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The Morbidity and Mortality of Vermiculite Miners and Millers Exposed to Tremolite-Actinolite: Part I. Exposure Estimates

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The vermiculite ore and concentrate of a mine and mill near Libby, Montana, was found to be contaminated with fibrous tremolite-actinolite. Of 599 fibers (length greater than 5 μm and width greater than 0.45 μm) counted in eight airborne membrane filter samples, 96% had an aspect ratio greater than 10 and 16% had an aspect ratio greater than 50. Additionally, 73% of the fibers were longer than 10 μm, 36% were longer than 20 μm, and 10% were longer than 40 μm. Estimates of exposure before 1964 in the dry mill were 168 fibers/cc for working areas, 182 fibers/cc for sweepers, 88 fibers/cc for skipping, and 13 fibers/cc for the quality control laboratory. In 1964-1971, exposure estimates for these areas were 33, 36, 17, and 3 fibers/cc, respectively. Estimates of exposures in the mine before 1971 ranged from 9-23 fibers/cc for drillers and were less than 2 fibers/cc for nondrilling jobs. All 8-hr TWA job exposure estimates decreased from 1972-1976, and from 1977-1982 were less than 1 fiber/cc.

Key words: tremolite-actinolite, fiber type, fiber dimension, fiber-years exposure

INTRODUCTION

Vermiculite is a micaceous mineral with a ferromagnesium-aluminum silicate composition. It exfoliates when heated and has properties of high bulk, good thermal insulation, inert composition, fire-proof nature, and high absorption [U.S. Bureau of Mines, 1970]. Expanded vermiculite is used in construction materials (aggregates in plaster and concrete), agricultural products (potting soil, soil conditioner, nursery stock packing material, fertilizer, and a carrier for chemicals), and other industrial uses.

Vermiculite alone has not been associated with significant health effects; however, it has never been systematically studied epidemiologically. Vermiculite deposits in Montana and South Carolina are contaminated with fibrous tremolite-actinolite [Atkinson et al, 1982], and health effects from Montana vermiculite concentrate have been attributed to exposure to the asbestos fibers [Lockey et al, 1984]. Concern for exposure to the tremolite contaminating the Montana vermiculite concentrate has led

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to (1) a cross-sectional study by Lockey et al [1984] of radiographic and pulmonary function findings in workers at an Ohio fertilizer plant that processed concentrate from South Africa and from the Libby, Montana, mine and mill; (2) a study by the Environmental Protection Agency of the asbestos content of the bulk and airborne dust in the Libby facility [Atkinson et al, 1982]; and (3) our studies of the mortality and morbidity of the Libby miners and millers [Amandus et al, 1987a,b]. In addition to our study, McDonald et al [1986b] have conducted a parallel but separate study of the Libby workers.

Atkinson et al [1982] found fibrous tremolite-actinolite, nonfibrous tremolite-actinolite, and non fibrous anthophyllite in the raw ore and vermiculite concentrate from the Libby mill. The percentage by weight of fibrous tremolite-actinolite was approximately 21–26% in the raw ore sampled at the head feed of the mill, and 2-6% in the concentrate. Results from similar analyses by the company in 1984 indicated that the percentage by weight of fibers varied from 3.5–6.4% in the raw ore at the head feed, and from 0.4–1.0% in the concentrate [Wolter, personal communication].

The objective of our study was to estimate the exposure–response relationship between tremolite exposure, lung cancer, and asbestosis. The primary purposes of this paper are to: (1) estimate a ratio to convert respirable airborne dust exposure (million particles per cubic foot, mppcf) to fiber exposure (fibers per cubic centimeter, fibers/cc). (2) estimate the 8-hr TWA fiber exposure for jobs in each year of operation of the Libby facility. (3) characterize the type and dimension of fibers contaminating the Libby vermiculite concentrate.

METHODS

Description and History of the Vermiculite Facility

Production of the Montana vermiculite concentrate begins at the mine where the ore is drilled, loaded, and hauled to a transfer point. Coarse fractions greater than 5/8 inch are separated while the fine fraction is transferred by belt to the mill. The milling operation is a wet beneficiation process comprised of several circuits. From the mill, the processed concentrate is transferred to a loading site, placed into enclosed trucks, and hauled to a screening plant. Screened concentrate is either stored or transferred across the Kootenai river for shipment, while a smaller quantity of concentrate is hauled to a bagging plant located in Libby. The mine and mill are located approximately 12 miles from Libby, and the screening and loading dock are approximately 7 miles from town. The history of engineering changes in the facility is described in Table I.

Exposure Estimates

Samples of airborne dust have been taken in the mill since 1942 and in the mine since 1968. Prior to 1969, 336 midget impinger samples were collected by the state of Montana primarily in the dry mill, and after 1967, 4116 membrane filter samples of airborne dust were collected by federal agencies (NIOSH, MESA, and MSHA) and the company in most areas of the facility (Table II). Before 1974, filter samples were either general area or short-term personal samplings collected over periods ranging from 20 minutes to several hours, and were not likely to have reflected the 8-hr TWA exposure.

TABLE I. History of Mine and Mill

Date	Event
1935	The dry mill began operation
1950	The wet mill operated in the same building as the dry mill
1935–1950	Bulk ore was loaded into railroad box cars at a loading station in Libby
1950–1959	Bulk ore was loaded into railroad tank cars at a loading station 7 miles from Libby
1960	Bulk ore was loaded into enclosed hopper cars
1961	An exhaust system was installed in the loading area
1964	An exhaust fan was installed in the dry mill
1968	The exhaust stack for the fan in the dry mill was moved to route the exhaust away from the shop area around mill
1970	A new drill was purchased with a dust control bagging system
1972	An automatic bagging machine replaced hand filling and sewing
1972	The skipper control room was pressurized (skipping is the process by which concentrate is transferred from the mill to a storage site)
1973	A new wet mill was constructed adjacent to the old dry and wet mill facility
1974	A new screen plant was constructed at the river loading dock
1974	The old dry and wet mills were closed

TABLE II. Description of Environmental Samples

Source	Units of measurement[a]	Year sample collected	No. of samples
State of Montana[b]	mppcf	1956–1969	336
NIOSH	f/cc	1967–1968	48
MESA/MSHA[c]	f/cc	1971–1981	789
Company	f/cc	1970–1982	3279

[a]Mppcf, million particles per cubic foot; f/cc, fibers per cubic centimeter.
[b]One sample report was available in 1942.
[c]From 1969 to 1977, membrane filter samples were collected by MESA; MSHA took over MESA's activities in 1977.

The 8-hr TWA fiber-exposure for jobs was estimated from short term samples employing a scheme derived by McDonald et al [1986a,b] in which the mine and mill was divided into "location-operations" (LO). The arithmetic average fiber-exposure (f/cc) was estimated in each LO, and an estimate of the 8-hr TWA fiber exposure (f/cc) for each job was computed as an average of LO estimates weighted by the proportion of time spent in the LO.

Using the scheme devised by McDonald et al [1985], we divided the facility into 25 LO. The LO were defined by dividing the facility into major locations (mine, mill, service, loading, and bagging), and then subdividing the locations by operations based on job exposures.

For the years after 1968, fiber exposure in the LO were estimated employing an arithmetic average of the fiber concentrations from filter samples. Samples were pooled for years when production processes and dust controls were assumed to be similar (Table III). For the years before 1968, fiber exposure in the dry mill was estimated from the average respirable dust exposure (mppcf), which was converted to fiber exposure (f/cc) employing a conversion ratio. For the years before 1968, fiber exposure in all other LO were estimated based on assumptions, which are discussed further below.

TABLE III. The Average f/cc Values Calculated From Membrane Filter Samples Collected in 1967–1982 by Location–Operation and Year

Location–operation	Year	Average	Standard error[a]	No. of samples	Confidence interval Upper	Lower
Bus ride	67–74	1.2	0.3	4	2.3	1.1
	>74	—	—	0	—	—
Mine office	67–74	1.0	.1	8	1.2	0.8
	>74	0.5	.1	18	0.7	0.3
Mine (miscellaneous)	67–74	1.6	.4	28	2.4	0.8
	>74	0.8	.1	33	1.0	0.6
Drilling	67–70	6.7	1.7	7	10.0	3.4
	71–74	9.2	5.4	13	19.8	0
	>74	0.6	0.9	63	2.4	0
Mine (nondrilling)	67–74	2.6	.3	140	2.0	3.2
	>74	0.6	0.1	157	0.7	0.5
Transfer point	67–74	2.2	0.4	21	3.3	1.7
	>74	0.6	0.0	116	0.7	0.5
Tails belt	67–74	7.3	1.3	28	9.8	4.8
	>74	0.7	0.1	30	0.9	0.5
Dry mill sweeping	67–71	35.9	4.4	28	44.5	27.3
	72–74	19.0	3.1	42	25.1	12.9
Dry mill	67–71	33.2	3.9	81	40.8	25.6
	72–74	16.6	0.9	155	18.4	14.8
Old wet mill (nonmillwright)	67–74	3.7	0.5	48	4.7	2.7
Old and new wet mill	67–74	7.0	4.9	16	16.7	0
(millwright)	>75	0.6	.2	14	1.0	0.2
New wet mill	73–74	4.6	.5	59	5.6	3.6
(nonmillwright)	75–76	2.0	.3	71	2.6	1.4
	>76	0.8	.1	1,214	0.9	0.7
Quality control lab	67–74	2.6	.4	39	3.4	1.8
	>74	0.6	0.1	205	0.8	0.4
Service area by mill	67–74	1.9	.6	83	3.1	0.7
	>74	0.2	0.0	108	0.2	0.2
Skip area	67–71	17.4	4.6	11	26.4	8.4
	72–74	4.8	2.6	31	9.9	0
	>74	0.6	0.1	190	0.7	0.5
Concentrate hauling	67–74	5.5	1.2	21	7.9	3.1
	>74	0.4	0.0	97	0.4	0.4
River station (binside)	67–74	21.2	8.7	18	38.3	4.1
	>74	0.7	0.1	62	0.9	0.5
River conveyor tunnel	67–74	112.5	34.3	20	179.7	45.7
	>74	0.3	0.1	12	0.4	0.2
River office (binside)	67–74	10.6	0	2	10.6	10.6
	>74	0.2	0	1	.2	.2
Ore loading	67–74	3.2	.8	18	4.8	1.6
	>74	0.2	0.1	8	0.3	0.1
River dock and car cleaning	70–74	5.1	1.7	11	8.4	1.8
	>74	0.5	0.1	64	0.6	0.4
Verxite plant	67–70	2.8	0.5	3	3.8	1.8
Bagging plant	67–71	4.6	.9	3	6.4	2.8
	72–74	6.0	1.2	50	8.4	3.6
	>74	1.2	.1	118	1.4	1.0
Downtown office building	>75	0.0	0.1	3	.2	.0
Screen plant	>74	0.5	0.1	443	0.7	0.3

[a]Standard error, standard deviation divided by the square root of the No. of samples.

Ideally, a conversion ratio (f/cc:mppcf) should be computed from impinger and membrane filter samples collected in the same areas and at the same time. Because no side-by-side samples were taken, we computed the ratio based on impinger and filter samples taken in the dry mill during 1964–1971 when the production processes were assumed to be similar. Few impinger samples were available for areas other than the dry mill. Filter samples taken after 1972 were not used for computation of the conversion ratio because fiber levels were significantly decreased after 1971 (Table IV). Impinger samples taken prior to 1965 were also not used because dust exposures from 1950–1964 were markedly higher (Table IV). The reduction in dust levels in 1964 was likely due, in part, to the installation of the exhaust fan in the dry mill.

The average respirable dust exposure (mppcf) and the average fiber exposure (f/cc) were computed for various time periods (Table IV), and conversion ratios were calculated (Table V), i.e., ratio = [(average f/cc)/(average mppcf)]. The most comparable period was from 1967–1968 when both impinger and membrane filter samples were taken in the dry mill. This comparison resulted in a conversion ratio of 8.0, based on 126 impinger and only 14 filter samples. Another possible comparison was 56 impinger samples collected in 1969 and 15 filter samples collected in 1970. This comparison resulted in a factor of 1.9, but again a small number of filter samples were taken in this period, and the average f/cc was significantly lower in 1970 than in 1967–1968 and 1971.

A conversion ratio of 4.0 was selected for this study, based on 336 impinger samples in 1965–1969 and 81 filter samples in 1967–1971. These time periods were chosen to obtain enough samples for the derivation of reasonable estimates of expo-

TABLE IV. Average Exposure by Year in the Dry Mill

Unit of measurement	Year of sample	Average	Standard deviation	Standard error	No. of samples
mppcf[a]	50-64	42.1	21.0	3.3	40
	65	9.5	6.7	0.7	84
	66	9.4	4.4	0.5	70
	67	9.0	4.0	0.5	56
	68	7.5	4.5	0.5	70
	69	5.7	3.2	0.4	56
	67-68	8.2	4.3	0.4	126
	67-69	7.4	4.0	0.3	182
	65-69	8.4	5.0	0.3	336
	68-69	6.7	4.0	0.4	126
f/cc[b]	67-68	65.3	67.3	18.0	14
	70	10.9	5.5	1.4	15
	71	31.0	17.1	2.4	52
	72	15.2	10.2	1.5	45
	73	15.8	11.1	1.3	79
	74	21.0	10.7	1.9	31
	67-70	37.1	53.7	10.0	29
	67-71	33.2	34.7	3.9	81
	67-74	22.3	23.4	1.5	236

[a]Midget impinger samples; mppcf, million particles per cubic foot.
[b]Membrane filter samples; f/cc, fibers per cubic centimeter.

TABLE V. Conversion ratios (f/cc:mppcf)

Year (average f/cc)[a]	Year (average mppcf)[b] 1967 (9.0)	1968 (7.5)	1969 (5.7)	1967–68 (8.2)	1967–69 (7.4)	1968–69 (6.7)	1965–69 (8.4)
1967–68 (65.3)	7.3	8.7	11.5	8.0	8.8	9.8	7.8
1970 (10.9)	1.2	1.5	1.9	1.3	1.5	1.6	1.3
1967–70 (37.1)	4.1	4.9	6.5	4.5	5.0	5.5	4.4
1967–71 (33.2)	3.7	4.4	5.8	4.1	4.5	5.0	4.0
1967–74 (22.3)	2.5	3.0	3.9	2.7	3.0	3.3	2.7

[a]f/cc, fibers per cubic centimeter.
[b]mppcf, million particles per cubic foot.

sure, and to control as much as possible for the effect of the continuing decline in dust levels. The derivation of the ratio will be discussed again later.

Assumptions were made as to the range of possible fiber exposures in some areas of the mill, and in the service, drilling, loading, and bagging areas, because samples were not available before 1968 (Table VI). Assumptions were based on NIOSH experience and the company staff's judgment as to the level of exposure in an LO relative to other LOs or to the dry mill. Exposures for areas in the dry mill (sweeping, quality control laboratory, and skipping) were assumed to be in the same proportion to the working area of the dry mill before and after 1968.

Exposures at the drilling, river dock, and ore loading areas prior to 1968 were more difficult to estimate than in other LOs due to significant engineering changes. Company officials believed that exposures at the river dock and loading area declined markedly in 1950 when box cars were replaced by hopper cars (Table I), and declined again in 1960–1961 when hopper cars were covered and an exhaust system was added. Exposures in drilling were believed to have declined markedly when a new drill, with a dust control bagging system, was employed after 1970. Due to the lack of exposure data in these areas, estimates before 1968 are considered "guesstimates."

However, the "guesstimates" for these LOs prior to 1968 had a small effect on the average cumulative exposure estimate for the overall cohort, and on the estimates of the exposure–response curves, because a small number of workers was employed in these areas. No drillers were employed from 1937–1948, and fewer than three were employed for most years during 1949–1960. No baggers were employed from 1937–1948, and only one to two from 1948–1968. Finally, fewer than five workers were employed in the loading area for all but 4 years before 1968.

For each year of operation, an estimate of the 8-hr TWA fiber exposure for each job was computed as an average of the 25 LO exposure estimates weighted by the proportion of time a worker employed in the job spent in the LO. An example of the calculation for a "transfer point operator" is as follows: A transfer point operator worked 9.5 hr over his shift; 2 hr on the tails belt, 6.5 hr at the transfer point, and 1 hr traveling by bus to and from the mine and Libby. His 8-hr TWA fiber exposure was calculated as follows for each year: [(2 hr × the tails belt exposure) + (6.5 hr × the transfer point exposure) + (1 hr × the bus ride exposure)] /8.0 hr. Employing

TABLE VI. Assumptions for Estimates of Fiber Exposure in the Location-Operations Before 1968

Location–operation	Assumptions
Mine	1) Exposures for all mine jobs but drillers were the same before and after 1968. 2) A range of estimates for drillers was assumed before 1970: a) *High estimates*: Exposures were 2.5 times higher prior to 1970 than after 1970 due to installation of a new drill with a dust control system. b) *Low estimates*: Estimated from seven samples collected in 1968–1970. c) Exposures were the same in each year before 1970.
Dry mill	1) Exposures for sweepers, quality control lab (QCL), and skippers (skip) were computed as a proportion of exposures in the dry mill working area: a) $\text{Sweeper}_{<68} = \text{Mill}_{<68} \times (\text{Sweeper}_{68\text{–}74}/\text{Mill}_{68\text{–}74})$ b) $\text{QCL}_{<68} = \text{Mill}_{<68} \times (\text{QCL}_{68\text{–}70}/\text{Mill}_{68\text{–}70})$ c) $\text{Skip}_{<68} = \text{Mill}_{<68} \times (\text{Skip}_{68\text{–}71}/\text{Mill}_{68\text{–}71})$
Service area	1) Exposures in 1964–1967 were two times higher than after 1967 due to contamination from the exhaust stack for the ventilation fan in the dry mill. 2) Exposures were similar before 1964 and 1967–1974.
Ore loading (OL)	1) A range of exposures was estimated before 1968: a) *High estimates*: 1960–1968: 30% higher than after 1970. 1950–1959: 36% higher than in 1960–1969. < 1950: Ore loader split time 50% by box car loading and operator's room, and 50% as a bagger. Exposure at loading dock and in the operator's room (150 f/cc) was slightly lower than in the dry mill (168 f/cc). b) *Low estimates*: company's estimates.
River dock and car cleaning (RD)	1) *High estimates*: 1960–1969: 30% higher than in 1970–1974. 1950–1959: 40% higher than in 1960–1969. < 1950: Exposure was computed as a proportion of the exposure in the OL: $\text{RD}_{<50} = \text{OL}_{<50} \times (\text{RD}_{70\text{–}74}/\text{OL}_{70\text{–}74})$ 2) *Low estimates*: company's estimates
Bagging	1) *High estimates*: Assumed a three-fold drop in exposure in 1972 due to installation of automatic bagger. 2) *Low estimates*: Estimated from samples in 1968–1971; assumed exposure is same before 1968 and in 1968–1971.

the LO exposure estimates (Table VII) for the tails belt, transfer point, and bus ride, the estimate of the 8-hr TWA exposure before 1974 is 3.8 f/cc: [(2 hr × 7.3 f/cc) + (6.5 hr × 2.2 f/cc) + (1 hr × 1.2 f/cc)]/8 hr.

RESULTS

Exposure Estimates

Estimates of exposure in the LO (Table VII) before 1964 for dry mill jobs were 168 f/cc for working areas, 182 f/cc for sweepers, 88 f/cc for skipping, and 13 f/cc for the quality control laboratory. In 1964–1971, estimates were 33, 36, 17, and 3 f/cc, respectively. Exposure estimates before 1971 for mine jobs ranged from 9–23 f/

TABLE VII. Estimates of Fiber Exposure by Location–Operation and Year

Location–operation	Year <50	50–59	60–63	64–67	68–70	71	72–74	75–76	77–79	80–82
High estimates										
Bus ride	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.0	0.0	0.0
Mine office	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5
Mine miscellaneous	1.6	1.6	1.6	1.6	1.6	1.6	1.6	0.8	0.8	0.8
Drilling	23.0	23.0	23.0	23.0	9.2	9.2	9.2	0.6	0.6	0.6
Mine nondrilling	2.6	2.6	2.6	2.6	2.6	2.6	2.6	0.6	0.6	0.6
Transfer point	2.2	2.2	2.2	2.2	2.2	2.2	2.2	0.6	0.6	0.6
Dry mill sweeping	182.1	182.1	182.1	35.9	35.9	35.9	19.0			
Dry mill	168.4	168.4	168.4	33.2	33.2	33.2	16.6			
Old wet mill nonmillwright		3.7	3.7	3.7	3.7	3.7	3.7			
Old and new wet mill millwright		7.0	7.0	7.0	7.0	7.0	7.0	0.6	0.6	0.6
New wet mill nonmillwright							3.2	2.0	0.8	0.8
Quality control lab	13.1	13.1	13.1	2.6	2.6	2.6	2.6	0.6	0.6	0.6
Service area by mill	1.9	1.9	1.9	3.8	1.9	1.9	1.9	0.2	0.2	0.2
Skip area	88.3	88.3	88.3	17.4	17.4	17.4	4.8	0.6	0.6	0.6
Concentrate hauling	5.5	5.5	5.5	5.5	5.5	5.5	5.5	0.4	0.4	0.4
River station binside	21.2	21.2	21.2	21.2	21.2	21.2	21.2	0.7	0.7	0.7
River conveyor tunnel	112.5	112.5	112.5	112.5	112.5	112.5	112.5	0.3	0.3	0.3
River office binside	10.6	10.6	10.6	10.6	10.6	10.6	10.6	0.2	0.2	0.2
Ore loading	82.5	27.7	10.7	10.7	3.2	3.2	3.2	0.2	0.2	0.2
River dock	116.9	42.5	17.0	17.0	17.0	5.1	5.1	0.5	0.5	0.5
Verxite plant	22.6	22.6	2.8	2.8	2.8					
Bagging plant	12.9	12.9	12.9	12.9	12.9	12.9	4.3	1.2	1.2	1.2
Downtown office building	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tails belt	7.3	7.3	7.3	7.3	7.3	7.3	7.3	0.7	0.7	0.7
Screen plant								0.5	0.5	0.5
Low estimates[a]										
Drilling	6.7	6.7	6.7	6.7	6.7	9.2	9.2	0.6	0.6	0.6
Ore loading	24.0	15.0	9.0	9.0	3.2	3.2	3.2	0.2	0.2	0.2
River dock	38.0	19.0	6.4	6.4	5.1	5.1	5.1	0.5	0.5	0.5
Bagging plant	4.6	4.6	4.6	4.6	4.6	4.6	4.3	1.2	1.2	1.2

[a]Low estimates are the same as high estimates for all other areas.

cc for drillers and were less than 2 f/cc for nondrillers. Exposure estimates before 1971 at the river-loading station ranged from 5–82 f/cc for ore loading, 10–11 f/cc for the river office, 112–113 f/cc for the conveyor tunnel, 5–117 f/cc for the river dock and car cleaning, and 20–21 f/cc for the river station bin area. Exposure estimates during 1972–1976 decreased annually. Exposures during 1977–1982 in most areas were less than 1.0 f/cc, and in the mill ranged from 0.6–1.0 f/cc.

Analysis of Bulk and Airborne Samples

Bulk samples from the mine were analyzed by polarized light microscopy in order to locate fibrous material and to determine various physical characteristics of the fibers. The fibrous component was estimated to be in the range of 5–10% by weight, was anisotropic, and had an index of refraction parallel to the fiber length of approximately 1.63, which suggests the fibers were of the tremolite series. Tremolite in the host rock was also fibrous in habit (Fig. 1).

Further examination of individual fibers by SEM/EDAX produced iron-to-magnesium peak intensity ratios in the range of 42–57%, indicating that despite the rather low refractive index, the fibers might be better described as actinolite [Deer et al, 1966]. This is consistent with the mineralogical classification reported by Atkinson et al [1982].

Area samples of the airborne dust from the mill and screening plant were obtained from the company, and analyzed by phase contrast light microscopy by NIOSH Physical and Chemical Analytical Method number 239. A picture of a sample of airborne fibers is presented in Figure 2. Additionally, 599 fibers (length greater than 4.98 μm and width greater than 0.44 μm) from eight airborne samples were sized according to length, width, and aspect ratio (Table VIII). Results indicate that

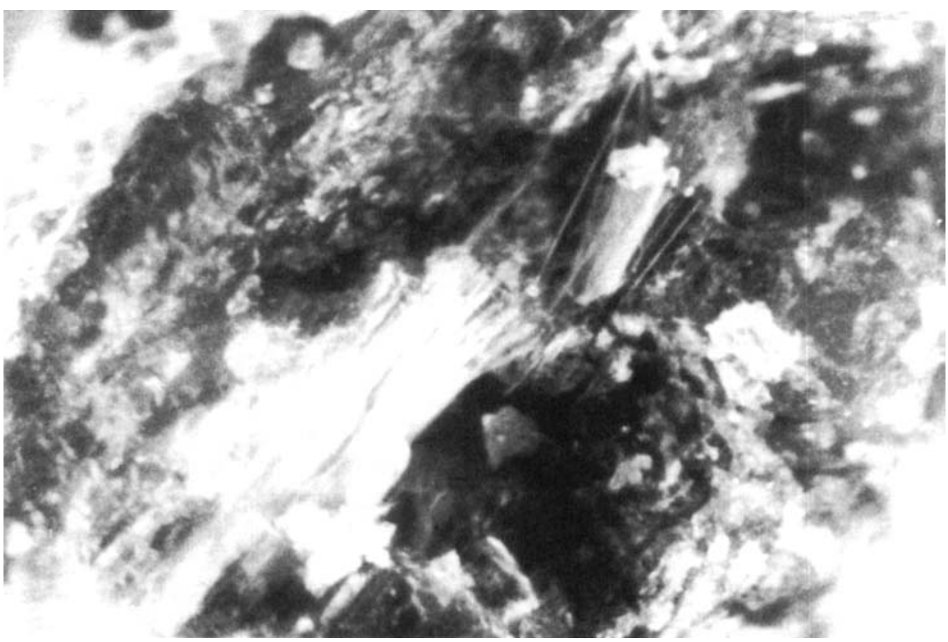

Fig. 1. Raw ore containing asbestos.

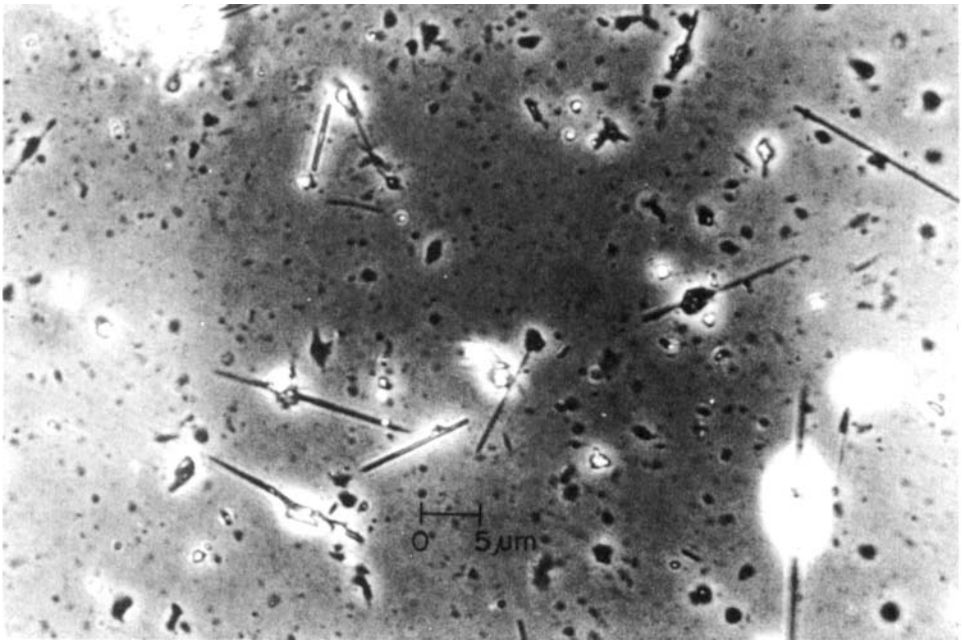

Fig. 2. Membrane filter sample.

96% of the fibers had an aspect ratio greater than 10, 67% greater than 20, and 16% greater than 50. Additionally, 73% of the fibers were longer than 10 μm, 36% were longer than 20 μm, and 11% were longer than 40 μm. All fibers counted had a width less than 2.49 μm.

DISCUSSION

The questionable accuracy of the exposure estimates before 1968 is recognized. Key factors that need to be considered in estimating exposure are precision, time periods for combining samples, estimators, the conversion ratio, and assumptions as to exposures in areas where samples have not been taken. In most studies such as ours, there is little one can do but work within the constraints of the available data.

With regard to precision, the standard error of the average annual impinger measurements was low (0.4–0.7) from 1965-1969 (Table IV). Additionally, the standard error of the filter sample fiber concentration was less than one-half of the mean for most LO (Table III). Although the variability was high for some LO, it was low in areas where exposures were extremely high, and where the greatest number of workers were employed (mill, service area, loading, and bagging).

Periods to pool samples and source of sample were difficult to evaluate. The average fiber exposure in the mill for 1967–1968 was significantly higher (65.3 f/cc) than during 1970–1974 (10.9-31.9 f/cc) (Table IV). The variability in the estimates was also greater for 1967–1968 samples.

The source of the samples could explain this variability. NIOSH collected the filter samples in 1967–1968, the company collected the samples in 1970, MSHA collected the samples in 1971, and the company and MSHA collected samples

TABLE VIII. Number of Fibers (Length > 5 μm and Width > 0.45 μm) in Eight Airborne Filter Samples by Their Length, Width, and Aspect Ratio

	Sample								Total	
	1	2	3	4	5	6	7	8	No.	%
Length (μm)										
4.98–7.04	3	11	13	4	5	1	10	7	54	9
7.04–9.96	9	22	27	20	1	3	8	19	109	18
9.96–14.08	8	24	12	15	5	4	19	20	107	18
14.08–19.91	9	18	17	22	2	13	10	20	111	19
19.91–28.16	8	11	16	20	5	11	5	14	90	15
28.16–39.82	8	12	3	11	5	5	11	10	65	11
39.82–66.00	3	4	7	6	3	8	6	9	46	8
66.00–88.00	2	2	2	1	0	1	1	1	10	2
>88.00	0	2	3	1	0	0	0	1	7	1
Total	50	106	100	100	26	46	70	101	599	100
Width (μm)										
0.44–0.62	34	84	63	59	14	23	52	77	406	68
0.62–0.88	12	17	29	31	9	19	14	70	151	25
0.88–1.24	2	3	5	8	0	2	3	4	27	5
1.24–1.76	2	2	3	1	3	2	1	0	14	2
1.76–2.49	0	0	0	0	0	0	0	0	0	0
>2.49	0	0	0	1	0	0	0	0	1	0
Total	50	106	100	100	26	46	70	101	599	100
Aspect ratios										
<5	0	0	0	0	0	0	0	0	0	0
5–10	0	4	3	2	7	1	4	3	24	4
10–20	16	35	41	29	7	6	15	27	176	29
20–50	23	51	46	58	11	28	36	52	305	51
50–100	10	13	8	10	1	10	15	17	84	14
>100	1	3	2	1	0	1	0	2	10	2
Total	50	106	100	100	26	46	70	101	599	100

annually after 1971. One might argue that NIOSH and company samples during 1967–1970 should be excluded, because exposures were markedly higher in 1967–1968, and lower in 1970, than in 1971–1974. However, an increased emphasis on dust control could also explain the decline after 1968. In any event, we assumed that the sampling methods from 1967–1974 were comparable, and combined all samples.

The choice of estimator has varied among epidemiological studies. J.C. McDonald et al [1980] and A.D. McDonald et al (1982, 1983, 1984) used the arithmetic mean (AM), and J.C. McDonald et al (1986) and Dement et al [1983] used an approximation of the AM that assumed that fiber concentration was distributed lognormally.

The choice of estimator must consider issues of statistical precision and bias. Sieber and Attfield [1985] and Attfield [1985] found that the geometric mean and approximations to the AM are less efficient than the AM when the population is not distributed lognormally. In our data, the fiber exposure concentration was not lognormally distributed for many areas. Thus, we chose not to use an approximation.

Additionally, the estimator needs to estimate the appropriate exposure index, and sampling strategy must be considered. In our epidemiological study, the individual cumulative fiber exposure is the index of interest, i.e., the sum of the product of daily fiber concentrations by time exposed. In an ideal situation, where samples are representative, accurate, and in sufficient number, the AM would be the appropriate statistic to estimate the daily concentration. However, the geometric mean (GM) is often used to discount the influence of outliers. If exposures tend to be overestimated due to invalid samples, the GM may be more realistic than the AM. We assumed that the samples were valid and used the AM (Table IX).

In the absence of side-by-side impinger and membrane filter sample measurements, it is difficult to assess the accuracy of our conversion ratio. Dement et al [1983] found a ratio of 7.8 for preparation areas and 3.0 for the nonpreparation areas of a chrysotile asbestos textile plant. J.C. McDonald et al [1980] reported a ratio between 1 and 5 for Quebec chrysotile mines and mills. J.C. McDonald et al [1985] used the same sample reports as we did, and estimated the ratio to be 4.6.

Clearly, the conversion ratio cannot be evaluated precisely from available data. The ratio is likely between 2–8 as noted in other studies, and the choice of 4.0 likely produces estimates of exposure with less than a two-fold error.

Estimates of the 8-hr TWA fiber exposure in 1981–1982 ranged from 0.6–0.8 f/cc for mine and mill jobs. However, based on 203 samples collected by the company in 1984, 92% of the 8-hr TWA exposures were less than 0.20 f/cc, 98% were less than 0.5 f/cc (OSHA's temporary asbestos standard [OSHA, 1983]), and 99.5% were less than 1.0 f/cc. The average TWA exposure from the 203 company samples was 0.1 f/cc.

Fiber dimensions are important risk factors for lung cancer. Thus, we measured the length and width of 599 fibers (>5 μm long and aspect ratio > 3) collected in eight filter samples of airborne dust (Table VIII). Using optical microscopy, we found that 73% of the fibers were longer than 10 μm, 93% were thinner than 0.88 μm, and 67% had an aspect ratio greater than 20.

Because previously published studies of fiber dimensions for chrysotile, amosite, and crocidolite have utilized electron microscopy (EM), it is unclear how our optical microscopic results compare to the EM studies of other fiber types. We offer

TABLE IX. Arithmetic and Geometric Mean Fiber per Cubic Centimeter Exposure for Samples Collected in 1967–74 for Some Location–Operations

Location–operation	No. of samples	Arithmetic mean	Geometric mean	AM/GM
Mine miscellaneous	28	1.58	0.63	2.5
Drilling	20	8.28	2.05	4.0
Mine nondrilling	140	2.61	0.93	2.8
Transfer point	21	2.49	1.97	1.3
Tails belt	28	7.25	4.31	1.7
Dry mill sweeping	70	25.77	17.81	1.5
Dry mill	236	22.32	15.03	1.5
Old wet mill	48	3.71	2.10	1.8
New wet mill	59	4.55	2.77	1.6
Service area	83	1.89	0.28	6.8
Skipping	42	8.09	0.39	23.7
Concentrate hauling	21	5.52	2.01	2.8
River station	18	21.18	6.11	3.5
River conveyor tunnel	20	112.45	37.34	3.0
Bagging	53	5.89	2.20	2.7

a brief review to suggest that tremolite is perhaps longer and thinner than crocidolite and amosite asbestiform fibers.

Langer et al [1974] counted all fibers visible to the TEM, and showed that the modal length for Libby, tremolite fibers was similar to UICC anthophyllite (5.1 μm), and greater than UICC amosite (1.4 μm) and UICC crocidolite (0.6 μm). They also reported that the modal width was 0.17 μm for tremolite, 0.18 μm for anthophyllite, 0.14 μm for amosite, and 0.13 for crocidolite. We then calculated the aspect ratios to be 28, 28, 10, and 5, respectively. Their results suggest that tremolite may be longer and thinner than UICC crocidolite and amosite. These results are consistent with results from Wylie [1979] who found a direct relationship between aspect ratio and fiber length.

In contrast to the results presented by Langer et al [1974], Wylie et al [1985] found an aspect ratio of 29 for amosite fibers from filter samples of airborne dust. Additionally, in a review of the aspect ratio for various fiber types from air and tissue samples, Wylie [1984] stated that the aspect ratio ranged from 8–19 for amosite and anthophyllite, and from 20–30 for crocidolite and chrysotile.

Further contrasting results were reported by Wylie [1979] and Dement and Harris [1979]. Wylie et al [1985], using the SEM, reported that the proportion of fibers with aspect ratio greater than 20, among fibers longer than 5 μm, was 96% for Canadian and California chrysotile, 84% for South African amosite, and 89% for South African crocidolite. Dement and Harris [1979], also using the SEM, measured the length and width of fibers collected in air samples in plants manufacturing chrysotile textiles, friction products, cement pipe, and amosite pipe insulation. We calculated the aspect ratio distribution from their results for fibers longer than 5 μm, wider than 0.4 μm, and an aspect ratio greater than 3. We found that the proportion with aspect ratio greater than 20 ranged from 35–69% for chrysotile and 36–51% for amosite.

It is difficult to compare studies of fiber dimension due to different sources of the same fiber type, methods of collecting fibers for analysis, and microscopic techniques. The results presented by Langer et al [1974] from the only reported study of Libby tremolite fibers showed the tremolite fibers to be very long and thin. The results provide a plausible argument for suggesting there is an increased risk of lung cancer and asbestosis (assuming risk is related to fiber dimension). However, because of the variability in published results on fiber dimensions, additional research on the dimensions of Libby tremolite compared to amosite and crocidolite would be useful.

We conclude that: (1) the conversion ratio (f/cc:mppcf) for tremolite/actinolite varied from 1.2–11.5 based on different subgroups; however, our ratio of 4.0 is not likely different from the true ratio by more than a factor of 2 based on results from other asbestos studies; (2) exposures were extremely high in the mine and mill prior to 1974. This must be considered when interpreting the results of exposure–response studies.

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