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Airborne Concentrations of Asbestos Onboard Maritime Shipping Vessels (1978–1992)

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The exposure of shipyard workers to asbestos has been frequently investigated during the installation, repair or removal of asbestos insulation. The same level of attention, however, has not been directed to asbestos exposure of maritime seamen or sailors. In this paper, we assemble and analyze historical industrial hygiene (IH) data quantifying airborne asbestos concentrations onboard maritime shipping vessels between 1978 and 1992. Air monitoring and bulk sampling data were compiled from 52 IH surveys conducted on 84 different vessels, including oil tankers and cargo vessels, that were docked and/or at sea, but these were not collected during times when there was interaction with asbestos-containing materials (ACMs). One thousand and eighteen area air samples, 20 personal air samples and 24 air samples of unknown origin were analyzed by phase contrast microscopy (PCM); 19 area samples and six samples of unknown origin were analyzed by transmission electron microscopy (TEM) and 13 area air samples were analyzed by scanning electron microscopy (SEM). In addition, 482 bulk samples were collected from suspected ACMs, including insulation, ceiling panels, floor tiles, valve packing and gaskets. Fifty-three percent of all PCM and 4% of all TEM samples were above their respective detection limits. The average airborne concentration for the PCM area samples (n = 1018) was 0.008 fibers per cubic centimeter (f cc^{-1}) (95th percentile of 0.040 f cc^{-1}). Air concentrations in the living and recreational areas of the vessels (e.g. crew quarters, common rooms) averaged 0.004 f cc^{-1} (95th percentile of 0.014 f cc^{-1}), while air concentrations in the engine rooms and machine shops averaged 0.010 f cc^{-1} (95th percentile of 0.068 f cc^{-1}). Airborne asbestos concentrations were also classified by vessel type (cargo, tanker or Great Lakes), transport status (docked or underway on active voyage) and confirmed presence of ACM. Approximately 1.3 and 0% of the 1018 area samples analyzed by PCM exceeded 0.1 and 1 f cc^{-1}, respectively. This data set indicates that historic airborne asbestos concentrations on these maritime shipping vessels, when insulation–handling activities were not actively being performed, were consistently below contemporaneous US occupational standards from 1978 until 1992, and nearly always below the current permissible exposure limit of 0.1 f cc^{-1}.

Keywords: asbestos; industrial hygiene; maritime; occupational exposure; retrospective exposure assessment; seamen

INTRODUCTION

Due to its widespread use in maritime applications, asbestos has warranted study in terms of occupational exposure and the possible connection to respiratory disease in sailors and shipyard workers (Marr, 1964; Nicholson *et al.*, 1971; Sheers and Coles, 1980; Hodgson and Darnton, 2000). From the early 1930s to the mid to late 1970s, naval and commercial shipyards used hundreds of tons of asbestos, primarily in the form of chrysotile and amosite asbestos-containing insulation, to build and repair maritime vessels. War ships, for example, contained roughly

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between 30 and 500 tons of asbestos insulation on pipes and machinery (United States Navy, 1945, 1947; Fleischer *et al.*, 1946; Mangold *et al.*, 1970; C. A. Mangold, personal communication). This mineral was an effective insulator that prevented condensation, reduced the amount of ventilation needed to cool compartment spaces, allowed machinery to operate economically with minimal heat loss and prevented injury to personnel from contact with hot shipboard components (United States Navy, 1939, 1941, 1945, 1947, 1960).

While there are a relatively large number of studies that have assessed airborne asbestos exposure among shipyard workers involved in installing, repairing or removing asbestos insulation, our review of the published literature found no studies that have characterized the exposure of maritime or merchant seamen to airborne asbestos (Balzer and Cooper, 1968; Cooper and Balzer, 1968; Harries, 1968, 1971a,b; Ferris *et al.*, 1971; Bell, 1976). A few studies, however, have reported an increased incidence of asbestos-related disease among this seafaring population (Jones *et al.*, 1984; Selikoff *et al.*, 1990; Varouchakis *et al.*, 1991; Pukkala and Saarni, 1996; Saarni *et al.*, 2002; Rafnsson and Sulem, 2003). It has been postulated that the increased incidence of asbestos-related disease among this population was, in part, due to the release of fibers from asbestos insulation occurring as a result of the natural movement and vibrations of a ship. No published studies, to the authors' knowledge, however, have measured such asbestos exposures to seamen onboard different maritime shipping vessels.

Our primary objective, then, was to analyze the industrial hygiene (IH) data for airborne asbestos concentrations, collected on maritime vessels but not during the direct handling of insulation and other asbestos-containing materials (ACMs). The purpose of this analysis was to characterize the 'background' exposure to asbestos of seamen from 1978 until 1992 and to evaluate whether the mere presence of asbestos on these ships constituted a health hazard. To that end, IH measurements generally associated with normal transport and docking scenarios of cargo vessels, based on 52 IH surveys (encompassing 1100 air and 482 bulk samples collected from the late 1970s through the early 1990s), are presented. Factors such as year sampled, vessel type, compartment and transport status were also considered. The airborne asbestos concentrations measured were compared to contemporaneous and current occupational permissible exposure limits (PELs).

BACKGROUND

Since the 1930s, asbestos insulation products have been used and applied according to naval and maritime commission specifications (Rushworth, 2005). These specifications vary considerably, depending on anticipated temperature ranges for machinery, as well as the temperature ranges and thickness of piping being insulated. The selection of asbestos for specific applications also depended upon other considerations, including water resistance, availability and cost. Although the application processes for insulation products have changed little since the 1930s, their composition has changed over time (United States Navy, 1939, 1941, 1945, 1947, 1960). The majority of asbestos-containing products, such as thermal insulation, gaskets and packing, for example, were beginning to be replaced in the mid to late 1970s with asbestos-free materials exhibiting similar heat-resistant properties.

Studies conducted both in the USA and in Europe during the 1960s and 1970s reported that shipyard workers were exposed to elevated concentrations of airborne asbestos (Harries, 1968; Mangold *et al.*, 1970; Ferris *et al.*, 1971; Nicholson *et al.*, 1971; NIOSH 1972). These studies described the work of shipyard insulators during construction and repair of marine vessels, and reported airborne fiber concentrations ranging from 1.1 to 100 f cc^{-1} for cutting and applying insulation and 2.4 to 132 f cc^{-1} for removing insulation. Short-term peak exposures during some insulating activities have reportedly exceeded 100 f cc^{-1}, usually during more intense activities, such as mixing or spraying (Balzer and Cooper, 1968; Harries, 1968; Mangold *et al.*, 1968, 1970; Harries, 1971a,b; Nicholson *et al.*, 1971; Selikoff and Hammond, 1978; Selikoff *et al.*, 1979a,b; EPA 1986). Installing and removing asbestos insulation was the source of the high concentrations of airborne asbestos found during major ship overhauls or machinery ripouts. To a much lesser degree, there can be exposure during accidental ruptures of pipes, failure of flange systems or pin holes in steam lines, because the insulation can degrade and fall to the floor but because, at that point, it is wet, the airborne concentrations are rarely appreciable.

Studies of merchant seamen have reported increased incidence and mortality rates due to lung cancer, mesothelioma, and other pleural abnormalities especially among deck and engine crew and officers (Jones *et al.*, 1984; Rafnsson *et al.*, 1988; Velonakis *et al.*, 1989; Kelman and Kavaler, 1990; Selikoff *et al.*, 1990; Greenberg, 1991; Rapiti *et al.*, 1992; Brandt *et al.*, 1994; Rafnsson and Gunnarsdottir, 1995; Pukkala and Saarni, 1996; Saarni *et al.*, 2002; Karlev *et al.*, 2005). Many of these studies suggest that such high cancer rates were possibly due to previous asbestos exposure and/or constant exposure to low levels of airborne asbestos fibers from damaged or deteriorated asbestos-containing insulation released due to the natural vibrations of the ship or from insulation repairs conducted during travel at sea, including ruptures, failures or blowouts on steam

piping. These assumptions, however, have not been quantitatively evaluated (Greenberg, 1991).

Although it is clear that absent proper engineering controls asbestos exposure while installing and repairing asbestos-containing insulation can be significant, one would expect that the concentration of airborne asbestos fibers released from undisturbed insulation would be very small; however, information on these exposures has not heretofore been available. Based on the dozens of studies of school buildings which took place in the USA in the 1970s and 1980s, it was determined that airborne concentrations of asbestos from undisturbed insulation are quite low (Mossman *et al.*, 1990). Many insulated surfaces, in addition to the lagging, have had coatings (mastics) and paint layers applied to the surface and this further reduces the possibility that asbestos fibers will be released from intact insulation. Thus, intuitively, one would not expect appreciable airborne concentrations on marine vessels when insulation is not being disturbed or removed, but because of speculation that ship movement might produce some stresses on the insulation, a number of studies have been conducted over the years. Our analysis of these previously unpublished studies presents the only data, to our knowledge, of the concentrations of airborne asbestos not associated with the direct handling of ACMs onboard maritime shipping vessels.

MATERIALS AND METHODS

The data presented in this analysis were compiled from 52 IH surveys, collected by at least 15 different consulting firms hired by ship vessel owners. Based on the available information, it appears that these data were collected during those time periods when OSHA proposed to significantly lower the occupational exposure limit for asbestos. The data were obtained from studies or surveys conducted onboard 42 vessels in which only air samples were collected, 40 vessels in which both air and bulk samples were collected and 2 vessels in which only bulk samples were collected. These surveys provided phase contrast microscopy (PCM) results for 63 vessels, transmission electron microscopy (TEM) air results for 6 vessels, both PCM and TEM air results for 7 vessels and both PCM and scanning electron microscopy (SEM) air results for 6 vessels. Of the 52 IH surveys, 26 were conducted by or under the supervision of certified industrial hygienists (CIHs), 4 were noted as being conducted by industrial hygienists and it was unclear whether the remaining 22 were conducted by CIHs. It was noted in 27 of the 52 surveys that the air samples were sent to an AIHA-, NIOSH- or NVLAP-accredited or -certified laboratory for analysis. Since these surveys were intended to satisfy regulatory expectations, we believe it is reasonable to infer that all samples were assayed by a qualified, if not certified, laboratory.

The air and bulk monitoring surveys were conducted on a variety of merchant vessels, including self-unloaders, dry and liquid cargo vessels, container ships, roll-on/roll-off vessels and a cement barge. Based on structural and functional similarities, these vessels were classified into four categories: dry cargo, tanker, Great Lakes and other types of vessels. Vessels that carried dry cargo, including roll-on/roll-off ships (those carrying wheeled cargo), and containers were classified as dry cargo vessels. Vessels that transported liquid cargo were classified as tankers. The cement barge and self-unloaders were generally older vessels, primarily operating in the Great Lakes, and thus were classified as Great Lakes vessels. Vessels classified in the other category included a vessel that installed marine cables and two vessels that were only identified as US flag ships.

Air sampling data, including airborne fiber concentration, duration, analytical method, date, location, type (personal versus area) and sample number, were entered in a database. Accompanying information, such as vessel name, status (dockside versus underway), owner, type, year built, modification date, propulsion type and surveyor information, was also included. For bulk sample data, similar information was recorded, including the type, condition and, in some cases, the percentage of asbestos in the bulk material. The bulk and air samples were collected from various areas of the ships, including the boiler and engine rooms, recreation areas and sleeping quarters.

Bulk sample data

A total of 482 bulk samples were collected from suspected asbestos-containing products and insulation, including lagging, valve packing, gaskets, boiler and turbine covering materials, ceiling panels and floor tiles on 42 merchant vessels. The results were cited in the IH reports either quantitatively as a percent of asbestos fiber concentration in the bulk material or qualitatively by confirming the presence or absence of asbestos in the material sampled. Of the 482 bulk samples collected, asbestos fiber concentrations were reported for 287 and the remaining 195 sample results were reported qualitatively. It was generally noted that bulk samples were analyzed by polarized light microscopy (PLM), according to either EPA or NIOSH bulk sampling methodology (EPA, 1982; NIOSH, 1994a). The IH reports noted that based on visual observations and the experience of the industrial hygienist, bulk samples were collected in areas where materials were expected to be comprised of asbestos, including areas where damage to the insulating material was visible or in areas of the ship occupied by personnel for work, eating,

recreating and sleeping. It was also noted that insulation and other materials containing asbestos were reasonably maintained and in good condition, and removal or similar tasks were generally infrequent and limited in duration while at sea. Thus, the samples collected were considered to represent the background concentration of airborne asbestos on these ships.

Air sample data

The air samples evaluated in this analysis were not associated with particular work activities onboard ships and were not collected when seamen were actively disturbing, repairing or handling ACMs. Of the 1062 PCM samples, 20 were classified as personal samples, 1018 were classified as area samples and 24 were of unknown type. The influences of sampling-specific variables such as type of ship (cargo, tanker or Great Lakes), sampling location (crew or engine spaces) and transport status of the ship (docked or underway) on the airborne concentrations of asbestos were evaluated.

Sampling times, when reported, varied between 4 and 971 min. While PCM was reportedly used for the analysis of most of the air samples, the analytical and sampling procedures changed over time. From 1978 until 1986, air samples were analyzed using NIOSH P&CAM Method 239 (NIOSH, 1977). Between 1985 and 1992, samples were analyzed according to NIOSH Method 7400 (NIOSH, 1994b). Between 1990 and 1992, 25 samples were analyzed by TEM, according to NIOSH Method 7402 and between 1985 and 1987, 16 samples were subsequently analyzed by SEM (NIOSH, 1994c). During the initial review of the IH reports, 28 air samples analyzed by PCM were excluded from the analysis due to dust interference and the failure to meet NIOSH analytical requirements regarding loading (i.e. too much nuisance dust was in the air in that specific environment for the air sampling rate).

In total, 499 PCM samples were reported as below the analytical detection limit, non-detect (ND) or as 0 f cc^{-1} (almost 50% of all samples collected). Twenty-three samples were excluded because of insufficient sample-specific information on volume, duration and analytical method to accurately calculate or estimate a detection limit. When this sample information was available and detection limits were not reported, they were *ad hoc* calculated by the authors, according to the P&CAM 239 method, for 20 samples (collected in 1984) and ranged from 0.014 to 0.194 f cc^{-1} (NIOSH, 1977). Detection limits for the remaining 456 ND samples were identified as less than a value (e.g. <0.001 f cc^{-1}) in the sample result data or identified in the text of the IH report and ranged from 0.0003 to 0.1 f cc^{-1}. It should be noted that the NIOSH P&CAM 239 method only reported a lower limit of quantitation (LOQ) of 0.1 f cc^{-1} (at 2.5 l.p.m., for 2 h, for a field area of 0.003 mm^2), while NIOSH Method 7400 reported both LOQs and limits of detection (LODs) for various values of filter fiber density and total volume of air sampled (NIOSH, 1977, 1994b).

Air data analysis

The air sampling data were highly censored, with >45% of the 1062 PCM samples below their respective detection limits, and the results were not found to be normally or log-normally distributed using the Lilliefors test ($P > 0.05$). Due to the relatively high percentage of ND samples, non-parametric methods accommodating left-censored data were selected for this analysis. Except where otherwise noted, the Kaplan–Meier (KM) estimation method (also known as the product limit estimate) was used to estimate the mean concentrations. This method is useful for analyzing left-censored data sets with multiple detection limits and is not based on an underlying distribution of the data set (Helsel, 2005). The 95% upper confidence limits of the mean reported in this analysis were based on the Chebyshev inequality using the KM-estimated mean and standard deviation (SD). Additionally, the Gehan test was used to assess whether concentrations were significantly different between specific sample groups as it is a non-parametric test for use on data sets with multiple detection limits (EPA, 2007a). ProUCL 4.0, statistical software developed and distributed by the US EPA, includes built-in algorithms for the above methods, and was thus used for these analyses (EPA, 2007b).

The impact of having a high fraction of ND samples on the mean and SD results was also evaluated. To this end, sample means were calculated using various substitution methods. Using these approaches, surrogate concentrations were substituted for samples with concentrations below their respective detection limits. A number of different substituted concentrations were assessed in this analysis, including zero, LOD/2, LOD/$\sqrt{2}$ and the LOD (Perkins *et al.*, 1990; Finkelstein and Verma, 2001). As noted by Rao *et al.* (1991), the sample mean is bounded by the value calculated after substituting ND concentrations of zero, and by the value calculated after substituting ND concentrations of the full LOD. Specifically, the latter method (substituting the full LOD) results in a sample mean that is biased high, and will thus be larger than the true sample mean. Using this approach, the impact of the degree of censoring on statistics, such as the mean and SD, can be assessed.

Airborne fiber concentrations were compared to contemporaneous PELs (8-h time weighted average) for asbestos. The fractions of samples exceeding specific concentrations, including 0.1 f cc^{-1} (e.g. the current OSHA PEL), were also calculated using

Table 1. Quantitative bulk sample results by source and percent concentration of asbestos type from 34 vessels

Source	*n*	*d*	% chrysotile		% amosite		% crocidolite	
			Min	Max	Min	Max	Min	Max
Ceiling panels	9	8	30	75			3	8
Debris[a]	8	0						
Floor tile	5	1	3	8				
Gasket[b]	2	2	90	95				
Insulation[c]	245	131	1	100	1	61	3	10
Valve packing	1	1	70	75				
Unspecified	13	10	12	60				
Total	287[d]	153						

n, number of samples; *d*, number of samples with detectable concentrations.
[a]Samples collected in the vicinity of an area air sampling location or underneath machinery.
[b]Samples collected from an unspecified location.
[c]Samples collected from various pipe, equipment and machinery insulation materials.
[d]Four additional bulk samples were obtained from a pump room brake lining, an electrical outlet wrap, foam ceiling insulation and a refractory material and were negative for asbestos content.

a non-parametric method (Mulhausen and Damiano, 1998). Although not as statistically powerful as parametric methods, this method is useful because it is not affected by detection limits and is based only on the total sample size and the number of data exceeding the specified concentration.

RESULTS

A total of 1100 air and 482 bulk samples collected from 84 merchant shipping vessels from 1978 until 1992 were considered in this analysis. Approximately 43% of the area air samples analyzed by PCM (n = 1018) and 96% of the air samples (n = 25) analyzed by TEM were below their respective LODs.

Bulk samples

Twenty-eight of the 42 ships sampled were found to contain asbestos-containing insulation, while the remaining 14 ships had bulk insulation sample results either below the LOD for PLM or did not contain asbestos. The asbestos bulk sample results were reported in the IH surveys either quantitatively (287 bulk samples collected from 34 vessels from 1981 until 1992) or qualitatively (195 samples collected from eight vessels from 1984 until 1989). Of the total 482 bulk samples, 392 were collected from insulation materials, including pipe and machinery lagging, cloth and blankets, while the remaining 90 samples were collected from other potential ACMs, such as ceiling and floor tiles, brakes, clutches, valve packing and gaskets. Asbestos was detected in 232 of the 392 bulk samples collected from pipe and equipment insulation materials.

Of the 287 quantitative bulk sample results, 153 samples contained detectable levels of one or more of the three types of asbestos (amosite, chrysotile or crocidolite) (Table 1). One hundred and forty samples contained detectable levels of chrysotile at concentrations ranging from 1 to 100%, which were found in ceiling panels, floor tiles, gaskets, insulation, packing and samples of unknown origin. Two hundred and forty-five samples were collected from insulation materials and 72 of these samples contained detectable levels of amosite ranging from 1 to 61%. Crocidolite was detected in three samples of insulation (one insulation jacket on a DC heater and two on an unspecified insulation material in the engine control area) and one ceiling panel at concentrations of 3–10%; amosite and/or chrysotile were also present in these samples (Table 1). Crocidolite sometimes appears as a contaminant in amosite used in the older asbestos ship insulations. In addition to asbestos, other types of materials were identified in the bulk material, such as fiberglass, glass wool, mineral wool, calcite, gypsum, quartz, diatoms, ceramic fiber, magnesium silicate and pumice.

Air samples

Area air samples (n = 1018) collected onboard 74 different merchant vessels and analyzed by PCM are summarized in Table 2. The average concentration for airborne fibers for all merchant vessels, calculated using the KM method, was 0.008 f cc^{-1} (SD = 0.039 f cc^{-1}; 95th percentile of the data set = 0.040 f cc^{-1}). When concentrations of zero or the LOD were substituted for ND sample results, average air concentrations were 0.007 and 0.011 f cc^{-1}, respectively; that is, there was virtually no difference in average air concentrations, irrespective of the value substituted for ND sample results. Figure 1 presents the average air concentrations over time, as calculated by various substitution methods, including the KM method. The KM average for each year falls between the lower (ND = 0) and upper (ND = LOD) estimates of the sample mean using

Table 2. Summary of airborne fiber concentrations for the area (rather than personal) samples collected onboard 74 shipping vessels from 1978 to 1992 analyzed by PCM (f cc^{-1})

	d/n	Mean						Percentile[b]						No. of studies
		(ND = 0)	(ND = LOD/$\sqrt{2}$)	(ND = LOD)	Mean[a]	SD[a]	UCL_{95}[a]	25th	50th	75th	95th	Max	≥PEL (%)[c]	
All vessels (1978–1992)	578/1018	0.007	0.010	0.011	0.008	0.039	0.013	0.001	0.002	0.007	0.040	1.000	1.4	50
1978	53/53	0.049	0.049	0.049	0.049	0.069	0.090	0.010	0.019	0.060	0.190	0.390	17.0	3
1980	36/88	0.028	0.030	0.030	0.031	0.114	0.085	0.002	0.010	0.020	0.130	1.000	5.7	4
1981	11/75	0.003	0.005	0.005	0.006	0.008	0.008	0.002	0.004	0.004	0.022	0.059	0.0	4
1983	6/7	0.014	0.015	0.016	0.016	0.005	0.005	0.010	0.020	0.020	0.000	0.020	0.0	1
1984	21/51	0.002	0.029	0.040	0.003	0.004	0.006	0.001	0.005	0.093	0.194	0.137	0.0	5
1985	33/48	0.003	0.003	0.003	0.003	0.005	0.005	0.001	0.002	0.003	0.013	0.030	0.0	1
1986	48/85	0.006	0.007	0.008	0.006	0.008	0.008	0.001	0.007	0.010	0.028	0.032	0.0	4
1987	46/68	0.003	0.005	0.005	0.004	0.003	0.005	0.002	0.004	0.010	0.010	0.020	0.0	1
1989	14/105	0.001	0.007	0.009	0.002	0.003	0.003	0.002	0.003	0.006	0.040	0.071	0.0	6
1991	245/339	0.003	0.003	0.003	0.003	0.005	0.004	0.001	0.002	0.003	0.010	0.068	0.0	17
1992	65/99	0.002	0.002	0.002	0.002	0.002	0.003	0.001	0.001	0.002	0.005	0.016	0.0	6
Dry cargo	152/327	0.007	0.008	0.008	0.008	0.031	0.015	0.001	0.002	0.004	0.030	0.390	2.1	14
Tanker	217/373	0.004	0.006	0.006	0.004	0.010	0.007	0.001	0.002	0.005	0.024	0.117	0.5	23
Great Lakes	155/260	0.004	0.010	0.012	0.004	0.006	0.006	0.001	0.003	0.010	0.091	0.137	0.0	10
Other	54/58	0.048	0.048	0.048	0.048	0.139	0.128	0.008	0.013	0.030	0.410	1.000	8.6	3
Crew area	232/295	0.004	0.004	0.004	0.004	0.009	0.006	0.001	0.002	0.005	0.014	0.124	0.3	33
Engine area	281/598	0.010	0.013	0.014	0.010	0.051	0.019	0.001	0.002	0.009	0.068	1.000	2.2	48
Other	55/104	0.004	0.008	0.010	0.005	0.010	0.010	0.001	0.004	0.010	0.050	0.086	0.0	28
Unknown	10/21	0.007	0.010	0.012	0.008	0.010	0.019	0.002	0.008	0.022	0.040	0.037	0.0	7
Docked	102/166	0.009	0.012	0.013	0.010	0.034	0.021	0.002	0.003	0.008	0.058	0.390	1.8	24
Docked and underway	1/6	0.0002	0.002	0.002	—[d]	—[d]	—[d]	0.001	0.002	0.007	0.000	0.005	0.0	2
Loading and/or unloading	19/35	0.006	0.007	0.007	0.006	0.017	0.019	0.001	0.002	0.006	0.100	0.100	2.9	7
NIS or on standby	13/29	0.007	0.007	0.007	0.007	0.010	0.016	0.001	0.001	0.019	0.032	0.032	0.0	2
Underway	374/609	0.004	0.006	0.006	0.005	0.015	0.008	0.001	0.002	0.005	0.018	0.190	0.8	40
Unknown	69/173	0.017	0.025	0.029	0.018	0.084	0.046	0.002	0.004	0.020	0.150	1.000	2.9	13
Ships confirmed to contain ACMs[e]	206/385	0.002	0.007	0.009	0.003	0.004	0.004	0.001	0.002	0.004	0.040	0.137	0.0	23
Ships not confirmed to contain ACMs[e]	100/203	0.003	0.004	0.004	0.003	0.006	0.005	0.002	0.003	0.004	0.013	0.068	0.0	18
Ships not tested	272/430	0.014	0.015	0.016	0.015	0.060	0.027	0.002	0.003	0.010	0.059	1.000	3.3	11

d, number of samples with detectable concentrations, *n*, number of samples; UCL_{95}, 95% upper confidence limit of the population mean, NIS, not in service.

[a]Based on the Chebyshev inequality using KM estimates for the mean and SD except 1978 (based on the Chebyshev inequality using log-normal estimates) and 1985 (based on the Chebyshev inequality using non-parametric estimates).

[b]Percentile calculations performed using the empirical CDF method, using SYSTAT statistical software version 11.

[c]Fraction of samples exceeding the current OSHA PEL of 0.1 f cc^{-1}.

[d]Single detect sample with concentration of 0.001 f cc^{-1}. KM cannot be used to estimate mean, SD or UCL.

[e]Confirmed presence of asbestos-containing insulation materials by bulk fiber analyses.

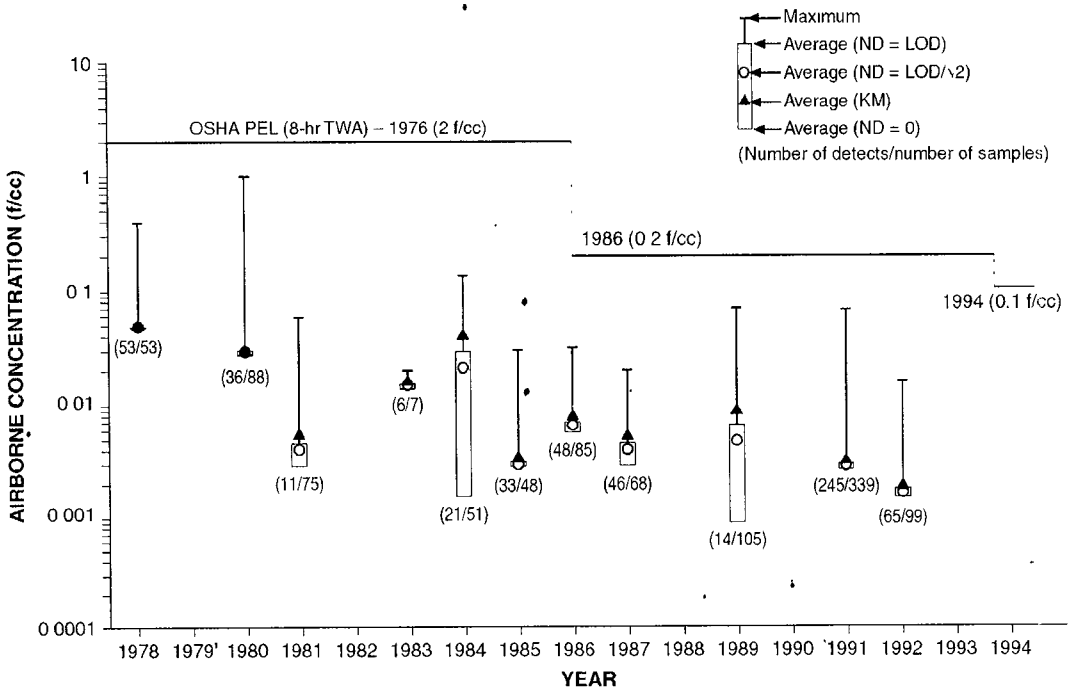


Fig. 1. Average airborne fiber concentrations for the area samples estimated using various substitution methods and the KM method. Vertical error bars represent the maximum detected sample concentration for each year.

substitution methods. As also shown in Fig. 1, comparisons between these air sample results and the occupational standards indicate that no samples were above the contemporaneous OSHA PELs. Moreover, upper-bound estimates of the sample mean (ND = LOD) were all well below the contemporaneous PEL for all years.

As shown in Table 3, 98.7% of the results were ≤ 0.1 f cc^{-1}. In addition, a non-parametric upper tolerance limit estimate suggested that, based on this data set, there was 95% confidence that ~2.1% of relevant historical asbestos air concentrations exceeded 0.1 f cc^{-1}. For comparative purposes, in Table 3, exceedance fractions and upper tolerance limits on these fractions are also shown for the concentration of 1 f cc^{-1}. Exceedance fractions generally decreased with time. When the 877 samples from 1981 and later are considered, for example, there is 95% confidence that >99% of the asbestos air concentrations were <0.1 f cc^{-1}. Based on our experience and published studies, in most industries and settings, asbestos air concentrations fell dramatically after 1981 because of stricter regulatory limits and increased awareness about the precautions that were necessary to decrease exposures and not because of the absence of ACMs since 275 bulk samples collected on ships after 1981 were positive for asbestos.

The average concentration of the 20 personal samples was 0.021 f cc^{-1} (SD = 0.024 f cc^{-1}; 95th percentile of the data set = 0.11 f cc^{-1}), which was significantly higher than average area concentrations

Table 3. Non-parametric exceedance fraction estimates and upper tolerance limits for various data sets

Concentration (f cc^{-1})	n	m[a]	EF[b] (%)	UTL[c] (%)
0.1	1018	13	1.3	2.1
1	1018	0	0.0	0.7

[a]The number of samples with concentrations exceeding the specified concentration.
[b]EF, exceedance fraction (fraction of samples exceeding the specified concentration).
[c]UTL, upper tolerance limit—there is 95% confidence that this fraction or fewer exposures exceeded the specified concentration.

($P = 0.03$). For approximately half of these samples, the IH reports noted that the seamen were either standing watch in a control room or involved in loading and/or unloading activities; this task information was not available for the remaining personal samples.

Mean area concentrations on dry cargo, tanker and Great Lakes vessels were 0.008, 0.004 and 0.004 f cc^{-1}, respectively. The mean area concentration on Great Lakes vessels was significantly higher ($P < 0.001$) than that measured for tanker and dry cargo vessels, while mean tanker and dry cargo area concentrations were not significantly different ($P = 0.9$). Of the 58 samples of unknown type, 54 samples were above their LODs, with a mean concentration of 0.048 f cc^{-1}; the LOD for the 4 ND samples was 0.001 f cc^{-1}.

The mean air concentration of samples collected in crew areas of the ships (crew mess, recreation,

lounge areas and sleeping quarters) was 0.004 f cc^{-1}, whereas the mean air concentration in the engine compartments (engine and boiler rooms and machine shops) was 0.010 f cc^{-1}. Air samples collected in areas of the ships such as hallways, stairwells and loading areas were classified as 'other', and had an average fiber concentration of 0.005 f cc^{-1}. The average concentration of those samples with unspecified sampling locations in the IH survey was 0.008 f cc^{-1}. The mean air concentration of samples collected in the crew areas was not significantly different than the mean concentration of samples collected in the engine compartment ($P > 0.05$) or other areas of the ship ($P > 0.05$). Of those ships confirmed to have asbestos-containing insulation, average air concentrations in the engine spaces and crew areas were 0.005 and 0.004 f cc^{-1}, respectively.

Air samples that were collected onboard ships at sea had similar fiber concentrations compared to docked ships. Of the 1018 area PCM air samples considered in this analysis, 166 were collected from docked ships, 35 were collected from ships docked and performing loading/unloading of cargo, 29 were collected from ships not currently in service or on standby and 609 samples were collected from ships at sea. In addition, six samples were collected from ships both docked and at sea for some portion of the sampling. In these instances, the sampling pumps were turned on while the ship was at dock, prior to departure. The sampling pumps continued to run after departure, and, as such, samples collected under these conditions were classified as average concentrations from the ship while docked and at sea. The ship's transport status, though, was not specified for 173 samples. Average fiber concentration of air samples collected while the ships were docked and at sea were 0.010 and 0.005 f cc^{-1}, respectively, a difference that was not statistically significant ($P > 0.05$). The average fiber concentration of samples collected onboard ships with unknown transport status was 0.018 f cc^{-1}. Only one sample collected while ships were both docked and at sea was above its LOD, with a concentration of 0.001 f cc^{-1}.

Comparisons were also made between air sampling data from ships with positive bulk samples for asbestos insulation and those ships in which the presence of asbestos was not confirmed, as well as to those ships in which bulk samples were not collected. The average airborne concentrations onboard the 28 ships with confirmed asbestos-containing insulation and the 13 ships unconfirmed to contain asbestos-containing insulation were both ~0.003 f cc^{-1} (rounded to one significant figure); mean air concentrations aboard ships confirmed to contain ACMs were not significantly higher than those collected aboard ships unconfirmed to contain ACMs ($P > 0.05$). The average airborne fiber concentration onboard ships where no bulk samples were collected was 0.015 f cc^{-1}, a value that is significantly higher than that from the ships in which bulk samples were collected ($P < 0.001$).

Twenty-five TEM air samples collected between 1990 and 1992 and 13 SEM air samples collected between 1985 and 1987 were included in this analysis. It is noteworthy that only one sample, with a concentration of 0.124 f cc^{-1}, was above the TEM analytical detection limit. Detection limits for the remaining 24 samples were 0.005 f cc^{-1} and smaller. Of the 25 TEM samples collected, only 16 were from the four ships in which bulk sampling was conducted and only two of these ships had bulk samples that tested positive for asbestos. Six TEM samples were collected onboard these two ships, all with concentrations below their respective LODs. Nine air samples were analyzed using both TEM and PCM. These samples were collected onboard six different vessels in 1991 and 1992. Interestingly, although all nine samples were above the LOD for PCM, with an average concentration of 0.015 f cc^{-1} (range of 0.01–0.02 f cc^{-1}), all nine of these samples were below their respective detection limits for TEM and ranged from 0.00017 to 0.001 f cc^{-1}.

Additionally, it was noted in the IH surveys that 13 air samples, collected between 1985 and 1987, appeared to contain asbestos under PCM and were further examined by SEM in order to possibly define the substrate as asbestos. Concentrations analyzed by SEM ranged from ND to 0.01 f cc^{-1}, with a mean concentration of 0.004 f cc^{-1}, ~4-fold lower than the mean PCM concentration for the same samples.

DISCUSSION

Although many studies have been conducted regarding asbestos workers (e.g. miners and those in the manufacturing environment) and professionals who work with ACMs (e.g. insulators, pipefitters and other craftsman), it has often been a matter of speculation regarding the airborne concentration of asbestos in environments containing intact insulation. The data presented in this analysis characterize airborne fiber concentrations onboard maritime shipping vessels not associated with insulation or other ACM work during the years 1978–1992. As described previously, the airborne fiber concentration on these ships during this period averaged 0.008 f cc^{-1}, with a 95th percentile of 0.040 f cc^{-1}. Moreover, the data indicate that, with 95% confidence, only 2.1 and 0.7% of air concentrations may have exceeded 0.1 and 1 f cc^{-1}, respectively (and only a fraction of these fibers may have been asbestos since most analyses were by the PCM method).

Since the 1970s, numerous studies have characterized both indoor ambient asbestos concentrations (US schools and buildings) and outdoor ambient asbestos concentrations (Crump and Farrar, 1989;

Mossman *et al.*, 1990; Corn *et al.*, 1991; HEI-AR, 1991; Lee *et al.*, 1992; Corn, 1994; Whysner *et al.*, 1994). The two common asbestos sources which contribute to the ambient or background airborne concentrations of these fibers include the application and removal of sprayed asbestos insulation in building construction and natural weathering and human activities that disturb serpentine rock formations (Crump and Farrar, 1989; Whysner *et al.*, 1994). Whysner *et al.* (1994) reported ranges of median urban air concentrations in US cities from 0.00002 to 0.00075 f cc^{-1} and in European cities from 0.001 to 0.01 f cc^{-1}. Mangold (1982) also reported US urban air fiber concentrations in Portland, OR, and Seattle, WA, of 0.01 and 0.02 f cc^{-1}, respectively. Average airborne asbestos concentrations collected in US schools and universities, residences and public and commercial buildings from the early 1980s until the 1990s have been reported in the literature at concentrations of 0.00008–0.00018, ND–0.0025, 0.0001–0.008 and 0.00003 f cc^{-1}, respectively (Table 4). Additionally, the Agency for Toxic Substances and Disease Registry has estimated lifetime background cumulative asbestos exposure of the general public, within the range of 0.002–0.4 f cc^{-1}-year (ATSDR, 2001). While results of the current analysis are generally higher than those reported for other ambient environments, they nonetheless are a fraction of the concentrations which have been reported to increase the risk of asbestos-related diseases, such as mesothelioma, asbestosis or lung cancer (Churg, 1998; Wong, 2001; Paustenbach *et al.*, 2004; Roggli *et al.*, 2004; Pierce *et al.*, 2007).

Numerous studies have analyzed health data for seamen, from about 1950 until 1980, suggesting an elevated mortality and morbidity risk from lung cancer and mesothelioma (Jones *et al.*, 1984; Rafnsson *et al.*, 1988; Velonakis *et al.*, 1989; Kelman and Kavaler, 1990; Moen *et al.*, 1990; Selikoff *et al.*, 1990; Varouchakis *et al.*, 1991; Morabia *et al.*, 1992; Rapiti *et al.*, 1992; Brandt *et al.*, 1994; Rafnsson and Gunnarsdottir, 1995; Pukkala and Saarni, 1996; Saarni *et al.*, 2002; Rafnsson and Sulem, 2003; Karlev *et al.*, 2005). Some of these studies have suggested that excess mortality and morbidity may be at least partly attributed to constant exposure to low levels of airborne asbestos generated from vibrations of the insulated shipboard equipment and the natural movements of the ship. Although vibrations and natural ship movements could potentially

Table 4. Some historical ambient airborne asbestos concentrations in buildings and outdoor environments reported in the literature

Location	City/area	Air concentrations (f cc^{-1})		Reference
		Mean	Range	
Outdoor				
Urban	Five regions of USA[a]	0.00039[c]		Crump and Farrar (1989)
	Portland, OR, USA	0.01[b]		Mangold (1982)
	Seattle, WA, USA	0.02[b]		Mangold (1982)
	Philadelphia, PA, USA	0.01[b]	0–0.03[a]	Wendlick (1984)
	European cities		0.0001–0.001	WHO 1987, as cited in Whysner et al. 1994
	USA		0.00002–0.00075	NRC (1984)
Urban and industrial areas	San Francisco, CA, USA	0.02[b]	0.004–0.033[a]	Mangold (1983)
	Oakland, CA, USA	0.02[b]	0.006–0.034[a]	Mangold (1983)
Rural	USA	0–0.00065		Corn (1994)
Indoor				
School	USA	0.00018[b]		Lee *et al.* (1992)
University	USA	0.00008[b]		Lee *et al.* (1992)
Residential building	USA—with ACM		ND–0.0025	US CPSC (1987)
Public building	Baltimore, MD, USA; Washington, DC, USA	0.004[b]	0.001–0.008[b]	NIOSH (1976)
	Five regions of USA[a]—no ACM	0.00099[c]		Crump and Farrar (1989)
	Five regions of USA[a]—undamaged ACM	0.00053[c]		Crump and Farrar (1989)
	Five regions of USA[a]—damaged ACM	0.00073[c]		Crump and Farrar (1989)
Commercial building	USA nationwide	0.00003[b]		Lee et al. (1992)

[a]Washington, DC, Kansas City, New York City, California (Los Angeles and San Francisco) and Denver.
[b]Fibers >5μm in length.
[c]Total asbestos fibers.

increase airborne asbestos concentrations, the current data suggest that this is not the case. The observation that concentrations were slightly higher for docked vessels than for those at sea might be explained by repairs or other ACM activities that generally occur while the ship is docked or simply because airborne concentrations in cities are higher than those in the open waters.

While the reported increased incidence and mortality from asbestos-related diseases most likely resulting from handling or being in the vicinity of those who handled asbestos insulation, these occupational epidemiological studies of maritime seamen have historically not been relied upon to characterize the dose–response relationship due to insufficient exposure information stemming from incomplete occupational histories (Jones *et al.*, 1984; Moen *et al.*, 1990; Greenberg, 1991; Brandt *et al.*, 1994; Rafnsson and Gunnarsdottir, 1995; Pukkala and Saarni, 1996; Saarni *et al.*, 2002; Karlev *et al.*, 2005). Further, with respect to risk estimates for lung cancer, the majority of these studies did not address potential confounders, such as smoking history or previous exposure to asbestos, radiation, mineral oil mists or polycyclic aromatic hydrocarbons (PAHs) (inside or outside the navy) (Svendsen and Borresen, 1999). While these studies can be useful in identifying adverse health outcomes in seamen, many do not have sufficient information to accurately assess the associations between exposure to asbestos, confounding exposure to asbestos in other occupations, other carcinogens, smoking and the resulting health outcomes.

Based on our review of dozens of case studies regarding seaman, we conclude that the bulk of their asbestos exposure resulted from insulation application or removal practices (Selikoff *et al.*, 1990; Greenberg, 1991; Varouchakis *et al.*, 1991; Saarni *et al.*, 2002). Although it is possible that airborne asbestos concentrations on ships at sea were higher in years prior to 1978 due to a lesser concern about importance of maintaining insulation, we would be surprised if earlier data for these vessels (except during wartime conditions) revealed improper maintenance of insulation because of the resulting housekeeping problems. Based on the available information, then, there is no reason to believe that background exposures to asbestos on ships would be responsible for causing adverse health effects.

Although the asbestos IH air sampling data presented here represent 14 years of sampling information and were collected from a wide variety of vessels, mechanical scenarios and areas on the ships, there were some limitations to our analysis. These are related primarily to the variability and differences in sampling methodologies and analytical measurement techniques over this timeframe. This limitation, of course, is also present in virtually all historical IH data sets for nearly every setting studied.

Extrapolating these results to other situations needs to account for a number of factors. First, depending on the design of the sampling program, area samples are intended to characterize exposure levels associated with a particular production process, task or point source, and may not be representative of workers' breathing zone exposures. Although many of the IH surveys included in this analysis relied heavily on area samples (since the purpose was to identify concentrations typically found on an ocean-going vessel) rather than on samples from repair activities, for understanding exposures on ships, area samples should be nearly as insightful as personal samples but this would not necessarily be true in other settings. An accurate characterization of seamen's exposures during this time period relies heavily on the results of area samples, for reasons previously discussed.

Second, we recognize that it would have been ideal to have had all the samples analyzed using a single method. However, the available air sampling data included in this analysis were collected during a time of considerable change in sampling or analytical methodologies, both in the USA and other countries, and the consistency and precision of the analytical techniques varied over time (i.e. sample collection and preparation, fiber counting methodology and instrumentation techniques). Changes in analytical methodology, especially the transition from P&CAM 239 to NIOSH Method 7400, almost certainly would yield some differences in results. Even with a considerable amount of progress toward standardization of procedures and technical guidelines, we recognize that even when the same method is used among different laboratories at different time periods, the results may not be equal (Beckett and Attfield, 1974; Beckett *et al.*, 1976; Gibbs *et al.*, 1977; Beckett, 1980; Ogden, 1982; Walton, 1982; Williams *et al.*, 2007). For example, the higher reported values in samples collected in earlier years may be a result of these differences. Of equal importance, the data set reported here resulted from the pooling of air monitoring data, taken from 52 IH surveys that were collected and analyzed by a number of IH firms and laboratories. Combining data from these mixed sources means that, by definition, there is some lack of homogeneity in the data set. This is regrettable but necessary when conducting retrospective analyses. We acknowledge that there is some lack of consistency in sampling and analysis over time and that there is a several-fold range in the LODs. Thus, while it is necessary to pool potentially non-homogenous data sets when conducting historical exposure assessments, the issue of laboratory analytical variability has almost certainly resulted in some degree of uncertainty regarding the precision of results reported here. This is not a significant concern with respect to making conclusions about the overall magnitude of exposure, but rather the precision of the statistical characterization.

Third, the results of the sampling program should be considered an upper-bound estimate of likely exposure since most air samples were analyzed by PCM, an analytical technique that reports total fiber concentrations rather than total asbestos fiber concentrations. Thus, these results are expected to overestimate the actual airborne asbestos fiber concentrations, a phenomenon that was evaluated by comparing PCM and subsequent TEM and SEM air concentration data compiled in this analysis. Additionally, an assessment as to whether higher detection limits might influence average concentrations, especially when substitution methods (replacing LOD/2 or LOD/$\sqrt{2}$ for non-detect sample concentrations) were used for samples below the detection limit, was also warranted. To address this issue, we examined how detection limits changed over time in this data set. LODs in 1991 and 1992 were indeed lower than those in prior years; variance analyses suggest a slight (0.007 f/cc) but significant ($P = 0.043$) decrease in detection limit between 1980 and 1992. The KM method was used to accommodate this small change in detection limit over time.

Fourth, one might ask whether these data are representative of the diversity of ships and the various weather conditions at sea. The data reported here may represent a subset of all the asbestos measurements that have been collected on maritime shipping vessels from this time period. That is, the current analysis only includes those data that were provided to the authors by various shipping vessel firms. However, while it is possible that there are other studies of these ships, the data presented here represent >1000 samples collected over 14 years on 84 different shipping vessels, encompassing a wide range of vessel types, mechanical scenarios and areas on these ships. Since this data set is relatively large compared to most other published studies, and because the data sets are remarkably similar, the authors believe that this data set is representative of background asbestos levels, when insulation-handling activities were not actively being performed, on shipping vessels during this time period.

These limitations notwithstanding, the results of this study confirm that a large percentage of ships used between the 1970s and 1990s possessed ACMs, and that a significant fraction of the insulation on these ships contained amosite. As expected, the airborne concentrations of asbestos in those ships where the asbestos remained undisturbed were quite small. These data, then, indicate that for the past 30 years, sailors and others who worked on similar ships while docked and at sea had minimal exposure to asbestos.

CONCLUSION

The IH data presented here are robust enough to conduct a retrospective exposure assessment for individual seamen working in the maritime shipping industry from the 1970s through the 1990s. The results indicate that the mere presence of undisturbed asbestos-containing insulation onboard these shipping vessels did not significantly increase seamen's exposure to airborne asbestos. Overall, the data indicate that background airborne asbestos concentrations onboard these ships from at least 1978 until 1992 were very low, and in most cases, they were at least 10-fold <0.1 f cc^{-1}, the current OSHA PEL.

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