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A STUDY OF PERSONAL AND AREA AIRBORNE ASBESTOS CONCENTRATIONS DURING ASBESTOS ABATEMENT: A STATISTICAL EVALUATION OF FIBRE CONCENTRATION DATA

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Abstract—Data were collected and analysed on airborne concentrations of asbestos generated by abatement of different asbestos-containing materials using various removal practices. Airborne concentrations of asbestos are dramatically variable among the types of asbestos-containing material being abated. Abatement practices evaluated in this study were removal of boiler/pipe insulation in a crawl space, ceiling tile, transite, floor tile/mastic with traditional methods, and mastic removal with a high-efficiency particulate air filter blast track (shot-blast) machine. In general, abatement of boiler and pipe insulation produces the highest airborne fibre levels, while abatement of floor tile and mastic was observed to be the lowest. A comparison of matched personal and area samples was not significantly different, and exhibited a good correlation using regression analysis. After adjusting data for outliers, personal sample fibre concentrations were greater than area sample fibre concentrations. Statistical analysis and sample distribution of airborne asbestos concentrations appear to be best represented in a logarithmic form. Area sample fibre concentrations were shown in this study to have a larger variability than personal measurements. Evaluation of outliers in fibre concentration data and the ability of these values to skew sample populations is presented. The use of personal and area samples in determining exposure, selecting personal protective equipment and its historical relevance as related to future abatement projects is discussed.

INTRODUCTION

Asbestos abatement involves one or more of the response actions (that is removal, encapsulation, enclosure or operations and maintenance/repair) that are defined by the United States Environmental Protection Agency (EPA), and has become a major construction business in the United States. This business developed from regulations that were implemented in the 1980s by federal and state governments to control public exposure from asbestos-containing material (ACM), which has been documented as a carcinogenic agent (Selikoff *et al.*, 1964; Nicholson *et al.*, 1982; Lange *et al.*, 1994b; Lange and Thomulka, 1993; Waage *et al.*, 1993, 1994; Muscat *et al.*, 1995). The primary route of exposure to this agent is through inhalation (Oliver *et al.*, 1991; Dement and Brown, 1993). Thus, worker protection mechanisms have focused on engineering controls, worker practices to minimize airborne concentrations and the use of personal protective equipment (PPE) (for example respirators) to reduce exposure (HEI-AR, 1991; Lange, 1993; Lange *et al.*, 1987) during abatement response actions. Although considerable controversy exists as to the actual hazard posed by low levels of airborne asbestos (Mossman and Gee, 1989), regulatory posed by low levels of airborne asbestos (Mossman and Gee, 1989), regulatory agencies have continued to strengthen the requirements of this industry (Lange *et al.*, 1994b; PADLI, 1995).

The United States Occupational and Safety and Health Administration (OSHA) and EPA require appropriate protection for both public and private employees who are exposed to airborne asbestos at or above the Permissible Exposure Limit (PEL) of 0.1 fibres per cubic centimetre of air (f cm^{-3}) for OSHA and 0.2 f cm^{-3} for EPA over an 8-h time-weighted average (TWA) (EPA, 1987a; OSHA, 1994; Lange *et al.*, 1994b). OSHA also requires appropriate protection for most classes of asbestos workers because there is a risk that airborne levels of asbestos may be exceeded; this requirement can be modified if air monitoring data permit a negative exposure assessment (OSHA, 1994).

Selection of the appropriate PPE is dictated by EPA and OSHA based on exposure levels found on-site during abatement by direct sampling; however, OSHA permits historical data relating to exposures and specific job tasks to act as a guide to proper selection in lieu of direct sampling data for each project (OSHA, 1987, 1994). The occupations relating to floor tile installation and removal have had remarkable success in documenting airborne exposure levels for various work practices and then seeking exemptions from the worker protection rules (Clark, 1992). Roofing contractors are following this lead of tracking historical data from abatement operations and have applied for a similar historical data exemption regarding asphaltic roofing materials (Good, 1992). Unfortunately, most asbestos abatement contractors have not maintained these historical data, and in general, this type of data is not readily available in the literature for specific work practices, although several reports do exist (Sawyer *et al.*, 1985; Brown, 1987; Paik *et al.*, 1983; HEI-AR, 1991; Lange *et al.*, 1993b, 1995a; Sawyer, 1977; Jaffrey *et al.*, 1988; Ganor *et al.*, 1992; Bozzelli and Russell, 1982; McKinnery and Moore, 1992). Proper historical documentation of exposure levels can result in significant cost savings for the asbestos contractor by allowing appropriate but lower (less expensive) levels of PPE and less sampling on a per-project basis.

The use of area samples as an estimate of exposure to airborne abatement has become a common practice in the United States asbestos abatement industry. Although OSHA requires samples for personal exposure determination to be performed from the breathing zone (EPA, 1990; OSHA, 1987, 1994), area samples are often used as a substitute. Area sampling is preferred because of the difficulty of obtaining valid or acceptable personal samples due to various factors, such as tampering with the equipment (Niven *et al.*, 1992), noise, the added weight and bulkiness of the personal pump (Cherrie *et al.*, 1994), and the requirement of disconnecting, changing and calibration of this equipment each time the worker leaves the abatement area. Traditionally, area samples have not been considered to adequately represent the potential exposure to an individual and have been reported to exhibit lower fibre concentrations than personal samples (Sherwood, 1966; Linch *et al.*, 1970; Linch and Pfaff, 1971; Leidel *et al.*, 1977; Sawyer *et al.*, 1985; Niven *et al.*, 1992). A recent study (Corn *et al.*, 1991) comparing area and personal samples did not observe a statistical difference between the sample methods. This lack of statistical difference between personal and area samples for airborne asbestos concentrations raises the issue as to whether area samples can be related to individual (personal) exposure (Breslin *et al.*, 1967; Ellis *et al.*, 1985). However, the use of area samples alone, with no additional exposure data from personal samples, cannot be used according to current regulatory standards (OSHA, 1987, 1994) and previous studies (Sherwood, 1966, 1971; Linch *et al.*, 1970; Linch and Pfaff, 1971; Tebbins, 1973; Leidel *et al.*, 1977; Niven *et al.*, 1992) in the assessment and determination of exposure concentrations for workers (OSHA, 1994). This concept is based on a lack of association between area or static and personal samples, wide variation of air concentrations, unusual incidents and occurrences, and spatial and temporal errors that have been observed for air contaminants in the industrial environment (Sherwood, 1966, 1971; Baretta *et al.*, 1969; Linch *et al.*, 1970; Linch and Pfaff, 1971; Tebbins, 1973; Leidel *et al.*, 1977; Niven *et al.*, 1992).

This paper presents historical air monitoring concentrations from area and personal samples that were collected during different types of asbestos abatement. A relationship between area and personal matched samples and unmatched samples are presented. The data presented should provide contractors with additional information for selecting appropriate personal protective equipment (for example respiratory equipment) (Lange *et al.*, 1995a; Lange, 1993) for different asbestos activities, and the applicability and limitations of evaluating area samples as a 'supplemental' methodology for estimating exposure to asbestos abatement worker populations. Procedures and methods for determination, evaluation and presentation of occupational airborne concentration data, particularly related to asbestos, are also discussed.

MATERIALS AND METHODS

Data obtained from these studies were collected after the project supervisors completed their reports. The investigators had limited involvement in the abatement. Individuals involved (for example laboratory technicians, supervisors or workers) had no prior knowledge that these data were part of the airborne asbestos concentration study. However, the job supervisors were requested to clearly document the project activities and air monitoring. The projects included in this study were selected on the basis of good documentation of sampling. The type of work performed was uniform, not consisting of mixed types of asbestos-containing materials being removed (such as floor tile/mastic and ceiling materials) from the same room at the same time.

Both personal and area samples were collected during various asbestos abatement projects using low flow sample pumps (Lange *et al.*, 1993a). Area samples were collected at least 3 ft off the ground surface (Bozzelli and Russell, 1992). Samples were collected on 25 mm dia. electrically-conductive extension cowl cassettes with a mixed cellulose ester membrane filter and were analysed using the NIOSH 7400 method, phase-contrast microscopy (Sawyer *et al.*, 1985; Paik *et al.*, 1983; Stewart, 1988). All cassettes were in a downward position with collection performed open face (Jaffrey *et al.*, 1988). The sample flow rate (2 l. min^{-1} nominal for both area and personal samples) were established at the beginning and checked at the end of each sample period with a calibrated rotameter (Paik *et al.*, 1983; Sawyer *et al.*, 1985; Crump and Farrar, 1989).

All samples were collected using standard techniques (OSHA, 1987; Sawyer *et al.*, 1985).

Since some sample results were below detection limits, these values were represented in the summary data results for range at their limit of detection (Keith *et al.*, 1983). The minimum detection limit for any sample in this study was 0.005 f cm^{-3}. For descriptive and statistical determinations airborne values were used at the concentration reported (Nehls and Akland, 1973). All samples reported in this study were collected from the work area environment during asbestos abatement activities (removal work area). The match comparison of personal and area samples was limited to boiler/pipe insulation-crawl space removal activities. Comparison of match area and personal samples were obtained from approximately the same general location, period and sample flow volume. Removal samples were collected as described by OSHA (1987) from the worker's breathing zone. Area samples were generally located between the work area location, boiler/pipe insulation being removed and the negative air machine (NAM) used to draw air. During the pipe/boiler abatement project, more area samples were obtained than personal samples. Thus, some area samples were obtained that had no personal match due no personal samples obtained or its corresponding match was too heavily loaded and could not be analysed (Chesson *et al.*, 1990). All sample locations were collected by the site supervisor or technician with limited direction from the authors, minimizing sample selection bias.

Air samples collected during ceiling tile abatement consisted of both personal and area samplers. Area samplers were located inside the mini-containment. These samples were not collected as matches, thus are not directly comparable.

Field and laboratory blanks were utilized to determine background concentration and to function as a control. Fibre concentration is reported per cm^{-3} of air (Sawyer, 1977; Lange *et al.*, 1993b).

Types of inside removal work from which air samples were obtained are boiler/pipe insulation in a crawl space, floor tile/mastic (traditional), ceiling tile and mastic removal with a high-efficiency particulate air (HEPA) black track (shot-blast) machine (Whellabrator Corporation, Newman, Georgia, U.S.A.) (HEI-AR, 1991; Lange *et al.*, 1995a). A set of samples was obtained from outside abatement work, during transite removal. Asbestos removal was performed using standard abatement practices, such as wet methods (EPA, 1990, 1994). Mastic removal was performed using either solvent techniques or with a HEPA blast track machine.

Containments for the work area inside buildings (pipe/boiler, floor tile and mastic) consisted of critical barriers on the windows, ventilation system intakes and exhausts, electric plugs, light switches, light fixtures and related items (Sawyer, 1977; EPA, 1990). The door's entrance was sealed with plastic flaps. If more than one door was present, the others were completely sealed. For boiler and pipe insulation removal, NAMs were placed near the door entrance/exit with the exhaust removed from the work area to the outside by a flex duct through the door opening (EPA, 1990). This allowed air to be drawn through the boiler/pipe area-crawl space. Asbestos-containing material existed on both the boiler and associated boiler pipe insulation, and the pipe insulation inside the crawl space. During floor tile/mastic removal the NAM was placed near the centre of the room, moving this device periodically as removal was performed, with its air exhaust being discharged out through the door by a flex duct into the hall. All NAMs used for boiler/pipe and floor tile/mastic removal had a manufacturer's exhaust rating of 2000 ft^3 min^{-1} (cfm). This resulted in a directional air flow in the containment, especially in the boiler/pipe-crawl space. In floor tile containments, the only direct source of make-up air was through the door flap, thus, most likely resulting in some degree of air mixing.

During mastic removal with blast tract machines, NAMs were located in the hall. This allowed air to be exhausted and circulated by NAMs without these devices interfering or having to be moved during the abatement activities (Sawyer, 1977; EPA, 1990). In locations where floor tile/mastic was removed by traditional methods, the mastic was removed at approximately the same time, except for rooms that had the mastic removed by blast tracking.

Exterior transite removal employed wind breaks. These were constructed from 6 mm plastic sheeting and wood frames.

Mini-containments were constructed out of wood frames and plastic sheeting for ceiling tile abatement. This containment was approximately 5 ft wide by 5 ft long by 8 ft high, and was on rollers for easy movement. NAMs used in this application were rated at 500 cfm.

Approximate quantities of ACM removed were boiler/pipe insulation 2000 ft^2 (boiler) and 2500 linear ft (pipe), floor tile 35 000 ft^2, mastic (traditional method) 20 000 ft^2, blast track (shot-blast) 15 000 ft^2, transite 20 000 ft^2 and ceiling tile 20 000 ft^2. The predominant type of asbestos in each material was chrysotile, with approximate percentages for boiler/pipe insulation, floor tile, mastic, transite and ceiling tile being 35, 3, 3, 30 and 25%, respectively.

A one-tailed z-test (Daniel, 1991; Timko and Downie, 1992), using arithmetic values (Sawyer *et al.*, 1985; Daniel, 1991; EPA, 1990), and correlation using logarithmic values (Niven *et al.*, 1992), were calculated for various sample comparisons, including area and personal samples that were matched. Air samples were converted to their log form (base 10) (Keyes *et al.*, 1991) for determining the correlation coefficients (Paik *et al.*, 1983; HEI-AR, 1991; Niven *et al.*, 1992; Iles and Shenton-Taylor, 1986). Statistical tests were performed using a statistical computer program (Timko and Downie, 1992). Airborne asbestos fibre concentrations were reported as both an arithmetic mean (Sawyer *et al.*, 1985; Keyes *et al.*, 1991) and a geometric mean (GM) (Paik *et al.*, 1983; Keyes *et al.*, 1991; McKinnery and Moore, 1992; Reist, 1993) and their corresponding standard deviation (SD) (Sawyer *et al.*, 1985; EPA, 1990; Keyes *et al.*, 1991) and geometric standard deviation (GSD) (McKinnery and Moore, 1992; Paik *et al.*, 1983; Leidel *et al.*, 1977), respectively. Descriptive statistics were calculated for all types of air samples obtained during abatement (Lange *et al.*, 1993b; Timko and Downie, 1992).

Confidence intervals (CI), at 95%, were calculated for personal and area match samples using a technique for non-normal populations (Daniel, 1991). Standard deviation was determined using a HP 325II Hewlett-Packard calculator (Hewlett-Packard, Corvellis, Oregon, U.S.A.). Outlier data were determined in boiler/pipe insulation samples using a technique for log-normal distributions (Gilbert, 1987). Mathematical determination of asbestos airborne fibre distribution data was performed using the Shapiro–Wilk W-test (Shapiro and Wilk, 1965; Gilbert, 1987). Airborne fibre concentration data were tested for normality and nonnormality (logarithmic). Transformation using common logarithms was used for evaluation of a non-normal distribution (EPA, 1992; Keyes *et al.*, 1991).

RESULTS AND DISCUSSION

Abatement procedures that were evaluated included boiler/pipe insulation, floor tile/mastic, transite and ceiling tile removal. Mastic removal was evaluated using traditional solvent removal methods and blast track (shot-blaster) methodology (Lange *et al.*, 1995a). Table 1 presents the descriptive characteristics of the work practices studied (types of abatement) and airborne fibre results (Sawyer *et al.*, 1985; HEI-AR, 1991).

Previous studies of dust (Breslin *et al.*, 1967; Leidel *et al.*, 1977; Niven *et al.*, 1992; Teschke *et al.*, 1994) and asbestos (Paik *et al.*, 1983; Perkins *et al.*, 1990; Keyes *et al.*, 1991) have suggested that airborne concentrations are log-normally distributed. The frequency distribution data of fibre concentrations observed in this study, for 1, 2 and 3 SDs (standard deviations) and its representation as a straight line when plotted on log-normal probability paper supports the previous study (Paik *et al.*, 1983) that airborne asbestos concentrations are not normally distributed (Table 1). In all types of abatement investigated for this study, no sample distribution is approximately normal for 1 SD (68.27%), although at 2 and 3 SDs (2 SD=95.44%; 3 SD=99.75%) a more normalized distribution is observed. Analysis of samples for total area, personal and match area with personal data using the *W*-test found a significant difference for normal and no significant difference for transformed distributed fibre concentrations at the 1% level ($P = 0.01$). This mathematical analysis for characteristics of the distribution support the linear analysis of these data being non-normally distributed (EPA, 1992; Gilbert, 1987). Thus, summary data on asbestos concentrations should be presented in the form of its GM and GSD (Paik *et al.*, 1983) as well as normal distribution descriptors (Keyes *et al.*, 1991).

A small number of values (less than 3%) were below the limit of detection described in this study. Since only a few values were below detection and in this study these values were generally categorized as outliers. Regardless of treatment of these values as outliers, trimmed censored or winsorized data, calculations will approximate determinations without these values, especially when the sample population is large (Gilbert, 1987). Therefore, outliers associated with these data (transformed and nontransformed) will not have an appreciable outcome on the final cumulative descriptors (arithmetic mean, geometric mean, median, standard deviation and geometric standard deviation) (Sokal and Rohlf, 1995; EPA, 1992; Gilliom and Helsel, 1986) beyond that reported and discussed for outliers in this study. The small magnitude of outcome after winsorization can be seen in this study's standard deviations, arithmetic and geometric means, and geometric standard deviations of data before and after removal of outliers for pipe/boiler insulation, although the geometric standard deviation for personal airborne asbestos samples does appear to exhibit a large descriptive difference.

Unfortunately most studies of airborne asbestos concentrations have reported asbestos air sample data by the arithmetic mean and its standard deviation only (Sawyer *et al.*, 1985; Sawyer, 1977). Re-analysis of Sawyer *et al.* (1985) fibre count

Table 1. Descriptive data on the results of fibre counts (f cm^{-3}) during various types of asbestos abatement (removal)

Type of abatement	Type	*N*	Mean*	GM†	Range‡	Sample distribution
Pipe/boiler in a crawl space	Area	102	0.202	0.149	0.005–1.542	1 SD—89% 2 SD—95% 3 SD—97% GSD—2.33
Pipe/boiler in a crawl space§	Area	42	0.192 (0.197)‖	0.097 (0.108)‖	0.005–0.998	1 SD—83% 2 SD—95% 3 SD—98% GSD—3.17
Pipe/boiler in a crawl space§	Pers	42	0.187 (0.206)‖	0.089 (0.133)‖	0.005–0.957	1 SD—86% 2 SD—95% 3 SD—98% GSD—2.75
Ceiling tile removal in a mini-containment	Area	11	0.043	0.019	0.005–0.331	1 SD—91% 2 SD—91% 3 SD—100% GSD—2.09
Ceiling tile removal in a mini-containment	Pers	9	0.022	0.007	0.005–0.154	1 SD—89% 2 SD—89% 3 SD—100% GSD—3.38
Transite removal	Pers	41	0.077	0.048	0.005–0.278	1 SD—89% 2 SD—95% 3 SD—97% GSD—3.50
Floor tile removal by traditional methods¶	Area	14	0.005	0.005	0.005–0.010	1 SD—89% 2 SD—89% 3 SD—100% GSD—NC
Mastic removal by blast track	Area	4	0.005	0.005	0.005–0.005	1 SD—89% 2 SD—89% 3 SD—100% GSD—NC

*Arithmetic mean.
†Geometric mean.
‡Arithmetic range. Some reported values were below 0.005 f cm^{-3}.
§Area samples were matched to personal samples, as discussed in the text.
‖Summary fibre concentrations (f cm^{-3}) after outlier data have been excluded. Standard deviations for personal and area samples were 0.199 and 0.232 f cm^{-3} for these summary data, respectively.
¶Activity included floor tile and mastic removal, usually in the same room at the same time. Mastic removal was performed by solvent methods.
GSD—geometric standard deviation.
Pers—personal samples.
SD—standard deviation.
NC—not calculated owing to the low concentration and its frequency range.
N—number of samples.

frequency data, when plotted on log-normal paper (log distribution of asbestos fibre concentration—f cm^{-3} vs per cent less than stated concentration) (Paik *et al.*, 1983; Niven *et al.*, 1992), a reasonable straight line can be drawn. Although the investigation by Sawyer (1985) used arithmetic values to represent their data, it does appear to fit a log-normal distribution better than a normal distribution as has been reported in this study. Evaluation of Sawyer's (1985) data using the Shapiro–Wilk *W*-test found a significant difference for normal and no significant difference for transformed distributed fibre concentrations at the 1% level ($P=0.01$). This mathematical analysis for characteristic of the distribution support the linear analysis of these data being non-normally distributed (EPA, 1992; Gilbert, 1987). Thus, summary data on asbestos concentrations should be presented in the form of its GM and GSD (Paik *et al.*, 1983) as well as common distribution descriptors, arithmetic and SD (Keyes *et al.*, 1991).

The arithmetic mean may serve as a better summary value for occupational epidemiological studies evaluating individual cumulative exposure (Seixas *et al.*, 1988; Armstrong, 1992). This is based on the linear relationship that is often hypothesized between culmulative exposure and resultant occurrence especially for chronic diseases and those having long latency periods as is associated with asbestos (Seixas *et al.*, 1988). Applicability of the arithmetic mean according to Seixas *et al.* (1988) is based on a reduction of bias from 'Berkson type grouping' and 'from errors in measurement of the exposure variable'. However, if a non-linear relation exists between the exposure and the resultant occurrence, a geometric mean exposure may be less biased, although an arithmetic mean exposure may also have an unbiased measure for a group outcome (Seixas *et al.*, 1985). Selection of the mean for exposure measurements is dependent on the type of model a disease best fits. Therefore, in attempting to better relate data from different studies, and provide the largest degree of information for occupational epidemiologists, both the geometric and arithmetic means are presented in this study.

Fibre concentrations for the various types of abatement methods are comparable to similar reported studies of asbestos roof (transite), floor tile/mastic, boiler/pipe insulation, shot-blast of mastic and ceiling tile removal (Brown, 1987; HEI-AR, 1991; Bozzelli and Russell, 1982; Lange *et al.*, 1995b). Arithmetic and geometric means for airborne concentrations of pipe/boiler insulation removal are above the current OSHA PEL numerical value (Lange, 1993; Lange *et al.*, 1994b; OSHA, 1994). Although the concentrations reported in this study are not time-weighted averages, and are not, in some cases, directly comparable, the elevated concentrations reported for mean values and their range provide some guidance on the potential of exposure and appropriate level of PPE (EPA, 1990).

These data suggest that removal of pipe/boiler asbestos insulation results in the highest fibre counts on both personal and area samples. However, this difference is only descriptive. The CI, arithmetically, for matched area and personal samples were ± 0.179 and ± 0.152 f cm^{-3}, respectively. This overlap between the two sample measurements suggest that the fibre concentrations observed are similar. A similar finding can be seen in ceiling tile area and personal samples, which had a CI of ± 0.058 and ± 0.032 f cm^{-3}, respectively. Standard deviation for pipe/boiler insulation matched area and personal, and ceiling tile area and personal match samples were 0.231 and 0.197, and 0.097 and 0.049, respectively. These data, along with the large GSD for boiler/pipe match area samples, suggest that area fibre concentrations are more variable than personal fibre concentrations in this study. Previous reports (Sherwood, 1971; Leidel *et al.*, 1977) have also suggested that area samples exhibit a wider variation than personal samples. Caution must be exercised when interpreting these data for ceiling tile removal due to the small number of samples.

Boiler/pipe insulation, in general, is more likely to become friable during its abatement than floor tile/mastic, transite, or suspended ceiling tile abatement, based on the data in this study and previous investigations (HEI-AR, 1991; Jaffrey *et al.*, 1988; Bozzelli and Russell, 1982). The general condition of each material must be independently considered when evaluating its potential for friability (Lange *et al.*, 1993b, 1995a,b). In this study, all the materials being abated were generally in good condition by visual inspection (EPA, 1987b, 1988).

It is surprising that some fibre concentrations during transite removal were numerically greater than the OSHA asbestos PEL (Lange, 1993; Lange *et al.*, 1994b; OSHA 1994). The methodology used in this investigation (PCM) to analyse fibre concentrations 'counts all fibres', provides a qualitative indication of exposure and is the measurement recognized by OSHA (OSHA, 1987; Stewart, 1988). Since transite removal is usually associated with a building's exterior environment, these elevated concentrations are a concern for not only the worker, but also the general public and the environment. A previous study by Brown (1987) has reported a similar finding of elevated asbestos fibre levels from outdoor (exterior) abatement. However, the contribution of non-asbestos fibres (for example cellulose fibres) to the observed airborne fibre concentration must be considered when evaluating any data that employ PCM as the measurement technique (Altree-Williams and Preston, 1985; Burdett and Jaffrey, 1986).

Removal of mastic with a shot-blaster or by traditional solvent methods appear to cause little, if any, fibre release. The shot-blaster results are similar to those reported in a previous study of air sampling during its use in removal (Lange *et al.*, 1995b). These results would be expected, since the shot-blast machine employs a HEPA-filtered vacuum system (OSHA, 1987).

The numerical fibre levels observed for the various asbestos abatement methods in this study suggest that personal protective equipment, including respirators, is appropriate (Lange, 1992, 1993), at least during some phases or types of work. However, caution must be applied since implementation of engineering controls can have a dramatic influence on the actual airborne fibre concentration and these data are not represented as TWA values. Air sample concentration ranges show a wide variation for most abatement practices performed. Three samples in the pipe/boiler abatement non-match data for area measurements exceeded the numerical protection factor (fibre concentration greater than 1.0 f cm^{-3} TWA) designated by OSHA for a half-mask air purifying respirator (OSHA, 1994). Since the values presented in this study are not TWA, any exceeding must be considered only numerical, with the possibility of no actual violation of the occupational standard actually occurring. Each work practice evaluated, except floor tile/mastic removal and the shot-blast technique, had samples that numerically exceeded the OSHA PEL for asbestos. The elevated fibre levels, mean values and ranges, observed in this and similar investigations (HEI-AR, 1991), which are supported by a previous questionnaire study of asbestos workers reporting their frequency of exposure above the OSHA PEL (Lange, 1993), suggest exposure above regulatory limits may occur. Thus, during some types of abatement practice, minimal respiratory protection (such as half-mask respirator with HEPA cartridges) is an important criteria to consider for reducing individual exposure (Lange, 1993). Combination of these observed exposure levels, and the reported inadequacy of respiratory protection, occupational medical surveillance (Lange, 1993), elevated smoking rates (Lange, 1992) and alcohol use (Lange, and Thomulka, 1993) may carry significant future health risks for this occupational population (HEI-AR, 1991; Lange *et al.*, 1991).

A concern of elevated exposure and inadequacies of personal protective practices (for example respiratory protection, occupational medical surveillance) suggested for asbestos abatement personnel may be extended to other occupational groups (for example maintenance, custodial) that commonly perform asbestos abatement work or 'clean up' of asbestos-containing residue or 'dust' as part of their employment duties. Exposure to airborne asbestos for these groups at concentrations significant to cause disease has been supported by occupational medical surveillance studies (Oliver *et al.*, 1985, 1990, 1991; Bresnitz *et al.*, 1993; Miller and Miller, 1995; Waage *et al.*, 1994), surveys during refresher asbestos abatement training courses that these groups attend (Lange, 1992), surface fibre concentrations reported in building at locations commonly used and cleaned by these occupational 'categories' (Lange *et al.*, 1995a, 1995b), asbestos airborne fibre concentrations reported in buildings after abatement has been completed (Massey and Fournier-Massey, 1987) and asbestos airborne fibre concentrations reported during work activities (for example dry sweeping, maintenance repair) (Sawyer, 1977; Paik *et al.*, 1983; HEI-AR, 1991; Keyes *et al.*, 1991). Unfortunately, many of these occupational groups (such as maintenance, emergency personnel) have not received the regulatory protection afforded personnel categorized as abatement workers (PADLI, 1994; Lange *et al.*, 1994a), although concerns discussed can also be extended to asbestos abatement workers as well. The lack of a clear definition for duties in these various occupational categories (such as custodian) must also be evaluated regarding exposure, since some personnel in these categories may actually be abatement workers, during part of their employment, although are actually never categorized or considered to be abatement workers by their employer (Oliver *et al.*, 1991; HEI-AR, 1991; Huuskonen *et al.*, 1995). Reports suggesting a low risk of disease for asbestos in buildings can be considered, in part, to temper these concerns (Mossman and Gee, 1989). These reasons were all considered by OSHA in instituting the class four asbestos work criteria (OSHA, 1994).

Comparing personal and area samples, area samples consistently exhibited a higher concentration than personal samples, which is opposite of that reported in a previous airborne asbestos study (Sawyer *et al.*, 1985). A higher fibre concentration of personal samples as compared to area samples was also reported for a study on airborne cotton dust (Niven *et al.*, 1992). Personal and area matched samples in this study were not significantly different at the 0.05 level ($P = 0.45$). The reason for area samples descriptively having a high arithmetic and geometric mean, as seen in this study, is unknown; however, the possibility of this occurring by chance must be considered along with other explanations. Since the sample population is large (greater than 30), even though the population variance is unknown, the central limit theorem allows sampling from a non-normally distributed population with the likelihood that the sample population drawn will be relatively normal (EPA, 1992;

Daniel, 1991; Reist, 1993). However, the presence of outliers must be considered in regard to the personal and area samples.

Area sample concentration data (matched to personal) are more widely dispersed based on GSD, SD, range and CI data than personal samples. This wider frequency distribution for area samples, may also, in part, be responsible for the arithmetic and geometric means being descriptively higher, although the CIs and ranges suggest these two populations are similar. It is therefore likely, even though some descriptive differences exist between the personal and area sample concentrations, based on the lack of a statistical difference and similarity of sample distribution parameters, both samples appear to have been drawn from the same population. The lower variation as represented by the GSD for non-matched area samples for abatement of pipe/boiler insulation in a crawl space in comparison to personal samples of the same abatement is intriguing.

This is further supported by evaluating in the boiler/pipe insulation match samples (Rosner, 1983; Gilbert, 1987). In personal samples the two lowest values and in area samples the lowest value were determined to be outliers at the 5% level. This finding is consistent regardless of whether data calculations are performed using the detection limit or the numerical values reported by the laboratory.

When these outlier values are excluded (adjusted data-boiler/pipe) from the arithmetic and geometric mean calculations, the personal sample concentration is larger than the matched area sample concentration (Table 1). This different rank order, as compared to calculations using all the data, is the same as reported in other studies evaluating the relationship between area and personal samples (Sawyer *et al.*, 1985; Niven *et al.*, 1992), although the arithmetic and geometric means are descriptively similar for both adjusted and unadjusted boiler/pipe data. All values that were determined to be outliers are below the detection limit of the analysis technique (PCM) used in this study. These outlier numerical values (f cm^{-3}) were numerically reported as 0.001 and 0.002 for personal and 0.001 for area samples. A similar finding is also observed for ceiling tile abatement samples taken in a mini-containment. However, no clear conclusion can be made with these data owing to the small number of samples collected and the lack of clearly defined matches. Fibre concentrations in both personal and area samples for mini-containment abatement appear to be descriptively similar.

These relationships described show the importance of data evaluation of outliers (Nair, 1948; Dixon, 1953; Rosner, 1975, 1977, 1983; Gilbert, 1987; Kelly *et al.*, 1992). Failure to isolate outliers, using unadjusted concentration results, can lead to a fallacious interpretation of data as seen in the initially observed relationship of personal and area samples. This importance of evaluation and exclusion of outliers is well illustrated in this example of area samples where an initial determination of a larger area mean f cm^{-3} concentration (arithmetic and geometric means) was observed as compared to personal samples before 'adjustment'. It is also important to determine if the population being studied is normally or non-normally distributed (Dixon, 1953; Rosner, 1983; Gilbert, 1987; Kelly *et al.*, 1992). The shape of the distribution will strongly influence the determination and testing to be performed for outliers in a population (Kelly *et al.*, 1992).

Other explanations (Teschke *et al.*, 1994) can be hypothesized to describe the descriptively higher fibre concentrations observed in total sample data, besides adjustment for outliers, for area samples as compared to personal samples in both pipe/boiler and ceiling tile abatement. These include that after wetting the ACM, heavier wet fibre material (and bundles) is carried toward the area sampler by air flow from the negative air machines. Since removal of both pipe/boiler insulation and floor tile do not allow the negative air machines directly beside the worker, usually an air flow from one direction results. Air flow from a make-up air source to the negative air machine at a relatively high rate, a minimum of four room exchanges per hour, is required by the regulatory agencies (such as the U.S. Environmental Protection Agency and the U.S. Occupational Safety and Health Administration) and is a standard practice in the United States (EPA, 1987b; OSHA, 1994). Wet fibres may be drawn towards the negative air machine and outside the personal sample pump area, but still within the area sample pump. These fibres may also dry out during their travel, resulting in re-entrainment into the air, at least to a partial degree, thus causing a higher concentration at the area sample location. Furthermore, as these fibres began to dry out, they may fracture resulting in a numerically larger fibre concentration. Overall, this wetting process would allow fibres to have a greater mass upon release, more rapidly falling away from the workers personal sample location and toward the floor and NAM than dry material. A directional flow may allow re-entrainment of some fibres toward the NAM. Area samplers were generally between the worker and NAM in the boiler/pipe insulation removal, thus possibly explaining, in part, the unadjusted results.

These explanations can only account for part of the fibre concentration differences. During removal of both lagging and floor tile, workers commonly step away from the source to obtain supplies, equipment, related items and breaks. Breaks and different individual work practices (Gressel *et al.*, 1988) must be considered as a major differential factor since this work was performed in the summer and asbestos abatement is considered an extremely 'hot' work activity (EPA, 1990; OSHA, 1994). These materials are usually not stored in the containment area, but at a location away from the actual work. Since the area samplers were continuously located in the work station, the worker departing this vicinity for short periods of time may result in a lower fibre concentration. In addition, if an episodic release occurred, it is the natural reaction for the worker to step away at that moment, thus reducing exposure that may be detected on the personal sampler.

These discussions may also explain, in part, the difference observed for the highest concentrations in area and personal samples for both matched and unmatched comparisons. Data collected for area and personal samples from the pipe/boiler in the crawl space are the only directly comparable samples. In this example, the area samples (both matched and unmatched) have the highest reported fibre concentration compared to the personal samples. This 'potential' outlier data observed for samples will also have an effect on the mean values reported. The GSD and to a lesser extent the difference at 1 SD are supportive of these findings, especially related to variance of distributions for airborne asbestos fibre populations. Information suggested previously for these mean concentration differences and the highest value obtained being for area samples partially explains the difference observed. However, since there is no statistical difference between these two samples (boiler pipe area and personal) and their CIs overlap, it is suggested that these samples are similar and the higher sample value for area measurements is either by chance, work practices employed during this study or outliers at the limit of detection. In fact, if there is no difference for area and personal samples in the asbestos work area(s) as suggested in this study and in other publications (Breslin *et al.*, 1967; Ellis *et al.*, 1985; HEI-AR, 1991; Corn *et al.*, 1991) then the likelihood of one sample set being higher than the other is random. The lower variation for non-matched area samples as compared to personal samples for abatement of pipe/boiler insulation in a crawl space, in part, can be considered supportive of the use of area samples in estimating personal exposure. However, these data and interpretation for such a criterion must be viewed with caution, especially when considering other published results contradicting this 'use' (Sherwood, 1966, 1971; Linch and Pfaff, 1971) and the suggestion that area sample data "grossly misrepresent the exposure of individual workers who are likely to be exposed to airborne activity of their own making" (Sherwood, 1966).

A higher area sample for the ceiling tile removal may be a result of the different sample number and that the samples are not directly comparable. If the highest area sample value, 0.331, is excluded, the arithmetic mean is then 0.014, which is lower than the arithmetic personal sample concentration mean. Area samples while having a higher SD and a lower GSD in comparison to personal samples further suggest a high degree of variability for these data. Examination of the ranges also support this conclusion. A likely contributor to the variability in this study is the small number of samples (Rappaport *et al.*, 1993), although previous investigations of different occupational contaminants (Baretta *et al.*, 1969; Sherwood, 1971; Donaldson and Stringer, 1976; Niven *et al.*, 1992) have reported similar findings of variation in air contaminants associated with the work environment.

Since the concentration of asbestos samples is considered to be log-normal, it is necessary to convert the values into the logarithmic form for correlation analysis (Paik *et al.*, 1983; Niven *et al.*, 1992). Correlation of the two sampling techniques is (r^2) 0.61, suggesting that a good relationship exists (Kelly *et al.*, 1992). In testing the slope of this line, it was found not to be equal to zero ($P<0.005$), suggesting that these techniques have a direct linear relationship (Daniel, 1991). The correlation and nonsignificant difference between personal and area samples observed in this study should allow asbestos contractors, architects, engineers, industrial hygienists and others to use area samples in predicting an estimate of personal exposure. Although this relationship is not exact and has limitations, its good correlation (Kelly *et al.*, 1992) can be used to minimize, after careful evaluation, the number of personal samples required. However, this will not eliminate or substitute completely the personal sampling requirement for compliance with OSHA regulations (Leidel *et al.*, 1977; OSHA, 1987), but allow the use of area samples to function as a predictor of the surrounding airborne asbestos concentration and likely personal exposure (Breslin *et al.*, 1967; Ellis *et al.*, 1985). This may assist employers in developing an effective monitoring program for establishing a negative exposure assessment. However, the variation observed in this study, particularly for area samples, and previous reports contradicting the concept of similar exposure concentrations everywhere in the workplace (Sherwood, 1966, 1971; Linch *et al.*, 1970) must be considered, and in part temper these findings.

Other studies comparing area and personal exposure measurements have suggested little relationship between these two collection techniques thereby limiting the usefulness of area sample data for occupational protection (Sherwood, 1966, 1971; Linch *et al.*, 1970; Linch and Pfaff, 1971; Tebbins, 1973; Niven *et al.*, 1992). Use of area samplers alone will not protect to the fullest extent abatement workers in regard to individual exposure (Leidel *et al.*, 1977). Area samples do, however, provide additional input for evaluating engineering controls and selection of personal protective equipment. Thus, can be used as a 'predictor' for the entire worker population in this industry with appropriate limitations and cautions applied (Breslin *et al.*, 1967; Smith *et al.*, 1980; Ellis *et al.*, 1985). Area and personal samples from different types of abatement were not matched since locations were often unrelated (Niven *et al.*, 1992). None of these comparisons had good correlation, but both were non-significantly different. A previous study of airborne cotton dust suggested that a direct linear relationship exists for area and personal samples when individually analysed for each work area (Niven *et al.*, 1992). This finding, in part, explains the lack of correlation for unmatched samples in this study. Although the cotton dust air sample data (Niven *et al.*, 1992) support an applicable comparison of matched personal and area samples, the authors of this study concluded that these two measurements cannot be directly compared. This discrepancy of interpretation may lie in the fact that the cotton dust study evaluated a different type of airborne fibre and compared general work area samples, whereas this study attempted to compare matched airborne asbestos samples by the same work location and time. The use of selected match samples in this study, although initially blind to the investigators, must be considered as a source of bias when evaluating the correlation and analysis of significant difference. Thus, caution must be considered when evaluating these data.

CONCLUSIONS

This study provides comparable data on different methods that are commonly used in the asbestos abatement industry. Since these data were obtained from asbestos abatement projects that were not specifically designed to evaluate air concentrations or work practices, bias that may be associated with a prior knowledge of the purpose of monitoring, especially in the form of more concise work techniques, has been minimized. Careful examination of data for outliers and their influence on data sets have been shown in this study. In general, the results are similar to previously reported studies. These data also provide a historical basis of exposure level concentrations associated with different asbestos abatement practices which can be used as an estimate of the potential exposure that may be encountered and in the selection of PPE. Airborne asbestos concentrations, as previously reported, appear to be log-normally distributed and should be reported, for comparison purposes, as a GM. Although previous studies have suggested that the arithmetic mean may best represent an average dose, more correctly indicate health risks and provide a less biased summary statistic for occupational epidemiological studies (Roach, 1977; Rappaport *et al.*, 1981; Seixas *et al.*, 1988), the actual concentration values as a logarithmic distribution, support the inclusion of both means, arithmetic and geometric, in published reports of asbestos airborne fibre data. Inclusion of both values will allow evaluation of different exposure models by epidemiologists (Seixas *et al.*, 1988) and historical data grouping by occupational statisticians in a manner selected directly by future investigators as to avoid with the greatest feasibility bias and random errors (Olsen *et al.* 1991).

This study suggests that area and personal sample concentrations have a good correlation and are not significantly different. After adjustment for outliers, personal samples appear to exhibit higher fibre concentrations than area samples. This relationship can be used as a predictor of exposure (Ellis *et al.*, 1985; Smith *et al.*, 1980) to asbestos abatement workers and be used as an additional source of data in selecting PPE and engineering controls. However, matched area samples are suggested to be more variable than personal samples. The use of area samples alone in determining individual exposure must be viewed with caution (Leidel *et al.*, 1977). Additional studies are warranted to better quantify these reported asbestos fibre concentrations and support the relationships observed.

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