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ASSESSMENT OF PARTICLE CONTROL TECHNOLOGY FOR ENCLOSED ASBESTOS SOURCES
Phase II

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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ASSESSMENT OF PARTICLE CONTROL TECHNOLOGY FOR ENCLOSED ASBESTOS SOURCES--PHASE II

by

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ABSTRACT

The report gives results of an experimental study to optimize control of emissions of asbestos fibers using a baghouse. Baghouse operating parameters that were studied in a statistically designed experimental plan were: (1) filter fabric, (2) air-to-cloth ratio, (3) dust loading, (4) relative humidity, (5) shaking amplitude, (6) frequency, (7) duration and time between shaking cycles, and (8) bag series configuration. Operating parameters which were found to be statistically significant in causing reductions in asbestos emissions were: (1) bag fabric, (2) waste type, (3) air-to-cloth ratio, (4) relative humidity, (5) period between shakes and shaking duration, and (6) shaking amplitude. The values of these operating parameters that are recommended for industry usage to significantly reduce outlet concentrations of asbestos are: (1) cotton sateen bags, (2) an air-to-cloth ratio of 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2), (3) a combination of period between shakes of 120 min with a shaking duration of 20 sec, and (4) a shaking amplitude of 3.500 cm. These operating conditions resulted in pressure drops across the fabric filter that were quite reasonable ($\leq$2.0 in. H_2O). Thus, the most economical alternatives of cotton sateen bags, high air-to-cloth ratio, and low pressure drop operating conditions were found to be among the most significant in reducing asbestos emissions.

This report was submitted in fulfillment of IITRI Project No. C6291, Contract No. 68-02-1353, by the IIT Research Institute, under the sponsorship of the Environmental Protection Agency. Work was completed as of June 1975.

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IITRI personnel who contributed to the program were: Paul Siebert, who was the principle investigator, and Thomas Ripley, who undertook the statistical design and analysis. Dr. Colin F. Harwood was the Project Leader, while John D. Stockham, Manager of the Fine Particles Research Section, had administrative responsibility. Other IITRI personnel who contributed to the program were Erdman Luebcke, M. Ranade, and Dr. Earl Knutson.

SECTION 1

CONCLUSIONS

For all the fabrics and values of the baghouse operating parameters tested, the mass efficiencies of asbestos collection exceeded 99.99%. However, as noted in the Phase I report, extremely high numbers of small fibers may still be emitted while attaining such high mass efficiencies. Typical outlet concentrations of asbestos fibers on the order of 10^5-10^7 fibers/m^3 (for fibers $\geq$ 1.5 μm) and 10^8-10^9 fibers/m^3 (for fibers $\geq$ 0.06 μm) were found to be emitted.

Operating parameters which were found to be statistically significant in causing reductions in asbestos emissions were: (1) bag fabric, (2) waste type, (3) air-to-cloth ratio, (4) relative humidity, (5) period between shakes and shaking duration, and (6) shaking amplitude. The following conclusions were drawn with regard to the effect of these variables on fiber outlet concentration:

1. Cotton sateen was as efficient or more efficient than all other fabrics tested in reducing emissions in all size ranges of fibers measured.

2. Raw asbestos fibrous waste emits fewer fibers of length $\geq$ 6.0 μm than does asbestos cement waste for equal dust loadings by mass in the air stream.

3. For the air-to-cloth ratios studied (0.46-1.22 $m^3/min/m^2$ or 1.5-4.0 cfm/ft^2), the optimum ratio was 4.0 cfm/ft^2.

4. There is some evidence to indicate that a decrease in relative humidity may reduce the outlet concentration of fibers $\geq$ 6.0 μm.

5. The combination of long period between shakes and short shaking duration produces significantly lower outlet concentrations than does that of short period between shakes and long shaking duration.

6. Higher shaking amplitudes produce lower outlet concentrations.

7. Outlet concentration is not a significant function of stabilization period for periods greater than 24 hours.

8. A bag series system of two baghouses in series is not significantly more efficient than is a single baghouse in a stabilized condition.

9. Recycling the exhaust from a section of stabilizing new bags to a previously stabilized section may drastically reduce the high initial outlet concentrations from a new bag.

The pressure drop across the fabric filter was found to be prohibitively high ($\geq$ 5.0 in. H_2O) in the stable condition in most tests at the low values of shaking amplitude, frequency, and duration of 0.875 cm, 1.0 cps, and 20 sec, respectively. However, it was found that when the high values of either shaking amplitude (3.500 cm) or frequency (5.0 cps) were employed, the resulting pressure drops were quite reasonable ($\leq$ 2.0 in. H_2O). Thus, the most economical alternatives of cotton sateen bags, high air-to-cloth ratio, and low pressure drop operating conditions have been shown to be among the most significant in reducing asbestos emissions.

It should also be noted that the results from the present sampling and analysis methodology for counting asbestos fibers in a gas stream is highly unreliable. Many inconsistencies were found in the data and results; it was only through extensive use of statistical techniques that the relationship between the operating parameters and control efficiency could be established.

SECTION 2

RECOMMENDATIONS

The study has shown that several baghouse operating parameters significantly affect the outlet concentrations from baghouses controlling asbestos emissions. Values of these operating parameters recommended for industry usage are: (1) cotton sateen bags, (2) an air-to-cloth ratio of 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2), (3) a combination of period between shakes in excess of 120 min with a shaking duration of 20 sec, and (4) a shaking amplitude of 3.500 cm.

Further study of all of these parameters in extended ranges and with more intermediate values would be valuable. An understanding of the interactions of the mechanical shaking variables with either the bag fabrics or the air-to-cloth ratio could prove to be very worthwhile. Initial studies of bag fabric, air-to-cloth ratio, relative humidity, and dust loading were made under the assumption that the maximum dust caking conditions of the shaking variables would produce the lowest outlet concentrations. This was shown to be incorrect in the study of the mechanical shaking variables. After establishing the most desirable operating parameters, it would be of great value to perform a field demonstration at an existing industrial installation.

Methods of sample preparation and counting of asbestos fibers should also be statistically studied to improve reliability and repeatability. This would be especially valuable if the smaller fibers are found to be a major health problem. The present method of counting by optical microscopy has been shown to be subject to high variability in the presently regulated size range $\geq$ 5.0 μm and is even less reliable for smaller fibers. Studies to improve analytical methodology are presently being undertaken in the electron microscope range, but not in the range of optical microscopy.

SECTION 3

INTRODUCTION

Asbestos has been shown to be a health hazard and a carcinogen. Control of atmospheric emissions of asbestos has been made mandatory under Section 112 of the Clean Air Act. It is necessary for the Environmental Protection Agency to assess control methodology for these emissions and to establish the best available technology based on optimum operating conditions. It is then possible to introduce legislation and promulgate regulations that will require the application of operating practices capable of protecting the public health. The applicability and effectiveness of these practices must be supported by sound scientific procedures and experimental evidence.

During Phase I of this study, it was shown that current control devices emit very large numbers of small fibers. Diffusion modelling inferred that these fibers travel large distances from the source, and it is suspected that the very small submicron fibers may remain suspended indefinitely. As baghouses were found to be the accepted best method of reducing asbestos emissions, it was decided to conduct an experimental study to optimize baghouse performance for controlling emissions of asbestos fibers.

Baghouse operating parameters were varied to establish optimum operating conditions for minimizing the number of fibers in the outlet. Parameters that were studied in a statistically designed experimental plan were: (1) filter fabric, (2) air-to-cloth ratio, (3) dust loading, (4) relative humidity, (5) shaking amplitude, (6) frequency, and (7) duration and time between shaking cycles. Also included in the original test plan were the alternative option of a cyclone pre-cleaner and double filtration by a series bag arrangement.

The first sets of samples were analyzed by optical and transmission electron microscopy. After these methods were found to be unreliable from the standpoint of reproducibility (especially for fibers in the 1.5-5.0 μm range), additional real time data were taken using the Royco light scattering instrument. The latter method gives outputs that are only suitable for comparison on a total particulate basis. The Royco instrument is calibrated for spherical rather than fibrous particles.

SECTION 4

DEVELOPMENT OF EXPERIMENTAL PLAN

Fabric filtration operating parameters were first studied in the literature and by contacts with the asbestos industry to determine the parameters most likely to have a major influence on efficiency and the operating conditions most commonly in use. The complete literature search on control methods and compilation of control equipment user's data in the asbestos industry was reported in the Phase I report (EPA-650/2-24-74-088). In this report, the operating parameters of fabric filtration were listed and evaluated on the basis of the literature to determine those variables which would be most worthy of experimental study from both a technical and economic standpoint.

Table 1 contains the list of control options. The major discussion of each option is given in the following sections.

OPTIONS BEFORE THE BAGHOUSE

It has been shown by Timbrell[2] that asbestos fibers can be aligned by the use of an electrostatic field. This presents the possibility of aligning asbestos fibers so that they would all strike the fabric filter broadside, and thus their high aspect ratio could always be utilized to increase efficiency. However, due to the experimental nature of this development and the high efficiencies (> 99%) reported by industry for the baghouses presently in use, this option was not studied.

Table 1. COMPLETE LIST OF CONTROL OPTIONS FOR BAGHOUSE

A. Options Before the Baghouse

1. Alignment of fibers by the use of electromagnetic fields.
2. Alteration of the state of agglomeration by:
   a. the use of ultrasonics
   b. aerodynamic changes
3. Changing the fibers' surface properties by altering the relative humidity of the system.
4. Optimize the air stream in terms of:
   a. temperature
   b. flow rate
   c. flow rate fluctuations
5. Optimize the dust loading in terms of:
   a. fluctuations
   b. total dust loading
6. Use of secondary pre-cleaner to remove major fraction.
   a. cyclone
   b. scrubber
   c. impinger device (e.g., Pentapure)

B. Options Within the Baghouse

1. Bag construction factors:
   a. fabric weave
   b. fabric denier
   c. type of thread (staple or filament)
   d. type of fiber
   e. thread count
   f. fabric texture
   g. physical properties (e.g., tensile strength, wear rate, electrostatic charging)
   h. quality control in manufacture
   i. pre-treatment of the fabric
   j. bag seams (stitched or bonded)
2. Improve baghouse design:
   a. optimize physical arrangement of bags
   b. optimize bag dimensions
   c. install baffles to evenly distribute the air flow
   d. optimize air-to-cloth ratio
   e. compare bag cleaning methods
   f. study mechanical shaking in terms of frequency, amplitude, time cycle
   g. the use of dual bags

C. Options After the Baghouse

1. Use of a second baghouse.
2. Use of an electrostatic precipitator.
3. Develop a method to recycle exhaust from newly cleaned bags through a caked bag.

Electrostatic charging of both the filter fabric and the particles being collected was discussed by Strauss[3]. It has the effect of increasing particle agglomeration; however, dust cake release may be hindered depending on the type of filter fabric, humidity, and conductivity of the particles.

Another method of altering the state of agglomeration of particles before collection is by the use of ultrasonics. Strauss[3] discusses the use of sonic agglomeration as a primary collection device. It achieved reasonable efficiencies for sulphuric acid mist (96-99.5%), carbon black (82%), zinc oxide fumes (78%), and lead oxide fumes (95-98%). No attempts of using sonic agglomeration for collection of a fibrous material such as asbestos were reported. It is, therefore, conceivable to use sonic agglomeration as a precleaner; however, high cost compared to a cyclone would make it uneconomical. Installation costs were reported as 15% less than an equivalent electrostatic precipitator. Operation and maintenance costs are high, and high efficiency muffling devices are required, which puts this option out of the range of practicality.

The state of agglomeration can also be altered by aerodynamic changes before the primary collector. The most common means of increasing agglomeration is by inducing a state of turbulence. However, high turbulence already exists both in the ductwork before the fabric filter, and within the filter itself. This option, therefore, is inherently included and very elaborate, and long ducting systems would be necessary to bring about any significant improvement in the state of agglomeration.

The effect of relative humidity on fabric filter performance was studied by Durham and Harrington[4]. The relative humidity was controlled between 20 and 60 percent. Using 4.0 μm median diameter fly ash as a test dust, 11 different fabrics were evaluated. Details of the fabrics are given in Table 2. The results obtained for the variation in outlet concentration and efficiency are shown in Table 3. It can be seen that cotton is by far the most efficient fabric tested having a mass collection efficiency of greater than 99.99% for all humidities tested. Humidity can be seen to have a marked effect on the continuous filament fabrics, that is, all except cotton. It is conjectured that the fibrous projections on spun cotton yarn are responsible for the high mass collection efficiency at all humidities. The efficiency for cotton bags is so high that the effect of humidity was beyond the sensitivity of the experiment to detect. However, it is reasonable to suppose that with increased experimental sensitivity, an increase in collection efficiency with increase in humidity would be observed with cotton bags.

An interesting finding of Durham and Harrington was that, while humidity had a marked effect on the collection efficiency using fly ash as the test dust, there was no apparent effect when using cement dust, pulverized limestone, or amorphous silica.

It can be seen from the above that humidity has the capability of drastically modifying collection efficiencies. Therefore, it was decided to include humidity as an important variable. Experiments were done using asbestos dust to establish the effect of humidity on collection efficiency as a function of size.

The air stream may be optimized with respect to temperature. Resistance to high temperatures is one of the primary considerations in the choice of filter fabric. However, in most asbestos processing applications, high temperature is not a problem. In conjunction with the relative humidity, the temperature affects the adhesion of particles as reported

Table 2. TEST FABRIC CHARACTERISTICS

Fiber Composition*	Type Yarn**		Yarn Dernier		Thread Count, threads/in.		Weave Pattern	Fabric Thickness, Mils	Fabric Weight oz/yd^{2}
	Warp	Fill	Warp	Fill	Warp	Fill			
Nylon	CF	CF	210	210	74	68	2 x 2 Twill	9.4	4.1
Creslan^{R}	CF	CF	200	200	80	76	3 x 1 Twill	10.8	4.0
Dacron^{R}	CF	CF	250	250	76	66	3 x 1 Twill	9.1	3.9
Polypropylene	CF	CF	210	210	81	69	3 x 1 Twill	12.4	4.6
Crylon^{R}	CF	CF	200	200	77	63	3 x 1 Twill	10.2	5.1
Dralon^{R}	CF	CF	200	200	76	71	3 x 1 Twill	9.8	4.4
Orlon^{R}	CF	CF	200	200	76	62	3 x 1 Twill	8.7	4.3
Cotton sateen	S	S			95	58	Satin	24.1	10
Glass filament	CF	CF			54	56	3 x 1 Twill	9.6	9
Glass combination	CF	S			48	22	2 x 2 Twill	24.6	16.5
Glass texturized	CF	T			46	24	3 x 1 Twill	16.5	14

* Creslan^{R} acrylic, Amer. Cyanamid; Dacron^{R} polyester, DuPont; Crylon^{R} acrylic, Crylon S.A.(Fr); Dralon^{R}, Farberfabriken Bayer (W.Ger.); Orlon^{R} acrylic, DuPont.

** CF = continuous filament; S = staple; T = texturized.

Table 3. EFFECT OF RELATIVE HUMIDITY ON OUTLET DUST CONCENTRATION AND EFFICIENCY

Bag Description	Outlet Dust Concentration, grains/1000 ft^3					Efficiency, weight %				
	Relative Humidity, %					Relative Humidity, %				
	20	30	40	50	60	20	30	40	50	60
Nylon	130	148	61	4.4	0.02	95.62	95.02	98.02	99.86	99.99+
Creslan[R]	168	177	100	37	3.1	94.47	94.02	96.35	98.78	99.90
Dacron[R]	34	32	13.1	1.9	0.7	98.86	98.95	99.12	99.94	99.98
Polypropylene	36	32	35	7.0	2.7	98.80	98.96	98.85	99.78	99.91
Crylor[R]	148	89	56	13	1.3	95.12	97.29	98.14	99.56	99.96
Dralon[R]	26	24	17	0.8	0.6	99.11	99.23	99.43	99.98	99.99+
Orlon[R]	12	7.5	6.9	3.9	0.8	99.59	99.75	99.78	99.87	99.97
Cotton	0.04	0.2	0.0	0.0	0.0	99.99+	99.99+	99.99+	99.99+	99.99+
Filament glass	148.1	135.9	106.4	25.4	9.1	95.00	95.31	96.55	99.18	99.71
Combination glass	10.4	10.3	2.2	0.1	0.1	99.65	99.66	99.92	99.99+	99.99+
Texturized glass	63.8	40.2	19.9	6.0	1.1	97.84	98.66	99.31	99.80	99.96

Note: Inlet dust concentration C_i = 3.0 gr/ft^3, fly ash, 4.0 μm median diameter.

by Werle[5]. These two parameters affect the agglomeration characteristics of particles and their adherence to the fabric. Therefore, as relative humidity was varied over a wide range, temperature was only varied over a limited ambient range that simulated anticipated environmental conditions within asbestos plants.

The gas flow rate was varied in order to optimize the air-to-cloth ratio for the fixed filter area that will be used. In order to vary the air-to-cloth ratio from 0.46 to 1.22 $m^3/min/m^2$ (1.5-4.0 cfm/ft^2), the gas flow rate was varied from 0.655-1.740 m^3/min (23.1-61.5 cfm) for two bags. This variation in flow rate affects the velocity at the face of the filter. The major collection mechanisms are diffusion to the fabric filter at low velocity and inertial impaction and interception at high velocity. Therefore, the flow rate variations in effect test the relative effectiveness of these collection mechanisms.

Asbestos processing rarely results in a constant flow rate through the filter. As the filter cake builds up, the pressure drop increases until the bags are cleaned, then the flow rate decreases again in a regular cycle. Stafford and Ettinger[6] reported that, as the filter becomes loaded, the efficiency increases for velocities less than 20 fpm; but for velocities greater than 100 fpm, the efficiency initially increases and later decreases. These efficiency fluctuations occur in the periods between each cleaning cycle and were studied.

Industrial plants operate under a wide range of dust loadings at the filter. Therefore, the experimental apparatus was made to be capable of varying the dust loading from 10 to 45 g/m^3 (4.4-19.7 gr/ft^3) over the entire range of air-to-cloth ratios in order to simulate the mid-range of actual conditions. Stenhouse[7] reported that, as dust load increases, the efficiency gradually: (1) decreases for particle diameters of 40 to 45 μm, (2) peaks at about 0.7 g for particles of 10 to 15 μm, and (3) peaks at about 7.0 g for particles of 0.0 to 5.0 μm. Therefore, this variation of efficiency with total dust load was investigated for a fabric filter collecting asbestos.

In Phase I of the program, the user's survey showed that cyclone-baghouse and scrubber-baghouse combinations are used by only 4.4% and 1.1%, respectively, of the plants questioned. The cyclone-baghouse combination, which is the most prevalent type of combination used, was to be investigated. The cyclone is used as a pre-cleaner and removes the major fraction of particles greater than 20 μm in effective diameter, so that the baghouse is not loaded as quickly with large fibers. However, when it was found during testing that increased dust loadings marginally increased the collection efficiency, this option was suspended.

Wet processes such as scrubbers and impinger devices are more often used as primary collection devices rather than as pre-cleaners for baghouses. Some wet collectors are being successfully used to remove asbestos particles above 5 μm; however, an EPA study[8] found the Pentapure to be very inefficient for sub-micron particles from a gray iron foundry. For systems such as these, it is generally difficult to follow them with a fabric filter after cleaner because the high moisture content following the wet collector would cause blinding of the fabric filter.

OPTIONS WITHIN THE BAGHOUSE

The effect of weave on filtering efficiency was studied by Draemel[9] in a single compartment test baghouse using a fly ash test dust having a mass median diameter of 3.7 μm at an inlet concentration of 6.86 g/m^3 (3.0 gr/ft^3). Fabrics tested were of Dacron with a 76 x 63 thread count made with both continuous filament and staple yarns in six different weaves. Results are shown in Table 4. For both types of yarn, the 3 x 2 twill was the most efficient (> 99.9% and 95.3%).

Fiber denier is a means of expressing fiber weight by expressing the weight in grams of 9,000 m of fiber. Generally, smaller fibers produce higher efficiencies and lower pressure drops.

The type of thread used is either staple or filament. Dick[10] stated that natural fibers are generally used in a staple (spun) form, while synthetics are used as filaments or artificial staple form (by spinning short or chopped filaments). In the study by Draemel mentioned above, the relative efficiencies of filament and staple Dacron was studied. The filament yarn group showed higher efficiencies (98-99%) than did the staple yarn due to the smaller free areas in the filament weaves.

Many types of fibers are commercially available in the form of filter bags. Natural fibers such as cotton and wool, and synthetics such as Dacron polyester, nylon, and Nomex nylon are most commonly used for asbestos. The type of fiber determines the temperature, abrasion, and chemical resistance of the bag as were reported for the most common fabrics in the Phase I report.

Thread count is determined by the number of threads in the warp (lengthwise) and fill (widthwise) directions. Increasing the thread count decreases the pore size or free area, and hence improves the efficiency of the fabric. Spaite and Walsh[11] have shown that a small change in the thread count can have a significant effect on the fabric's efficiency.

Fabric texture is dependent on the finish of the fabric. Fabrics may be napped to expose more surface area for

Table 4. EFFICIENCIES FOR CLOTHS OF DIFFERENT WEAVES

Weave	Yarn Type	Free Area	Outlet Concentrations		Weight Efficiencies
			$g/10^3m^3$	$(gr/10^3ft^3)$	%
3 x 1 Twill	Filament	0.001	112.00	(49.10)	98.36
3 x 2 Twill	"	0.0	4.80	(2.10)	99.93
2 x 2 Twill	"	0.0	8.67	(3.79)	99.87
Plain	"	0.002	8.44	(3.69)	99.88
Satin	"	0.0	15.80	(6.89)	99.77
Crowfoot	"	0.0	6.66	(2.91)	99.90
3 x 1 Twill	Staple	0.139	805.00	(352.00)	88.27
3 x 2 Twill	"	0.130	323.00	(141.00)	95.30
2 x 2 Twill	"	0.172	760.00	(332.00)	88.93
Plain	"	0.139	428.00	(187.00)	93.77
Satin	"	0.155	977.00	(427.00)	85.77
Crowfoot	"	0.169	444.00	(194.00)	93.53

Note: All fabrics have 76 x 63 thread count.
Filament yarns are 250/50 warp and fill Dacron.
Staple yarns are 250 equivalent denier warp and fill Dacron.

collection, therefore increasing efficiency. Napped fabrics are harder to clean, but Dick states that they are useful for light dust loads at low pressure drops, and high air-to-cloth ratios. The physical properties of the bag are determined by the fabric used. The tensile strength should be at least 9.0-17.9 kg/cm (50-100 lbs/in.) for abrasion resistance and dimensional stability[9]. Dimensional stability may be a problem with synthetics, some of which may either stretch with weight or shrink at high temperature, thus changing fabric porosity and permeability. Wear rate is largely dependent on the abrasion resistance. Abrasion causes either yarn failure (surface abrasion) or intrayarn (fiber to fiber) abrasion. Generally, filament fibers are more resistant than the staple form. The permeability or resistance of the fabric is generally determined by the fiber and the weave. Pressure is equal to permeability times linear velocity by Darcy's Law. Other physical and chemical properties of the fabric determine its applicability; however, for use on asbestos bearing dusts, these are generally not of concern.

A bag manufacturer's quality control and method of construction can be important. Both the reliability and special features of the bag can be influenced by quality control. This variable cannot be easily studied or quantified.

Fabric pre-treatment is discussed by Billings and Wilder[12]. Since asbestos floats are usually used for this pre-treatment, the benefits of pre-treatment are inherently achieved in asbestos collection. The bridging of the fabric pores by asbestos fibers does increase efficiency.

Bag seams may be either stitched or bonded. Stitched bags have the disadvantage of an uneven velocity distribution across the seam which may cause unequal filtration. Therefore, the seam length should be minimized. Bonded seams are less of a problem but should still be minimized.

It was decided to select six bag fabrics for the actual study, subject to the statistical experimental design. Three each of natural and synthetic fabrics were chosen. In each case, the weave chosen was that most likely to be the most efficient rather than the most economical, subject to the fabrics' commercial availability.

Physical arrangement of the bags is usually determined by maintenance considerations. Bags or envelopes are arranged to facilitate inspection and replacement. As only one or twc bags, or several bags in series, were used in this project within the small experimental baghouse available at IITRI, the rearrangement of bags to improve performance was beyond the scope of this project.

Bag dimensions and shape may also be optimized to improve efficiency. Some manufacturers use tube shaped bags while others use envelopes. Dimensions also vary with the manufacturer within the general limit of a length to diameter ratio of 30:1. For the particular baghouse used in this project, only one size and shape of bag can be used. Therefore, the bag was a tubular one of 12.7 cm D x 178.0 cm L (5 in. D x 70 in. L).

Installation of baffles to evenly distribute air flow and to cause initial inertial separation is sometimes utilized in industry. As the authors used a two bag Y-shaped entry system with an evenly distributed dust loading from the dust feeder, this option was not necessary.

Air-to-cloth ratio was tested within the experimental ranges of 0.46-1.22 $m^3/min/m^2$ (1.5-4.0 cfm/ft^2) for mechanical shaking. The typical range of air-to-cloth ratios for asbestos was found to be less than 0.92 $m^3/min/m^2$ (3.0 cfm/ft^2) in Phase I and 0.77-0.92 $m^3/min/m^2$ (2.5-3.0 cfm/ft^2) by Strauss. Rozovsky[13] stated that the preferable ratio was 0.61-0.74 $m^3/min/m^2$ (2.0-2.5 cfm/ft^2), while the economical ratio was 0.92 $m^3/min/m^2$ (3.0 cfm/ft^2). Therefore, it was supposed that the optimum air-to-cloth ratio would fall within the range to be experimentally tested.

There are many bag cleaning methods commercially available including mechanical shakers, reverse air, and pulse jet. These three methods are the most commonly used methods; however, the pulse jet method requires special equipment which is not available on a small scale. It was initially intended that a reverse air mechanism using a traversing blow ring would be used; however, this was found to be commercially unavailable in the size required and infeasible to construct. Mechanical shaking is the most common method used in the asbestos industry and was studied.

During the cleaning cycle, bags are taken out of line, shaken, and then put back into line. Goldfield[14], working with asbestos as a test dust, reported that a photometer placed on the outlet of the baghouse indicated a marked surge in the dust concentration after the bags had been shaken. He reported a period of two to three minutes before steady state exit concentrations were achieved.

Goldfield[14] and Dennis[15] noted that different materials gave characteristic effluent dust concentration vs. time curves. Synthetic cloths gave higher peaks and took longer to reach a low value. This is thought to be due to the better cake release and lower adherence characteristics of synthetics. The study by Goldfield was lacking in quantitative data. However, it did indicate the necessity to study this cycle in emissions in relation to the total emission for the options of recycling and pre-caking of the filters.

The effect of varying the shake rate and duration on the minimum filter drag was studied by Billings and Wilder[12]. Minimum drag decreases with increasing shake duration, thus decreasing the pressure drop and increasing the filter velocity. This temporarily decreases filter efficiency which increases again as the filter cake builds up. This increase continues until the next shaking cycle is initiated.

For this study, the variables of shake amplitude, frequency, duration, and interval of the mechanical shaker were to be investigated to as great a degree as determined by the statistical design of the experiments.

Dual bags are used by some manufacturers. These bags consist of two fabric filters, one within the other. This type of dual bag was not readily available for the size of baghouse to be used; therefore, this option was not investigated.

OPTIONS AFTER THE BAGHOUSE

Use of a second baghouse in series with the first has not, to our knowledge, been investigated previously for economic reasons. The efficiency of one baghouse has generally been deemed sufficient without further cleaning of the gas stream. However, this option, which is similar in effect to that of the dual bag, was investigated. This option was feasible because of the small scale of the laboratory experiment. Two bags, or two sets of two bags, can be connected in series with the same overall effect as having two baghouses in series.

A high cost option would be to place an electrostatic precipitator in series after the baghouse. The purpose would be to collect the very fine submicron particles not collected by the baghouse. This option is especially attractive in that electrostatic precipitators are more effective if subjected to a light dust loading. Another possibility would be to precede the baghouse with an electrostatic precipitator so that the fabric filter could take advantage of the electrostatic charging of the uncollected fibers. This option was not investigated during this program due to economic limitations.

Efficiency of a newly cleaned filter bag is greatly decreased until the filter cake rebuilds. This is the basis of the concept of pre-caking a filter before use. Generally in industry, one section is cleaned as a unit and then put back on line at lowered efficiency. This practice tends to keep the efficiency of the entire collector somewhat uniform, but not at its optimum. This option could be studied with the same apparatus and testing as needed for the two baghouses in series option. Therefore, the authors investigated the improved performance expected by recycling the exhaust from a bag in which the filter cake was rebuilding.

Thus, the following reduced list of options (see Table 5) affecting baghouse performance was actually investigated. The initial experiment design was based on this reduced list of options. Limitations imposed by theoretical, apparatus, operational, and time considerations necessitated considerable modification to this initial design as experiments progressed.

Ranges of the values of the variables were chosen in accordance with the literature and the industrial user's survey as stated above. After consultation with the EPA[16], several ranges were adjusted, i.e., the range of the shaking variables was modified to increase the probability of dust cake build-up. Other variable's values were modified slightly because of design considerations. The number of levels for each variable was limited to three by the statistical design in order to limit the tests in the experimental test plan to a reasonable number. Upper and lower values were chosen for each variable, and then the middle value was determined by the average of the logarithms of the extreme values. Levels of the variables actually tested are given in Table 6.

Table 5. REDUCED LIST OF OPTIONS FOR BAGHOUSE

A. Options Before the Baghouse

1. Changing the fibers surface properties by altering the relative humidity of the system.
2. Optimize the air stream in terms of:
    a. flow rate
    b. flow rate fluctuations
3. Optimize the dust loading in terms of:
    a. fluctuations
    b. total dust load
4. Use of cyclone to remove major fraction.

B. Options Within the Baghouse

1. Bag construction factors:
    a. fabric weave
    b. fabric denier
    c. type of thread (staple or filament)
    d. type of fiber
    e. thread count
    f. fabric texture
    g. physical properties (e.g., tensile strength, wear rate)
2. Improve baghouse design:
    a. optimize air-to-cloth ratio
    b. study mechanical shaking in terms of amplitude, rate, duration, and frequency.

C. Options After the Baghouse

1. Use of a second baghouse.
2. Develop a method to recycle exhaust from newly cleaned bags through a caked bag.

Table 6. FINAL LIST OF OPTIONS FOR BAGHOUSE

A. Options Before the Baghouse

1. Type of waste collected:
   - a. asbestos cement processing
   - b. raw fiber asbestos
2. Relative humidity:
   - a. 20% (modified to 30% or ambient in Phase II)
   - b. 40%
   - c. 80% (modified to 60% in Phase II)
3. Optimize total dust loading.
   - a. 10 g/m^3
   - b. 21 g/m^3
   - c. 45 g/m^3
4. Use of cyclone to remove major fraction (found unprofitable in Phase II).
   - a. cyclone
   - b. without cyclone

B. Options Within the Baghouse

1. Bag construction.
   - a. cotton sateen, 96 x 60 thread count, 9.7 oz/yd^2
   - b. napped cotton, 98 x 60 thread count, 8.7 oz/yd^2
   - c. cotton twill, 73 x 60 thread count, 7.4 oz/yd^2
   - d. Dacron twill, 75 x 71 thread count, 5.8 oz/yd^2
   - e. Dacron twill, 64 x 51 thread count, 8.5 oz/yd^2
   - f. Nomex twill, 95 x 60 thread count, 5.2 oz/yd^2
2. Improve baghouse design:
   - a. optimize air-to-cloth ratio (dependent on flow rate for constant filter area, i.e., number of bags)
     - (1) 0.46 $m^3/min/m^2$ (1.5 cfm/ft^2)
     - (2) 0.76 $m^3/min/m^2$ (2.5 cfm/ft^2)
     - (3) 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2)
   - b. study mechanical shaking
     - (1) amplitude
       - (a) 0.875 cm
       - (b) 1.750 cm
       - (c) 3.500 cm
     - (2) frequency
       - (a) 1.0 cps
       - (b) 2.2 cps
       - (c) 5.0 cps
     - (3) duration
       - (a) 20 sec
       - (b) 40 sec
       - (c) 80 sec
     - (4) time between shake cycles
       - (a) 16.0 min
       - (b) 42.0 min
       - (c) 120.0 min
3. Bag series:
   - a. in series
   - b. not in series

The Phase I experimental design was modified insofar as testing order so that all tests with the same filter fabric and waste type could be made in order of increasing humidity. Thus, the stabilized set of bags would be moved as little as possible in order to maximize dust cake retention. Due to feeding problems with the raw asbestos fiber waste, only two fabrics were tested using this waste material. Raw asbestos fiber waste is representative of the asbestos milling process and asbestos fabric industry. Installations which perform these processes are very few in number compared to the number of facilities generating asbestos cement waste.

As no further testing was conducted with the fibrous waste, the number of tests in Phase II was also greatly reduced. Due to time limitations and the wide scatter of data up to that point, the studies of the second fabric, Nomex, were not conducted in Phase II. Loss of this data is not a major problem in that, because of expense, Nomex is used only on high temperature gas streams. High temperatures are not typical of asbestos industry.

After Phase II of the test program, a critique and reevaluation of the test program was undertaken. This was decided upon in consultation with the EPA[16], due to the fact that the counting error and other factors contributing to error were, up to that time, of the same order of magnitude as the differences between the results of different tests. Therefore, it was decided to delay all further testing and electron microscope work until these problems were considered more fully. The critique and reevaluation were carried out with the cooperation of Mr. Richard Gerber of Aerospace Corp.

Feasibility of alternate sampling and sizing methods were considered for application to fibers. Those considered were: (1) optical microscope, (2) electron microscope, (3) Royco and other light scattering techniques, (4) Anderson impactor and other inertial techniques, (5) mobility analyzer, and (6) techniques using the Condensation Nuclei Counter (CNC) including the diffusion battery. It was decided to optically count all fibers, but to analyze only those greater than 5 or 6 μm in length as they are most clearly viewed and measured, thus producing the least statistical error. Experiments with increased sampling time were also to be conducted to determine the effect on data reliability. Electron microscope counting was suspended until statistical questions could be resolved. Royco total number of particle concentrations for equivalent diameters would be recorded in as many size ranges as possible. The Royco traces would only be suitable for comparison, as total particles are measured for an equivalent diameter dependent on fiber orientation. It was also decided to employ intermittant sampling with the CNC as an additional corroborating tool.

The possible program alternatives, from total cancellation or suspension of the program to drastic modification of the test series, were considered. It was decided to use new bags for each test and to stabilize them until both the pressure drop and the Royco traces were constant. Only cotton sateen bags would be tested at an air-to-cloth ratio of 0.92 $m^3/min/m^2$ (3.0:1 cfm/ft^2), the highest ratio in common use and as near to 1.22 $m^3/min/m^2$ (4.0:1 cfm/ft^2) as could be sustained for extended stabilization. The dust loading would be 45 g/m^3 (19.7 gr/ft^3) and the humidity at ambient levels, in accordance with the statistical analysis of Phase III. However, the dust loading was later reduced to 21 g/m^3 (9.2 gr/ft^3) to enable continuous 24 hour operation for increased stabilization.

In order to allow time for the increased stabilization of new bags for each test, Phase III testing was reduced to a total of eight tests. Extreme conditions of the shaking variables were to be tested in a search for order of magnitude changes in outlet concentrations. It was decided to conduct four tests at both the lowest dust caking conditions (16 min cycle with 80 sec duration) and the highest dust caking conditions (120 min cycle with 20 sec duration). The four tests were of the 0.875 and 3.500 cm (0.344 and 1.378 in.) shake amplitudes with both 1 and 5 cps shake frequencies. If order of magnitude or statistically significant differences in outlet concentration were detected in this modified Phase III plan, then a Phase IV test would be run. This would consist of one stabilization and testing series on the double filtration system using the optimized system as the primary filter and a pre-stabilized bag as the secondary filter. If significant differences were not detected, the remainder of the program was to be devoted to improving sampling and sizing techniques. The cyclone pre-cleaner option was suspended due to time limitations and the fact that Phase II analysis showed a correlation between increased dust loading and decreased outlet concentration.

SECTION 5

EXPERIMENTAL APPARATUS

The baghouse used for the project was a No. 1 Model 70-BC Assembled Intermittent Wheelabrator Dustube Dust Collector manufactured by Wheelabrator-Frye, Corp. This baghouse has a capacity of twelve filter bags. The bags are of a nominal size of 12.7 cm D x 178.0 cm L (5 in. D x 70 in. L). For most tests, only two filter bags were used at a time. For this arrangement, a special Y-shaped inlet adaptor with two conical hoppers was constructed and installed. The purpose of the adaptor is to maintain similar flow conditions in the inlet plenum as would exist for all twelve bags. The remaining holes for bags were closed with gasketing, sealant, and metal plates to ensure no flow through them.

The manual shaker mechanism was adapted to automatic mechanical operation. A 1/4 hp, 3,450 rpm motor with a variable transmission producing 0-675 rpm was mounted on the rear of the baghouse. The motor drive was then connected to the shaking lever by a cam with three eccentric positions producing shaking amplitudes of 0.875, 1.750, and 3.500 cm (0.344, 0.689, and 1.378 in.). The transmission was calibrated by stroboscope with nearly linear results to the values given in Table 7. The desired shaking frequencies of 1, 2.2, and 5 cps are equivalent to settings 1, 3, and 8.

An automatic timing system based on a 4-pole, 16-min adjustable cammed timer and a single-pole or 120-min adjustable cammed timer was constructed. A fused 220 V AC line

Table 7. SHAKER ASSEMBLY MOTOR CALIBRATION

Gear Setting	Motor Speed (rpm)
1	58*
2	93*
3	132
4	150
5	192
6	230
7	266
8	306
9	344
10	380
11	417
12	453
13	490
14	524
15	558
16	590
17	621
18	655
19	685
20	700

* Extrapolated

was used to power the timers, as well as the timer switches and relays used to control the power supply to various 110 V outlets (see Figure 1, Schematic of Automatic Timer System). The timer system is set for a specific shaking duration (preceded and followed by one minute of settling) and time between shakes, and controls the operation of the main blower, an optional auxiliary blower, the dust feeder, sampler, shaker, and pressure transducer and chart.

Filter fabrics chosen for experimental study included three cottons, two Dacrons, and one Nomex. Cotton is the most commonly used fabric for asbestos control in industry and has been found by Dennis[15] to have dramatically lower outlet concentrations over a 30 min cycle than does Dacron for fly ash. The three cotton fabrics chosen were a sateen (the most commonly used), a napped fabric (more efficient in some applications), and the only twill commercially available. Draemel's[9] work indicated that, for fly ash, a 3 x 1 or 3 x 2 twill with as high a thread count as possible would be the most efficient. Dacron fabrics were chosen as they are the second most commonly used fabric in the asbestos industry. Nomex is the most common fabric for high temperature asbestos applications. The filter fabrics and their characteristics are given in Table 8.

The original dust feeder used was an IITRI-built screw feeder modified with a more powerful variable speed motor capable of breaking large pieces (∿3 cm [1.18 in.]) of asbestos cement. However, it was found that this feeder would jam after periods longer than 30 min. Vibra-Screw, Inc. then graciously offered to lend a SCR-20 feeder for the duration of the project. This feeder maintains a constant, linearly variable feed rate over the required range of 5-60 g/min (2.2-26.2 gr/ft^3) using asbestos cement waste sifted through a No. 4 mesh. The calibration curve of the

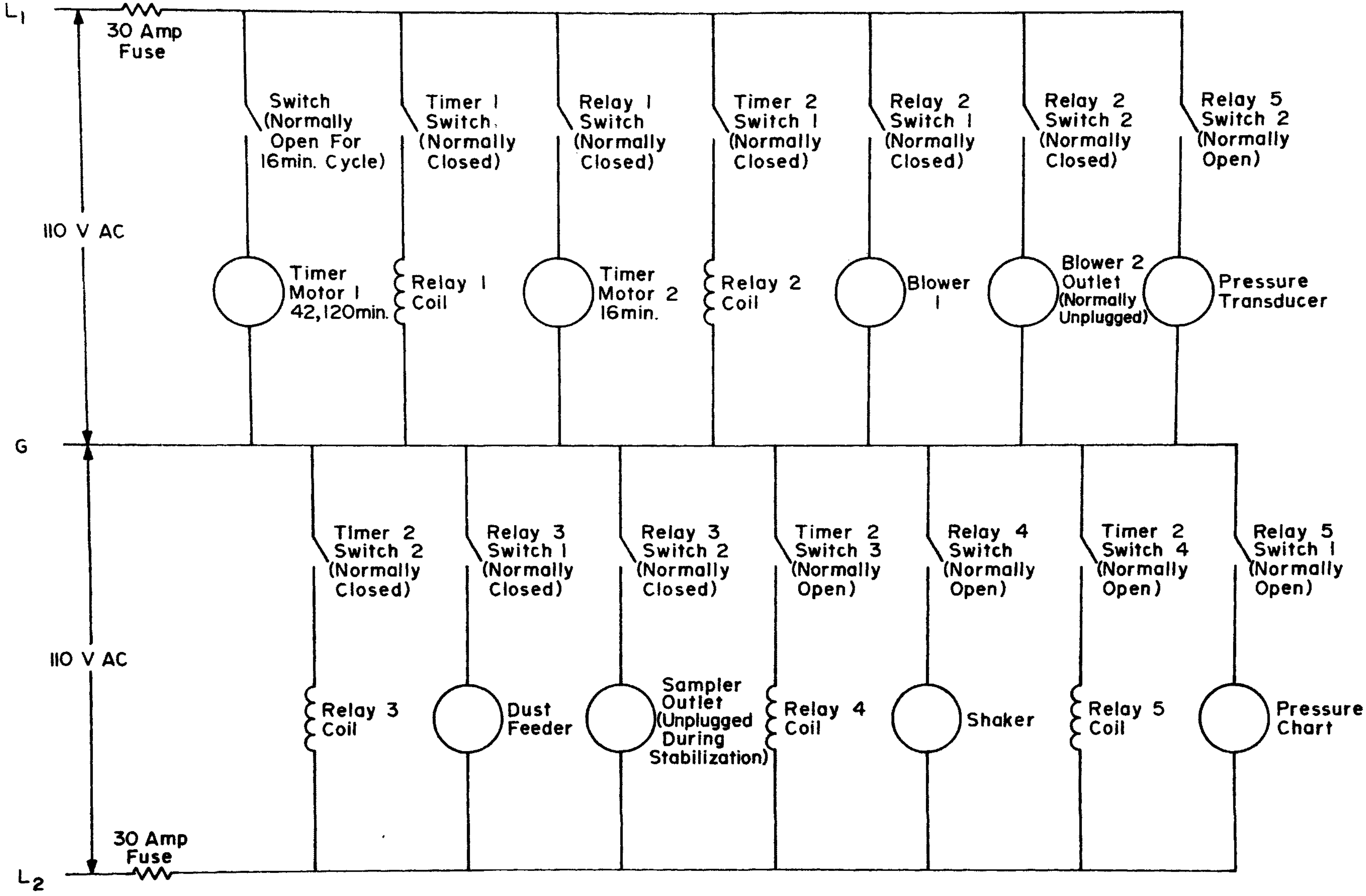

Figure 1. Schematic of automatic timer system

was used to power the timers, as well as the timer switches and relays used to control the power supply to various 110 V outlets (see Figure 1, Schematic of Automatic Timer System). The timer system is set for a specific shaking duration (preceded and followed by one minute of settling) and time between shakes, and controls the operation of the main blower, an optional auxiliary blower, the dust feeder, sampler, shaker, and pressure transducer and chart.

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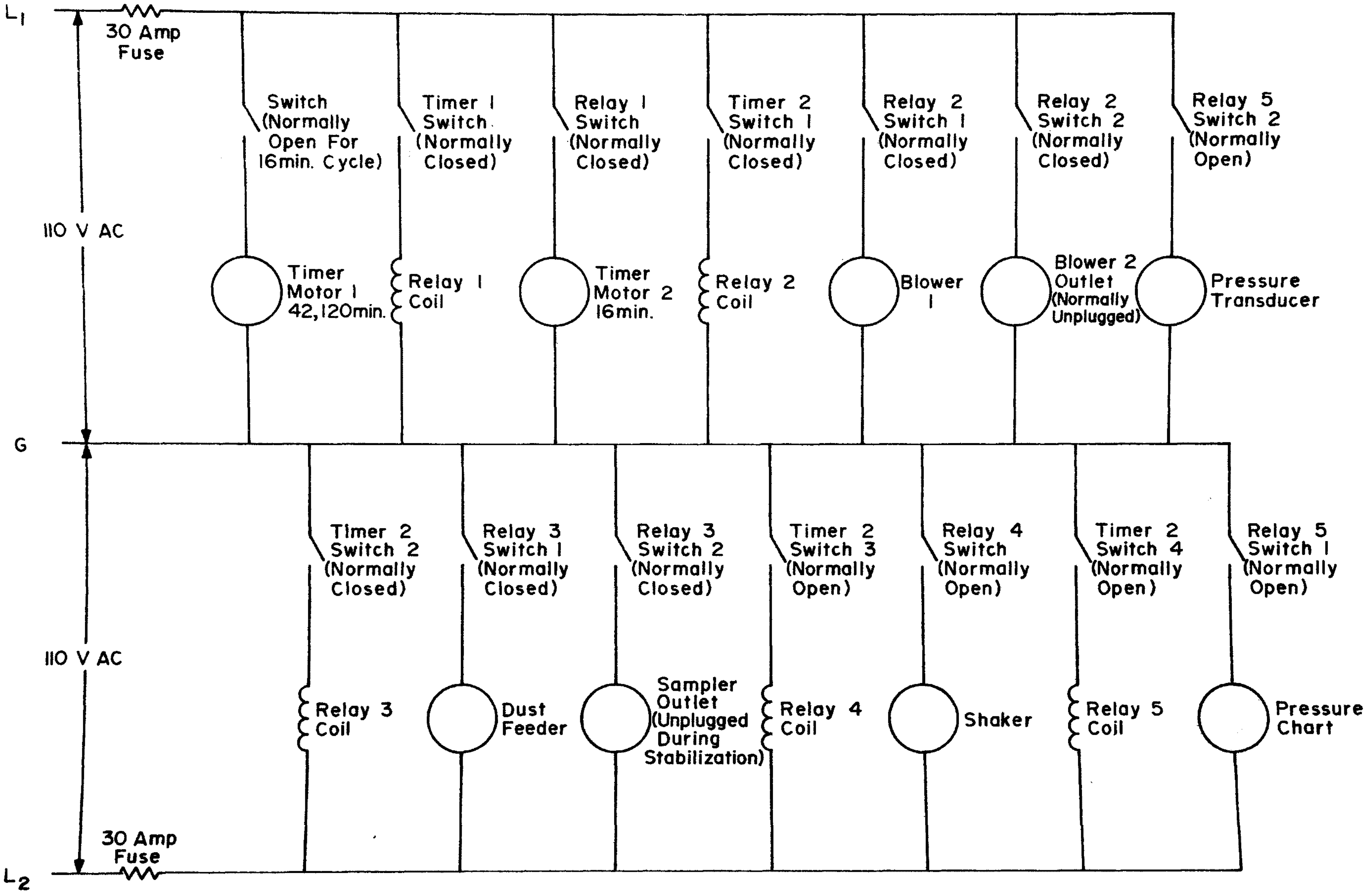

Figure 1. Schematic of automatic timer system

Table 8. FILTER BAG CHARACTERISTICS*

	#101-00	#101-10	#102-00	#736-50	#757-52	#340-50
Fabric	Cotton	Cotton	Cotton	Dacron	Dacron	Nomex
Warp Yarns	Spun	Spun	Spun	Filament	Spun	Filament
Fill Yarns	Spun	Spun	Spun	Spun	Spun	Spun
Thread Count	96 x 60	98 x 60	73 x 60	75 x 71	64 x 51	95 x 60
Weight	9.7	8.7	7.4	5.8	8.5	5.2
Permeability (cfm/ft^2 @ 1/2 in. H_2O)	15-20	10-15	14.5	15-25	30-40	20-35
Finish	Woven Sateen	Desized & Napped	Woven Twill	Woven Twill	Woven Twill	Woven Twill
Weave	4 x 1	4 x 1	2 x 1	3 x 1	2 x 2	2 x 1
Price per Bag	$2.85	$3.60	$3.95	$3.65	$3.60	$8.30

* All filter bags 12.7 cm D x 178.0 cm L (5 in. D x 70 in. L) and supplied by W.W. Criswell Co., Division Wheelabrator-Frye Inc.

Vibra-Screw SCR-20 feeder is given in Figure 2. The dust feeder hopper has a capacity of 56.6 ℓ (2 ft^3), allowing unattended operation at low feed rates for long periods.

It was discovered that the raw asbestos fiber could not be fed through the IITRI screw feeder or the Vibra-Screw SCR-20 dust feeder. This material has a very low bulk density of 0.117 g/cc (7.28 lb/ft^3). This low bulk density results in its tendency to mat and form a composite structure which gives it extremely bad flow properties. Even with the vibrations applied by the SCR-20, the raw fiber would not feed evenly into the screw feeder. Therefore, a manually fed, steeply inclined vibrating trough feeder had to be used to feed the fibrous asbestos. This method was not nearly as accurate as the SCR-20 for asbestos cement waste, but supplied average mass concentrations over a shaking cycle of adequate accuracy and repeatability to test for major differences in efficiency caused by waste type.

A velocity of 300 m/min (∿1,000 fpm) must be maintained in order to keep the asbestos cement waste suspended in the inlet duct. Velocities as high as 1,200 m/min (4,000 fpm) are commonly used in industry. (This is only necessary to keep non-sifted waste suspended.) To accomplish suspension for the lowest air-to-cloth ratio of 0.46 $m^3/min/m^2$ (1.5 cfm/ft^2), an inlet duct of ∿5 cm diameter (2 in. schedule 40) PVC pipe was used on the inlet and at least two bags were used simultaneously. The inlet ducting was made as straight as possible to minimize frictional losses in the pipe. The downstream ducting was made of four inch diameter stove pipe to reduce friction loss. A 745.7 w (1 hp), 3,450 rpm centrifugal blower was used as the primary suction fan. This blower, equipped with a sliding damper to control the flow, was capable of maintaining the system

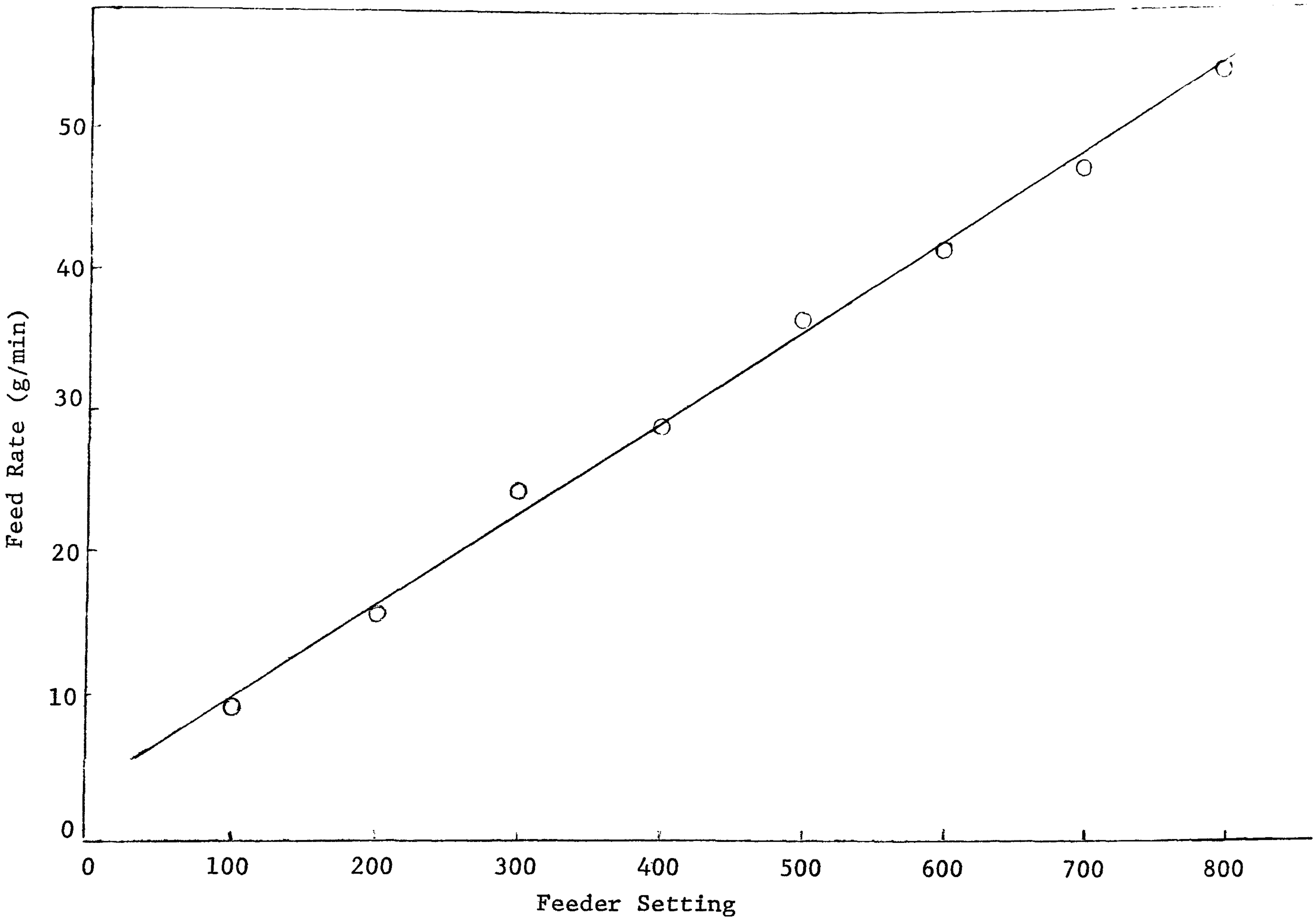

Figure 2. Calibration curve of Vibra-Screw SCR-20 dust feeder for asbestos cement waste using 1/2 in. screw

at an air-to-cloth ratio of 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2) at moderate pressure drops ($\leq$ 7.6 cm H_2O [3.0 in. H_2O]) across the filter bag. An auxiliary Tornado 447.4 w (3/5 hp) blower was attached to the inlet of the air stream in order to achieve and maintain the flow necessary to stabilize six bags at an air-to-cloth ratio of 0.76 $m^3/min/m^2$ (2.5 cfm/ft^2). This stabilization method for treating two bags of each of three fabrics simultaneously was used during Phase I of the experimental plan. Velocity measurements were made by pitot tube in both the inlet and outlet ducts.

The relative humidity was raised by injecting steam into the inlet flow. When the steam was added after the asbestos waste, a moist slurry was formed which blocked the duct at the 80% RH level. The injection point was then changed to before the dust addition. The 20% RH level was often below ambient conditions, so for the second experimental phase, the relative humidity levels were changed from 20, 40, and 80% to 30, 40, and 60%. Wet and dry bulb thermometers were used to measure relative humidity. When located in the inlet duct after the addition of cement waste and steam, agglomerated moist dust was impacted on the bulbs of the thermometers making the readings inaccurate representations of gas flow conditions. Therefore, the wet and dry bulb thermometers were moved to the clean side of the baghouse.

The pressure drop across the fabric filter is measured by a 0-25 mm Hg (0-1 in. Hg) differential pressure transducer. The transducer output is recorded on a Leeds and Northrup Speedomax G variable input chart recorder. Due to the high chart speed ($\sim$2.5 cm/min [$\sim$1 in./min]) and the desire to conserve chart paper, only the pressure drop at the beginning and end of each filtering cycle is measured and recorded. The period recorded extends from approximately one minute before the pre-shake settling period to approximately one and one-half minutes after the recommencement of filtering after the post-shake settling period.

Particulate sampling was conducted by isokinetic sampling onto a filter and by Royco light scattering. Isokinetic sampling was done using a modified EPA Method 5 sampling train consisting of a short ($\leq$ 38.1 cm [$\leq$ 15 in. including nozzle]) probe and S-type pitot tube with the filter holder connected directly to the sampling meter box. The isokinetic sampling port was a 3 x 1-1/2 in. port in the vertical outlet section at the EPA required distances (eight diameters downstream and five diameters upstream) from changes of direction. The filter used was a Millipore (MF) filter of 0.8 μm pore size. A Royco Model 245 particle counter with Module 510 display was used to measure total particles in concentrations less than or equal to 10^5 particles/ft^3 in the overall size range of 0.3-5.0 μm and in sub-ranges of 0.3-0.6, 0.6-1.5, 1.5-3.0, and 3.0-5.0 μm. A 1-100:1 porous tube diluter (see Figure 3) was constructed and installed so that the smaller size ranges could be used without going off-scale for the instrument. The 0-1 milliamp output for the various size sub-ranges was then attached to a LSE Model M24 4-channel chart recorder for Phases III and IV testing. A schematic of the major features of the experimental baghouse apparatus is shown in Figure 4.

A separate, non-shaking, two bag baghouse was designed and constructed of 1.9 cm (3/4 in.) plywood (see Figure 5) for the Phase IV bag series system. This second baghouse was installed in the bag series configuration using collapsible ∿10.2 cm (4 in.) D ducting for the connections and a section of ∿10.2 cm (4 in.) D stove pipe for a sampling section. The operating conditions chosen for the first, shakeable baghouse were the optimum conditions from Phases I, II, and III. Two new bags were installed in the first

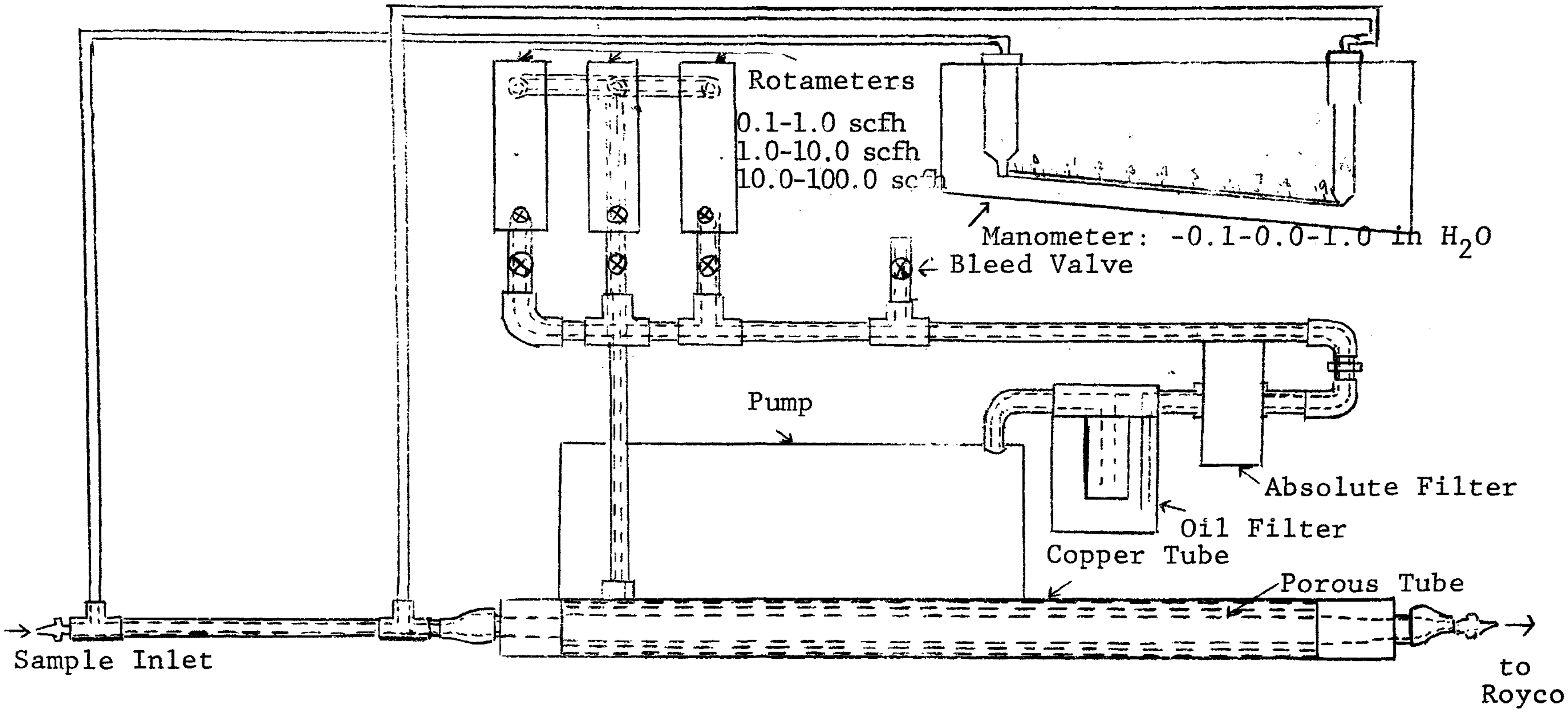

Figure 3. Porous tube diluter

Scale: 1/4" = 1"

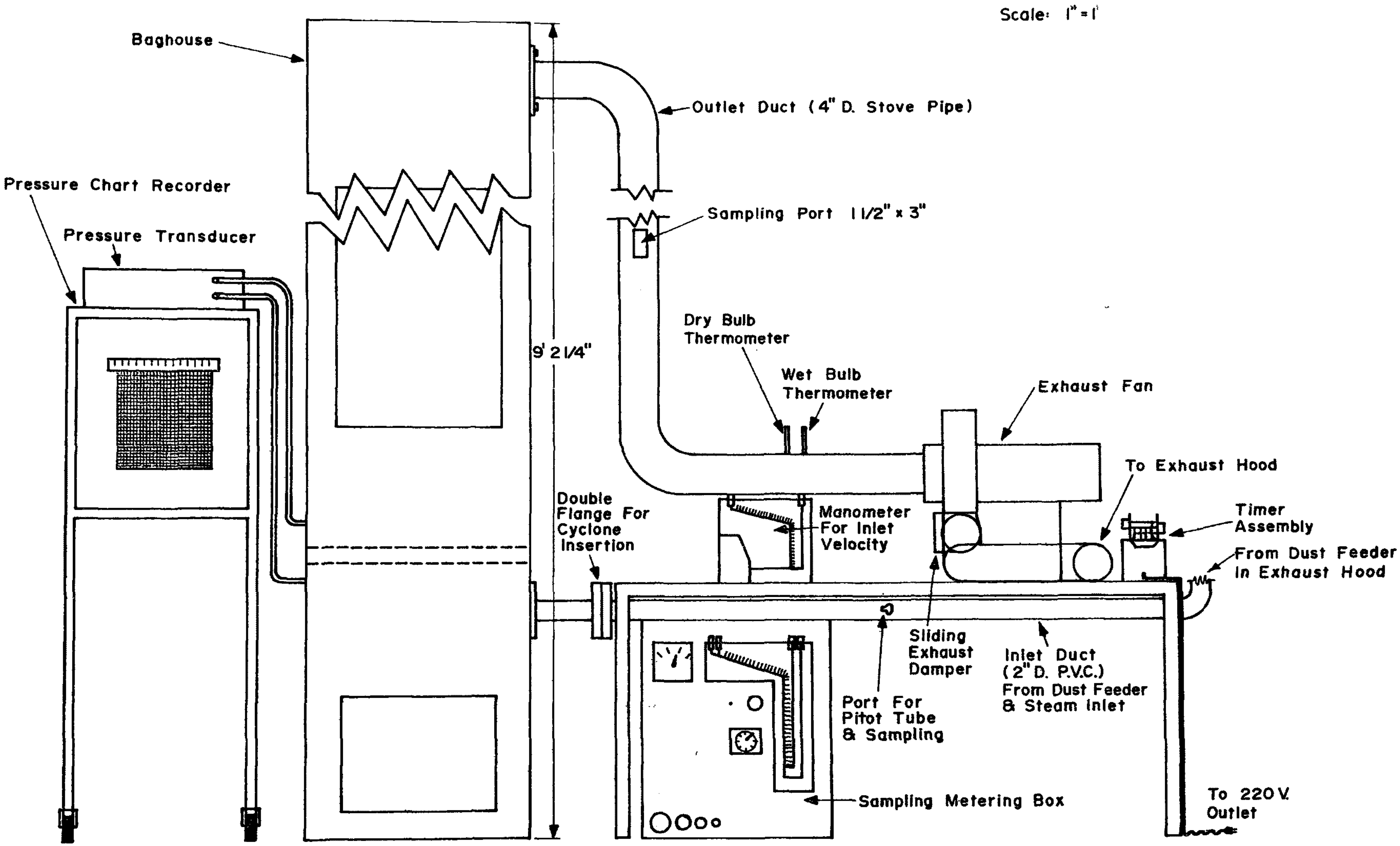

Figure 4. Baghouse testing apparatus

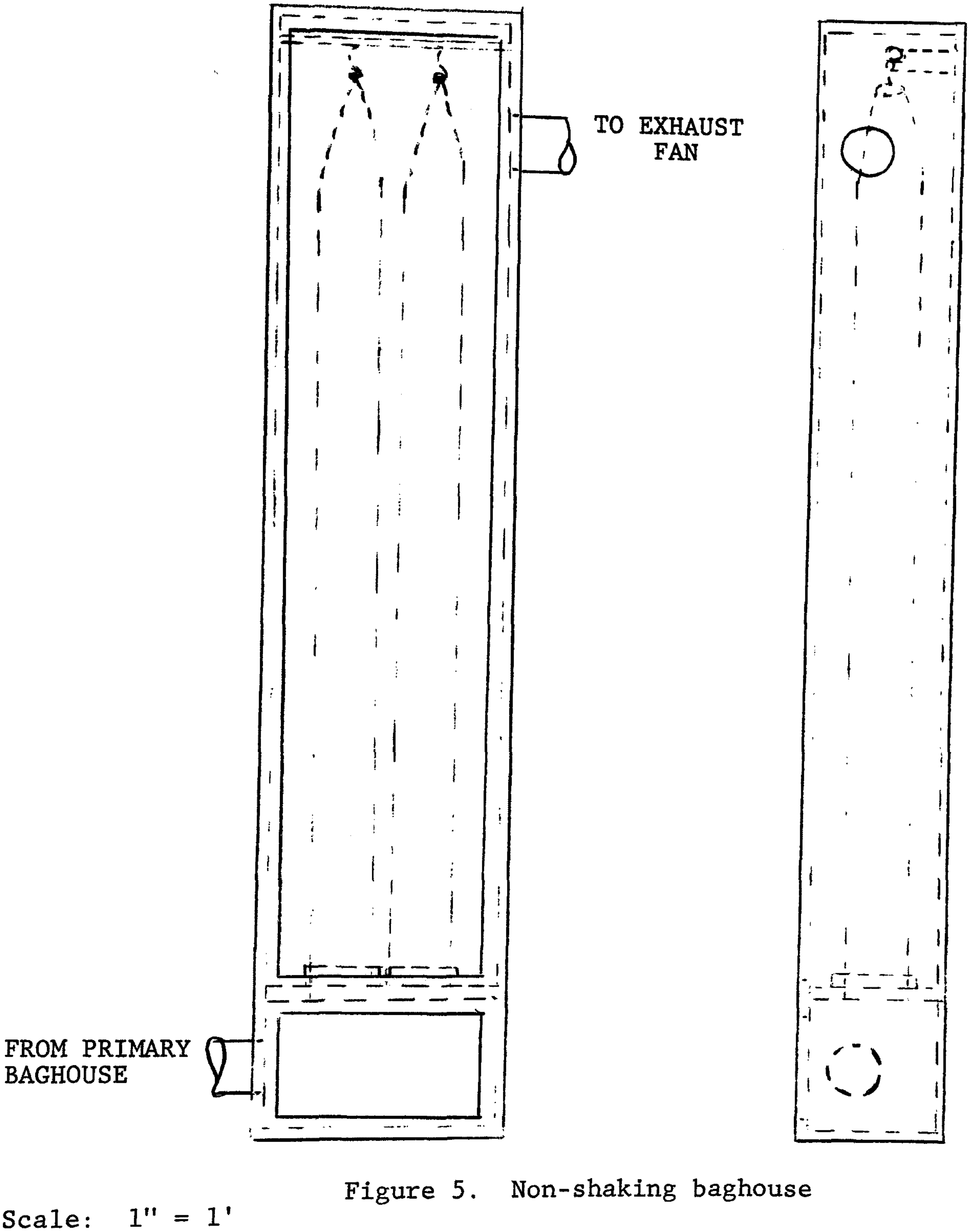

Figure 5. Non-shaking baghouse

Scale: 1" = 1'

baghouse, while those previously stabilized in Phase III (minus the dust shaken loose during moving and installation) were installed in the second (non-shakeable) baghouse. Pressure taps connected to a U-tube manometer were installed in the second baghouse to measure pressure drop across the fabric.

SECTION 6

EXPERIMENTAL PROCEDURE

SAMPLE ANALYSIS TECHNIQUES

Optical Microscope Counts

The optical microscope slides were prepared and counted by the procedures of the Joint AIHA-AGCIH Aerosol Hazards Evaluation Committee[17]. Slides were prepared using the recommended counting medium on a one-to-one by volume solution of dimethyl phthalate and diethyl oxylate with 50 mg of membrane filter material added per milliliter of solution. Fibers greater than or equal to 1.5 μm in length were counted and sized using phase contrast at 400-500X magnification.

Full field counts were continued until at least 100 fibers were viewed. The minimum number of fields viewed was 20, unless at least 1,000 fibers greater than 1.5 μm and 100 fibers greater than 5.0 μm or 6.0 μm were viewed in fewer fields. The data reported are in terms of fibers of length ≥ 1.5 μm or ≥ 5.0 or 6.0 μm; however, the larger numbers of fibers in the smaller size ranges dominate the concentration values for the smaller ranges. The exact counting magnification and technique varied somewhat from one experimental phase to the next so that the results of several phases are not exactly comparable. The highest repeatability and thus reliability of results was achieved in the last two phases. A minimum of duplicate counts of the same filter were made in Phases II to IV.

Electron Microscope Counts

The Phase I electron microscope grids of samples were prepared and counted in the following manner. The electron microscope grids were prepared by punching out a 3.05 mm diameter portion from near the center of the sample and placing it on a carbon coated 200 mesh grid. The grid with the sample was then placed in a slow acetone wash to dissolve the membrane filter. Six grids from three samples were processed simultaneously. Fibers were then sized and counted using the electron microscope at a nominal (photograph) magnification of 33,000X. This is equivalent to a magnification of 26,400X at the viewing screen. The fibers greater than 0.06 μm on each grid were counted and sized until 100 fibers were viewed in at least 20 fields or until 100 fields were viewed (unless there were fewer than 100 viewable fields).

Calculation of Outlet Concentrations

The number concentrations of fibers per cubic meter for each size range ($\geq$ 0.6 μm, $\geq$ 1.5 μm, and $\geq$ 5.0 or 6.0 μm) were calculated by the following equation

$$\frac{\text{no. of fibers}}{\text{m}^3 \text{ of air}} = \frac{\text{no. of fibers counted}}{\text{no. of fields viewed}} \cdot \frac{\text{effective filter area}}{\text{area of each field viewed}} \cdot \frac{1}{\text{sampled volume}}$$

The effective filter area for the filter holder used is 7.39×10^{-3} m^2 (11.46 in.^{2}); the field area was 5.72×10^{-8} m^2 (8.86×10^{-5} in.^{2}) for Phases I and II; 10.18×10^{-8} m^2 (1.58×10^{-4} in.^{2}) for Phases III and IV for the optical microscope; and 10.57×10^{-12} m^2 (1.64×10^{-8} in.^{2}) for Phase I for the electron microscope.

PHASE I TESTING

The Phase I experimental plan tested the operating parameters of fabric, relative humidity, and waste type at a constant air-to-cloth ratio, dust loading, and shaking cycle. The air-to-cloth ratio and dust loading chosen were the median values of 0.76 $m^3/min/m^2$ (2.5 cfm/ft^2) and 21 g/m^3 (9.2 gr/ft^3), respectively. After discussions with the EPA[16], the maximum dust cake retention values of the shaking variables of amplitude (0.875 cm [0.344 in.]), frequency (1 cps), and duration (20 sec) were used. These values were used in the hope of maximizing collection efficiency by maximizing dust cake. The 16 minute shake cycle was chosen to maximize the number of shake cycles in a given time period. A one minute settling period was used before and after each shake.

Stabilization of two bags each of three fabrics was conducted simultaneously at ambient humidity. The bags were stabilized for a minimum of eight hours or until the trace of pressure drop across the fabric was consistently repeated. Each set of two bags was then restabilized under the same conditions for four cycles to replace the filter cake that was loosened or partially removed during the moving of the bags for storage and reinstallation. Sampling of the emissions from the baghouse was then conducted for an additional four cycles. This restabilization and sampling process was then conducted for the 40% and 80% relative humidity levels in the order of increasing humidity. The entire series for the six fabrics at ambient, 40%, and 80% relative humidity was done for the asbestos cement waste using the IITRI screw feeder. Analytical results are presented in Table 9. Ambient humidity levels were sometimes above the desired 20% on any given day and were sometimes as high as 40%. At the 80% humidity level, saturation of the fabric occurs as some of the moisture condenses on the

Table 9. PHASE I RESULTS FOR ASBESTOS CEMENT WASTE*

Test Sample Number	Filter Fabric	Humidity Range (% R.H.)	Sampled Volume (ft^3)	Outlet Concentration (No. of fibers/m^3) > 0.06 μm	> 1.50 μm	> 6.00 μm
1	Cotton Sateen 96 x 60 9.7 oz/yd^2	20-30	13.92	2.15×10^8	1.18×10^6	0.95×10^6
2		15-25	11.31	5.57×10^8	1.12×10^6	0.97×10^6
3		35-45	10.00	13.62×10^8	2.28×10^6	1.74×10^6
4		75-85**	10.09	3.49×10^8	3.31×10^6	1.72×10^6
5	Napped Cotton 98 x 60 8.7 oz/yd^2	30-40	12.87	0.37×10^8	5.40×10^6	2.70×10^6
6		35-45	8.02	13.88×10^8	9.06×10^6	3.10×10^6
7		65-75	7.72	3.99×10^8	8.14×10^6	3.28×10^6
8		75-85**	4.43	4.45×10^8	14.35×10^6	6.27×10^6
9	Nomex 95 x 60 5.2 oz/yd^2	30-40	10.46	1.35×10^8	8.71×10^6	3.02×10^6
10		35-45	4.64	1.06×10^8	19.43×10^6	5.10×10^6
11		75-85**	7.04	7.51×10^8	15.56×10^6	6.04×10^6
12	Dacron 75 x 71 5.8 $oz.yd^2$	25-35	5.64	9.77×10^8	20.60×10^6	4.36×10^6
13		35-45	2.63	31.67×10^8	10.83×10^6	3.12×10^6
14		75-85**	14.43	4.34×10^8	3.02×10^6	1.09×10^6
15	Cotton Twill 73 x 60 7.4 oz/yd^2	20-40	6.46	28.64×10^8	4.83×10^6	1.48×10^6
16		35-45	11.90	2.75×10^8	3.24×10^6	0.99×10^6
17		75-85**	7.96	9.36×10^8	4.67×10^6	1.29×10^6
18	Dacron 64 x 51 8.5 oz/yd^2	30-45	6.20	28.36×10^8	5.95×10^6	1.47×10^6
19		35-45	5.00	10.75×10^8	53.76×10^6	3.28×10^6
20		75-85**	6.52	13.05×10^8	3.77×10^6	0.73×10^6

* All tests at air:cloth ratio of ∿2.5:1 (cfm/ft^2), dust loading ∿22 g/m^3.

** At high humidity, plugging of inlet at dust feeder inlet occurs due to supersaturation.

clean side of the baghouse. Under these conditions, the pressure drop builds to a value much higher than for the lower humidity levels, due to either blockage of the fabric or increased dust cake. The dust cake then falls when it becomes too saturated to be supported. This causes an abrupt decrease in filtering efficiency.

Due to the physical and flow characteristics of raw asbestos fibrous waste, the manually fed vibrating trough feeder had to be used for the second part of Phase I. Therefore, only two fabrics were tested with the fibrous asbestos waste, cotton sateen, and Dacron #1, manufactured of filament by spun fibers. Each set of two bags was stabilized separately for a minimum of eight hours at ambient humidity and then was restabilized and tested as before at each humidity level in increasing order. When the bags were removed, it was found that the dust cake bridged across the entire bag. The results of the electron and optical microscope analyses are given in Table 10. Because of feeding difficulties and the fact that raw fibrous asbestos is used in fewer industrial applications, raw fibrous waste was not studied in the following phases.

It can be seen from Tables 9 and 10 that cotton sateen and cotton twill fabrics are the most efficient of the natural, low temperature fabrics. Because of its economy, availability, performance, and wide usage, cotton sateen was chosen for further study. For high temperature applications, Nomex was to be studied in Phase II because of its performance relative to the other synthetic, high temperature fabrics -- especially in the electron microscope size range.

Obvious trends between relative humidity, fabric type, and humidity are nearly indeterminable from the data. Thus, the accuracy of sampling and analysis and of the values of

Table 10. PHASE I RESULTS FOR FIBROUS ASBESTOS WASTE*

Test Sample Number	Filter Fabric	Humidity Range (% R.H.)	Sampled Volume (ft^3)	Outlet Concentration (No. of fibers/m^3)		
				≥ 0.06 µm	≥ 1.50 µm	≥ 6.00 µm
1	Cotton Sateen	20-30	7.61	4.86×10^8	3.68×10^6	1.05×10^6
2	96 x 60	35-45	7.32	5.06×10^8	4.14×10^6	1.06×10^6
3	9.7 oz/yd^2	40-80**	6.40	1.50×10^8	4.13×10^6	1.14×10^6
4	Dacron (fxs)	25-35	7.19	7.00×10^8	3.68×10^6	0.89×10^6
5	75 x 71	35-45	7.28	4.24×10^8	3.10×10^6	0.77×10^6
6	5.8 oz/yd^2	75-80**	6.16	5.27×10^8	5.62×10^6	1.26×10^6

* All tests at air:cloth ratio of ∿2.5:1 (cfm/ft^2) and dust loading ∿22 g/m^3.

** At high humidity ranges, blockage of inlet occurs (not as severe as with cement waste).

the experimental variables was questioned. As counting error appeared to be the largest source of error due to inherent problems in the procedure, it was decided to attempt to refine the optical microscope technique and to suspend the electron microscope analysis.

PHASE II TESTING

Phase II tested the effects of relative humidity, air-to-cloth ratio, and dust loading for the two fabrics of cotton sateen and Nomex, chosen for low and high temperature applications from Phase I. Relative humidity was kept at levels of 30, 40, and 60% with the usual accuracy of $\pm$ 5%. The air-to-cloth ratio was to be fixed at the values of 0.46, 0.76, and 1.22 $m^3/min/m^2$ (1.5, 2.5, and 4.0 cfm/ft^2); however, as pressure drop across the fabric rose to over 12.7 cm H_2O (5 in. H_2O), the air-to-cloth ratio of 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2) could not be maintained. Dust loadings were 10, 21, or 45 g/m^3 (4.4, 9.2, or 19.7 gr/ft^3) for the desired air-to-cloth ratios. A prestabilized set of bags from Phase I was used with restabilization for four 16 minute cycles before each test. A one-half fractional experimental design of 27 combinations for cotton sateen and Nomex for cement waste was planned. The tests for both fabrics were to be conducted in random order of the combinations to be tested; however, the cotton sateen series was performed first with internal random order.

The Phase II optical microscope analysis was begun immediately after the completion of testing for the cotton sateen series. This was done to insure that any inaccuracies in sample counting encountered in Phase I would not be continued into the Nomex series. The data and results for the cotton sateen series are presented in Table 11. The initial series of optical counts resulted in a high variability ($\pm$ 50%) in the data for the replicate tests

Table 11. DATA AND RESULTS FOR COTTON SATEEN, PHASE II

Sample Number	Relative Humidity (%)	Air:Cloth Ratio (cfm/ft^2)	Dust Loading (g/m^3)	Sampled Volume (ft^3)	Number of Fibers in 20 fields[1] @ 400X ≥ 1.5 µm		≥ 6.0 µm		Number of Fibers/cc ≥ 1.5 µm		≥ 6.0 µm	
					#1	#2	#1	#2	#1	#2	#1	#2
1	55-65	1.5:1	45	4.768	350	375	74	98	16.722	17.916	3.536	4.682
2	35-45	1.5:1	21	4.278	508	362	80	40	27.051	19.276	4.260	2.130
3	35-45	1.5:1	21	4.284	365	463	44	68	19.409	24.620	2.340	3.616
4	35-45	1.5:1	10	3.937	232	509	59	67	13.424	29.451	3.414	3.877
5	55-65	2.1:1	45	3.537	360	543	83	107	23.186	34.972	5.346	6.891
6	25-35	1.5:1	45	6.298	391	628	67	105	14.143	22.715	2.423	3.798
7	25-35	3.92:1[2]	10	8.927	427	524	57	76	10.896	13.372	1.454	1.939
8	35-45	3.92:1[2]	21	9.590	307	755	41	64	7.292	17.934	1.211	1.520
9	35-45	3.23:1[2]	55.7[4]	8.155	466	577	22	95	13.017	16.118	0.614	2.654
10	25-35	2.5:1	21	5.552	178	767	31	118	7.303	31.470	1.272	4.842
11	55-65	2.95:1[2]	28.5[5]	9.937	550	964	73	84	12.608	22.099	1.674	3.021
12	35-45	2.5:1	45	6.333	481	932	74	78	17.302	33.521	2.662	2.806
13	55-65	1.5:1	10	4.685	482	1029	77	70	23.436	50.033	3.744	3.404
14	55-65	2.95:1[2]	13.6[6]	7.100	470	1073	52	67	15.080	34.427	1.668	2.150
15	55-65	2.5:1	21	6.835	638	1358	82	67	21.264	45.260	2.733	2.233
16	25-36	2.5:1	10	5.329	555	1027	102	58	23.725	43.901	4.360	2.479
17	25-35	2.50:1[2]	72.0[4]	9.483	582	1418	61	76	13.981	34.063	1.465	1.826
18	25-35	2.11:1[2]	85.3[4]	8.968	844	1374	83	81	21.439	34.902	2.108	2.058
19	35-45	2.23:1[3]	11.2[6]	5.145	1372	943	114	88	60.747	41.752	5.048	3.896

[1] Field area is equal to 5.723×10^{-8} m^2 (8.86×10^{-5} in.^{2}); effective filter area is 7.386×10^{-3} m^2 (11.46 in.^{2}).

[2] Design of air:cloth ratio = 4.0:1 cfm/ft^2.

[3] Design air:cloth ratio = 2.5:1 cfm/ft^2.

[4] Design dust loading = 45 g/m^3 (19.7 gr/ft^3).

[5] Design dust loading = 21 g/m^3 (9.2 gr/ft^3).

[6] Design dust loading = 10 g/m^3 (4.4 gr ft^3).

(i.e., 2 and 3). Therefore, it was decided to perform duplicate optical counts of the Phase II samples. Also, electron microscope analysis of samples was suspended until the error could be assigned to sampling or analysis. Both sets of data are given in Table 11. The duplicate samples counted were from the same filter sample, but from different wedge shaped segments of the filter. It can be seen that the counting error is quite large, i.e., at least ± 50% in both size ranges and often even greater in the 1.5 μm size range.

Some trends are discernible from the results for cotton sateen bags:

1. The outlet concentration generally decreases with increasing air-to-cloth ratio.
2. No trends of effects on outlet concentration by relative humidity or dust loading are readily apparent.

It should be noted that the OSHA standard of 2 fibers/cc appears to be exceeded in several cases. Due to the high variability in the results for the cotton sateen series, the Nomex series of tests was not performed.

As the concentration data by membrane filter from Phase I samples were suspect, both a Condensation Nuclei Counter (CNC) and a Royco Model 245 light scattering monitor with Module 510 display were tested as outlet concentration sampling methods. The Royco, which has a total range of 0-100,000 particles/ft^3 in sizes 0.3-5.0 μm, was operative the last few tests of the cotton sateen series and showed that definite increases in emissions occurred immediately after cleaning.

PHASE III TESTING

Phase III tests of the mechanical shaking variables investigated the effects of the high dust caking conditions (120 min, 20 sec) and the lowest dust caking conditions

(16 min, 80 sec) of shaking interval and duration. Extreme values of the shaking variables of amplitude (0.875 and 3.500 cm [0.344 and 1.378 in.]) and frequency (1 and 5 cps) were tested at each dust caking condition. All stabilization and testing was conducted at an air-to-cloth ratio of 0.92 $m^3/min/m^2$ (3.0:1 cfm/ft^2), dust loading of 21 g/m^3 (9.2 gr/ft^3), and ambient humidity (40-90%). A new pair of cotton sateen bags were run until the pressure drop and Royco particle count indicated that the cake build-up and emissions had stabilized for each set of conditions. Baghouse operation was 24 hours per day, five days per week.

Optical microscope analysis results are presented in Table 12. Duplicate counts were performed in all cases, and in those in which the variability was high, a third count was made. In most cases, the duplicates were in reasonable agreement. Several changes in sampling and counting technique may have resulted in this improvement in analytical reproducibility of results over those of the previous phases. They are the use of a more accurate dry gas meter, denser fiber loading, counting experience, change in magnification from 400X to 500X, change in cut size from 6.0 µm to 5.0 µm, and use of a tally counter.

Some trends can be observed from the data:

1. The outlet concentrations for the 120 min cycle with 20 sec shake are all lower than those for 16 min cycle with 80 sec shake.

2. The high level of shaking amplitude produces lower outlet concentrations in both cases.

3. The high level of either shaking amplitude or frequency reduces the pressure drop across the fabric.

The Royco traces of total particle concentrations substantiate these observations. The peak in outlet concentration occurs during the shaking and settling period when

Table 12. PHASE III FIBER COUNTS*

Sample Number	Shake Cycle: Interval (min)	Shake Cycle: Duration (sec)	Shake Cycle: Amplitude (cm)	Shake Cycle: Frequency (cps)	Sampled Volume** (ft^3)	No. of Fibers ≥ 1.5 $\mu m/cm^3$ Count No. 1	2	3	No. of Fibers ≥ 5.0 $\mu m/cm^3$ Count No. 1	2	3	Stable Δp (in. H_2O)
1	120	20	0.875	1	286.6	1.1259	3.5993	3.0918	0.3181	1.3189	0.5064	7.5
2	16	80	3.500	5	169.0	5.0280	5.5615	-	1.9670	1.8882	-	0.6
3	16	80	0.875	5	149.6	17.1133	10.0717	7.7378	8.7649	1.9002	1.2269	2.0
4	16	80	3.500	1	170.6	4.6736	6.6152	-	1.7063	1.3160	-	1.5
5	16	80	0.875	1	143.8	8.1092	7.6284	-	2.3924	1.4663	-	2.8
6	120	20	0.875	5	344.0	3.2037	3.0821	-	0.7395	0.5956	-	1.3
7	120	20	3.500	1	362.2	1.4636	2.2320	-	0.2758	0.3370	-	1.3
8	120	20	3.500	5	362.8	2.4165	2.9695	-	0.3365	0.3247	-	1.0

* All runs at 3.0:1 cfm/ft^2 air-to-cloth ratio, 21 g/m^3 dust loading, and ambient humidity (40-90%).

** 120 min. cycles sampled for 1-2 hr cycle, 16 min cycles sampled for 4-16 min cycles.

the concentration is high but the flow is low and when the air flow starts after shaking. During the remainder of the cycle, the outlet concentration remains at a low, stable level. Thus, the two hour cycle has a lower total emission than an equal time period of successive 16 min cycles. Also, the peak in outlet concentration when the blower starts after a 3.500 cm (1.378 in.) shake is visibly lower than after a 0.875 cm (0.344 in.) shake for particles $\geq$ 0.3 μm. Examples of Royco traces for several shaking conditions for particles $\geq$ 1.5 μm are given in Figure 6.

PHASE IV TESTING

Phase IV tested the feasibility and effectiveness of a bag series system. A separate non-shaking, two bag baghouse was installed as the second baghouse in the bag series configuration. The operating conditions chosen for the first shakeable baghouse were the optimum shaking conditions of 120 min cycle, 20 sec, 3.500 cm (1.378 in.), and 1 cps shake from Phase III. Two new bags were installed in the first baghouse, while those previously stabilized in Phase III for the same shaking conditions (minus the dust shaken loose during moving and installation) were installed in the second (non-shakeable) baghouse.

The results of the optical analyses of samples completed after the completion of 24, 70, and 164 hours of operation are given in Table 13. These results show that the outlet concentrations for the bag series system are slightly higher than those for the most efficient single bag systems in Phase III. The mechanism that could be causing this slight increase in outlet concentration which is of marginal statistical significance is that the filtered air from the first bag is freeing dust from the cake of the second bag due to air velocity while not rebuilding the cake by dust loading. Thus, it would appear that two baghouses in series

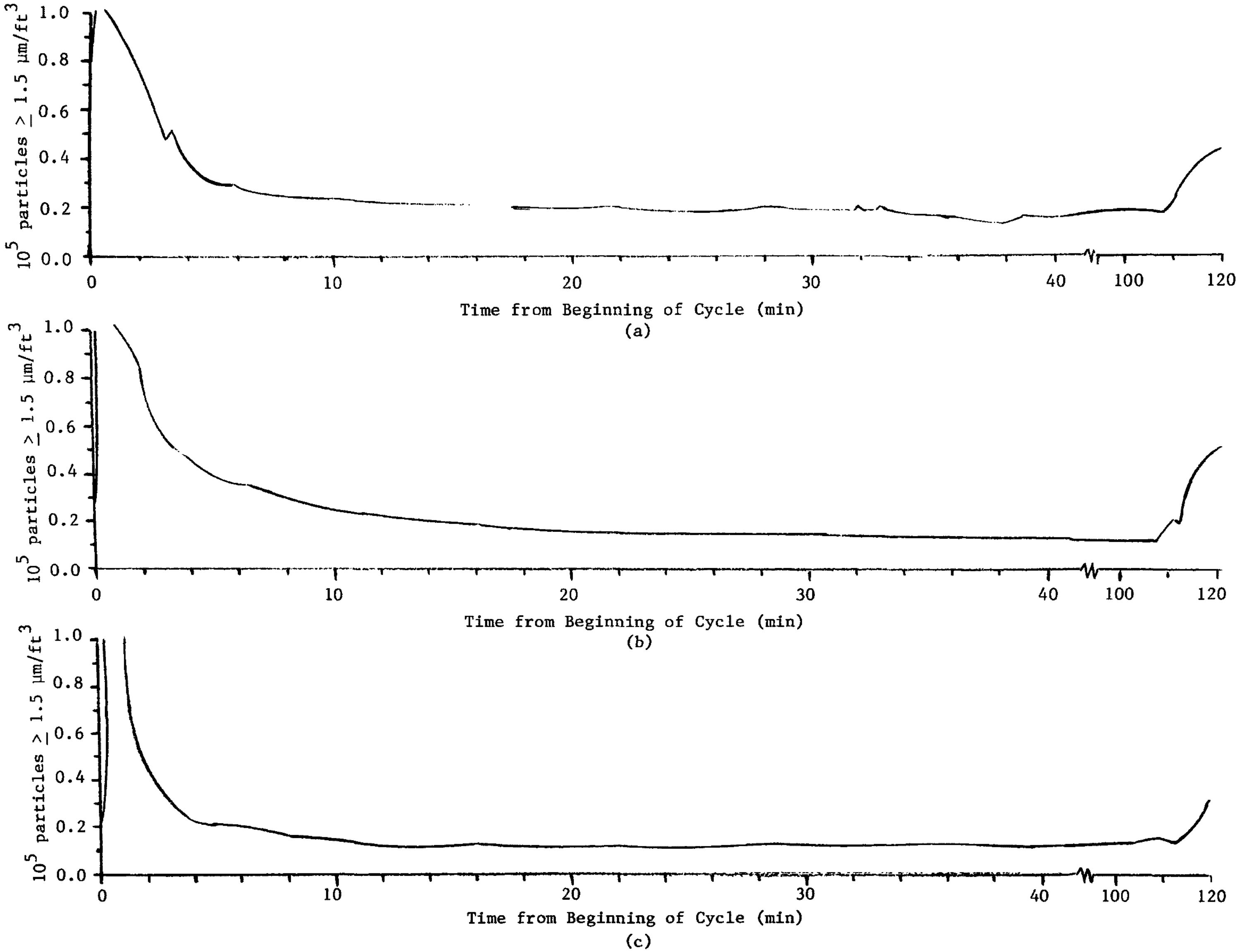

Figure 6. Phase III Royco Particle Counter traces: (a) 120 min cycle, 20 sec, 0.875 cm, 5 cps shake; (b) 120 min cycle, 20 sec, 3.500 cm, 5 cps shake; (c) 120 min cycle, 20 sec, 3.500 cm, 1 cps shake

Table 13. PHASE IV FIBER COUNTS*

Sample Number	Operating Hours to End of Sampling	Sample Volume** (ft^3)	No. of Fibers ≥ 1.5 μm/cm^3 Count No. 1	No. of Fibers ≥ 1.5 μm/cm^3 Count No. 2	No. of Fibers ≥ 5.0 μm/cm^3 Count No. 1	No. of Fibers ≥ 5.0 μm/cm^3 Count No. 2	Stable Δp Across Bag #1 (in. H_2O)	Stable Δp Across Bag #2 (in. H_2O)
1	24	328.1	1.8702	3.0754	0.3169	0.3278	1.50	0.55
2	70	248.5	4.2941	4.8472	0.8554	0.7317	2.20	0.55
3	164	412.6	3.5959	3.9890	0.5193	0.5628	2.65	0.47

* All runs at 0.92 $m^3/min/m^2$ (3.0:1 cfm/ft^2) air-to-cloth ratio, 21 g/m^3 (9.2 gr/ft^3) dust loading, ambient relative humidity (60-90%), and shaking variables of 120 min, 20 sec, 3.500 cm (1.378 in.), and 1 cps.

** All samples taken for 1-2 hr cycle.

are not a viable approach to reducing emissions. However, it was observed that during the initial hours of stabilization, the Royco trace for particles greater than 0.3 μm at 100:1 dilution on the ∿3,530,000 particles/m^3 (100,000 particles/ft^3) scale remained on scale. This was in contrast to all Phase III experiments with a single baghouse and indicated that a steady state low outlet concentration was being emitted from the second bag at the beginning of the bag series run. The peak observed when air flow was resumed after cleaning was very low in the case of the initial stabilization of the bag series. Therefore, the bag series system may prove valuable for reducing high emissions during stabilization of a section of new bags by recycling flow through a previously stabilized section of the baghouse.

SECTION 7

DISCUSSION OF RESULTS OF TESTING BASED ON STATISTICAL ANALYSIS OF DATA

INTRODUCTION

An experiment employing four phases was conducted to investigate the effects of nine factors on the exit side concentration of asbestos fibers emitted from a baghouse. These factors are:

- Type of waste
- Humidity
- Bag fabric
- Air-to-cloth ratio
- Dust loading
- Bag-shaking amplitude
- Bag-shaking frequency
- Joint effect of duration and period of bag-shaking
- The use of one bag or two bags in a series

Measurements of exit concentrations were taken after a 24-hour stabilization period. The type of waste, bag fabric, amplitude, joint effect of duration and period of bag-shaking, and number of bags were shown to significantly affect exit concentration.

The discussion of the statistical analyses and their results is divided into six major sections. The first section is a brief presentation of the statistical methods used in analyzing the data. The next four sections discuss each phase of the experiment and its results. These sections first discuss the experimental design; then the data are presented followed by a discussion of the results of the statistical analyses. The last part of each section summarizes the findings for the particular phase. The sixth and final section summarizes the findings for all four phases and recommends efficient baghouse operation alternatives.

METHODS OF ANALYSIS

Two of the nine factors considered in this study are qualitative in nature: asbestos and bag cloth. The qualitative distinction among the levels of these two factors can be represented numerically by five new variables. The values of these new variables and their corresponding factor levels are given in Tables 14 and 15. The general rule is that if a factor has N mutually exclusive states, then N-1 appropriately coded variables with associated coefficients can represent any possible pattern of differences among the states with respect to a quantitative property such as mean concentration. These five new variables were used to investigate the effects of various bag fabrics and asbestos waste.

Analysis of the quantitative factors employed both their actual values and their common logarithms. The common logarithm is often applied to variables which are inherently positive and which have a large range. They provide an opportunity for more complex relationships between outlet concentration and the factors to be investigated.

The values of the outlet concentrations of asbestos fibers were also transformed to their common logarithms, because they too are inherently positive. More importantly, the distribution of these concentrations was log-normal. By taking the log of the concentrations, a well-developed

Table 14. NUMERIC CODING OF WASTE TYPE

Waste Type	Coded Variable Z_1
Asbestos Cement	+1
Asbestos Fibers	-1

Table 15. NUMERIC CODING OF BAG TYPE

Bag Type	Coded Variables Z_{31}	Z_{32}	Z_{33}	Z_{34}	Z_{35}
Cotton Sateen	+1	0	0	0	0
Napped Cotton	0	+1	0	0	0
Nomex	0	0	+1	0	0
Dacron No. 1	0	0	0	+1	0
Cotton Twill	0	0	0	0	+1
Dacron No. 2	0	0	0	0	0

field of statistical theory based on normal variates could be applied.

The size ranges reported in the data are greater than 0.06 μm in Phase I, greater than 1.5 μm in all phases, greater than 6.0 μm in Phases I and II, and greater than 5.0 μm in Phases III and IV. Because of the much greater numbers of fibers in the smaller size ranges of the outlet concentration, the smaller fibers dominate the concentration values in each size range.

The effects of the factors on outlet concentration were analyzed three ways:

1. Correlation coefficients were computed between outlet concentration or its log transform, and the factors or their log transforms.

2. 90% confidence intervals were constructed about the geometric* means of outlet concentration for various factor values.

3. Relations between the log of fiber concentration and the factors were investigated using stepwise linear regression.

The specific methods of analysis used in each phase are stated in their respective sections. Appendix A presents a more detailed discussion of these statistical methods.

DISCUSSION OF PHASE I RESULTS

The main purpose of Phase I was to determine the effects of different bag fabrics and asbestos waste on the outlet concentration of asbestos fibers. Both the asbestos cement waste and raw asbestos waste were obtained from Johns-Manville,

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* Geometric rather than arithmetic means were computed since the logs of concentration were more normally distributed than the observed concentrations. This further enhanced the appropriateness of the t-distribution's application for computing confidence intervals.

Waukegan, Illinois, from their baghouse control equipment of the Transite asbestos cement pipe process. All combinations of humidity and bag fabric were used with asbestos cement waste. However, the unsuitability of the SCR-20 dust feeder to feed raw asbestos waste necessitated manual feeding. This consumed more time than anticipated, thus limiting the fabrics exposed to raw asbestos waste to cotton sateen and Dacron No. 1. This limitation required the analysis of Phase I data to be carried out on two separate subsamples.

Subsample 1 Results

The factors or independent variables investigated using the first subsample of data are presented in Table 16 along with their respective values or levels. All six bag fabrics, but only one type of asbestos waste (cement waste), were included.

The data base generated by Phase I testing is given in Table 17. In this phase of testing, the outlet concentrations of fibers greater than 6.0 μm, 1.5 μm, and 0.06 μm were the dependent variables.

Only the first twenty tests in Table 17 were included in Subsample 1. These tests used asbestos cement waste only.

Correlations Between Subsample 1 Variables -

Correlation coefficients, r, for Subsample 1 are given in Table 18. The range within which the associated probability, P, falls is indicated in conjunction with each correlation. P is the probability that a correlation as large in magnitude as r would occur due only to sampling error. If P is greater than 0.10, the correlation is not considered to be statistically significant.

The correlation analysis of Subsample 1 indicates that cotton sateen is the best fabric for reducing outlet concentration of asbestos fibers greater than 1.5 μm. For

Table 16. THE INDEPENDENT VARIABLES AND THEIR DESIRED LEVELS FOR SUBSAMPLE 1 OF PHASE I

Variable	Level
X_1, Waste Type	1. Asbestos Cement
X_2, Humidity	1. 20% 2. 40% 3. 80%
X_3, Bag Type	1. Cotton Sateen 2. Napped Cotton 3. Nomex 4. Dacron No. 1 5. Cotton Twill 6. Dacron No. 2
X_4, Air-to-Cloth Ratio	1. 0.76 $m^3/min/m^2$ (2.5 cfm/ft^2)
X_5, Dust Loading	1. 22 g/m^3 (9.6 gr/ft^3)
X_6, Amplitude of Shake Cycle	1. 0.875 cm (0.344 in.)
X_7, Frequency of Shake Cycle	1. 1.0 cps
X_8, Period and Duration of Shake Cycle	1. Period - 16 min Duration - 20 sec
X_9, Number of Bags	1. 1

Table 17. DATA BASE FOR PHASE I

Test No.	Comb. No.	Waste Type	Humidity	Coded Bag Variables*					Outlet Concentration (No. of fibers/cm^3)		
		Z_1	X_2	Z_{31}	Z_{32}	Z_{33}	Z_{34}	Z_{35}	$\geq$ 0.06 μm	$\geq$ 1.5 μm	$\geq$ 6.0 μm
1	1	1	25	1	0	0	0	0	215	1.18	0.95
2	1	1	20	1	0	0	0	0	557	1.12	0.97
3	2	1	40	1	0	0	0	0	1362	2.28	1.74
4	3	1	80	1	0	0	0	0	349	3.31	1.72
5	4	1	35	0	1	0	0	0	37	5.40	2.70
6	4	1	40	0	1	0	0	0	1388	9.06	3.10
7	5	1	70	0	1	0	0	0	399	8.14	3.28
8	6	1	80	0	1	0	0	0	445	14.35	6.27
9	7	1	35	0	0	1	0	0	135	8.71	3.02
10	7	1	40	0	0	1	0	0	106	19.43	5.10
11	8	1	80	0	0	1	0	0	751	15.56	6.04
12	9	1	30	0	0	0	1	0	977	20.60	4.36
13	10	1	40	0	0	0	1	0	3167	10.83	3.12
14	11	1	80	0	0	0	1	0	434	3.02	1.09
15	12	1	30	0	0	0	0	1	2864	4.83	1.48
16	13	1	40	0	0	0	0	1	275	3.24	0.99
17	14	1	80	0	0	0	0	1	936	4.67	1.29
18	15	1	37	0	0	0	0	0	2836	5.95	1.47
19	15	1	40	0	0	0	0	0	1075	53.76	3.28
20	16	1	80	0	0	0	0	0	1305	3.77	0.73
21	17	-1	25	1	0	0	0	0	486	3.68	1.05
22	18	-1	40	1	0	0	0	0	506	4.14	1.06
23	19	-1	60	1	0	0	0	0	150	4.13	1.14
24	20	-1	30	0	0	0	1	0	700	3.68	0.89
25	21	-1	40	0	0	0	1	0	424	3.10	0.77
26	22	-1	77	0	0	0	1	0	527	5.62	1.26

* Variable coding given in Tables 14 and 15.

Table 18. CORRELATIONS BETWEEN PHASE I VARIABLES FOR SUBSAMPLE 1 (N = 20)

Concentration of Fibers ≥	Independent Variable	Correlation r	Probability P
0.06 μm	Z_{31} First Bag Var.	-0.194	*
	Z_{32} Second Bag Var.	-0.223	*
	Z_{33} Third Bag Var.	-0.294	*
	Z_{34} Fourth Bag Var.	+0.247	*
	Z_{35} Fifth Bag Var.	+0.171	*
	X_2 Humidity	-0.198	*
1.50 μm	Z_{31} First Bag Var.	-0.346	*
	Z_{32} Second Bag Var.	-0.031	*
	Z_{33} Third Bag Var.	+0.168	*
	Z_{34} Fourth Bag Var.	+0.055	*
	Z_{35} Fifth Bag Var.	-0.208	*
	X_2 Humidity	-0.073	*
6.00 μm	Z_{31} First Bag Var.	-0.386	$0.05 < P < 0.1$
	Z_{32} Second Bag Var.	+0.360	*
	Z_{33} Third Bag Var.	+0.525	$0.01 < P < 0.02$
	Z_{34} Fourth Bag Var.	+0.056	*
	Z_{35} Fifth Bag Var.	-0.348	*
	X_2 Humidity	+0.175	*
Log_{10} Concentration of Fibers ≥			
0.06 μm	Z_{31} First Bag Var.	-0.079	*
	Z_{32} Second Bag Var.	-0.281	*
	Z_{33} Third Bag Var.	-0.361	*
	Z_{34} Fourth Bag Var.	+0.235	*
	Z_{35} Fifth Bag Var.	+0.161	*
	Z_2 Log_{10} Humidity	+0.044	*
1.50 μm	Z_{31} First Bag Var.	-0.664	$0.001 < P < 0.005$
	Z_{32} Second Bag Var.	+0.172	*
	Z_{33} Third Bag Var.	+0.349	*
	Z_{34} Fourth Bag Var.	+0.148	*
	Z_{35} Fifth Bag Var.	-0.179	*
	Z_2 Log_{10} Humidity	+0.186	*
6.00 μm	Z_{31} First Bag Var.	-0.393	$0.05 < P < 0.10$
	Z_{32} Second Bag Var.	+0.403	$0.05 < P < 0.10$
	Z_{33} Third Bag Var.	+0.483	$0.02 < P < 0.05$
	Z_{34} Fourth Bag Var.	+0.087	*
	Z_{35} Fifth Bag Var.	-0.357	*
	Z_2 Log_{10} Humidity	+0.135	*

* Not significant at 0.10 probability level.

outlet concentrations of fibers greater than 0.06 μm, no bag fabric had any significant correlation. Relative humidity did not significantly correlate with outlet concentration or its log regardless of fiber lengths.

Geometric Means of Outlet Concentration for Subsample 1 -

Table 19 gives the geometric mean and 90% confidence limits for the data of Subsample 1. The results are given separately for each of the three fiber sizes. The geometric means and 90% confidence limits of outlet concentrations are plotted in Figures 7, 8, and 9.

A confidence interval which overlaps the mean of another indicates that no significant difference exists between the two respective bag fabrics; the significance level being 0.10. The reader, however, is cautioned against making multiple pairwise comparisons and drawing conclusions about the significance of differences among all bag fabrics, since the probability of making correct inferences among all pairwise comparisons is much lower than the 0.10 significance level for making one pairwise comparison. The plots of the geometric means and their confidence intervals for the six bag fabrics are presented only to provide the reader with a visual representation of the experimental results and magnitude of experimental error. The regression analysis provides a statistically sound basis for determining which bag fabrics are significantly different, and these results are given in the next section.

Figure 7 shows that, while Nomex, napped cotton, and cotton sateen had the lowest outlet concentrations, the confidence intervals about the geometric means overlap, indicating that the means are not significantly different from one another. Figure 8 shows that cotton sateen had the lowest geometric mean outlet concentration for fibers greater than 1.5 μm of any fabric. Dacron No. 1 and cotton

Table 19. GEOMETRIC MEANS AND 90% CONFIDENCE LIMITS

FOR PHASE I - SUBSAMPLE 1

Type of Bag Fabric	N	Outlet Concentration (Number of fibers/cm^3)								
		Fibers $\geq$ 0.06 μm			Fibers $\geq$ 1.5 μm			Fibers $\geq$ 6.0 μm		
		Geometric Mean	Confidence Limits		Geometric Mean	Confidence Limits		Geometric Mean	Confidence Limits	
			Lower	Upper		Lower	Upper		Lower	Upper
Cotton Sateen	4	489	211	1132	1.78	1.02	3.11	1.29	0.90	1.85
Napped Cotton	4	309	61	1567	8.69	5.68	13.30	3.62	2.43	5.41
Nomex	3	221	52	942	13.80	7.85	24.27	4.53	2.77	7.40
Dacron No. 1	3	1104	284	4295	8.77	2.33	33.04	2.45	0.92	6.56
Cotton Twill	3	904	184	4436	4.18	3.09	5.64	1.24	0.94	1.63
Dacron No. 2	3	1585	789	3184	10.64	1.55	73.28	1.52	0.55	4.23

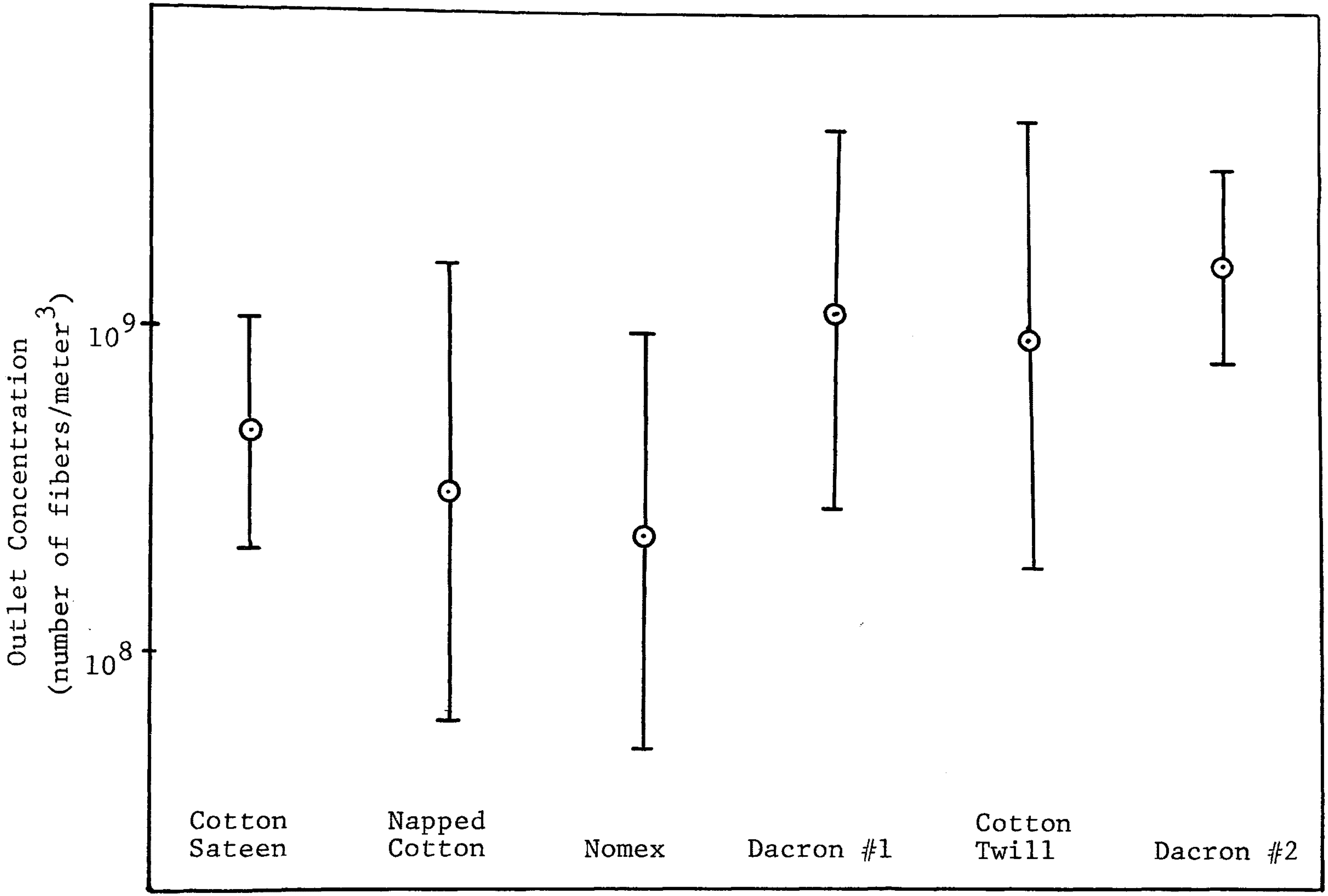

Figure 7. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 0.06 μm by type of bag - Phase I - Subsample 1

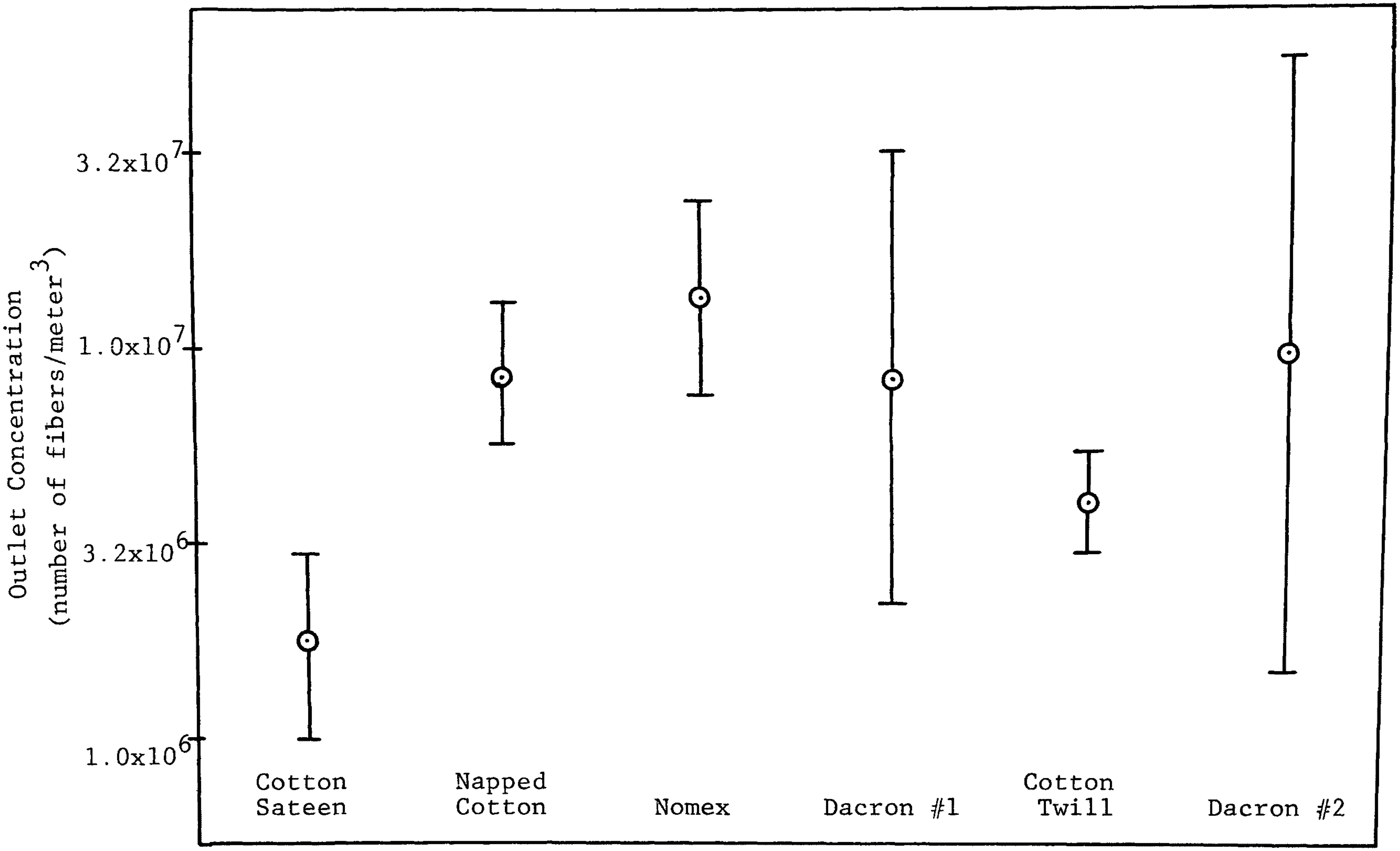

Figure 8. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 1.5 μm by type of bag - Phase I - Subsample 1

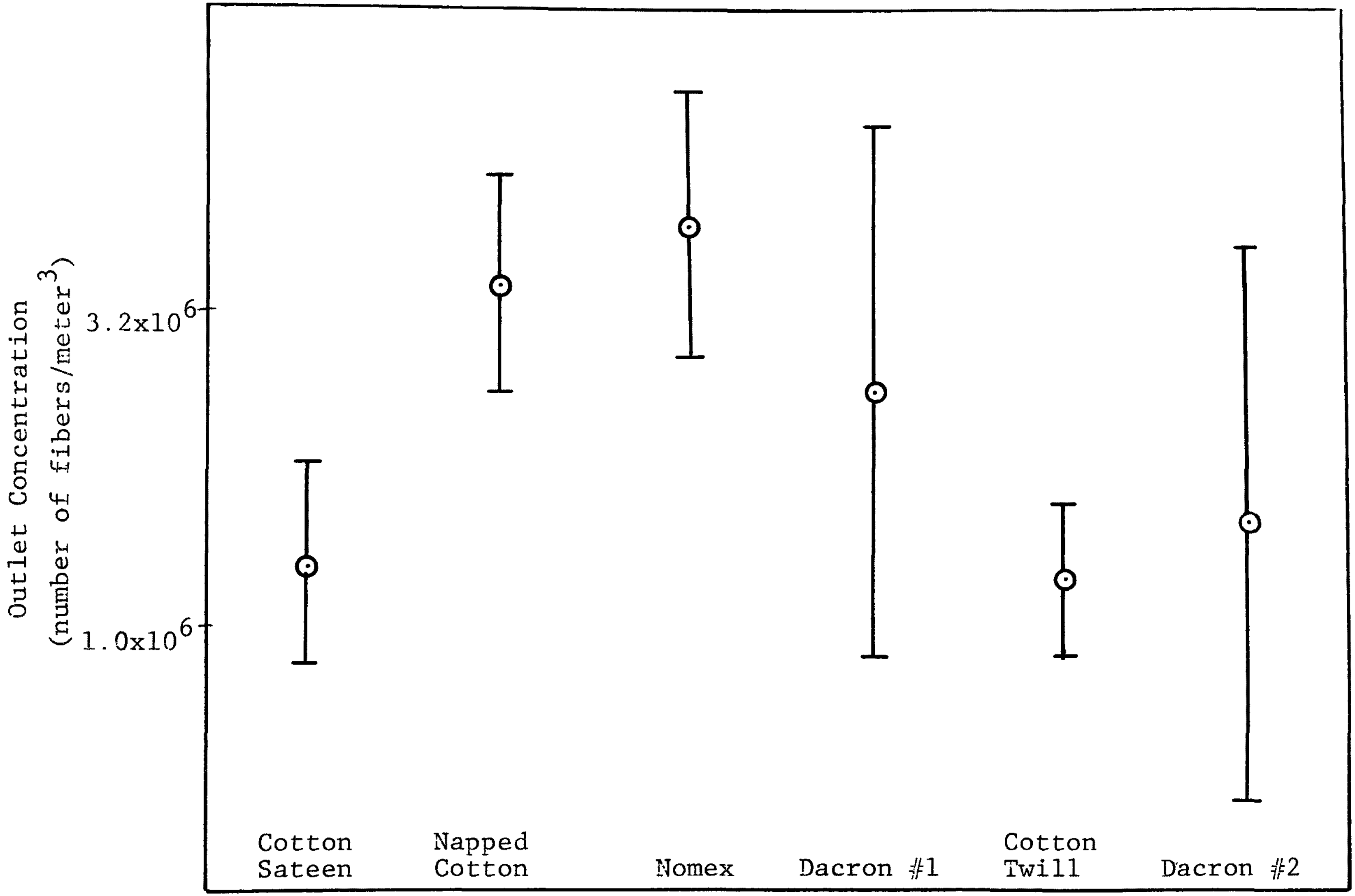

Figure 9. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 6.0 μm by type of bag - Phase I - Subsample 1

twill bag produced the second lowest geometric mean outlet concentration for outlet concentration of fibers greater than 1.5 μm. Figure 9 shows that both cotton sateen and cotton twill have the lowest geometric mean outlet concentrations of fibers greater than 6.0 μm. Thus, the best overall bag fabric for reducing outlet concentration of asbestos fibers is cotton sateen. This result supports that of the correlation analysis.

Regression Analysis of Subsample 1

The regression model considered for Subsample 1 data included the numeric coding of bag fabric and the log of humidity, the dependent variables being the log of outlet concentration for the three fiber lengths. None of these factors were significantly related to outlet concentration of fibers greater than 0.06 μm. However, bag fabric was significantly related to outlet concentration of fibers that were greater than 1.5 μm and 6.0 μm. The regression statistics and equations for these two fiber lengths are presented in Tables 20 and 21. The computed geometric means of outlet concentration from these relations are given in Table 22. It is apparent from this table that, overall, the cotton sateen fabric produced the lowest outlet concentration of asbestos fibers. Again, this supports the correlation and confidence interval results.

Subsample 2 Results

Only two bag fabrics, but both types of asbestos waste and three humidity levels, are included in the analysis of the second subsample of data from Phase I. The data included in this subsample are tests 1-4, 12-14, and 21-26 in Table 17. Table 23 presents the values of the nine factors employed.

Table 20. RESULTS OF REGRESSION ANALYSIS OF SUBSAMPLE 1 - PHASE I FOR FIBERS GREATER THAN 1.5 μm

Dependent Variable:	Y_2 = Log_{10} of Outlet Concentration of fibers ≥ 1.5 μm
Data Base:	Phase I - Subsample 1
Degree of Determination:	54.8%
Residual Standard Deviation:	0.301

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Constant Term:	+1.007	-	-
Z_{31}, First coded bag variable	-0.757	0.172	0.0004
Z_{32}, Fifth coded bag variable	-0.385	0.193	0.0591

Variables Not Significant ($P > 0.10$)

Z_{32}, Second coded bag variable
Z_{33}, Third coded bag variable
Z_{34}, Fourth coded bag variable
Z_2, Log_{10} of humidity

Regression Equation

$$Y_2 = 1.007 - 0.757Z_{31} - 0.385Z_{32}$$

Table 21. RESULTS OF REGRESSION ANALYSIS OF SUBSAMPLE 1 - PHASE I FOR FIBERS GREATER THAN 6.0 μm

Dependent Variable:	Y_3 = Log_{10} of Outlet Concentration of fibers $\geq$ 6.0 μm
Data Base:	Phase I - Subsample 1
Degree of Determination:	60.1%
Residual Standard Deviation:	0.199

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Constant Term:	+0.126	-	-
Z_{32}, Second coded bag variable	+0.433	0.178	0.0021
Z_{33}, Third coded bag variable	+0.530	0.131	0.0010
Z_{32}, Fourth coded bag variable	+0.264	0.131	0.0587

Variables Not Significant ($P > 0.10$)

Z_{31}, First coded bag variable
Z_{35}, Fifth coded bag variable
Z_2, Log_{10} of humidity

Regression Equation

$$Y_3 = 0.126 + 0.433Z_{32} + 0.530Z_{33} + 0.264Z_{34}$$

Table 22. COMPUTED GEOMETRIC MEANS OF OUTLET CONCENTRATION

Type of Bag	Computed Geometric Mean of Outlet Concentration (Number of fibers/cm^3)		
	Fibers ≥ 0.06 μm	Fibers ≥ 1.5 μm	Fibers ≥ 6.0 μm
Cotton Sateen	585	1.78	1.34
Napped Cotton	585	10.16	3.62
Nomex	585	10.16	4.53
Dacron No. 1	585	10.16	2.46
Cotton Twill	585	4.18	1.34
Dacron No. 2	585	10.16	1.34

Table 23. THE INDEPENDENT VARIABLES AND THEIR DESIRED LEVELS FOR SUBSAMPLE 2 OF PHASE I

Variable	Level
X_1, Waste Type	1. Asbestos Cement 2. Raw Asbestos Fiber
X_2, Humidity	1. 20% 2. 40% 3. 80%
X_3, Bag Type	1. Cotton Sateen 2. Dacron No. 1
X_4, Air-to-Cloth Ratio	1. 0.76 $m^3/min/m^2$ (2.5 cfm/ft^2)
X_5, Dust Loading	1. 22 g/m^3 (9.6 gr/ft^3)
X_6, Amplitude of Shake Cycle	1. 0.875 cm (0.344 in.)
X_7, Frequency of Shake Cycle	1. 1.0 cps
X_8, Period and Duration of Shake Cycle	1. Period - 16 min Duration - 20 sec
X_9, Number of Bags	1. 1

Correlations Between Subsample 2 Variables -

The correlations of the outlet concentration or log outlet concentration and the independent varibles in Subsample 2 are given in Table 24. Since only two bag fabrics, cotton sateen and Dacron No. 1, were used, only one coded variable, Z_{31}, for bag type was necessary. The cotton sateen bag was coded as 1 and the Dacron No. 1 bag as 0.

There are no significant correlations between these three independent variables and the outlet concentration and log outlet concentration of fibers greater than 0.06 μm. This is in agreement with Subsample 1 results.

For outlet concentration and log outlet concentration of fibers greater than 1.5 μm, only the type of bag had a significant correlation. The correlations are both negative, indicating that cotton sateen tended to have a significantly lower outlet concentration and log outlet concentration than that of Dacron No. 1. This is again in agreement with Subsample 1 results. Both humidity and type of waste were not significantly correlated with outlet concentration or log outlet concentration for this set of fiber lengths.

Waste type is the only correlation of significance for fibers greater than 6.0 μm. Both bag type and humidity are not correlated with outlet concentration or log outlet concentration. The significant correlation of waste type with both outlet concentration and log outlet concentration is positive, indicating that asbestos cement waste tended to have a higher outlet concentration and log outlet concentration than that of raw asbestos fibers.

Geometric Means of Outlet Concentration for Subsample 2 -

The geometric means and their 90% confidence limits for Subsample 2 data are presented in Table 25. The means are given separately for bag fabric and type of waste.

Table 24. CORRELATIONS BETWEEN PHASE I VARIABLES FOR SUBSAMPLE 2 (N = 13)

Concentration of Fibers ≥	Independent Variable		Correlation r	Probability P
0.06 μm	Z_1	Waste Type	+0.357	*
	Z_{31}	Bag Type	-0.342	*
	X_2	Humidity	-0.172	*
1.50 μm	Z_1	Waste Type	+0.197	*
	Z_{31}	Bag Type	-0.492	0.05 < P < 1.10
	X_2	Humidity	-0.100	*
6.00 μm	Z_1	Waste Type	+0.479	0.05 < P < 0.10
	Z_{31}	Bag Type	-0.338	*
	X_2	Humidity	-0.088	*
Log_{10} Concentration of Fibers ≥				
0.06 μm	Z_1	Waste Type	+0.329	*
	Z_{31}	Bag Type	-0.416	*
	Z_2	Log_{10} Humidity	-0.178	*
1.50 μm	Z_1	Waste Type	-0.083	*
	Z_{31}	Bag Type	-0.569	0.02 < P < 0.05
	Z_2	Log_{10} Humidity	+0.222	*
6.00 μm	Z_1	Waste Type	+0.524	0.02 < P < 0.05
	Z_{31}	Bag Type	-0.250	*
	Z_2	Log_{10} Humidity	+0.071	*

* Not significant at 0.10 probability level.

Table 25. GEOMETRIC MEANS AND 90% CONFIDENCE LIMITS

FOR PHASE I - SUBSAMPLE 2

Type of Bag Fabric	N	Outlet Concentration (Number of Fibers/cm^3)								
		Fibers ≥ 0.6 μm			Fibers ≥ 1.5 μm			Fibers ≥ 6.0 μm		
		Geometric Mean	Confidence Limits		Geometric Mean	Confidence Limits		Geometric Mean	Confidence Limits	
			Lower	Upper		Lower	Upper		Lower	Upper
Cotton Sateen	7	414	245	700	2.51	1.65	3.82	1.20	0.099	1.45
Dacron No. 1	6	771	412	1442	5.92	3.12	11.23	1.53	0.085	2.74
Type of Waste										
Cement	7	693	354	1353	3.52	1.58	7.83	1.70	1.10	2.63
Raw Fiber	6	424	273	657	3.99	3.39	4.70	1.02	0.88	1.17

These means and their confidence intervals are plotted in Figures 10-13. These plots show that cotton sateen produced significantly lower fiber concentrations for fiber lengths greater than 1.5 μm than did Dacron No. 1, and that cement waste had higher outlet concentrations of fibers greater than 6.0 μm than did raw asbestos fiber waste. No significant effects were detected for the other fiber lengths. These findings support the correlation results.

Regression Analysis of Subsample 2

The regression analysis for Subsample 2 of Phase I data included the type of waste along with bag type (cotton sateen and Dacron No. 1) and the log of humidity as candidate variables. Again, none of the candidate variables were related to the log outlet concentration of fibers greater than 0.06 μm. For fibers greater than 1.5 μm, the type of bag significantly affected the log of outlet concentration. The computed geometric mean of outlet concentration for these fibers was 2.51 fibers per cubic centimeter for the cotton sateen bag and 5.92 fibers per cubic centimeter for the Dacron No. 1 bag. These means were computed from the regression equation in Table 27. For fibers greater than 6.0 μm, only the type of waste significantly affected the log of outlet concentration. For this fiber size, the geometric mean of outlet concentration generated by cement waste is 1.70 fibers per cubic centimeter, and that generated by raw asbestos fiber is 1.02 fibers per cubic centimeter. Again, the log of humidity did not significantly affect outlet concentration beyond experimental error. The regression statistics and equations are given in Tables 26 and 27.

Conclusions from Phase I Results

The results of Phase I all support the use of cotton sateen bag fabric for reducing the outlet concentration of

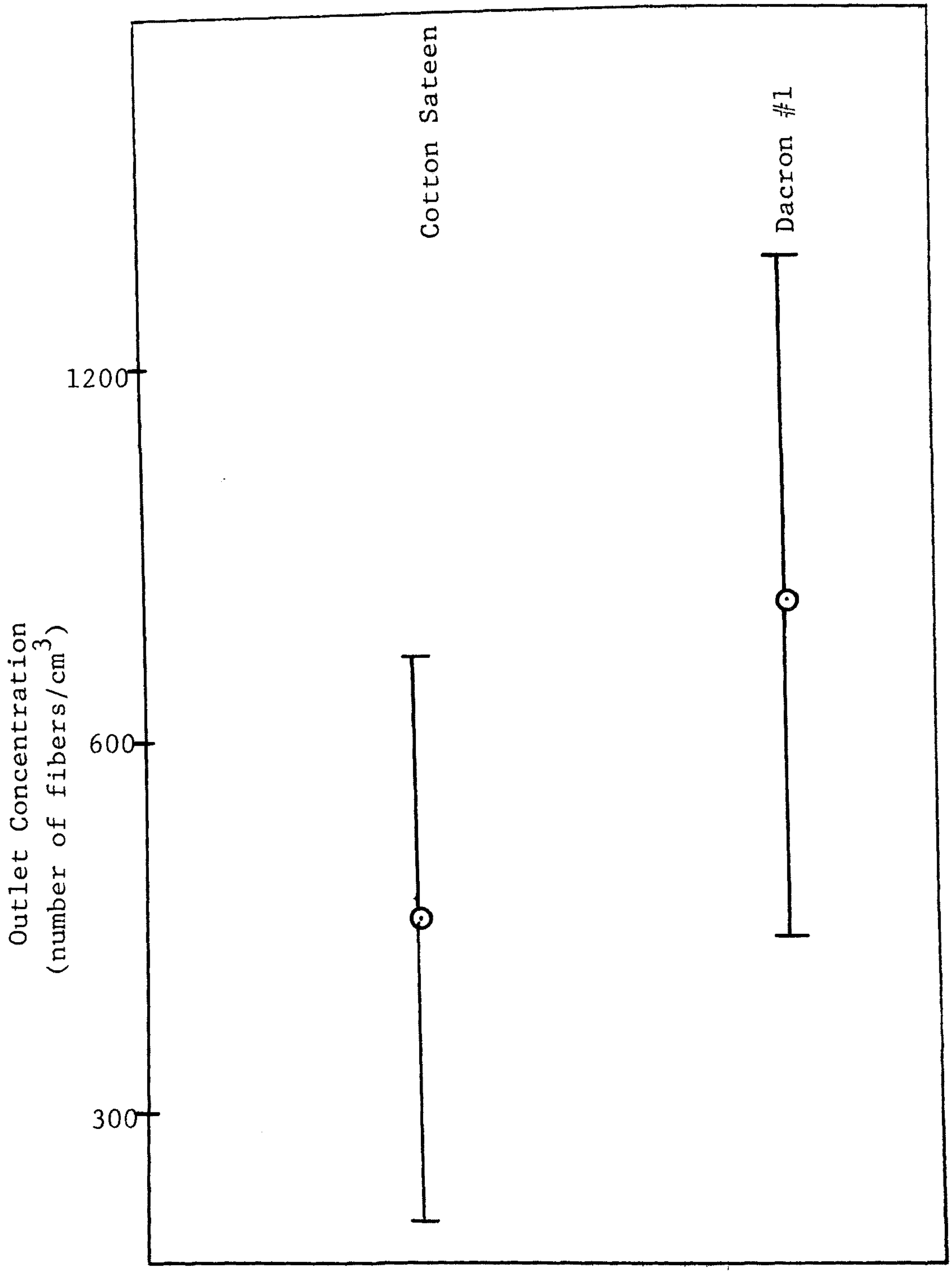

Figure 10. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 0.06 μm by type of bag - Phase I - Subsample 2

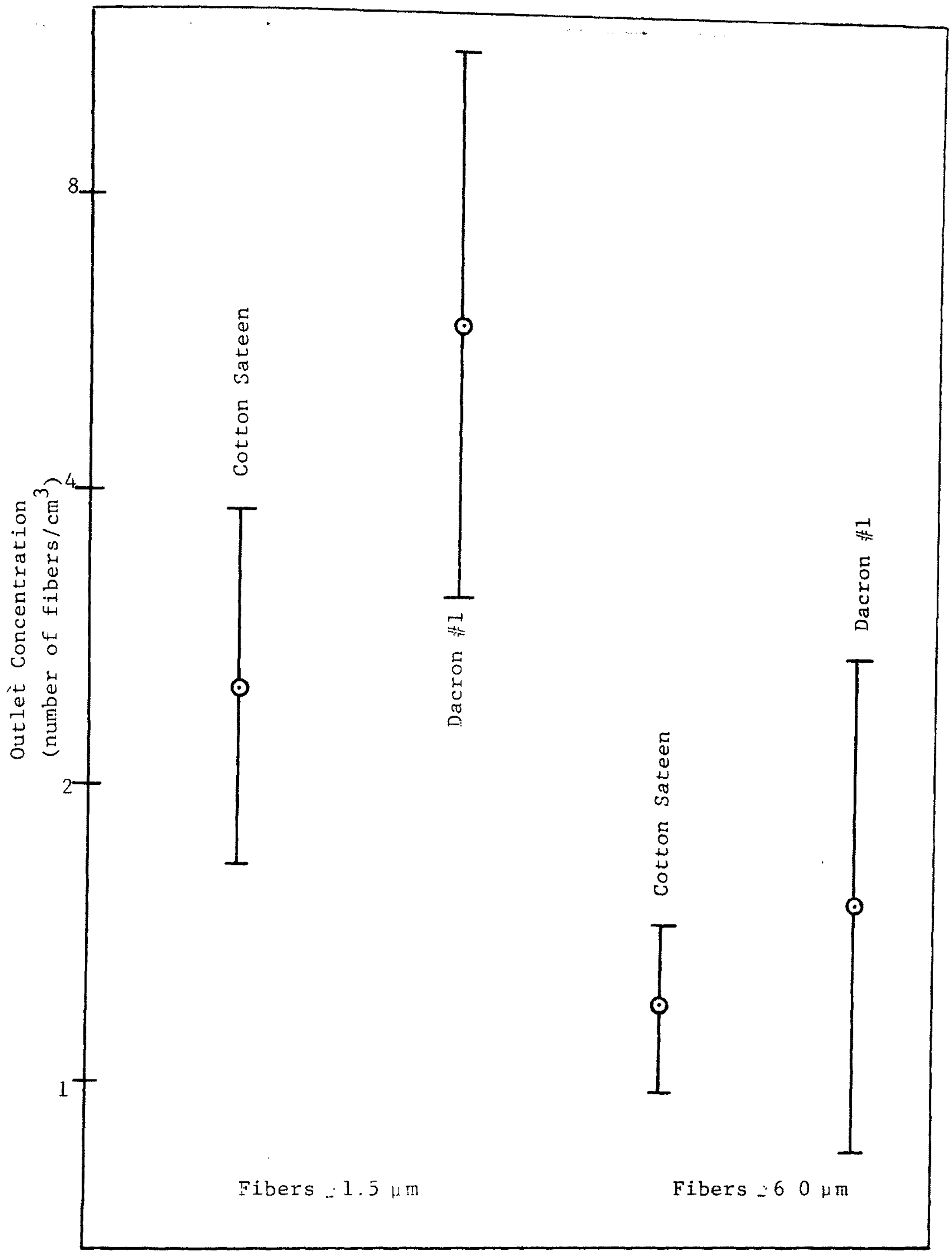

Figure 11. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers by type of bag - Phase I - Subsample 2

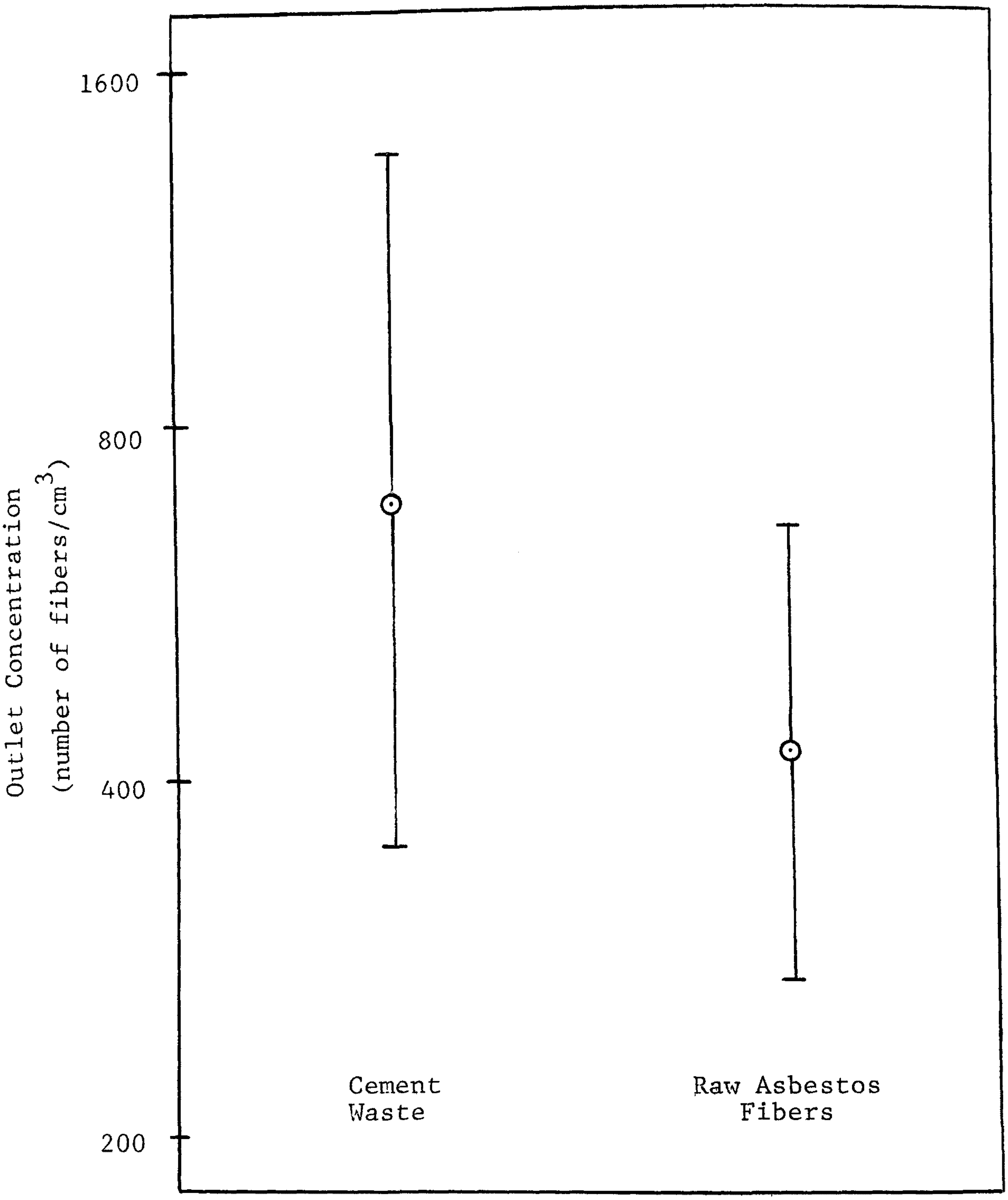

Figure 12. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 0.06 μm by type of waste - Phase I - Subsample 2

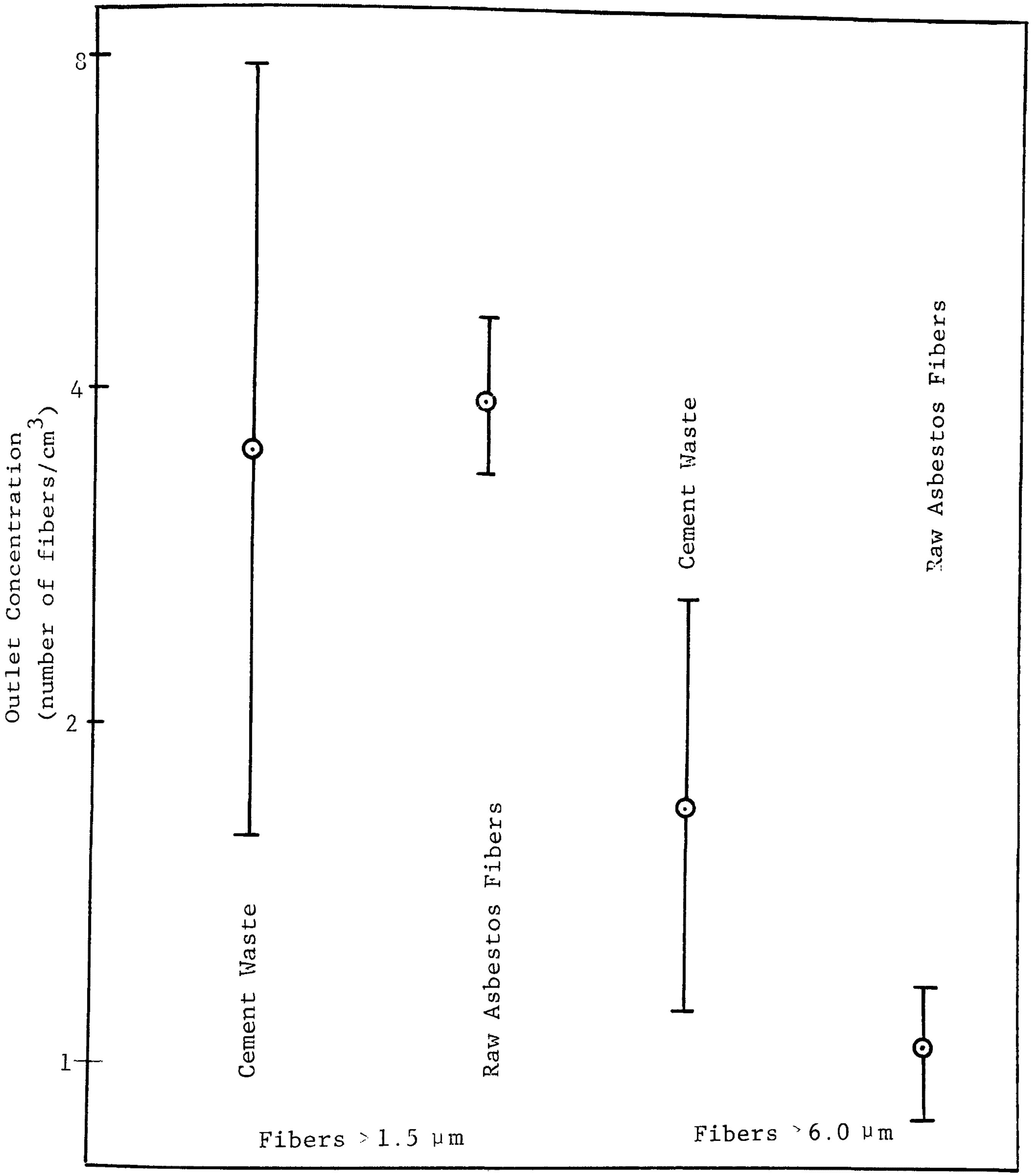

Figure 13. Estimates of the geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers by type of waste - Phase I - Subsample 2

Table 26. RESULTS OF REGRESSION ANALYSIS OF SUBSAMPLE 2 - PHASE I FOR FIBERS GREATER THAN 1.5 μm

Dependent Variable:	Y_2 = Log_{10} of Outlet Concentration of fibers ≥ 1.5 μm
Data Base:	Phase I - Subsample 2
Degree of Determination:	32.4%
Residual Standard Deviation:	0.292

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Constant Term:	+0.773	-	-
Z_{31}, Coded bag variable	-0.373	0.162	0.0438

Variables Not Significant (P > 0.10)

Z_1, Coded waste variable

Z_2, Log_{10} of humidity

Regression Equation

$$Y_2 = 0.773 - 0.373Z_{31}$$

Table 27. RESULTS OF REGRESSION ANALYSIS OF SUBSAMPLE 2 - PHASE I FOR FIBERS GREATER THAN 6.0 μm

Dependent Variable:	Y_3 = Log10 of Outlet Concentration of fibers $\geq$ 6.0 μm
Data Base:	Phase I - Subsample 2
Degree of Determination:	27.5%
Residual Standard Deviation:	0.197

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Constant Term:	0.118	-	-
Z_1, Coded waste variable	0.112	0.055	0.0662

Variables Not Significant (P > 0.10)

Z_{31}, Coded bag variable

Z_2, Log_{10} of humidity

Regression Equation

$Y_3 = 0.118 + 0.112Z_1$

asbestos fibers. For fibers greater than 0.06 μm, cotton sateen is not significantly different from other bag fabrics. For fibers greater than 1.5 μm, cotton sateen had outlet concentrations significantly lower than any of the other bags tested. And for fibers greater than 6.0 μm, cotton sateen had outlet concentrations significantly lower than napped cotton, Nomex, and Dacron No. 1, and performed as well as cotton twill or Dacron No. 2.

Humidity had no effect on outlet concentration greater than experimental error, but type of waste significantly affected the outlet concentration of fibers greater than 6.0 μm.

For fibers greater than 6.0 μm, the raw asbestos fiber waste had a significantly lower outlet concentration than that of asbestos cement waste.

That cotton sateen allows the lowest outlet concentration is not surprising. This fabric has one of the fullest weaves (4 x 1) and highest thread counts (96 x 60) of the fabrics tested, thus reducing pore size. Also, the fabric is manufactured from all spun fibers, so that the fabric fabriles also act to effectively reduce the pore size.

That humidity has no effect on outlet concentration can be attributed to two factors. First, the experimental error was very high in this phase, thus possibly masking any effects. Second, at the highest level of relative humidity (75-85%), both settling of agglomerated dust in the inlet duct and blinding of the fabric by moisture were observed.

The conclusion that raw asbestos fiber waste had a lower outlet concentration in the greater than 6.0 μm range is reasonable in that the longer fibers expected in the raw asbestos fiber waste would be collected more easily than those fibers shortened by the asbestos cement process. If the raw asbestos fiber had been from one of the longer length grades of fiber, such as those used in textiles, etc., a correlation would also be expected between waste type and outlet concentration for the smaller fibers. However, the raw asbestos fibers used were also of the shorter length grades used in the asbestos cement industry.

DISCUSSION OF PHASE II RESULTS

Phase II examined effects of relative humidity, air-to-cloth ratio, and dust loading. Phase I demonstrated that a bag made of cotton sateen was more efficient overall than other bag fabrics. Thus, this bag fabric was used throughout the remaining tests. Phase I also demonstrated that the outlet concentration for asbestos cement waste was higher than that for fibrous asbestos waste under similar baghouse conditions. Since asbestos cement waste has higher outlet concentrations, it is a larger scale problem industrially; and since fibrous asbestos waste could not be fed by the SCR-20 dust feeder, only asbestos cement waste was used for Phase II and the remaining phases of the study. The independent variables are given in Table 28. Desired and actual levels of the independent variables differed; however, these differences did not significantly affect the validity of statistical analysis.

Outlet concentrations of asbestos fibers were measured for two different size ranges ($\geq$ 1.5 μm and $\geq$ 6.0 μm) in Phase II. The data base generated by this phase of testing is given in Table 29. A total of nineteen tests were conducted. Tests 2 and 3, and 17 and 18 were treated as replicate tests. Due to the poor precision in counting the fibers, two counts of the concentration of fibers for each test and size range were made. Although these second estimates are not complete replicates of each test, they were treated as replicates since the variation in the

Table 28. PHASE II INDEPENDENT VARIABLES AND THEIR DESIRED LEVELS

Variable	Level
X_1, Waste Type	1. Asbestos Cement
X_2, Humidity	1. 30% 2. 40% 3. 60%
X_3, Bag Type	1. Cotton Sateen
X_4, Air-to-Cloth Ratio	1. 0.46 $m^3/min/m^2$ (1.5 cfm/ft^2) 2. 0.76 $m^3/min/m^2$ (2.5 cfm/ft^2) 3. 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2)
X_5, Dust Loading	1. 10 g/m^3 (4.4 gr/ft^3) 2. 21 g/m^3 (9.2 gr/ft^3) 3. 45 g/m^3 (19.7 gr/ft^3)
X_6, Amplitude of Shake Cycle	1. 0.875 cm (0.344 in.)
X_7, Frequency of Shake Cycle	1. 1 cps
X_8, Period and Duration of Shake Cycle	1. Period - 16 min Duration - 20 sec
X_9, Number of Bags	1. 1

Table 29. DATA BASE OF PHASE II

Test No.	Comb. No.	X_2	X_4	X_5	Outlet Concentration (No. fibers/m^3 x 10^6) $\geq$ 1.5 μm	$\geq$ 6.0 μm
1	1	60	1.5	45	16.72	3.54
2	1	60	1.5	45	17.92	4.68
3	2	40	1.5	21	27.05	4.26
4	2	40	1.5	21	19.28	2.13
5	2*	40	1.5	21	19.41	2.34
6	2*	40	1.5	21	24.62	3.62
7	3	40	1.5	10	13.42	3.41
8	3	40	1.5	10	29.45	3.88
9	4	60	2.5	45	23.19	5.35
10	4	60	2.5	45	34.97	6.89
11	5	30	1.5	45	14.14	2.42
12	5	30	1.5	45	22.71	3.80
13	6	30	3.9	10	10.90	1.45
14	6	30	3.9	10	13.37	1.94
15	7	40	4.0	21	7.29	1.21
16	7	40	4.0	21	17.93	1.52
17	8	40	3.2	56	13.02	0.61
18	8	40	3.2	56	16.12	2.65
19	9	30	2.5	21	7.30	1.27
20	9	30	2.5	21	31.47	4.84
21	10	60	3.0	28	12.61	1.67
22	10	60	3.0	28	22.10	3.02
23	11	40	2.5	45	17.30	2.66
24	11	40	2.5	45	33.52	2.81
25	12	60	1.5	10	23.44	3.74
26	12	60	1.5	10	50.03	3.40
27	13	60	3.0	14	15.08	1.67
28	13	60	3.0	14	34.43	2.15
29	14	60	2.5	21	21.26	2.73
30	14	60	2.5	21	45.26	2.23
31	15	30	2.5	10	23.72	4.36
32	15	30	2.5	10	43.90	2.48
33	16	30	2.5	72	13.98	1.47
34	16	30	2.5	72	34.06	1.83
35	16*	30	2.1	85	21.44	2.11
36	16*	30	2.1	85	34.90	2.06
37	17	40	2.2	11	60.75	5.05
38	17	40	2.2	11	41.75	3.90

* Full replicates

X_2 - Percent Humidity, X_4 - Air-to-Cloth Ratio (cfm/ft^2)
X_5 - Dust Loading (g/m^3)

Fixed Variables

X_1 - Asbestos Cement Waste, X_3 - Cotton Sateen Bag
X_6 - Amplitude 0.875 cm (0.344 in.)
X_7 - Frequency 1.0 cps
X_8 - Period - 16 min.
Duration - 20 sec.

counting is on the same order of magnitude as the complete replicates. Thus, there are a total of thirty-eight observations of outlet concentrations for seventeen combinations of the independent variables.

Correlations Between Phase II Variables

Correlation coefficients, r, are given in Table 30 for outlet concentrations in each of the two size ranges and their common log transforms when paired with the specified independent variables. The range within which the associated probability, P, falls is indicated in conjunction with each correlation.

There are no significant correlations between dust loading and outlet concentration or its transform, and between relative humidity and outlet concentration and its transform except for the outlet concentrations of fibers greater than 6.0 μm. The probability that this correlation is not significant is approximately 0.10.

The most significant correlation for all fiber sizes considered is between the outlet concentration or its log and the air-to-cloth ratio. This correlation is strongest for the log transformed variables for fiber sizes greater than 6.0 μm. The sign of this correlation is negative, indicating that increasing air-to-cloth ratio in the range addressed by this study decreases the outlet concentration of asbestos fibers.

Regression Analysis of Phase II

The candidate variables for predicting the outlet concentration of asbestos fibers for each of the two size ranges were:

- Percent humidity
- Air-to-cloth ratio
- Dust loading

Table 30. CORRELATIONS BETWEEN PHASE II VARIABLES

Dependent Variable	Independent Variable	(N = 38) Correlation r	Probability P
Conc. of fibers $\geq$ 1.5 μm	X_2 Percent Humidity	+.122	*
Conc. of fibers $\geq$ 1.5 μm	X_4 Air-to-Cloth Ratio	-.266	$.10 > P > .05$
Conc. of fibers $\geq$ 1.5 μm	X_5 Dust Loading	-.141	*
Conc. of fibers $\geq$ 6.0 μm	X_2 Percent Humidity	+.275	$.10 > P > .05$
Conc. of fibers $\geq$ 6.0 μm	X_4 Air-to-Cloth Ratio	-.458	$.005 > P > .001$
Conc. of fibers $\geq$ 6.0 μm	X_5 Dust Loading	-.142	*
Log_{10} Conc. of fibers $\geq$ 1.5 μm	Z_2 Log_{10} of Percent Humidity	+.156	*
Log_{10} Conc. of fibers $\geq$ 1.5 μm	Z_4 Log_{10} of Air-to-Cloth Ratio	-.281	$.10 > P > .05$
Log_{10} Conc. of fibers $\geq$ 1.5 μm	Z_5 Log_{10} of Dust Loading	-.134	*
Log_{10} Conc. of fibers $\geq$ 6.0 μm	Z_2 Log_{10} of Percent Humidity	+.258	*
Log_{10} Conc. of fibers $\geq$ 6.0 μm	Z_4 Log_{10} of Air-to-Cloth Ratio	-.517	$P < .001$
Log_{10} Conc. of fibers $\geq$ 6.0 μm	Z_5 Log_{10} of Dust Loading	-.162	*

* Not significant at 0.10 probability level

Separate analyses were performed for each fiber size range. The analyses attempted to relate the independent variables and their common log transformations to the log of outlet concentrations. The log transforms provided the best fit to the data. Pertinent statistics for the equations of fibers of the two size ranges are given in Tables 31 and 32. The only significant variable is air-to-cloth ratio which tends to decrease the outlet concentration of asbestos fibers when it is increased. The equation for fibers greater than 1.5 μm is given in Table 31. By taking the antilog of this equation, the relation between outlet concentration and air-to-cloth ratio is

$$\text{outlet concentration} = \frac{30.9}{(\text{air-to-cloth ratio})^{0.430}}$$

This relation, along with the geometric mean and 90% confidence intervals for each level of air-to-cloth ratio, is plotted in Figure 14. From this plot, it is strikingly apparent that there is a large variation in the replicate counts for a given combination of independent variables. However, the fit of the regression line is good, given the variance of measurement; the F value for the lack of fit being 1.43 with an associated probability of 0.22.

The equation relating air-to-cloth ratio and outlet concentration of asbestos fibers of a size greater than 6.0 μm is given in Table 32. This equation can be transformed by taking its antilog. The resulting equation is then

$$\text{outlet concentration} = \frac{4.98}{(\text{air-to-cloth ratio})^{0.784}}$$

This relation, along with the geometric means and 90% confidence intervals for each level of air-to-cloth ratio, are plotted in Figure 15. The geometric means were calculated by taking the antilog of the arithmetic mean of log outlet concentration. Again, the variation in the data for given

Table 31. RESULTS OF REGRESSION ANALYSIS OF PHASE II FOR FIBERS GREATER THAN 1.5 μm

Dependent Variable:	Y_1 = Log_{10} of Outlet Concentration of fibers $\geq$ 1.5 μm		
Data Base:	All tests shown in Table 29		
Degree of Determination:	7.9%		
Residual Standard Deviation:	0.212		
Independent Variables			
Constant Term:	1.490		
Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Z_4, Log_{10} of air-to-cloth ratio	-0.430	0.245	0.084
Variables Not Significant ($P > 0.10$)			
Z_2, Log_{10} of relative humidity			
Z_5, Log_{10} of dust loading			

Regression Equation

$$Y_1 = 1.490 - 0.430Z_4$$

Table 32. RESULTS OF REGRESSION ANALYSIS OF PHASE II FOR FIBERS GREATER THAN 6.0 μm

Dependent Variable:	Y_2 = Log_{10} of Outlet Concentration of fibers $\geq$ 6.0 μm
Data Base:	All tests shown in Table 29
Degree of Determination:	26.72%
Residual Standard Deviation:	0.187

Independent Variables

Constant Term: 0.697

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Z_4, Log_{10} air-to-cloth ratio	-0.784	0.216	0.001

Variables Not Significant (P > 0.10)

Z_2, Log_{10} of relative humidity (P = 0.122)
Z_5, Log_{10} of dust loading

Regression Equation

$$Y_2 = 0.697 - 0.784Z_4$$

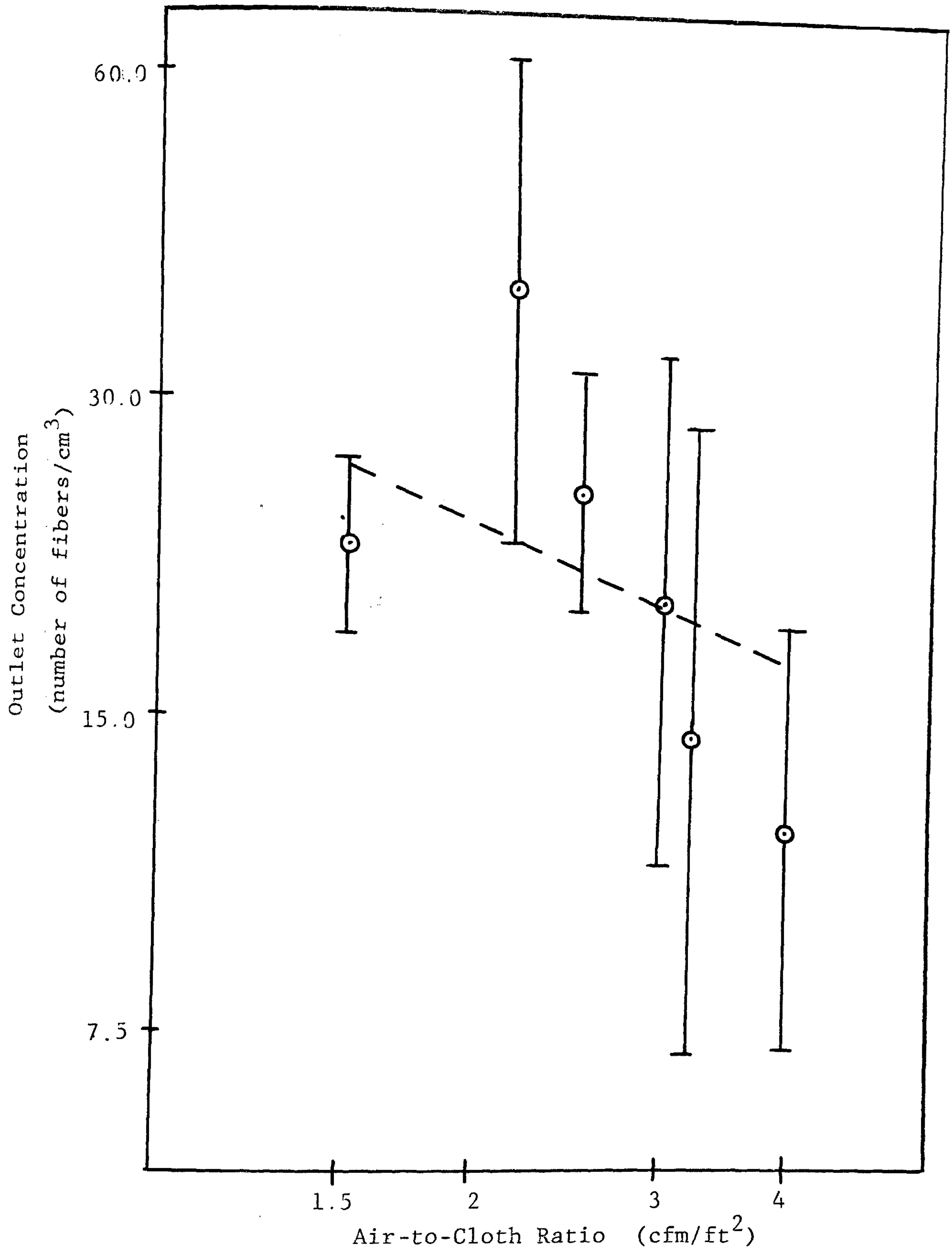

Figure 14. Geometric means, 90% confidence intervals, and the regression line for outlet concentration of fibers greater than 1.5 μm by air-to-cloth ratio - Phase II

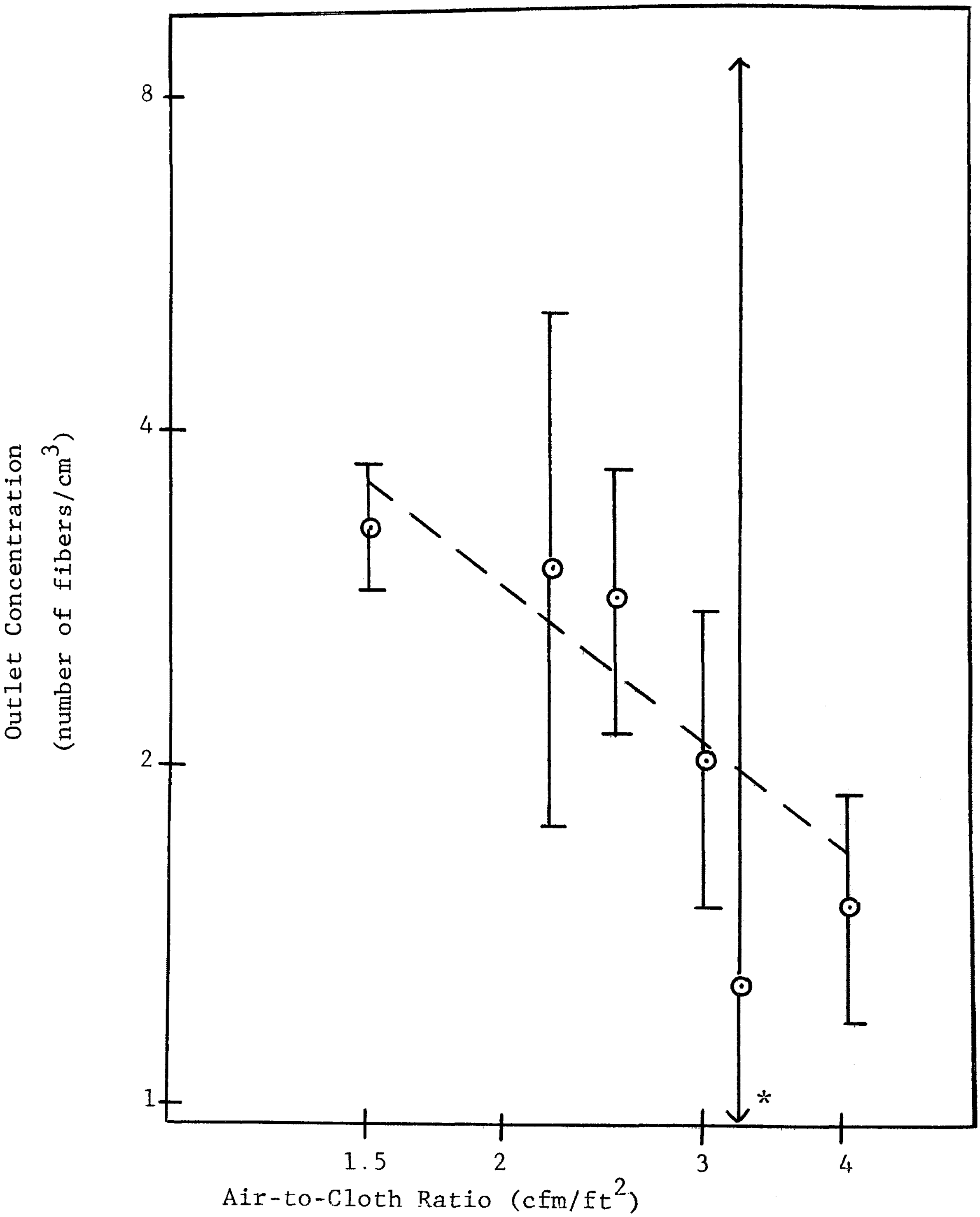

Figure 15. Geometric means, 90% confidence intervals, and the regression line for outlet concentration of fibers greater than 6.0 μm by air-to-cloth ratio - Phase II

* Confidence interval runs from 0.123 to 13.125.

values of air-to-cloth ratio is high. However, the 1.64 F value and 0.14 probability level for lack of fit demonstrate that the fit of the equation to the observations is not inappropriate.

The percentage of the total variance in the Phase II data base that can be attributed to experimental error is 80% for fibers greater than 1.5 μm and 59% for fibers greater than 6.0 μm. The experimental error was computed from the full replicate tests and the replicate counts made for each experimental run.

Conclusions from Phase II Results

Air-to-cloth ratio has been shown to be a significant variable to control for reducing the concentration of emitted asbestos fibers from a baghouse. For air-to-cloth ratios ranging from 0.46 to 1.22 $m^3/min/m^2$ (1.5 to 4.0 cfm/ft^2), an air-to-cloth ratio of 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2) tends to be the best value for reducing outlet concentrations of asbestos fibers.

The relative humidity and dust loading did not demonstrate an effect on outlet concentration. However, since the variance accounted for by these variables had to be greater than experimental error, these variables cannot be ruled out as factors that affect the outlet concentration. The experimental error is quite high and may have masked the effects of these variables. New techniques are necessary to precisely calculate the outlet concentration of fibers. For fiber sizes greater than 6.0 μm, the estimates of outlet concentration became more precise. For these fiber sizes, relative humidity had a positive correlation with outlet concentration that was slightly less than the 0.10 significance level. This means that humidity may decrease the outlet concentration of asbestos fibers. Although such a relation is not definitive, from a practical standpoint, low humidity should be maintained for baghouse operations, if possible.

Thus, Phase II results established that for air-to-cloth ratios within the range of 0.46 to 1.22 $m^3/min/m^2$ (1.5 to 4.0 cfm/ft^2), the higher air-to-cloth ratio decreases the outlet concentration of asbestos fibers from baghouses. And secondly, the results indicate that a low humidity may decrease outlet concentration particularly for fibers greater than 6.0 μm.

The demonstrated effect of outlet concentration decreasing with increasing air-to-cloth ratio is not the normally expected result; however, that effect has been extrapolated by some workers. In fact, ultra-high air-to-cloth ratios have been suggested as a possible means of increasing baghouse collection efficiency. It seems that, in the low range of air-to-cloth ratios studied, the highest air-to-cloth ratio of 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2) increases the rate of dust cake build-up in a manner that increases collection efficiency for asbestos cement waste.

A possible mechanism for the decrease in outlet concentration with reduced humidity may be forwarded from the experimental operating difficulties of Phases I and II. At very high relative humidity levels (75-85%), agglomeration of fibers due to condensation occurs to such a degree that much of the dust loading is collected in the inlet duct. Also, blinding of the fabric by moisture is evident, thus increasing the pressure drop. Assuming that this agglomeration still takes place at moderate levels of relative humidity, it can be postulated that many of the larger fibers grow to such size as to be settled in the gravity settling chamber and thus never reach the filter fabric. Therefore, the filtering dust cake build-up is less rapid and the dust cake consists of smaller fibers, some of them incapable of bridging the fabric pores, and the outlet concentration of fibers increases.

The lack of a significant effect on outlet concentration by dust loading may be explained in the following manner. At relatively high dust loadings, the filtering dust cake build-up is so rapid regardless of the level of dust loading, that the outlet concentration is decreased to such a degree that it is independent of the dust loading. Also, at the higher levels of relative humidity, a large fraction of the dust loading may be removed by gravity separation of the agglomerated fibers.

DISCUSSION OF PHASE III RESULTS

Phase III investigated the effects of shake frequency, amplitude, and the joint variation of period and duration of the mechanical shaking cycle on outlet concentration of asbestos. The air-to-cloth ratio, dust loading, and relative humidity were all held constant throughout this phase. All combinations of the independent variables were tested. Actual levels of the independent variables and observed concentrations of asbestos emissions are given in Table 33. As in Phase II, the bag fabric was cotton sateen, and the waste was from an asbestos cement plant. The outlet concentration of asbestos fibers was measured for two different size ranges ($\geq$ 1.5 μm and $\geq$ 5.0 μm). (The size range of $\geq$ 5.0 μm was substituted for that of $\geq$ 6.0 μm after the post Phase II critique in order to extend the limits of the more accurate larger size range to the limits of those fibers clearly and easily viewed. This size range also corresponds with those of the standard OSHA and AIHA methods.) A total of eight combinations of the shaking variables were examined. Estimates of outlet concentration were made two or three times for each combination by duplicate counts. These independent estimates of outlet concentration were treated as replicates to assess the fit of the regression equations and estimate the percent of overall variation that can be attributed to experimental error. Thus, there are eighteen tests listed in Table 33 comprised of eight different combinations of the independent variables.

The period and duration were treated as a single variable with only two levels. The first level represents a period of 120 minutes and a duration of 20 seconds. The second level represents a period of 16 minutes and a duration of 80 seconds. These levels and those of amplitude and frequency were combined to form a full factorial design.

Correlations Between Phase III Variables

Correlation coefficients, r, are given in Table 34 for each of the two outlet concentrations and their common log transforms. The range within which the associated probability, P, falls is indicated in conjunction with each correlation.

There are no significant correlations between the dependent variables and amplitude or frequency of the shake cycle. The correlations between all the dependent variables and the joint period and duration levels are significant. These correlations indicate that an increase in period with a corresponding decrease in duration reduces the outlet concentration of asbestos fibers.

Regression Analysis of Phase III

The candidate variables for predicting the emission concentration of asbestos fibers for each of the two size ranges were:

- Amplitude
- Frequency
- Period

Table 33. DATA BASE FOR PHASE III

Test No.	Comb. No.	X_8	X_6	X_7	Outlet Concentration (No. of fibers/cm^3)	
					≥ 1.5 μm	≥ 5.0 μm
1	1	120	0.875	1	1.1259	0.3181
2	1	120	0.875	1	3.5993	1.3189
3	1	120	0.875	1	3.0918	0.5064
4	2	16	3.500	5	5.0280	1.9670
5	2	16	3.500	5	5.5615	1.8882
6	3	16	0.875	5	17.1133	8.7649
7	3	16	0.875	5	10.0717	1.9002
8	3	16	0.875	5	7.7378	1.2269
9	4	16	3.500	1	4.6736	1.7063
10	4	16	3.500	1	6.6152	1.3160
11	5	16	0.875	1	8.1092	2.3924
12	5	16	0.875	1	7.6284	1.4663
13	6	120	0.875	5	3.2037	0.7395
14	6	120	0.875	5	3.0821	0.5956
15	7	120	3.500	1	1.4636	0.2758
16	7	120	3.500	1	2.2320	0.3370
17	8	120	3.500	5	2.4165	0.3365
18	8	120	3.500	5	2.9695	0.3247

X_8 - Period and duration setting
a period of 120 min dictates a duration of 20 sec
a period of 16 min dictates a duration of 80 sec

X_6 - Amplitude (cm)

X_7 - Frequency (cps)

Fixed Variables

X_1 - Asbestos cement waste

X_2 - 40-90% humidity

X_3 - Cotton sateen bag

X_4 - 0.92 $m^3/min/m^2$ (3.0 cfm/ft^2) air-to-cloth ratio

X_5 - 21 g/m^3 (9.2 gr/ft^3) dust loading

X_9 - No second bag

Table 34. CORRELATIONS BETWEEN PHASE III VARIABLES

Dependent Variable	Independent Variable		(N = 18) Correlation r	Probability P
Conc. of fibers ≥ 1.5 μm	X_6	Amplitude	-0.343	*
Conc. of fibers ≥ 1.5 μm	X_7	Frequency	+0.275	*
Conc. of fibers ≥ 1.5 μm	X_8	Period	-0.727	P < 0.01
Conc. of fibers ≥ 1.5 μm	X_9	Duration	+0.727	P < 0.01
Conc. of fibers ≥ 5.0 μm	X_6	Amplitude	-0.239	*
Conc. of fibers ≥ 5.0 μm	X_7	Frequency	+0.239	*
Conc. of fibers ≥ 5.0 μm	X_8	Period	-0.528	0.02 < P < 0.01
Conc. of fibers ≥ 5.0 μm	X_9	Duration	+0.528	0.01 < P < 0.01
Log_{10} Conc. of fibers ≥ 1.5 μm	Z_6	Log_{10} Amplitude	-0.276	*
Log_{10} Conc. of fibers ≥ 1.5 μm	Z_7	Log_{10} Frequency	+0.290	*
Log_{10} Conc. of fibers ≥ 1.5 μm	Z_8	Log_{10} Period	-0.833	P < 0.01
Log_{10} Conc. of fibers ≥ 1.5 μm	Z_9	Log_{10} Duration	+0.833	P < 0.01
Log_{10} Conc. of fibers ≥ 5.0 μm	Z_6	Log_{10} Amplitude	-0.274	*
Log_{10} Conc. of fibers ≥ 5.0 μm	Z_7	Log_{10} Frequency	+0.193	*
Log_{10} Conc. of fibers ≥ 5.0 μm	Z_8	Log_{10} Period	-0.819	P < 0.01
Log_{10} Conc. of fibers ≥ 5.0 μm	Z_9	Log_{10} Duration	+0.819	P < 0.01

* Not significant at 0.10 probability level

of the shake cycle. The period of the cycle was used in lieu of the duration of the cycle. Both of these variables had a perfect inverse correlation. Thus, the effects of period on the outlet concentration are the effects of both period and duration jointly.

Separate analyses have been performed for each set of fiber lengths. The common log transformation of the variables provided the best fit to the data. The pertinent statistics for each equation are given in Tables 35 and 36.

The equation for the relation between outlet concentration of asbestos fibers greater than 1.5 μm and the mechanical shaking variables is given in Table 35. By taking the antilog of this equation, the relation becomes

$$\text{concentration} = \frac{39.90}{(\text{period})^{0.557} \cdot (\text{amplitude})^{0.270}}$$

Thus, as period and amplitude are increased, the outlet concentration is reduced. However, since period and duration were varied jointly, an increase in period must be accompanied by a corresponding decrease in duration for this relation to hold. Plots of this equation with the corresponding 90% confidence intervals about the geometric means at various amplitudes and period levels are given in Figures 16 and 17.

The equation for the relation between outlet concentration of asbestos fibers greater than 5.0 μm and the mechanical shaking variables is given in Table 36. By taking the antilog of this equation, the relation becomes

$$\text{concentration} = \frac{18.64}{(\text{period})^{0.736} \cdot (\text{amplitude})^{0.360}}$$

This equation is functionally the same as the equation for fibers greater than 1.5 μm. Plots of this equation with the corresponding 90% confidence intervals about the geometric

Table 35. RESULTS OF REGRESSION ANALYSIS OF PHASE III FOR FIBERS GREATER THAN 1.5 μm

Dependent Variable:	Y_1 = Log_{10} of Outlet Concentration of fibers $\geq$ 1.5 μm		
Data Base:	All tests shown in Table 33		
Degree of Determination:	77%		
Residual Standard Deviation:	0.1538		

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Constant Term:	+1.600	-	-
Z_8, Log_{10} of period	-0.557	0.083	<0.001
Z_6, Log_{10} of amplitude	-0.260	0.121	0.040

Variables Not Significant ($P > 0.10$)

Z_7, Log_{10} frequency

Regression Equation

$$Y_1 = 1.600 - 0.260Z_6 - 0.557Z_{10}$$

Table 36. RESULTS OF REGRESSION ANALYSIS OF PHASE III FOR FIBERS GREATER THAN 5.0 μm

Dependent Variable:	Y_2 = Log_{10} of Outlet Concentration of fibers $\geq$ 5.0 μm		
Data Base:	All tests shown in Table 33		
Degree of Determination:	74.5%		
Residual Standard Deviation:	0.2178		

Variables of Significance	Regression Coefficient	Standard Error	Prob. Level
Constant Term:	1.270	-	-
Z_8, Log_{10} of period	-0.736	0.1173	<0.0001
Z_6, Log_{10} of amplitude	-0.360	0.1716	0.0511

Variables Not Significant ($P > 0.10$)

Z_7, Log_{10} of Frequency

Regression Equation

$$Y_2 = 1.270 - 0.360Z_6 - 0.736Z_8$$

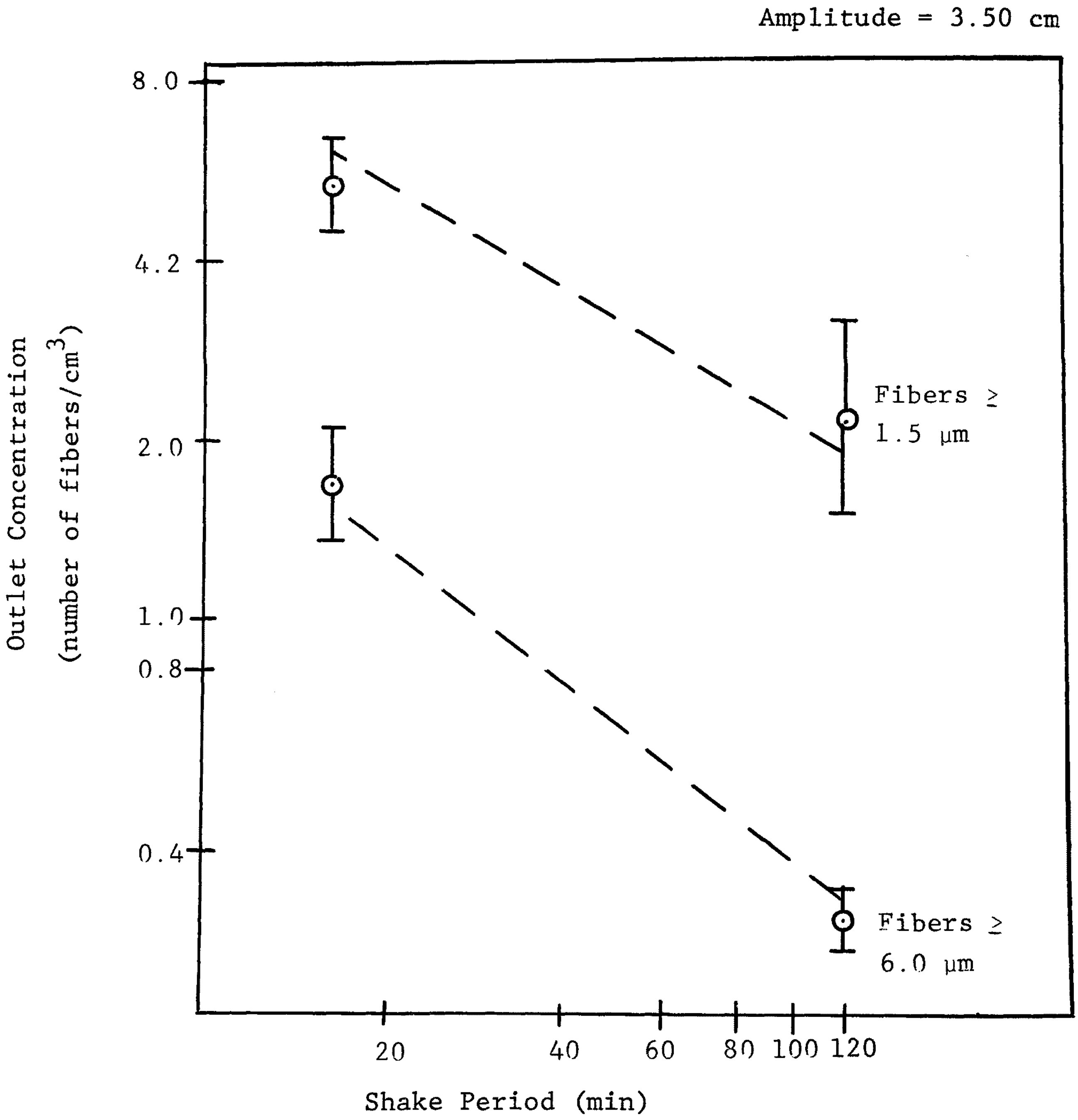

Figure 16. Geometric means, 90% confidence intervals, and the regression lines for outlet concentration of asbestos fibers by shake period for an amplitude = 3.50 cm - Phase III

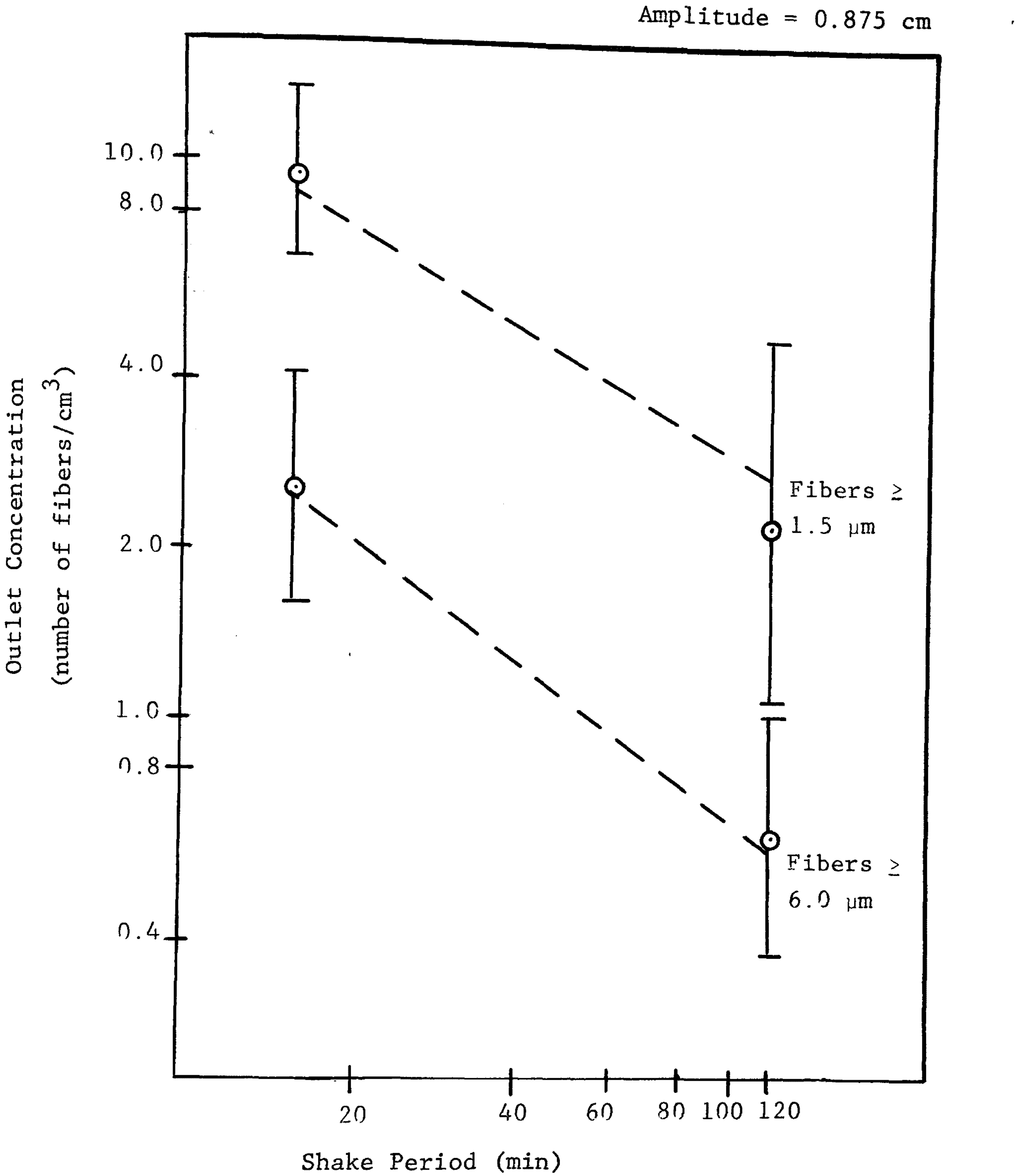

Figure 17. Geometric means, 90% confidence intervals, and the regression lines for outlet concentration of asbestos fibers by shake period for an amplitude = 0.875 cm - Phase III

means at various amplitude and period levels are also shown in Figures 16 and 17.

The percentage of the total variance in the data base that can be attributed to experimental error is 27% for fibers greater than 1.5 μm and 39% for fibers greater than 5.0 μm. The experimental error for Phase III was computed from replicate counts of outlet concentration. No full replicate experimental runs were made in this phase.

Conclusions from Phase III Results

Both the correlation and regression analysis establish the joint variation of period and duration as the most important mechanical shaking factor affecting outlet concentration for both asbestos fiber sizes. Outlet concentration was the least when a long period (120 min) and a short duration (20 sec) were used. The regression analysis also indicated that amplitude may have a significant effect on outlet concentration. The higher amplitude (3.5 cm) had an overall lower outlet concentration for both fiber sizes. However, amplitude was not by itself significantly correlated with the outlet concentrations.

This anomaly occurred because the values of period and amplitude were not completely uncorrelated in the experiment. Since period was included in the equation, one can consider that amplitude is a significant factor in reducing outlet concentration when the effects of period and duration are controlled.

The percent of variance attributed to experimental error was less in Phase III than Phase II. However, this percentage was between 25 and 40%, and a method for reduction of this error would be useful in any follow-up work.

As substantiated by the Royco traces of total particles (see Figure 6), the outlet concentration of fibers is reduced by using a combination of long period and short duration shaking. The long period allows the filtering dust cake to remain intact and at high efficiency for longer periods of operation than do several short periods. The short duration shake of 20 sec allows removal of the major portion of the dust cake in order to reduce pressure drop[3] while minimizing the disturbance of the filtering efficiency of the dust cake. The higher levels of either shaking amplitude or frequency reduce the maximum pressure drop during a cycle by increasing dust release. However, it seems that the greater amplitude better maintains the filtering characteristics of the dust cake than does the greater frequency. Thus, amplitude becomes important as a means of reducing pressure drop for the long period and short duration cycle while maintaining efficiency of collection.

DISCUSSION OF PHASE IV RESULTS

Phase IV investigated the effects of placing a second bag in series with the original bag on the concentration of asbestos emissions. The two bags were made of cotton sateen fabric. The other variables were held constant (see Table 37).

As a secondary investigation, the stabilization period was varied for this phase of experimentation. Prior to this, a 24-hour period of stabilization had been used. The outlet concentrations of asbestos fibers were measured for two different size ranges ($\geq$ 1.5 µm and $\geq$ 5.0 µm). The data generated by this phase consisted of three combinations of tests; one combination for the three different periods of stabilization time. First, the effect of stabilization time on the outlet concentration of asbestos fibers was investigated. Then the effects of a bag in series was assessed.

The data generated from Phase IV were compared with that of combinations No. 7 and No. 8 of Phase III (refer to Table 33) to assess the effects of using a double bag

Table 37. PHASE IV INDEPENDENT VARIABLES AND THEIR DESIRED LEVELS

Variable	Level
X_1, Waste Type	1. Asbestos Cement
X_2, Humidity	1. 60-90%
X_3, Bag Type	1. Cotton Sateen
X_4, Air-to-Cloth Ratio	1. 0.92 $m^3/min/m^2$ (3.0 cfm/ft^2)
X_5. Dust Loading	1. 21 g/m^3 (9.2 gr/ft^3)
X_6, Amplitude of Shake Cycle	1. 3.5 cm (1.378 in.)
X_7, Frequency of Shake Cycle	1. 1.0 cps
X_8, Period and Duration of Shake Cycle	1. Period - 120 min Duration - 20 sec
X_9, Number of Bags	1. 1 2. 2
X_{10}, Stabilization Period	1. 24 hours 2. 70 hours 3. 164 hours

arrangement over that of a single bag. Combinations No. 7 and No. 8 were found appropriate for comparison since the independent variables, other than number of bags, humidity, and frequency of shake cycle, were identical. Phases I, II, and III established that the latter two variables did not affect outlet concentration beyond the level of experimental error.

Stabilization Period Results

The data base for Phase IV is given in Table 38. Two estimates of outlet concentration were made for each combination. The mean and 90% confidence limits for the outlet concentration for each stabilization period for both fibers greater than 1.5 μm and 5.0 μm are given in Table 39 and plotted in Figures 18 and 19. The confidence intervals overlap the geometric means for all three stabilization times for fibers greater than 1.5 μm, thus indicating that there is no significant effect of stabilization time on outlet concentration for fibers greater than 1.5 μm beyond the experimental error of this phase.

For fibers greater than 5.0 μm, the lowest stabilization time (24 hours) produced a confidence interval that does not overlap the means of the other stabilization levels. The geometric mean of the outlet concentration for this stabilization time, 0.322, is lower than that of the other two stabilization times. Thus, for fibers greater than 5.0 μm with all other conditions being constant, the outlet concentration is significantly lower for a stabilization time of 24 hours as compared with stabilization times of 70 and 164 hours. No other conclusions other than this should be drawn from these results.

Results of Two Bags in Series

Since frequency was not established as a significant variable on outlet concentration during Phase III,

Table 38. DATA BASE FOR PHASE IV

Test No.	Comb. No.	Stabilization Period (hrs)	Outlet Concentration (No. of fibers/cm^3)	
			$\geq$ 1.5 μm	$\geq$ 6.0 μm
1	1	24	1.8702	0.3169
2	1	24	3.0754	0.3278
3	2	70	4.2941	0.8554
4	2	70	4.8472	0.7317
5	3	164	3.5959	0.5193
6	3	164	3.9890	0.5628

Fixed Variables

X_1 - Asbestos cement waste
X_2 - 60-90% relative humidity
X_3 - Cotton sateen bag
X_4 - 0.91 $m^3/min/m^2$ (3.0 cfm/ft^2) air-to-cloth ratio
X_5 - 21 g/m^3 (9.2 gr/ft^3) dust loading
X_6 - 3.5 cm (1.378 in.) amplitude of shake cycle
X_7 - 1.0 cps frequency of shaking
X_8 - Shake period 120 min; duration 20 sec
X_9 - Two bags in series

Table 39. GEOMETRIC MEAN AND 90% CONFIDENCE LIMITS OF OUTLET CONCENTRATION FOR DIFFERENT STABILIZATION PERIODS

Stabilization Period	Outlet Concentration*							
	Fibers > 1.5 μm				Fibers > 5.0 μm			
	N	Geometric Mean	Confidence Limits Lower	Confidence Limits Upper	N	Geometric Mean	Confidence Limits Lower	Confidence Limits Upper
24	2	2.632	0.449	11.523	2	0.322	0.290	0.359
70	2	4.562	3.112	6.688	2	0.791	0.483	1.295
164	2	3.787	2.730	5.255	2	0.541	0.419	0.697

* No. of fibers/cm^3.

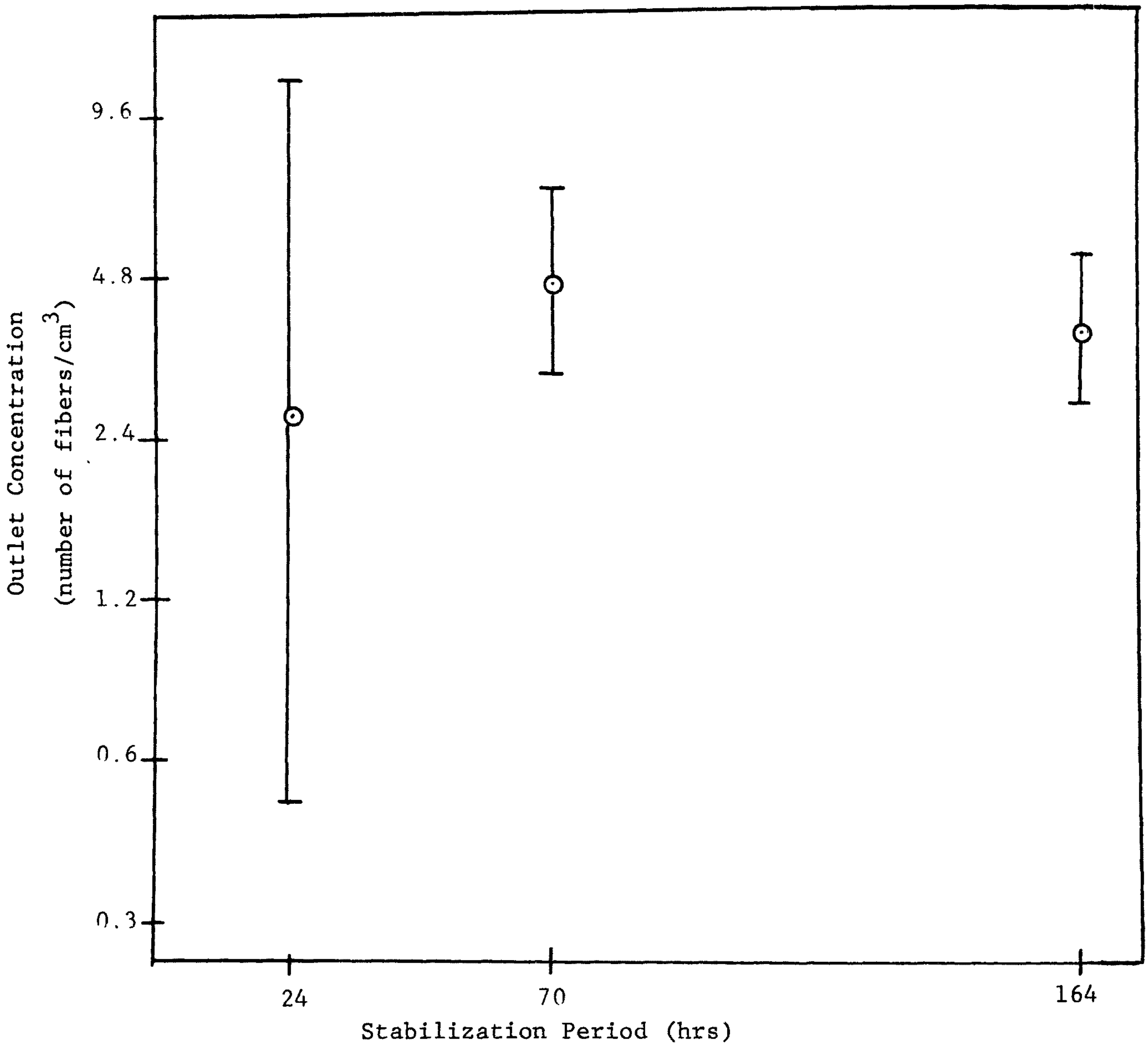

Figure 18. Estimates of geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 1.5 μm by stabilization period - Phase IV

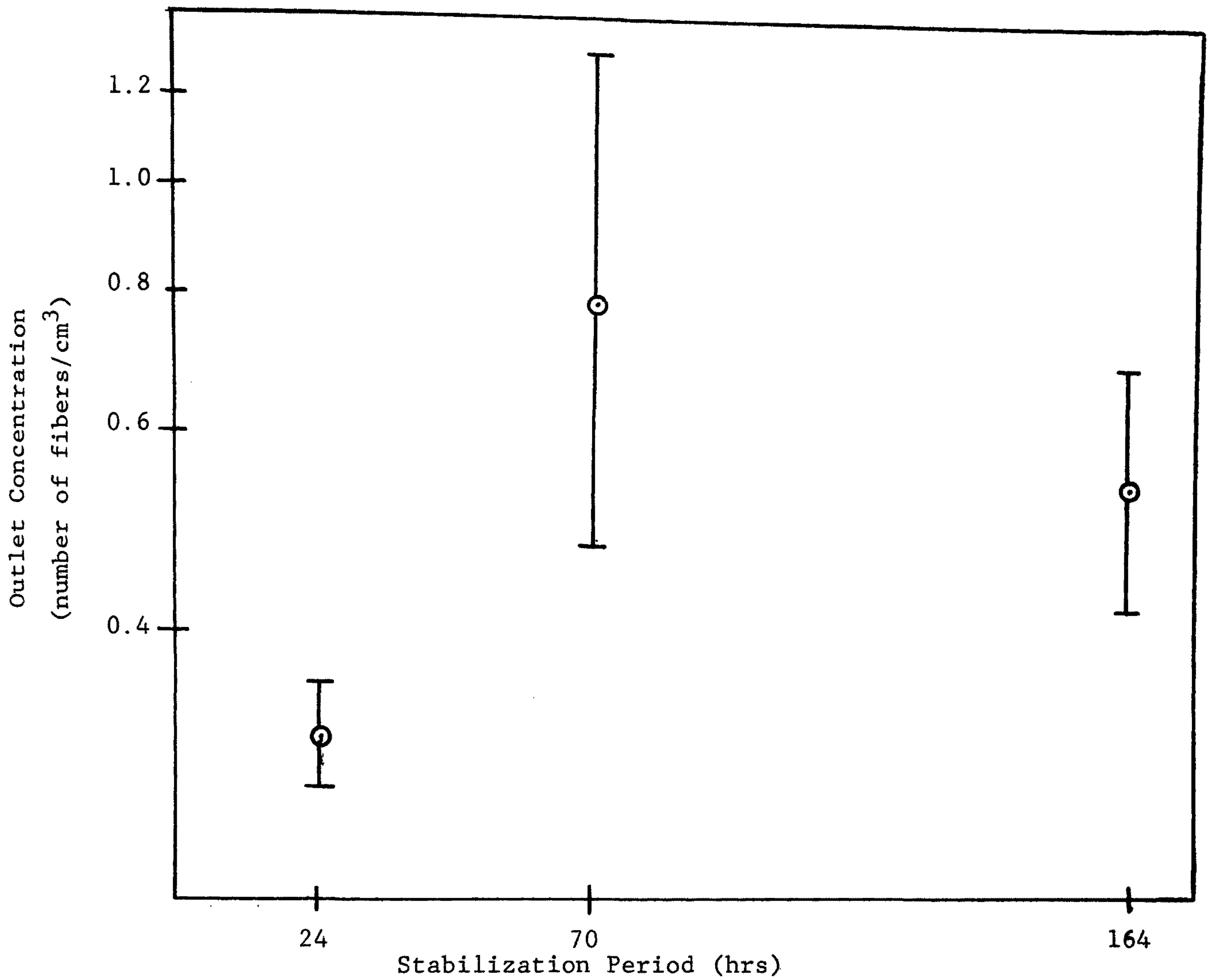

Figure 19. Estimates of geometric mean and their 90% confidence intervals for outlet concentration of asbestos fibers greater than 5.0 μm by stabilization period - Phase IV

combinations No. 7 and No. 8 were pooled to calculate the mean and 90% confidence intervals of outlet concentration of a baghouse with only one bag. These two combinations are similar to the combinations of variables tested for a baghouse with two bags in series. Thus, the mean and 90% confidence intervals of Phase III combinations No. 7 and No. 8 are used to compare the effects of using one or two bags.

Since stabilization time did not have an effect on outlet concentration greater than the experimental error, the outlet concentration of the three stabilization levels were pooled to measure bag series effect for fibers greater than 1.5 μm. However, only the two estimates of outlet concentration for a stabilization of 24 hours were pooled to compute the geometric mean and 90% confidence limits of outlet concentration for fibers greater than 5.0 μm. This is the same stabilization period that was used in Phase III.

Again, the log transforms of outlet concentration are employed to compare the effects of bag series. The geometric means and their 90% confidence intervals for these tests are given in Table 40 and plotted in Figure 20. For fibers greater than 5.0 μm in length, the confidence interval for the single bag tests overlaps the geometric mean of the tests using two bags in series. This indicates that for fibers greater than 5.0 μm, the difference between using two bags in series or just a single bag is not significantly greater than the experimental error of the tests.

However, for fibers greater than 1.5 μm in length, the confidence intervals for both one and two bags do not overlap each other's geometric means. Thus, the effect of using one or two bags is significantly different for fiber lengths greater than 1.5 μm. The better alternative in this case is using a single bag rather than two bags in series since the mean outlet concentration for a single bag was lower than for the two bag arrangement.

Table 40. GEOMETRIC MEAN AND 90% CONFIDENCE LIMITS OF OUTLET CONCENTRATION FOR ONE AND TWO BAG BAGHOUSES

Number of Bags	Outlet Concentration*							
	Fibers ≥ 1.5 μm				Fibers ≥ 5.0 μm			
	N	Geometric Mean	Confidence Limits Lower	Confidence Limits Upper	N	Geometric Mean	Confidence Limits Lower	Confidence Limits Upper
1	4	2.200	1.551	3.122	4	.317	.284	.355
2	6	3.460	2.618	4.573	2	.322	.290	.352

* No. of fibers/cm^3.

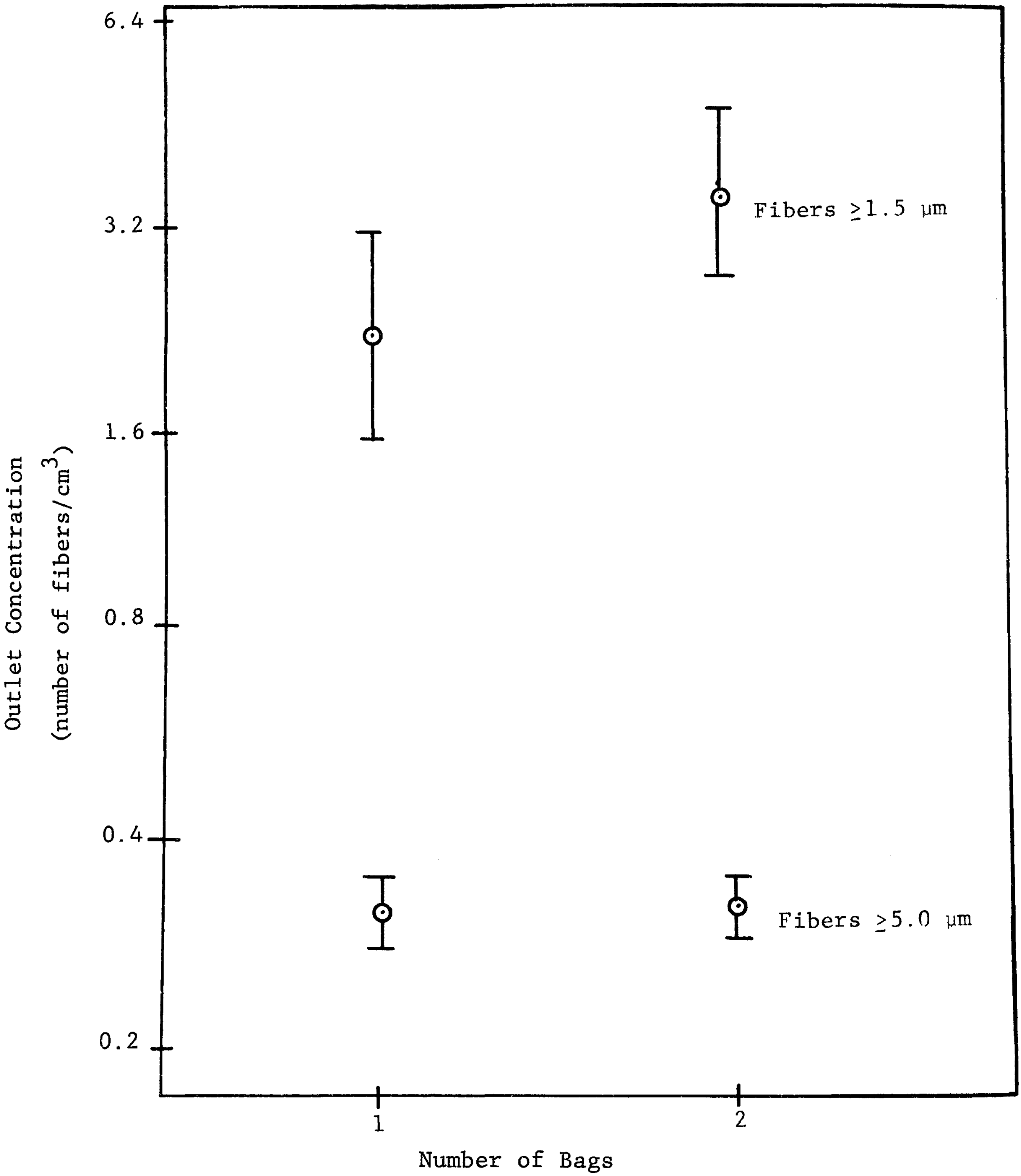

Figure 20. Estimates of geometric mean and their 90% confidence limits for outlet concentration of asbestos fibers by stabilization period - Phase IV

Assuming that the inlet concentration to the second baghouse in Phase IV is the same as the outlet concentration of the single baghouse in Phase III for the same operating conditions, it would appear that the second baghouse cannot maintain the filtering dust cake efficiency when challenged with such low loadings. As stated previously, the filtering dust cake of the second baghouse may not even be capable of maintaining the same filtering characteristics when the inlet loading is very low. However, when the first baghouse is being stabilized and the inlet loading to the second one is higher, the series outlet concentration is lower than that of a single baghouse.

SUMMARY OF THE RESULTS OBTAINED FROM PHASES I THROUGH IV

The four phases of the experimental program have established the individual effects of factors that can be manipulated by the users and manufacturers of baghouses employed to reduce the outlet concentration of asbestos fibers from enclosed sources. Of the factors listed in Table 6, the type of bag, air-to-cloth ratio, shake amplitude, and the shake cycle period and duration jointly, significantly affect the outlet concentration of asbestos fibers. To reduce the outlet concentration of asbestos fibers, the levels of these variables considered in this study should be set as follows:

- Bag type - cotton sateen
- Air-to-cloth ratio - 1.22 $m^3/min/m^2$ (4.0 cfm/ft^2)
- Amplitude of shake cycle - 3.5 cm(1.378 in.)
- Period and duration of shake cycle - 120 min and 20 sec

These recommendations are based on the results of the individual effects of the levels of factors considered and degree of precision of the measurement of outlet concentration attained.

SECTION 8

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APPENDIX A

METHODS OF ANALYSIS

Statistical Methods

The effects of the independent variables or their appropriate transformations on the dependent variable, outlet concentration of asbestos fibers, or its appropriate transformation, have been analyzed in three ways. Correlation coefficients have been computed between the independent and dependent variables. Ninety percent confidence intervals have been constructed about the mean of concentration levels of particular variables such as bag fabric and type of asbestos waste. Regression equations have been developed for variables in each of the experimental design phases except Phase IV.

The regression equations were developed by the stepwise least-squares method. Prior to the development of the actual regression equations for each phase, a mathematical model was in each instance formulated expressing the way in which the relevant independent variables might be functionally related to the dependent variable. The general form of the mathematical models employed was a linear expression of the independent variables or their appropriate transformations. The terms in each model were candidates for inclusion in the fitted regression equation.

The general model takes the form

$$Y = b_0X_0 + b_1X_1 + . . . + b_NX_N + e = \hat{Y} + e$$

where Y stands for the observed values of the dependent variable or its appropriate transformation, $\hat{Y}$ stands for the corresponding values of the dependent variable or its transformation from the expression involving the X's and the b's; the X's are the values of the independent variables or their transformations, the b's are the coefficients to be estimated from the data, and e represents the differences between the observed and the computed values of the dependent variables due to residual variation in the observations.

The set of data for each model for each phase was analyzed by computer (Univac 1108) for the purpose of selecting the terms (X's) to appear in the equation and computing the values of the regression coefficients (b's) and other relevant statistics. The computer program used, a modification of BMD-02R, performs stepwise multiple regression -- i.e., the equation is built up, term by term, by introducing at each step that candidate term which will result in the greatest reduction in the sum of squared deviations between the observed values of the dependent variable and the values computed from the resulting regression equation. A cutoff point for this process can be set by the analyst through the choice of a critical "F" value. The F value associated with the coefficient of a term (b's) in a regression equation is the square of the ratio of the coefficient to its standard error. In other words, no candidate term is introduced into the equation unless the value of the coefficient of that term is a specified multiple of its standard error. This excludes from the equation terms with coefficients of a magnitude that could readily arise due merely to the inevitable residual variation between measurements. Thus, no term (X's) is considered to have a significant effect on the dependent variable unless the variation resulting from different values of this term is greater than that resulting from measurement variation.

By inserting various values of the terms in the final equation, the effects on the dependent variable become readily apparent. For those variables represented by terms that did not enter into the final equation, their effect on the dependent variable is equal to or less than the multiple of the F level and residual variation due to measurement and, thus, are considered to have relatively little effect on the dependent variable.

The 90% confidence intervals constructed for the particular dependent variables are based on the t-distribution. The interval spanned indicates with a 90% probability where the population mean of the dependent variable might lie. When an interval overlaps the mean of a different level of a variable, the population mean of the outlet concentration of asbestos for each of these two levels are not significantly different.

The correlation coefficients computed are standard Pearson Product correlations. Correlations vary from -1 to +1 with both -1 and +1 indicating perfect correlation between two variables and a zero indicating no correlation at all. The probability that a correlation is significantly different from zero can be computed. As correlations tend to -1, the relation between two variables tends to be more inversely related. As correlations tend to +1, the relation between two variables tends to be more directly related. A knowledge of the correlations between the independent variables of this study and the observed concentrations of asbestos emissions provides a straightforward method for assessing the type and strength of the effects of the independent variables but does not provide a functional relation between them. For a relation between the independent variables and the emissions of asbestos fibers, a regression equation must be constructed.

From the results of these three types of analyses, the affects of the ten baghouse variables on the outlet concentration of asbestos fibers can be determined.

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16. ABSTRACT The report gives results of an experimental study to optimize control of emissions of asbestos fibers using a baghouse. Baghouse operating parameters found to be statistically significant in reducing asbestos emissions were: bag fabric, waste type, air-to-cloth ratio, relative humidity, period between shakes and duration of shaking, and shaking amplitude. Values of these operating parameters are recommended for industry usage to significantly reduce outlet concentrations of asbestos. These operating conditions resulted in pressure drops across the fabric filter that were quite reasonable (= or < 2.0 in. H2O). The most economical alternatives of cotton sateen bags, high air-to-cloth ratio, and low pressure drop operating conditions were found to be among the most significant in reducing asbestos emissions. Among the recommendations are: an air-to-cloth ratio of 1.22 cu m/min/sq m (4.0 cfm/sq ft), a combination of period between shakes of 120 min with a shaking duration of 20 sec, and a shaking amplitude of 3.500 cm.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Measurement	Air Pollution Control	13B
Asbestos	Air Filters	Stationary Sources	11E,08G
Fibers	Fabrics	Enclosed Sources	11E
Dust	Filters	Particulate	11G
Dust Collectors		Baghouses	13A
Assessment		Fabric Filters	14B

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