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Simulation Tests to Assess Occupational Exposure to Airborne Asbestos from Asphalt-Based Roofing Products

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This study sought to evaluate exposure from specific products to evaluate potential risk from roof repair activities. Five asbestos-containing fibered roof coatings and plastic cements, representing a broad range of these types of products, were tested in exposure simulations. These products were applied to representative roof substrates. Release of asbestos fibers during application and sanding of the product shortly thereafter (wet sanding) were tested initially. Other roof substrates were cured to simulate a product that had been on a rooftop for several months and then were tested to evaluate release of fibers during hand sanding and hand scraping activities. Additional tests were also conducted to evaluate asbestos release during product removal from tools and clothing. Two personal (n = 84) and background/clearance (n = 49) samples were collected during each 30-min test and analyzed for total fiber concentration [phase-contrast microscopy (PCM)] and for asbestos fiber count [transmission electron microscopy (TEM)]. PCM concentrations ranged from <0.005 to 0.032 fibers per cubic centimeter (f cc^{-1}). Chrysotile fibers were detected in 28 of 84 personal samples collected. TEM concentrations ranged from <0.0021 to 0.056 f cc^{-1}. Calculated 8-h time-weighted averages (TWAs) ranged from 0.0003 to 0.002 f cc^{-1} and were comparable to the background TWA concentration of 0.0002 f cc^{-1} measured in this study. Based on these results, it is unlikely that roofers were exposed to airborne asbestos concentrations above the current or historical occupational guidelines during scraping and sanding of these products during roof repair.

Keywords: asbestos; curing; exposure simulation; occupational exposure; plastic cement; roof coating

INTRODUCTION

Asbestos was used in the past in a variety of roofing products, such as a filler material in asphalt, roofing felts and mastics (Stern *et al.*, 2000), as well as a structural fiber in asphalt- and coal tar-saturated ply sheets and flashing felts (Brzozowski, 1989). In 1994, the National Roofers Contractors Association (NRCA, 1994) estimated that 20% of built-up roof felts and >90% of flashings, coatings, cements and mastics on commercial low-sloped roof jobs contained asbestos. The use of asbestos in roofing materials was discontinued in the early 1980s, with the exception of roof coatings, mastics and cements. These exceptions contain encapsulated asbestos in certain product lines sold today (NRCA, 1994). The roof coatings, mastics and cements are widely used on various parts of 'roof systems' for waterproofing and adhesion, including adhering flashing to roof surfaces or sealing around chimneys, air vents and other penetrations (NRCA, 1994). Some studies report that asphalt-based roof coatings are typically composed of 5–10% asbestos, and the more viscous roofing cements typically contain 15–20% asbestos (ICF Incorporated, 1988). Others note that the amount of asbestos used is proportional to the desired final consistency—that is more fluid coating-like materials contained 5–20% asbestos, while heavy mastics contained 15–45% asbestos (Brzozowski, 1989; NRCA, 1994).

In general, the asbestos fibers in asbestos-containing roofing materials are encapsulated in bituminous matrices or resins, thereby binding the fibers and preventing their release (NRCA, 1994). During the course of their work, many roofers may have been

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exposed to asbestos during the repair or tear-off of old roofing materials, including roofing cements and coatings. Very few studies have reported airborne concentrations of asbestos associated with the application, repair or removal of roof coatings or cements. Data do exist for a subset of the coating products—sprayed-on coatings—and airborne concentrations of asbestos during the spraying of asphalt-based roof coatings were reported to range from 0.003 to 0.3 fibers per cubic centimeter (f cc^{-1}) based on data collected in the 1970s (Anderson et al., 1982). Two specific activities were evaluated regarding the sprayed coatings: spraying asphalt cutback (0.003–0.15 f cc^{-1}; sample duration, 342–432 min) and spraying asphalt emulsion (0.01–0.3 f cc^{-1}; sample duration not provided).

Studies conducted by the NRCA from 1986 to 1991 indicate that removal of asbestos-containing roof flashings, mastics, coatings and cements yielded low asbestos fiber concentrations (range, 0.004–0.027 f cc^{-1}; mean, 0.024 f cc^{-1}) (NRCA, 1994). In addition, the NRCA reports that, of the >1500 individual monitoring results for built-up roofing, none exceeded 0.1 f cc^{-1}. These data consisted of several thousand personal breathing-zone and area samples collected between 1986 and 1991. Anderson *et al.* (1982) also reported airborne asbestos concentrations of 0.1 to 0.6 f cc^{-1} during tear-out and replacement of roofing materials, but these data were not specific regarding the type of material removed. Finally, in a study of weathered roofing materials, estimated time-weighted averages (TWAs) during building demolition in old Australian buildings ranged from 0.02 to 0.60 f cc^{-1} (Brown, 1987). Due to the use of fibro sheeting (a corrugated asbestos cement product) and other asbestos-containing materials in the construction of buildings in Australia (NOHSC, 2002), the relevance of these concentrations to the US is unknown.

Due to the paucity of exposure data regarding hand-applied roofing cements and coatings, products that were widely used in past decades, and due to the fact that many of the asbestos exposure data on coatings and cements are complicated by the fact that underlying substrates (such as flashing, shingles etc.) could also have contained asbestos, this study was undertaken to generate data on fiber releases and to estimate potential exposures specific to these types of roofing products. Five different roofing products that were historically manufactured and sold by Monsey Products Company (Monsey) and Henry Company (Henry) in the 1950s, 1960s and 1970s were selected as representative of the variety of roofing cements and coatings.

The initial objective of this work was to quantitatively measure the airborne asbestos fibers in the breathing zone of a worker during simulated application, scraping and sanding of five products from representative roof substrates, and the scraping of two of the products from clothing and tools. Because evaluation of exposure during a roofing job entails potential exposure to a variety of substances and products (as in the field during a roof removal), this investigation sought to isolate the exposures from specific product types during specific tasks. Exposure simulation was used due to our inability to separate asbestos-containing coatings and cements from other asbestos materials used in the construction of roofs. The ultimate objective of the testing was to compare the airborne asbestos concentrations from these tests to past and present Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) for asbestos fiber exposures.

METHODS

Five asbestos-containing commercial roofing products that were sold in the 1950s, 1960s and 1970s were evaluated for their potential release of asbestos fibers under different testing scenarios: three fibered roof coatings (B-10 Fibered Roof Coating, 201 Fibered Roof Coating and D-21 Fibered Aluminum Roof Coating) and two plastic roof cements (C-8 Plastic Roof Cement and C-30 Plastic Roof Cement). A brief description of the five products and their intended use is provided in Table 1, along with their composition, asbestos content and physical/chemical properties. These products were considered to be representative of Monsey and Henry plastic roof cement and fibered coating product lines.

Because the five products tested are no longer manufactured or sold, representatives from Monsey and Henry mixed and produced the product in June 2005 at Henry's facility in Kimberton, PA, with materials obtained from original suppliers when possible, so that these exposure tests could be conducted. The formulated product met all quality control standards specified for the original products, indicating that the products made in 2005 had the same properties as those manufactured historically. These products were mixed on original equipment still present at the site; therefore, we believe that the type of mixing and degree to which the asbestos fibers were coated during the mixing process were similar to historical conditions.

Preparation of roof substrates

The plastic roof cements and fibered roof coating products were applied to three different types of roofs—composition asphalt shingle roofing (termed 'asphalt shingle'), bituminous built-up roofing (termed 'BUR') and modified bitumen roofing (termed 'composite roofing')—depending on the manufacturer's product specification and intended use. The base of each roof substrate was a 4 × 8-ft (total surface area

Table 1. Characteristics and description of asbestos-containing test products

Product	Composition	Chrysotile asbestos content (%)	Description/use	Physical/chemical properties
C-8	Asphalt, petroleum distillate and encapsulated asbestos	15.5	Repairing leaks in asphalt, metal and composition roof surfaces. Used for waterproofing on flashing and as an emergency patching compound that provides good weather resistance. Useful in repairing leaks in shingles, concrete and gutters, and around chimneys, downspouts and eaves.	High-grade mastic compound with maximum water and weathering resistance. Soft material that gradually hardens to a coating that is pliable, durable and resistant to water.
B-10	Asphalt, petroleum distillate and encapsulated asbestos	3.04	Heavy-bodied asphalt coating, reinforced with encapsulated asbestos fibers, used for surfacing asphalt, metal or composition roofs. Adheres to brick, concrete or steel.	Cures to a tough, flexible, weather-resistant film. Resists damage from expansion and contraction caused by weather, temperature variation and normal building vibration, due to its ability to retain pliability.
C-30	Asphalt, petroleum distillate, calcium carbonate and encapsulated asbestos	4.3	Repairing leaks in asphalt, metal and composition roof surfaces. Used for waterproofing on flashing and as an emergency patching compound that provides good weather resistance. Useful in repairing leaks in shingles, concrete and gutters, and around chimneys, downspouts and eaves.	High-grade mastic compound with maximum water and weathering resistance. Soft material that gradually hardens to a coating that is pliable, durable and resistant to water.
201	Asphalt, petroleum distillate and encapsulated asbestos	4.9	Heavy-bodied asphalt coating, reinforced with encapsulated asbestos fibers, used for surfacing asphalt, metal or composition roofs. Adheres to brick, concrete or steel.	Cures to a tough, flexible, weather-resistant film. Resists damage resulting from expansion and contraction caused by weather, temperature variation and normal building vibration due to its ability to retain pliability.
D-21	Asphalt, petroleum distillate, aluminum metal, amorphous silica, and encapsulated asbestos	4.24	Can be used to coat barns, industrial buildings, built-up asphalt roof systems, prepared roll roofing, weatherized galvanized iron and tin.	Forms a reflective, durable, flexible and waterproof surface. Produces a bright aluminum roof surface that reflects damaging ultraviolet sunlight.

of 32 ft^2), 3/4-in.- or 5/8-in.-thick plywood board. Figure 1 shows typical examples of the three roof types that were constructed. Repair activities were not measured in the field because it was impossible to determine the types of materials used in original roof construction and the composition of these materials; therefore, representative roofs were built using nonasbestos-containing products, to allow for isolation of exposure to the roof coatings and cements alone.

The asphalt shingle roofing entailed a composition asphalt shingle roofing system over a 3/4-in.-thick plywood board with a representative masonry chimney (common veneer brick laid using commercial adhesive) and metal flashing (noncorrosive, nonstaining, 26-gauge galvanized metal). CertainTeed Landmark 30 fiberglass-based asphalt shingles were laid on a 'breather-type' underlayment (Fontana VulcaSeal 30), per the manufacturer's specifications. Products C-8 and C-30 were applied to the asphalt shingle roofs.

The BUR entailed a base plus three-ply, smooth-surfaced fiberglass built-up roof membrane over a 5/8-in.-thick plywood board. A layer of lightweight, asphalt-coated, fiberglass base felt [Johns Manville (JM) PermaPly 28] was placed on the plywood and covered by a two-component, solvent-free, elastomeric cold-application adhesive (JM MBR Bonding Adhesive), consisting of an asphalt base material and an activator. A primer (Henry 104 Quickdry) was used over the base ply, upon which a coated fiberglass mat ply sheet with a light film of asphalt (JM GlasPly IV) was placed to cover the cold-application adhesive layer. Products B-10 and 201 were applied to the BUR substrates.

The composite roofing entailed a composition smooth cap sheet and base ply over a 5/8-in.-thick plywood board. A rosin sheathing paper (Ratan Red 3.3-lb rosin paper) was used to cover the plywood and was covered with a high-quality cold-process adhesive (Siplast PA 311 Adhesive). A modified bitumen base ply consisting of a lightweight random fibrous mat impregnated and coated with high-quality styrene–butadiene–styrene modified bitumen (Siplast Paradiene 20) was applied to the adhesive. The cap sheet, a smooth-surface cap sheet impregnated and coated with ceramic granules (Siplast Paradiene 30) was fastened on top.

None of the materials used to construct the roof substrates contained asbestos, with the exception of the product under study that was applied to the fully constructed roof panel. All roofs were constructed in late

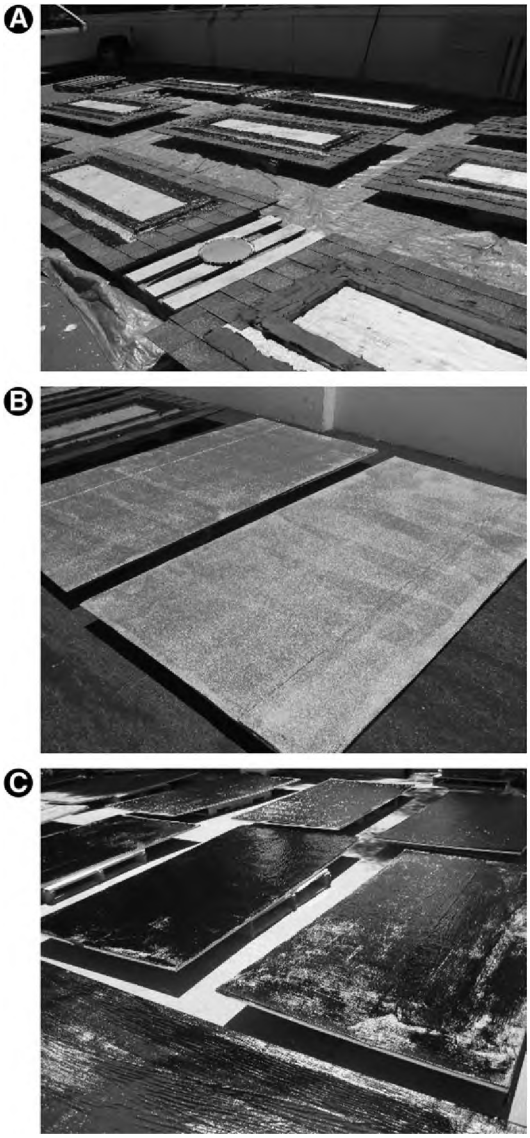

Fig. 1. Typical examples of the three constructed roof types: (A) composition asphalt shingle roofing (asphalt shingle), (B) modified bitumen roofing (composite roofing) and (C) BUR.

June 2005 by professional roofers from Western Roofing Service, based in San Francisco, CA. The professional roofers applied the plastic roof cement products with a trowel to the shingles, flashing and masonry, using the manufacturer's specifications for coverage (trowel product to a thickness of 3/8–1/2 in.). The fibered roof coatings were applied with a roller (two coats, with a 24- or 48-h drying period between coats). The roof substrates were allowed to dry outdoors for at least 1 week prior to being placed in the curing oven.

Curing process

Once constructed, the roof substrates were weighed and placed in a custom-built oven for a period of 14 days, to accelerate the volatilization of solvents and the curing of the product, consistent with ASTM (1981, 1994) standards. Full cure was determined based on successive weighing of the smaller samples. Product-coated roof panels were heated to 220 ± 5°F for 14 days. Eight thermocouples placed within the oven and connected to an external digital read-out ensured that temperature was maintained in the desired range for the full curing period. This curing process ensured that the test substrates were all similar in condition and representative of the product after several months of natural curing on roofs under ambient conditions.

Testing protocol

The purpose of this exposure testing was to collect representative air samples in the breathing zone of a worker during application, hand scraping and sanding of the five products on representative roof substrates, clothing and tools under controlled conditions and to determine the total fiber concentration and asbestos fiber counts in those samples following OSHA and National Institute of Occupational Safety and Health (NIOSH) procedures. Six different activities were evaluated in the testing program: (i) application, (ii) wet sanding, (iii) removal from laundered clothing, (iv) removal from soiled tools, (v) hand sanding and (vi) hand scraping. The first four activities used wet and uncured product, while the latter two involved cured products. Each test was conducted for 30 min, either in triplicate (for C-8 Plastic Roof Cement and B-10 Fibered Roof Coating) or as single-exposure tests (201 Fibered Roof Coating, C-30 Plastic Roof Cement, and D-21 Fibered Aluminum Roof Coating). These tests are described in detail in Table 2. Abatement technicians from MARCOR Environmental performed all removal activities.

Testing facility

All exposure tests were carried out in two adjacent 12 × 16 × 8-ft testing chambers (clean rooms) that were constructed at the Forensic Analytical Specialties, Inc., facility in Hayward, CA, in a large indoor room with a roll-up garage door. The test chambers were constructed of high-quality plywood and were lined with polyethylene sheeting to prevent migration of fibers into the room from outside, to contain any fibers released during testing and to allow for easier cleanup between exposure tests. A high-efficiency particulate air (HEPA)-filtered negative air unit regulated at ~200–400 ft^3 min^{-1} was used, with the exhaust channeled through an opening of 10–12 in. diameter. Use of the HEPA air unit resulted in a ventilation rate in the testing chambers of 6–18 air changes h^{-1}, depending on the replicate, which was thought to adequately represent outdoor

Table 2. Test activities performed on roof products

Activity	Description of task
Application	This test was used to quantitatively estimate the release of asbestos fibers (if any) during the application of B-10 Fibered Roof Coating and C-8 Plastic Roof Cement to the surface of representative roof substrates using either roller brushes (coating) or a trowel (cement).
Wet sanding	This test was used to quantitatively estimate the release of asbestos fibers (if any) during the wet sanding of uncured products (B-10 Fibered Roof Coating and C-8 Plastic Roof Cement) from the surfaces of representative roof substrates using either coarse sandpaper or a wire brush. These tests were conducted after the application test, where coated roof substrates were allowed to dry in ambient air for 1 week.
Hand scraping	This test was used to quantitatively estimate the release of asbestos fibers (if any) during the hand scraping of all five cured products from the surface of representative roof substrates using a long-handled putty knife. This activity might be performed by roofers in removing this product during a small roof repair or emergency patch. The approximate surface area of roof coating that was removed was 10 ft^2 for the plastic roof cement products and 32 ft^2 for the fibered roof coatings.
Hand sanding	This test was used to quantitatively estimate the release of asbestos fibers (if any) during the sanding of all five cured products from the surfaces of representative roof substrates using 60-grit sandpaper. Hand sanding represents an aggressive manipulation of these products and a 'worst-case' test of fiber release and potential exposure. The approximate surface area of roof coating that was removed was 10 ft^2 for the plastic roof cement products and 32 ft^2 for the fibered roof coatings.
Removal from laundered clothing (clothing test)	This test was used to quantitatively estimate the release of asbestos fibers (if any) during the hand scraping and picking of C-8 Plastic Roof Cement and B-10 Fibered Roof Coating from representative laundered clothing (that had been smeared or soiled with the product prior to laundering) using a plastic scraper or blunt butter knife. These activities were conducted to represent attempted removal of the product from workers' clothing following laundering.
Removal from soiled tools (tool test)	This test was used to quantitatively estimate the release of asbestos fibers (if any) during the hand scraping and picking of C-8 Plastic Roof Cement and B-10 Fibered Roof Coating from representative soiled tools (that had been dipped and coated with product and left to dry outdoors) using a flathead screwdriver. These activities were conducted to represent removal of the product from workers' tools coated with residual product from past application activities.

conditions where roofers might conduct their work (indoor air exchanges are typically >4 changes h^{-1}, as described by the ASHRAE (2001). A custom-built holder was used to hold the product-coated roof panels during testing. This holder was composed of wooden two-by-fours and angled at a 4 : 12 pitch, to simulate a common roof angle and ensure that the worker performing the removal activities was in an appropriate body position for roofing work. A diagram of the testing room setup is shown in Fig. 2. Prior to testing, the roof surface was thoroughly cleaned with a HEPA vacuum to remove any extraneous dust and to ensure that results would be specific to the product tested.

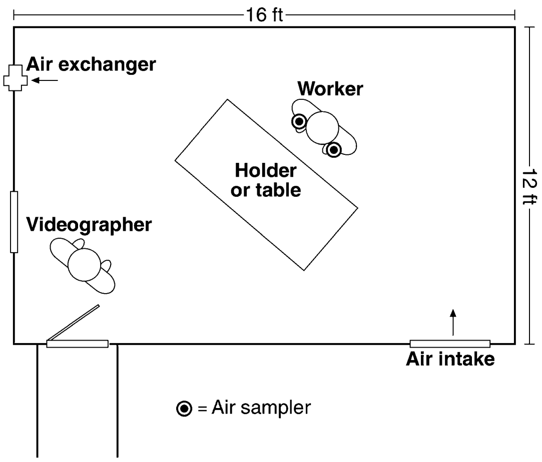

Fig. 2. Diagram of the testing room setup.

Test design/air sampling data

During the testing of the five roofing products, air samples were collected to analyze for the presence of airborne asbestos fibers. The exposure tests were performed in triplicate for C-8 Plastic Roof Cement and B-10 Fibered Roof Coating. Single-exposure tests were conducted for 201 Fibered Roof Coating, C-30 Plastic Roof Cement and D-21 Fibered Aluminum Roof Coating. During each replicate of each test, two personal samples were collected from the breathing zone of the worker performing the removal activity. Personal samples (rather than area samples) were collected because these were thought to best represent a worker's exposure. These samples were collected on 0.8-μm (pore size) mixed cellulose ester

(MCE) filters with a diameter of 25 mm, housed in a carbon-impregnated polyethylene cassette, for phase-contrast microscopy (PCM) and transmission electron microscopy (TEM) analyses. Personal air samples for fiber analysis were collected at a rate of 15 l min^{-1} for 30 min, using electrically powered vacuum pumps with flexible tubing to attach the filter cassettes to the pump. Airflow rates for the sampling trains were calibrated before and after each sampling event. A relatively high airflow rate was selected to ensure that an adequately low detection limit was achieved.

Background air samples were collected in the testing chamber to provide information on ambient concentrations of asbestos fibers in the room air prior to each test and clearance air samples were collected in the testing chamber after each replicate. These samples were collected before and after each exposure test. Background and clearance samples were collected using the perimeter pumps located in the testing room and were collected on 0.8-μm (pore size) MCE filters, 25 mm in diameter. Samples were collected for 2 h at a flow rate of 15 l min^{-1}, corresponding to an air volume $\geq$1500 l.

Samples collected during testing were analyzed according to standard NIOSH methods. The personal samples collected during sampling were analyzed for fiber concentrations by PCM using NIOSH Method 7400, and for asbestos concentrations by TEM using NIOSH Method 7402 (NIOSH, 1994a,b). Quality control samples encompassed blanks (10%), replicates (10%) and duplicates (5%). Both replicates and duplicates were run on the PCM samples; only duplicates were run on the TEM samples. Forty grid openings were counted on both the initial and duplicate filters, where the duplicate involved analysis of a new filter prepared by a different analyst from the analyst who prepared the initial filter. (For some samples, it is possible that a different grid was counted because two grids were prepared per sample.) The acceptable range of fiber counts was determined using a 95% confidence interval of the Poisson distribution of the fiber results.

TWA concentrations

For samples in which a detectable concentration of asbestos was measured, total fiber concentration obtained by PCM was converted to a PCM-equivalent (PCM-E) asbestos concentration using the asbestos-to-total fiber ratio by TEM. The PCM-E represents the fraction of PCM total fibers that is estimated to be asbestos fibers, as opposed to other nonasbestos fibers such as cotton or wood fibers. The PCM-E concentrations were then used to calculate 8-h TWA exposure concentrations in an attempt to estimate the airborne concentration during a typical workday. Eight-hour TWAs were calculated to (i) estimate potential exposure of workers conducting hand scraping and sanding activities for 30-min durations during the 8-h workday and (ii) to allow for direct comparison to current and historical occupational exposure limits or guidelines. Given the fact that the activities tested in this exposure simulation were not likely to have been performed by workers using these products, particularly for the duration of time tested, 8-h TWAs were calculated only for 30 min of each activity in a given workday.

The estimated 8-h TWA was calculated using the following equation:

$$\sum_{i=1}^{n} \frac{(c_i)(t_i)}{8}, \qquad (1)$$

where:

n = the total number of activities evaluated in a particular scenario (for our calculations, one of the six activities was tested),
c_i = PCM-E asbestos concentration measured during activity i (in fibers per cubic centimeter) and
t_i = duration of activity i performed by a worker (in hours).

When calculating the 8-h TWA, the sum of all t_i must equal 8 h. In our calculations of 8-h TWAs, the activity was considered to have occurred for 30 min; for the remaining 7.5 h of the 8-h workday wherein no scraping or sanding activity was performed, the airborne asbestos background PCM-E concentration estimated for this specific exposure simulation was used in the TWA calculation. This value is a nonzero PCM-E background concentration of 0.0002 f cc^{-1}, based on the background sample for this study, in which a single asbestos fiber was identified.

RESULTS

Total fibers

During the simulated application, wet sanding, hand scraping, hand sanding, clothing and tool tests, total airborne fiber concentrations measured by PCM (all fibers, including nonasbestos) ranged from <0.005 to 0.032 f cc^{-1} (Table 3). The detection limits in this study ranged from 0.003 to 0.006 f cc^{-1}. Total fibers (which are composed of nonasbestos and asbestos fibers) were detected in 38 of the 84 personal samples (Table 3). PCM total fiber counts for personal samples ranged from 0 to 29.5 fibers. However, only a relatively small fraction of these were asbestos fibers, as evidenced by the TEM asbestos fiber counts (see below). The remaining nonasbestos fibers likely represented cotton fibers from the workers' clothing, wood fibers present in the test room or other fibers present in air. The raw PCM total fiber

Table 3. Analysis of samples using PCM (NIOSH Method 7400)

Test activity	Product	Number of samples	Number of detects	PCM total fiber concentrations (f cc^{-1})			
				Arithmetic mean	Standard deviation	Minimum	Maximum
Application	C-8	6	2	0.007	0.002	ND (<0.006)	0.009
	B-10	6	1	0.006	Not applicable	ND (<0.006)	0.006
Wet sanding	C-8	6	0	0.006	Not applicable	ND (<0.006)	ND (<0.007)
	B-10	6	3	0.01	0.01	ND (<0.006)	0.032
Hand scraping	C-8	6	5	0.008	0.002	ND (<0.006)	0.011
	B-10	6	2	0.009	0.004	ND (<0.006)	0.015
	C-30	2	2	0.008	0.0007	0.007	0.008
	201	2	2	0.02	0.003	0.016	0.02
	D-21	2	2	0.01	0.004	0.009	0.015
Hand sanding	C-8	6	3	0.007	0.002	ND (<0.006)	0.01
	B-10	6	1	0.008	0.004	ND (<0.006)	0.015
	C-30	2	0	0.006	Not applicable	ND (<0.006)	ND (<0.006)
	201	2	2	0.02	0.01	0.012	0.027
	D-21	2	1	0.008	0.003	0.006	0.01
Clothing	C-8	6	6	0.01	0.003	0.008	0.017
	B-10	6	3	0.01	0.006	ND (<0.006)	0.019
Tools	C-8	6	1	0.006	0.0006	ND (<0.005)	0.007
	B-10	6	2	0.006	0.0004	ND (<0.006)	0.007
Total		84	38				

ND, not detected.

concentrations were adjusted based on TEM analyses to derive a PCM-E asbestos concentration that would enable calculation of an 8-h TWA.

Asbestos fibers

No asbestos fibers were found in any of the tool exposure tests or during the application or wet sanding tests. During the simulated hand scraping, sanding, clothing and tool tests, airborne asbestos fiber concentrations measured by TEM ranged from <0.0021 to 0.056 f cc^{-1}. Asbestos fibers were detected in 28 of 84 personal samples, and the number of asbestos fibers found ranged from 0 to 26 (Table 4). All detected asbestos fibers were identified as chrysotile fibers. The samples that contained ≥10 asbestos fibers were collected during the hand sanding test on cured material. Representative micrographs of the samples used to determine asbestos counts in the hand scraping and hand sanding of cured product (tasks that produced the highest counts) are provided in Fig. 3. Overall, most of the samples showed fibers attached to 'chunks' of matrix (Fig. 3A,C), while a few others showed free, curly fibers (Fig. 3B). In general, the hand scraping test generated larger pieces of matrix compared to sanding; in the sanding test, the observed length of fibers was typically shorter than that for the scraping test. For the scraping tests, typical fiber lengths ranged from 15 to 40 μm, with widths of 1–3 μm. Fiber lengths for the sanding tests were 7–18 μm, with all widths >1 μm.

Background concentrations

For all replicates, total fiber concentrations measured by PCM in background/clearance samples ranged from below the detection limit of <0.002 to 0.009 f cc^{-1} (Table 5). In all six replicates for application, total fiber concentrations ranged from 0.003 to 0.007 f cc^{-1}. For wet sanding, total fiber concentrations in the six replicates ranged from 0.002 to 0.007 f cc^{-1}. In all nine replicates for hand scraping, total fiber concentrations ranged from 0.002 to 0.009 f cc^{-1}. For hand sanding, total fiber concentrations in the nine replicates ranged from 0.002 to 0.006 f cc^{-1}. For the clothing test, total fiber concentrations for the six replicates ranged from below the detection limit (<0.002 f cc^{-1}) to 0.005 f cc^{-1}. Finally, for the tool test, total fiber concentrations for the six replicates ranged from 0.003 to 0.007 f cc^{-1}. For the PCM fiber counts, 1–22 fibers (total fibers, including nonasbestos) were identified in the background/clearance samples.

As part of the exposure simulation, 49 background/clearance samples were collected. Forty-two of these samples were obtained between the periods of time when the exposure simulation experiments were being performed (e.g. immediately before and after each replicate test), and the remaining background samples were taken prior to conducting the exposure tests. Of the 42 exposure-related samples, two background samples were identified by TEM analysis as containing a single asbestos fiber. TEM asbestos fiber concentrations were below the analytical sensitivity

Table 4. TEM asbestos fiber counts (NIOSH Method 7402) and PCM-E

Test activity	Product	Number of samples	Number of samples with detected asbestos fiber counts	TEM asbestos fiber counts	F/f		PCM-E (f cc^{-1})		
					Minimum	Maximum	Arithmetic mean	Minimum	Maximum
Application	C-8	6	0	ND	NA	NA	NA	NA	NA
	B-10	6	0	ND	NA	NA	NA	NA	NA
Wet sanding	C-8	6	0	ND	NA	NA	NA	NA	NA
	B-10	6	0	ND	NA	NA	NA	NA	NA
Hand scraping	C-8	6	2	1, 2	0	0.5	0.0014	0	0.0055
	B-10	6[a]	2	1, 2	0	1	0.0014	0	0.006
	C-30	2	1	1	0	0.33	0.0012	0	0.0023
	201	2	2	8, 9	1	1	0.018	0.02	0.016
	D-21	2	2	2, 4	0.57	0.67	0.0073	0.006	0.0086
Hand Sanding	C-8	6	5	3, 3, 6, 12, 13	0	0.86	0.0040	0	0.0076
	B-10	6[b]	3	1, 2, 10	0	0.67	0.0038	0	0.006
	C-30	2	2	12, 15	0.8	0.83	0.0049	0.0048	0.005
	201	2	2	24, 26	1	1	0.020	0.012	0.027
	D-21	2	2	13, 21	0.91	0.93	0.0074	0.0056	0.0091
Clothing	C-8	6	3	1, 1, 4	0	0.67	0.0024	0	0.011
	B-10	6	2	2, 5	0	0.5	0.0010	0	0.0035
Tools	C-8	6	0	ND	NA	NA	NA	NA	NA
	B-10	6	0	ND	NA	NA	NA	NA	NA
Total		84	28						

No asbestos fibers were found in any tool test, so PCM-E and TWAs were not calculated. F/f, percentage of asbestos fibers to total fibers (by TEM); NA, not applicable; ND, not detected; PCM-E, product of F/f and PCM fiber concentration.
[a]One sample overloaded; data not included in analysis.
[b]Two samples overloaded; data not included in analysis.

(0.0005–0.0009 f cc^{-1}, depending on replicate) for all but these two of the 42 samples, where the TEM asbestos fiber concentration for both was at the limit of analytical sensitivity of 0.0008 f cc^{-1} (Table 5). One asbestos fiber was detected in the background sample for the first sanding test of B-10 Fibered Roof Coating and the background sample for the second sanding test of product 201 Fibered Roof Coating. Zero asbestos fibers were found in all other background samples. Based on the fact that ~95% of the samples had zero asbestos fibers detected, the sample with the lower asbestos concentration was used to estimate PCM-E background concentrations for the 8-h TWA calculations. This value is a nonzero PCM-E background concentration of 0.0002 f cc^{-1}.

Quality assurance

Due to the low fiber count in this study, there is a wide variability associated with the acceptable range of fiber counts. For all but one sample, results of the duplicate analysis indicated a 'pass'. For that sample, the initial sample contained six fibers; the duplicate sample contained one fiber. The acceptable range was 2–13 fibers. The most likely explanation for the variability in fiber count between the initial and duplicate samples was the heterogeneous distribution of particulate matter on the filters. Due to the nature of the roofing material and the activities evaluated, the filter contained a mixture of fine dust, fibers and large, black chunks of matrix, some of which also may have contained fibers. These matrix chunks resulted in uneven concentrations of fibers in certain locations on the filter and contributed to the difference in fiber count between the initial and duplicate sample. To ensure that the initial fiber count was accurate, the second analyst recounted the fibers on the first sample. This recounting confirmed the finding of six fibers in the initial sample; thus, the finding of a single fiber in the duplicate sample is likely due solely to the heterogeneity of particulate matter on the filter and differences in the grid openings counted by the analysts.

TWA concentrations

Many of the results indicated asbestos concentrations at or below the detection limit; therefore, 8-h TWAs were not calculated for these data. The estimated 8-h TWAs ranged from 0.0003 to 0.002 f cc^{-1} based on 30 min of activity in an 8-h workday for three of the four activities evaluated in this exposure simulation; 8-h TWAs were not calculated for the application, wet sanding or tool tests because no asbestos fibers were identified in any of these

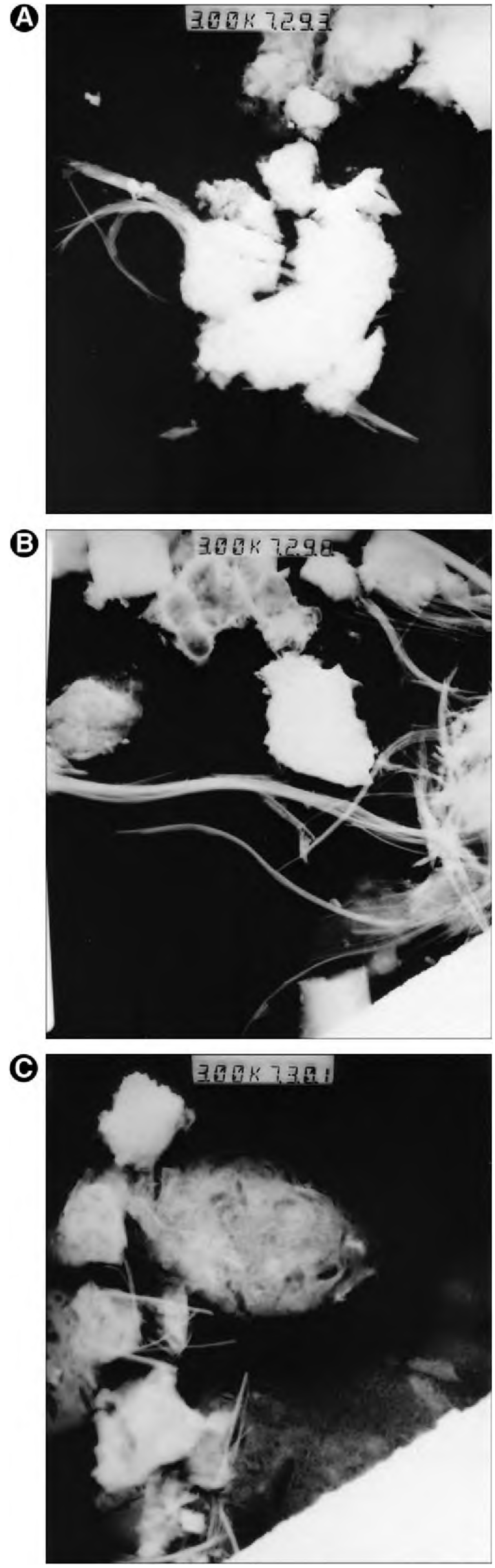

Fig. 3. Example photomicrographs of debris from scraping and sanding activities.

samples (Fig. 4). The 8-h TWA estimates are comparable to the PCM-E background concentration of 0.0002 f cc^{-1} measured in this study. In addition, airborne asbestos TWA concentrations in this study were similar to ambient outdoor air concentrations reported in the literature (e.g. Selikoff and Hammond, 1968; Selikoff et al., 1972; Nicholson and Pundsack, 1973; Chesson et al., 1985; Bignon, 1989; Corn, 1994). The reported concentrations range from nondetect to $\sim$0.0003 f cc^{-1} in rural air and to 0.003 f cc^{-1} in urban air.

DISCUSSION

The abundant natural supply, low cost, fireproof nature, chemical inertness, ease of mixing and reinforcement properties of asbestos led to its use in a variety of applications, including the roofing industry (Brzozowski, 1989). With regard to mastics and coatings specifically, asbestos allows the mixture to remain in a consistent state; therefore, if the mastic is applied to a vertical or sloping surface such as a roof, the prevention of running or sagging due to the consistency is a beneficial property provided by the asbestos content (Hodgson, 1985; Brzozowski, 1989). In addition to controlling viscosity, asbestos provides mechanical properties once the product has cured and improves weathering effects (Brzozowski, 1989). OSHA regulates asbestos-containing cements, coatings and mastics and flashings as 'intact incidental materials', which are less stringently regulated than other types of asbestos-containing materials due to their nonfriable nature and because the asbestos is encapsulated in matrix material that prevents the release of airborne fibers (Good, 1997). This is particularly evident for asbestos-containing roof coatings, mastics and cements, which even today, are sold legally in some hardware stores.

This simulation provides the first data specific to hand-applied roof coatings, mastics and cement products. The products tested were cured to simulate the presence of these products on a roof for several months, after volatilization of solvents and other chemicals. Although these products were fully cured, they remained pliable, per the manufacturer's design, particularly on hot days. The present study did not evaluate the effect of long-term weathering on the roofing products (as would be expected on a roof that is typically in service for $\geq$30 years); however, studies to evaluate the potential for fiber release from roofs that have been subjected to weathering conditions (e.g. sun and rain) for long periods of time will be undertaken. It is possible that weathering of the roofing material may result in the matrix drying out and perhaps becoming more brittle. An Australian study of asbestos cement roof 'cladding' materials in 40-year-old buildings indicated the potential for

Table 5. Background/clearance samples by PCM and TEM during test activities

Test activity	Product	Number of samples	PCM total fiber concentrations (f cc^{-1})			TEM fiber concentrations (f cc^{-1})		
			Number of detects	Minimum	Maximum	Number of detects	Minimum	Maximum
Application	C-8	3	3	0.003	0.004	0	ND (<0.0007)	ND (<0.0008)
	B-10	3	3	0.003	0.007	0	ND (<0.0007)	ND (<0.0008)
Wet sanding	C-8	3	3	0.002	0.005	0	ND (<0.0007)	ND (<0.0007)
	B-10	3	3	0.003	0.007	0	ND (<0.0007)	ND (<0.0008)
Hand scraping	C-8	3	3	0.005	0.007	0	ND (<0.0007)	ND (<0.0009)
	B-10	3	3	0.002	0.008	0	ND (<0.0005)	ND (<0.0008)
	C-30	1	1	0.008	0.008	0	ND (<0.0008)	ND (<0.0008)
	201	1	1	0.009	0.009	0	ND (<0.0009)	ND (<0.0009)
	D-21	1	1	0.003	0.003	0	ND (<0.0008)	ND (<0.0008)
Hand sanding	C-8	3	3	0.004	0.005	0	ND (<0.0007)	ND (<0.0008)
	B-10	3	3	0.003	0.006	1	ND (<0.0008)	0.0008
	C-30	1	1	0.003	0.003	0	ND (<0.0009)	ND (<0.0009)
	201	1	1	0.002	0.002	1	0.0008	0.0008
	D-21	1	1	0.004	0.004	0	ND (<0.0008)	ND (<0.0008)
Clothing	C-8	3	2	ND (<0.002)	0.005	0	ND (<0.0008)	ND (<0.0008)
	B-10	3	3	0.003	0.005	0	ND (<0.0008)	ND (<0.0008)
Tools	C-8	3	3	0.003	0.006	0	ND (<0.0008)	ND (<0.0008)
	B-10	3	3	0.003	0.007	0	ND (<0.0007)	ND (<0.008)
Total		42	41			2		

ND, all values were not detected.

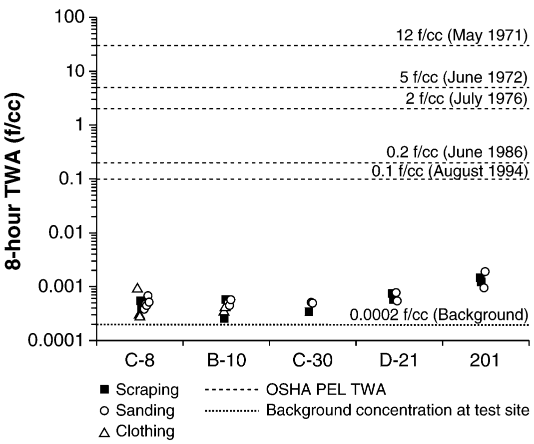

Fig. 4. Estimated 8-h TWA concentrations.

a thin layer, or 'fleece', of asbestos fibers to become exposed as the roofing surfaces weather (Brown, 1987). Exposures of <0.1 to 0.22 f cc^{-1} were measured when the roof surface was painted or cleaned with a water jet for several hours. During roof replacement (including unfastening, removal and disposal of roof sheets), concentrations ranged from below the limit of detection to 0.32 f cc^{-1}, with estimated TWAs ranging from 0.03 to 0.21 f cc^{-1}. Once long-term weathering is completed on representative roof substrates, these results will be reported.

The results of this exposure simulation indicate that workers involved in application, wet sanding, hand scraping and hand sanding of these cured products from roof panels, laundered clothing and soiled tools for an extended period of time would not have been exposed to asbestos concentrations above the current applicable occupational health standards. Although a relatively high air exchange rate was used, possibly resulting in dilution of the resulting airborne asbestos fiber concentration, this airflow was comparable to what roofers would experience outdoors, where wind and other factors affect exposure. Some of the activities tested (e.g. hand scraping, hand sanding) would not be typical, or even expected, practice in the use of this product, based on the manufacturer's specifications; however, they may have been conducted for quick, small-scale repairs. It is unlikely that hand scraping or sanding would ever be conducted continuously for the 30-min time period tested in this study, but these results indicate potential exposure for worst-case scenarios of fiber release for these small-scale activities.

Per the manufacturer's specifications, the plastic roof cement products were used to repair leaks and as a patching compound for small repairs. These products were single-coat products; as such, long-term sanding or scraping of the C-8 and C-30 products between coats was unlikely, although small-scale sanding may have been done to 'scuff' existing product. For the fibered roof coatings, the products were generally applied to an entire roof. A roof in need of repair likely would be removed in large sections or in its entirety; therefore, the coating typically would not be scraped or sanded in the process of removing it. These products were two-coat products that did not require sanding between coats. The NRCA states that BURs are usually removed with power roof cutters that cut through the felts and underlying insulation to separate the roof into smaller sections that are more easily handled (NRCA, 1994). These sections are then pulled up using prying tools, 'power roof cutters' or 'power tear-off machines'. In effecting small repairs, the NRCA states that BURs could be removed using manual tools and methods, such as chopping or cutting through the plies with axes, hatchets or utility knives. They note that roof coatings, mastics and cements are removed by hand methods, usually together with the components of the roof (e.g. plies, flashing, shingles etc.) to which they are adhered (NRCA, 1994). However, assuming an exposure scenario in which a worker manipulates these products in a manner that was evaluated in this study, airborne asbestos concentrations would not exceed current or historical occupational exposure limits.

More aggressive cutting, tear-out and sawing activities were not conducted because it would be difficult to conduct these activities for a full 30 min (to ensure adequate sampling) on a 4 × 8-ft roof substrate. Exposure resulting from removal activities in the field was not measured because it was not possible to determine the composition and type of underlying products (e.g. shingles, plies etc.) that were used in combination with the cements and coatings; as such, we could not isolate potential asbestos exposures to the products of interest. Although this investigation did not evaluate roof tear-out activities, the NRCA reports that removal of BURs with power tools produces exposures well below 0.1 f cc^{-1} (NRCA, 1994). These included projects in which 63 personal breathing-zone samples were collected where there were no dust suppression or collector controls (e.g. wetting the roof, misting the work area and HEPA vacuuming or other dust removal activity). Although the majority of the samples were of short duration (usually <120–180 min), all samples were below the current OSHA PEL. The NRCA states that, although dust is generated during removal, most of the dust was likely nonasbestiform material such as mineral or glass fibers found in the insulation underlying the BURs. This was confirmed in several projects where TEM analysis indicated no asbestos fibers present during roof removal (NRCA, 1994).

TWAs are generally the best indicator of worker exposure based on the nature and duration of the worker's activity over a typical 8-h day. In this study, 8-h TWAs were calculated assuming 30 min of activity in a given workday. For the five roofing products evaluated in the present study, calculated 8-h TWAs ranged from 0.0003 to 0.002 f cc^{-1} (based on 30 min of activity), all of which are well below the current OSHA PEL of 0.1 f cc^{-1}. Specifically, 8-h TWA results were 100-fold below the current OSHA PEL of 0.1 f cc^{-1}, which has been in place since 1994, and 100- to 1000-fold below historical exposure limits in the workplace. In addition, many of the TEM asbestos concentrations and 8-h TWAs were close to the background concentrations of asbestos present in ambient air at the test site and reported historically in ambient air in US cities (e.g. Selikoff and Hammond 1968; Selikoff et al., 1972; Nicholson and Pundsack, 1973; Chesson et al., 1985; Bignon, 1989; Corn, 1994).

In conclusion, this simulation study indicates a low probability that asbestos will become airborne during manipulation of coating- and cement-type roofing products such as those tested. The results indicate an exceedingly small asbestos exposure associated with the repair of these products, even during the unlikely 30-min application, hand scraping and sanding of these products from roof substrates.

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