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Airborne asbestos exposures associated with gasket and packing replacement: A simulation study and meta-analysis

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ABSTRACT

Exposures to airborne asbestos during the removal and installation of internal gaskets and packing associated with a valve overhaul were characterized and compared to published data according to different variables (e.g., product, equipment, task, tool, setting, duration). Personal breathing zone and area samples were collected during twelve events simulating gasket and packing replacement, clean-up and clothing handling. These samples were analyzed using PCM and TEM methods and PCM-equivalent (PCME) airborne asbestos concentrations were calculated. A meta-analysis was performed to compare these data with airborne asbestos concentrations measured in other studies involving gaskets and packing. Short-term mechanic and assistant airborne asbestos concentrations during valve work averaged 0.013 f/cc and 0.008 f/cc (PCME), respectively. Area samples averaged 0.008 f/cc, 0.016 f/cc, and 0.003 f/cc (PCME) for center, bystander, and remote background, respectively. Assuming a tradesman conservatively performs 1–3 gasket and/or packing replacements daily, an average 8-h TWA was estimated to be 0.002–0.010 f/cc (PCME). Combining these results in a meta-analysis of the published exposure data showed that the majority of airborne asbestos exposures during work with gaskets and packing fall within a consistent and low range. Significant differences in airborne concentrations were observed between power versus manual tools and removal versus installation tasks. Airborne asbestos concentrations resulting from gasket and packing work during a valve overhaul are consistent with historical exposure data on replacement of asbestos-containing gasket and packing materials involving multiple variables and, in nearly all plausible scenarios, result in average airborne asbestos concentrations below contemporaneous occupational exposure limits for asbestos.

1. Introduction

Asbestos-containing gaskets and packing materials were used in industrial and maritime settings, such as refineries, chemical plants, naval ships, and energy plants (Cheng and McDermott, 1991; Lindell, 1973, Spence and Rocchi, 1996). Naval specifications required that asbestos containing gaskets be used on many ships (United States Navy, 1924, 1953). In the past, the asbestos content of gaskets typically ranged from 40% to 90%, with binders and fillers making up the rest of the material (Madl et al., 2007). In most cases, chrysotile asbestos was the only asbestos fiber used in these materials, although crocidolite asbestos was sometimes used within very specialized acidic or corrosive environments.

Relatively few studies in the 1970s and 1980s evaluated exposures related to gasket and packing work, especially when compared to the many evaluations of asbestos insulation, due to a perception that asbestos exposures during such work would be negligible or relatively small (Lindell, 1973, Selikoff, 1970). Studies, both published and unpublished, which evaluated airborne asbestos exposures due to handling gaskets and packing were generally conducted at worksites or simulated in a controlled environment. Later studies tried to limit background asbestos levels (e.g., the extensive use of asbestos insulation on pipes and machinery) by simulating the work activity in controlled environments (e.g., laboratory test facilities). The first comprehensive study which characterized potential worker exposures to airborne asbestos

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during the removal and installation of asbestos-containing gaskets was conducted by the U.S. Navy in 1978 (Liukonen et al., 1978). This worksite study was performed in a shipyard setting and, although unclear how background airborne concentrations resulting from other asbestos-containing materials being used at the shipyard may have influenced the results, the vast majority of airborne asbestos exposures were below contemporaneous occupational exposure limits (Liukonen et al., 1978).

A review published by Madl et al. (2007) was the first to summarize all of the published data, as well as selected unpublished data, on airborne asbestos concentrations associated with the handling of asbestos-containing gaskets and packing materials (Madl et al., 2007). In that study, eight simulation studies (or series of simulation studies) and four worksite studies of industrial and maritime settings, which involved collection of more than 300 air samples, were analyzed (Boelter et al., 2002; Cheng and McDermott, 1991; Liukonen et al., 1978; Longo et al., 2002; Mangold et al., 2006; McKinnery and Moore, 1992, Millette and Mount, 1993; Spence and Rocchi, 1996; Spencer, 1998a,b). The replacement of gaskets and packing using hand-held tools showed, with few exceptions, short-term average exposures less than the current 30-min OSHA Excursion Limit of 1.0 f/cc and all of the long-term average exposures were less than the current 8-h TWA PEL of 0.1 f/cc. It was concluded that the use of hand tools and hand-operated power tools to remove or install gaskets or packing should not, under conditions normally encountered, have produced airborne concentrations in excess of contemporaneous regulatory levels (Madl et al., 2007).

While several published studies have evaluated asbestos exposures to workers removing and installing gaskets and packing, none have characterized exposures to a worker performing valve repair work limited to the replacement of internal gaskets and packing materials (e.g., as would be performed during a valve overhaul). Therefore, it was of interest to evaluate airborne asbestos concentrations generated during replacement of gaskets and packing internal to the valve and how these concentrations might contribute to asbestos exposures experienced by a worker or bystander. The primary objective of this work was to: (1) characterize exposures to airborne asbestos during the removal and installation of asbestos-containing packing and gaskets contained within vintage valves, (2) measure short- and long-term exposures during packing and gasket replacement and characterize the fiber type, size distribution (e.g., >5 and >20 μm length), and morphology of airborne asbestos fibers generated during these work activities, (3) compare short-term and long-term measurements to the occupational exposure limits (OELs) set forth by the Occupational Safety and Health Administration (OSHA), 30-min Excursion Limit (EL) and 8-h Time Weighted Average Permissible Exposure Limit (PEL), (4) conduct a statistical comparison of the airborne asbestos concentrations measured in this study to the body of available data from similar studies in the published literature, and (5) use the combined dataset (i.e., data from this simulation study and the published literature) to perform additional statistical comparisons according to different variables (e.g., product type, tool, task, or equipment) and explore any other trends that may be discerned when considering the full body of data available to date.

2. Methods

2.1. Valve simulation study

2.1.1. Equipment, test site and study conditions

Ten vintage Edward valves manufactured prior to the 1980s, an era in which some packing and gaskets contained asbestos, were selected for this study. Two 1-in. (2.54 cm) valves and eight 3-in. (7.62 cm) valves were used; all of the valves were globe valves with the exception of one gate valve. Each valve was blasted with abrasive material prior to testing to remove possible external debris or contamination. The service life of each valve was unknown; however, it was understood by the investigators that the valves were historically used on maritime vessels. It was not determined until after the testing through bulk sample analysis whether each valve housed asbestos-containing packing and gasket material.

Complete valve overhauls were performed inside an enclosed room by two retired mechanics with 50 combined years of training and experience in the U.S. Navy, servicing and repairing equipment. Further description of the study room is described in the Supplementary Information (SI). Prior to conducting the study, permission from a medical institutional review board (IRB) was requested and obtained (Copernicus Group IRB, Research Triangle Park, NC, USA).

2.1.2. Exposure scenarios

Airborne asbestos concentrations were measured during activities conducted during twelve sampling events. Ten of these events characterized exposures during valve overhaul work which included the removal and installation of asbestos-containing packing and/or gaskets contained within ten vintage valves (Event 1, 3–11), one characterized exposures associated with post-valve overhaul clean-up work (Event 2), and one characterized exposures during the handling of coveralls worn during the study (Event 12).

The packing replacement process was similar for all ten valves (Event 1, 3–11). On nine of the ten valves (Event 1, 3–4, 6–11), the gasket was also removed, and on three of those occasions (Event 3, 4, and 6), a new gasket was fabricated. In general, the mechanics took approximately 15–40 min to replace the packing material and approximately 10–30 min to replace the gasket, thus resulting in a total duration of approximately 30–60 min for a complete valve overhaul. The process of packing and gasket removal and installation and cleanup are described in further detail in the SI.

Clothes handling (i.e., shaking and folding of coveralls worn during valve overhaul work) was also studied. In total, six coveralls worn by the worker and the assistant (one pair each per day) were collected and sealed separately in plastic-lined bags. At the conclusion of the study, coveralls worn by the mechanic and assistant and collected each day of the testing (new coveralls were worn each day) were shaken, folded, and turned inside out for approximately 1–3 min by a volunteer, simulating the handling of these potentially contaminated work clothes (Event 12).

2.1.3. Sampling and analytical methods

Collection and analysis of air samples. Airborne asbestos were collected onto mixed cellulose ester membranes as described elsewhere, as well as further described in the SI (Madl et al., 2009). During an entire valve job, personal samples from the mechanic's and assistant's lapel, bystander and remote area samples, and ambient samples for airborne asbestos were collected. Consecutive 30-min samples, long-term samples, and samples spanning the duration of one complete study day were collected on the right and left lapels of both the mechanic and the assistant. After each event, once the work activities had ceased, the room was ventilated for 30 min and background samples were taken prior to the start of the next testing event. All air samples were collected and analyzed for asbestos by phase contrast microscopy (PCM) and transmission electron microscopy (TEM) according to NIOSH Methods 7400 and 7402 which defines fibers >5 μm in length and ⩾0.25 μm in diameter and having at least a 3:1 aspect ratio (National Institute for Occupational Safety and Health (NIOSH), 1994). Using the ISO methodology 10312 (1995), asbestos fibers were classified according to fiber size and morphology as described in the SI.

During each overhaul, samples of all packing and gasket material removed and installed were collected for bulk sample analysis of asbestos content. Bulk samples were also taken of the debris found on the workbench for two events (Events 10 and 11) and of the material removed from the bonnet area of one valve (Event 9). The bulk materials were analyzed by EMS Laboratories, using polarized light microscopy (PLM) according to NIOSH Method 9002 (National Institute for Occupational Safety and Health (NIOSH), 1994). Sulfur hexafluoride (SF_6) was used as a tracer gas to estimate the air exchange rate within the study room (see SI). The air exchange in the room (passive ventilation) was found to be approximately 2–3 air changes per hour (ACH).

2.1.4. Data analysis of valve simulation study results

Descriptive statistics were performed on PCM, TEM, and PCM-equivalent measurements of airborne fiber concentrations collected during gasket and packing replacement on valves, as well as during clothes handling. Results below the analytical sensitivity limit were assigned a value equal to one-half the sensitivity limit. Description of the analytical sensitivity limits and the calculation of the 'PCM equivalent' (PCME) concentration is described in the SI.

Results were analyzed by sample location (e.g., worker, assistant, center, bystander, and remote area) and task. Eight-hour TWA asbestos exposures during gasket and packing replacement on valves and flanges were calculated. In order to determine the average worst-case frequency and duration of gasket and/or packing work and assure potential exposures are not underestimated, the testimony of over 60 workers who had filed lawsuits against gasket and packing manufacturers were reviewed and the frequency and duration information for several tasks, such as gasket removal, fabrication, installation, and replacement, and packing removal, installation, and replacement, was extracted and qualitatively reviewed (further detail provided in the SI). For the purposes of our 8-h TWA calculation, we assumed that under worse case conditions, a worker whose primary job duties involve the greatest opportunity for routine in-field gasket and packing work (e.g., machinist, mechanic, plumber/pipefitter, boilermaker) would perform this type of work 1–3 times per day for a duration of 30–60 min each time on average over a given year. Thus, personal 8-h TWAs were calculated for 1–3 gasket and/or packing replacements as follows:

$$\sum (C_i * t_i)/480\ \text{min}$$

where C_i is the average airborne concentration (f/cc) for the left and right lapel collected for each of the sampling segments and t_i is the duration (30–60 min) of the task. Therefore, it was assumed that gasket and packing work could comprise 30 min to 3 h of an 8 h workday.

2.2. Meta-analysis of gasket and packing exposure studies

2.2.1. Literature review and compilation of combined dataset

In order to provide a statistical comparison of the samples collected in this simulation study to airborne asbestos concentrations measured in other studies involving gaskets and packing, the available published data were compiled and analyzed as a whole. A literature search was conducted using several database search engines (e.g., TOXNET, PUBMED) to identify potentially relevant publications in the peer-reviewed literature, in particular those published since Madl et al. in 2007 (Madl et al., 2007). Description of the studies included and excluded in the analysis is described in the SI. After the relevant studies were identified, each individual study was reviewed in detail to obtain information regarding the tasks performed, number and types of products and tools used, task and sample duration, and asbestos content. A total of 11 studies were identified for the combined data analysis (Boelter et al., 2002, 2011; Cheng and McDermott, 1991; Liukonen et al., 1978; Longo et al., 2002; Mangold et al., 2006; McKinnery and Moore, 1992; Millette and Mount, 1993; Spence and Rocchi, 1996; Spencer, 1998a,b). One published study provided only summary level information such as mean values or ranges (Boelter et al., 2011) and therefore could not be incorporated into the combined analysis (described below). However, the reported average concentrations were included in comparisons of average airborne asbestos concentrations across all of the studies.

Specific variables were recorded for each study, including the reported airborne asbestos concentration (based on PCM and, if available, TEM results), sampling time, sampling location (including whether the samples were collected in a chamber), task performed (including a description of any tools that were used), asbestos-containing material that was handled (including information about percent asbestos or fiber type, if available), type of equipment being handled, sampling information (i.e., flow rate, total air volume, analytical methods used), and a description of any engineering controls that may have been in place during the sampling. Analyses were performed using one-half the limit of detection for all samples that reported non-detectable quantities, unless otherwise noted.

2.2.2. Statistical analyses of combined dataset

Statistical comparisons of airborne asbestos concentrations were performed for several different factors, including sample duration, material, equipment, task, and study (Fig 1). For the "material" variable, differences in asbestos concentration between gaskets (includes plate gasket and spiral wound gasket), packing, and packing/gasket were evaluated. For the "equipment" variable, asbestos concentration differences based on the type of equipment and specific material being serviced were evaluated and included gasket and/or packing work on boiler headers, flanges, valves, pumps, "valves and flanges" (work was conducted on both types of equipment simultaneously), ventilation duct heaters, and unknown (equipment was unknown or not specified but the task would have required the use of a specific type of equipment, as in the case of gasket removal). Samples where the type of equipment was not specified or applicable (meaning that the task was not necessarily associated with a specific type of equipment, as in the case of fabricating gaskets) were not included in the equipment analysis.

Worker task descriptions were coded in the combined database as gasket removal, gasket fabrication, gasket installation, gasket replacement, packing removal, packing installation, packing replacement, combined gasket/packing work (this code usually referred to replacement of gaskets and packing within a single sampling period), and clean-up (this code involved clean-up following gasket and packing work). Similarly, the studies frequently provided information regarding the tools that were used in the course of installing or replacing a gasket or packing material. Tools were grouped based on whether they were hand-held manual or power tools. Power tools that were likely only to be found in a machine shop (e.g., machine puncher) were also grouped separately. For the tool analysis, gasket and packing materials were pooled, since few tools were specified for work involving packing materials.

The analysis was limited to personal samples collected on the worker handling the gaskets and/or packing, although general summary statistics for personal samples collected on bystanders or assistants were also calculated. Worker samples were grouped according to analytical method (PCM or TEM) and the underlying sample distributions were tested using ProUCL 4.0 software (EPA,

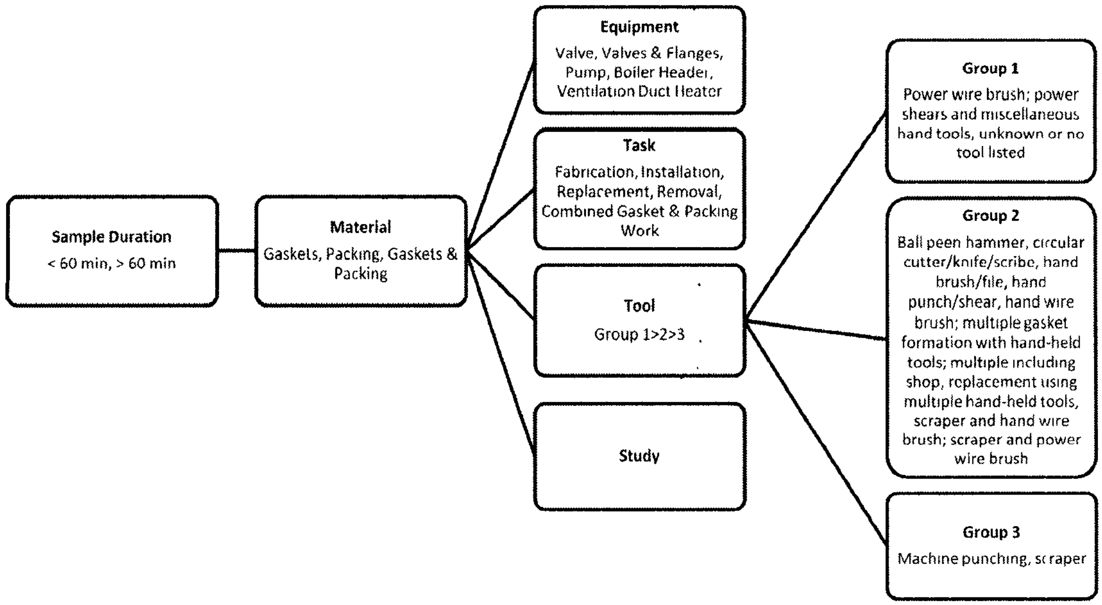

Fig. 1. Hierarchy of variables evaluated in the meta-analysis of airborne fiber concentrations during work with gasket and packing materials.

1975). Probability plots were also used to evaluate the sample distribution. Based on the probability plots, which indicated that the sample distributions appeared to be lognormal, data were log transformed prior to performing any statistical analyses. All analyses were conducted with SYSTAT® statistical software (Chicago, IL). Several statistical analyses were conducted using the full dataset. All comparisons were performed initially using PCM data. Three published studies (McKinnery and Moore, 1992; Millette and Mount, 1993; Spence and Rocchi, 1996), underlying data from Longo et al. (2002), and our simulation study also reported TEM data, and therefore, a separate analyses were repeated using these TEM results.

Although samples involving work with non-asbestos containing materials were excluded, there were some samples that were collected during work that involved asbestos and non-asbestos materials simultaneously. This occurred in both Spence and Rocchi (Spence and Rocchi, 1996) and our simulation study. The samples encompassing work with both asbestos and non-asbestos materials from the simulation study were included in the analysis and the reported concentration was adjusted to account for the portion of the sampling time that was spent handling only asbestos-containing components, where possible. This adjustment was not possible for samples of longer duration; however, these samples were included in the analysis if any of the materials used during the sample time were asbestos-containing. For consistency, three samples from Spence and Rocchi (1996) whose sampling time spanned work with both asbestos and non-asbestos containing gaskets were also included in the analysis (Spence and Rocchi, 1996).

For purposes of comparison, samples were initially categorized by sample duration as follows: <60 min; 60–240 min; and >240 min. These groupings were established based on professional judgment and knowledge of the nature and duration of the various tasks, and to ensure that each group contained a sufficient number of samples to facilitate statistical analysis. A single factor generalized linear model (GLM) analysis of variance (ANOVA), however, indicated that there was not a significant difference between samples in the 60–240 min and >240 min sample groups, so all subsequent analyses were performed separately for two groups: <60 min and ⩾60 min. It should be noted that, for the long-term samples, several simulation studies evaluated a worker's daily exposure by collecting breathing zone samples while the worker repeatedly performed specific tasks over the course of an 8-h workday. Not all of these studies reported the number of repetitions of the task during the sampling period; however, many of the studies reported that the worker performed four to eight repetitions of the activity of interest over the course of the day (Boelter et al., 2002, Mangold et al., 2006; Spencer, 1998b). Thus, in these cases it is possible that there were portions of the total sampling time where the workers were not handling asbestos-containing components.

GLM ANOVAs were performed to evaluate whether there were significant differences based on type of equipment, task, tool, material, or the individual study. These analyses were conducted separately for PCM and TEM sampling results. A p-value of less than 0.05 was considered to be significant.

To evaluate consistency across analytical methods, PCM results were plotted against TEM results for studies that reported both measurements. Comparisons between PCM and TEM were conducted separately for two sample duration categories (<60 and ⩾60 min) using a multiple linear regression model of TEM concentrations versus PCM concentrations with the categorical variable representing the individual studies (study), and PCM by study. The purpose of this multiple linear regression model is to determine if there are any significant differences in the slope or y intercept for linear regression models of TEM versus PCM by study.

3. Results

3.1. Simulation study

A total of 228 airborne asbestos samples were collected over the course of the 3-day study, including 78 worker samples, 40 assistant samples, 57 area samples, 18 clearance samples, six background samples, nine ambient samples, and 20 field blanks. Of these samples, a total of 58 worker samples, 26 assistant samples, and 52 area samples were used in the analysis since they were collected during activities involving asbestos-containing components. In addition, a total of 59 bulk samples were collected on the associated packing and gasket material, as well as on miscellaneous dust created during valve work.

Ten of the 12 events involved gasket and packing work on valves, and each of these ten events involved work on a single valve. Nine of the ten events involved removing or replacing at least one asbestos-containing component (packing removed and/or installed, gasket removed and/or installed). During the one event that did not involve any asbestos-containing components (Event 5), the stem and bonnet of the valve were frozen and the mechanic was unable to remove the packing rings or the gasket. No asbestos was detected in the pieces of packing material removed from this valve and, thus, results from this event were not included in the analysis.

The asbestos bulk content of the packing material removed from the valves was ND-<1% chrysotile (1 valve) and 40–70% chrysotile (3 valves); no asbestos was detected in the packing material removed from the remaining six valves. The bulk content of the packing material installed in the valves ranged from 25% to 70% chrysotile asbestos. The asbestos bulk content of the gasket material removed from the valves was ND-<1% chrysotile (4 valves), <1% chrysotile (1 valve), and 50–55% chrysotile (2 valves); no asbestos was detected in the gasket material removed from the remaining two valves. The bulk content of the gasket material installed in the valves ranged from 45% to 65% chrysotile asbestos. No amphibole fibers were detected in any of the gasket or packing materials removed or installed into the valves.

Average worker airborne asbestos concentrations as measured by PCME during packing-only and gasket-only work were higher than assistant airborne asbestos concentrations during the same tasks. Average short-term airborne asbestos concentrations for the worker performing gasket and/or packing work (16–36 min sample duration) were 0.059, 0.014, and 0.013 f/cc as measured by PCM, TEM, and PCME, respectively, whereas average short-term concentrations for the assistant were 0.056 f/cc, (PCM), 0.006 f/cc (TEM), and 0.008 f/cc (PCME) (Table 1). Cleanup activities following packing and gasket work, when both the packing material and gaskets removed and installed were positive for asbestos, showed average airborne asbestos concentrations of 0.049, 0.005, and 0.006 f/cc as measured by PCM, TEM, and PCME, respectively. During clothes handling, the average airborne asbestos concentrations measured on the volunteer (handling the clothes) were 0.107 f/cc (PCM), 0.005 f/cc (TEM), and 0.005 f/cc (PCME). As mentioned above, PCME was only calculated for samples in which asbestos fibers were detected by TEM. Asbestos fibers were not detected by TEM in approximately 40% of the short-term worker samples and approximately 55% of the short-term assistant samples.

Table 1
Q3 Airborne asbestos fiber concentrations for worker and assistant (30 min[a]) during the replacement of gaskets and packing in valves.

Task[b]	# of events	Asbestos fiber concentrations (f/cc)																		
		PCM							TEM							PCME[*]				
		n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	Avg	SD	MIN	MAX
Worker																				
Packing-only work																				
Removal	1	2	0	0	0.047	–	0.047	0.047	2	0	0	0.020	–	0.020	0.020	2	0.013	–	0.013	0.013
Installation	6	12	0	0	0.073	0.038	0.041	0.137	12	4	0	0.019	0.026	0.002	0.068	8	0.020	0.024	0.003	0.061
Replacement	1	2	0	0	0.078	–	0.078	0.078	2	2	0	0.002	–	0.002	0.002	0	–	–	–	–
Summary – packing-only	**8**	**16**	**0**	**0**	**0.071**	**0.034**	**0.041**	**0.137**	**16**	**6**	**0**	**0.017**	**0.023**	**0.002**	**0.068**	**10**	**0.019**	**0.022**	**0.003**	**0.061**
Gasket-only work																				
Removal	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Installation	2	4	0	0	0.047	0.010	0.040	0.054	4	1	0	0.008	0.001	0.008	0.009	3	0.006	0.000	0.005	0.006
Replacement	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Summary – gasket-only	**2**	**4**	**0**	**0**	**0.047**	**0.010**	**0.040**	**0.054**	**4**	**1**	**0**	**0.008**	**0.001**	**0.008**	**0.009**	**3**	**0.006**	**0.000**	**0.005**	**0.006**
Combined gasket/packing work																				
Packing and gasket removal	1	2	–	2	–	–	–	–	2	1	0	0.007	–	0.007	0.007	–	–	–	–	–
Packing and gasket installation	1	2	0	0	0.012	–	0.012	0.012	2	0	0	0.026	–	0.026	0.026	2	0.004	–	0.004	0.004
Packing installation, gasket removal	1	2	0	0	0.036	–	0.036	0.036	2	1	0	0.002	–	0.002	0.002	1	0.004	–	0.004	0.004
Summary – combined gasket/packing	**3**	**6**	**0**	**2**	**0.024**	**0.017**	**0.012**	**0.036**	**6**	**2**	**0**	**0.012**	**0.012**	**0.002**	**0.026**	**3**	**0.004**	**0.000**	**0.004**	**0.004**
Summary – all valve work	**13**	**26**	**0**	**2**	**0.059**	**0.033**	**0.012**	**0.137**	**26**	**9**	**0**	**0.014**	**0.018**	**0.002**	**0.068**	**16**	**0.013**	**0.018**	**0.003**	**0.061**
Misc. activities																				
Cleaning	2	4	0	0	0.049	0.034	0.025	0.073	4	2	0	0.005	0.002	0.004	0.006	2	0.006	0.005	0.002	0.010
Clothes handling	1	2	0	0	0.107	–	0.107	0.107	2	1	0	0.005	–	0.005	0.005	1	0.005	–	0.005	0.005
Assistant																				
Packing-only work																				
Removal	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Installation	6	12	0	0	0.060	0.023	0.039	0.096	12	7	0	0.008	0.010	0.002	0.026	5	0.012	0.012	0.002	0.028
Replacement	1	2	0	0	0.072	–	0.072	0.072	2	2	0	0.002	–	0.002	0.002	0	–	–	–	–
Summary – packing-only	**7**	**14**	**0**	**0**	**0.062**	**0.021**	**0.039**	**0.096**	**14**	**9**	**0**	**0.007**	**0.009**	**0.002**	**0.026**	**5**	**0.012**	**0.012**	**0.002**	**0.028**
Gasket-only work																				
Removal	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Installation	2	4	0	0	0.036	0.001	0.035	0.037	4	1	0	0.003	0.002	0.002	0.004	3	0.002	0.001	0.001	0.002
Replacement	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Summary – gasket-only	**2**	**4**	**0**	**0**	**0.036**	**0.001**	**0.035**	**0.037**	**4**	**1**	**0**	**0.003**	**0.002**	**0.002**	**0.004**	**3**	**0.002**	**0.001**	**0.001**	**0.002**
Summary – all assistant samples	**9**	**18**	**0**	**0**	**0.056**	**0.022**	**0.035**	**0.096**	**18**	**10**	**0**	**0.006**	**0.008**	**0.002**	**0.026**	**8**	**0.008**	**0.011**	**0.001**	**0.028**

PCM, phase contrast microscopy; TEM, transmission electron microscopy; PCME, PCM concentration multiplied by the ratio of asbestos fibers to total fibers measured by TEM; *n*, number of samples; *n*(ND), number of samples in which asbestos was not detected, *n*(NR), number of samples not readable; Avg, average; SD, standard deviation; – not applicable.

[*] Based on samples in which asbestos fibers were detected by TEM

[a] Short-term samples ranged from 16–36 min in length

[b] Event 5 was excluded from the analysis because no asbestos in the packing material removed and the gasket was not replace due to a frozen valve stem and bonnet

Because some of the packing material and gaskets removed from the valves did not contain asbestos, the time handling non-asbestos components was subtracted from the total sample duration for the short-term (16–36 min) samples. When adjusted for time handling non-asbestos components, the average airborne asbestos concentrations as measured by PCM, TEM, and PCME for the worker were 0.121, 0.027, and 0.027 f/cc, respectively (Table 2). Samples collected for longer durations (31–84 min over the course of the complete valve overhaul) could not be adjusted for time handling non-asbestos materials and showed average airborne asbestos concentrations as measured by PCM, TEM, and PCME of 0.069, 0.013, and 0.015 f/cc, respectively (Table 3).

Average area asbestos concentrations were lower than those observed for the personal lapel worker and assistant samples (Table 4). Asbestos was not detected in approximately 70% (center), 30% (bystander), and 45% (remote background) of the area samples as determined by TEM. In addition, average airborne asbestos concentrations as measured by PCME at the center (0.008 f/cc) and bystander (0.005 f/cc) locations were approximately one-half to two-thirds less than those measured for the worker (0.015 f/cc). Airborne asbestos concentrations found at the remote background locations were even lower than those found at the bystander locations. No asbestos fibers were detected in any of the ambient or field blank samples, as measured by TEM.

Of the total asbestos fibers detected in samples collected from the lapel of the worker, fiber size and morphology analysis of the airborne asbestos fibers showed that approximately 40% of fibers existed in a cluster or matrix, whereas the remaining proportion of fibers existed as free fibers or bundles (Table 5). Based on the abovementioned designation of a respirable fiber (i.e., <0.7 μm or ⩽3 μm diameter), approximately 42–65% of fibers counted were non-respirable. If either designation of respirability is applied (fiber <0.7 μm or ⩽3 μm diameter or particle <10 μm), between 24% and 65% of fibers counted were non-respirable.

Estimated 8-h TWA asbestos exposures were calculated for the worker using short-term PCME data taking into account the duration in which asbestos-containing products (gaskets or packing material) were handled (Table 2). Based on the assumption that under worse case conditions, a worker, whose primary job duties involve the greatest opportunity for routine in-field gaskets and packing work (e.g., machinist, mechanic, plumber/pipefitter, boilermaker), would perform 1–3 times per day for a duration of 30–60 min each time on average. Additionally based on the average worker exposure during all valve work involving gasket and packing replacement of 0.027 f/cc (PCME, Table 2), the resulting average 8-h TWAs was estimated to be 0.002–0.010 f/cc (0.5–3 h of gasket and packing in a workday). Based on the results of the valve simulation study, a mechanic performing similar work 1–

Table 2
Comparison of worker and assistant average asbestos concentrations (30 min[a]) with and without adjustment for time handling non-asbestos components

Task[b]	# of events	Average asbestos fiber concentrations (f/cc) (total sample duration)			Average asbestos fiber concentrations (f/cc) (adjusted for time handling non-asbestos components)		
		PCM	TEM	PCME	PCM	TEM	PCME
Worker							
Packing-only work							
Removal	1	0.047	0.020	0.013	0.047	0.020	0.013
Installation[c]	6	0.073	0.019	0.020	0.183	0.046	0.047
Replacement[c]	1	0.078	0.002	–	0.133	0.003	–
Summary – packing-only work	**8**	**0.071**	**0.017**	**0.019**	**0.160**	**0.037**	**0.041**
Gasket-only work							
Removal	0	–	–	–	–	–	–
Installation[c]	2	0.047	0.008	0.006	0.063	0.011	0.007
Replacement	0	–	–	–	–	–	–
Summary – gasket-only work	**2**	**0.047**	**0.008**	**0.006**	**0.063**	**0.011**	**0.007**
Combined gasket and packing work							
Packing and gasket removal	1	–	0.007	–	–	0.007	–
Packing and gasket installation	1	0.012	0.026	0.004	0.012	0.026	0.004
Packing installation, gasket removal	1	0.036	0.002	0.004	0.036	0.002	0.004
Summary – combined gasket and packing work	**3**	**0.024**	**0.012**	**0.004**	**0.024**	**0.012**	**0.004**
Summary – all valve work	**13**	**0.059**	**0.014**	**0.013**	**0.121**	**0.027**	**0.027**
Misc. Activities							
Cleaning	2	0.049	0.005	0.006	0.049	0.005	0.006
Clothes Handling	1	0.107	0.005	0.005	0.107	0.005	0.005
Assistant							
Packing-only work							
Removal	0	–	–	–	–	–	–
Installation[c]	6	0.060	0.008	0.012	0.142	0.018	0.027
Replacement[c]	1	0.072	0.002	–	0.113	0.003	–
Summary – packing-only work	**7**	**0.062**	**0.007**	**0.012**	**0.138**	**0.016**	**0.027**
Gasket-only work							
Removal	0	–	–	–	–	–	–
Installation[c]	2	0.036	0.003	0.002	0.047	0.004	0.002
Replacement	0	–	–	–	–	–	–
Summary – gasket-only work	**2**	**0.036**	**0.003**	**0.002**	**0.047**	**0.004**	**0.002**
Summary – all assistant samples	**9**	**0.056**	**0.006**	**0.008**	**0.118**	**0.013**	**0.019**

PCM, phase contrast microscopy; TEM, transmission electron microscopy; PCME, PCM concentration multiplied by the ratio of asbestos fibers to total fibers measured by TEM, – not applicable.
[*] Based on samples in which asbestos fibers were detected by TEM.
[a] Short-term samples ranged from 16–36 min in length.
[b] Event 5 was excluded from the analysis because no asbestos in the packing material removed and the gasket was not replace due to a frozen valve stem and bonnet
[c] Tasks affected by adjusting task time when non-asbestos components were handled.

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Table 3
Airborne asbestos fiber concentrations for worker (60 min[a]) according to task, valve size and event during the replacement of gaskets and packing in valves

Task/valve size/event[b]	# of events	Asbestos fiber concentrations (f/cc)																		
		PCM							TEM								PCME*			
		n	*n*(ND)	*n*(NR)	Avg	SD	MIN	MAX	*n*	*n*(ND)	*n*(NR)	Avg	SD	MIN	MAX	*n*	Avg	SD	MIN	MAX
Task																				
Packing replacement	1	2	0	0	0.081	–	0.081	0.081	2	1	0	0.007	–	0.007	0.007	1	0.006	–	0.006	0.006
Packing installation	4	8	0	0	0.084	0.032	0.055	0.126	8	4	0	0.021	0.023	0.002	0.049	4	0.033	0.007	0.028	0.037
Packing and gasket installation	2	4	0	0	0.056	0.008	0.050	0.062	4	0	0	0.006	0.002	0.004	0.007	4	0.006	0.004	0.004	0.009
Packing replacement; gasket removal	1	2	0	0	0.021	–	0.021	0.021	2	0	0	0.005	–	0.005	0.005	2	0.005	–	0.005	0.005
Packing and gasket replacement	1	2	–	2	–	–	–	–	2	0	0	0.006	–	0.006	0.006	–	–	–	–	–
Valve size																				
1-in.	2	4	0	0	0.073	0.011	0.065	0.081	4	3	0	0.005	0.003	0.003	0.007	1	0.006	–	0.006	0.006
3-in	7	14	0	2	0.067	0.036	0.021	0.126	14	2	0	0.015	0.018	0.002	0.049	10	0.016	0.015	0.004	0.037
Event																				
1	1	2	0	0	0.021	–	0.021	0.021	2	0	0	0.005	–	0.005	0.005	2	0.005	–	0.005	0.005
3	1	2	0	2	–	–	–	–	2	0	0	0.006	–	0.006	0.006	–	–	–	–	–
4	1	2	0	0	0.050	–	0.050	0.050	2	0	0	0.004	–	0.004	0.004	2	0.004	–	0.004	0.004
6	1	2	0	0	0.062	–	0.062	0.062	2	0	0	0.007	–	0.007	0.007	2	0.009	–	0.009	0.009
7	1	2	0	0	0.065	–	0.065	0.065	2	2	0	0.003	–	0.003	0.003	0	–	–	–	–
8	1	2	0	0	0.081	–	0.081	0.081	2	1	0	0.007	–	0.007	0.007	1	0.006	–	0.006	0.006
9	1	2	0	0	0.089	–	0.089	0.089	2	0	0	0.049	–	0.049	0.049	2	0.037	–	0.037	0.037
10	1	2	0	0	0.126	–	0.126	0.126	2	0	0	0.031	–	0.031	0.031	2	0.028	–	0.028	0.028
11	1	2	0	0	0.055	–	0.055	0.055	2	2	0	0.002	–	0.002	0.002	0	–	–	–	–
Summary – all long-term samples	**9**	**18**	**0**	**2**	**0.069**	**0.031**	**0.021**	**0.126**	**18**	**5**	**0**	**0.013**	**0.016**	**0.002**	**0.049**	**11**	**0.015**	**0.014**	**0.004**	**0.037**

PCM, phase contrast microscopy; TEM, transmission electron microscopy; PCME, PCM concentration multiplied by the ratio of asbestos fibers to total fibers measured by TEM; *n*, number of samples; *n*(ND), number of samples in which asbestos was not detected; *n*(NR), number of samples not readable; Avg, average, SD, standard deviation; – not applicable.

* Based on samples in which asbestos fibers were detected by TEM.

[a] Long-term samples ranged from 31–84 min in length.

[b] Event 5 was excluded from the analysis since no asbestos was found in the pieces of packing material removed and the stem and bonnet of the valve were frozen

3 times over the course of a workday would have an 8 h TWA approximately one-fiftieth to one-tenth below the current OSHA PEL of 0.1 f/cc.

3.2. Meta-analysis of gasket and packing exposure studies

A total of 395 PCM sample results for workers were available for analysis in the combined dataset. Initial statistical comparisons indicated that sample time had a significant impact on airborne asbestos concentration ($p < 0.001$) and further analyses were conducted within two sample duration categories: <60 min ($n = 265$) and ⩾60 min ($n = 127$) (no sample duration was provided for three samples from McKinnery and Moore (1992) and as such, these data were excluded from the analysis).

A total of 89 TEM sample results were available from five studies and the simulation study for analysis in the combined dataset (Longo et al., 2002; McKinnery and Moore, 1992; Millette and Mount, 1993; Spence and Rocchi, 1996). Similar to the PCM results, sample time had a significant impact on airborne asbestos concentrations wherein the <60 min samples ($n = 75$) were significantly greater than the ⩾60 min samples ($n = 14$) at a $p < 0.0001$ based on a two sample Student t test. Other than for a comparison between studies, the number of samples for the ⩾60 min category was too few for further pairwise comparisons.

Additionally, a Student t test was conducted to compare the average worker (personal) data to the associated bystander (bystander or assistant) data for the entire PCM combined dataset without accounting for duration, study, or task. Overall, there was no significant difference between worker and bystander airborne fiber concentrations ($p = 0.926$). The influence of study, duration (<60 and ⩾60 min), and task on bystander versus worker exposures were evaluated for the following variables in a two factor GLM ANOVA paired approach. Each personal and bystander sample was paired based on events, where possible, to avoid diluting differences between samples collected during two different events where exposures may have differed (e.g., removal versus installation). The worker/bystander comparison using paired t tests and repeated measures GLM showed a significant overall difference between worker and bystander samples ($p = 0.004$), a significant difference by study, and no significant difference by task. Because we evaluated the data on a paired sample basis, sampling duration was not an issue because each pair of personal and bystander samples had similar durations. In the comparison by study, the Longo et al. (2002) worker samples differed significantly than bystander samples ($p < 0.0001$), while the simulation study worker samples and those reported in Spencer 1998 were not significantly different than bystander samples ($p \geqslant 0.094$). A lack of statistical difference between worker and bystander measurements in the simulation and Spencer studies is likely attributed to the overall low intensity of exposure (e.g., near the limits of detection), in contrast to that reported by Longo et al. (2002).

For personal samples measured by PCM, a more detailed analysis was performed to assess differences in fiber concentration in the breathing zone during the use of gaskets and packing associated with specific equipment, tasks, and tools (Fig. 1).

3.2.1. Comparison of airborne asbestos concentrations by study

An initial comparison was performed in order to determine if the airborne asbestos concentrations by PCM for each sample duration category were consistent across studies. Only four of the studies, one of which was our simulation study, had samples in both the <60 and ⩾60 min sample duration categories (Cheng and McDermott, 1991; Liukonen et al., 1978; Spencer, 1998b). The seven studies with samples <60 min were ranked into three general categories from highest to lowest based on the relative mean airborne asbestos concentrations: ranking category one included the Longo studies; ranking category two included Millette and Mount (1993), McKinnery and Moore (1992), and

Table 4
Q4 Airborne asbestos fiber concentrations for area locations during the replacement of gaskets and packing in valves.

Valve size/event[b]	# of events	Asbestos fiber concentrations (f/cc)																		
		PCM							TEM							PCME				
		n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	Avg	SD	MIN	MAX
Center																				
Valve size																				
1-in.	2	2	0	0	0.062	0.013	0.053	0.071	2	2	0	0.003	0.000	0.002	0.003	0	–	–	–	–
3-in	5	5	0	0	0.059	0.014	0.039	0.076	5	3	0	0.006	0.007	0.001	0.015	2	0.008	0.001	0.007	0.009
Event[c]																				
4	1	1	0	0	0.039	–	0.039	0.039	1	1	0	0.001	–	0.001	0.001	0	–	–	–	–
6	1	1	0	0	0.065	–	0.065	0.065	1	1	0	0.001	–	0.001	0.001	0	–	–	–	–
7	1	1	0	0	0.071	–	0.071	0.071	1	1	0	0.002	–	0.002	0.002	0	–	–	–	–
8	1	1	0	0	0.053	–	0.053	0.053	1	1	0	0.003	–	0.003	0.003	0	–	–	–	–
9	1	1	0	0	0.064	–	0.064	0.064	1	0	0	0.015	–	0.015	0.015	1	0.007	–	0.007	0.007
10	1	1	0	0	0.076	–	0.076	0.076	1	0	0	0.012	–	0.012	0.012	1	0.009	–	0.009	0.009
11	1	1	0	0	0.051	–	0.051	0.051	1	1	0	0.002	–	0.002	0.002	0	–	–	–	–
Summary – center	**7**	**7**	**0**	**0**	**0.060**	**0.013**	**0.039**	**0.076**	**7**	**5**	**0**	**0.005**	**0.006**	**0.001**	**0.015**	**2**	**0.008**	**0.001**	**0.007**	**0.009**
Bystander																				
Valve size																				
1-in	2	4	0	0	0.046	0.021	0.024	0.064	4	4	0	0.001	0.000	0.001	0.001	0	–	–	–	–
3-in	7	14	0	4	0.050	0.016	0.031	0.077	14	2	0	0.006	0.005	0.001	0.019	8	0.005	0.005	0.002	0.016
Event																				
1	1	2	0	2	–	–	–	–	2	0	0	0.004	0.002	0.003	0.006	–	–	–	–	–
3	1	2	0	2	–	–	–	–	2	0	0	0.004	0.003	0.002	0.006	–	–	–	–	–
4	1	2	0	0	0.036	0.002	0.034	0.037	2	1	0	0.003	0.003	0.001	0.005	1	0.004	–	0.004	0.004
6	1	2	0	0	0.045	0.008	0.039	0.051	2	1	0	0.004	0.004	0.001	0.007	1	0.004	–	0.004	0.004
7	1	2	0	0	0.028	0.006	0.024	0.032	2	2	0	0.001	0.000	0.001	0.001	0	–	–	–	–
8	1	2	0	0	0.064	0.001	0.063	0.064	2	2	0	0.001	0.000	0.001	0.001	0	–	–	–	–
9	1	2	0	0	0.075	0.003	0.073	0.077	2	0	0	0.010	0.012	0.002	0.019	2	0.009	0.010	0.002	0.016
10	1	2	0	0	0.056	0.007	0.051	0.061	2	0	0	0.009	0.001	0.009	0.010	2	0.006	0.001	0.005	0.007
11	1	2	0	0	0.040	0.012	0.031	0.049	2	0	0	0.004	0.003	0.002	0.006	2	0.002	0.001	0.002	0.003
Summary – bystander	**9**	**18**	**0**	**4**	**0.049**	**0.017**	**0.024**	**0.077**	**18**	**6**	**0**	**0.005**	**0.005**	**0.001**	**0.019**	**8**	**0.005**	**0.005**	**0.002**	**0.016**
Remote background																				
Valve size																				
1-in.	2	4	0	0	0.038	0.007	0.032	0.048	4	4	0	0.001	0.000	0.001	0.001	0	–	–	–	–
3-in	7	14	0	4	0.050	0.017	0.026	0.082	14	4	0	0.003	0.003	0.001	0.010	7	0.003	0.002	0.001	0.006
Event																				
1	1	2	0	2	–	–	–	–	2	0	0	0.002	0.000	0.002	0.003	–	–	–	–	–
3	1	2	0	2	–	–	–	–	2	1	0	0.001	0.001	0.001	0.002	–	–	–	–	–
4	1	2	0	0	0.038	0.007	0.032	0.043	2	1	0	0.001	0.000	0.001	0.001	1	0.001	–	0.001	0.001
6	1	2	0	0	0.051	0.014	0.041	0.061	2	1	0	0.003	0.003	0.001	0.005	1	0.004	–	0.004	0.004
7	1	2	0	0	0.033	0.001	0.032	0.033	2	2	0	0.001	0.000	0.001	0.001	0	–	–	–	–
8	1	2	0	0	0.043	0.007	0.038	0.048	2	2	0	0.001	0.000	0.001	0.001	0	–	–	–	–
9	1	2	0	0	0.070	0.017	0.058	0.082	2	0	0	0.007	0.005	0.003	0.010	2	0.005	0.001	0.004	0.006
10	1	2	0	0	0.039	0.019	0.026	0.052	2	0	0	0.005	0.002	0.004	0.006	2	0.003	0.002	0.002	0.004
11	1	2	0	0	0.054	0.017	0.041	0.066	2	1	0	0.002	0.001	0.001	0.002	1	0.001	–	0.001	0.001
Summary – remote background	**9**	**18**	**0**	**4**	**0.047**	**0.016**	**0.026**	**0.082**	**18**	**8**	**0**	**0.003**	**0.002**	**0.001**	**0.010**	**7**	**0.003**	**0.002**	**0.001**	**0.006**

Activity/sample	# of events	Asbestos fiber concentrations (f/cc)																		
		PCM							TEM							PCME				
		n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	Avg	SD	MIN	MAX
Misc activities																				
Cleaning[c]																				
Bystander	1	2	0	0	0.060	0.014	0.050	0.070	2	1	0	0.004	0.002	0.003	0.005	1	0.003	–	0.003	0.003
Remote background	1	2	0	0	0.085	0.036	0.060	0.111	2	2	0	0.002	0.000	0.002	0.002	0	–	–	–	–
Clothes handling																				
Center	1	1	0	0	0.204	–	0.204	0.204	1	0	0	0.010	–	0.010	0.010	1	0.008	–	0.008	0.008
Bystander	1	2	0	0	0.099	0.008	0.093	0.104	2	2	0	0.003	0.000	0.003	0.003	0	–	–	–	–
Remote background	1	2	0	0	0.096	0.003	0.094	0.097	2	2	0	0.003	0.000	0.002	0.003	0	–	–	–	–
Ambient																				
Day 1	–	3	0	0	0.0024	0.0020	0.0004	0.0043	3	3	0	0.0008	0.0003	0.0005	0.0011	0	–	–	–	–
Day 2	–	3	0	0	0.0018	0.0009	0.0008	0.0026	3	3	0	0.0003	0.0001	0.0002	0.0004	0	–	–	–	–
Day 3	–	3	0	0	0.0014	0.0005	0.0010	0.0020	3	3	0	0.0003	0.0001	0.0002	0.0005	0	–	–	–	–
Summary – ambient samples	**–**	**9**	**0**	**0**	**0.0019**	**0.0012**	**0.0004**	**0.0043**	**9**	**9**	**0**	**0.0005**	**0.0003**	**0.0002**	**0.0011**	**0**	**–**	**–**	**–**	**–**

(continued on next page)

Table 4 (*continued*)

Activity/sample	# of events	Asbestos fiber concentrations (f/cc)																		
		PCM							TEM							PCME				
		n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	n(ND)	n(NR)	Avg	SD	MIN	MAX	n	Avg	SD	MIN	MAX
Background	–	6	0	0	0.0159	0.0032	0.0113	0.0198	6	5	0	0.0010	0.0005	0.0006	0.0016	1	0.0004	–	0.0004	0.0004
Clearance	–	18	0	2	0.0174	0.0056	0.0088	0.0268	18	18	0	0.0016	0.0001	0.0014	0.0018	0	–	–	–	–

PCM, phase contrast microscopy; TEM, transmission electron microscopy; PCME, PCM concentration multiplied by the ratio of asbestos fibers to total fibers measured by TEM; *n*, number of samples; *n*(ND), number of samples in which asbestos was not detected, *n*(NR), number of samples not readable; Avg, average, SD, standard deviation, – not applicable

[a]Area samples ranged from 17 to 91 min in length.

[*] Based on samples in which asbestos fibers were detected by TEM.

[b] Event 5 was excluded since no asbestos was found in the pieces of packing material removed and the stem and bonnet of the valve were frozen; Events 2 (cleaning) and 12 (clothes handling) are presented separately.

[c] Center samples were collected beginning with Event 4. Thus, no center sample was collected for Events 1–3, including cleaning (Event 2).

Table 5
Fiber size and Morphology of the Airborne Asbestos Fibers in the Worker's Breathing Zone.

Fiber structure classification	n	Percent of total fibers (%)	Percent of total fibers (%) classified as respirable with dimensions of:					
			Respirable fiber				Respirable particle	
			<0.7 μm width		⩽3 μm width		< 10 μm width	
			5–20 μm length	>20 μm length	5–20 μm length	>20 μm length	5–20 μm length	>20 μm length
Total fibers	196	–	–	–	–	–	–	–
Free fiber/bundle	115	59	29	6	43	12	–	–
Fiber clusters	22	11	0	0	0	0	2	0
Matrix disperse	58	30	0	0	3	0	15	4

Cheng and McDermott (1991); and ranking category three included Liukonen et al. (1978), Spencer (1998 – involving removal and installation of gaskets and packing material), and the simulation study dataset. An additional comparison indicated that there were some significant differences within the Longo data, with the first test results being significantly different than the second and third test results (average airborne asbestos concentrations were 3.89, 16.2, and 22.4 f/cc, respectively); the second and third test results were not found to differ significantly from each other. Combining the three Longo test results into a single group resulted in several slight changes to p-values but did not change the overall significance of any pairwise comparisons; therefore, the three data sets underlying Longo et al. (2002) were kept as separate groups in this analysis (Longo et al., 2002). The average airborne asbestos concentrations for ranking category one, which included the Longo studies, was 12.4 f/cc (range 1.6–29.8 f/cc) and was 44 times higher than ranking category two (average 0.28 f/cc, range 0.019–1.4 f/cc) and 62 times higher than ranking category three (average 0.20 f/cc, range 0.005–5 f/cc).

Comparisons using TEM data yielded similar results, although the number of studies with TEM data was considerably less. The studies <60 min were grouped into three ranking categories from highest to lowest asbestos air concentrations: ranking category one included the three datasets in Longo et al. (2002); ranking category two included Millette and Mount (1993) and McKinnery and Moore (1992); and ranking category three included our simulation study. An additional comparison revealed that there were some significant differences within the Longo TEM data, with the first test being significantly less than the third (average airborne asbestos concentrations were 82 and 1169 f/cc, respectively; $p = 0.011$); the second (average airborne asbestos concentration of 470 f/cc) and third tests were not found to differ significantly. Average airborne asbestos concentrations for the remaining studies with TEM data were considerably lower in the ranking category two group (2.5 and 6.4 f/cc for Millette and Mount (1993) and McKinnery and Moore (1992), respectively) and in ranking category three (0.022 f/cc for our simulation study).

For the ⩾60 min samples using PCM, there were also differences in mean asbestos concentrations among the individual studies ($p < 0.0001$). Similar to the <60 min sample duration datasets, the studies with the ⩾60 min sample data can be divided into three ranking groups based on significant differences in their average asbestos concentrations. The first ranking group was comprised of the simulation study results, two of the underlying reports of the Mangold publication, and Spence and Rocchi (1996); among these studies, the average asbestos concentrations ranged from 0.027 to 0.058 f/cc (Mangold, 1982b, 1983; Spence and Rocchi, 1996). The second group included Boelter et al. (2002) and Liukonen et al. (1978), with average concentrations of 0.019 and 0.041 f/cc, respectively (Boelter et al., 2002; Liukonen et al., 1978). The third group was comprised of Cheng and McDermott (1991), ten of the Mangold reports, and the two Spen-

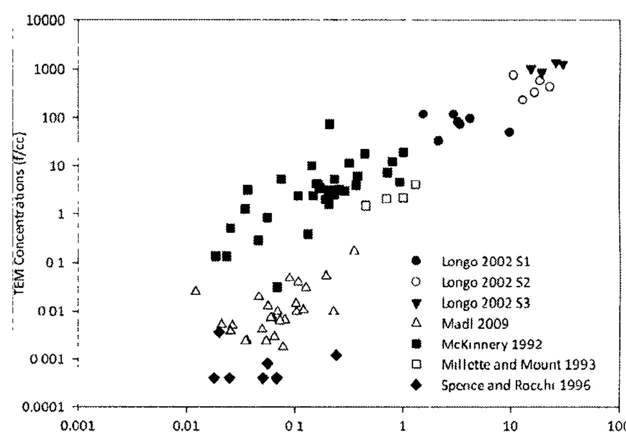

Fig. 2. Comparison across studies of the airborne fiber concentrations by phase contrast microscopy (PCM) in fibers per cubic centimeter (f/cc) and by transmission electron microscopy (TEM) in f/cc.

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cer reports, with average airborne asbestos concentrations ranging from 0.0042 to 0.0092 f/cc (Cheng and McDermott, 1991; Mangold, 1982a; Mangold, 1989a,b,c,d,e,f,g,h; Mangold and Gay, 1991; Spencer, 1998a,b). As with the short-term sample data, mean asbestos concentration of each ranking group was significantly different from one another, but mean asbestos concentrations of the studies within each ranking group did not differ significantly. Only two studies had TEM results in the ⩾60 min category, our simulation study (mean 0.01 f/cc, $n = 7$) and Spence and Rocchi (1996) (mean 0.001 f/cc; $n = 7$); the simulation study was significantly greater than Spence and Rocchi (1996) using a Student t test with $p = 0.0005$.

3.2.2. Comparison of PCM and TEM results by study

A comparison of the results from gasket and packing studies that report both PCM and TEM data generally show that as PCM concentration increases, TEM concentration also increases (Fig. 2). Differences, however, were noted among the individual studies in the magnitude of increase of TEM concentrations compared with PCM concentrations. Spence and Rocchi (1996) and our simulation study show average TEM/PCM ratios of less than one [average ratio 0.04 (range 0.005–0.19) and average ratio 0.25 (range 0.02–2.11)), respectively] (Spence and Rocchi, 1996), while Millette and Mount (1993) demonstrated an average ratio of 2.9 (range 2.2–3.3) (Millette and Mount, 1993). The ratios reported by Longo et al. (2002) and McKinnery and Moore (1992) were markedly higher [average ratio 37 (range 5.2–77) and average ratio 31 (range 0.5–354), respectively] (Longo et al., 2002; McKinnery and Moore, 1992).

3.2.3. Evaluation of equipment

A total of 165 PCM samples (<60 min sample duration) were available in ten equipment categories (flange; pump; valve and flange; valve – pertaining to the handling of packing, gaskets, or both packing and gaskets; ventilation duct heater; boiler header; and not specified – pertaining to the handling of gaskets or packing). Results are presented in Fig. 3 and show concentrations measured during the use of gaskets and packing associated with

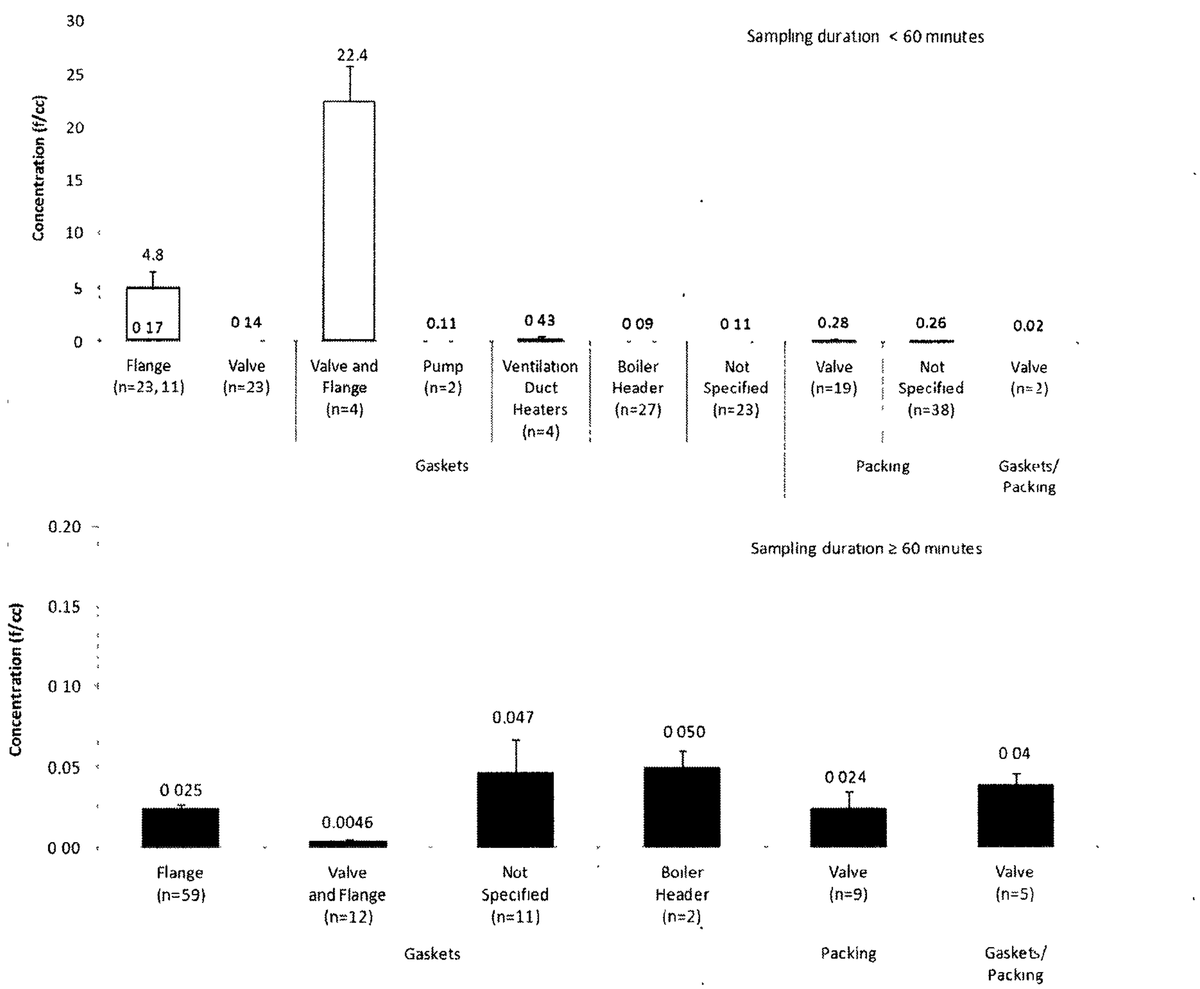

Fig. 3. Airborne asbestos concentrations during work with gasket and packing materials by equipment type. *Legend:* average airborne fiber concentrations (f/cc) by phase contrast microscopy during personal gasket and packing tasks performed on the indicated equipment for sampling durations less than 60 min or greater than or equal to 60 min. The flange category (<60 min) was the only category that contained data from the Longo 2002 study as well as from other studies. Thus, for the <60 min flange category, the data was analyzed including (white) and excluding (black bar) the Longo data. Sample numbers (n) including and excluding data from Longo 2002, respectively, are provided for the flange category. The <60 min "valve and flange" category only contained data from Longo 2002 (white bar). Pair-wise statistical comparisons were performed to identify significant differences ($p < 0.05$). No comparisons were performed in categories with <3 samples. Statistical significance for samples <60 min in duration is as follows: gasket work on "valves and flanges" is significantly greater than gasket work on all other equipment (includes Longo 2002 data; $p \leqslant 0.0007$); flange gasket work is significantly greater than gasket work on boiler headers, valves, or when the specific equipment was unspecified and packing work on unspecified equipment ($p \leqslant 0.008$). when data from Longo 2002 is excluded, packing work on valves and not specified equipment and gasket work on ventilation duct heaters is significantly greater than flange gasket work ($p < 0.02$). Results for samples ⩾60 min is as follows: gasket work on flanges, gasket work on unspecified equipment, packing work on valves and combined packing and gasket work on valves are significantly greater than gasket work on "valves and flanges" ($p \leqslant 0.007$). No data were available for samples ⩾60 min in duration for gasket work associated with pumps, ventilation duct heaters, or valves. Error bars represent standard error.

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the various types of equipment. For gasket and packing samples <60 min in duration, many of the samples in the two categories with the highest asbestos concentrations were from the Longo simulation tests, which were previously shown to differ from the rest of the published studies by a factor of 5–100. Specifically, "valve and flange" gasket samples had a significantly higher average concentration than all other categories ($p \leqslant 0.0007$). The samples in the "valve and flange" gasket category were all derived from the Longo et al. (2002) study and were collected over a 10-min period during gasket removal with a power wire brush (Longo et al., 2002). Average concentrations during "flange" gasket work, the second highest category, were significantly higher than the average concentrations for gasket work on boiler headers, valves, and unknown equipment as well as packing work on unknown equipment ($p \leqslant 0.0008$). While the majority of the samples in the "flange" group involved gasket removal using handheld tools, there were also a few samples collected during gasket installation, as well as one sample collected during gasket removal with a power sander. With the Longo data excluded, the "valve and flange" category was removed, as there were no other data representing work with combined types of equipment. In addition, the flange category had a much lower average airborne asbestos concentration (0.17 f/cc compared to 4.8 f/cc) once the Longo data had been excluded (Fig. 3). Two categories, including gasket work on pumps and combined gasket and packing work on valves, had inadequate sample size for statistical comparison.

TEM data were available for comparisons by equipment type for seven of the ten equipment categories evaluated for PCM data for sample durations <60 min and $\geqslant$60 min (flange; valve and flange; valve – pertaining to the handling of packing, gaskets, or both packing and gaskets; and not specified – pertaining to the handling of gaskets or packing). Results from pairwise comparisons for sampling durations <60 min indicated similar trends as were observed in the PCM data, with "valves and flange" and "flange" categories, consisting of data only from the Longo et al. (2002) study, having significantly greater average airborne asbestos concentrations than the other equipment categories ($p \leqslant 0.0001$; all comparisons), but not from each other. In general, the average airborne asbestos concentrations associated with work with equipment as measured by TEM decreased in the following order (including data from Longo et al. (2002)): valves and flanges (gaskets) > flanges (gaskets) > not specified (gaskets) > valves (gaskets) > not specified (packing) > valve (packing) > valve (packing and gasket combined). When data from Longo et al. (2002) was both included and excluded, combined "packing and gasket" work and packing-only work associated with valves was significantly less than gasket work on valves and gasket work when the equipment was not specified ($p \leqslant 0.003$) and packing-only samples when the equipment was not specified ($p \leqslant 0.003$). The samples in which the equipment was not specified were largely from the McKinnery and Moore (1992) study, in which all fibers greater than 0.5 μm in length were counted by TEM (McKinnery and Moore, 1992).

A similar comparison was performed on PCM samples $\geqslant$60 min ($n = 98$), across six equipment categories (flange, valve and flange, valve – pertaining to the handling of packing or combined gaskets and packing, boiler header, and equipment not specified). Although average asbestos concentration for the category of "boiler header" is included in Fig. 3, there were too few samples to include this category in the statistical analysis. Average airborne asbestos concentrations for samples collected $\geqslant$60 min among the gasket, packing, and combined gasket and packing samples were considerably lower compared to <60 min samples. The "valve and flange" equipment category for gasket samples was significantly less than all other categories ($p \leqslant 0.007$), with an average value of 0.0046 f/cc compared to a range of average concentrations of 0.025–0.047 f/cc for the other four categories (Fig. 3). Only two equipment categories existed for the available TEM samples $\geqslant$60 min and, based on pairwise comparison, asbestos concentrations during combined gasket and packing work on valves was higher than gasket work on unknown equipment ($p = 0.0004$).

3.2.4. Evaluation of task

A total of nine tasks were considered in this evaluation (gasket and packing installation, removal and replacement, gasket fabrication, combined gasket and packing work, and clean-up). The combined gasket and packing category only contained two samples which precluded its inclusion in the analysis. For samples <60 min, the average asbestos concentrations measured during gasket removal were greater than average concentrations during all other gasket-related activities, as well as packing installation ($p \leqslant 0.018$; Fig. 4). Sixteen of the 72 shorter-term samples in the gasket removal task category were from the Longo tests. When these samples were excluded, the average airborne asbestos concentration for the removal task decreased to 6% of the original calculated average when the Longo data were included (average excluding Longo 0.17 f/cc, range 0.015–1.4 f/cc; $n = 56$). In addition, average asbestos concentrations during packing removal were greater than gasket installation and gasket replacement, when Longo data were included. Concentrations during packing removal were also greater than during gasket-fabrication, -installation, -replacement, and -removal, and greater than packing installation when the data from Longo were excluded ($p \leqslant 0.016$). Average concentrations across all studies for gasket and packing work <60 min, with the exception of Longo et al. (2002), are well below the current OSHA Excursion Limit of 1 f/cc.

TEM data were available for eight task categories among the <60 min samples (gasket removal, -fabrication, -installation; packing removal, -installation, -replacement; combined gasket and packing work; and clean-up). Less than three samples were available for gasket installation, so this task was not included in the statistical analysis. In general, the average airborne asbestos concentration associated with specific tasks as measured by TEM decreased in the following order: gasket removal > gasket fabrication > packing removal > clean-up > packing installation > combined packing and gasket work > packing replacement. Sixteen of the 25 gasket removal samples originated from the Longo et al. (2002) study. When the Longo data was included, gasket removal tasks had significantly greater average airborne asbestos fiber concentrations than all other activities ($p \leqslant 0.003$). When these samples were removed from the analysis, the tasks of packing removal and gasket fabrication were no longer significantly less than gasket removal ($p \geqslant 1$). Moreover, gasket fabrication tasks were significantly greater than packing installation, packing replacement, and combined packing and gasket tasks (including and excluding Longo data; $p \leqslant 0.047$). In addition, the average asbestos concentration for the task of packing removal was significantly higher than packing installation, packing replacement, and combined packing and gasket tasks (including Longo data; $p \leqslant 0.001$) in addition to clean-up tasks when the Longo data was excluded ($p < 0.028$).

For samples $\geqslant$60 min by PCM ($n = 123$), gasket removal tasks were statistically greater than gasket replacement tasks (average airborne asbestos concentrations was 0.03 f/cc compared to 0.01 f/cc, respectively, $p = 0.0001$) (Fig. 4). Moreover, combined gasket and packing work was also significantly greater than gasket replacement ($p = 0.0085$). Although it had the highest average asbestos concentration, the packing installation category only contained one sample which precluded its inclusion in the analysis. The average airborne fiber concentrations for sampling duration $\geqslant$60 min across all tasks were less than the current OSHA PEL. Similar to the equipment analysis, only two task categories existed for the available TEM samples $\geqslant$60 min and, based on pairwise

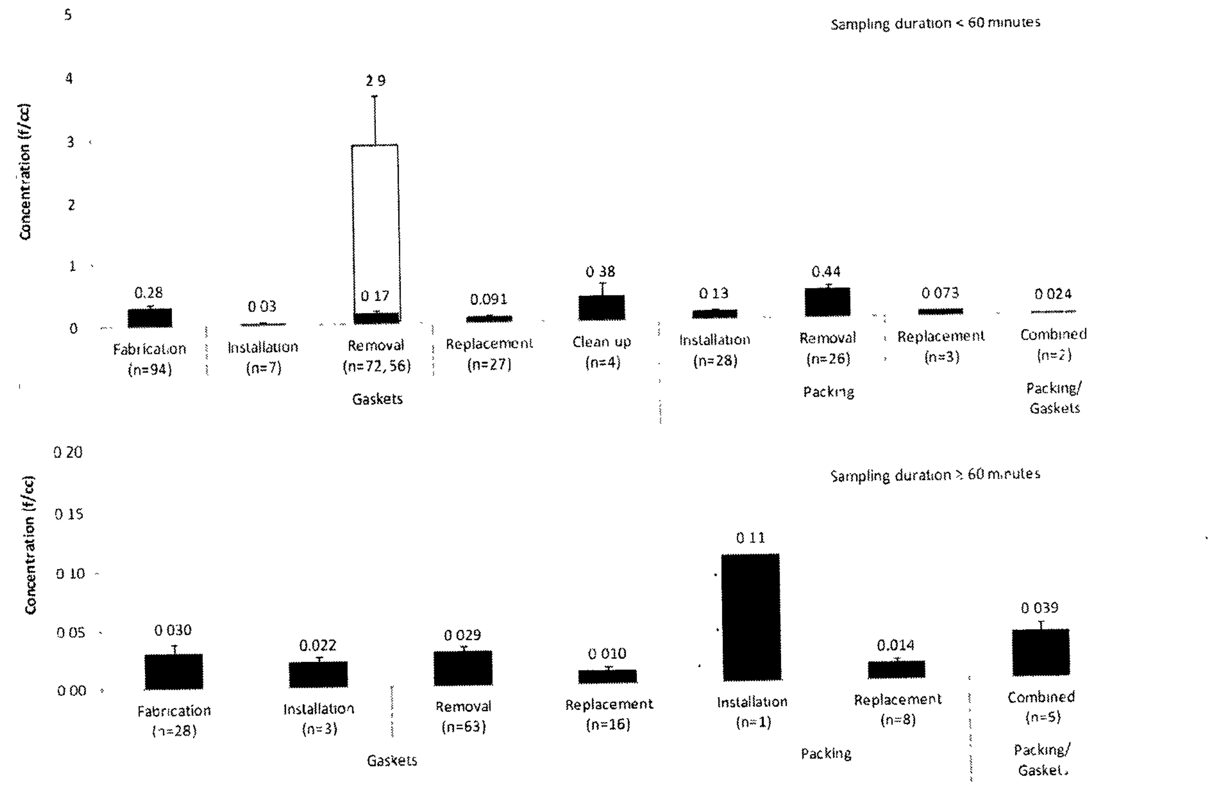

Fig. 4. Airborne asbestos concentrations during work with gasket and packing materials by task. *Legend.* average airborne fiber concentrations (f/cc) by phase contrast microscopy during specific personal tasks associated with gaskets and packing for samples less than 60 min or greater than or equal to 60 min in duration. For the one category that contained data from the Longo 2002 study (gasket removal), the data are plotted including (white bar) and excluding (black bar) the Longo results Sample numbers (n) including and excluding data from Longo 2002 are provided for gasket removal, respectively. 'combined' signifies combined gasket and packing work Pair-wise statistical comparisons were performed to identify significant differences ($p < 0.05$). No comparisons were performed in categories with <3 samples. Statistical significance for samples <60 min is as follows: gasket removal and packing removal is significantly greater than gasket installation and gasket replacement (includes Longo 2002 data, $p \leqslant 0.02$); gasket removal is also significantly greater than gasket fabrication and packing installation ($p \leqslant 0.02$) When data from Longo 2002 is excluded, packing removal tasks are significantly greater than gasket fabrication, -installation, -removal, and -replacement as well as packing installation (excludes Longo 2002 data; $p \leqslant 0.003$), gasket fabrication is significantly greater than gasket installation ($p = 0.03$). Statistical significance for samples ⩾60 min is as follows: gasket removal and combined gasket and packing work are significantly greater than gasket replacement ($p \leqslant 0.009$) No data were available for samples ⩾60 min in duration for cleanup and packing removal tasks Error bars represent standard error.

comparison, asbestos concentrations during combined gasket and packing work was higher than gasket removal ($p = 0.0004$).

3.2.5. Evaluation of tool

A total of 15 tool categories were considered (Fig. 1). As previously mentioned, no significant differences were observed between packing and gasket samples and only a few of the tool groups included samples associated with work on packing material; as such, packing and gasket samples were pooled for the evaluation by tool. Similar to the study categorization, when all sample durations are combined, tools fall into three general groups from highest to lowest airborne asbestos concentrations including the Longo data: group one included power wire brushing and the use of a scraper and hand wire brush; group two included hand punching and shearing, power shearing and the use of miscellaneous hand tools, machine punching, the use of multiple tools including shop, and not specified tools; while group three consisted of all other tool categories. For the ⩾60 min data, no samples were available for hand brush/file and multiple tools including shop although two additional tool categories were added: ball peen hammer and scraper and power wire brush. A total of five tool categories had inadequate sample size ($n < 3$) for inclusion in either the <60 min or ⩾60 min pairwise analysis. For the <60 min sample duration category, average airborne asbestos concentrations for scraper and hand wire brushing (including the Longo data) were significantly greater than all other tool categories, with the exception of power wire brush, which also included data from Longo et al. (2002) ($p \leqslant 0.002$) (Fig. 5). Similarly, power wire brushing (including the Longo data) was significantly greater than all tools, except miscellaneous tools including shop tools and power shears and miscellaneous hand tools ($p \leqslant 0.007$). When the Longo data were excluded from the tool comparison, scraping and hand wire brushing and power wire brushing were no longer greater than any of the other tool categories (Fig. 5). However, average concentrations during work with power shears and miscellaneous hand tools were greater than concentration during machine punching, when data from Longo were included ($p \leqslant 0.031$), as well as scraping, when data from Longo were excluded ($p \leqslant 0.04$). For the ⩾60 min data, there were no significant pairwise differences between the tool categories.

For the TEM results in the <60 min sample duration category, the average airborne asbestos concentrations across the available tool categories, including the Longo data, decreased in the following order: power wire brushing > scraper and hand wire brushing > power shears and miscellaneous hand tools > hand brush/file > tool not specified > circular cutter > replacement using multiple hand-held tools. Four of the seven power wire brush samples and all of the scraper and hand wire brush samples originated from the Longo studies. When the data from Longo et al. (2002) were included, the average airborne asbestos concentrations dur-

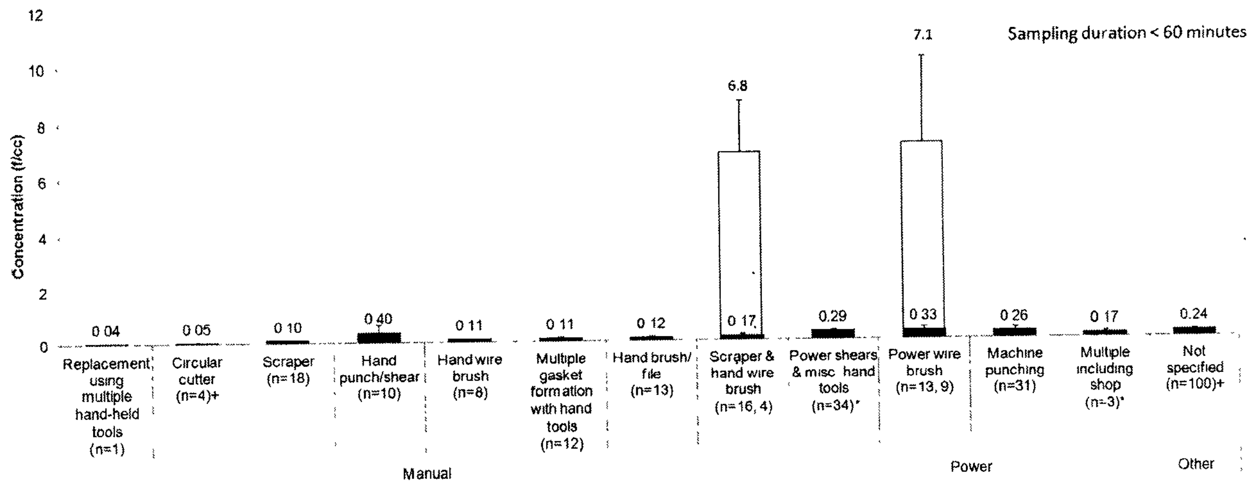

Fig. 5. Airborne asbestos concentrations during work with gasket and packing materials by tool type. *Legend:* average airborne fiber concentrations by phase contrast microscopy during the use of specific manual and power tools associated with gasket and packing removal, fabrication, and installation tasks. Samples were grouped by durations of less than 60 min and greater than or equal to 60 min. For the samples <60 min, the two categories that contain data from Longo 2002 (scraper & hand wire brush and power wire brush) are presented including (white bars) and excluding (black bars) the Longo data. Sample numbers including and excluding data from Longo 2002 are provided for these two categories. Pair-wise statistical comparisons were performed to identify significant differences between the tool categories, both including and excluding data from Longo 2002 ($p < 0.05$). No comparisons were performed in categories with <3 samples. Statistical significance for samples <60 min is as follows: scraper & hand wire brush is significantly greater than all other categories except power wire brush (including Longo 2002 data; $p \leqslant 0.002$); power wire brush is significantly greater than all other categories except scraper & hand wire brush, miscellaneous including shop, and power shears & miscellaneous hand tools (including Longo 2002 data, $p \leqslant 0.007$). Power shears & miscellaneous hand tools is significantly greater than machine punch (including and excluding Longo 2002 data; $p \leqslant 0.003$) and also greater than scraper when data from Longo 2002 is excluded ($p = 0.04$). For the samples $\geqslant$60 min, there were no significant pairwise differences between tool categories ($p < 0.05$). Tool categories for which all or some of the samples were taken in a machine shop setting are noted with an asterisk (*). Samples were predominantly collected during gasket work; however, tool categories for which some of the samples were taken during packing work or combined packing and gasket work are noted with a positive sign (+). Error Q5 bars represent standard error.

ing power wire brushing was significantly greater than all tool categories except scraper and hand wire brushing and hand brush/file ($p \leqslant 0.018$). Similarly, average concentrations during the use of a scraper and hand wire brush were significantly greater than the reported concentrations during the use of all other tools except power wire brushing ($p \leqslant 0.027$). Work with power shears and miscellaneous hand tools as well as hand brush/file resulted in average asbestos concentrations significantly greater than those measured during work with a circular cutter/knife and when no tool was listed ($p = 0.032$). Removal of the Longo data resulted in elimination of the category of scraper and hand wire brush. In addition, average concentrations during power wire brushing were only greater than one category (circular cutter/knife; $p \leqslant 0.028$). Average airborne concentrations during the use of power shearing and miscellaneous hand tools and the use of a hand brush/file were significantly greater than average concentrations during work with a circular cutter/knife and when the specific tool was unspecified ($p \leqslant 0.034$). Three categories were available for comparative analysis among the $\geqslant$60 min data (circular cutter/knife, replacement using multiple hand held tools, and tool not specified), but no significant differences were measured between these categories.

4. Discussion

Results of the simulation study showed that exposures associated with replacement of gasket and packing materials internal valves are consistent with the body of exposure data collected over the last 30 years representing a wide range of variables, including equipment, task, tool, and duration. The creation of a combined dataset not only allowed us to test for consistency between the simulation study and previously published data, but also enabled statistical comparisons across multiple variables. The average airborne asbestos concentrations measured in this simulation study for both a mechanic performing a valve overhaul, as well as a bystander working in the vicinity of such activity, were below both the current and all previous U.S. occupational asbestos standards. This study found that short-term exposures (<30 min) of a mechanic to airborne asbestos during packing and gasket replacement on a valve as measured by PCME were 0.027 f/cc (range: 0.004–0.047 f/cc), whereas 8-h TWA exposure averaged 0.002–0.010 f/cc (based on the assumption that 1–3 gasket or packing replacements could be performed within a workday over the course of a year). Similarly, in the analysis of the combined gasket and packing data by PCM ($\leqslant$30 min), the overall average of all samples was 0.24 f/cc (95th percentile 0.78 f/cc) and only six of 155 samples ($\leqslant$30 min), excluding the Longo data, exceeded the current OSHA excursion limit. It is noteworthy that all six samples exceeding the current Excursion Limit represented activities involving power or machine equipment in an industrial setting, where background fiber sources can confound measurements (Cheng and McDermott, 1991; Liukonen et al., 1978). For longer-term samples ($\geqslant$60 min) in the combined dataset, 95% were below the current OSHA PEL 8-h TWA of 0.1 f/cc (average 0.026 f/cc; 95th percentile 0.087 f/cc; 95% UCL 0.031 f/cc). Airborne asbestos concentrations for six of 127 samples exceeded the current OSHA PEL (ranging from 0.11 to 0.24 f/cc). Similarly noted for the short-term samples, at least four of the six samples ($\geqslant$60 min) were either collected in industrial locations (e.g., shipyard, maritime vessel, plant), where background asbestos concentrations likely confounded results, or in a machine shop setting (Liukonen et al., 1978; Mangold et al., 2006; Spence and Rocchi, 1996). In support of the results from the combined analysis, a recent study conducted by Boelter et al. (2011) gathered over 10 years' worth of asbestos fiber release exposure assessment data, representing more than 700 samples associated with removal and/or replacement of gaskets and packing, and used three methods to estimate the geometric mean and geometric standard deviation of the maximum likelihood estimation (nonparametric, Kaplan–

Meier, and lognormal statistics). Boelter et al. concluded that "all three sets of statistics suggest that the mean and median exposures were less than 25% of 0.1 f/cc 8-h TWA sample or 1.0 f/cc 30-min samples" (Boelter et al., 2011).

After accounting for sample duration, there were certain datasets that appeared to influence the low and high end of the data distribution, which in turn influenced the statistical significance of certain variables (e.g., equipment, task, tool type). The upper range of the complete worker dataset represented data from the Longo studies, whereas the valve simulation study presented herein reflected data at the low end of the distribution. Statistical comparisons showed that the Longo data was greater than the 99th percentile, which provided compelling evidence that the Longo data was an outlier compared to all other samples in the dataset. Pairwise comparisons demonstrated that exposure data categorized by equipment, task, or tool were no longer statistically significant for categories highly represented by the Longo data once it was excluded. For example, gasket removal activities with sample times <60 min were no longer significantly different from fabrication, installation, or replacement once the Longo data were excluded. A similar outlier analysis was performed on the valve simulation study data at the low end of the data distribution. Excluding the 20 worker samples from the valve simulation study that were <60 min showed minimal impact (~1%) on the 1st and 5th percentiles of the combined dataset and only two of the 20 samples were less than the 25th percentile of the overall dataset, which supported the conclusion that the simulation study data was not an outlier at the low end of the overall data distribution in the same way that the Longo et al. (2002) data were for the upper end of the distribution. Explanation for the Longo dataset being inconsistent or an outlier with other published studies on gaskets and packing has been described by others (Boelter, 2003). In short, the aggressive use of a power wire brush, unrealistic number of gaskets removed within a short time period, low sample volume, fiber density outside the recommended range, work performed by a non-tradesman, fiber size classification outside regulatory guidelines, and high background levels likely contribute to the measurements being outlier to the combined published data.

The fiber and asbestos concentrations measured during work with gaskets and packing associated with various equipment, tasks, and tools were fairly consistent (aside from the studies by Longo et al. (2002)), with pairwise comparisons showing some significant differences between the tasks by material, equipment by material, and between the various tool categories. The use of power tools was associated with higher airborne asbestos concentrations compared to hand tools (<60 min), with the average airborne asbestos concentrations associated with the use of hand tools being all below 0.2 f/cc, with the exception of the use of a hand punch or shear (Longo data excluded). In support of this, Boelter et al. (2011) reported detectable total and asbestos fiber average concentrations of 0.269 f/cc and 0.200 f/cc, respectively, for power tools and 0.060 f/cc for the use of a hand held wire brush (Boelter et al., 2011).

While comparisons of TEM results by task, equipment, and tool show generally similar relative trends with PCM results, inappropriate sample preparation methods and varying fiber counting classification criteria for over half of the TEM results prevent any meaningful comparisons between studies. Our simulation study, as well as studies by Millette and Mount (1993) and Spence and Rocchi (1996) used NIOSH 7402 for TEM analysis; however, Spence and Rocchi (1996) did not provide details of the counting criteria used in their study (Millette and Mount, 1993; Spence and Rocchi, 1996). Per the requirements of NIOSH 7402, all studies with the exception of Longo et al. (2002), presumably utilized the direct preparation of MCE or polycarbonate filters prior to counting. McKinnery and Moore (1992) report using a modified version of the AHERA method, with the modifications including low sample volumes and high loadings such that the number of grid openings counted were reduced from 200 to approximately five (McKinnery and Moore, 1992). The EPA AHERA method specifies that all fibers ⩾0.5 μm in length are counted, while NIOSH classifies fibers ⩾5 μm in length, ⩾0.25 μm in diameter and having at least a 3:1 aspect ratio. TEM results by Longo were based on the indirect sample preparation method, ASTM D5755-95, and included fibers of all widths in addition to those ⩾5 μm in length. It has been demonstrated by other researchers that this indirect method yields higher counts than samples prepared by the direct method, in some reports as high as 1700 times greater than fibers seen using the direct method (Boelter, 2003; CDC (Centers for Disease Control and Prevention), 2008; Chatfield, 2000). The indirect method involves sonication, as well as resuspension of fibers in liquid, which can alter the physical form and ultimately the number of fibers counted. It is also noteworthy that the ASTM method is for settled dust and states "this test method does not describe procedures or techniques required to evaluate the safety or habitability of building with asbestos-containing materials, or compliance with federal, state, or local regulations or statues" (American Society for Testing Materials (ASTM), 1995). Therefore, the TEM results derived from samples prepared by indirect methods or analyzed with alternative counting criteria are not informative in terms of comparison to any occupational exposure limits or instructive for implications of health risk.

In summary, the simulation study results and meta-analysis of the available published exposure data associated with work involving asbestos-containing gaskets and packing material and considering the range of variables (product, equipment, task, tool, duration) that could influence potential exposures have shown that tradesmen performing such work in nearly all plausible scenarios are exposed to airborne asbestos concentrations below historical and current occupational exposure limits for asbestos. Of note, when considering the number of air samples described in the Boelter et al. (2011) study in addition to the data considered in this analysis, over a 1000 industrial hygiene samples of gasket and packing work during varying work practices and workplace conditions have been characterized in the published literature during the last 30 years. This meta-analysis shows that, with few exceptions, airborne asbestos exposures during work with asbestos-containing gaskets and packing fall within a relatively narrow and low range. Summary of the historical exposure data on gasket and packing materials according to different variables (product, equipment, task, tool, and duration) should provide useful information to exposure and health risk assessors in conducting quantitative historical exposure assessments for a variety of industrial settings.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx doi org/10.1016/j.yrtph.2014.04.007.

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