

# Estimates of historical exposures by phase contrast and transmission electron microscopy in North Carolina USA asbestos textile plants

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## ABSTRACT

**Objectives:** To develop a job-exposure matrix (JEM) for fibre exposures in three asbestos textile plants and to develop estimates of fibre size-specific exposures.

**Methods:** Historical dust samples from three North Carolina, USA asbestos textile plants were obtained. Plant specific samples were used to express impinger dust concentrations as fibre concentrations by phase contrast microscopy (PCM). Mixed models were used to estimate PCM exposures by plant, department, job and calendar time. Archived membrane filter samples were analysed by transmission electron microscopy (TEM) to determine the bivariate diameter/length distribution of airborne fibres by plant and operation.

**Results:** PCM fibre levels estimated from the models were very high in the 1930s, with some operations having in excess of 200 fibres/ml, and decreased appreciably over time. TEM results for 77 airborne dust samples found that only a small proportion of airborne fibres were measured by PCM ( $>0.25\ \mu\text{m}$  in diameter and  $>5\ \mu\text{m}$  in length) and the proportion varied considerably by plant and operation (range 2.9% to 10.0%). The bivariate diameter/length distribution of airborne fibres demonstrated a relatively high degree of variability by plant and operation. PCM adjustment factors also varied substantially across plants and operations.

**Conclusions:** These data provide new information concerning airborne fibre levels and characteristics in three historically important asbestos textile plants. PCM concentrations were high in the early years and TEM data demonstrate that the vast majority of airborne fibres inhaled by the workers were shorter than  $5\ \mu\text{m}$  in length, and thus not included in the PCM-based fibre counts.

Asbestos textiles provided early evidence of the adverse health effects of asbestos exposure both in Europe and the USA.<sup>1-4</sup> Quantitative exposure-response data for asbestosis and lung cancer among asbestos textile workers have been used extensively for risk assessments and establishment of occupational exposure standards.<sup>5-7</sup>

In general, slopes of the exposure-response relationships for asbestosis and lung cancer among chrysotile asbestos textile workers are greater than observed for chrysotile mining.<sup>8-13</sup> Various hypotheses have been put forth to explain these differences such as exposures to mineral oils; however, further analyses found little evidence that mineral oil confounded asbestos exposure-mortality associations.<sup>8, 14</sup> Modification of the exposure-response association by asbestos fibre size has also been posited as a reason for the differences between asbestos textile and asbestos mining cohorts as

## What this paper adds

- ▶ Exposure-response estimates for asbestos-related lung cancer have largely used phase contrast microscopy (PCM)-based exposure estimates, but PCM measures only a small portion of the actual total worker fibre exposures.
- ▶ Estimates of PCM and transmission electron microscopy (TEM) exposures for three historically important asbestos textile plants were derived demonstrating very high fibre exposures in the 1930s with significant exposure reductions over calendar time.
- ▶ While asbestos textile operations generally processed the longest fibre grades, airborne fibre size data by TEM show that textile workers were exposed to predominately short fibres ( $<5\ \mu\text{m}$  in length), with the vast majority of fibres not being enumerated by the PCM method.
- ▶ Data from this study, when linked with ongoing epidemiological studies and risk assessments, will provide new data for the development of occupational exposure standards with greater consideration of fibre size.
- ▶ Improved methods for routine measurement of airborne asbestos exposures are needed in order to fully address the total spectrum of exposures experienced by workers.

airborne fibres in textile plants tend to be longer and thinner compared to those produced by chrysotile mining and milling.<sup>8, 15-17</sup> Additionally, studies in experimental animals have generally shown long thin fibres to be more biologically active in the production of lung cancer and mesothelioma.<sup>18-20</sup> Lippmann<sup>21</sup> reviewed published human and animal data and concluded that asbestosis is most closely related to the surface area of retained fibres that are between  $>0.15$  and  $<2.0\ \mu\text{m}$  in diameter, mesothelioma is most closely associated with numbers of fibres longer than approximately  $5\ \mu\text{m}$  and thinner than approximately  $0.1\ \mu\text{m}$ , and lung cancer is most closely associated with fibres longer than approximately  $10\ \mu\text{m}$  and thicker than approximately  $0.15\ \mu\text{m}$ .

Few epidemiological studies have directly addressed fibre size-specific risks, as limited data are available concerning fibre size-specific exposures for most study populations. Cumulative exposures estimated using phase contrast microscopy (PCM)

are strong predictors of asbestosis and cancer risks,<sup>8,9</sup> but the PCM method enumerates only a small portion of airborne fibres in the occupational environment (ie, fibres >5 µm in length). Additionally, PCM has a limit of resolution of approximately 0.2–0.3 µm,<sup>17</sup> and consequently asbestos fibres <0.25 µm in diameter are not counted even if longer than 5 µm. Limitations of the PCM method suggest that a more predictive exposure–response relationship might be observed in epidemiological studies using a fibre size-specific exposure metric based on transmission electron microscopy (TEM), which can measure the entire asbestos aerosol.<sup>22</sup> Our prior studies of an asbestos textile plant located in Charleston, South Carolina demonstrated that short (ie, <5 µm) and thin fibres (ie, <0.25 µm) constituted the predominate exposure for workers. Furthermore, TEM-based cumulative exposure estimates were found to provide stronger predictions of asbestosis and lung cancer mortality than PCM-based estimates.<sup>17,22</sup>

The current paper expands upon our prior studies of fibre size-specific risks among textile workers.<sup>17,19,22</sup> This manuscript describes the development of a historical job-exposure matrix (JEM) for PCM exposures and the development of fibre size-specific exposure estimates by TEM for workers employed between 1950 and 1973 at three asbestos textile plants located in North Carolina.

## METHODS

### Overview

Detailed employment histories were available for workers employed between 1950 and 1973 at three asbestos textile plants. Our objective was to develop a JEM that allowed us to compute both PCM and TEM fibre size-specific cumulative exposure metrics for workers employed in these facilities.

Development of PCM and TEM size-specific exposure estimates relied upon historical asbestos monitoring data collected via impingers in early years and by PCM in later years. Therefore, we first developed a method to convert the impinger sample results to comparable PCM values. We next developed a JEM using mixed linear models to estimate average PCM concentrations by plant, department, job group and calendar time period. In order to derive fibre size-specific estimates, we randomly selected 77 historical dust samples and analysed these via TEM. We used these fibre size data in conjunction with the PCM JEM to characterise asbestos exposures by plant, department, job group and calendar period according to diameter and length distributions.

### Plant descriptions and exposure data sources

The current investigation included four asbestos textile plants located in western North Carolina, USA. Three of these plants (1, 2 and 4) began production prior to 1930 and were included in the cross-sectional respiratory disease study conducted by the United States Public Health Service (USPHS) in the 1930s.<sup>3</sup> The fourth plant began production in approximately 1942. Asbestos production ceased in plants 1 and 2 in 1970 and 1971, respectively, and plant 3 ceased asbestos production in 1987. Plant 4 continued asbestos production at least through 1994.

In three of these plants (1, 3, 4), crude asbestos and raw cotton were converted into asbestos yarn and woven goods using production methods typical of the US asbestos textile industry.<sup>3,23,24</sup> Plant 2 purchased yarn and woven asbestos tape and converted these into finished goods, including woven brake bands. Dreessen *et al* reported that approximately 90% of the asbestos used in these plants came from Canada with lesser

amounts from Arizona and South Africa, and infrequently from Russia and Australia.<sup>3</sup> In addition to chrysotile textile products, plant 3 had a small, separate operation that produced woven amosite insulation materials. Workers involved in the amosite operation were identifiable in plant personnel records and the first history showing amosite work was in 1963 and the last in 1976. Application of engineering controls for reduction of dust exposures was underway in these plants in the mid-1930s; however, controls were not yet implemented for many operations at the time of the USPHS 1930s study.<sup>3</sup> The plant which only processed yarn and woven tape to make brake-bands was omitted from the JEM due to the small size of the worker population in this plant, limited historical air sampling data, and concerns for confounding exposures to resins and asphaltic compounds associated with brake-band production.<sup>3</sup>

All known industrial hygiene samples (n = 3420) for plants 1, 3 and 4 were collected from several sources including periodic hygiene surveys by the North Carolina Dusty Trades program between 1935 and 1986 and USPHS from 1935 through 1971. Prior to 1964 all air samples were collected using the impinger method,<sup>25</sup> from 1964 to 1971 both the PCM and impinger methods were used, and after 1971 only the PCM method was used.<sup>26</sup>

For JEM development, each plant was divided into exposure zones. Exposure zones corresponded closely to textile departments (eg, fibre preparation, carding, spinning, twisting, weaving, finishing, etc), and are thought to produce more homogeneous asbestos exposures based on similarity of asbestos materials, processes, physical location and control measures. Within each exposure zone, jobs were a priori grouped into uniform job categories (UJC) as defined by Dement *et al*<sup>8,27</sup> in a study of an asbestos textile plant in Charleston, South Carolina. Personnel involved with plant and machine cleaning in these plants were generally not assigned to a specific plant department; therefore, a separate exposure zone was established for these workers. The UJC groups used for each exposure zone and examples of jobs grouped by UJC within the preparation and carding zones are shown in table 1.

### Impinger to PCM conversion estimates

The first task in developing the JEM involved estimating conversion factors which would allow historical impinger dust concentrations, expressed as millions of particles per cubic foot of air (MPPCF) to be expressed as PCM fibre concentrations (fibres >5 µm/ml). Fortunately, paired impinger and membrane filter samples were collected in the study plants by the USPHS between 1964 and 1968 and were used to model the relationship between the impinger and PCM measurements.

For the impinger to PCM conversion estimates, exposure zones were grouped into three categories based on process and similarity of airborne fibre characteristics as measured by TEM.<sup>15</sup> The first exposure zone group included operations involved with the processing of raw asbestos fibres or wastes prior to spinning into yarns and included fibre preparation and carding. The second exposure zone group included processes involved with the production of yarns and included spinning and twisting. The final exposure zone group included all textile operations following the production of yarns and included winding, weaving, finishing and shipping, and rope, wick, braid and cord.

The principal statistical tool used to analyse conversion factors for paired samples was maximum likelihood multivariate linear regression using SAS PROC GENMOD in SAS v 9.1 (SAS Institute, Cary, North Carolina, USA, 2004). Nested effects of exposure zone within plant were explored in the

**Table 1** Uniform job category (UJC) groups used for each exposure zone and examples of jobs grouped by UJC

UJC	Description	Preparation: job examples	Carding: job examples
General area personnel	Workers in area but not assigned to a specific machine or process	Fixer Foreman Forklift operator	Fixer/oiler Foreman Grinder (scratchman)
Machine operators	Workers operating process machinery	Blender operator Condenser reclaim Stock opening operator (crusher) Waste machine operator Wheelabrator operator Willow operator	Card operator Card tender
Clean-up personnel	Machine and general plant cleaning	Janitor/sweeper Machine cleaner	Janitor/sweeper Machine cleaner
Raw fibre handling	Manual handing of raw unspun fibre or fibre waste	Packer Stock hauler, stocker Stock packer or stocker	Roving hauler Winder/doffer Stock hauler, stocker, mixer

models in order to account for possible differences in the composition and physical characteristics of the airborne dusts by plant and process. In order to stabilise variances, square root transformations of impinger and PCM fibre concentrations were explored. A square root transformation is suggested in the context of count data and this transformation was successfully used in a study of the Charleston, South Carolina asbestos textile plant.<sup>27 28</sup>

In addition to the paired air samples, data from air samples collected in the same plants and departments using both sampling methods were available from 1964 through 1971. While these samples were not paired, they were collected over a defined and limited time frame and allowed calculation of plant and zone average exposures by both methods. These data are referred to as “concurrent samples” and were used to provide a second independent estimate of the impinger to PCM conversion. In calculating the ad hoc estimate of conversion multipliers from the concurrent data, it was assumed that within a plant and zone the concentration and composition of fibres was constant over the data collection, except for stochastic variation. These assumptions are reasonable given few changes in processes, control measures or asbestos fibre sources over this time period. Additionally, linear regression models for log PCM and log impinger concentrations found the parameter for calendar year to be non-significant ( $p > 0.05$ ) after control for plant and exposure zone.

The impinger samples within a plant and zone can be viewed as replicates, and thus the mean of the impinger samples provided an estimate of the concentration of total dust (MPPCF) within each plant and zone. Likewise, the mean of the individual membrane samples provided an estimate of the PCM concentrations within each plant and zone, and the ratio of these means provided an ad hoc approximation of the conversion multipliers. Bootstrapping was used to calculate approximate 95% confidence intervals for the concurrent sample conversion factors based on 500 re-samples drawn with replacement with each air sample within plant and exposure zones having an equal probability of selection.<sup>29</sup> The impinger/PCM conversion ratios were then calculated for each bootstrap sample and the percentile method was used to estimate the 95% confidence intervals. Each of the 500 bootstrapped re-samples was restricted to set the sample size equal to the original sample.

Conversion factors derived from the paired and concurrent data analyses were examined for consistency and ultimately combined based on a weighted average of the two estimators, the assumption being that the “statistically most likely” conversion is represented by the weighted average. The weights

for these averages were chosen to be the reciprocal of each estimator’s variance from the regression models or bootstrapping for the concurrent samples.

### Plant, department, job and period-specific PCM fibre concentrations

All impinger data were converted to estimated PCM concentrations using the plant and exposure zone-specific conversion factors derived for this study. Initial analyses of the PCM estimates included plots of PCM concentrations by plant, zone, UJC and time periods as well as calculation of arithmetic means (AM), geometric means (GM) and geometric standard deviations (GSD) by these same strata. A probability plot of the PCM measurements was highly right-skewed and resembled a log-normal distribution; therefore, all PCM data were log transformed (base  $e$ ) for exposure modelling, a transformation common for occupational sample data.<sup>30</sup>

The PCM data were unbalanced in that the number of samples varied by plant, exposure zone, UJC and time period; therefore, nested multivariate models to predict mean PCM levels were developed using SAS PROC MIXED, which allows unbalanced data. PROC MIXED also allowed use of restricted maximum likelihood estimation (REML), which is robust to misspecification of the variance-covariance structure.<sup>31</sup> The USPHS industrial hygiene studies in these plants in the 1930s provided an excellent starting point for our models and avoided any substantial backward extrapolation to time periods without plant-specific exposure measurements.

In building our models, we first modelled the mean structure by specification of the fixed effects.<sup>32</sup> Calendar time was introduced into the models as a continuous fixed effect variable (centred on 1935). A plot of log transformed PCM measurements by calendar year suggested non-linearity; therefore, time trend was modelled as a fixed effects linear spline in PROC MIXED.<sup>33–35</sup> A linear spline function was constructed by specifying boundaries (knots) based on changes in threshold limit values (TLVs) (1946) or USA Occupational Safety and Health Administration permissible exposure limits (PELs) (1971 and 1976). An additional boundary was established in 1964, a period of increased interest and industrial hygiene sampling in these plants by the USPHS. Plant, exposure zone and UJC were treated as fixed effects in all models with UJC nested within exposure zone and plant. Our a priori decision to model UJC nested within exposure zone was motivated by our prior analyses of exposures in asbestos textiles using over 6000 samples, which found differences in the effect of UJC by

department.<sup>27</sup> Also, nearly all textile jobs (eg, carders, spinners, weavers, etc) are only relevant for specific exposure zones, making nesting appropriate for model validity. The Akaike's information criterion (AIC) was used to compare models and likelihood ratio (LR) tests were used to compare nested models.<sup>36</sup> The maximum likelihood (ML) estimation method was used for comparison of nested fixed effects models for validity of the LR tests; however, the final model parameter estimates used REML due to the superiority of REML parameter estimates.<sup>37</sup> The Satterthwaite approximation option in PROC MIXED was used for computing the denominator degrees of freedom for the tests of fixed effects. Model fit was further evaluated by examination of residuals plotted by model covariates and by examination of Pearson correlations between observed and predicted log PCM values for the sample set.

We were not able to model between and within worker variance components as worker identification was not recorded in the historical data available. Very few repeated samples by worker were expected given the long time period and sampling frequency; therefore, inability to account for within worker correlation in the models would have little effect.<sup>33–38</sup> However, since specific jobs were grouped into UJCs, we explored effects of two sources of random variance in our models: that between jobs and that among repeated measurements by job.<sup>30–33–38</sup> We evaluated these effects in models that treated job as a random effect and assumed compound symmetry. AIC was used to compare models with the same fixed effects but different covariance structures.<sup>32</sup>

Predicted arithmetic means by plant, zone, UJC and calendar year were calculated using model parameter estimates and variance ( $AM = \exp[\ln(GM) + 0.5 \times \text{variance}]$ ), where the variance represents the model variance for predicted mean log PCM.<sup>36</sup>

### TEM size-specific exposure estimates

In order to develop a fibre size-specific JEM, measurements obtained by TEM were used to determine the bivariate diameter/length distribution of fibres using archived PCM filters. Historical membrane filter samples ( $n = 333$ ) collected by the USPHS during industrial hygiene studies of these plants during 1964–1971 were located in archives of the National Institute for Occupational Safety and Health (NIOSH) and assigned to the same exposure zones and uniform job categories used for the PCM exposure modelling. Based on resources and available archived samples, a stratified random sample of 77 membrane filters was selected with sampling strata defined by the plants and exposure zones. The number of filters available by plant ranged from 44 to 266 and when only a few archived filters were available for a specific exposure zone all usable samples for that zone were used for TEM analysis. The distribution of samples by time period was 1964–13, 1967–42 and 1971–22.

TEM methods, data reduction and derivation of size-specific exposure estimates followed methods previously described.<sup>17</sup> Briefly, these methods involved estimation of the bivariate diameter/length size distribution for each plant and exposure zone using TEM data obtained using a modification of the ISO direct transfer method.<sup>39</sup> The bivariate fibre diameter/length data by plant and exposure zone were then used to estimate size-specific TEM exposures based on the "adjustment factor" method proposed by Quinn *et al*,<sup>40</sup> which "adjusts" standard fibre concentration measures determined by PCM to the biologically relevant size-specific fibre concentrations using proportions from bivariate fibre size distributions. These "adjustment factors" take into account the proportion of all

TEM fibres counted by PCM as well as the distribution of TEM fibres by diameter and length, resulting in fibre size-specific exposures.<sup>17</sup> Bivariate TEM fibre size distributions and PCM adjustment factors were calculated for 28 diameter and length categories by plant and zone. The PCM adjustment factors were applied to the estimated PCM fibre levels by plant, zone, UJC and calendar time to arrive at TEM size-specific exposure estimates.

## RESULTS

### Impinger to PCM conversion estimates

The paired sample data set consisted of 208 side-by-side sets of impinger and membrane filters and the concurrent data collected by the impinger and membrane filter method consisted of 790 samples. A summary of samples by plant as well as conversion estimates using the paired samples, concurrent samples and the combined data are shown in table 2. In both the paired and concurrent sample models, plant and exposure zone were statistically significant predictors of conversion factors ( $p < 0.05$ ). The independent sets of impinger to PCM conversion algorithms have associated strengths and limitations. The paired sample set provides data for each sample method based on sampling of the same physical environment in space and time. However, the number of sample pairs is limited for some plant and exposure zone groups, resulting in relatively wide confidence intervals. The conversions derived from the concurrent samples have the advantage of greater sample numbers; however, additional variability is introduced by not having the samples in a side-by-side sampling frame to minimise temporal variations.

Final conversion factors based on the combined data are consistent with the range of prior estimates for the textile industry<sup>27–41</sup> and have the advantage of being derived using data specifically for the plants under study. Nonetheless, use of these conversion factors may cause error in the PCM exposure estimates.

### Estimates of PCM concentrations using mixed models

Table 3 provides descriptive statistics for PCM equivalent exposures (fibres  $>5 \mu\text{m}/\text{ml}$ ) by plant, exposure zone (department) and time period for the three textile plants included in the exposure assessment. These data demonstrate very high fibre levels in all plants and departments during early years of plant operation and substantial reductions over calendar time. Differences in mean fibre concentrations by plant and exposure zone were demonstrated. Substantial differences were observed by UJC job groups within zones (data not shown).

We evaluated the contribution of model fixed effects in a series of nested models, starting with the null model. Table 4 provides the AIC, the  $-2 \log$  likelihood and LR test results for the nested models. All fixed effects were statistically significant and retained in the model.

After selection of the fixed effects, we next explored within and between UJC variance components by specifying specific job as a random effect and assuming compound symmetry for the covariance structure for repeated measurements by job. Our initial model assumed a distinct variance between job for each UJC and a common variance within job for each UJC.<sup>36</sup> This model did not improve AIC; therefore, a less restrictive model assuming common within and between job variance for all UJCs was fit. This model resulted in negligible improvement in model fit by AIC and did not appreciably change estimates or variances for the fixed effects. Our findings in this regard are similar to those of Peretz *et al*<sup>38</sup> who observed that multiple linear regression, which assumes independence, can be correctly

**Table 2** Impinger to PCM conversion estimates using paired and concurrent samples

Study plant ID	Exposure zone group	Paired samples (n)	Concurrent samples (n)	Paired samples			Concurrent samples			Combined estimates		
				PCM/imp ratio*	95% LCL	95% UCL	PCM/imp ratio	95% LCL	95% UCL	PCM/imp ratio	95% LCL	95% UCL
1	Prep-card	12	40	5.24	3.31	7.60	4.45	3.28	6.03	4.77	4.16	5.37
1	Spin-twist	12	58	3.09	1.82	4.69	2.47	1.51	3.85	2.73	2.20	3.27
1	Weave-product	7	52	2.63	0.23	7.60	1.52	0.88	2.45	1.60	0.42	2.78
3	Prep-card	30	149	3.84	2.64	5.25	8.78	6.99	10.88	5.52	4.95	6.09
3	Spin-twist	40	131	1.54	0.92	2.31	4.52	3.27	6.07	2.60	2.13	3.07
3	Weave-product	46	75	6.40	4.46	8.71	5.66	3.15	9.62	6.16	5.42	6.89
4	Prep-card	15	85	8.72	6.25	11.59	7.23	5.26	9.71	8.04	7.37	8.71
4	Spin-twist	18	80	8.48	6.57	10.73	4.90	3.37	6.81	7.02	6.46	7.58
4	Weave-product	27	120	9.16	7.20	11.35	4.32	3.24	5.72	6.98	6.47	7.49

\*PCM fibres >5 µm/ml per MPPCF.

Imp, impinger; LCL, lower confidence limit; MPPCF, millions of particles per cubic foot of air; PCM, phase contract microscopy; UCL, upper confidence limit.

applied when each worker has only a single measurement. While some degree of heteroscedasticity of the variance component by combinations of plant, zone, UJC and time period was observed, more complex heterogeneous variance models did not improve model AIC. Furthermore, we did not observe any discernable pattern in the geometric standard deviations for PCM fibre concentrations by plant, zone, UJC and time period. Based on these analyses and observations, only the fixed effects were retained in the final model with an assumption of sample independence.

Pearson correlations between the observed and predicted PCM exposures found that the final model accounted for 64% of

the variability in log PCM measurements. Inclusion of the model fixed effects reduced between job variance by 97% and within job variance by 54%.

Parameter estimates from the final mixed model for log PCM concentrations are presented in table 5 for five major textile operations by plant. Also included in this table is an example calculation for the arithmetic average PCM concentration using the model parameter estimates and the model residual variance (1.169). The model parameter estimates for UJC groups nested within zone and plant were found to be substantially different for many combinations of plant and zone. These differences are shown graphically in fig 1 for plant 1, which shows predicted

**Table 3** Arithmetic and geometric mean PCM fibre concentrations (fibre >5 µm/ml) by plant, exposure zone and calendar period, North Carolina asbestos textile plants

Plant	Exposure zone	1935–1946				1947–1970				1971–1986			
		No	AM	GM	GSD	No	AM	GM	GSD	No	AM	GM	GSD
1*	All combined†	129	65.3	23.2	4.7	419	9.5	5.9	3.1	*			
1	Preparation	25	139.2	65.0	3.9	43	15.8	10.6	2.2				
1	Carding	35	110.4	64.9	3.2	76	13.4	11.4	1.9				
1	Spinning	17	18.9	14.4	2.1	106	9.7	7.1	2.4				
1	Twisting	18	21.6	16.2	2.2	66	9.8	7.1	2.4				
1	Weaving	17	10.4	7.3	2.4	75	3.4	2.0	3.4				
1	Winding	10	14.7	10.1	2.9	41	7.0	4.3	2.8				
1	Finishing	2	5.2	5.2	1.2	2	1.7	1.6	1.4				
1	All others	5	6.5	0.9	9.9	10	7.2	3.4	4.7				
3	All combined†	279	100.5	39.2	4.0	767	10.1	5.3	3.1	831	5.1	1.4	5.3
3	Preparation	59	182.3	64.2	4.2	124	11.1	6.9	2.5	116	7.0	1.1	6.1
3	Carding	60	128.9	72.6	3.1	158	14.7	9.9	2.4	187	7.7	1.8	6.1
3	Spinning	35	16.0	12.5	2.2	133	4.0	2.9	2.5	99	4.2	1.9	4.6
3	Twisting	21	22.4	15.1	3.0	118	6.5	4.2	3.0	93	4.7	2.0	4.4
3	Weaving	65	104.5	47.1	3.7	153	14.4	5.9	3.3	170	3.6	1.3	4.5
3	Winding	18	54.2	46.3	1.8	30	7.5	4.4	3.1	56	4.0	2.3	3.1
3	Finishing	5	31.0	18.6	3.2	16	2.1	1.0	2.8	44	1.0	0.7	2.7
4‡	All combined†	16	46.0	25.8	3.7	514	21.2	13.9	2.9	456	3.5	1.1	5.1
4	Preparation					52	25.9	17.9	2.4	52	3.1	1.0	6.0
4	Carding					94	21.4	14.0	3.2	119	6.1	1.7	5.4
4	Spinning					83	19.5	14.9	2.1	27	1.1	0.8	2.4
4	Twisting					55	29.5	19.9	2.7	25	6.5	5.0	2.2
4	Weaving	14	47.7	25.8	4.0	147	21.3	15.0	2.5	80	2.5	1.6	2.9
4	Winding					39	16.5	10.2	3.3	51	1.7	0.6	4.4
4	Finishing	2	33.9	25.7	3.0	19	9.2	4.5	4.8	15	3.6	1.6	3.5
4	All others					25	12.7	7.2	4.6	83	2.1	0.5	5.9

\*Plant 1 ceased asbestos production in 1970; †all departments combined; ‡plant 3 began asbestos operations in approximately 1942.

AM, arithmetic means; GM, geometric means; GSD, geometric standard deviation; PCM, phase contract microscopy.

**Table 4** Nested mixed models showing effects of added parameters to model fit, North Carolina asbestos textile plants

Model effects	AIC	-2 Log likelihood	Likelihood ratio test p value
Intercept only	13594	13590	
Year	11539	11533	<0.001
Year, splines	11184	11171	<0.001
Year, splines, plant	11107	11089	<0.001
Year, splines zone (plant)	10385	10303	<0.001
Year, splines, UJC (zone, plant)	10270	10132	<0.001

AIC, Akaike's information criterion.

mean PCM levels by zone and UJC. Workers handling raw unspun fibre (UJC D) in preparation and carding were found to have very high predicted exposure levels, while machine operators (UJC B) in these departments experienced high exposures which were however lower than those for workers handling raw fibre. Similar patterns were observed for plants 3 and 4. While PCM concentrations demonstrated a significant downward trend for the entire follow-up period, the slope changed significantly after passage of the first OSHA standards in 1971 (table 5, parameter for spline 3).

### TEM size-specific exposures

Seventy seven membrane filter samples were analysed by TEM and a total of 22 776 fibres or fibre bundles were enumerated and sized. The number of fibres or fibre bundles analysed by combinations of plant and zone ranged from 290 to 1843.

Table 6 provides data on the overall joint fibre size distribution by length and diameter for each plant, expressed as the proportion of all airborne fibres by TEM within each cell of the diameter/length matrix. These same estimates were generated for each exposure zone of the plants studied (not shown). The preponderance of short (<1.5 µm) and thin (<0.25 µm) fibres by plant ranged from 47.4% in plant 4 to 55.8% in plant 3. More detailed data by plant zones found the proportion of fibres detectable by PCM ( $\geq 0.25$  µm in diameter

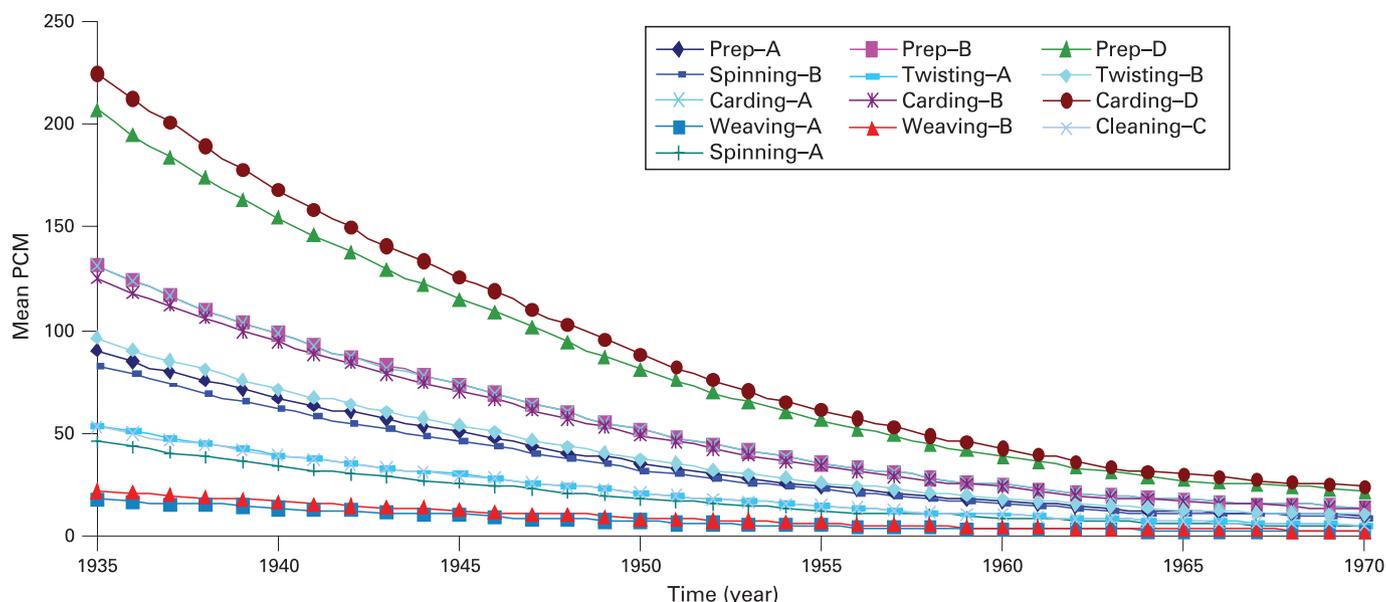
and >5 µm in length) to range from 2.9% (95% CI 1.9% to 4.0%) for zone 6 (winding) in plant 4 to 10.0% (95% CI 8.0% to 12.3%) for zone 2 (carding) in plant 3. In most plant exposure zones, only a small proportion of airborne fibres were longer than 15 µm, with a range of 1.6% (95% CI 1.1% to 2.2%) in zone 1 (carding) of plant 4 to 6.7% (95% CI 4.8% to 8.8%) in zone 7 (finishing and shipping) of plant 1.

A comparison of plant overall PCM adjustment factors by diameter and length category is presented in table 7 and some potentially important differences were noted. Generally, the adjustment factors for plant 4 were higher for fibres <5 µm. In addition to differences by plant, considerable differences were observed between zones within plants (data not shown). For example, the PCM adjustment factor for very thin and long fibres (<0.25 µm in diameter and >40 µm in length) in plant 1 ranged from 0.0056 in preparation to 0.0422 in weaving, a more than sevenfold difference.

In order to demonstrate use of the PCM adjustment factors to estimate size-specific exposures, adjustment factors by zone and UJC for plant 1 were applied to PCM estimates to generate estimated mean exposures to long thin fibres (<0.25 µm in diameter and >5 µm in length and not counted by PCM). Estimated mean exposures by calendar time for long thin fibres are plotted in fig 2. The PCM adjustment factor for fibres of this size ranged from 0.74 in preparation to 1.29 in weaving and application of these factors to the PCM estimates resulted in a number of changes in the rank order of exposures by zone and UJC. For example, based on TEM exposures to long thin fibres, twisting (UJC B) was ranked third highest whereas this job was fifth highest by PCM. Should exposures to longer and thinner fibres be more predictive of disease risks, the data in fig 2 demonstrate the potential for considerable exposure misclassification based on PCM exposures.

### DISCUSSION

Historical dust samples collected in three asbestos textile plants were used to develop a JEM that estimated fibre exposure levels by plant, department, job group within departments, and calendar time. The 1938 USPHS study<sup>2</sup> and the North Carolina



**Figure 1** Predicted mean PCM concentrations (fibres >5 µm/ml) by time period, department, and job group – plant 1. PCM, phase contract microscopy.

**Table 5** Mixed model coefficients and standard errors for estimated log fibre concentrations (fibres >5 µm/ml) by plant, exposure zone, calendar period and job group, North Carolina asbestos textile plants

Model fixed effects	Plant	Zone and department	UJC	β Coefficient	SE
Intercept				2.636	0.632
Follow-up year (Year-1935)				-0.058	0.012
Spline 1 (Year-46, If >0)*				-0.016	0.016
Spline 2 (Year-64, If >0)				0.029	0.012
Spline 3 (Year-71, If >0)				-0.210	0.025
Spline 4 (Year-76, If >0)				0.092	0.028
UJCs nested within zones and plants	1	1-Preparation	A	1.281	0.675
	1	1-Preparation	B	1.659	0.650
	1	1-Preparation	D	2.113	0.735
	1	2-Carding	A	1.658	0.639
	1	2-Carding	B	1.613	0.670
	1	2-Carding	D	2.198	0.767
	1	3-Spinning	A	0.603	0.640
	1	3-Spinning	B	1.200	0.648
	1	4-Twisting	A	0.758	0.646
	1	4-Twisting	B	1.344	0.653
	1	5-Weaving	A	-0.329	0.651
	1	5-Weaving	B	-0.123	0.644
	3	1-Preparation	A	1.241	0.634
	3	1-Preparation	B	1.621	0.634
	3	1-Preparation	D	1.371	0.650
	3	2-Carding	A	1.595	0.632
	3	2-Carding	B	1.916	0.631
	3	2-Carding	D	1.610	0.659
	3	3-Spinning	A	0.292	0.637
	3	3-Spinning	B	0.920	0.631
	3	4-Twisting	A	0.307	0.641
	3	4-Twisting	B	1.553	0.632
	3	5-Weaving	A	1.604	0.640
	3	5-Weaving	B	1.033	0.629
	4	1-Preparation	A	1.608	0.670
	4	1-Preparation	B	1.683	0.639
	4	1-Preparation	D	2.231	0.723
	4	2-Carding	A	1.610	0.635
	4	2-Carding	B	1.696	0.636
	4	2-Carding	D	2.908	0.705
	4	3-Spinning	A	1.913	0.649
	4	3-Spinning	B	1.938	0.640
	4	4-Twisting	A	2.279	0.661
	4	4-Twisting	B	1.926	0.643
	4	5-Weaving	A	1.279	0.643
	4	5-Weaving	B	1.573	0.631

Example arithmetic mean PCM concentration calculation for a weaver (UJC B) in plant 1 in 1955. Model residual variance = 1.169.

$AM = \exp[(\text{intercept} + (\beta_{\text{year}}) \times (1955 - 1935) + (\beta_{\text{spline}_1}) \times (1955 - 1946) + \beta_{\text{UJC zone plant}} + 0.5 \times (\text{residual model variance}))]$

$AM = \exp[2.636 + (-0.058 \times 20) + (-0.016 \times 9) + (-0.123) + (0.5 \times 1.169)]$

$AM = 6.01 \text{ fibres} > 5 \text{ } \mu\text{m/ml}$

\*In linear spline time trends the coefficients for the second term through remaining terms are constrained to apply only when the variable (year-boundary) is a positive value.

A, arithmetic mean; PCM, phase contrast microscopy; SE, standard error; UJC, uniform job category.

Dusty Trades program provided excellent historical plant and process information and dust sample results. Another strength of this study was the availability of both paired samples and concurrent samples for estimating plant- and department-specific impinger to PCM conversion factors.

Nested mixed models were used to estimate mean PCM exposures and the final fixed effects model accounted for a high proportion of sample variance. Due to the very limited possibility for repeated samples by worker and our initial analyses which showed little effect when job was treated as a random effect with compound symmetry, we chose a covariance structure that assumed independence of all samples, a

finding similar to other studies where repeated samples by worker was minimal.<sup>33-38</sup> While the model fits the data reasonably well, the predicted mean exposures and trends by time, plant, exposure zone and UJC are largely determined by model assumptions and constraints. A key aspect of the models developed for predicting exposures was the use of a linear spline time trend in the mixed models to account for exposure reductions in response to exposure guidelines and standards. The calendar year and linear splines were thus used as surrogates for technological and administrative changes not captured in the model. Our final model assumed that all combinations of plant, exposure zone and UJC had the same

**Table 6** Fibre diameter and length data – overall plant summaries

Fibre diameter, $\mu\text{m}$	Fibre length, $\mu\text{m}$	Plant 1	Plant 3	Plant 4
		Bivariate size proportion (CI)*†	Bivariate size proportion (CI)†	Bivariate size proportion (CI)†
<0.25	<1.5	0.529 (0.515 to 0.541)	0.558 (0.543 to 0.570)	0.474 (0.463 to 0.484)
	1.5–3.0	0.188 (0.178 to 0.198)	0.168 (0.157 to 0.178)	0.212 (0.204 to 0.220)
	>3.0–5.0	0.080 (0.073 to 0.087)	0.065 (0.058 to 0.072)	0.078 (0.072 to 0.083)
	>5.0–10.0	0.043 (0.040 to 0.048)	0.041 (0.037 to 0.045)	0.061 (0.058 to 0.065)
	>10.0–15.0	0.011 (0.010 to 0.013)	0.013 (0.011 to 0.015)	0.016 (0.014 to 0.017)
	>15.0–20.0	0.007 (0.006 to 0.008)	0.008 (0.006 to 0.009)	0.006 (0.005 to 0.007)
	>20.0–40.0	0.007 (0.006 to 0.008)	0.009 (0.008 to 0.010)	0.008 (0.007 to 0.008)
	>40.0	0.003 (0.002 to 0.003)	0.003 (0.002 to 0.004)	0.002 (0.001 to 0.003)
0.25–1.0	<1.5	0.0103(0.008 to 0.013)	0.014 (0.011 to 0.018)	0.019 (0.016 to 0.022)
	1.5–3.0	0.026 (0.022 to 0.031)	0.030 (0.025 to 0.035)	0.040 (0.037 to 0.044)
	>3.0–5.0	0.021 (0.017 to 0.025)	0.020 (0.016 to 0.024)	0.030 (0.026 to 0.033)
	>5.0–10.0	0.024 (0.021 to 0.027)	0.021 (0.018 to 0.024)	0.022 (0.020 to 0.024)
	>10.0–15.0	0.009 (0.007 to 0.010)	0.008 (0.007 to 0.010)	0.008 (0.007 to 0.010)
	>15.0–20.0	0.005 (0.004 to 0.006)	0.005 (0.004 to 0.006)	0.003 (0.003 to 0.004)
	>20.0–40.0	0.009 (0.008 to 0.011)	0.008 (0.007 to 0.009)	0.005 (0.004 to 0.006)
	>40.0	0.006 (0.005 to 0.007)	0.004 (0.003 to 0.005)	0.003 (0.002 to 0.003)
>1.0–3.0	>1.5–3.0	0.001 (<0.001 to 0.002)	0.001 (<0.001 to 0.002)	0.001 (<0.001 to 0.001)
	>3.0–5.0	0.002 (0.001 to 0.003)	0.003 (0.001 to 0.004)	0.003 (0.002 to 0.004)
	>5.0–10.0	0.006 (0.004 to 0.007)	0.006 (0.004 to 0.007)	0.004 (0.003 to 0.004)
	>10.0–15.0	0.003 (0.002 to 0.004)	0.004 (0.003 to 0.005)	0.003 (0.002 to 0.003)
	>15.0–20.0	0.002 (0.002 to 0.003)	0.003 (0.002 to 0.003)	0.001 (0.001 to 0.002)
	>20.0–40.0	0.003 (0.003 to 0.004)	0.003 (0.002 to 0.004)	0.002 (0.001 to 0.002)
	>40.0	0.003 (0.002 to 0.003)	0.001 (0.001 to 0.002)	0.001 (0.001 to 0.001)
	>5.0–10.0	0.000 (0.000 to 0.000)	<0.001 (0.0000 to 0.001)	<0.001 (0.0000 to 0.001)
>3.0	>10.0–15.0	0.001 (<0.001 to 0.002)	0.001 (<0.001 to 0.001)	0.001 (<0.001 to 0.001)
	>15.0–20.0	0.001 (<0.001 to 0.001)	0.001 (<0.001 to 0.001)	<0.001 (0.000 to 0.001)
	>20.0–40.0	0.001 (0.001 to 0.002)	0.002 (0.001 to 0.003)	0.001 (<0.001 to 0.001)
	>40.0	0.001 (<0.001 to 0.001)	0.001 (<0.001 to 0.002)	<0.001 (0.000 to 0.001)
	>5.0–10.0	0.000 (0.000 to 0.000)	<0.001 (0.0000 to 0.001)	<0.001 (0.0000 to 0.001)

\*Size proportions and confidence intervals are rounded to the third decimal for presentation. †Lower 5% and upper 95% confidence intervals from bootstrap analyses.

relative decrease in exposure within each time period and, while model time variables greatly improved model fit, we did not have more detailed data concerning technical changes by process to allow more detailed modelling. The model also assumed constant variance and misspecification of variance components would impact the arithmetic means. However, we observed little evidence of heteroscedasticity in the mixed models, so this assumption should minimally impact estimated mean exposures. Additionally, the high proportion of overall PCM variance explained by our model provides a reasonable degree of assurance that predicted exposures accurately reflect the measurement data.

Estimated PCM exposure levels were extremely high in 1935 and decreased significantly over time, reflecting progressive application of dust control measures. Large differences in exposure levels were observed by departments and jobs within departments. Data for plants 3 and 4, which operated after 1970, demonstrated greatly reduced exposures after the first OSHA asbestos standard was promulgated in 1972. Asbestos exposure levels in these three plants were generally higher than those observed in the Charleston plant studied by Dement *et al*,<sup>27</sup> a finding consistent with the USPHS studies in these plants in the 1930s.<sup>3, 23</sup>

Results of current TEM analyses are consistent with prior TEM studies of chrysotile asbestos textile plants<sup>15–17</sup> demonstrating a preponderance of short fibres in airborne aerosols. The TEM fibre size data, combined with the PCM fibre concentration estimates by plant, zone, job and time period, provide the ability to define new metrics based on single bivariate size categories or any combination of size categories. A strength of the current study is

the sizing of a reasonable number of fibres (290–1843) for each plant and exposure zone with additional efforts in the TEM analyses to better capture the entire fibre size spectrum, including fibres as thin as <0.25  $\mu\text{m}$  in diameter and as long as >40  $\mu\text{m}$ . A limitation is the unavailability of samples and resources to further study differences by job groups within each zone. However, based on published information concerning plant processes, jobs and fibre characteristics within each zone, the assumption that jobs within a given exposure zone share similar airborne fibre size characteristics appears justified.

Given that the samples for TEM analyses do not cover the entire period for which PCM estimates are available, only point estimates of the PCM adjustment factors were possible. The implicit assumption is stability of the airborne fibre size distribution over calendar time within each exposure zone (while changes in the airborne fibre concentration over time in each exposure zone were based on industrial hygiene sampling data over time). The processes involved in making asbestos textiles in the USA changed relatively little over the study period, both with regard to the sources of asbestos fibre used and processing equipment. Quinn *et al*<sup>42</sup> demonstrated that bulk material factors for fibrous glass are important determinants of the airborne fibre size distribution, supporting the assumption that similar production processes applied to similar bulk fibrous material are likely to produce similar airborne fibre size distributions. Our assumption of stability of airborne fibre characteristics within a given plant operation over calendar time therefore seems reasonable and appropriate; however, we cannot completely rule out some changes in airborne fibre characteristics over time.

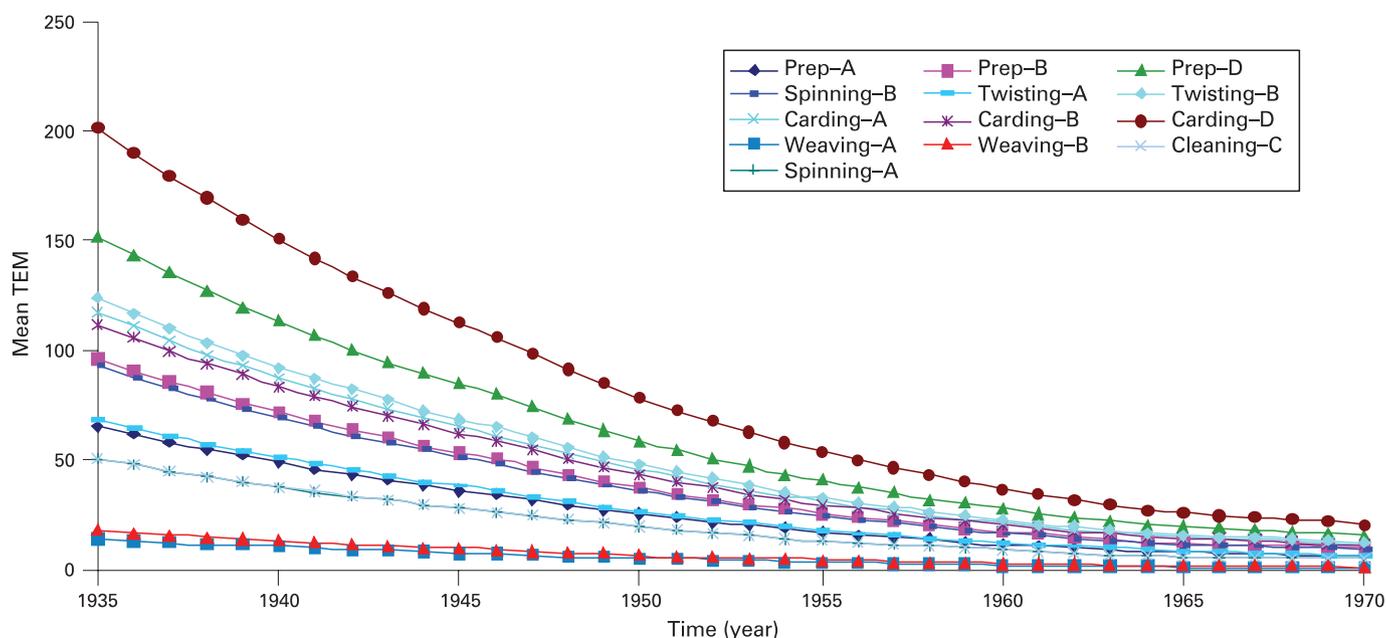
**Table 7** Phase contract microscopy (PCM) adjustment factors – overall plant summaries

Fibre diameter, $\mu\text{m}$	Fibre length, $\mu\text{m}$	Plant 1	Plant 3	Plant 4
		PCM factor (CI)*†	PCM factor (CI)†	PCM factor (CI)†
<0.25	<1.5	7.274 (6.668 to 7.946)	8.325 (7.546 to 9.215)	9.150 (8.534 to 9.803)
	1.5–3.0	2.583(2.347 to 2.854)	2.508 (2.215 to 2.797)	4.094 (3.779 to 4.425)
	>3.0–5.0	1.094 (0.970 to 1.231)	0.973 (0.828 to 1.118)	1.507 (1.360 to 1.661)
	>5.0–10.0	0.597 (0.539 to 0.666)	0.604 (0.545 to 0.676)	1.184 (1.104 to 1.270)
	>10.0–15.0	0.1534(0.129 to 0.180)	0.196 (0.165 to 0.229)	0.301 (0.272 to 0.331)
	>15.0–20.0	0.090 (0.076 to 0.104)	0.113 (0.093 to 0.136)	0.111 (0.098 to 0.124)
	>20.0–40.0	0.097 (0.083 to 0.111)	0.132 (0.111 to 0.155)	0.145 (0.131 to 0.159)
0.25–1.0	>40.0	0.035 (0.027 to 0.044)	0.047 (0.036 to 0.059)	0.044 (0.037 to 0.052)
	<1.5	0.142 (0.104 to 0.187)	0.214 (0.163 to 0.272)	0.366 (0.312 to 0.424)
	1.5–3.0	0.360 (0.293 to 0.430)	0.453 (0.371 to 0.532)	0.778 (0.696 to 0.863)
	>3.0–5.0	0.285 (0.228 to 0.342)	0.298 (0.236 to 0.368)	0.571 (0.497 to 0.648)
	>5.0–10.0	0.329 (0.299 to 0.355)	0.311 (0.278 to 0.343)	0.419 (0.394 to 0.445)
	>10.0–15.0	0.118 (0.097 to 0.140)	0.125 (0.103 to 0.148)	0.159 (0.139 to 0.179)
	>15.0–20.0	0.067 (0.055 to 0.079)	0.076 (0.062 to 0.090)	0.059 (0.052 to 0.068)
>1.0–3.0	>20.0–40.0	0.127 (0.113 to 0.141)	0.118 (0.100 to 0.136)	0.087 (0.077 to 0.097)
	>40.0	0.086 (0.074 to 0.099)	0.062 (0.049 to 0.075)	0.053 (0.046 to 0.061)
	>1.5–3.0	0.012 (0.004 to 0.021)	0.017 (0.004 to 0.036)	0.009 (0.003 to 0.017)
	>3.0–5.0	0.029 (0.014 to 0.044)	0.040 (0.019 to 0.064)	0.049 (0.030 to 0.069)
	>5.0–10.0	0.075 (0.059 to 0.092)	0.083 (0.066 to 0.101)	0.070 (0.057 to 0.083)
	>10.0–15.0	0.0400 (0.028 to 0.052)	0.061 (0.047 to 0.077)	0.048 (0.036 to 0.062)
	>15.0–20.0	0.032 (0.025 to 0.039)	0.037 (0.027 to 0.048)	0.022 (0.017 to 0.027)
>3.0	>20.0–40.0	0.045 (0.036 to 0.055)	0.042 (0.032 to 0.055)	0.032 (0.026 to 0.038)
	>40.0	0.036 (0.029 to 0.044)	0.015 (0.009 to 0.023)	0.013 (0.010 to 0.017)
	>5.0–10.0	0.0000 (0.000 to 0.000)	0.003 (0.000 to 0.007)	0.005 (0.002 to 0.009)
	>10.0–15.0	0.013 (0.006 to 0.021)	0.012 (0.004 to 0.018)	0.011 (0.006 to 0.016)
	>15.0–20.0	0.007 (0.003 to 0.010)	0.009 (0.004 to 0.014)	0.006 (0.003 to 0.009)
	>20.0–40.0	0.017 (0.012 to 0.023)	0.030 (0.021 to 0.039)	0.010(0.007 to 0.013)
	>40.0	0.008 (0.004 to 0.012)	0.018 (0.011 to 0.026)	0.007 (0.004 to 0.010)

\*PCM factors are rounded to the third decimal for presentation. †Lower 5% and upper 95% confidence intervals from bootstrap analyses.

Our results have significant implications for epidemiological studies that seek to estimate fibre exposure–response relationships. While exposure estimates obtained by PCM provide data useful for risk assessments, the PCM method is relatively insensitive to differences in airborne fibre

characteristics across and within industries and does not allow for analyses of fibre size-specific risks. Our aim is to use exposure estimates from this study in conjunction with ongoing epidemiological studies to better assess risks by fibre size for chrysotile.



**Figure 2** Predicted mean size-specific TEM concentrations (fibres <0.25  $\mu\text{m}$  in diameter and >5  $\mu\text{m}$  length/ml) by time period, department and job group – plant 1. TEM, transmission electron microscopy.

## CONCLUSIONS

Data from the current study contribute to the literature concerning historical exposures among asbestos textile workers and will be valuable in ongoing exposure–response analyses for lung cancer and asbestosis among workers at these plants. While animal studies have suggested that longer and thinner fibres are more biologically active in the production of disease, few human data exist to support or refute these findings. Occupational cohorts are exposed to a wide range of airborne asbestos fibres, with the vast majority being shorter than 5 µm in length. While asbestos textile operations typically used grades of chrysotile with longer fibre lengths, the resulting aerosol to which workers were exposed was primarily comprised of short fibres. The fibre size distributions and the PCM adjustment factors were shown to vary considerably across plants and operations. The methods used in this study for developing the PCM JEM and the fibre size-specific JEM are applicable in other situations where historical data on dust exposures exist and TEM data or archived samples are available to generate bivariate size distributions.

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**Competing interests:** None.

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