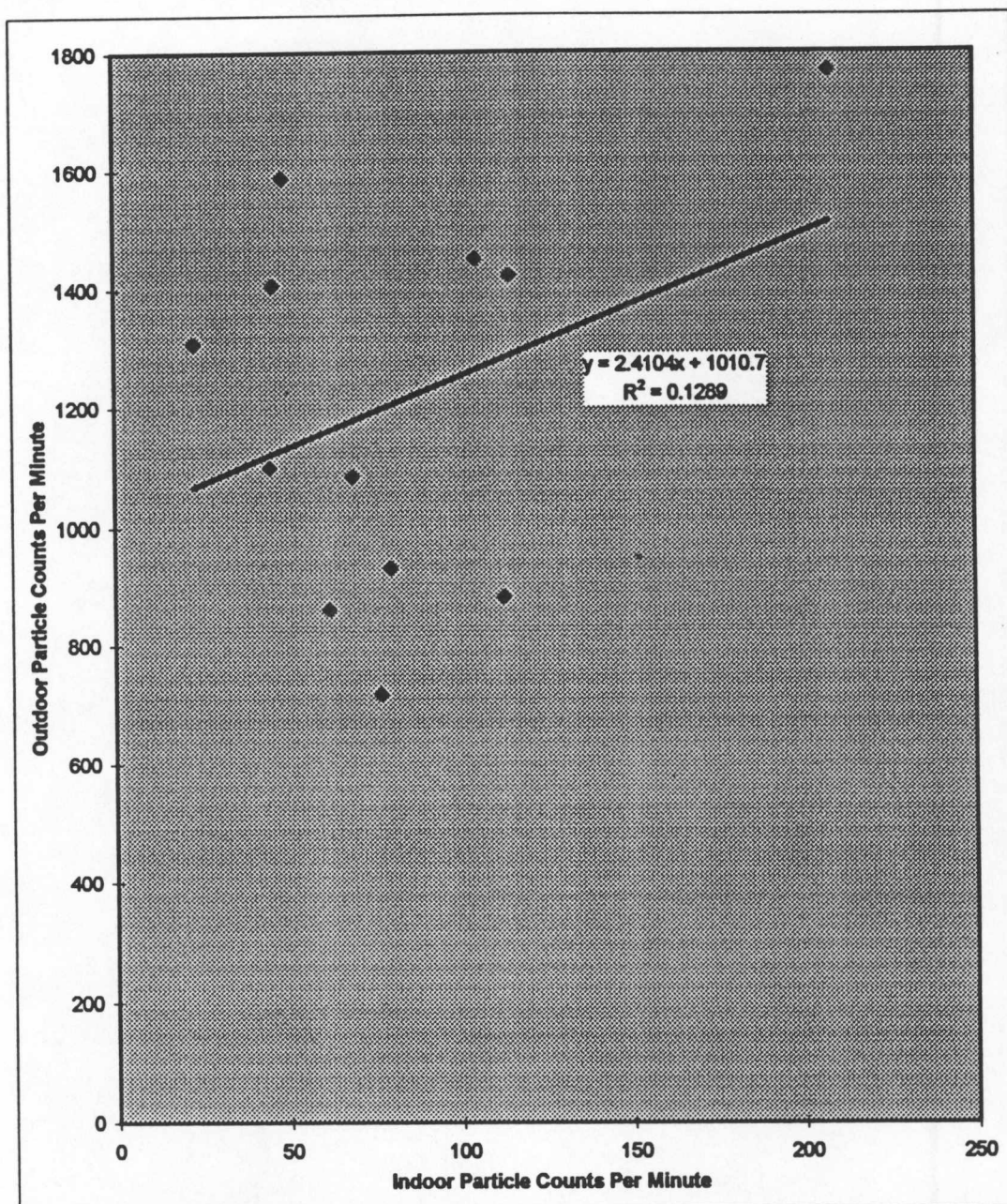
c. particle size 1.0 - 1.5 μm

Figure A - 22. (continued)



d. particle size 1.5 - 2.0 μm

Figure A - 22. (continued)



e. particle size 2.0 - 2.5 μm

Figure A - 22. (continued)

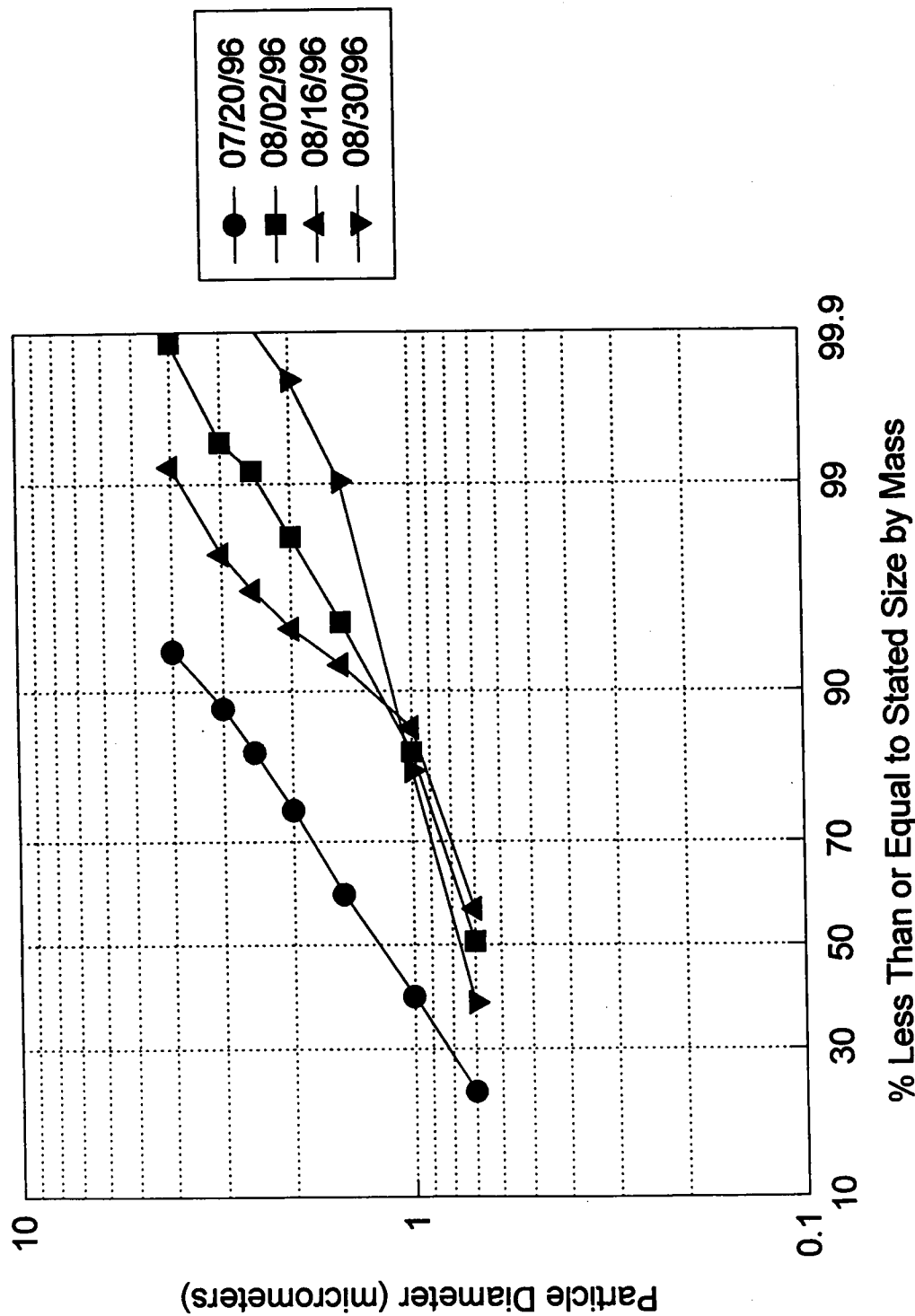


Figure A - 23. A log-probability plot of the mass distributions of four indoor particle samples 6 minutes after beginning of data collection

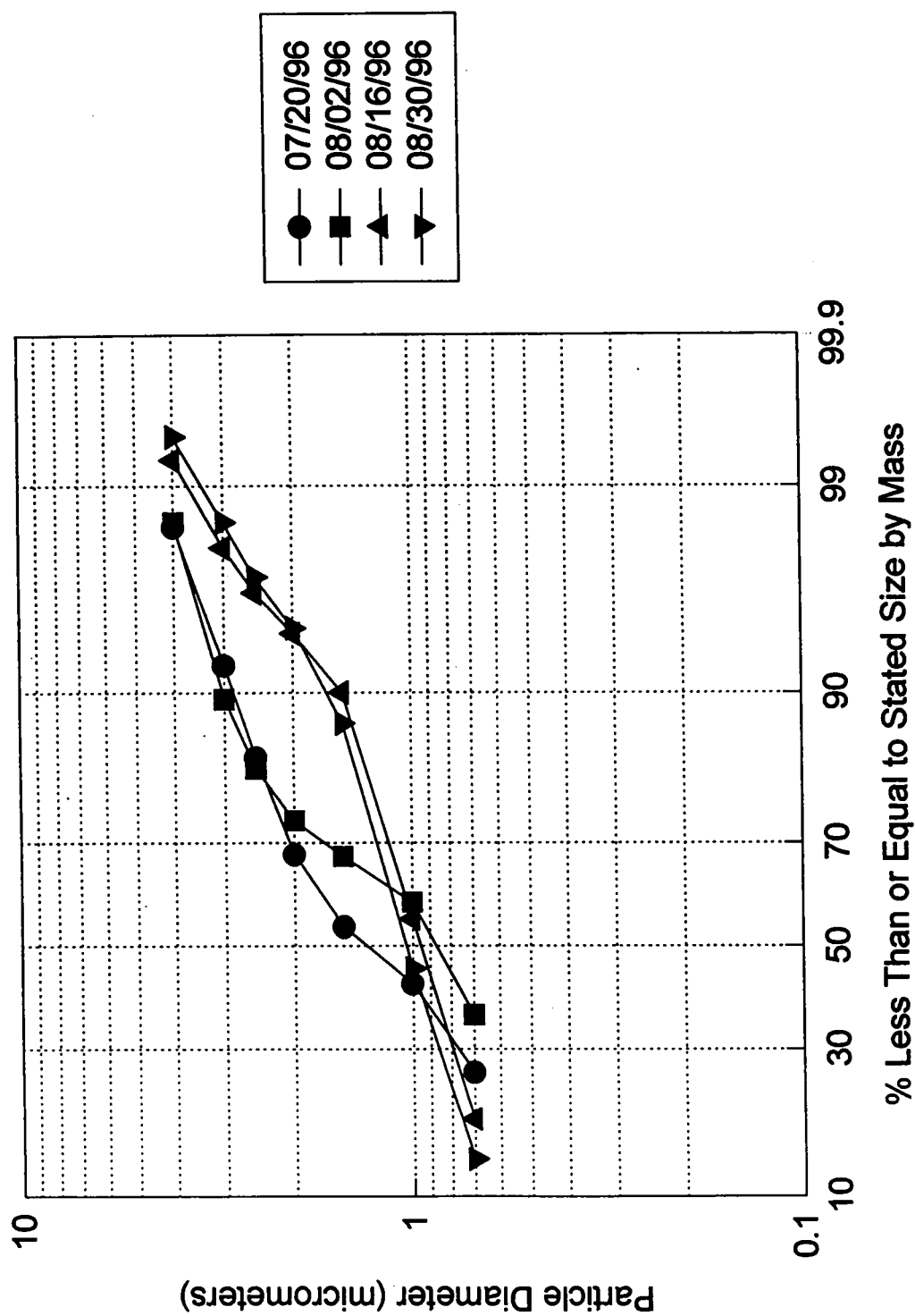


Figure A - 24. A log-probability plot of the mass distributions of four outdoor particle samples 6 minutes after beginning of data collection

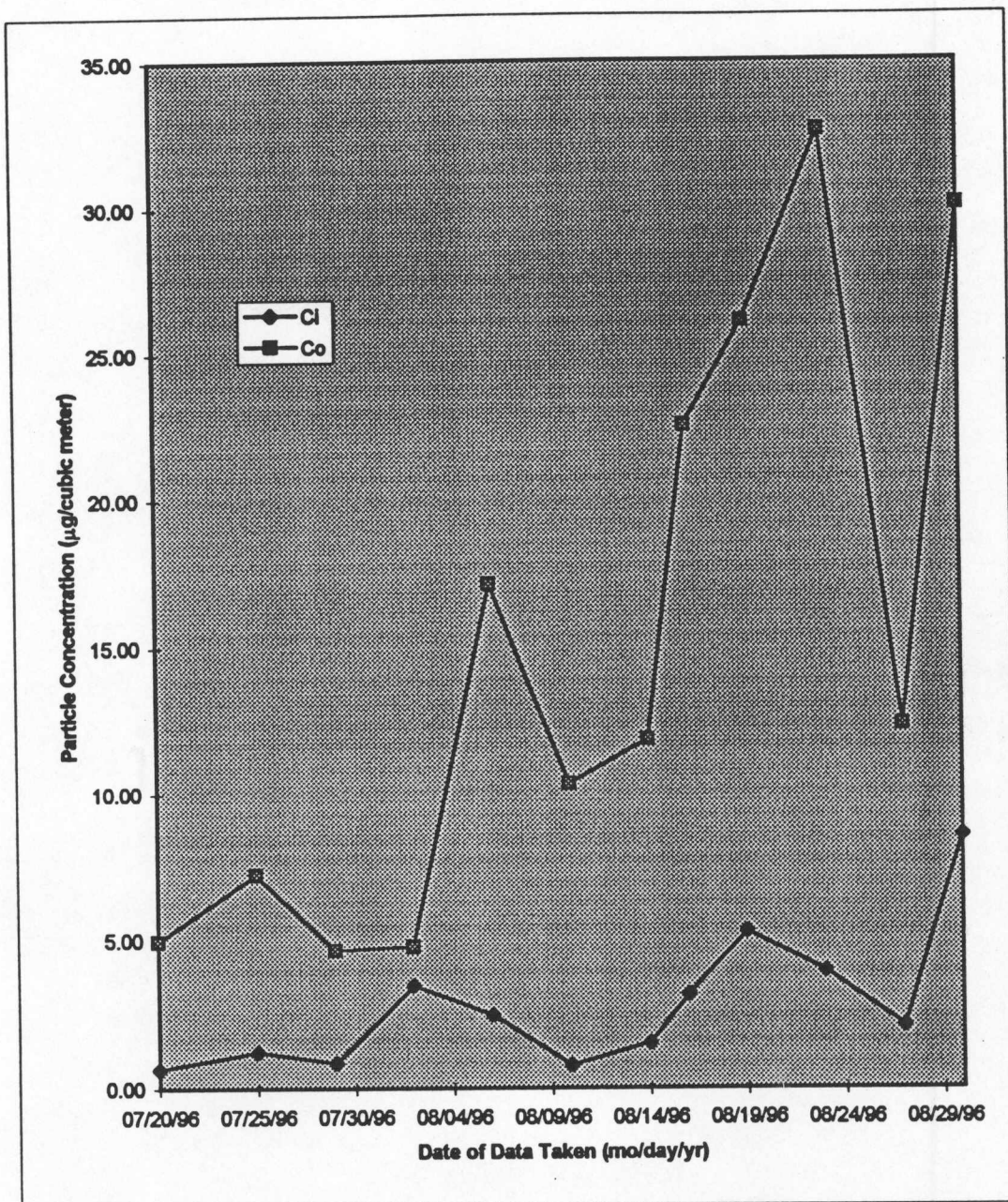


Figure A - 25. Comparison of the outdoor particle concentration (Co) and the indoor particle concentration (CI)
6 minutes after beginning of data collection - indoor and outdoor

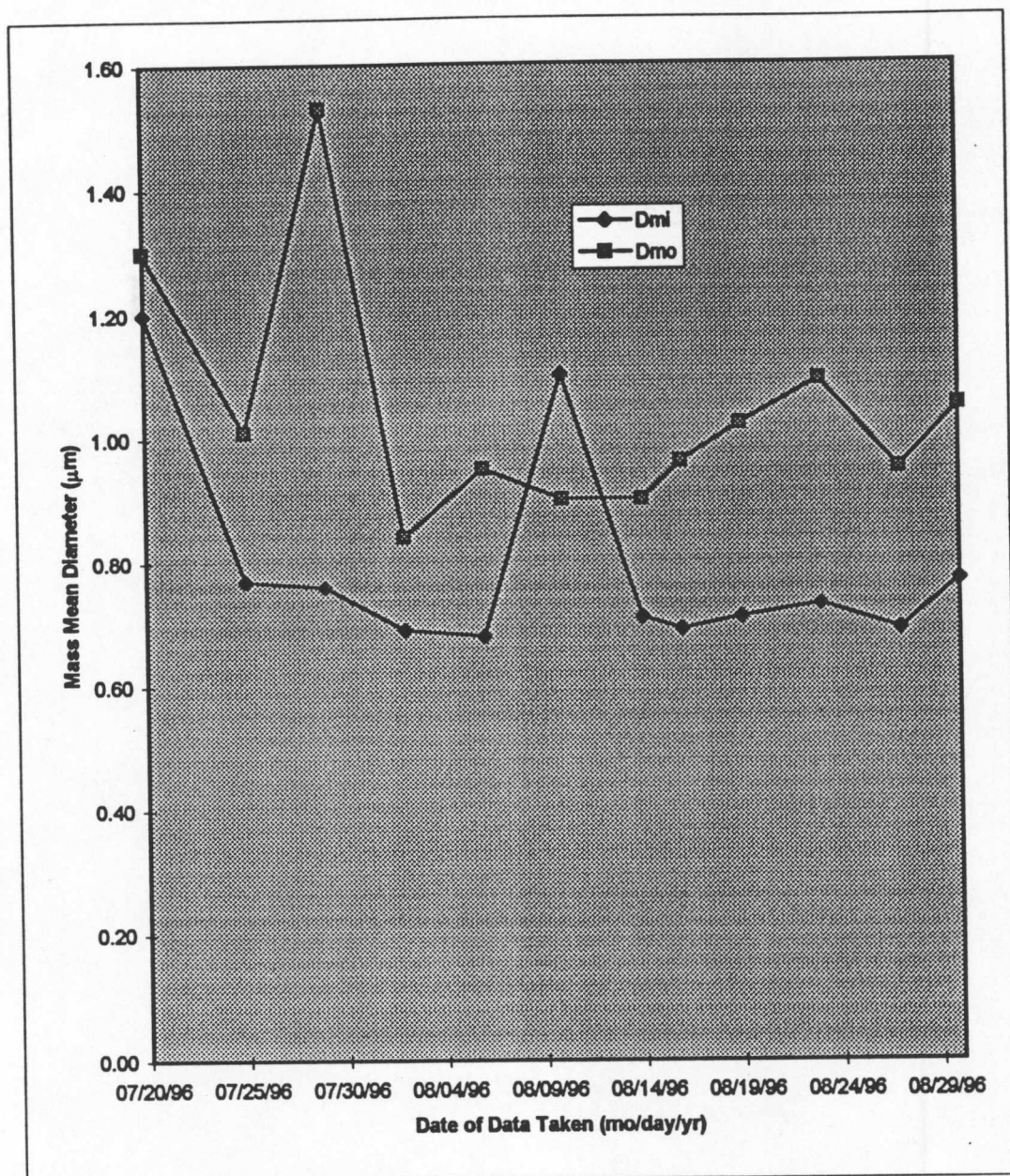


Figure A - 26. Comparison of the outdoor mass mean diameter (Dmo) and the indoor mass mean diameter (Dmi) 6 minutes after beginning of data collection - indoor and outdoor

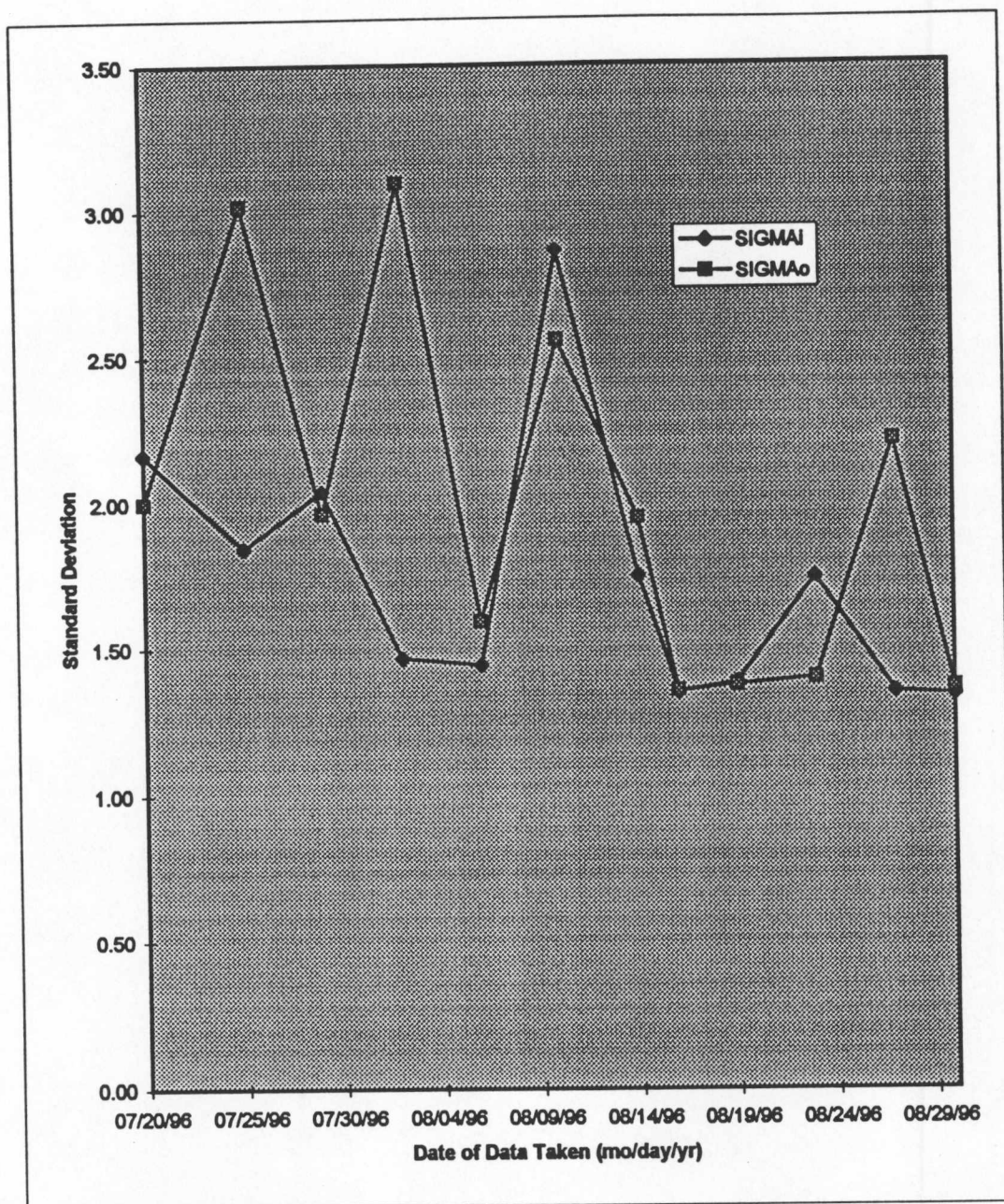


Figure A - 27. Comparison of the standard deviations of the outdoor mass distribution (SIGMA_o) and the indoor mass distribution (SIGMA_i) 6 minutes after beginning of data collection - indoor and outdoor

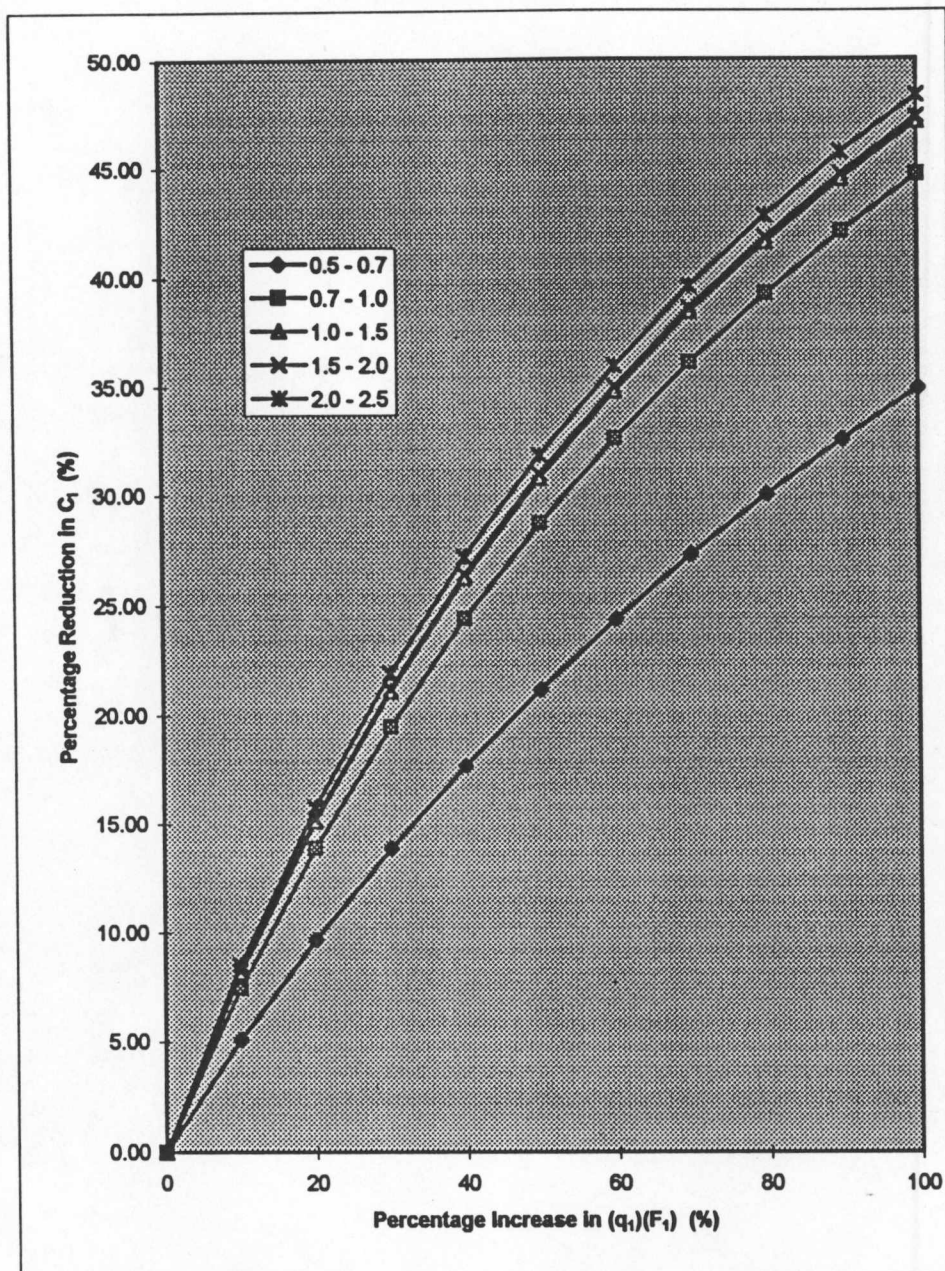


Figure A - 28. Percentage reduction in indoor particle concentration (C_i) due to percentage increase in recirculation flow rate and/or filter efficiency $(q_i)(F_i)$

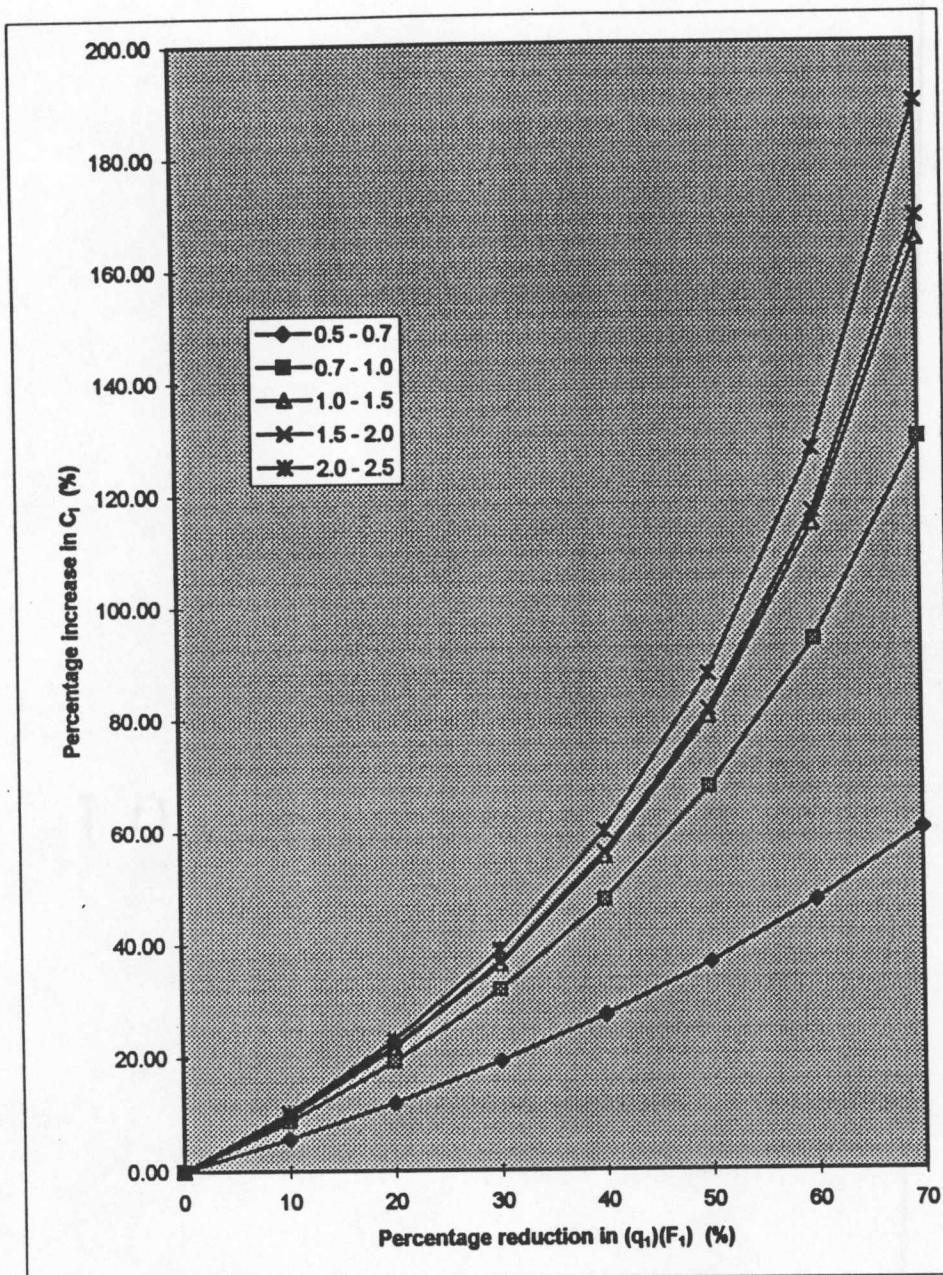


Figure A - 29. Percentage increase in indoor particle concentration (C_i) due to percentage reduction in recirculation flow rate and/or filter efficiency ($(q_i)(F_i)$)

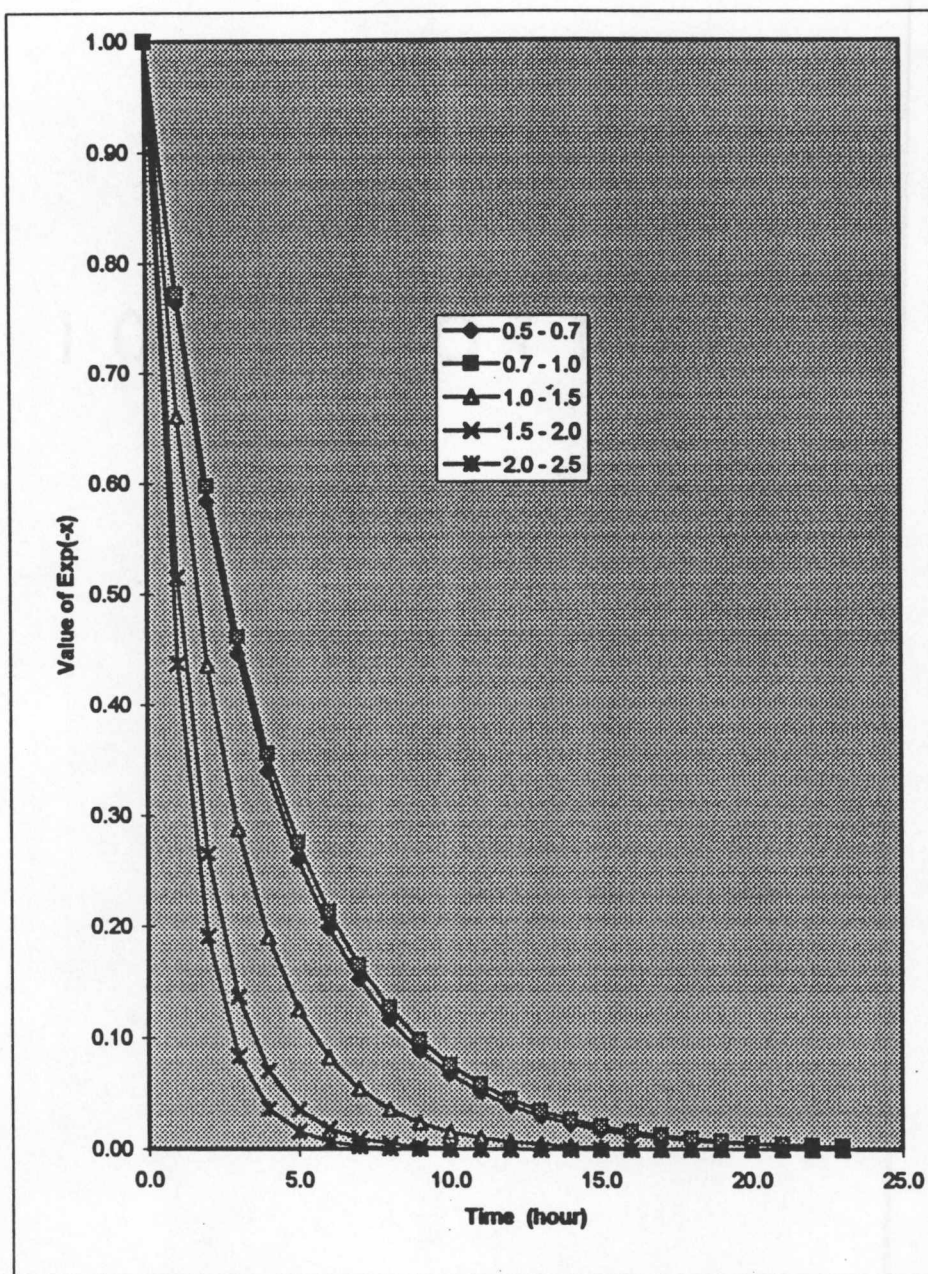


Figure A - 30. Time required for the indoor particle concentrations to reach the steady-state values (i.e., The term, $\text{Exp}(-x)$, as defined in Section D, Chapter 3, approaches zero.)

APPENDIX B

Table B - 1. Average initial (prior to dust loading) filter efficiencies

(a) normal air flow

Particle size (μm)	Filter A	Filter B	Filter C	Filter D	No Filter
0.5	5.2	2.0	1.3	1.9	1.9
0.7	7.7	2.5	1.1	2.3	1.6
1.0	12.6	8.0	2.5	1.4	0.8
1.5	21.8	19.7	9.2	3.8	3.1
2.0	30.5	22.5	11.3	14.0	0.0
2.5	37.0	37.1	5.1	4.8	4.5

(b) higher air flow

Particle size (μm)	Filter A	Filter B	Filter C	Filter D
0.5	2.2	2.2	1.8	2.1
0.7	2.3	2.0	1.7	2.0
1.0	3.5	3.6	1.1	4.6
1.5	12.1	12.9	11.7	11.5
2.0	25.3	26.7	19.8	18.7
2.5	25.6	23.1	25.2	28.4

Table B - 2. Values of parameters measured during the collection of the sample data for calculation of the initial efficiencies of Filters A, B, C, and D

filter type	normal air flow				higher air flow			
	humidity (%)	temperature (F)	delta p (in. of water)	filtration velocity (fpm)	humidity (%)	temperature (F)	delta p (in. of water)	filtration velocity (fpm)
Filter A	70.00	77.00	0.16	215.65	68.00	78.00	0.21	382.25
Filter B	70.00	78.00	0.19	215.85	68.00	78.00	0.22	367.00
Filter C	68.00	78.00	0.10	354.50	70.00	78.00	0.14	478.50
Filter D	70.00	78.00	0.10	353.25	72.00	78.00	0.15	474.25

Table B - 3. Values of parameters measured during the collection of the sample data for calculation of the efficiencies of Filters A and B after dust loading

stages after dust loading	Filter A					Filter B				
	humidity (%)	temperature (F)	delta p (in. of water)	filtration velocity (fpm)	weight of filter (gram)	humidity (%)	temperature (F)	delta p (in. of water)	filtration velocity (fpm)	weight of filter (gram)
initial	70.00	77.00	0.160	215.65	523.64	70.00	78.00	0.160	215.85	523.72
2nd week	74.00	79.00	0.170	259.90	525.75	74.00	80.00	0.170	242.00	525.96
4th week	75.00	78.00	0.176	261.50	527.22	76.00	78.50	0.185	240.25	528.25
6th week	72.00	78.00	0.185	257.50	528.51	70.00	78.00	0.195	239.00	531.93

Table B - 3a. Average indoor particle concentration removed by Filters A and B

	Filter A ($\mu\text{g}/\text{m}^3$)	Filter B ($\mu\text{g}/\text{m}^3$)
1st 2 weeks	6.12	6.49
2nd 2 weeks	3.54	5.92
3rd 2 weeks	3.08	9.58
average of 6 weeks	4.25	7.33

Table B - 4. Average efficiencies of Filters A and B (Initial and after dust loading) under normal air flow

Particle size (mm)	Filter A Initial	Filter A 2nd wk	Filter A 4th wk	Filter A 6th wk	Filter B Initial	Filter B 2nd wk	Filter B 4th wk	Filter B 6th wk	No Filter
0.5	5.2	5.3	3.9	3.4	2.0	5.5	2.0	2.8	1.9
0.7	7.7	5.9	5.2	5.7	2.5	6.1	3.5	5.0	1.6
1.0	12.6	8.2	7.4	12.5	8.0	6.9	5.5	10.5	0.8
1.5	21.8	2.1	14.3	28.7	19.7	1.1	19.0	19.0	3.1
2.0	30.5	9.7	6.6	43.7	22.5	8.8	20.0	32.7	0.0
2.5	37.0	25.5	26.1	45.2	37.1	-22.0	45.8	50.7	4.5

Table B - 5. Values of indoor and outdoor particle concentration data

	particle concentration ($\mu\text{g}/\text{cubic meter}$)		mass mean diameter (μm)		standard deviation		ratio of particle concentration (outdoor/indoor)
	indoor	outdoor	indoor	outdoor	indoor	outdoor	
07/20/96	0.66	4.96	1.20	1.30	2.17	2.00	7.52
07/25/96	1.24	7.25	0.77	1.01	1.84	3.02	5.85
07/29/96	0.87	4.64	0.76	1.53	2.04	1.96	5.33
08/02/96	3.46	4.77	0.69	0.84	1.46	3.10	1.38
08/06/96	2.46	17.13	0.68	0.95	1.44	1.59	6.96
08/10/96	0.78	10.32	1.10	0.90	2.86	2.56	13.23
08/14/96	1.52	11.84	0.71	0.90	1.75	1.94	7.79
08/16/96	3.15	22.50	0.69	0.96	1.35	1.35	7.14
08/19/96	5.27	26.07	0.71	1.02	1.38	1.37	4.95
08/23/96	3.94	32.60	0.73	1.09	1.74	1.39	8.27
08/27/96	2.09	12.34	0.69	0.95	1.35	2.21	5.90
08/30/96	8.55	30.06	0.77	1.05	1.34	1.36	3.52
average value	2.83	15.37	0.79	1.04	1.73	1.99	6.49

Table B - 5a. Ratios of particle concentration (outdoor/indoor) at different size ranges

	0.5 - 0.7 μm	0.7 - 1.0 μm	1.0 - 1.5 μm	1.5 - 2.0 μm	2.0 - 2.5 μm	2.5 - 3.0 μm	3.0 - 4.0 μm	4.0 - 5.0 μm
07/20/96	8.63	7.22	4.34	7.00	13.83	14.03	10.00	1.82
07/25/96	3.44	5.26	5.00	3.69	13.89	54.92	46.00	11.25
07/29/96	2.43	3.42	4.89	7.38	15.71	32.56	31.70	18.00
08/02/96	0.99	0.94	1.07	2.70	9.32	39.60	28.25	18.00
08/06/96	2.78	7.47	20.19	19.59	32.41	27.61	17.88	9.00
08/10/96	11.67	24.99	18.28	6.99	12.37	15.26	10.45	2.20
08/14/96	4.41	9.68	10.38	9.38	24.42	34.62	19.60	22.00
08/16/96	2.35	8.99	42.72	12.91	7.81	8.50	6.59	6.50
08/19/96	1.66	4.44	17.34	15.23	11.64	11.70	7.75	8.00
08/23/96	2.27	7.36	30.78	21.18	8.50	7.89	6.53	2.06
08/27/96	2.61	5.63	15.67	22.46	30.57	91.25	44.00	5.00
08/30/96	1.26	2.62	8.12	35.75	56.83	97.00	180.00	33.00
average ratio	3.71	7.34	14.90	13.69	19.77	36.24	34.06	11.40

Table B - 6. Calculated values of the volumetric flow rate for recirculation

stages after dust loading	particle size (μm)	Filter A		Filter B		Filter E		sum (cubic ft./min.)	suma (cubic ft./min.)
		q_a (cubic ft./min.)	F_a (%)	q_b (cubic ft./min.)	F_b (%)	q_e (cubic ft./min.)	F_e (%)		
Initial	0.5	600.00	5.2	600.00	2.0	880.00	1.6	57	
Initial	0.7	600.00	7.7	600.00	2.5	880.00	1.7	76	67
Initial	1.0	600.00	12.6	600.00	8.0	880.00	2.0	141	109
Initial	1.5	600.00	21.8	600.00	19.7	880.00	6.5	306	224
Initial	2.0	600.00	30.5	600.00	22.5	880.00	12.7	430	368
Initial	2.5	600.00	37.0	600.00	37.1	880.00	5.0	489	459
2nd week	0.5	722.00	5.3	667.00	5.5	880.00	1.6	89	
2nd week	0.7	722.00	5.9	667.00	6.1	880.00	1.7	98	94
2nd week	1.0	722.00	8.2	667.00	6.9	880.00	2.0	123	111
2nd week	1.5	722.00	2.1	667.00	1.1	880.00	6.5	80	101
2nd week	2.0	722.00	9.7	667.00	8.8	880.00	12.7	240	160
2nd week	2.5	722.00	25.5	667.00	-22.0	880.00	5.0	81	161
4th week	0.5	722.00	3.9	667.00	2.0	880.00	1.6	56	
4th week	0.7	722.00	5.2	667.00	3.5	880.00	1.7	76	66
4th week	1.0	722.00	7.4	667.00	5.5	880.00	2.0	108	92
4th week	1.5	722.00	14.3	667.00	19.0	880.00	6.5	287	197
4th week	2.0	722.00	6.6	667.00	20.0	880.00	12.7	293	290
4th week	2.5	722.00	26.1	667.00	45.8	880.00	5.0	538	415
6th week	0.5	722.00	3.4	667.00	2.8	880.00	1.6	57	
6th week	0.7	722.00	5.7	667.00	5.0	880.00	1.7	89	73
6th week	1.0	722.00	12.5	667.00	10.5	880.00	2.0	178	134
6th week	1.5	722.00	28.7	667.00	19.0	880.00	6.5	391	285
6th week	2.0	722.00	43.7	667.00	32.7	880.00	12.7	645	518
6th week	2.5	722.00	45.2	667.00	50.7	880.00	5.0	709	677

Table B - 6. (continued) Calculated values of the volumetric flow rate for recirculation

notes:

V_a = filtration velocity measured at the surface of Filter A as included in Table B-3

V_b = filtration velocity measured at the surface of Filter B as included in Table B-3

V_c = filtration velocity measured at the surface of Filter C (or D) as included in Table B-2

$V_e = (.16/.10)(V_d)$, filtration velocity assumed for Filter E at the basement (values of pressure drop taken from Table B-2)

$q_a = (V_d)(2.78 \text{ sq. ft.})$, (cubic ft./min.) - recirculation flow rate on the 1st floor

$q_b = (V_d)(2.78 \text{ sq. ft.})$, (cubic ft./min.) - recirculation flow rate on the 2nd floor

$q_e = (V_d)(1.56 \text{ sq. ft.})$, (cubic ft./min.) - recirculation flow rate on the basement floor

F_a = efficiency of filter A, (%)

F_b = efficiency of filter B, (%)

F_e = average value of the initial efficiencies of Filter C and D, which is assumed to be the efficiency of Filter E on the basement floor, (%)

$\text{sum} = (q_1)(F_1) = (q_a)(F_a) + (q_b)(F_b) + (q_e)(F_e)$, (cubic ft./min.)

$\text{suma} = \text{adjusted } (q_1)(F_1) = \text{average value of two adjacent sizes, (cubic ft./min.)}$

Table B - 7. Calculated values of the flow rate for infiltration

	0.5 - 0.7 μm		0.7 - 1.0 μm		1.0 - 1.5 μm		1.5 - 2.0 μm		2.0 - 2.5 μm	
	$(q_1)(F_1)$ (cubic ft./min.)	q_2 (ach)	$(q_1)(F_1)$ (cubic ft./min.)	q_2 (ach)	$(q_1)(F_1)$ (cubic ft./min.)	q_2 (ach)	$(q_1)(F_1)$ (cubic ft./min.)	q_2 (ach)	$(q_1)(F_1)$ (cubic ft./min.)	q_2 (ach)
07/20/96	67	0.016826	109	0.033606	224	0.128862	368	0.117847	459	0.068834
07/25/96	67	0.052651	109	0.049104	224	0.107594	368	0.26301	459	0.068521
07/29/96	94	0.125854	111	0.087675	101	0.050004	160	0.048294	161	0.021039
08/02/96	94	-13.3386	111	-3.64488	101	2.886207	160	0.180896	161	0.037176
08/06/96	94	0.101039	111	0.03287	101	0.010148	160	0.016565	161	0.009854
08/10/96	94	0.016879	111	0.008861	101	0.011271	160	0.051382	161	0.02721
08/14/96	66	0.037095	92	0.020328	197	0.040494	290	0.066547	415	0.034104
08/16/96	66	0.093955	92	0.022093	197	0.009101	290	0.04684	415	0.117377
08/19/96	66	0.192419	92	0.051238	197	0.023233	290	0.03919	415	0.075092
08/23/96	66	0.099287	92	0.027742	197	0.012748	290	0.027629	415	0.106437
08/27/96	73	0.087647	134	0.055556	285	0.037306	518	0.04645	677	0.044032
08/30/96	73	0.547293	134	0.158657	285	0.076874	518	0.028684	677	0.023319
*average value	75	0.125	108	0.050	192	0.046	310	0.068	402	0.054

* The data associated with 08/02/96 were excluded from the calculation of the average values

notes:

average infiltration rate of the residence = $(0.125+0.050+0.046+0.068+0.054)/5 = 0.07$ ach

$(q_1)(F_1)$ = values of adjusted $(q_1)(F_1)$ as shown on Table B-6

$q_2 = (C_i/(C_o - C_i))(q_1)(F_1)$, flow rate for infiltration

C_i = indoor particle concentrations (at 6 minutes after the beginning of data collection on each data collection day)

C_o = outdoor particle concentrations (at 6 minutes after the beginning of data collection on each data collection day)

Table B - 8a. Correlation between the percentage reduction in indoor particle concentration and the percentage increase in recirculation flow rate and/or filter efficiency

P % Increase in $(q_1)(F_1)$	0.5 - 0.7 μm		0.7 - 1.0 μm		1.0 - 1.5 μm		1.5 - 2.0 μm		2.0 - 2.5 μm	
	C_i/C_o (%)	reduction in C_i (%)	C_i/C_o (%)	reduction in C_i (%)	C_i/C_o (%)	reduction in C_i (%)	C_i/C_o (%)	reduction in C_i (%)	C_i/C_o (%)	reduction in C_i (%)
0	46.39	0.00	19.40	0.00	11.12	0.00	10.29	0.00	6.56	0.00
10	44.03	5.09	17.95	7.46	10.21	8.16	9.44	8.23	6.00	8.55
20	41.89	9.68	16.71	13.88	9.44	15.09	8.72	15.21	5.52	15.75
30	39.96	13.86	15.62	19.47	8.78	21.05	8.10	21.21	5.12	21.90
40	38.19	17.66	14.67	24.38	8.20	26.23	7.57	26.41	4.77	27.21
50	36.58	21.14	13.83	28.72	7.70	30.77	7.10	30.97	4.47	31.84
60	35.10	24.34	13.08	32.60	7.25	34.78	6.69	34.99	4.20	35.92
70	33.73	27.29	12.40	36.07	6.85	38.35	6.32	38.57	3.96	39.54
80	32.46	30.02	11.79	39.20	6.50	41.56	5.99	41.78	3.75	42.78
90	31.29	32.55	11.24	42.04	6.18	44.44	5.69	44.67	3.56	45.68
100	30.20	34.90	10.74	44.63	5.89	47.06	5.42	47.29	3.39	48.31

notes:

$(q_1)(F_1)$ = average values as shown on Table B-7

q_2 = average values as shown on Table B-7

$C_i/C_o = q_2/((q_1)(F_1)(1 + p) + q_2)$, - ratio of indoor particle concentration and outdoor particle concentration

p = percentage increase

Table B - 8b. Correlation between the percentage increase in indoor particle concentration and the percentage reduction in recirculation flow rate and/or filter efficiency

p % reduction in $(q_1)(F_1)$	0.5 - 0.7 μm		0.7 - 1.0 μm		1.0 - 1.5 μm		1.5 - 2.0 μm		2.0 - 2.5 μm	
	C_i/C_o (%)	Increase in C_i (%)	C_i/C_o (%)	Increase in C_i (%)	C_i/C_o (%)	Increase in C_i (%)	C_i/C_o (%)	Increase in C_i (%)	C_i/C_o (%)	Increase in C_i (%)
0	46.39	0.00	19.40	0.00	11.12	0.00	10.29	0.00	6.56	0.00
10	49.01	5.67	21.10	8.77	12.20	9.76	11.30	9.86	7.23	10.31
20	51.96	12.01	23.13	19.22	13.52	21.62	12.53	21.87	8.06	22.98
30	55.28	19.17	25.58	31.89	15.16	36.36	14.07	36.83	9.11	38.95
40	59.05	27.30	28.63	47.58	17.25	55.16	16.04	55.97	10.47	59.69
50	63.37	36.63	32.49	67.51	20.01	79.99	18.65	81.35	12.30	87.70
60	68.38	47.42	37.57	93.65	23.82	114.26	22.28	116.58	14.92	127.62
70	74.25	60.08	44.51	129.47	29.43	164.67	27.65	168.82	18.95	189.11
80	81.22	75.10	54.61	181.54	38.48	246.07	36.44	254.25	25.97	296.13
90	89.64	93.25	70.65	264.19	55.58	399.81	53.41	419.29	41.23	528.94
100	100.00	115.58	100.00	415.51	100.00	799.33	100.00	872.23	100.00	1425.49

notes:

$(q_1)(F_1)$ = average values as shown on Table B-7

q_2 = average values as shown on Table B-7

$C_i/C_o = q_2 / ((q_1)(F_1)(1 - p) + q_2)$, - ratio of indoor particle concentration and outdoor particle concentration

p = percentage reduction

VITA

Chung-Tung (C. T.) Shen was born in Shanghai, China on October 26, 1943. He grew up and attended schools in Taiwan, where he graduated from Pan-Chow High School in June, 1962. He entered Chung-Yuan University, Taiwan in September, 1962 where in June, 1966 he received the Bachelor of Science in Civil Engineering. After fulfilling his ROTC commitment, he came to the United States and entered the Master's program in Engineering Mechanics at Tennessee Technological University, Cookeville, Tennessee in September, 1968, officially receiving the Master's degree in February, 1970. He joined Tennessee Valley Authority, Knoxville, Tennessee as a civil engineer working in the area of engineering and construction of nuclear plant facilities in March, 1970. As part of the solution to his middle-age crisis, he returned to the University of Tennessee, Knoxville in January of 1992 to pursue the Master's degree in Environmental Engineering while working at Watts Bar Nuclear Power Plant. He left Tennessee Valley Authority and joined the Department of Energy-Oak Ridge Operations Office in December, 1994. The Master degree was received in May, 1997.

He is presently working as an engineer in the Office of Assistant Manager for Environment, Safety, and Quality, at the Department of Energy-Oak Ridge Operations Office.