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Exposures and Mortality Among Chrysotile Asbestos Workers. Part I: Exposure Estimates

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A detailed study of plant processes and dust control methods over the period 1930–1975 was conducted in an asbestos textile plant processing chrysotile. Linear statistical models for reconstructing historic dust exposure levels, taking into account textile processes, dust control measures, and job assignments, were developed. Parameters of these statistical models were estimated using 5,952 industrial hygiene sampling measurements covering the period 1930–1975. For most textile operations, exposure levels were significantly reduced by about 1940, when most engineering dust control measures were in place. Results of the exposure estimates indicated "precontrol" exposure levels to range from 3 to 78 fibers/cc with typical levels well above 10 fibers/cc. After textile operations were provided with dust control measures, estimated exposure levels ranged from 3 to 17 fibers/cc and were usually in the range of 5 to 10 fibers/cc. These exposure estimates were combined with an assessment of mortality among workers at this plant to investigate exposure-response relationships. Exposure-response results are presented in the companion manuscript in this volume.

Key words: chrysotile, asbestos, textile, exposures, controls

INTRODUCTION

The term "asbestos" is the generic name for a group of naturally occurring mineral silicates that have commercial value due to their fibrous morphology. There are six fibrous silicates currently classified as asbestos by various governmental and industrial groups. These include the fibrous serpentine, mineral chrysotile, and the fibrous amphibole minerals crocidolite, amosite, anthophyllite, actinolite, and tremolite. In the United States, more than 95% of all asbestos used is of the chrysotile variety [Clifton, 1975].

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Epidemiologic studies have repeatedly demonstrated associations between exposure to asbestos and increased mortality due to nonmalignant respiratory diseases (asbestosis), lung cancer, pleural and peritoneal mesothelioma, and in some studies, gastrointestinal cancer; these data have been adequately reviewed elsewhere [IARC, 1977; Selikoff and Lee, 1978; NIOSH, 1980]. In most industries, blends of several fiber types typically have been used; thus epidemiologic studies of workers exposed to a single fiber type such as chrysotile are rare. Mortality among chrysotile miners and millers has been studied [McDonald et al, 1980; Rubino et al, 1979; Nicholson et al, 1979]; however, only one small study has been conducted analyzing mortality among factory workers using chrysotile [Weiss, 1970].

To provide further information on mortality risks associated with chrysotile exposures, a retrospective mortality study was conducted among a cohort of asbestos textile workers. Methods for reconstructing historic dust exposures, taking into account jobs and controls, were developed and combined with the mortality data to evaluate exposure-response relationships for lung cancer and nonmalignant respiratory diseases. This paper describes plant processes and controls and methods used to estimate historic exposure levels. Mortality data and exposure-response analyses are presented in the companion manuscript in this volume.

MATERIALS AND METHODS

Description of the Facility

The plant under study began production of asbestos packing materials for steam engines and pumps in 1896. In 1901 high pressure packings were added and asbestos textiles (yarns and cloths) were first produced in 1909. Production of asbestos textiles remained stable, and in 1937 operations were expanded to include manufacture of rubber rollers and rubber linings for pipes and tanks used in the paper, textile, and chemical industries. In 1955, additional facilities were added for production of roll covers used on flatwork ironers.

Textile production operations at this plant were always concentrated in five buildings of one or two stories each. Fortunately, rubber production facilities were always physically separated from textile operations with relatively little mobility of employees between the two. These factors served to minimize confounding exposures in rubber operations on mortality results.

Chrysotile is the only type of asbestos ever processed at this plant as a raw fiber. A small amount of crocidolite yarn was woven into a tape or made into a braided packing beginning in the 1950s until approximately 1975. Crocidolite was never carded, spun, or twisted. The total quantity of crocidolite ever processed was extremely small (less than 2000 pounds), and all weaving of crocidolite tapes was done wet on a single loom; thus exposures were low. According to company personnel, an average of approximately 6-8 million pounds of chrysotile were processed annually at this point. Chrysotile was received from Quebec, British Columbia, and Rhodesia.

Plant Processes and Controls

Processes for production of asbestos textiles at this plant were typical of this industry and remained remarkably unchanged for the period 1940-1975.

Historically, the plant studied has been progressive in the application of modern dust control measures in asbestos textile production. This plant was the subject of an extensive study of dust control measures and occupational exposures by the U.S. Public Health Service in January and February, 1937 [Page and Bloomfield, 1937]. Page and Bloomfield stated regarding this plant: "These results [of the study] should not be interpreted as representing the maximum possible efficiency in the control of asbestos dust, but it is believed that they are representative of the best practice in this country at this time."

Subsequent to the Page and Bloomfield study, additional local exhaust ventilation was added to twisting frames and cop (shuttle) winding machines. At the request of the company, an industrial hygiene study was conducted in November, 1937 to evaluate the effectiveness of these added controls [Brown, 1937]. Plant processes remained fairly constant over the period 1940–1975, with most engineering controls being in place by 1940.

For the current study, an attempt was made to document changes in textile processes and engineering control measures between 1930 and the study ending date of 1975. This was a painstaking process involving detailed studies of Public Health Service, insurance carrier, state and plant engineering records. These data were supplemented through discussions with long-time plant engineering personnel employed at the plant for the greater part of the study period. A summary of important control measures is given in Table I. Detailed process and control descriptions may be found elsewhere [Dement, 1980].

Most engineering controls in this plant were in place by 1940 and their effectiveness documented by the U.S. Public Health Service Study [Page and Bloomfield, 1937]. Photographs of textile operations demonstrating engineering controls in place before 1940 are shown in Figures 1–10. In addition to local exhaust ventilation shown in these figures, some spinning frames were supplied with wetting rolls to dampen rovings prior to twisting. In addition, wet weaving was begun in approximately 1937.

TABLE I. Summary of Engineering Controls by Operation in Textile (1930–1975)

Operation	Dates	Summary of engineering controls
Fiber preparation		
Crushing	1930–1965	No local exhaust ventilation. Phased out in approximately 1965
Opening	1930–1975	Openers and combers enclosed and exhausted, screens exhausted
Blending	1930–1945	Blending done in exhausted blending booths (canopy hood)
	1945–1964	Blending done on elevated station without ventilation
	1964–1975	Automatic blending with total enclosure and exhaust
Picking and combing	1930–1975	Machines enclosed and exhausted, screens exhausted
Carding	1935–1975	Carding machines enclosed and exhausted at 11 points
Spinning	1930–1975	No local exhaust ventilation, some wet spinning since 1966, although modest
Twisting	1938–1975	Bottom of twisting frame enclosed and exhausted
Winding		
Foster	1937–1975	Individual conical hood around each spindle with exhaust
Universal	1930–1975	No ventilation
Cop	1937–1975	Exhaust on each spindle
Weaving	1937–1975	Combination of local exhaust and wet weaving, light weaving done wet since 1930
Inspection	1937–1975	Exhaust at cleaning brushes
Braiding	1930–1975	Exhaust on some braiders, improved by better enclosure in 1958
Waste recovery	1930–1975	Exhaust and ventilation on willower and roving reopener

Fig. 1. Asbestos opener showing hood, pneumatic pick-up, and vibrating screens in 1937.

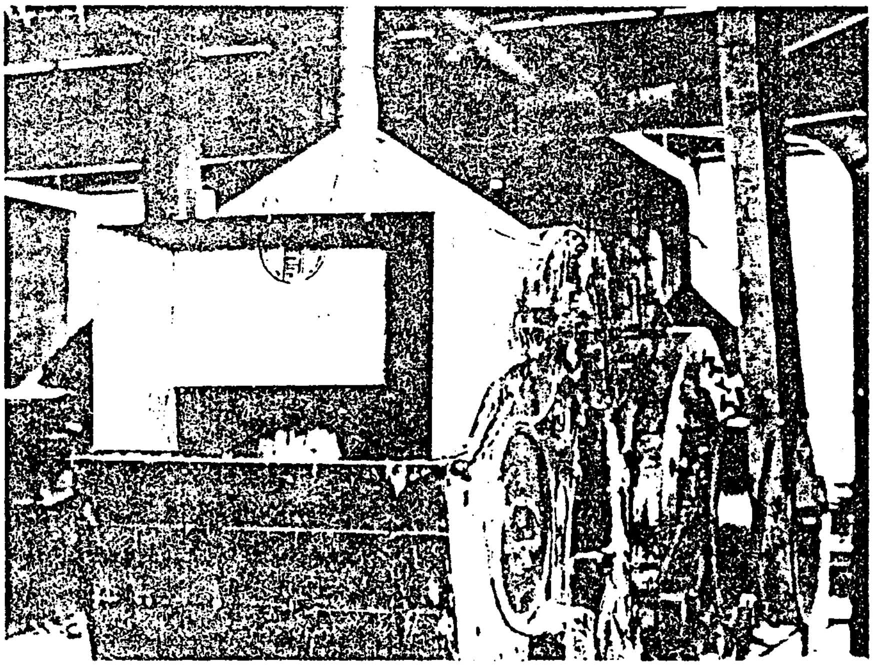

Fig. 2. Picker machines showing ventilation at charging hopper in 1937.

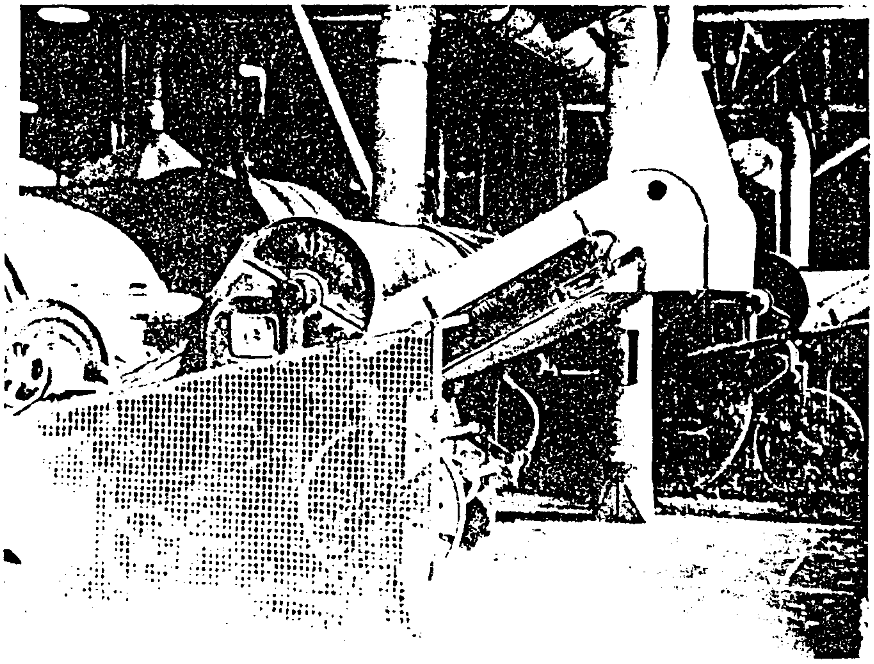

Fig. 3. Picker machines in 1937 showing ventilation at discharge apron.

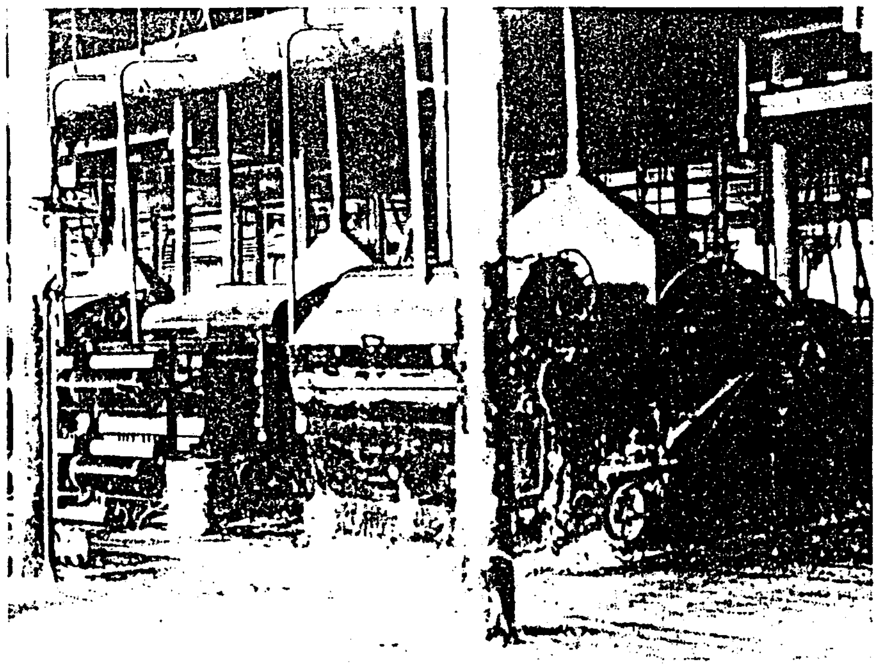

Fig. 4. A 1937 photograph showing carding machine ventilation.

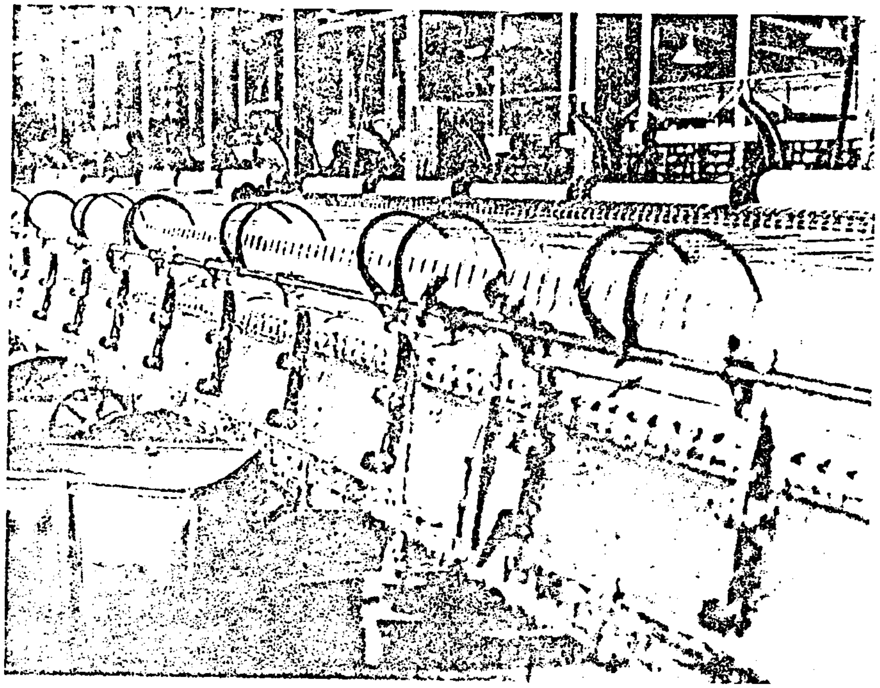

Fig. 5. Mule spinning frame without local exhaust ventilation in 1937.

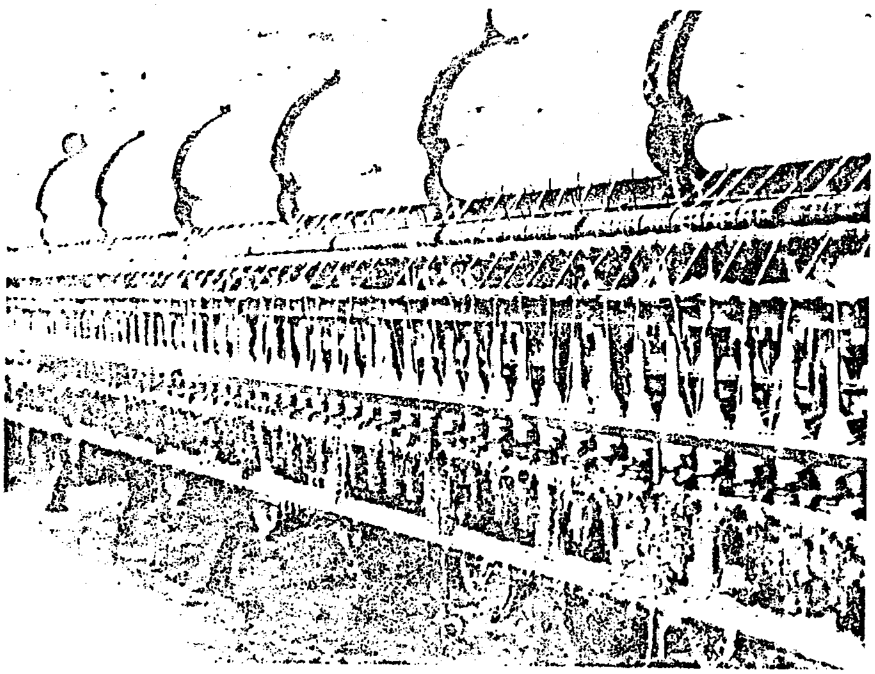

Fig. 6. Ring spinning frame without local exhaust ventilation in 1937.

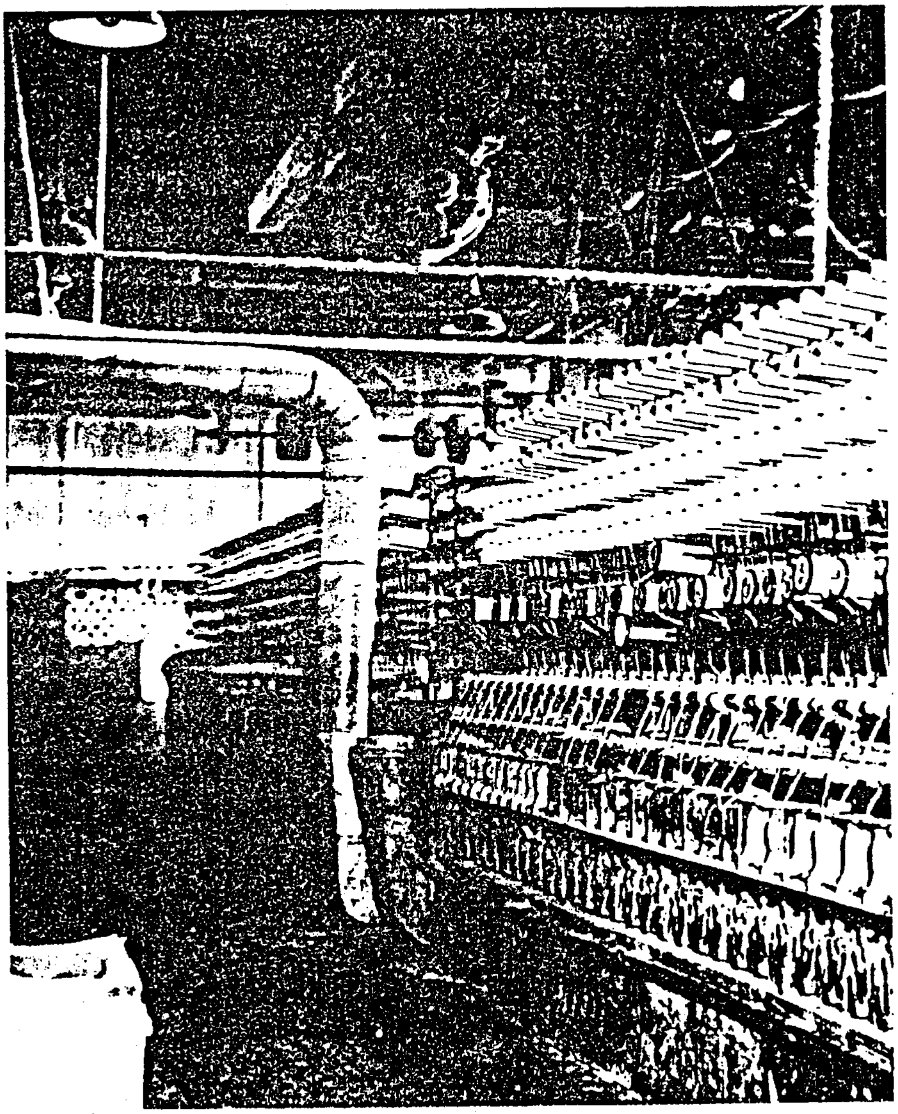

Fig. 7. Twisting frame in 1937 with partially installed downdraft ventilation system.

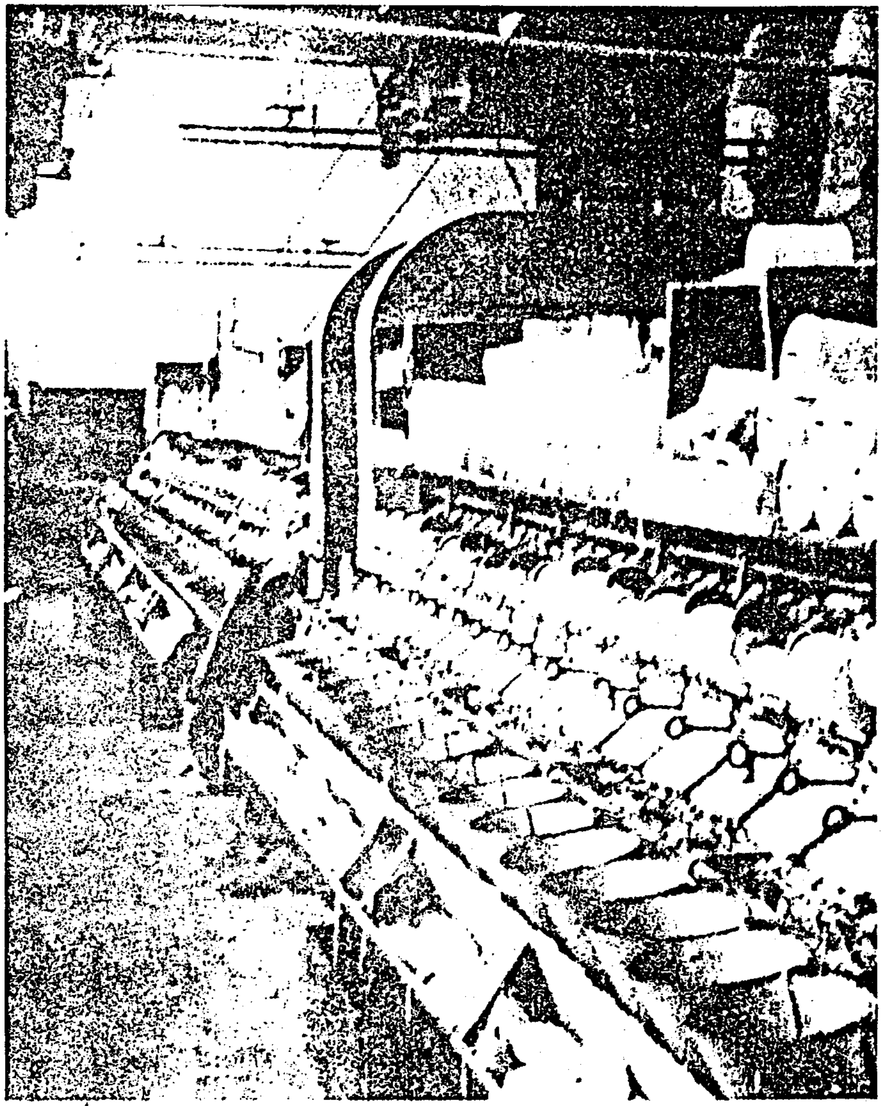

Fig. 8. Spooking machine showing downdraft ventilation system in 1937.

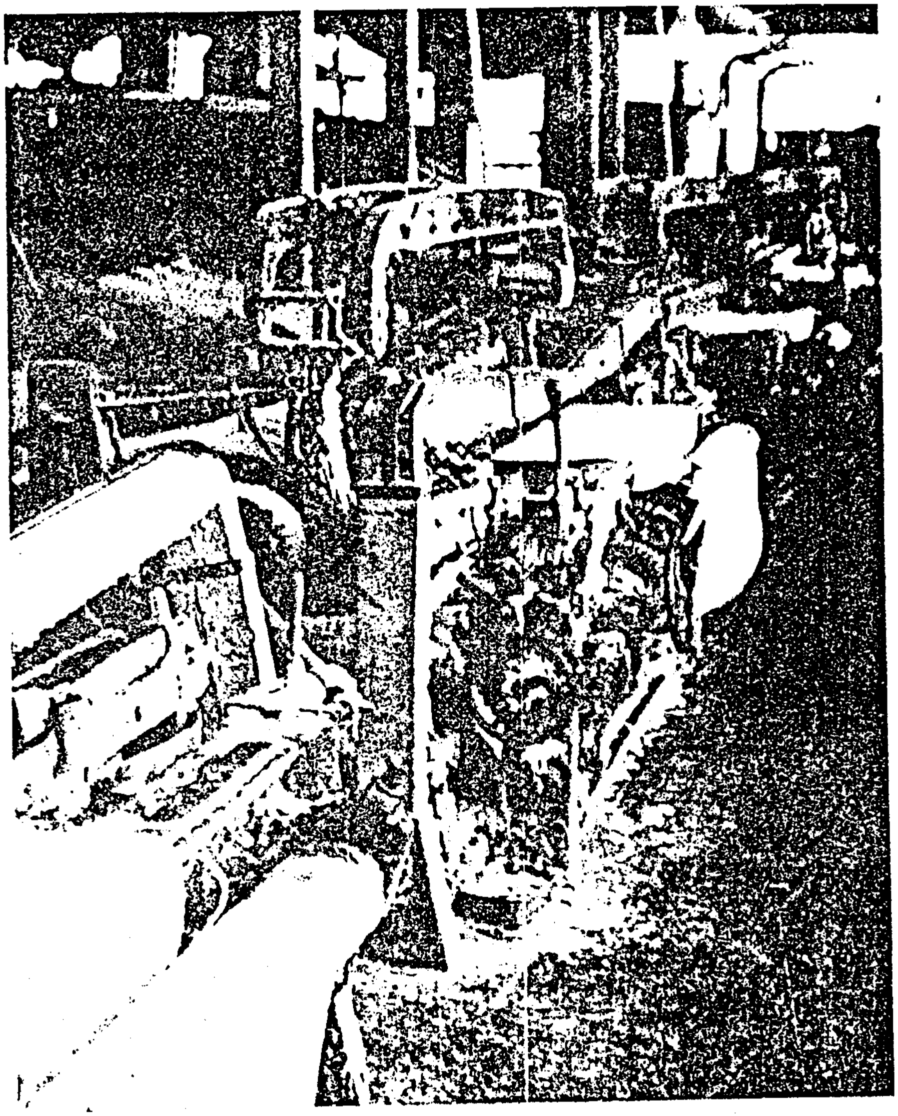

Fig. 9. A 1937 photograph of cloth loom with local exhaust ventilation.

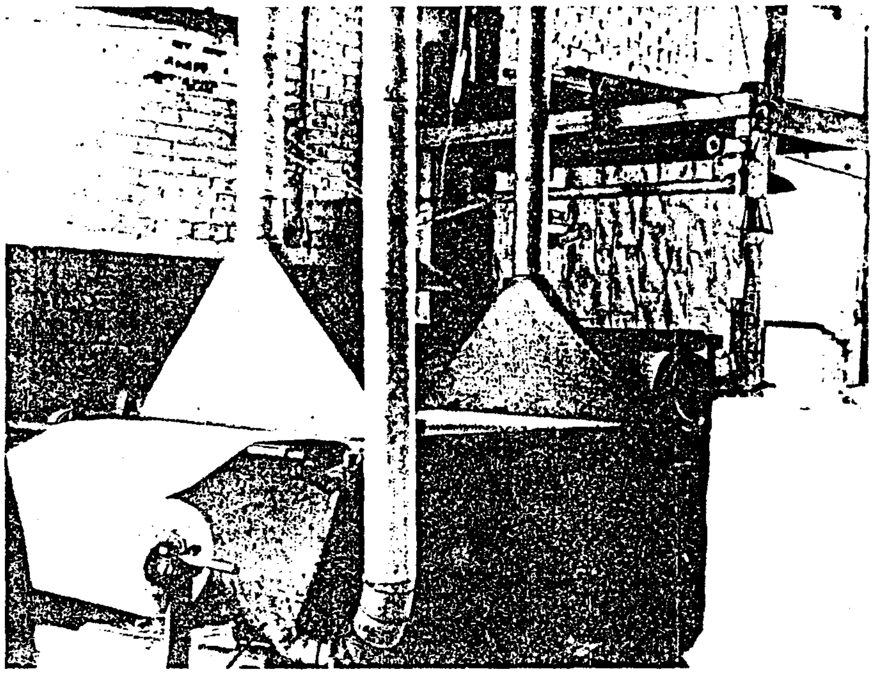

Fig. 10. Cloth inspection table in 1937 showing ventilation at brushes.

Industrial Hygiene Data

All known industrial hygiene data were collected from many sources including the company insurance carrier, the State Board of Health, the U.S. Public Health Service, and the Company sampling program. In total, 5,952 environmental samples were available covering the period 1930–1975. Prior to 1965 all samples were of the impinger type; from 1965 until 1971 membrane filter samples were also collected. In 1971, the impinger method was discontinued and from that time on the membrane filter method was used exclusively.

For purposes of evaluating worker exposure levels, it was necessary to estimate a conversion between the impinger and membrane filter data. Fortunately, there were two good sources of data for this conversion estimate specific for the plant under study. These included 120 paired impinger and membrane filter samples collected in 1965 by the U.S. Public Health Service and 986 concurrent samples by these two methods collected in plant operations during 1968–1971.

Linear correlation analyses were used to evaluate impinger-membrane filter conversions taking into account plant operations by means of indicator variables. For the paired sample data, a square root transformation of X and Y variables was used to stabilize variances of impinger and membrane filter particle counts which are approximately described by a Poisson distribution [Leidel et al, 1979; Kleinbaum and Kupper, 1978]. For concurrent sample data, a log conversion of the dependent variable was used to take into account the approximate log-normal distribution of environmental sample data collected over a period of time [Breslin et al, 1967; Sherwood, 1971; Gale, 1965; Coenen, 1966]. Possible differences in conversions with calendar time were analyzed using the concurrent samples. More details concerning statistical models employed are given elsewhere [Dement, 1980].

Using the paired sample data, no statistically significant differences ($\alpha = 0.05$) were observed by plant operation nor any significant differences in conversion factor with increasing impinger concentration. For the paired sample data, a mean conversion of 2.9 fibers $> 5\ \mu m/cc$ was estimated to be equivalent to one MPPCF.

The concurrent sample data allowed an assessment of changes in conversion estimates with time (1968–1971) and differences by plant operation. No significant trends with calendar time were noted nor were there any significant differences among plant operations except fiber preparation. For all operations except preparation, a mean conversion of 2.5 fibers $> 5\ \mu m/cc$ per MPPCF was obtained. A higher conversion of 7.8 fibers $> 5\ \mu m/cc$ per MPPCF was observed for preparation.

Comparisons of conversions obtained using the two independent data sets indicate excellent agreement except for fiber preparation where a higher conversion was obtained. For the present study, impinger sample data were converted to fiber concentrations using a conversion of 3 fibers longer than 5 μm per MPPCF for all operations except preparation where a factor of 8 was used. These factors are near the upper limits of the estimated 95% confidence intervals and are likely conservatively high conversion values (ie, may overestimate true fiber exposure levels).

Exposure Estimates

For evaluating exposure-response in the current study, it was necessary to have estimates of each worker's cumulative dust exposure throughout his working lifetime. Such estimates require detailed knowledge of all jobs held by the worker, the dates these were held, and estimates of average exposure levels for each job. Stated mathematically, a worker's cumulative dust exposure (E_T) at any time (T) since initial employment may be expressed as follows:

$$E_T = \sum_{i=1}^{N} C_i t_i$$

where

C_i = dust concentration for job i during calendar time period worker was employed in that job,
t_i = time spent in job i, and
N = number of jobs held until time T.

For this study, occupational histories for each worker were obtained from plant personnel records, and dust concentrations for each job were estimated using an exposure model whose parameters were estimated using historical exposure data.

Occupational histories. Detailed occupational histories for personnel at this plant were first recorded in approximately 1930. Occupational histories included both an indication of plant department and job held by the worker and beginning and ending dates for each job. These records also contain dates when workers were absent and dates of termination and rehire.

In order to calculate a worker's dust exposure, a method of relating work history information to estimates of exposure was needed. For this purpose, a four-digit job coding scheme was developed through discussions with plant personnel and by reviewing company personnel records. Fortunately, processes in this plant remained reasonably constant with the result being that job titles remained stable over the study period. All work histories were coded according to a four-digit coding scheme, and estimates of exposure levels were made specific to the job coding scheme.

Exposure classification. Since exposure data are not available for each worker in the present cohort, methods of estimating exposure by plant job category were required.

For estimating historic exposures, Woitowitz et al [1970] suggested breaking a plant into "exposure zones" with each zone ranked according to exposure. Corn and Esmen [1979] have proposed an extension of the exposure zone concept for purposes of designing industrial hygiene sampling programs. Corn and Esmen described an exposure zone as a grouping of workers based on similarity of job and exposure characteristics. An exposure zone may be a definable area of the plant or, alternatively, persons from different areas but sharing the requirement of similarity of job and exposure characteristics may form an exposure zone. By using exposure zones, available environmental data may be used more efficiently in estimating worker exposures, since all workers need not be monitored.

While dividing a plant into zones of similar dust exposure characteristics results in more homogeneous exposure classifications, there still may exist differences in jobs or tasks for selected workers within these zones which may have an effect on exposure. Esmen [1979] suggests that jobs may be further grouped into "uniform task categories." Workers within these task categories experience more homogeneous exposures and further reduce the variability of exposures for a given exposure zone.

Both the exposure zone concept and the uniform task concept were utilized to develop exposure models for the present study. Plant textile production operations were assigned to one of nine exposure zones (Table II) according to similarity of processes and exposures. For textile operations at this plant, these zones correspond to physically defined areas of the plant.

The uniform task concept suggested by Esmen was modified for the present study. All jobs within each exposure zone where asbestos exposure occurred were assigned to one of four Uniform Job Categories (UJC) based upon tasks associated with the particular job. These categories are as follows:

Category A: General area personnel. All personnel generally within a given plant area but not specifically associated with a particular machine or operation. These jobs include service personnel, fixers, helpers, oilers, elevator operators, doffers, clerks, supervisory personnel, etc.

Category B: Machine operation. Persons who normally operate textile production machinery. These jobs would include operators of opener machines, screens, cards, spinning frames, looms, winders, etc. Each exposure zone may contain several subcategories of machine operators.

Category C: Clean-up. Persons involved with cleaning production areas such as floor sweeping, cleaning of machines, etc.

Category D: Raw fiber handling. Persons handling or transporting raw unspun fiber or fiber waste. These jobs would include stockrollers, fly handlers, card grinders, etc.

TABLE II. Plant Operations and Exposure Zone Assignments

Operation	Exposure zone number
Preparation/waste recovery	1
Carding	2
Ring and gang spinning	3
Mule spinning	4
Spooling (Foster winding)	5
Twisting	6
Universal winding	7
Heavy weaving	8
Draper weaving	9

Within each exposure zone, estimates of exposure for the different UJCs require different considerations. Workers in category A move throughout a given exposure zone and are not usually associated with a particular process or piece of equipment. The best estimate of average exposure at any given time for these workers would be obtained by pooling all dust samples within a given exposure zone to obtain an average exposure for that zone. In a few instances, workers such as service personnel may spend part of their working day in more than one exposure zone. An estimated average exposure would then be obtained as follows:

$$\overline{X}_A = \Sigma_{\text{all zones, } i}\ \overline{C}_i f_i$$

where

$\overline{X}_A$ = average exposure for UJC A,
$\overline{C}_i$ = average dust concentration for exposure zone i, and
f_i = usual fraction of working day spent in exposure zone i.

The above estimation procedure is particularly applicable to the present study, as the textile operations being considered consist of many dust sources nearly uniformly distributed throughout a given exposure zone.

Workers in categories B, C, and D require different exposure estimates. These workers also experience the average exposure for a given zone; however, workers in these categories also experience an increment in exposure attributable to machine operation or performance of especially dusty manual tasks such as cleaning machines and floors or handling of raw unspun fiber or fiber waste. For the category machine operator, there may be several subcategories. For example, cop winders and weavers would be subcategories of Uniform Job Category B for exposure zone 8. Exposure estimates for workers in categories B–D may be expressed as follows:

$$\overline{X}_k = \Sigma_{\text{all zones, } i}\,[\overline{C}_i f_i] + \Sigma_{\text{all zones, } i}\, I_{ki}$$

where

$\overline{X}$ = average exposure for UJC k,
$\overline{C}_i$ = average dust concentration for exposure zone i,
f_i = usual fraction of working day spent in exposure zone i, and
I_{ki} = increment in average concentration in exposure zone i due to Uniform Job Category k.

All workers in categories B–D remain within one exposure zone during a working day; therefore, their exposure may be estimated by the following reduced expression:

$$\overline{X}_k = \overline{C}_i + I_{ki}.$$

Statistical model for exposure zones. Using the exposure zones and Uniform Job Categories described above, log-linear models were developed to allow estimation of worker exposures in each exposure zone over time.

Numerous investigators have demonstrated that environmental data collected over time are best described by a log-normal frequency distribution [Breslin et al, 1967; Sherwood, 1966, 1971; Jones and Brief, 1971; Hounam, 1965; Juda and Budzinski, 1967]. Since regression techniques require normality of the dependent variable, the exposure models for each zone were based on the log of the dust concentration values.

For each exposure zone, the log concentration values may be described by the following model for any given point in time:

$$\overline{Y}_i = \Sigma_k \beta_{ik} Z_{ik}$$

where

$\overline{Y}_i$ = mean of log concentration values for exposure zone i,
β_{ik} = multiple regression parameter for UJC k in exposure zone i, and
Z_{ik} = independent variable used to identify UJC k in exposure zone i.

The variables Z_{ik} are nominal variables used to identify each UJC and may take the values 0 and 1. Since the estimate of exposure for UJC A is the overall average for a given exposure zone and estimates for other UJCs are represented as increments to this overall average, the Z_{ik} are defined as follows:

Z_{iA} = 1 if exposure zone i: 0 otherwise,
Z_{iB} = 1 if UJC = B: 0 otherwise,
Z_{iC} = 1 if UJC = C: 0 otherwise, and
Z_{iD} = 1 if UJC = D: 0 otherwise.

This model estimates exposures for UJCs B–D as the overall area average plus an increment or "effect" due to the particular UJC within the exposure zone. The estimates for UJC A are the exposure zone averages "corrected" for the effects of particularly dusty jobs within the exposure zones (UJCs B–D).

The above model represents exposures at a given point in time; however, exposures over time are affected by both changes in the manufacturing processes and engineering control methods. To account for these changes, additional nominal variables were introduced into the model for each exposure zone. These variables then assumed the value of 0 and 1 depending on whether the process of engineering control change was present or absent at a given point in time. These variables are expressed in the model as follows:

$$\overline{Y}_i = \sum_k \beta_{ik} Z_{ik} + \sum_j \alpha_{ij} Z_{ij}$$

where

$\overline{Y}_i$, β_{ik}, and Z_{ik} are as previously defined,
α_{ij} = multiple regression parameter for control j in exposure zone i, and
Z_{ij} = independent variable used to represent dates of control changes for exposure zone i.

Even after job categories and changes in engineering controls are accounted for in the regression models, there still may exist trends in dust concentration for an exposure zone as a function of calendar time. These may be the result of such things as a gradual increase in production volume or perhaps residual interaction not accounted for by the models. To account for such trends, it is desirable to enter calendar time into the model. However, it is undesirable to enter calendar time into the model as continuous variable (eg, exact year samples were collected), since this would tend to extrapolate any trends into calendar time periods where few samples may have been taken. To avoid this problem, calendar time was broken into discrete intervals depending on the particular exposure zone and assigned a nominal value. The entire model may then be expressed as follows:

$$\overline{Y}_i = \sum_k \beta_{ik} \; Z_{ik} + \sum_j \alpha_{ij} \, Z_{ij} + \sum_t \delta_{it} \; Z_{it}$$

where

all other variables are as previously defined,
δ_{it} = multiple regression parameter for time interval t in exposure zone i, and
Z_{it} = independent variable used to represent calendar time periods.

Estimation of model parameters. Parameters of the previously described regression models for each txtile exposure zone were estimated by multiple linear regression using historic industrial hygiene sampling data. These data were obtained from a number of sources, as previously described.

For estimating model parameters, each impinger or membrane filter sample was assigned to both an exposure zone and a Uniform Job Category. For the membrane filter samples, which were collected on individual workers, this assignment was done using the worker's department and job code.

Using descriptions of sample location from industrial hygiene reports and plant engineering layout diagrams, each impinger sample was first assigned to one of the routine sampling points established for the company sampling program in about 1956. Using this sampling network, all impinger samples were then assigned to an appropriate exposure zone Uniform Job Category. Uniform Job Categories were assigned according to location of the particular sampling point within a given exposure zone. For UJC B in preparation (zone 1) and heavy weaving (zone 8), several subcategories of "machine operator" were required. These categories are as follows:

Preparation (zone 1). Fly machine operator, shaker screen operator, vertical machine operator, crusher operator, waste machine operator.

Heavy weaving (zone 8). Beamers and creelers, winders, weavers, inspectors.

The data concerning process modifications or changes in engineering controls were used to assign nominal values for these variables in the exposure models. A summary of significant process or control modifications considered in the models is shown in Table III.

The parameters for each exposure zone model were estimated using typical least squares fitting procedures. For each exposure zone, the variables for UJC and engineering controls were first entered into the model along with a continuous variable (t) representing the calendar year the samples were collected. This latter variable was used to determine if any important residual trends of dust concentration with calendar time existed after all other main effect variables were in the models. The significance of this time variable was tested using a partial F statistic. If the time variable was not significant ($p > 0.05$), the model was refitted without this variable. Only carding and ring spinning had residual time trends in the exposure data. For all analyses, impinger concentrations were converted to fiber concentrations using the conversions previously derived. Each exposure model used the log of the dust concentration data.

A significance level of 0.10 was used for inclusion of any variable in the models. Nearly all estimated regression parameters were significant at the 0.05 level, however. The lower level of significance of 0.10 was chosen for considerations of validity of the models in accounting for jobs and controls.

Mean exposures and confidence intervals. The regression models incorporate the assumption of log-normality of dust concentration values. Estimated model parameters for the statistical models can be used to predict the mean for the log of dust concentration values and, by exponentiating these values, geometric mean dust exposures are estimated.

While the regression models work well using the log normality assumption, others have shown that the arithmetic mean may be the best estimator of the time averaged concentration to which workers are exposed [Sherwood, 1966; Coenen, 1966, 1970; Leidel and Busch, 1975]. This is especially true when short "grab" samples of approximately equal sampling duration are used to estimate worker exposures. Such is the case for the present study, since both impingers and membrane filter samples were of short duration and can be considered "grab" samples for statistical considerations. Arithmetic mean exposures and confidence interval estimates must, therefore, be approximated from the regression analysis estimates of parameters and variances. Two

TABLE III. Summary of Process and Control Variables in Exposure Zone Models

Operation (zone)	Control or process modifications	Date
Preparation (1)	Mixing beds phased out	1945
	Automatic blending lines added	1964
Carding (2)	Carding ventilation completed	1935
Ring spinning (3)	Some wet spinning	1966
Mule spinning (4)	No major changes	—
Foster winding (5)	Ventilation of winders completed	1937
Twisting (6)	Twister ventilation completed	1938
Universal winding (7)	No major changes	—
Heavy weaving (8)	Loom, cop winding and inspection ventilation added	1937
Light weaving (9)	No major changes	—

situations exist with regard to worker job categories. The first involves those workers who spend all their time in one plant exposure zone, whereas the second concerns workers, although few in number, who may spend time in more than one zone. The former situation will be considered first.

The regression models predict the mean values for the log of dust concentration as follows:

$$\overline{Y} = \Sigma \beta_i Z_i \tag{1}$$

where

$\overline{Y}$ = mean of log concentration,
β_i = estimated regression coefficients, and
Z_i = independent variables for controls, UJC, time, etc.

An estimate of the arithmetic mean dust concentration may be obtained from the following expression:

$$\overline{X} = \exp(\overline{Y} + 1/2\sigma^2) \tag{2}$$

where

$\overline{X}$ = estimated arithmetic mean concentration,
$\overline{Y}$ = mean of log concentration values, and
σ^2 = pooled estimate of variance of Y from the regression model.

For workers who may spend part of their working day in more than one exposure zone, their average exposures may be estimated as follows:

$$\overline{X} = \Sigma W_i \overline{X}_i$$

where

W_i = fraction of working day in exposure i as determined from job descriptions plant interviews, and
$\overline{X}_i$ = arithmetic average dust concentration for specified UJC in exposure zone i.

Using the above derived expressions and estimated regression parameters, mean exposure values by calendar time and 95% confidence intervals were estimated for each job. An expression for estimating the variance of the means exposure values by use of a Taylor series approximation was developed and is described elsewhere [Dement, 1980].

RESULTS AND DISCUSSION

Estimates of mean exposure levels along with 95% confidence intervals are given in Tables IV-XII for the various textile production operations. For most operations, exposures were significantly reduced by about 1940 when most engineering controls were in place. Significant reductions were accomplished in most textile operations with "precontrol" exposures ranging from about 3 to 78 fibers/cc and were typically well above 10 fibers/cc. After textile operations were provided with controls, exposures ranged from approximately 3 to 17 fibers/cc and were usually in the range of 5 to 10 fibers/cc.

TABLE IV. Summary of Exposure Estimates for Fiber Preparation and Waste Recovery Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1944	1945–1964	1965–1975
A: General area personnel	26.2 (12.2–40.2)	8.1 (6.0–10.1)	5.8 (4.4–7.2)
B: Machine operators			
Fly machine operator	78.0 (38.1–117.8)	23.9 (17.7–30.2)	17.2 (13.1–21.3)
Crusher operator	78.0 (38.1–117.8)	23.9 (17.7–30.2)	—
Waste machine operator	45.9 (21.0–70.8)	14.1 (9.5–18.7)	10.1 (7.1–13.2)
C: Clean-up personnel	54.4 (10.7–98.1)	16.7 (5.4–28.0)	12.0 (4.4–19.6)
D: Raw fiber handling	35.0 (17.0–53.0)	10.8 (7.3–14.2)	7.3 (5.7–9.0)

TABLE V. Summary of Exposure Estimates for Carding Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1935	1936–1945	1946–1965	1966–1975
A: General area personnel	10.8 (7.1–14.5)	5.3 (3.6–6.9)	2.4 (2.3–2.5)	4.3 (4.0–4.6)
B: Card operators	13.3 (9.5–18.1)	6.5 (4.3–8.7)	2.9 (2.6–3.3)	5.3 (4.8–5.8)
C: Clean-up personnel	18.1 (9.2–27.1)	8.8 (4.6–13.0)	4.0 (2.6–5.4)	7.2 (4.7–9.7)
D: Raw fiber handling	22.8 (13.2–32.0)	11.0 (8.3–13.7)	5.0 (3.8–6.1)	9.0 (7.0–11.0)

TABLE VI. Summary of Exposure Estimates for Ring Spinning Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1965	1966–1970	1971–1975
A: General area personnel	8.2 (7.6–8.8)	8.6 (7.7–9.5)	6.2 (5.3–7.1)
B: Spinner operators	6.6 (5.6–7.6)	6.9 (6.0–7.9)	5.0 (4.5–5.4)
C: Clean-up personnel	NP[a]		
D: Raw fiber handling	NP		

[a]NP: No personnel within job category in this operation.

TABLE VII. Summary of Exposure Estimates for Mule Spinning Operation

Uniform job category	Estimated mean fiber exposures (fiber > 5 μm/cc) and 95% confidence intervals 1930–1975
A: General area personnel	6.3 (5.8–6.9)
B: Spinner operators	4.8 (4.2–5.0)
C: Clean-up personnel	6.7 (4.3–9.1)
D: Raw fiber handling	NP[a]

[a]NP: No personnel with job category in this operation.

TABLE VIII. Summary of Exposure Estimates for Foster Winding Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1937	1938–1975
A: General area personnel	10.4 (2.1–19.3)	4.2 (3.5–5.1)
B: Winder operator	13.6 (2.4–24.8)	5.5 (2.8–8.1)
C: Clean-up personnel	20.9 (1.1–40.7)	8.4 (3.4–12.5)
D: Raw fiber handling	NP[a]	

[a]NP: No personnel with job category in this operation.

TABLE IX. Summary of Exposure Estimates for Twisting Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1938	1939–1975
A: General area personnel	24.6 (14.0–35.2)	5.4 (4.8–6.1)
B: Twister operators	36.0 (19.2–52.7)	7.9 (6.7–9.2)
C: Clean-up personnel	31.9 (13.1–50.7)	7.0 (4.3–9.8)
D: Raw fiber handling	31.9 (13.1–50.7)	7.0 (4.3–9.8)

TABLE X. Summary of Exposure Estimates for Universal Winding Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1975
A: General area personnel	4.1 (3.4–4.8)
B: Winder operators	4.1 (3.4–4.8)
C: Clean-up personnel	8.4 (4.0–12.7)
D: Raw fiber handling	NP[a]

[a]NP: No personnel within job category in this operation.

TABLE XI. Summary of Exposure Estimates for Heavy Weaving Operations

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1936	1937–1975
A: General area personnel	9.2 (5.6–12.8)	2.6 (1.8–3.1)
B: Machine operators		
Beamers and creelers	14.3 (8.1–20.5)	3.8 (3.5–4.1)
Winders	9.7 (5.3–14.1)	2.6 (2.2–3.0)
Weavers	14.3 (8.1–20.5)	3.8 (3.5–4.1)
Inspectors	5.3 (2.1–8.5)	1.4 (1.1–1.8)
C: Clean-up personnel	30.6 (22.4–36.8)	8.2 (4.3–12.0)
D: Raw fiber handling	30.6 (22.4–38.8)	8.2 (4.3–12.0)

TABLE XII. Summary of Exposure Estimates for Light Weaving Operation

Uniform job category	Estimated mean fiber exposures (fibers > 5 μm/cc) and 95% confidence intervals 1930–1975
A: General area personnel	2.7 (2.1–3.2)
B: Weavers, winders and calendar operators	2.7 (3.1–3.2)
C: Clean-up personnel	6.9 (4.2–9.5)
D: Raw fiber handling	NP[a]

[a]NP: No personnel within job category in this operation.

Exposures in a large cross-section of the U.S. asbestos textile industry have been studied by the U.S. Public Health Service [Lynch and Ayer, 1966]. These studies were conducted using the membrane filter method. A comparison between the Lynch and Ayer exposure measurements and those estimated for the plant under study is given in Table XIII. In the Lynch and Ayer study, those plants with highest exposures likely approximate dust controls in the textile industry prior to implementation of dust controls. Table XIII shows these levels to be approximated by the precontrol exposure estimates

TABLE XIII. Comparison of Exposure Estimates with Data for Other Textile Mills

	Estimated mean exposure (fibers > 5 μm/cc)			
	Lynch and Ayer [1966]		Present study[a]	
Operation	Best plant	Worst plant	Precontrols	With controls
Preparation	2.6	17.0	26.2–78.0	5.8–17.2
Carding	2.0	15.2	10.8–22.1	4.3– 9.0
Spinning[b]	1.8	18.9	4.8– 8.2	4.8– 6.7
Twisting	1.1	22.4	24.6–36.0	5.4– 7.9
Winding[c]	1.3	17.5	4.1–20.9	4.1– 8.4
Weaving	1.5	17.8	5.3–30.6	1.4– 8.2

[a]For the present study, data shown are for the highest and lowest exposures by job within a particular operation.
[b]Includes ring and mule spinning as Lynch and Ayer did not present separate data.
[c]Includes Foster winding and universal winding as Lynch and Ayer did not present separate data.

studied here. Likewise, data from the best controlled plants studied by Lynch and Ayer are lower than postcontrol estimates in this plant. These comparisons suggest that the exposure estimates for the plant being studied are well within reasonable limits and consistent with findings of others relative to textile operations. The exposure estimates shown in Tables IV–XII were used in conjunction with mortality data to estimate exposure-response relationships.

It is realized that some exposure misclassification is unavoidable in any retrospective epidemiological study. However, the exposure models derived and used for this study appear to give reasonable exposure estimates without significant upward or downward bias. Since exposures for both diseased and nondiseased individuals are calculated in the same manner by use of work histories, misclassification on exposure would be nondifferential in nature (ie, effecting both diseased and nondiseased individuals). Shy et al [1978] have shown that nondifferential misclassification on exposure biases toward the null effect. In the current study of various cumulative exposure levels, the effect would be to make strata more homogeneous with respect to exposure, thus reducing any exposure-response gradients.

The linear model approach for exposure estimation as was used in this study has several advantages. First, and perhaps most important, the models allowed for simultaneously adjusting exposure estimates for changes in engineering controls, job categories, and process changes. Second, this approach serves to minimize variances in the exposure estimates while accounting for the log-normal distribution of environmental sample data. The linear model approach may be useful in other retrospective studies where historic exposure estimates are desired.

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