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Review

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Exposure hazards from continuing use and removal of asbestos cement products

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Abstract

Asbestos cement (AC) is used in water pipes, roofing, exterior siding, water tanks, cooling towers, and other applications. Although the global market for asbestos is slowly shrinking, AC products continue to dominate the remaining uses in many countries. This review focuses on asbestos exposures during the installation, maintenance, and ultimate removal of these materials. This assessment summarizes the available published and unpublished reports of airborne asbestos exposures during the cutting and removal of AC pipes, roofing, sheets, and cooling tower components and the range of exposures associated with the most common work practices. Task-based exposures from cutting AC pipe ranged from 11.3 to 129.0 f/cm^3 with a mean exposure of 53.8 f/cm^3. Cutting flat boards and corrugated roofing AC sheets resulted in exposures ranging from 1.3 to 130.0 f/cm^3 with a mean of 24.0 f/cm^3. Exposures for power saw cutting of AC sheets and pipes fit lognormal distributions and suggest that more than 86% of these tasks with AC sheet and 100% of the tasks with AC pipe exceed the US short-term Excursion Limit. Intermittent high exposures from the ongoing use of AC products in countries around the world are associated with an increased lifetime risk of asbestos-related disease.

Key words: Asbestos; asbestos cement; asbestos exposures; exposure.

What's Important About This Paper?

This review summarizes the available data describing exposures to asbestos fibers during the most common ongoing uses of asbestos in cement products in countries around the world. Task-specific exposures for cutting asbestos cement pipes and sheets almost always exceed the U.S. short-term Excursion Limit of 1 f/cm^3. Short-duration asbestos exposures observed during the installation and maintenance of asbestos cement products pose a significant risk for asbestos-related disease.

Introduction

As countries have banned or restricted the use of asbestos, global consumption is slowly declining but production totals approximately 1.3 million tons per year, primarily from mines in China, Kazakhstan, Russia, and Zimbabwe (USGS 2022). More than 50 countries still use raw asbestos, primarily for asbestos cement (AC) products used in construction applications (Lin et al. 2019). In China, there are almost 2,000 asbestos-related processors and product manufacturers (Chen et al. 2020). In Zimbabwe where asbestos mining still continues, there are 2 major factories that manufacture AC products (Mutetwa et al. 2021). India has more than 50 AC manufacturing plants (Fibre Cement Products Manufacturers' Association 2023). Vietnam has 36 plants that employ more than 2,400 workers and a majority of these factories are considered "small-scale" (Le et al. 2023).

Historically, AC products account for the majority of asbestos consumed. One estimate puts past use of

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AC products at 66% of global consumption (ECHA, 2021). In India AC products make up an estimated 85% of all commercial applications of asbestos (Ansari et al. 2007b). The market for AC is primarily for sheets used in roofing, interior and exterior siding, cooling tower components, and pipes used for industrial or residential water and sewer system applications. In addition, AC products are also used in cooling towers for commercial buildings and industrial facilities.

The concentration of asbestos in AC products varies but is generally reported in the range of 10% to 25% (US Occupational Safety and Health Administration (OSHA) 1994). Although chrysotile was, and still is, the most commonly used form in AC, amphibole asbestos including amosite and crocidolite is also used for some applications (Giaroli et al. 1994; Van Orden et al. 2012). Note that the asbestos contained within AC products is not coated or altered in any way and remains an exposure hazard when disturbed during installation, repair, and removal (Burdett 2007). Asbestos fibers in cement do not have reduced carcinogenic potency when compared with chrysotile asbestos not mixed with cement (Burdett 2007).

Aside from asbestos exposures in manufacturing AC products, there is a similar concern for less regulated and often informal sector construction and demolition workers. The few studies pertaining to asbestos exposures in informal sector settings show that exposures can exceed levels reported for formal sector workers (Ansari et al. 2007a). In many countries, there is little awareness of asbestos hazards due to installing, maintaining, and removing asbestos-containing materials. Even in France, the mean asbestos exposure level over the last decade was 0.4 f/cm^3 during the removal and disposal of asbestos-containing materials (ECHA 2021).

Asbestos is responsible for an estimated 230,000 deaths globally each year (Arachi et al. 2021). Although the hazards of asbestos exposure have been well documented for decades, there is little to suggest that the use of AC products will cease in the near future. Therefore, it is important to understand the range of exposures associated with these materials during installation and eventual removal. This review focuses on the largest applications of AC products—pipes, sheets, roofing, and cooling towers—and summarizes the available reported exposures from installing and removing these materials.

AC pipe is used in drinking water distribution and sewer systems, and also inindustrial applications. Approximately 13% of water distribution pipes in the United States and Canada are AC based (Folkman 2018). In the Netherlands, AC pipe covers approximately 25% of the water distribution network (van Laarhoven et al. 2021) and approximately 11% in the United Kingdom (Mordak and Wheeler 1988). In many countries, AC pipe is reaching the end of its service life such that the pipes are experiencing breakage and leaks due to corrosion. Pipe failure will accelerate the need to replace AC pipes in the coming years (Folkman 2018).

AC flat sheets are used for a range of interior and exterior walls. Corrugated AC sheets are used primarily for roofing. Even in recent years, AC roofing has maintained a significant market share. It is estimated that the market for this product totalled 16.85 billion U.S. dollars in 2020 (GlobeNewswire 2021). The legacy of AC roofing will be with us for decades even in countries where installing this material is now banned.

Facility heating, ventilation, and air conditioning (HVAC) systems in commercial and industrial applications commonly rely on AC cooling towers. Asbestos has been used in casings, fill, eliminators, and louvers, and also in water distribution pipes. Louvers and drift eliminators constructed from AC are components designed to allow airflow but reduce emission of water droplets and associated solids. Fill on the interior of the towers used to spread cooling water to a droplet size was often manufactured with asbestos. Today plastic films are more commonly used as fill material, but many projects still require the removal of older asbestos fill.

In the United States, the ongoing release of asbestos fibers from normal cooling tower operations was well documented in the 1970s. A study conducted by Argonne National Laboratory found asbestos fibers in water from the majority of cooling towers tested (Lewis 1977). The deterioration of cooling tower components was understood to be part of the normal wear of this equipment from physical breakage, chemical deterioration, and dissolution from acidity or microorganisms in water. The same study also estimated that "asbestos-fiber concentrations in air near ground level close to a standard mechanical-draft tower may exceed the current OSHA standard" (Lewis 1977).

Methods

A literature review was conducted utilizing online databases (PubMed, Google Scholar, and Google) of the published literature and general internet searches to obtain a number of federal government reports, investigations, and regulations. Search terms included: asbestos cement, exposure, airborne, AC products, cooling towers, asbestos pipe, asbestos boards, and asbestos fibers. Selected articles and reports were reviewed to identify studies that included personal air samples of asbestos exposure in the workplace during installation, maintenance, or removal of AC products. Unpublished data were collected from various sources obtained in the course of previous litigation and

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discovery. Some of these studies were contemporaneously conducted by asbestos product manufacturers during product installation or removal and some were simulated under controlled conditions. Excluded studies included those that did not report the duration of personal air samples or results of asbestos exposures from phase-contrast microscopy in units of f/cm^3.

Task-specific air sampling results were summarized for common construction activities in the installation and removal of AC. Statistical analysis was done with Multilingual IHSTAT+ (©2019 American Industrial Hygiene Association, v.238, 2021) to test for goodness of fit and graph the selected data. These analyses were limited to short-duration exposure monitoring results of power saw cutting of AC pipe and sheets in outdoor environments.

Results

Construction tasks involving the disturbance of asbestos vary based on site conditions, weather, employee experience, work practices, equipment, and other factors. Resulting exposures are often intermittent and span widely variable time frames, a situation that contributes to highly variable airborne asbestos fiber exposure values. Supplementary Tables S1–S5 present airborne asbestos exposure data for all task-specific work with AC reflecting diverse jobsites, time frames, and work practices. Some of the reported exposure levels are from simulation studies conducted for a number of purposes, while others are results from monitoring construction and asbestos removal project sites. The majority of field studies date from the 1970s through the 1990s a period during which the United States and other countries regulating occupational exposures to asbestos lowered the permissible exposure limit (PEL) and short-term exposure levels (e.g. OSHA Excursion Limit) as employers implemented improvements in engineering controls and work practices.

Typically wetting asbestos-containing materials before disturbing the surfaces will reduce airborne fiber concentrations. Therefore, the tables identify dry versus wet cutting methods used when the author provided this information. In the case of the cooling tower data given in Tables 4 and 5, it is assumed that wet methods were used as these projects were done by asbestos abatement contractors with trained abatement workers for compliance with US OSHA standards and exposure monitoring was conducted by third-party industrial hygienists.

When assessing air contaminant exposure for short-duration tasks, it is most informative to sample during the time period when performing a task and separately sample exposure levels when the contaminant is not being actively generated but may remain airborne in the work area. It is expected that the exposure level during the former is higher than during the latter. If only a time–weighted–average (TWA) sampling result is available (without information on the percentages of sampling time attributed to specific tasks), then the result is not reliable for estimating a task-specific exposure. This uncertainty is present when evaluating the asbestos fiber exposure data involving tasks with AC products.

For example, in one study involving dry cutting of AC pipe outdoors, the sampling time was 5 min during which two pipe cuts were made, and the mean of 3 samples was 57 f/cm^3 (Kumagai et al. 1993), whereas in a second study involving dry cutting of AC pipe outdoors, the sample times were 60 min, the mean of two cutter operator samples was 3.45 f/cm^3, and no information was provided about the number of pipe cuts made (U.S. National Inst. for Occupational Safety and Health (NIOSH) 1986). Simply averaging the 5-min sample results with the 60-min sample results would substantially underestimate the mean asbestos fiber exposure level during active pipe cutting. To limit the degree of such underestimation bias, sampling times of 15 min or less were assumed to represent periods during which a substantial share of time was spent performing a given task.

AC pipe

To install and later remove AC pipe, it is usually necessary to cut the pipe either manually or more commonly with a powered saw. Table 1 summarizes the results of 54 personal breathing zone air samples from 6 studies that were collected during the cutting of AC pipe at outdoor sites. The reported range is from 0.43 to 129.0 f/cm^3 and the arithmetic mean of these samples is 38.0 f/cm^3. A total of 18 of these samples were collected during the use of wet methods with a mean exposure of 34.1 f/cm^3 and 26 samples were collected without the use of water and had a mean of 41.0 f/cm^3.

The March 1972 Johns Manville Corporation simulation study involved 3 trials of dry cutting AC pipe with a powered skill saw in an outdoor location subject to moderate to strong winds (Johns Manville Corporation 1972a). The sample periods of 4.2–4.8 min were stated to cover "the time required for a single operation." The personal sample results ranged from 96 to 129 f/cm^3 (mean = 116 f/cm^3). The April 1972 Johns Manville Corporation simulation study involved repeating 3 trials of dry cutting AC pipe with a powered skill saw in an outdoor location subject to moderate wind, and extending the sampling periods to 20 min (Johns Manville Corporation 1972b). The report's author noted that the earlier results were "not truly representative of the average concentration," so the tests were repeated "in order to obtain sufficient

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Table 1. Cutting asbestos cement pipe outdoors.

AuthorYear	Work description	Dry or wet	*N*	Range asbestos f/cm^3
Johns Manville March (1972a)	Operator cutting with skill saw	dry	3	96.0–129.0
Johns Manville April (1972b)	Operator cutting with skill saw	dry	3	2.9–4.5
Equitable Environmental March (1977a)	Operator cutting sewer pipe with abrasive disc	dry	13	14.7–81.2
Equitable Environmental Dec (1977c)	Operator cutting pressure pipe with abrasive disc	wet	12	7.8–109.1
NIOSH (1986)	Cutter operator and Assistant	dry	4	2.27–3.54
NIOSH (1986)	Cutter operator and Assistant	wet	4	0.43–0.76
Kumagai (1993)	Operator cutting in trench high-speed disc cutter	dry	1	60.0
Kumagai (1993)	Operator cutting in trench high-speed disc cutter	wet	2	48–63.0
Abelmann (2017)	Operator cutting in trench with powered saw	dry	4	12.4[a]
Abelmann (2017)	Operator cutting above ground with powered saw	dry	8	5.2[b]

[a] Mean reported for 4 samples.
[b] Mean reported for 8 samples.

sampling time." No further clarification of the comment was offered, but it is understood that a more "representative" exposure level would include some time for set-up and pipe handling during which no actual pipe cutting was performed. The 20-min personal sample results ranged from 2.9 to 4.5 f/cm^3 (mean = 3.8 f/cm^3).

The March 1977 Equitable Environmental Health simulation study involved 7 trials of dry-cutting AC pipe with a gasoline-powered Stihl saw in an above-ground outdoor location (Equitable Environmental Health, Inc. 1977a). For the saw operator, the sampling periods were 4–8 min, 4 pipe cuts were made per sample period, and the TWA personal sample results ranged from 14.7 to 49.3 f/cm^3 (mean = 26 f/cm^3). For the person helping the saw operator, the sampling periods were 4–7 min, and the TWA personal sample results ranged from 52.6 to 81.2 f/cm^3 (mean = 61.9 f/cm^3).

The December 1977 Equitable Environmental Health simulation study involved 6 trials of wet-cutting AC pipe with a gasoline-powered Stihl saw in an above-ground outdoor location (Equitable Environmental Health, Inc. 1977c). For the saw operator, the sampling periods were 3–6 min, 2–3 pipe cuts were made per sample period, and the personal sample results ranged from 11.3 to 109.1 f/cm^3 (mean = 53.6 f/cm^3). For the person helping the saw operator, the sampling periods were 4–6 min, and the personal sample results ranged from 7.8 to 54 f/cm^3 (mean = 29.7 f/cm^3).

The 1986 NIOSH study involved 60-min samples collected during the cutting of AC pipe, presumably using a powered saw, with and without a water suppression system for dust (NIOSH 1986). For the cutter operator, during two sampling periods using dry cutting, the personal exposure levels were 3.36 and 3.54 f/cm^3, whereas, during two sampling periods using wet cutting, the personal exposure levels were 0.76 and 0.60 f/cm^3. The authors note the difficulty of using water suppression outdoors during the winter due to freezing temperatures.

The 1993 Kumagai et al. simulation study involved 3 trials of AC pipe cutting with a powered disc cutter in an outdoor trench 3.2 m deep. In each trial, 2 cuts of AC pipe were made during a 5-min period. One 5-min personal sample result during dry cutting was 60 f/cm^3, and two 5-min personal sample results during wet cutting were 48 and 63 f/cm^3. The authors note that wetting did not sufficiently reduce the concentration of airborne fibers.

The 2017 Abelmann simulation study involved 1 trial of dry cutting AC pipe with a powered abrasive saw in an outdoor trench 2.1 m deep and 2 trials of dry cutting AC pipe with a powered abrasive saw in an above-ground outdoor location. In each trial, 2 cuts of AC pipe were made during a 30-min period. The reported 30-min TWA personal sample result for dry cutting in the trench was 12.4 f/cm^3, and the reported mean of the two 30-min TWA personal sample results for dry cutting above ground was 5.2 f/cm^3.

The two Equitable Environmental Health studies that collected personal samples for helpers present during power saw operations yielded variable results. The March 1977 study found that the helpers were exposed at approximately twice the mean level as the saw operators (61.9 f/cm^3 vs. 26 f/cm^3, respectively, for the combined sewer and pressure pipe results) (Equitable Environmental Health, Inc. 1977a), whereas the December 1977 study found that the saw operators were exposed at approximately twice the

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mean level as their helpers (53.6 f/cm³ vs.29.7/cm³, respectively, for the combined sewer and pressure pipe results) (Equitable Environmental Health, Inc. 1977c). The reasons for the disparate results are not known but may have involved the position of the helpers relative to the saw exhaust. The authors note that cutting an AC pipe with an abrasive disk saw resulted in excessive airborne exposures even when the pipe was wet.

Figure 1 plots the results for 19 personal samples from Supplementary Table S1 for power saw operators performing cutting of AC pipe outdoors with durations of ≤8 min to exclude other set-up and cleanup activities. The mean exposure level is 53.8 f/cm³ and the geometric mean (GM) is 40.8 f/cm³ and the geometric standard deviation (GSD) is 2.21. The distribution of the cumulative probability plot of the measured concentration results is reasonably described as lognormal based on a goodness-of-fit Shapiro–Wilk test (*W* test) and the *P* value was >0.05.

The data given in Table 1 are limited to cutting AC pipe outdoors, as would pertain to most pipe installation, maintenance, and removal jobs. Table 2 summarizes the results from 5 simulation studies measuring asbestos fiber exposure levels during pipe cutting in an enclosed chamber with a dilution air supply of 5–6 air changes per hour. The arithmetic mean of these 18 samples is 1,034.6 f/cm³.

In the Materials Analytical Services, Inc. (MAS) simulation study, a subject made one cut on an AC pipe using a powered skill saw with an abrasive blade during a 5-min sampling period (MAS 2002). The mean of two sample filters (one located on each shoulder) was 208 f/cm³. For the saw operator's helper, the mean of two simultaneous personal samples was 220 f/cm³. In the second study by MAS (2003), a subject again made one cut on an AC pipe using a powered skill saw with an abrasive blade during a 5-min sampling period. The mean of 2 simultaneous personal samples was 60 f/cm³. For the saw operator's helper, the mean of 2 simultaneous personal samples was 66 f/cm³.

Two additional simulation studies were done on CertainTeed and Johns Manville AC pipe (MAS 1998a, 1998b), respectively. The results ranged from 1,003.0 to 4,070.0 f/cm³ for 12-min samples of pipe cutting with an abrasive skill saw in a chamber. In the final study conducted in 2009, a subject made one cut on an AC pipe using a gas-powered abrasive disc saw during a 2.4-min sampling period and subsequently made a second cut with the same saw during a 1.35-min sampling period (Millette et al. 2018). The personal exposure results during the two cuts were, respectively, 182 and 625 f/cm³. It was noted that the substantially higher level during the second cut may have been due to resuspension of dust that had settled following the first cut.

In addition to pipe cutting, the installation of AC pipe often involves tapping operations with a hammer and chisel at connections, For some installations, the pipe ends must be beveled with a lathe, grinder, rasp, or other tool. In 1972 Johns Manville Corporation conducted outdoor simulation tests limited to these activities which resulted in exposures 0.4 to 3.3 f/cm³ for sampling times of 20 min and from 3.3 to 28.0 f/cm³ for sampling periods ranging from 3 to 7 min. (Millette et al. 2018). Equitable Environmental reported results for an outdoor simulation test of a manual lathe for durations from 9 to 20 min with average results of 0.33 f/cm³ and 0.21 for a power lathe for sample times from 13 to 20 min. Results from using a chisel and rasp averaged 1.15 f/cm³ for samples ranging from 9 to 14 min (Equitable Environmental Health 1977a).

AC sheets

Table 3 summarizes the results of 5 studies that included 29 individual personal (breathing zone) air samples that were collected during the cutting of AC flat sheets and corrugated roofing. Installation of these sheets typically involves cutting with a power saw and pre-drilling holes to fasten the board to the underlying structure. The 2 NIOSH studies included are from actual field sites and include monitoring other tasks during the installation of these panels.

An engineering feasibility study reported personal exposure levels during simulation of dry cutting of AC sheet in the absence of any control measures (Equitable Environmental Health 1997b). It is assumed that all the cutting was outdoors and used powered saws because other measurements included in the study evaluated control devices during the use of powered saws outdoors. The study noted that drilling AC sheets without controls had exposures ranging from 2 to 5 f/cm³ and from 4 to 10 f/cm³ for drilling overhead without dust controls.

In a 1979 study conducted by NIOSH, a 26-min personal sample of 10.48 f/cm³ was measured for a worker who sawed and handled an AC sheet on an upper floor of a building under construction (NIOSH 1979). The 1981 NIOSH study reported results for four 6-h personal samples ranging from .05 to 0.32 f/cm³ were measured for workers who sawed and installed AC sheets during building construction (NIOSH 1981). No more specific details about work activities during the sampling periods were provided.

In one simulation study described in Millette et al. (2018), 24-inch dry cuts on one-half-inch thick AC sheet were made using a powered saw with a masonry blade in an enclosed chamber that was supplied with dilution ventilation (Millette et al. 2018). When 2 cuts were made during a 3-min period, the personal exposure level was 45 f/cm³, and when 3 cuts

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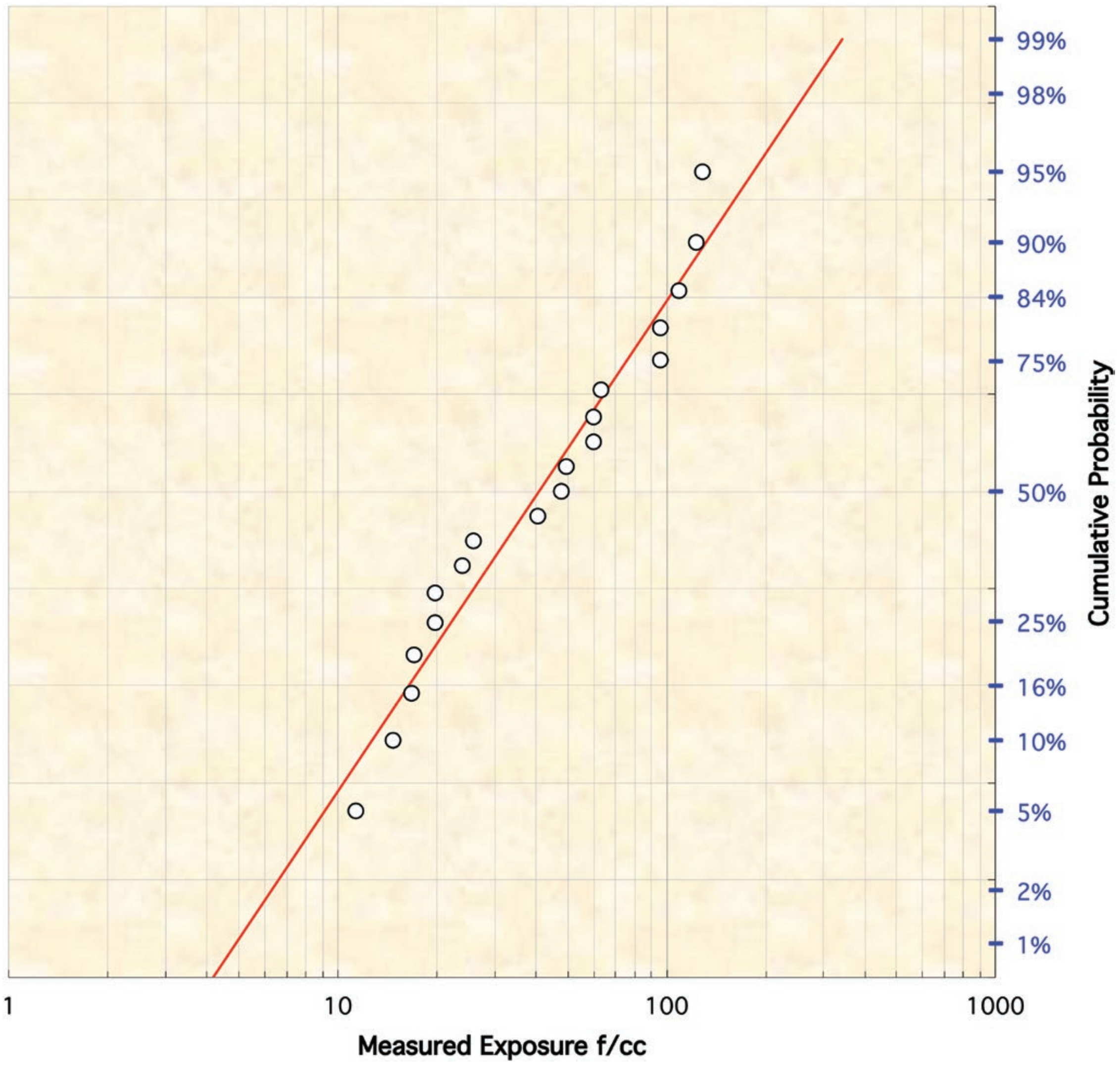

Fig. 1. Cumulative probability plot of airborne asbestos exposures for power saw cutting of AC pipe.

Table 2. Cutting AC pipe indoors.

Author/Year	Work description	*N*	Range asbestos f/cm^3
MAS February (1998a)	Cutting A/C pipe with abrasive skill saw—CertainTeed	4	1003.0–1808.0
MAS February (1998b)	Cutting A/C pipe with abrasive skill saw—Johns Manville	4	1605–4070.0
MAS October (2002)	Cutting A/C pipe with abrasive skill saw—CertainTeed	4	171.3–247.8
MAS October (2003)	Cutting A/C pipe with abrasive skill saw—Johns Manville	4	47.1–73.2
Millette et al. (2018)	Cutting A/C pipe with gas-powered abrasive disk saw	2	182.0–625.0

subsequently were made during a 2-min period, the personal exposure level was 42 f/cm^3. In a second simulation study described in Millette et al. (2018), one 5-inch dry cut on a corrugated AC sheet was made using a powered saber saw during a 2-min sampling period in an enclosed chamber. The mean of the 2 simultaneous personal samples was 2.0 f/cm^3. In the same chamber, 2 holes were cut in a corrugated AC sheet using

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Table 3. Cutting of flat and corrugated AC sheets.

Author/Year	Work description	*N*	Range asbestos f/cm^3
Equitable Env Health (1977b)	Power saw cutting of AC sheet	11	4.5–130.0
NIOSH (1979)	Sawing and installing asbestos cement board	1	10.48
NIOSH (1981)	Sawing and installing asbestos cement board	4	0.05–0.32
Phanprasit (2012)	Sawing asbestos cement roofing board (power saw)	4	1.33–12.41
Phanprasit (2012)	Sawing asbestos cement roofing board (hand saw)	3	0.01–5.0
Millette et al. (2018)	Cutting an AC flat sheet with a power saw	6	<2.7–42.0

Table 4. Removal of cooling tower fill.

Author/Year	Work description	*N*	Range asbestos f/cm^3
BAC (1984)	Removal of MNA fill	1	0.6
Clayton (1988b)	Removal and cleanup of MNA fill Atlanta, GA	16	0.02–0.1
Marley (1987)	Removal drift eliminators/ fill Allstate Nortbook, IL	4	0.11–0.16

Table 5. Removal of asbestos cement panels on cooling towers.

Author/Year	Work description	*N*	Range asbestos f/cm^3
Clayton (1988a)	Removal of AC panels Los Angeles, CA	2	0.09–0.15
J. Scott Environmental (1988)	Removal of AC panel Monroe, MI	20	0.003–0.227

a 1.75-inch diameter powered hole saw during a 9-min sampling period. The mean of the 2 simultaneous personal samples was 2.9 f/cm^3.

Figure 2 shows a cumulative probability plot for task-based exposure values of ≤15 min from Supplementary Table S3 for AC sheet cutting outdoors with powered saws. The 15 samples were lognormally distributed based on a *W*-test ($P > 0.05$) and have a sample mean of 24.0 f/cm^3, and the distribution is lognormal with a GM of 11.5 f/cm^3 and a GSD of 3.59 f/cm^3.

A number of other studies report on exposures for cutting AC sheets in manufacturing facilities. Gardner et al. reported the mean of 136 personal samples as 0.8 f/cm^3 during dry cutting of AC sheets in a manufacturing plant in the period 1971–1982 (Gardner et al. 1986). In a paper by Panahi et al., summary statistics for 9 60-min personal sample results for workers involved in the cutting and drilling of AC sheets under a ventilated hood in an AC manufacturing plant were reported (Panahi et al. 2011). The reported range for the TWA results for cutting and drilling were 0.075 to 0.243 f/cm^3, and the mean exposure level was 0.0775 f/cm^3. In a paper by van Orden et al., summary statistics for 6 personal samples during “sawing” of AC sheet in a manufacturing plant in 2011 were reported (Van Orden et al. 2012). The range was 1.69–3.50 f/cm^3, and the mean exposure level was 2.65 f/cm^3.

AC roofing

As noted, Table 3 summarizes the results of personal (breathing zone) air samples from a study that was collected during the cutting of AC roofing sheets. Phanprasit et al. reported results for 15 min of cutting during 30 min of personal sampling for 4 workers at several sites who used power saws or hand saws to dry-cut AC roofing sheets (Phanprasit et al. 2012). At least several roofing panels were cut during a sampling period, but the exact number was not specified. The locations varied from outdoors to buildings under construction with no walls. Wind conditions at the locations varied from stagnant to brisk. Exposure levels for power sawing ranged from 1.7 to 12.41 f/cm^3 with a mean of 6.88 f/cm^3. In addition, personal samples were measured at these same locations for 3 workers who used a hand saw to dry-cut AC roof panels. Exposure levels ranged from 0.01 to 5.0 f/cm^3 with a mean of 1.71 f/cm^3.

In a study by Brown, personal TWA exposure levels were measured during the removal of weathered AC roofing sheets (Brown 1987). The number-weighted average of the 4 means for dry removal was 0.42 f/cm^3, the number-weighted average of the 3 means for wet removal was 0.3 f/cm^3, and the number-weighted average of the 3 means for removal of acrylic resin-coated sheets was 0.28 f/cm^3.

Cooling tower fill

Although cooling tower design and components vary by manufacturer, these are often made with AC sheets and asbestos was a common component of corrugated fill material used in many units. This material was generally made of asbestos paper with a neoprene and/or Melamine resin base that becomes very brittle with use. The asbestos content of this material can range up to

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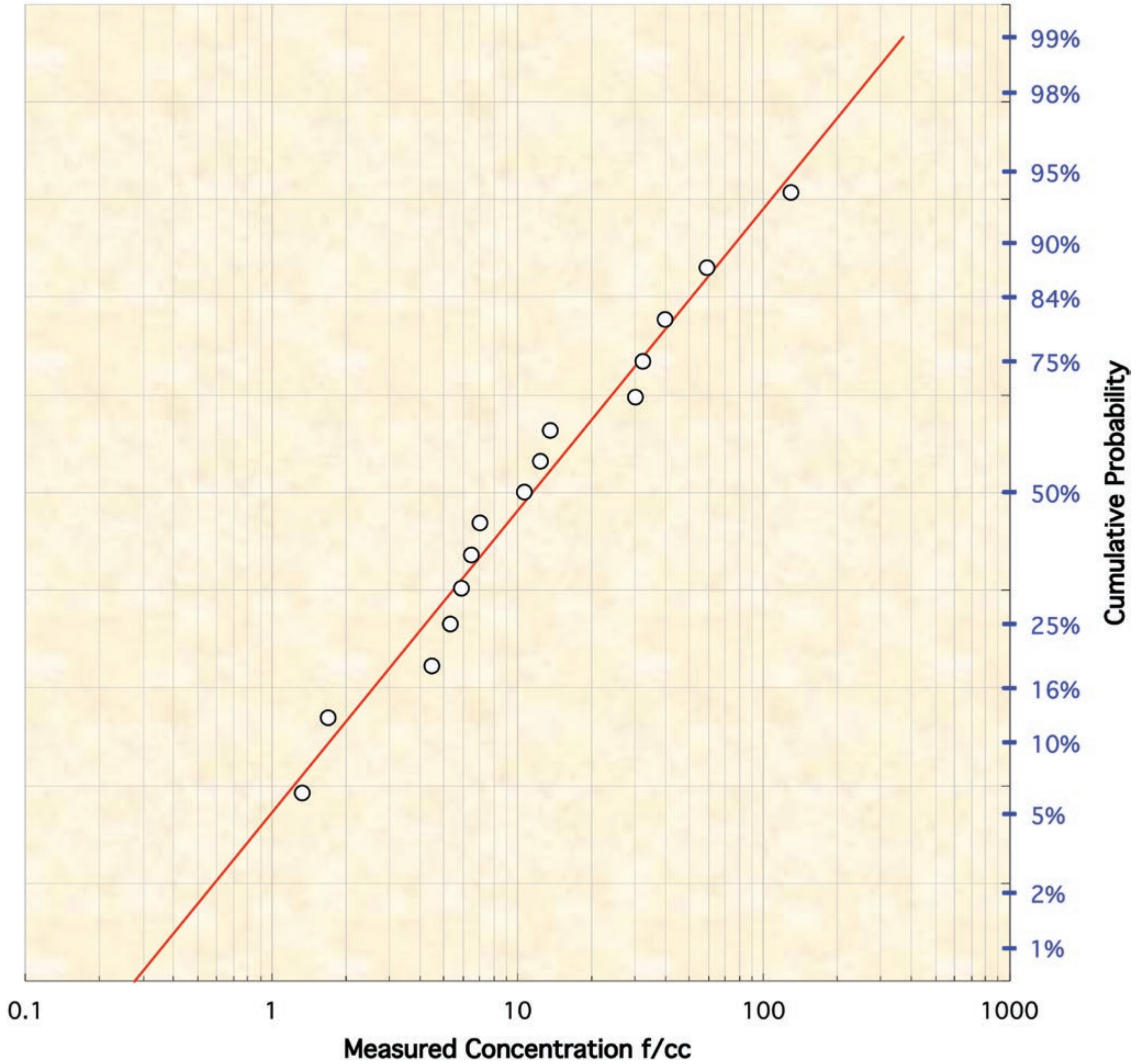

Fig. 2. Cumulative probability plot of airborne asbestos exposures for power saw cutting of AC sheets.

90% asbestos (Lewis 1977) and is sometimes used in conjunction with AC drift eliminators.

Fill-type cooling towers require that this material be removed and replaced over time due to damage or to improve the performance when the fill becomes clogged with dirt, algae, or mineral deposits. Old fill material easily breaks apart when handled. Electric saws, grinders, hammers, and other hand tools are used to remove fill and drift eliminators. After fill removal, workers must clean up the debris for disposal.

Table 4 summarizes personal air sampling results for asbestos abatement contractors performing fill and drift eliminator removal at various outdoor sites in 1987–1988. With the exception of one simulation conducted by the cooling tower manufacturer BAC, these results are from actual asbestos abatement job sites where independent air sampling was conducted by an outside firm. All of these jobs were conducted by first wetting the material as per US OSHA requirements.

The exposures for the 21 samples summarized in Table 4 range from 0.02 to 0.6 f/cm^3 for samples taken from 75 to 242 min. It is not known what percentage of the sampling period involved the removal and which portion may reflect other activities such as set up and cleanup practices.

Removal of AC panels on cooling towers

Cooling towers were often constructed of AC panels or louvers that need to be cleaned and sometimes removed and replaced if damaged during regular maintenance. In addition, these components must also be removed when these units are being decommissioned.

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Table 5 summarizes results for the removal of AC panels on cooling towers on a commercial building and at a power plant by abatement contractors. These 22 personal samples were taken on employees of asbestos abatement contractors while conducting the removal and handling of these AC panels.

Discussion

This article summarizes the available exposure data for AC construction materials. The exposures represent a mixture of construction practices and removal projects conducted by trained asbestos abatement workers. Exposures included actual job sites and simulated work practices. Although most of the data presented represent exposures in outdoor environments, a number of simulation studies on cutting AC pipe were conducted inside test chambers and may better reflect exposures inside more confined work areas.

In the case of installing or removing cooling tower fill and AC panels, there are no published studies documenting these exposures. The only air sampling results found were collected during asbestos abatement projects or, in the case of fill removal, by cooling tower manufacturers. It is likely that exposures would be considerably higher if these tasks were conducted in countries where the removal of asbestos-containing materials is unregulated and the work is performed by untrained laborers who are not aware of the hazards of asbestos.

AC products if disturbed, damaged, or cut will become friable under US Environmental Protection Agency (EPA) regulations. Friable is a temporary condition used to characterize waste materials and does not characterize the ability of asbestos fibers to become airborne following typical construction activities in the installation or removal of these products. EPA regulates these types of roofing materials if they have a “high probability of becoming or has become crumbled, pulverized, or reduced to powder by the forces expected to act on the material in the course of demolition or renovation operations” (US EPA 2015). AC products are within this category.

Overall, these data do not support the assumption that water use during AC pipe cutting sufficiently reduces exposure intensity. Comparing the mean for dry cutting (41.0 f/cm^3) and wet cutting (34.1 f/cm^3) from Supplementary Table S1 indicates only a small reduction in exposures. However, continual spray-misting may further reduce exposures from those noted in the available studies where surfaces may have been briefly wet and then disturbed. None of the available studies compared exposures with dry cutting and cutting with ongoing spray-misting under the same controlled conditions to provide reliable evidence on the efficacy of this work practice.

The lognormal distribution for AC sheet cutting (Fig. 2) indicates that 86.7% of the short term (≤15 min) are predicted to exceed 2.0 f/cm^3. To compare these task-specific results to the US OSHA Excursion Limit (EL) of 1.0 f/cm^3 over 30-min, we can assume that workers performing these cutting procedures had no exposure for the remaining 15 min of a continuous 30-min period. Therefore, it is reasonable to conclude that 86.7% of sheet-cutting exposures are predicted to exceed the EL. Similarly, the lognormal distribution for pipe cutting (Fig. 1) indicates that essentially 100% of the short-term (≤15 min) exposures are predicted to exceed 2.0 f/cm^3 and therefore 100% of these exposure measures would exceed the EL.

Given the high exposure levels associated with some of the tasks monitored, there are also likely scenarios when the OSHA 8-h TWA PEL would also be exceeded. For example, an exposure at 4 f/cm^3 for 15 min would cause exposure above the OSHA PEL of 0.1 f/cm^3. On the basis of the estimated short-term distribution parameters noted for AC pipe cutting (GM = 40.8 f/cm^3 and GSD = 2.21), one 15-min work period would exceed the OSHA PEL 99.8% of the time. Similarly, given one 15-min period of AC sheet cutting, with the estimated short-term distribution parameters (GM = 11.5 f/cm^3 and GSD = 3.39), 80.7% of the time this activity would exceed the OSHA PEL.

Intermittent, short-term exposures to asbestos come with a significant health risk as determined by US OSHA in adopting the EL in 1988 and they noted that this would reduce cancer risk by 67% for workers “exposed only to one burst of asbestos per day” (OSHA 1988). Pharmacokinetic modeling has shown that spikes in exposure concentrations are a “critically important predictor for asbestos-related disease risk, including mesothelioma” and may be more important than limiting TWA exposures (Cox 2020). These modeling approaches are supported by epidemiological studies showing that workers with only brief exposures have positive x-ray abnormalities (Ehrlich et al. 1992) and from the hundreds of cases of mesothelioma among family members of occupationally exposed workers (Noonan 2017).

A review of the exposures associated with AC suggests that the installation and removal of these products are associated with increased cancer risks that should be considered in regulatory decisions on banning or restricting these materials. It is important to note that there are safer substitutes for the asbestos content in AC construction materials including cellulose, polypropylene fiber, and glass fibers (Harrison et al. 1999; Park 2018). In 1982 GCA Corporation in a report prepared for US EPA noted that the available substitutes “compare favorably with A/C sheet with respect to density, strength, corrosion and weather resistance” (GCA 1982).

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Conclusion

There are limited data on exposures from the ongoing uses of AC products. However, the historical exposure measurements reviewed here suggest that substantial and intermittently high exposures are associated with the installation and removal of AC. Task-specific exposures from cutting AC pipe outdoors ranged from 11.3 to 129.0 f/cm^3 with a mean exposure of 53.8 f/cm^3. Cutting AC sheets resulted in exposures ranging from 1.3 to 130.0 f/cm^3 with a mean of 24.0 f/cm^3. More than 86% of exposures from cutting AC sheets with power saws, and essentially 100% of exposures from cutting AC pipe with power saws, are predicted to exceed the EL. Pharmacokinetic models, epidemiological studies, and hundreds of reports of mesothelioma cases among families of asbestos workers suggest that intermittent spikes in asbestos exposures as noted in this review of AC products are associated with an increased lifetime risk of asbestos-related disease.

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Disclaimer

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Data availability

The unpublished studies from which data were extracted for this article will be shared upon reasonable request to the corresponding author.

Supplementary data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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