



Airborne Asbestos Exposures from Warm Air Heating Systems in Schools

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ABSTRACT

The aim of this study was to investigate the concentrations of airborne asbestos that can be released into classrooms of schools that have amosite-containing asbestos insulation board (AIB) in the ceiling plenum or other spaces, particularly where there is forced recirculation of air as part of a warm air heating system. Air samples were collected in three or more classrooms at each of three schools, two of which were of CLASP (Consortium of Local Authorities Special Programme) system-built design, during periods when the schools were unoccupied. Two conditions were sampled: (i) the start-up and running of the heating systems with no disturbance (the background) and (ii) running of the heating systems during simulated disturbance. The simulated disturbance was designed to exceed the level of disturbance to the AIB that would routinely take place in an occupied classroom. A total of 60 or more direct impacts that vibrated and/or flexed the encapsulated or enclosed AIB materials were applied over the sampling period. The impacts were carried out at the start of the sampling and repeated at hourly intervals but did not break or damage the AIB. The target air volume for background samples was ~3000 l of air using a static sampler sited either below or ~1 m from the heater outlet. This would allow an analytical sensitivity (AS) of 0.0001 fibres per millilitre (f ml^{-1}) to be achieved, which is 1000 times lower than the EU and UK workplace control limit of 0.1 f ml^{-1} . Samples with lower volumes of air were also collected in case of overloading and for the shorter disturbance sampling times used at one site. The sampler filters were analysed by phase contrast microscopy (PCM) to give a rapid determination of the overall concentration of visible fibres (all types) released and/or by analytical transmission electron microscopy (TEM) to determine the concentration of asbestos fibres. Due to the low number of fibres, results were reported in terms of both the calculated concentration and the statistically relevant limits of quantification (LOQ), which are routinely applied. The PCM fibre concentrations were all below the LOQ but analytical TEM showed that few of the fibres counted in the background samples were asbestos. The background TEM asbestos concentrations for the individual samples analysed from all three schools were at or below the AS, with a pooled average below the LOQ ($<0.00005 \text{ f ml}^{-1}$). At the two CLASP schools, there was no significant increase in the airborne amosite concentration in the classrooms during simulated disturbance conditions. At the third school, four of the five classrooms sampled gave measurable concentrations of amosite by TEM during simulated disturbance conditions. The highest concentration of amosite fibres countable by PCM was 0.0043 f ml^{-1} with a pooled average of 0.0019 f ml^{-1} . The air sampling strategy was effective and worked well and the results provide further important evidence to inform the sampling and management of asbestos in schools.

KEYWORDS: asbestos; CLASP; concentration; fibre; heaters; schools

INTRODUCTION

The aim of this study was to investigate the concentrations of airborne asbestos that can be released into classrooms of schools that have amosite-containing asbestos insulation board (AIB) in ceiling plenums or other spaces where there is forced recirculation of air as part of warm air heating systems. Both background concentrations and those during disturbance of the classroom structure were investigated.

Previous work (Burdett *et al.*, 2009) summarized a large number of measurements in CLASP (Consortium of Local Authorities Special Programme) system-built school buildings during a range of activities including: maintenance, simulated disturbances, and normal occupation. However, as these data were collated from several sources, the number of sites with in-ceiling heating systems or which used the ceiling void as a return-air plenum was uncertain. This new work provides measurements on the concentration of airborne asbestos from disturbance to AIB materials, dust, and debris in air circulating, heating, and ventilation systems.

As asbestos material in buildings continues to be a focus of concern, it is intended that the presentation of this new data, along with other relevant peer-reviewed published exposure data, will help inform scientific debate on the risk and its assessment and management.

Background

An asbestos issue in one CLASP system-built school was first reported to the UK Health and Safety Executive (HSE) in September 2006. Following an initial investigation, a 'task and finish' Asbestos in Schools Working Group (ASWG) was set up by HSE and produced interim guidance that was issued to CLASP schools by the start of the October half-term holiday in 2006. This was later updated and extended to other types of system-built schools (HSE, 2008). This guidance was based on the findings from a programme of HSE inspections and air measurements in schools (Burdett *et al.*, 2009). The measurements were taken by the Health and Safety Laboratory (HSL) during and after remediation. Since issuing the updated guidance HSE has carried out further school inspections (HSE, 2010, 2014) and the UK Department for Education (DfE) has reviewed its policy and issued guidance to asbestos in schools (DfE, 2013, 2015a,b).

The issue reported to HSE in September 2006 was a failure to achieve clearance after an asbestos

removal when the metal casings enclosing vertical steel support columns were repeatedly struck and the windows and doors adjacent to the columns were banged. A detailed investigation concluded that airborne asbestos fibres were being released from cracks and holes from the poorly joined or damaged column casings that had AIB attached to the inside (Fig. 1). It was found that external sealing of all gaps or holes in the column casing, accessible from the classroom, reduced airborne fibre concentrations released by up to two orders of magnitude (Burdett *et al.*, 2009). This approach had the advantage that there was no direct work with the AIB, which meant that remedial work could be carried out rapidly using the existing Local Authority and school maintenance staff.

It was also recognized that the column casings extended into the ceiling plenum and the tops were unsealed, often with a few centimetres of AIB protruding above the casing. While the gap at the top of the casing provided a potential route for fibre release, the results from the air monitoring available showed that sealing the tops made no significant difference to the fibre concentrations monitored inside the classrooms during disturbance testing (i.e. banging columns and doors etc.).

Previous research into mechanisms of releases from asbestos-containing materials and surface dust

The potential release of particulates and fibres from ventilation systems and air circulation through plenums into rooms has been studied for various types of asbestos-containing materials (ACMs). Air erosion, resuspension of settled dust, vibrational disturbances (e.g. mechanical, human, and wind), and direct disturbance of the ACMs (e.g. damage and maintenance work) are all potential sources of release, so the airborne concentration will vary with time and the types of disturbance taking place.

Early measurement of releases of asbestos following air erosion was reviewed by the Health Effects Institute (HEI-AR, 1991) and found that, 'the release of fibres by air erosion at the velocities normally present in buildings has been shown to be minimal, even on friable sprayed surfaces in return-air plenums (Nicholson *et al.*, 1975; Sebastien *et al.*, 1980; Burdett and Jaffrey, 1986), at ventilation outlets directed across friable sprayed ACM (Guillemin *et al.*, 1989) and in specific experiments (Burdett, 1986; Keyes



Figure 1 Example of a gap in a poorly joined CLASP column casing.

and Chesson, 1990)'. The HEI report also considered that, 'it is doubtful if the normal vibrations of a building structure are sufficient in amplitude or frequency to cause release of a measurable concentration of airborne asbestos fibres from an ACM (HEI-AR, 1991).

The cohesive and adhesive forces for respirable particles on surfaces are quite strong, and in wind tunnel studies, resuspension rates of settled dust (when expressed as the fractional resuspension rate per second) have been reported to vary from 10^{-13} to 10^{-4} (Wu *et al.*, 1992). A recent wind tunnel investigation (Goldasteh *et al.*, in press) observed minimal resuspension for 1 to 10- μm dust particles from linoleum flooring for velocities below 18 m s^{-1} . Other authors found that air velocities of 50 and 117 m s^{-1} were needed to resuspend $\sim 11\text{-}\mu\text{m}$ particles (Corn and Stein, 1965; Jiang *et al.*, 2008). Even when resuspension does occur, wind tunnel studies show an initial release in the first few seconds were some two to three orders of magnitude higher than the release that followed (Hall and Reed, 1989; Wu *et al.*, 1992; Nicholson, 1993; Ibrahim *et al.*, 2003). While the particle size, deposit

density, agglomeration, and the amount of dust are important determinants of resuspension (Boor *et al.*, 2013); other environmental variables such as relative humidity, temperature, and moisture content will also modify resuspension (EN 15051-1, 2013).

The measurement of the concentration of airborne asbestos

For work with asbestos, the phase contrast microscopy (PCM) method is used to count all visible fibres $>5 \mu\text{m}$ long, $<3 \mu\text{m}$ wide, and with an aspect ratio $>3:1$ (WHO, 1997; HSE, 2005) with results expressed as fibres per millilitre (f ml^{-1}). For ambient and indoor air measurements, often few of the fibres counted will be asbestos and analytical transmission electron microscopy (TEM) is required to unambiguously identify the asbestos fibres (ISO 10312:95, 1995; HSE, 1998). As TEM has much better resolution than PCM, it can also be used to count and size shorter and/or thinner asbestos fibres. ISO 10312:95 reports concentrations of $>5\text{-}\mu\text{m}$ -long fibres in units of (f ml^{-1}) but distributions containing shorter fibres

are reported as structures per millilitre ($s\text{ ml}^{-1}$). The ISO method also allows TEM results to be expressed in terms of PCM equivalent (PCME) fibres if $>5\ \mu\text{m}$ long and between 0.2 and $3\ \mu\text{m}$ width with an aspect ratio of 3:1 or greater. PCM concentrations are used as the index of exposure for epidemiology and risk assessment of asbestos workers. Even though their health effects are uncertain, short asbestos fibres are considered helpful in detecting if very low emissions are present (AFSSET, 2009; Boulanger *et al.*, 2014). Early TEM studies expressed the asbestos concentration in terms of mass concentration (ng m^{-3}). Mass measurements have poorer precision than fibre counts and only approximate conversions can be made, typically $0.0005\ \text{PCME f ml}^{-1}$ is $\sim 20\text{--}40\ \text{ng m}^{-3}$ (RCO, 1982).

Previous measurements of airborne asbestos released from heating and ventilation systems based on the main asbestos type/material of concern

The average airborne asbestos mass concentrations in selected US buildings containing chrysotile in the return-air plenum and surfacing were reported to be some 48 and $15\ \text{ng m}^{-3}$ for friable and cementitious sprayed materials, respectively (Nicholson *et al.*, 1975, 1976). These results were only marginally higher than chrysotile levels in ambient air in New York (e.g. $83\% < 20\ \text{ng m}^{-3}$), which was considerably higher than results for Ontario schools ($2.1\ \text{ng m}^{-3}$) containing sprayed chrysotile and UK schools, laboratories, and factories ($1.5\ \text{ng m}^{-3}$) containing mainly sprayed chrysotile, amosite, and crocidolite, respectively under various levels of occupancy (Pinchin, 1982; Burdett *et al.*, 1984). The 99th percentile ($7\ \text{ng m}^{-3}$) for asbestos in Paris urban air was exceeded in over half of the 22 Paris buildings sampled (Sebastien *et al.*, 1980), including four schools with sprayed (mainly crocidolite) asbestos. However, sprayed asbestos in the ventilation systems was not considered to have contributed to elevated asbestos levels. Both the Paris and later US studies (Nicholson *et al.*, 1978, 1979) showed that in occupied rooms, where debris from unsealed damaged sprayed asbestos was visible, air concentrations were often $>100\ \text{ng m}^{-3}$. Visibly damaged low-density sprayed chrysotile asbestos and the resulting debris found in a university library (Sawyer, 1977) led to specific US advice for managing asbestos in buildings (Sawyer and Spooner, 1978).

Burdett and Jaffrey (1986) reported fibre levels in several UK situations where return-air plenums and heaters contained asbestos. In an occupied shopping centre where the metal structure inside the plenum had a friable sprayed amosite coating, the average asbestos fibre concentration was $<0.0001\ \text{f ml}^{-1}$ even though areas of damage and delamination were visible. A college with sprayed amosite on structural steelwork in the plenum, with a suspended ceiling of perforated AIB ceiling tiles, gave an average concentration ($n = 16$) of $<0.0001\ \text{f ml}^{-1}$ during normal occupation. A block of system-built flats containing sprayed amosite asbestos on steel work in the ceiling void and AIB inside the flats ($n = 16$) gave an average asbestos concentration of $0.0007\ \text{f ml}^{-1}$ during normal occupation. Measurement in 23 buildings (mostly domestic dwellings) heated by asbestos-containing electric warm air heaters (storage radiators), which contained amosite insulation blocks over which the air circulated, was also reported. Twenty two of the sites gave averages of $<0.001\ \text{f ml}^{-1}$ for $>5\text{-}\mu\text{m}$ -long asbestos fibres with an overall average of $0.0002\ \text{f ml}^{-1}$.

Gazzi and Crockford (1987) reported TEM asbestos fibre concentrations in UK residential apartments with an amosite-containing AIB lined airing cupboard with a recirculating warm air heater below. Single samples collected in 25 occupied apartments for either an 8-h period during the day or a 16-h period at night, gave average concentrations of 0.0004 and $0.0002\ \text{f ml}^{-1}$ respectively, with some 19 apartments at or below the analytical sensitivity (AS). The higher daytime value was due mainly to two samples of 0.0025 and $0.0019\ \text{f ml}^{-1}$, but no supervised repeat measurements were made to assess the source. Overall, there was no statistically significant difference from flats without asbestos but the authors felt that a small increase in exposure was indicated.

TEM fibre concentrations in a US office building, which had sprayed chrysotile asbestos in the return-air plenum and amosite thermal pipe insulation, were reported by HEI-AR (1992). Over a 3-year period, a total of 328 air samples were collected and analysed by analytical TEM. The mean concentration of $>5\text{-}\mu\text{m}$ -long asbestos fibres was reported as $0.00004\ \text{f ml}^{-1}$. Nolan and Langer (2001) reported air measurements in 12 US public buildings—including six schools and three universities, which had friable sprayed insulation fireproofing (containing 25%

amosite and 60% man-made mineral fibre) on structural steel and surrounding areas. These would often be in the return-air plenums. The insulation was generally reported to be in poor condition and air samples were taken during different levels of activity. Areas sampled included boiler rooms and storage areas as well as classrooms. Indoor asbestos concentrations for both static ($n = 117$) and personal samples ($n = 34$) were not significantly different from the outdoor samples ($n = 63$). The average amosite concentration was reported as $0.000007 \text{ f ml}^{-1}$.

A US study by Lee and Van Orden (2008) was by far the most extensive of the published studies. The study focussed on one type of sprayed chrysotile insulation, much of which would be expected to be present in the ceiling and the return-air plenums of the 600 US buildings sampled. This litigation funded study reported an average of 0.0001 f ml^{-1} for the 371 schools and colleges in the study, each sampled over at least 2 days. There was an increased concentration in asbestos-containing buildings under normal occupation compared to their immediate outdoor environment—by a factor of 4 for public and commercial buildings and a factor of 5 for schools.

Burdett *et al.* (2009) summarized PCM and TEM air concentration measurements from a range of disturbance activities carried in CLASP schools by both the HSL and private laboratories. Each main design of CLASP buildings up to early Mark (Mk) 6, usually contained AIB in their structure, although the amount and types of asbestos materials can vary due to design changes introduced by local architects. The mean airborne PCM fibre concentration monitored when the AIB containing columns were struck and vibrated as described in this paper was 0.094 f ml^{-1} ($n = 31$), which was higher than when tested again after sealing the column (0.004 f ml^{-1} , $n = 95$). The mean concentration during work to seal the column casing visible from inside the classroom was low (0.002 f ml^{-1} , $n = 188$), but when reoccupied and in normal use, it increased to 0.005 f ml^{-1} ($n = 96$) reflecting that these were counts of all fibre types rather than asbestos. TEM results from continuous daytime monitoring over the 5-week period in one CLASP Mk 4 ex-school used as offices, had a calculated TEM concentration for PCME asbestos fibres equal to the AS ($0.000005 \text{ f ml}^{-1}$). Twenty-eight TEM samples from classrooms in seven schools did not detect any asbestos during

normal occupation after the amosite AIB containing columns were sealed. One amosite fibre was detected in a school corridor where heavy swing fire doors were attached to the column casings.

Direct damage to amosite-containing AIB (Burdett, 1986) or maintenance work on heating systems containing low-density amosite insulation blocks (Burdett and Jaffrey, 1986) has been shown to give rise to increased releases of asbestos fibres.

METHOD

Three schools (A to C) were selected, based on notifications to HSE and where there was considered to be appreciable circulation of air into the classroom from a plenum which contained AIB. Selection was also dependent on the co-operation of the school authorities. Two of the schools were of CLASP design, where they had AIB in the vertical columns and the tops of the casing in the plenum were unsealed. They also had in-ceiling heating systems manufactured by Andrews Weatherfoil, the most common type of in-ceiling heater used in CLASP buildings. School A was a CLASP Mk 5 building of $\sim 1900 \text{ m}^2$ floor area and School B was a CLASP Mk 2 building of $\sim 2300 \text{ m}^2$ floor area.

The third school had classrooms where AIB had been used extensively in the cupboards surrounding the classroom heaters, for internal under-window panels and for some ceiling tiles. It was also reported that the plenum and heater cupboards were contaminated with asbestos debris from several previous poor removals of areas of AIB ceiling tiles. As the ceiling tiles had not been replaced some cupboards connected directly into the ceiling plenum. The first floor area sampled was $\sim 800 \text{ m}^2$ but was divided into three sections by two stairwells that had double fire doors on each entrance to the corridor, which limited any lateral air movement of resulting from wind pressure.

Sampling strategy

As in previous work, United Kingdom Accreditation Service (UKAS) accredited laboratories that were contracted to the local education authority (LEA) were used to carry out the air sampling and PCM analysis. This meant that the laboratory would have a detailed knowledge of the school, would simplify access and liaison issues, and ensured that PCM results would be rapidly available to the LEA. Copies of the sampling

and PCM worksheets along with half-filters were then forwarded HSL to undertake TEM analysis and to compare the results.

At least three classrooms from each school were selected for sampling, as these are the areas where the majority of the pupils are likely to be. All three schools were sampled with restricted access arrangements in place and were unoccupied. The two CLASP schools were sampled during a short spring school holiday. Sampling for TEM by a local laboratory proved more problematic at School C. HSL carried out side-by-side sampling 6 weeks after the school was closed pending refurbishment.

The site asbestos survey was consulted, to determine what asbestos was present and the types, amount, and condition. The column casings in the CLASP classrooms selected for sampling were also inspected to confirm that all gaps in the casing at classroom level were sealed.

The potential sources of asbestos release in the CLASP schools were considered to be either from AIB, dust, and debris in the plenum or from fibres emitted from the tops of the casing due to human disturbance (e.g. the opening and closing of doors and windows). A similar disturbance sampling protocol to the previous study was used (Burdett *et al.*, 2009).

Background and disturbance sampling of the columns was carried out in three isolated classrooms in the CLASP schools following methods set out in HSE guidance HSG 248 (HSE, 2005). Background samples, when possible, were started just before the fans were switched on. The sampling strategy called for at least one static sampler to be placed either below or ~1 m from the heater outlet and to sample a target volume of 3000 l of air through the 25-mm-diameter filter. This is roughly six times the minimum volume recommended in HSG 248 (HSE, 2005). Additional static samples were also collected to give a range of sample volumes and positions and ran for between 1.5 and 14 h. Disturbance sampling was carried out at the end of the visit and sampled over ~2–4 h to take account of the rates of dispersion, settling, and dilution of airborne fibres. This hourly frequency for disturbance is similar to the frequency of class/lesson changes.

Simulated disturbance was designed to exceed normal occupied classroom disturbance levels. The disturbance protocol for the CLASP schools (A and B) was: opening and shutting the door five times;

opening and closing a window five times; and striking five columns with an open hand. All windows and doors were then left closed, before repeating the disturbance at the start of every hour of air sampling (i.e. four repetitions, 60 disturbances). Each repetition was carried out over several minutes using typical force. For School C, each AIB panel reachable from the classroom floor by an adult was hit hard twice with an open hand at the start of each hour of sampling (i.e. two repetitions, ~100 disturbances). In all cases the heater fans were running.

All the air samples were collected using the same batch of pre-loaded Millipore (MAWP 025AO) 0.8 µm pore size mixed esters of cellulose filters in new conductive plastic cowl.

Analysis and reporting

Samples collected by the private laboratories were analysed at ×500 magnification by PCM using the standard analytical protocol (HSE, 2005). For the higher volume samples an AS (based on one fibre) of 0.0001 f ml⁻¹ was achieved. The actual numbers of fibres counted was tabulated for each sample and the equivalent volume of air analysed during the analysis (i.e. the fractional area of the exposed filter analysed times the volume of air sampled) was used to calculate the concentration. The limits of quantification (LOQ) based on 20 fibres in ~200 graticule areas was calculated as detailed in HSG 248 (HSE, 2005).

HSL's own samples from site C and selected samples from the private laboratories sent to HSL from the sampling at sites A and B were analysed for asbestos fibres using an analytical TEM method based on ISO 10312:95 but with enhanced imaging, sizing, and identification procedures. The prepared EM grids were scanned at approximately ×5000 magnification or higher using the image from a 16 MP Advanced Microscopy Techniques XR16 bottom mounted camera system on an FEI Inc. Tecnai Spirit TEM. PCME asbestos fibres (fibres >5 µm long and between 0.2 and 3 µm width with an aspect ratio of 3:1 or greater) were identified, sized, and counted. Due to the much higher contrast and resolution of the camera system compared to the phosphor screen, any shorter <5-µm-long asbestos structures seen (i.e. particles of >3:1 aspect ratio with largely parallel or stepped sides present as single particles, bundles or clusters or present in agglomerates of other material) were also identified, sized, and

counted. Identification was based on electron diffraction and/or energy dispersive X-ray analysis using ISO 10312:95 and relevant HSL in-house procedures, accredited by the UKAS. The asbestos fibre concentrations were calculated in a similar way to the PCM results with the reported AS and LOQ based on a count of 1 and 3 asbestos fibres respectively, in line with ISO 10312:95. For the high volume samples the target AS was 0.0001 f ml^{-1} , which is 1000 times lower than the current EU and UK control limit (CAR, 2012).

As most individual samples had PCM fibre and PCME asbestos concentrations <LOQ, the results from several samples in each building from the same test period/procedure were combined to calculate a pooled average. This gives both improved AS and a more representative measure of the average exposure inside the school, as it will be based on samples from several different classrooms. The pooled average is calculated by integrating the number of fibres counted and the equivalent volumes of air analysed for the individual samples in each set of similar samples, and then dividing the two integrals.

RESULTS

The results for the PCM [any fibre type (f ml^{-1})], PCME asbestos fibres (f ml^{-1}), and the short $<5\text{-}\mu\text{m}$ -long asbestos structures (s ml^{-1}) are given in Tables 1–4. At sites A and B, only the samples positioned underneath the heater outlets were analysed by TEM. At site C, all the HSL samples collected when the heater fans were running were analysed by TEM.

Site A

Tables 1 and 2 summarize the PCM and TEM results from Site A for the background and disturbance sampling with the heaters running. The PCM analysis of the background samples found low numbers of fibres (average of 5 with a range of 2–10 fibres counted). These counts are well below the LOQ and within the 95% confidence interval for a count of five fibres. The calculated PCM fibre concentrations were between 0.0004 and 0.0009 f ml^{-1} . The PCM results from the disturbance sampling had an average count of 8.2 fibres, with a range from 4 to 13 fibres. These counts are well below the LOQ and within the 95% confidence interval for a count of eight fibres. The calculated PCM fibre concentrations were between 0.0005 and 0.0016 f ml^{-1} .

Overall, there was a small increase in the number of PCM fibres counted ($\times 1.62$) from the disturbance sampling.

The TEM results from samples directly under the vents showed that no PCME asbestos fibres were detected during the background or disturbance sampling. Pooling the three classrooms together, the concentrations of PCME asbestos fibres were below both the AS ($<0.000033 \text{ f ml}^{-1}$) and the LOQ ($<0.0001 \text{ f ml}^{-1}$). Four $\leq 5\text{-}\mu\text{m}$ -long asbestos fibres were counted during the analysis of the disturbance samples (two amosite, a chrysotile, and an actinolite). All individual samples were at or below the LOQ. Pooling the analysis from all three classrooms gave a concentration of $0.00013 \text{ s ml}^{-1}$ for $\leq 5\text{-}\mu\text{m}$ -long asbestos fibres.

Site B

Tables 1 and 3 summarize the PCM and TEM results from site B with the heaters running. The tables compare the results from the background and disturbance sampling. The low background counts (0.5–3.5 fibres) gave calculated PCM fibre concentrations from 0.0001 to 0.0006 f ml^{-1} . The PCM counts from disturbance sampling varied between 1 and 5.5 fibres and gave calculated concentrations between 0.0001 and 0.0005 f ml^{-1} . The low PCM fibre counts from site B are similar to what would be expected for blank filter counts and were all well below the LOQ. All the individual background and disturbance results were within the 95% confidence interval for a count of two fibres and there was no evidence for any significant release of fibres into the classrooms of School B.

The TEM results from analysing the filters from the samples collected directly under the vents showed that only one asbestos fibre was detected. This was a PCME crocidolite fibre in a background sample. Pooling the three classrooms together, the concentrations of PCME asbestos fibres were at the AS ($0.000033 \text{ f ml}^{-1}$) and below the LOQ ($<0.00005 \text{ f ml}^{-1}$) before disturbance sampling and were below the AS during the disturbance sampling. No short ($\leq 5 \mu\text{m}$ long) asbestos structures or any amosite was found during the TEM analysis.

Site C

No PCM results or samples from the side-by-side sampling were released to HSL. However, PCM results from background monitoring over a weekend some 8 weeks earlier, while the school was open, were

Table 1. Summary of PCM static sampling results in Schools A–C analysed by local laboratories.

School	Activity	Number of samples	Range of actual calculated PCM fibre concentrations (f ml ⁻¹)	Range of calculated LOQ (f ml ⁻¹) for PCM (based on 20 fibres counted)
A	Ceiling heaters running with no disturbance	9	0.0005–0.0009	All < LOQ (<0.0016 to <0.0038)
A	Ceiling heaters running and disturbance	9	0.0005–0.0016	All < LOQ (<0.0016 to <0.0038)
B	Ceiling heaters running with no disturbance	9	0.0001–0.0006	All < LOQ (<0.0016 to <0.0038)
B	Ceiling heaters running and disturbance	9	0.0001–0.0006	All < LOQ (<0.0016 to <0.0038)
C	Ceiling heaters running with no disturbance ^a	16	0.001–0.007	All < LOQ (<0.010)
C	Ceiling heaters running and disturbance		Not available	

^aSamples taken over a weekend several weeks before the TEM sampling and with lower volumes of air sampled. No PCM data was made available to HSL from the side-by-side sampling.

Table 2. School A, detailed comparison of the individual PCM and TEM results for samples collected directly under the inlet.

Sample number	Number of PCM fibres counted	Calculated PCM fibre concentration (f ml ⁻¹)	TEM analytical sensitivity	Number and type of TEM asbestos fibres found			TEM asbestos concentration		
				>5 µm	PCME	≤5 µm	>5 µm (f ml ⁻¹)	PCME (f ml ⁻¹)	≤5 µm (s ml ⁻¹)
Fibre counts and calculated concentrations with heaters running but no disturbance									
3A	10	0.0008	0.000093	0	0	0	<0.0003	<0.0003	<0.0003
6A	6	0.0005	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
9A	7	0.0006	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
Fibre counts and calculated concentrations with heaters running and disturbance									
12A	13	0.0011	0.000094	0	0	1Act	<0.0003	<0.0003	<0.0005
15A	6	0.0005	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
18A	11.5	0.0009	0.000096	0	0	2A + 1C	<0.0003	<0.0003	<0.0008

The < values are based on the upper 95% confidence limit.

Type of asbestos: A, amosite; Act, actinolite; C, chrysotile.

available (Table 1), but the LOQ was only just below the minimum (0.010 f ml⁻¹) recommended in HSG 248. Sixteen measurements were made on the Saturday

(in storerooms, classrooms, and stairwells). All results were <LOQ and gave a calculated average concentration of 0.002 f ml⁻¹ (range 0.001–0.007 f ml⁻¹). The 10

Table 3. School B, detailed comparison of the individual PCM and TEM results for samples collected directly under the inlet.

Sample number	Number of PCM fibres counted	Calculated PCM fibre concentration (f ml ⁻¹)	TEM analytical sensitivity (f ml ⁻¹)	Number and type of TEM asbestos fibres found			TEM asbestos concentration		
				>5 µm	PCME	≤5 µm	>5 µm (f ml ⁻¹)	PCME (f ml ⁻¹)	≤5 µm (s ml ⁻¹)
Fibre counts and calculated concentrations with heaters running but no disturbance									
3B	3	0.0006	0.000100	1K	1K	0	0.0005	0.0005	<0.0003
6B	6	0.0005	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
9B	2	0.0002	0.000098	0	0	0	<0.0003	<0.0003	<0.0003
Fibre counts and calculated concentrations with heaters running and disturbance									
12B	2.5	0.0002	0.000094	0	0	0	<0.0003	<0.0003	<0.0003
15B	2	0.0004	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
18B	1	0.0001	0.000096	0	0	0	<0.0003	<0.0003	<0.0003

The < values are based on the upper 95% confidence limit.
Type of asbestos: K, crocidolite.

samples on the first floor where the heater fans were running gave an average of 4.25 fibres per count compared to an average of 3.9 fibres for the six ground floor samples where no heater cupboards were present, and are not significantly different at the 95% confidence level. No disturbance sampling of the ACMs was carried out but some personal samples were taken during surface cleaning activities on three operatives a week later. The results were again all below the LOQ, although the average counts were higher.

TEM results from the HSL sampling are given in Table 4. These were taken 6 weeks after the school closed and surfaces inside the classrooms had been cleaned and the furniture removed. The background in the first floor classrooms before disturbance, but with the fans running, gave individual results at or below the AS (<0.0001 f ml⁻¹). Only one PCME amosite fibre and one ≤5-µm-long amosite structure was found, which meant that the pooled average for the background samples was <LOQ (0.000031 f ml⁻¹) and at the AS (0.00001 f ml⁻¹).

Four of the five classrooms where disturbance sampling took place gave PCME amosite fibres above the AS and two exceeded the LOQ. The range of individual concentrations was between <0.0012 and 0.0043 f ml⁻¹. A total of 20 PCME amosite fibres were counted in the five samples analysed. The disturbance samples were taken over a shorter period ~2 h and had a lower

volume of air sampled so were less sensitive than the background samples, which were run for up to 14 h.

Only one >5-µm-long amosite fibre was counted which was too thin to be included in the PCME count but some 45 ≤5-µm-long amosite fibres were counted. Three fibres that were embedded in matrix and not identified were also seen. This gave a pooled average for the four classrooms of 0.0019 f ml⁻¹ for PCME asbestos fibres and 0.0044 s ml⁻¹ for ≤5-µm-long asbestos fibres.

Blank filters are routinely prepared during the TEM sample preparation, to be analysed if necessary. However, as only one PCME asbestos fibre was found in 12 TEM analyses at sites A and B, no additional useful information would be provided by analysing the blanks. The same applied to site C, where 12 TEM analyses of samples before disturbance also found only one PCME asbestos fibre in the same batch of filters. No blank filter counts were reported by PCM laboratories that carried out the sampling for the LAs. However, the PCM results were all <LOQ and many higher volume static samples were within a typical blank filter upper 95% confidence limit (i.e. 5 fibres per 100 graticules) (HSE, 2005).

DISCUSSION

It is well-known that PCM counts may not provide a reliable measure of non-occupational asbestos exposure (RCO, 1982; HEI-AR, 1991; HSE, 1998). There

Table 4. School C, TEM asbestos fibre concentrations.

Sample number	Room number	Air volume sampled (l)	Analytical sensitivity (f ml ⁻¹)	Number of asbestos fibres found			Airborne concentration of asbestos		
				>5 µm long	PCME	≤5 µm	>5 µm long (f ml ⁻¹)	PCME (f ml ⁻¹)	≤5 µm (s ml ⁻¹)
Background no fans running, no disturbance									
1C	179	6691	0.000065	0	0	0	<0.0002	<0.0002	<0.0002
Background with fans running minor disturbance with several entries and exits									
2C	175	1292	0.000097	0	0	0	<0.0003	<0.0003	<0.0003
3C	179	2904	0.000076	0	0	1	<0.0003	<0.0003	<0.0004
4C	184	2365	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
5C	201	1578	0.000096	0	0	0	<0.0003	<0.0003	<0.0003
6C	203	2192	0.000093	1	1	0	<0.0005	<0.0005	<0.0003
7C	203	2052	0.000154	0	0	0	<0.0003	<0.0003	<0.0003
With fans running no disturbance (overnight)									
8C	175	2083	0.000100	0	0	0	<0.0003	<0.0003	<0.0003
9C	179	9737	0.000024	0	0	0	<0.0001	<0.0001	<0.0001
10C	184	6124	0.000087	0	0	0	<0.0003	<0.0003	<0.0003
11C	201	3290	0.000086	0	0	0	<0.0003	<0.0003	<0.0003
12C	203	4090	0.000090	0	0	0	<0.0003	<0.0003	<0.0003
With fans running and disturbance sampling									
13C	175	991.9	0.00041	3	3	10	<0.0032	<0.0032	0.0041
14C	179	1386.6	0.00036	3	3	11	<0.0028	<0.0028	0.0040
15C	184	1209.6	0.00039	0	0	0	<0.0012	<0.0012	<0.0012
16C	201	795.6	0.00043	11	10	16+3 ^a	0.0047	0.0043	0.0082
17C	203	953.6	0.00042	4	4	8	0.0017	0.0017	0.0034

The < values are based on the upper 95% confidence limit.

^aAll asbestos fibres were identified as Amosite except for three fibres embedded in a large particle which were assumed to be amosite.

are many types and sources of non-asbestos fibres (HSE, 2005)) and PCM does not identify whether the fibres are asbestos. Low concentrations are particularly unreliable as blank filters will contribute a few fibre counts (HSE, 2005). In most buildings under normal occupancy, non-asbestos fibres are likely to be present in much greater numbers than asbestos fibres. When unoccupied, the six filters from School A, analysed by both PCM and TEM, gave a combined count

of 53.5 PCM fibres but no equivalent sized asbestos fibres were found. As all the PCM concentrations were <LOQ and many were similar to the counts that could be expected from blank filters, it is only possible to conclude that the PCM results gave no evidence for significantly raised levels of asbestos.

The assessment of the concentration of PCME asbestos fibres is the key measurement for assessing the exposure and risk and the analysis closely followed

the ISO 10312:95 method. However, the evaluation of the $\leq 5\text{-}\mu\text{m}$ -long amosite structures as carried for this study had a number of small differences from the published method, and this could result in a small bias for the short fibre count. However, as shown, these counts gave increased sensitivity in detecting low concentrations of airborne asbestos, without the need to repeat the analysis at a higher magnification.

The sample collection used in this study, which required close collaboration with the schools, LEAs, and their contracted air sampling laboratories, demonstrated that it would be an effective strategy to use for a larger survey. It also allowed the samples to be quickly screened on-site by PCM for any significant fibre counts above the LOQ. Half-filters were retained for further TEM analysis of the higher volume or higher fibre count samples, to assess whether the PCM fibre counts were due to asbestos, or the many types of non-asbestos fibres that may be present.

The air movement from the ceiling mounted heaters in two CLASP schools appears to have been too low to erode or resuspend asbestos fibres from the AIB, debris, and dust in the plenum. In addition, the disturbance sampling did not give rise to any measurable increase in PCME asbestos fibre exposure in the CLASP classrooms. Therefore, this study supports the HSE guidance (HSE, 2008) that sealing of the tops of columns in CLASP schools can be carried out when it is convenient to do so (e.g. when the plenum is accessed for refurbishment or for other significant building maintenance purposes) rather than as an urgent priority.

At School C, the PCME asbestos fibre concentrations for all the background samples were at or below the AS (0.0001 f ml^{-1}). This confirmed that the <LOQ PCM concentrations monitored some weeks earlier were not a reliable or accurate measure of the airborne asbestos concentration. The reported contamination of the plenum and heater cupboards by AIB dust and debris from previous poor removal did not produce significant background asbestos concentration in the classrooms due to air erosion or re-entrainment by the heating system.

Vigorous disturbance of all the accessible AIB panels, including the heating cupboard panels, gave short-term PCME asbestos concentrations of between <0.0012 and 0.0043 f ml^{-1} in five classrooms at School C. The number and intensity of the impacts applied (4 to each AIB panel and ~ 100 impacts per classroom)

over a 2h sampling period was designed to far exceed any normal occupied classroom disturbance level. This showed that direct disturbance of the AIB was the only significant source of release, hence the need to manage the ACMs in accordance with regulations, codes of practice, and guidance (CAR, 2012; HSE, 2010, 2013).

In the literature reviewed above, there is bias towards monitoring buildings and/or the areas where the ACMs were in poor condition and had the potential to give increased airborne asbestos concentrations (Sawyer, 1977; Sebastien *et al.*, 1980; Burdett *et al.*, 1984; Burdett, 1986; Burdett and Jaffrey, 1986; Burdett *et al.*, 2009; Nicholson *et al.*, 1978, 1979; Nolan and Langer, 2001). Airborne releases from dust (EN 15051-1, 2013) and ACMs are dependent on the moisture content and relative humidity. Individuals may sweat and respire significant amounts of moisture per day into an occupied school building, which may influence the airborne release of fibres. In this study the schools were sampled without occupants. Buildings may also become damp when not in use. As Schools A and B were sampled over a 1-week holiday and School C had originally been sampled over a weekend in term-time, this was unlikely to greatly alter the result. TEM sampling at School C took place 6 weeks after the school closed. The classrooms were dry and the conditions outside were cold and sunny with low relative humidity, although the previous weekend had been stormy and a small rain leak had occurred in one corridor.

CONCLUSIONS

The PCM fibre concentrations were all below the LOQ but analytical TEM showed that few of the fibres counted in the background samples were asbestos. The background TEM air concentrations for individual samples from all three schools with warm air heating systems for asbestos fibres were at or below the AS (0.0001 f ml^{-1}). These results are consistent with other experimental and field studies, in that the air velocities in ventilation and plenum warm air heating systems are generally too low to produce significant resuspension or erosion of asbestos fibres.

Disturbance sampling of the columns, in two CLASP schools (A and B) containing amosite AIB did not give rise to any significant increase of airborne amosite fibres or PCME asbestos fibres in the

classroom air from the unsealed casing tops. Only two short amosite fibres were found during the analysis.

A more vigorous disturbance in School C, by directly striking the AIB panels on heater cupboards and under the windows ~100 times in each classroom over a 2-h sampling period, released airborne PCME amosite fibres with short-term concentrations of up to 0.0043 f ml⁻¹ with a pooled average of 0.0019 f ml⁻¹ for the four classrooms giving measurable releases. The level of disturbance used was considered to replicate a peak exposure event from disturbances which did not damage the AIB.

The air sampling strategy was effective and worked well, and the results provide further important evidence to inform the sampling and management of asbestos in schools.

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