Science of the Total Environment 722 (2020) 137891

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Measurement of asbestos emissions associated with demolition of abandoned residential dwellings

Richard L. Neitzel [a,*], Stephanie K. Sayler [a], Avery H. Demond [b], Hannah d'Arcy [a], David H. Garabrant [a], Alfred Franzblau [a]

[a] *University of Michigan, Department of Environmental Health Sciences, Ann Arbor, MI, USA*
[b] *University of Michigan, Department of Civil and Environmental Engineering, Ann Arbor, MI, USA*

HIGHLIGHTS

- Asbestos in abandoned residential dwellings (ARDs) is a potential health risk.
- Data regarding the emissions of asbestos during ARD demolitions are sparse.
- Air sampling during 25 ARD demolitions identified only two asbestos fibers.
- Emissions of airborne asbestos during unabated ARD demolitions was negligible.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 7 January 2020
Received in revised form 10 March 2020
Accepted 11 March 2020
Available online xxxx

Editor: Mae Sexauer Gustin

Keywords:
Demolition
Asbestos exposure
Health risk
Cancer risk
Public health cost

ABSTRACT

Many cities are revitalizing their urban cores through the demolition of abandoned residential dwellings (ARDs). However, data regarding the emissions of asbestos during such an operation are sparse. We measured airborne asbestos emissions from emergency demolitions (demolitions on structures deemed too dangerous to enter and remove asbestos) of ARDs in Detroit.

High-flow air sampling was conducted during ARD demolitions. Air samples were analyzed using Phased Contrast Microscopy (PCM), and a subset using Transmission Electron Microscopy (TEM).

One hundred and one air samples were collected on 25 emergency demolitions. Fifty-four of the 101 PCM samples (53%) exceeded the limit of detection (LOD). However, only 2 of 46 TEM samples (4%) exceeded the LOD for asbestos; these latter samples were from two different demolitions and each contained a single chrysotile asbestos fiber. Using conservative exposure assumptions and commonly-accepted risk estimation formulae, we estimated the lifetime risk of mesothelioma and lung cancer combined to be less than one case per one million people. Emissions of airborne asbestos during emergency (unabated) ARD demolition operations appear to be negligible. As a result, the associated health risk for asbestos-related disease is also negligible. Reconsideration of current regulatory mandates for asbestos abatement in ARDs may be warranted.

Abbreviations: ACM, asbestos-containing material; ARD, abandoned residential dwelling; LOD, limit of detection; PCM, Phased Contrast Microscopy; TEM, Transmission Electron Microscopy.

* Corresponding author at: University of Michigan, Department of Environmental Health Sciences, 1415 Washington Heights, Ann Arbor, MI 48109-2029, USA.
E-mail address: rneitzel@umich.edu (R.L. Neitzel).

https://doi.org/10.1016/j.scitotenv.2020.137891
0048-9697/

1. Introduction

Abandoned residential dwellings (ARDs) affect community health and well-being. They attract crime, such as drug use and vandalism (Garvin et al., 2013a); harbor rodents, feral dog packs (Lyu, 2015), mold, and insects (Sheffield et al., 2014); and have a high incidence of fires with consequent injuries, deaths, and damage to adjacent structures (Neavling, 2016; USFA/FEMA, 2015). The simple removal of these structures has been demonstrated to significantly reduce crime (Spelman, 1993), possibly reduce gun violence (Jay et al., 2019) and promote health by decreasing anxiety and increasing exercise and active transportation (e.g., walking, running, and bicycling) (Branas et al., 2011; Garvin et al., 2013b). Post-industrial cities across the US struggle with high rates of ARDs. The City of Detroit has the highest percentage of ARDs in the US: >67,000 properties (an estimated 23% of the total housing stock) are abandoned dwellings, of which about 30,000 are residential single-family homes (United States Government Accountability Office, 2011). To address this problem, the City has been engaged in an ambitious effort to demolish these ARDs, with about 18,000 structures demolished over five years, from January 2014 through July 2019 (City of Detroit, n.d.).

The rapid removal of ARDs is complicated by the presence of asbestos in many of these structures. Inhalation exposure to asbestos has been linked to adverse health outcomes including asbestosis (a form of pulmonary fibrosis), lung cancer, and mesothelioma (Working Group on the Evaluation of Carcinogenic Risk to Humans, 2012; Hodgson and Darnton, 2000; N. R. Council, 1971; Attanoos, 2010). While lung cancer and mesothelioma have been extensively studied in workers (Working Group on the Evaluation of Carcinogenic Risk to Humans, 2012; Attanoos, 2010; Albin et al., 1999), there is also evidence of adverse health outcomes from asbestos exposures among children (Wilson et al., 2008; Yano et al., 2009; Hansen et al., 1993; Vinikoor et al., 2010; Ryan et al., 2013; Reid et al., 2013; Kang et al., 2013) and others living in communities near industrial facilities with levels elevated above natural background (Kurumatani and Kumagai, 2008; Chang et al., 1999; Marinaccio et al., 2015; Maule et al., 2007; Ravikrishna et al., 2010; Alexander et al., 2012; US Department of Housing and Urban Development, n.d.). Asbestos has been found in environmental air samples from urban (Selikoff et al., 1972) and rural areas (Royal Society of New Zealand and the Office of the Prime Minister's Chief Science Advisor, 2015; Singh and Thouez, 1985), even in the absence of an obvious industrial source (Pan et al., 2005; Abelmann et al., 2015; Corn, 1994; Luo et al., 2003; Rake et al., 2009). However, there is no evidence that exposure to such ambient background concentrations of asbestos is associated with elevated risk of disease. Asbestos can be classified as serpentine (chrysotile) or amphibole (amosite, crocidolite, tremolite, anthophyllite, actinolite); >99% of all asbestos used in the US was chrysotile, crocidolite or amosite (Virta, 2006) While all types of asbestos are carcinogenic (Working Group on the Evaluation of Carcinogenic Risk to Humans, 2012), the potency with respect to mesothelioma is about 1:100:500 for chrystile: amosite:crocidolite (Hodgson and Darnton, 2000; Berman and Crump, 2008a; Garabrant and Pastula, 2018).

We are unaware of any previous studies of airborne asbestos releases from the demolition of ARDs. Two studies of partially-abated structures found no or minimal increases in airborne asbestos following demolition (Perkins et al., 2007; Wilmoth et al., 1994). Notably, neither of the two demolitions studied by Perkins et al., was a single-family dwelling: one was a 4-story commercial hotel (floor area estimated to be ~18,300 square feet), the other was an entire city block of wooden structures (combined floor area estimated to be ~17,760 square feet). Similarly, the report by Wilmoth et al. focused on asbestos emissions during the demolition of two elementary schools (approximate areas of 22,000 and 24,000 square feet). There was no indication of increased asbestos-related disease following the destruction of the World Trade Center from this short but intense exposure (Nolan et al., 2005). These limited data suggest that demolition may not result in an increased risk of asbestos-related disease to community residents due to the low airborne asbestos emissions and the short duration of exposure, particularly where the asbestos is not in a friable form (Lange, 2001). Furthermore, a large proportion of the released asbestos is likely to be chrysotile, the least potent type of asbestos (Hodgson and Darnton, 2000; Berman and Crump, 2008b), and single-family ARDs are likely to contain a smaller amount of asbestos than commercial and industrial structures (National Research Council, 1971). To date, there are no estimates of the risk of asbestos-related disease stemming from widespread ARD demolition, and no assessment of the association between benefits and cost of abatement and demolition.

The Environmental Protection Agency (EPA) requirements for demolition-related asbestos abatement have undergone periodic revisions. In 1973, the agency stated that the need for asbestos abatement prior to demolition applied to apartment buildings only if they included four or more dwelling units (U.S. Environmental Protection Agency (EPA), 1973), which the agency later updated to specifically exclude residential buildings (including condominiums, cooperatives, apartments, and other multi-dwelling structures) having four or fewer dwelling units (U.S. Environmental Protection Agency (EPA), 1995). This determination was consistent with an earlier National Academy of Sciences finding that "…single-family residential structures contain only small amounts of asbestos…" (National Research Council, 1971). However, in 1995, the EPA issued a clarification stating that ARDs that were to be demolished as part of commercial or public works projects would be classified as a facility and consequently would require abatement (Environmental Protection Agency, 1995). This ruling substantially increased the economic burden on cities seeking to reduce urban blight, as the cost of asbestos abatement significantly increases the cost of ARD demolitions, without a demonstrated improvement in public health, given the NAS's assessment that single-family structures do not contain appreciable asbestos.

Over 93% of the housing stock in Detroit was built before 1978 (Michigan Department of Community Health, 2013), largely before the use of asbestos in residential construction was discontinued in the late 1970s and 1980s. Thus, most homes can be assumed to contain various forms of asbestos-containing materials, including window caulk, insulation, plaster and taping compounds, floor and roofing tiles, and siding. According to the Detroit Land Bank Authority, the average cost of ARD demolitions in 2016 was $12,619, of which $3971 was the cost of asbestos abatement, nearly a third of the overall cost. Based on the information available to date, this expenditure of public funds for asbestos abatement of uninhabited dwellings may not provide a commensurate improvement in public health. Furthermore, the inspection and asbestos abatement process adds additional time to blight removal, impeding the safety and public health benefits achieved through demolition.

To determine concentrations of asbestos present during the demolition of abandoned residential dwellings, we measured airborne asbestos concentrations during the demolition of ARDs which were sufficiently damaged due to fire and/or structural deterioration that asbestos inspection and abatement could not be performed prior to demolition. Such 'emergency' demolitions are conducted by Detroit Land Bank Authority under specially-permitted conditions. Samples of airborne asbestos were collected during these demolitions and analyzed using the standard technique used by demolition contractors and regulators, Phase Contrast Microscopy (PCM). This technique has been criticized as it cannot differentiate asbestos fibers from other non-asbestos fibrous materials or distinguish among types of asbestos fibers (Corn, 1994; Dement and Wallingford, 1990). Numerous studies have shown that PCM significantly overestimates the amount of asbestos present; for example, in a study by Burdett and Jaffrey, measurements were conducted in 39 buildings where asbestos was present in the heating systems (Burdett and Jaffrey, 1986). Two hundred thirty-five samples were analyzed by PCM and 13% gave fiber concentrations above 0.01 f/mL. However, a parallel analysis using TEM showed that most of the fibers counted were not asbestos, and, in only one location, did the asbestos fiber concentrations exceed 0.001 f/mL. A similar pattern was reported by Perkins et al. (Perkins et al., 2007). Thus, it appears that PCM may overestimate asbestos concentrations by at least an order of magnitude.

In order to provide a more accurate assessment of asbestos concentrations, we also analyzed samples using Transmission Electron Microscopy (TEM), which can more definitively identify and quantify asbestos fibers, but is not as frequently used for routine asbestos measurements because of the greater expense. Finally, we compared characteristics of the ARDs in our sample of emergency demolitions that were not abated prior to demolition, with those from a database of abated ARD demolitions in Detroit, randomly sampled, to determine the difference in demolition costs (Franzblau et al., 2019). The risk of adverse health outcomes, specifically lung cancer and mesothelioma, associated with emissions of airborne asbestos from ARDs removed via emergency demolition, was estimated using methods described by Hodgson and Darnton (Hodgson and Darnton, 2000) and Berman and Crump (Berman and Crump, 2008b; Berman and Crump, 2008c). This paper complements our companion paper (Franzblau et al., 2019) describing asbestos bulk sampling results for abated and demolished ARDs in Detroit.

2. Methods

2.1. Selection of demolitions for air emissions sampling

We worked with the Detroit Land Bank Authority and participating demolition contractors to identify 25 emergency demolitions planned during the sampling time period, October 2017 to March 2018. Once particular demolitions were identified, we worked directly with contractor staff to determine the specific date and time of each demolition, and arranged to be at the site prior to the start of the demolition to allow sufficient time for sampling setup.

2.2. Collection of air samples

Flite 3 air sampling pumps (SKC, Inc) were configured to sample air at 12 ± 1.2 L/min, to collect air samples from around the emergency demolition of 25 ARDs. All pumps were calibrated before and after each measurement period, and calibration values were recorded on a demolition log. On each sampling day, one blank sample was collected and analyzed. Pumps were set up prior to the demolition according to the wind direction at the site. At least one pump was placed downwind, and one pump was placed on each of the other three sides of the house, if possible. Pumps were placed outside of the demolition zone, but as close as possible to the structure without risking damage, interfering with demolition operations, or trespassing on private property. Typical pump placements were 40–60 ft. from the demolition zone, at a height of three feet (this height was chosen to better simulate exposure of small children). For each pump, the location and distance from the structure was recorded on a map of the property. Pump start and stop times were also recorded. Pump run times and pre- and post-calibration pump flow rates were used to calculate the volume of the collected air samples. Samples were collected on 25-mm, three piece cassettes with 50-mm electrically conductive cowls and cellulose ester filters with backups according to National Institute for Occupational Safety and Health (NIOSH) method 7400 for PCM (National Institute for Occupational Safety and Health (NIOSH), 1994a) and NIOSH method 7402 for TEM (National Institute for Occupational Safety and Health (NIOSH), 1994b). Filter cassettes were not grounded, as relative humidity was >20% during all samples.

For one demolition, two samples were collected for about twenty minutes prior to the start of demolition activities to determine background levels of airborne asbestos. Further pre-demolition samples were not collected due to concerns for the safety of the research team. After these samples were collected, each pump was calibrated again and this value was used as the pre-calibration value for the subsequent measurements taken during the demolition. Then sampling was conducted during the entire time required to demolish the structure. In some cases, samples were also collected during the collection and loading of debris onto trucks for removal. Finally, during four demolitions, we collected measurements after the demolition, to evaluate how much asbestos concentrations declined after demolition ceased. Previous research suggests that 99% of chrysotile asbestos fibers settle out of air over a period of 20–80 min after initial suspension (Sahmel et al., 2015).

Since weather conditions may play a role in the quantity of airborne asbestos, weather conditions (e.g., temperature, average and peak wind speed, and relative humidity) were measured for five minutes prior to the start of sampling using an AcuRite 5-in-1 Weather Sensor (Chaney Instrument, Lake Geneva, Wisconsin, USA) positioned five feet off of the ground within 100 ft. of the structure to be demolished. In addition, the presence of precipitation during the demolition was noted and whether water was sprayed on the structure during the demolition, and, if so, for how long. The practice of wetting during demolition is prescribed by the National Emission Standard for Hazardous Air Pollutants (NESHAP) (Environmental Protection Agency, 1995), though the requirement is suspended or optional during sub-freezing temperatures. Finally, research staff visually assessed each ARD prior to demolition for fire damage, though it was not possible to complete a full visual inspection at many sites due to limited access.

2.3. Collection of demolition cost information

The Detroit Land Bank Authority provided the investigators with access to information on each structure demolished under emergency conditions including year built, number of floors, total square footage, and estimated demolition costs. Additionally, the Land Bank Authority provided the investigators with access to a dataset of already-demolished ARDs, including information on square footage, presence of asbestos through bulk sampling, abatement cost, demolition cost, and total cost (the sum of abatement and demolition costs). This dataset is described in greater detail in our companion paper (Franzblau et al., 2019). This dataset contained information on 11,043 completed demolitions, including 1232 emergency demolitions. After removing the emergency demolitions, we created a database of 605 ARDs, based on a random sample of the remaining 9811 non-emergency demolition.

2.4. Laboratory analysis of air samples

All laboratory analyses were conducted by Maxxam Analytics (Novi, MI). All samples were analyzed according to the NIOSH 7400 method for PCM (National Institute for Occupational Safety and Health (NIOSH), 1994a); due to budget constraints, only a subset of samples was analyzed using the NIOSH 7402 method for TEM (National Institute for Occupational Safety and Health (NIOSH), 1994b), given that per-sample TEM analysis costs were more than twenty-fold greater than PCM analysis costs. The TEM analyses were concentrated on the largest air volume samples at measurement locations downwind of the demolition site. The laboratory combined the fiber numbers it measured with our reported air sample volume to calculate an average fiber concentration for each sample. For the TEM analyses, the laboratory also reported the number and type of asbestos fibers (as determined using energy-dispersive x-ray spectroscopy) per cubic centimeter, as well as the length, diameter, and aspect ratio of the asbestos fibers. The TEM analyses also included the identification of 'non-regulated amphiboles' (if found), such as winchite and richterite, which can be present in vermiculite insulation.

2.5. Data analysis

Data from the demolition log, laboratory analyses, and Detroit Land Bank Authority database were combined in Excel (Microsoft, Inc., Redmond, WA) and exported into SPSS version 25 (SPSS Inc., Chicago, IL) and SAS version 9.4 (SAS Institute Inc., Cary, NC) for analysis. We used descriptive statistics to characterize the houses being demolished as well as the environmental conditions during demolition. Further descriptive statistics were computed for all air samples, and for the subset of air samples where TEM was also performed. We computed the median, 75th percentile, and 90th percentile concentrations of airborne asbestos fiber concentrations. Conventionally, concentrations below the limit of detection (LOD) are assigned the value LOD/2 or LOD/√2 (Hornung and Reed, 1990). However, Gillespie et al. (Gillespie et al., 2010) have shown that using LOD/2 (which assumes values below the LOD have a uniform distribution) or LOD/√2 (which assumes these values have a triangular distribution) results in substantial bias when the percentage of censored values is high. Based on their recommendations, we used the Reverse Kaplan-Meier method (Reverse K-M) to estimate levels below the LOD, since this method does not require any assumptions about the nature of values below the LOD, leading to more accurate percentile calculations (Gillespie et al., 2010). The LODs for the samples taken in this study were 0.00038 to 0.5 fibers/cc for PCM and 0.000086 to 0.013 fibers/cc for TEM.

Histograms were used to examine costs for emergency (non-abated) and abated demolitions, and scatter plots were used to visualize relationships between total costs, abatement costs, age, and the total square footage of the homes. In addition, Pearson correlations were also used to assess relationships among these variables.

2.6. Risk estimates

In order to estimate the risk of adverse health outcomes, specifically lung cancer and mesothelioma, associated with emissions of airborne asbestos from homes removed via emergency demolition, we estimated lifetime risk using methods described by Hodgson and Darnton (Hodgson and Darnton, 2000), wherein the relationship between percent excess mortality due to pleural cancer and cumulative exposure was $P_{pl} = A_{pl}X^r$. P_{pl} is the percent excess mortality from pleural cancer, X is cumulative exposure, and A_{pl} and r are parameter estimates obtained from Poisson regression models. For pleural cancer, A_{pl} was estimated as 0.0057 and 0.02, and r was estimated as 0.72 and 1.2, for chrysotile and amosite (respectively), by Hodgson and Darnton. For lung cancer the corresponding exponential model was used ($P_L = A_LX^r$), with A_L estimated as 0.028 and 1.6, and r estimated as 1.3 and 1.3, for chrysotile and amosite (respectively), by Hodgson and Darnton. We also estimated lifetime risk of pleural cancer and lung cancer using the methods of Berman and Crump (Berman and Crump, 2008a; Franzblau et al., 2019), which at low cumulative exposures gave identical results as the methods based on Hodgson and Darnton.

3. Results

The vast majority of the demonlition homes (88%) had 1.5 or more floors (Supplemental Materials, Table S1). The mean total square footage was 1795 ± 873 square feet; 20% of homes were <1000, and 28% ≥ 2000, square feet. All homes were built between 1900 and 1970 (average year 1919). Most (56%) homes, based on visual observations of the researcher staff, did not appear to be fire damaged.

Roughly half (52%) of the 25 demolitions took place during days when the air temperatures was below freezing (mean temp. = 33.1 °F), while the majority (60%) took place when the relative humidity was greater than or equal to 60% (Supplemental Materials, Table S2). Mean and peak wind speeds were low (<5 mph) during most demolitions. Demolition and debris removal/cleanup activities typically took about 4–6 h to complete; a major source of variation was related to wait times for additional dump trucks to transport debris. Water was sprayed for dust suppression during both active demolition and cleanup in 84% of the demolitions, and during demolition only for 8%. No water was sprayed in 2 (8%) of demolitions; the temperature was below freezing (16 °F and 31 °F, respectively) during these days. (As previously noted, the EPA requirement to spray water is suspended when the ambient temperature is below freezing, but in most such cases the contractors sprayed water anyway.) During more than two thirds of sampled operations, there was no precipitation.

The mean demolition cost per house was $15,573 ± $3906, with a range of $7950–$25,960 (Supplemental materials, Table S2). The correlation between total cost and year built for the emergency demolitions was shown to be negligible and statistically insignificant (data not shown). On the other hand, we found a positive association between demolition cost and total square footage (r = 0.46, p = 0.020) (Fig. 1). Fig. 2 shows the distribution of the total cost for the 25 emergency demolitions (Fig. 2A), as well as for the random sample of 605 non-emergency ARDs for comparison (Fig. 2B). While emergency demolitions did not involve inspection or abatement costs, the median total demolition cost for the emergency demolitions was nearly $2000 greater than that for the non-emergency demolitions ($15,573 vs $13,645, respectively) which included inspection and abatement costs, though the standard deviation and range of costs were greater among non-emergency demolitions. Compared to the random sample of abated ARDs, the emergency demolitions examined here were more likely to have two floors (88% here vs. 69% of non-emergency ARDs), larger mean square footage (1795 sq. ft. here vs. 1270 sq. ft. for non-emergency ARDs), and older (mean date of construction 1919 here vs. 1929 for non-emergency ARDs) (data not shown).

One hundred and one air samples were collected during the 25 demolitions and analyzed via PCM (Table 1); of these, TEM was conducted on 46 samples (45.5%). The majority of samples were collected at a distance of 40–60 ft., with the mean distance between the demolition site and air sampling equipment equal to 52.4 ft. for all samples, and to 46.2 ft. for samples analyzed via TEM. A slight majority of all samples, as well as TEM samples, involved pump run times >5 h, but the average run time was approximately 4 h, reflecting measurements that spanned both demolition and cleanup activities. This, combined with the average pump sampling rate of 12.3 L/min, yielded an average sample volume of approximately 3000 L for all samples.

Fiber concentrations are shown in Table 2. Asbestos was found in the air samples of only two (8%) of the sampled homes; in both cases, a single asbestos fiber was identified. Among all 101 samples, 54 (53%) of samples had fiber concentrations (fibers/cc) above the PCM LOD. Among the 46 TEM samples, only 2 (4%) had detectable concentrations of asbestos fibers, while 39 (85%) had detectable concentrations of non-asbestos fibers, primarily organic matter. Based on the LODs in our TEM samples, we would expect that 95% of the time we would detect a concentration of 0.0075 fibers/cc or greater. No amphibole asbestos fibers (e.g., amosite or crocidolite) and no non-regulated amphibole fibers were detected in any of the samples analyzed via TEM. The concentrations of all fibers/cc (n = 101 samples), asbestos fibers/cc (n = 46), and non-asbestos fibers/cc (n = 46) were all quite low, and the concentrations of asbestos fibers/cc in particular were small, even at the 90th percentile (0.0001 fibers/cc). By comparison, background concentrations in urban areas of the US in the 1990s (the last date for which concentrations were reported) were estimated to have a mean of 0.0016 fibers/cc, (Abelmann et al., 2015) using a dataset where approximately 94% of samples were analyzed via TEM. Sixty-six percent of the LODs for our samples were lower than this background concentration. The two background samples we collected prior to a single ARD demolition were also below the LOD, and both of these LODs were below the background concentration reported by Abelmann (Abelmann et al., 2015).

Table 3 shows information from the two emergency ARD demolitions at which two chrysotile asbestos fibers were measured. The two ARDs were located immediately adjacent to one another, and were

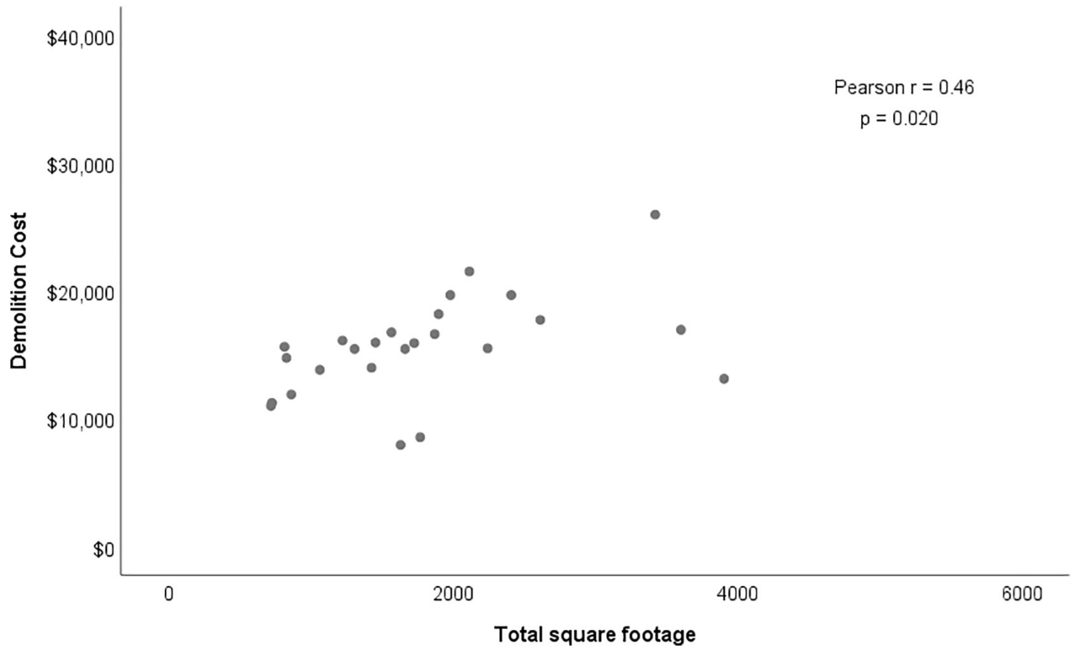

Fig. 1. Relationship between total cost and square footage from 25 sampled ARDs.

demolished on the same day, in wind conditions typical for the 25 ARDs we sampled, and during rain precipitation. The pumps were run over the same period for both structures, and the two demolitions were completed at the same time, but demolition for home 1 started earlier in the pump run time than did home 2. Demolition and debris removal occurred concurrently for both homes. The two structures were relatively similar in size and configuration, but despite their close proximity, they were built 28 years apart. The filter from home 2 was found to be overloaded on analysis. Under standard laboratory practice, a redistribution of the sample was performed, so that only a fraction of the original sample was analyzed. This resulted in a higher limit of detection for home 2, and a marked difference in asbestos fiber concentrations between the two homes. The two chrysotile asbestos fibers observed were similar in fiber length (both were 10-20 μm), but differed substantially in fiber diameter and aspect ratio.

Notably, 96% of the 605 ARDS demolished under non-emergency conditions were found to contain asbestos based on bulk sampling results, almost all of which was chrysotile (Franzblau et al., 2019). Eight of the 605 had commercial amphibole asbestos (~1%, 8 with amosite and 1 also with crocidolite), and 36 were found to have vermiculite (~6%). Thus, it appears that little of the asbestos in the structure becomes airborne during demolition.

The following assumptions were employed to estimate cancer risks for community residents: 1) average airborne exposure concentrations were equal to the 90th percentile of our TEM measurements for chrysotile based on the reverse Kaplan-Meier method (i.e., 0.0001 fiber/cc); 2) although ARD demolitions (including demolition and cleanup) typically lasted 4 to 6 h, to be conservative, we assumed that a community resident was exposed to such concentrations for a 'working month' (i.e., 5 days per week, 8 h per day, for one month); and, 3) that follow-up extended from birth to 80 years after exposure. The risk was expressed as the number of cancer cases (i.e., lung cancer and/or mesothelioma) per one million lifetimes. With these assumptions, the estimated risk of cancer, and the associated upper bound estimate, were both $<1 \times 10^{-6}$, the *de minimis* level used by US regulators (Castorina and Woodruff, 2003). As noted above, none of the TEM measurements for the 25 emergency demolitions found any amphibole asbestos or non-regulated amphibole fibers. In addition, few of the 605 ARDs demolished after abatement were found to contain amphibole asbestos (~1%) or vermiculite (~6%). Nevertheless, if one were to assume that airborne amosite was present at the same concentration as measured for chrysotile (i.e., the 90th percentile was 0.0001 fiber/cc), that exposure lasted for 10 8-h work days (i.e., two 'working weeks', less than the 'working month' used for chrysotile given the comparative rarity of airborne amosite in our samples), and that follow-up extended for 80 years, the estimated risk of cancer (and associated upper bound estimate) would again be $<1 \times 10^{-6}$.

Given the chrysotile exposure assumptions above (i.e., exposure for one working month at 0.0001 f/cc), the estimated lifetime cumulative exposure of community residents to chrysotile from demolition of ARDs would be 8.3×10^{-6} f/cc-years. Based on review of relevant cohort studies, Pierce et al. (Pierce et al., 2016) determined the range of "best estimate" no-observed-adverse-effects levels (NOAELs) for cumulative exposures to chrysotile asbestos for lung cancer to be 89–168 f/cc-years, and 208–415 f/cc-years for mesothelioma, in each case >7 orders of magnitude above the estimated lifetime cumulative exposure of community residents from demolition of ARDs.

4. Discussion

Demolition of abandoned residential dwellings in post-industrial cities represents a method for revitalization of the urban core. However, it is thought that demolition may release toxic materials, such as asbestos, into the surrounding community. Our study appears to be one of the first to evaluate emergency demolitions of structures without abatement of asbestos in a city where the vast majority of the housing stock is likely to contain asbestos, as indicated by the presence of asbestos in 95% of ARDs in a random sample of 605 non-emergency demolitions (Franzblau et al., 2019). While the results of the traditional PCM analyses estimated a 90th percentile concentration of 0.0097 fibers/cc, TEM analyses indicated a 90th percentile asbestos concentration almost two orders of magnitude smaller (0.0001 fibers/cc). This difference in concentrations resulting from PCM and TEM analyses is well known. The inability of PCM to positively identify fibers as asbestos is particularly problematic in outdoor environmental settings where asbestos fiber levels are often low relative to other airborne fibers (Health Effect Institute, 1991). The levels we measured do not appear to be meaningfully different from background concentrations of asbestos in urban areas of the US (Abelmann et al., 2015; Van Orden et al., 1995).

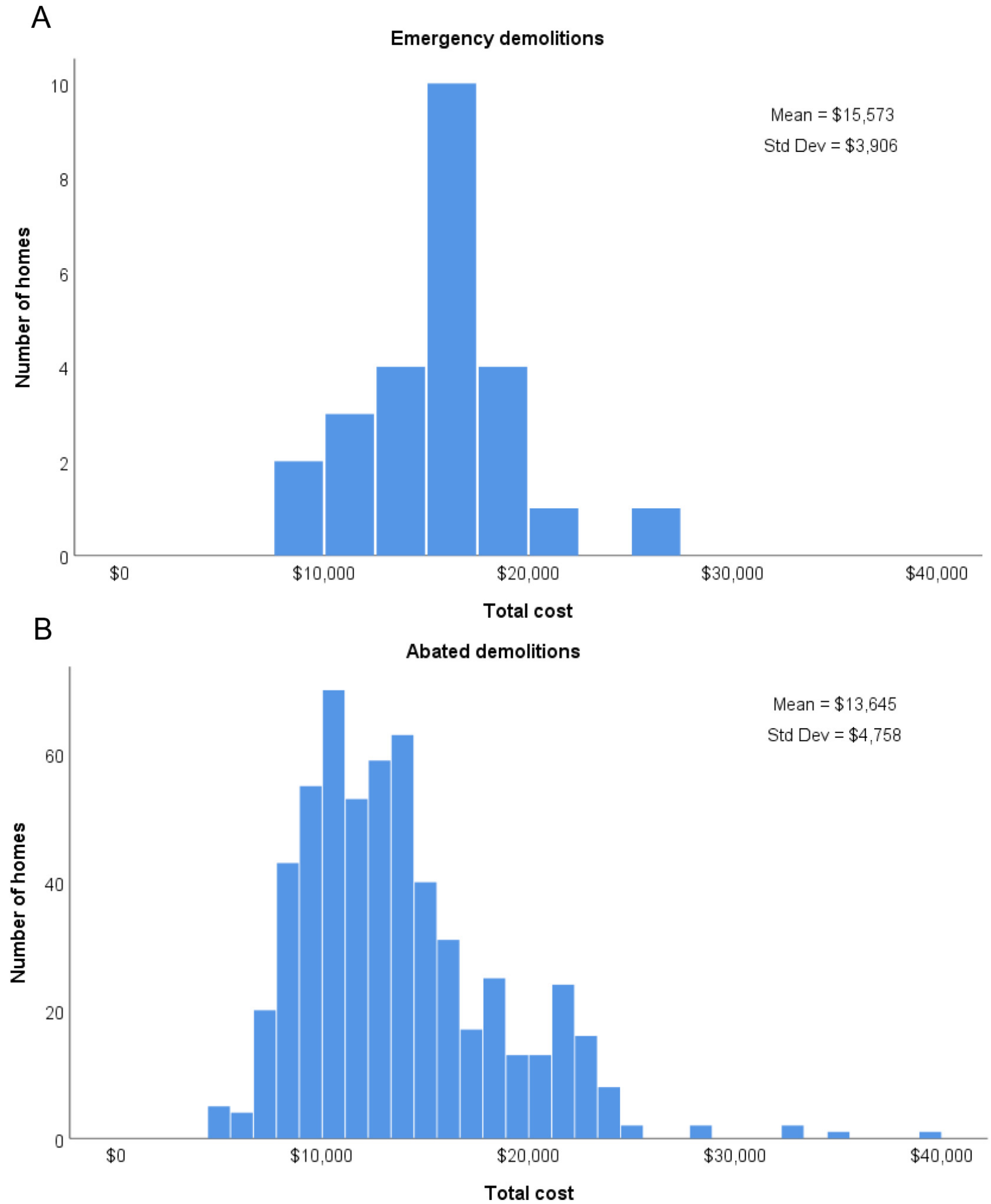

Fig. 2. Distribution of total costs, which includes demolition only for the emergency demolitions (A), and demolition and abatement for the non-emergency demolitions (B).

Only two asbestos fibers were identified in the 46 air samples analyzed by TEM during the demolitions of 25 ARDs demolished with no abatement. These fibers were both chrysotile, the least carcinogenic type of asbestos. The two ARDs were located adjacent to one another, were demolished on the same day, and were relatively similar in size and configuration, despite being built 28 years apart. The possibility that both fibers came from only one of these demolitions cannot be discounted, given the proximity of the demolished structures and the close timing of the demolitions on the sampling day. However, regardless of whether the fibers came from one or two of the emergency demolitions, the finding remains that the demolition of unabated ARDs did not result in significant emissions of asbestos fibers.

Emergency ARD demolitions had higher totals costs than non-emergency demolitions (difference between the medians was roughly $2000). The emergency demolitions were, on average, 565 square feet larger. On a square footage basis, the emergency demolitions had a demolition cost per square foot of $10.20, compared to $9.65 per square foot for the non-emergency demolitions excluding the cost of abatement (data not shown). Abatement added an additional cost of $2.39 per square foot to the non-emergency demolitions, for an average cost of $12.04 per square foot, or a cost difference of $1.84 per square foot even with the additional cost of sending the demolition wastes to an asbestos waste landfill. For a 1795 square foot home (the mean size of the ARDs examined here demolished under emergency conditions), the total difference in cost would be $3303. Waste from demolishing single-family houses can usually be sent to a municipal waste landfill. If the waste from demolishing ARDs on an emergency basis could be disposed of in the same manner as the wastes from demolishing other houses, the cost savings would be $2.39 per square foot (the cost of abatement) or $4290 per structure, or perhaps even greater, since the process of taking down ARDs would be greatly expedited.

Table 1
Characteristics of air samples taken during demolitions of 25 abandoned residential dwellings without asbestos abatement.

Variable	All samples (n = 101)		Transmission Electron Microscopy samples only (n = 46)	
	n (%)	Mean (SD) [range]	n (%)	Mean (SD) [range]
Distance from house				
<40 ft.	24 (24%)	52.4 (16.4)	16 (35%)	46.2 (14.2)
40 to 60 ft.	46 (46%)	[18, 90]	23 (50%)	[25, 75]
>60 ft.	31 (31%)		7 (15%)	
Down wind				
Yes	34 (34%)	–	31 (67%)	–
No	67 (66%)		15 (33%)	
Total pump run time				
<3 h	30 (30%)	3.9 (2.0)	11 (24%)	4.2 (1.9)
3 to 5 h	34 (34%)	[0.4, 7.1]	15 (33%)	[0.4, 7.1]
>5 h	37 (37%)		20 (44%)	
Average flow rate				
<12 L/min	13 (13%)	12.3 (0.3)	8 (17%)	12.3 (0.3)
12 to 12.5 L/min	68 (67%)	[11.6, 13.1]	29 (63%)	[11.6, 13.0]
>12.5 L/min	20 (20%)		9 (20%)	
Total volume				
<2500 L	34 (34%)	2880 (1494)	13 (28%)	3122 (1429)
2500 to 3500 L	25 (25%)	[258, 5279]	12 (26%)	[258, 5279]
>3500 L	42 (42%)		21 (46%)	

Table 3
Characteristics of the two adjacent home demolitions, at each of which a single chrysotile asbestos fiber was detected.

	Home 1	Home 2
Year built	1970	1942
# of stories	2	2
Square footage	1065	728
Date of demolition	1/15/18	1/15/18
Demo start and stop times	1:30 pm–4:22 pm	12:05 pm–4:22 pm
Temperature	18° F	18° F
Humidity	82%	82%
Samples taken downwind?	Yes	Yes
Average wind speed	3 mph	3 mph
Peak wind speed	5 mph	5 mph
Precipitation	Yes	Yes
Pump run time (mins)	258	262
Average flow rate	12.2	12.0
Total volume (L)	3146	3148
TEM asbestos fibers/cc	0.00027	0.015
Fiber length	13.33 μ	19.99 μ
Fiber diameter	0.27 μ	4.00 μ
Fiber aspect ratio	49.4	5.0

There is very limited literature with which to compare our results. Our observation that the fiber concentrations measured using PCM far overestimated the concentration of asbestos fibers echoes the limitations of the use of PCM in environmental asbestos analysis due to the inability of the method to positively identify asbestos fibers as found in other studies (Corn, 1994; Dement and Wallingford, 1990). In fact, the weaknesses of PCM have been suggested as a primary cause of the research gaps that exist today regarding asbestos, including fiber characteristics and toxicological mechanisms (Nelson et al., 2010). TEM analyses, while more costly, allow for the positive identification of asbestos fibers (and non-regulated amphibole fibers), the differentiation of fiber types, and the assessment of asbestos fiber dimensions (Nelson et al., 2010). The more recent models of risk estimation of asbestos related disease now include the type of information that only TEM can provide (Berman and Crump, 2008b; Berman and Crump, 2008c).

Although we cannot be certain that the individual emergency ARD demolitions we sampled contained asbestos, 96% of ARDs in a random sample of 605 houses in the Detroit Land Bank Authority database contained asbestos based on bulk sampling (Franzblau et al., 2019). Consequently, there is a 99.87% likelihood that at least 20 of the 25 homes included in the present study contained asbestos. It is conceivable that the emergency demolitions could have contained less asbestos than expected due to material removal or deterioration. However, the results presented here are consistent with other reports of low asbestos emissions, even in the case of the unabated demolition of commercial properties. Two studies of asbestos emissions during the demolition of commercial and public structures indicated that a large percentage of airborne fibers classified as asbestos using PCM was not confirmed as asbestos when evaluated using more advanced methods such as TEM, suggesting a possible routine overestimation of risk (Ravikrishna et al., 2010; Perkins et al., 2007). Perkins et al. (Perkins et al., 2007) determined that the small increase in airborne fiber concentrations during the demolition of a partially-abated commercial structure still remained below the occupational exposure limit, and Wilmoth et al. (Wilmoth et al., 1994) found that the demolition of two partially-abated schools while using dust-suppression resulted in no increase in downwind asbestos concentrations. A study of demolition and renovation debris from residential and nonresidential sites found ACM in only about 1% of sampled waste loads (Powell et al., 2015). Another study found that concentrations of asbestos following the 1989 Loma Prieta earthquake differed little from background levels, even immediately after the earthquake (Van Orden et al., 1995). When our results are combined with the results of previous studies, the available data suggest that airborne asbestos exposures from ARD demolition likely do not constitute a significant public health risk, and suggest that abatement of asbestos from ARDs prior to demolition may not be warranted.

5. Conclusions

Our results indicate that asbestos emissions resulting from the demolition of ARDs that likely contained asbestos were negligible and consistent with background levels. In the two cases of demolitions where a

Table 2
Selected percentiles of fiber concentrations[a] in air samples taken during the demolitions of 25 abandoned residential dwellings without asbestos abatement, with values below LOD estimated using the Reverse Kaplan-Meier method.[b]

Variable	Phased Contrast Microscopy All fibers/cc (n = 101)	Samples analyzed by Transmission Electron Microscopy (n = 46)		
		Phased Contrast Microscopy for subset of 46 samples All fibers/cc	Asbestos fibers/cc	Other fibers/cc
n (%) above LOD[c]	54 (53%)	25 (54%)	2 (4%)	39 (85%)
Median	0.0012	0.0018	–	0.0016
75th percentile	0.0022	0.0034	–	0.0084
90th percentile	0.0097	0.0400	0.0001	0.0310

[a] For comparison purposes, background levels in urban US areas in the 1990s (the last period for which data were reported) had a median concentration of 0.0016 fibers/cc (Abelmann et al., 2015) in a dataset where approximately 94% of samples were analyzed via TEM.
[b] A single asbestos fiber was identified in each of two samples from two (8%) of 25 homes.
[c] LODs ranged from 0.00038 to 0.5 fibers/cc for PCM, 0.000086 to 0.013 fibers/cc for TEM.

single fiber of asbestos was detected, the asbestos fiber was chrysotile, the least hazardous type of asbestos. Calculations of the health risk to community residents from airborne asbestos associated with ARD demolitions showed a lifetime cancer risk of $<1 \times 10^{-6}$, a level that is considered to be negligible. Thus, there does not appear to be a significant benefit to the public's health tied to the abatement of ARDs prior to demolition. Whatever minimal risk there may be associated with the background-level concentrations is likely far outweighed by the benefits associated with the efficient use of funds and time to expand demolition activities which have been found to be positively correlated with reductions in urban blight and crime (Branas et al., 2018), including homicides (Jay et al., 2019).

CRediT authorship contribution statement

Richard L. Neitzel: Conceptualization, Methodology, Supervision, Writing - original draft. **Stephanie K. Sayler:** Project administration, Investigation, Writing - review & editing. **Avery Demond:** Conceptualization, Methodology, Writing - review & editing. **Hannah d'Arcy:** Formal analysis, Writing - review & editing. **David H. Garabrant:** Formal analysis, Writing - review & editing. **Alfred Franzblau:** Conceptualization, Methodology, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Franzblau and Dr. Garabrant have served as expert witnesses in asbestos-related litigation.

None of the other authors have any financial interests/personal relationships which may be considered as potential competing interests.

Acknowledgements

The authors wish to acknowledge Brian Farkas, the Detroit Building Authority (DBA), and the Detroit Land Bank Authority (DLBA), as well as the management and workers of the participating demolition contractors, without whose logistical assistance this research would not have been possible. We also wish to thank Dr. Abdul el-Sayed, previously Director of the Detroit Health Department, for his support of the project. Additionally, we wish to thank the following individuals for their assistance with data collection and entry: Alexander Bartko, Sandar Bregg, Katherine Galen, Luyi Lu, Emily Nash, Ritu Pandit, Michael Sacchetti, and Peiyan Sun. Funding for this study was provided by a pilot grant from the University of Michigan Center on Lifestage Environmental Exposures and Disease, funded by grant P30ES017885 from the National Institute of Environmental Health Sciences, National Institutes of Health. The DBA and DLBA provided no funding. Neither the NIH, the DBA, nor the DLBA had any role in the study design, data analyses or interpretation, manuscript preparation, conclusions, or the decision to submit the manuscript for publication. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health, the DBA or the DLBA. Drs. Garabrant and Franzblau have served as expert witnesses in asbestos-related litigation. The other authors declare they have no actual or potential competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137891.

References

Abelmann, A., Glynn, M.E., Pierce, J.S., Scott, P.K., Serrano, S., Paustenbach, D.J., 2015. Historical ambient airborne asbestos concentrations in the United States – an analysis of published and unpublished literature (1960s–2000s). Inhal. Toxicol. 27 (14), 754–766 Dec.

Albin, M., Magnani, C., Krstev, S., Rapiti, E., Shefer, I., 1999. Asbestos and cancer: an overview of current trends in Europe. Environ. Health Perspect. 107 (Suppl), 289–298 May.

Alexander, B.H., et al., 2012. Radiographic evidence of nonoccupational asbestos exposure from processing Libby vermiculite in Minneapolis, Minnesota. Environ. Health Perspect. 120 (1), 44–49.

Attanoos, R.L., 2010. Asbestos-related lung disease. Surgical Pathology Clinics 3 (1), 109–127.

D. W. Berman and K. S. Crump, "Update of potency factors for asbestos-related lung cancer and mesothelioma.," Crit. Rev. Toxicol., vol. 38 Suppl 1, no. sup1, pp. 1–47, Jan. 2008a.

Berman, D.W., Crump, K.S., 2008b. Update of potency factors for asbestos-related lung cancer and mesothelioma. Crit. Rev. Toxicol. 38 (Suppl. 1), 1–47 September.

Berman, D.W., Crump, K.S., 2008c. A meta-analysis of asbestos-related cancer risk that addresses fiber size and mineral type. Crit. Rev. Toxicol. 38 (Suppl. 1), 49–73 no. sup1. Jan.

Branas, C.C., Cheney, R.A., MacDonald, J.M., Tam, V.W., Jackson, T.D., Ten Havey, T.R., 2011. A difference-in-differences analysis of health, safety, and greening vacant urban space. Am. J. Epidemiol. 174 (11), 1296–1306.

Branas, C.C., et al., 2018. Citywide cluster randomized trial to restore blighted vacant land and its effects on violence, crime, and fear. Proc. Natl. Acad. Sci. 115 (12), 2946–2951.

Burdett, G.J., Jaffrey, S.A., 1986. Airborne asbestos concentrations in buildings. Ann. Occup. Hyg. 30 (2), 185–199 Apr.

Castorina, R., Woodruff, T.J., 2003. Assessment of potential risk levels associated with U.S. environmental protection agency reference values. Environ. Health Perspect. 111 (10), 1318–1325.

Chang, H.Y., Chen, C.R., Wang, J.D., 1999. Risk assessment of lung cancer and mesothelioma in people living near asbestos-related factories in Taiwan. Arch. Environ. Health 54 (3), 194–201.

City of Detroit, d. Detroit demolitions. [Online]. Available. http://www.detroitmi.gov/demolition, Accessed date: 3 October 2016.

Corn, M., Aug. 1994. Airborne concentrations of asbestos in non-occupational environments. Ann. Occup. Hyg. 38 (4), 495–502 410.

Dement, J.M., Wallingford, K.M., 1990. Comparison of phase contrast and electron microscopic methods for evaluation of occupational asbestos exposures. Appl. Occup. Environ. Hyg. 5 (4), 242–247 Apr.

Environmental Protection Agency, 1995. 40 CFR Part 61 [FRL-5266-2] Asbestos NESHAP Clarification of Intent. pp. 38725–38726.

Franzblau, A., Demond, A., Sayler, S., D'Arcy, H., Neitzel, R., 2019. Asbestos-containing materials in abandoned residential dwellings in Detroit. Sci. Total Environ. 714 (20 April 2020, Article 136580). https://doi.org/10.1016/j.scitotenv.2020.136580 In press.

Garabrant, D.H., Pastula, S.T., 2018. A comparison of asbestos fiber potency and elongate mineral particle (EMP) potency for mesothelioma in humans. Toxicol. Appl. Pharmacol. 361, 127–136.

Garvin, E., Branas, C., Keddem, S., Sellman, J., Cannuscio, C., 2013a. More than just an eyesore: local insights and solutions on vacant land and urban health. J. Urban Health 90 (3), 412–426.

Garvin, E.C., Cannuscio, C.C., Branas, C.C., 2013b. Greening vacant lots to reduce violent crime: a randomised controlled trial. Inj. Prev. 19 (3), 198–203 Jun.

Gillespie, B.W., et al., 2010. Estimating population distributions when some data are below a limit of detection by using a reverse Kaplan-Meier estimator. Epidemiology 21 (4), S64–S70.

Hansen, J., De Klerk, N.H., Eccles, J.L., William Musk, A., Hobbs, M.S.T., 1993. Malignant mesothelioma after environmental exposure to blue asbestos. Int. J. Cancer 54 (4), 578–581.

Health Effect Institute, 1991. Asbestos in Public and Commercial Buildings: A Literature Review and Synthesis of Current Knowledge.

Hodgson, J.T., Darnton, A., Dec. 2000. The quantitative risks of mesothelioma and lung cancer in relation to asbestos exposure. Ann. Occup. Hyg. 44 (8), 565–601.

Hornung, R.W., Reed, L.D., 1990. Estimation of average concentration in the presence of nondetectable values. Appl. Occup. Environ. Hyg. 5 (1), 46–51 Jan.

Jay, J., Miratrix, L., Branas, C., Zimmerman, M., Hemenway, D., 2019. Urban building demolitions, firearm violence and drug crime. J. Behav. Med. 42, 626–634.

Kang, D., Myung, M.-S., Kim, Y.-K., Kim, J.-E., 2013. Systematic review of the effects of asbestos exposure on the risk of cancer between children and adults. Ann. Occup. Environ. Med. 25 (1), 10.

Kurumatani, N., Kumagai, S., 2008. Mapping the risk of mesothelioma due to neighborhood asbestos exposure. Am. J. Respir. Crit. Care Med. 178 (6), 624–629.

Lange, J., 2001. Airborne asbestos concentrations during abatement of floor tile and mastic: evaluation of two different containment systems and discussion of regulatory issues. Indoor and Built Environment 10 (3–4), 193–199.

Luo, S., Liu, X., Mu, S., Tsai, S.P., Wen, C.P., 2003. Asbestos related diseases from environmental exposure to crocidolite in Da-yao, China. I. Review of exposure and epidemiological data. Occup. Environ. Med. 60 (1), 35–41 discussion 41-2.

Lyu, P., 2015. Proposal on solutions to stray dog problem in American cities. J. Polit. Sci. Public Aff. 3 (3).

Marinaccio, A., et al., 2015. Malignant mesothelioma due to non-occupational asbestos exposure from the Italian national surveillance system (ReNaM): epidemiology and public health issues. Occup. Environ. Med. 72 (9), 648–655.

Maule, M.M., Magnani, C., Dalmasso, P., Mirabelli, D., Merletti, F., Biggeri, A., 2007. Modeling mesothelioma risk associated with environmental asbestos exposure. Environ. Health Perspect. 115 (7), 1066–1071.

Michigan Department of Community Health, 2013. 2012 Annual Data Report on Blood Lead Levels of Children in Michigan. Lansing, MI. .

N. R. Council, 1971. Airborne Asbestos. National Academies Press, Washington, D.C.
National Institute for Occupational Safety and Health (NIOSH), 1994a. Method 7400: asbestos and other fibers by PCM. NIOSH Manual of Analytical Methods (NMAM), 4th ed. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH.
National Institute for Occupational Safety and Health (NIOSH), 1994b. Method 7402: asbestos by TEM. NIOSH Manual of Analytical Methods (NMAM), 4th ed. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH.
National Research Council, 1971. Biologic Effects of Atmospheric Pollutants: Asbestos-the Need for and Feasibility of Air Pollution Controls. Washirngton DC. .
Neavling, S., 2016. How 10,000+ Fires Devoured Detroit Neighborhoods Over the Past 3 Years. Motor City Muckraker, Detroit, MI 17-Mar-.
Nelson, A.R., Liverman, C.T., Eide, E.A., 2010. A Review of the NIOSH Roadmap for Research on Asbestos Fibers and Other Elongate Mineral Particles. National Academies Press (US), Washington, D.C.
Nolan, R.P., et al., 2005. Risk assessment for asbestos-related cancer from the 9/11 attack on the World Trade Center. J. Occup. Environ. Med. 47 (8), 817–825.
Pan, X.L., Day, H.W., Wang, W., Beckett, L.A., Schenker, M.B., 2005. Residential proximity to naturally occurring asbestos and mesothelioma risk in California. Am. J. Respir. Crit. Care Med. 172 (8), 1019–1025 Oct.
Perkins, R., Hargesheimer, J., Fourie, W., 2007. Asbestos release from whole-building demolition of buildings with asbestos-containing material. J. Occup. Environ. Hyg. 4 (768371016), 889–894.
Pierce, J.S., Ruestow, P.S., Finley, B.L., 2016. An updated evaluation of reported no-observed adverse effect levels for chrysotile asbestos for lung cancer and mesothelioma. Crit. Rev. Toxicol. 46 (7), 561–586.
Powell, J., Jain, P., Bigger, A., Townsend, T.G., 2015. Development and application of a framework to examine the occurrence of hazardous components in discarded construction and demolition debris: case study of asbestos-containing material and lead-based paint. J. Hazardous, Toxic, Radioact. Waste 19 (4), 05015001 Oct.
Rake, C., Gilham, C., Hatch, J., Darnton, A., Hodgson, J., Peto, J., 2009. Occupational, domestic and environmental mesothelioma risks in the British population: a case-control study. Br. J. Cancer 100 (7), 1175–1183.
Ravikrishna, R., Lee, H.W., Mbuligwe, S., Valsaraj, K.T., Pardue, J.H., 2010. Air quality during demolition and recovery activities in post-Katrina New Orleans. Environ. Toxicol. Chem. 29 (7), 1438–1444.
Reid, A., et al., 2013. All-cause mortality and cancer incidence among adults exposed to blue asbestos during childhood. Am. J. Ind. Med. 56 (2), 133–145.
Royal Society of New Zealand and the Office of the Prime Minister''s Chief Science Advisor, 2015. Risks From Asbestos Exposure in the Non-occupational Environment. Auckland, NZ. .
Ryan, P.H., Lemasters, G.K., Burkle, J., Lockey, J.E., Black, B., Rice, C., 2013. Childhood exposure to Libby amphibole during outdoor activities. J. Expo. Sci. Environ. Epidemiol. 25 (10), 4–11.
Sahmel, J., et al., 2015. Measured removal rates of chrysotile asbestos fibers from air and comparison with theoretical estimates based on gravitational settling and dilution ventilation. Inhal. Toxicol. 27 (14), 787–801 Dec.
Selikoff, I.J., Nicholson, W.J., Langer, A.M., 1972. Asbestos air pollution. Arch. Environ. Heal. An Int. J. 25 (1), 1–13 Jul.
Sheffield, P., Rowe, M., Agu, D., Rodriguez, L., Aviles, K., 2014. Health impact assessments for environmental restoration: the case of Cano Martin Pena. Ann. Glob. Heal. 80 (4), 296–302.
Singh, B., Thouez, J.P., 1985. Ambient air concentrations of asbestos fibers near the town of Asbestos, Québec. Environ. Res. 36 (1), 144–159 Feb.
Spelman, W., 1993. Abandoned buildings: magnets for crime? J. Crim. Justice 21 (5), 481–495.
U.S. Environmental Protection Agency (EPA), 1973. Part 61 - national emission standards for hazardous air pollutants: absestos, beryllium, and mercury. Fed. Regist. 38 (66), 8820.
U.S. Environmental Protection Agency (EPA), 1995. Asbestos NESHAP clarification of intent. Fed. Regist. 60 (145), 38725.
United States Government Accountability Office, "Vacant properties: growing number increases communities' costs and challenges," no. GAO-12-34. 2011.
US Department of Housing and Urban Development, d. The healthy homes technical studies grant program. [Online]. Available. https://portal.hud.gov/hudportal/HUD?src=/program_offices/healthy_homes/hhi/hhts, Accessed date: 30 January 2017.
USFA/FEMA, 2015. Vacant Residential Building Fires (22010-2012). Emmitsburg, MD. .
Van Orden, D.R., Lee, R.J., Bishop, K.M., Kahane, D., Morse, R., 1995. Evaluation of ambient asbestos concentrations in buildings following the Loma Prieta earthquake. Regul. Toxicol. Pharmacol. 21 (1), 117–122.
Vinikoor, L.C., Larson, T.C., Bateson, T.F., Birnbaum, L., 2010. Exposure to asbestos-containing vermiculite ore and respiratory symptoms among individuals who were children while the mine was active in Libby, Montana. Environ. Health Perspect. 118 (7), 1033–1038.
Virta, R., 2006. Worldwide Asbestos Supply and Consumption Trends From 1900 Through 2003. Circular 1298. Washington, D. C. .
Wilmoth, R.C., Taylor, M.S., Meyer, B.E., 1994. Asbestos release from the demolition of two schools in Fairbanks, Alaska. Appl. Occup. Environ. Hyg. 9 (6), 409–417.
Wilson, R., McConnell, E.E., Ross, M., Axten, C.W., Nolan, R.P., 2008. Risk assessment due to environmental exposures to fibrous particulates associated with taconite ore. Regul. Toxicol. Pharmacol. 52 (1 SUPPL).
Working Group on the Evaluation of Carcinogenic Risk to Humans, "Asbestos (chrysoltile, amosite, crocidolite, tremolite, actinolite and anthophyllite)," 2012.
Yano, E., et al., 2009. Mesothelioma in a worker who spun chrysotile asbestos at home during childhood. Am. J. Ind. Med. 52 (4), 282–287.