RESEARCH ARTICLE

Legacy Asbestos, the Third Wave of Asbestos Disease, and Implications for Domestic Exposure

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Abstract

Asbestos-containing products have been utilized extensively in home and building construction during the first eight decades of the 20th century. While substantial literature exists regarding occupational asbestos exposure, limited information is available concerning asbestos exposure in residential settings. In addition to asbestos containing building products in homes, exposures to asbestos may also result from the use of products in which asbestos occurs as a contaminant. Despite regulation by EPA and OSHA, ongoing occupational and environmental exposures to asbestos remain a continuing cause for concern. The aim of this paper is to review the scope of legacy asbestos and highlight the implications for domestic exposure.

Introduction

Asbestos-containing products have been utilized extensively in home and building construction during the first eight decades of the 20^{th} century. The use of asbestos has been decreasing in developed countries, but asbestos imports and consumption is increasing in developing countries. The term asbestos generally refers to the six regulated asbestos minerals that include the serpentine mineral chrysotile, and the amphibole minerals amosite, crocidolite, actinolite, anthophyllite, and tremolite asbestos. Chrysotile asbestos has been the major fiber type used commercially, and represents approximately 95% of the total world production of all forms of asbestos with Canada being largest producer[1]. Amosite and crocidolite accounted for only 5% of the asbestos usage in the U.S. over the years 1936-1950.[2,3]

Asbestos has been used in hundreds of products, which include asphalt-based roofing materials, thermal and electrical insulation, friction materials (e.g. brake pads, shoes and clutches), cement pipe and sheets, flooring, gaskets and packing, coating and compounds, plastics, textiles, paper, mastics, thread, fiber jointing, and millboard.[4,5,6] The World Trade Organization (2000)[7] defined five main asbestos product categories: "(i) bulk asbestos: asbestos wadding for the thermal insulation of ovens, boilers, fire-doors, refrigerating equipment, flocked asbestos for the underside of concrete slabs and for steel frames for the fireproofing and soundproofing of buildings; (ii) asbestos sheets or boards: asbestos paper and board for thermal insulation, for the protection of welded joints (plumbing) and for the protection of work surfaces (glass industry), boards for the fitting of false ceilings, fireproof surfaces, partitions, etc.; (iii) textile asbestos: asbestos cord (sealing of oven doors, laboratory applications), buffer strips (to protect against heat), fireproof coverings and curtains, air, gas and liquid filters, insulation of electrical equipment; (iv) asbestos incorporated in cement products (asbestos-cement): roof tiles, roof cladding, window sills, facing of buildings, interior partitions and false ceilings, other forms of panelling, flues, ventilation shafts, rainwater pipes, plant tubs and gardening equipment; (v) asbestos in binding or bonding agents (resins, bitumens): friction linings (brake linings, clutch linings, linings for presses, winches, gantries, lifts, engines), road surfaces, flooring, decorative shingles, sealants, plaster-based finishes and coatings, glues and gums and asbestos-based paints."

Disease associated with exposure to asbestos among workers engaged in mining and milling of ore and the processing of asbestos into asbestos products began to be recognized in the 1920's. This has been referred to as the first wave of asbestos disease, and relates to 'primary users' of asbestos. The second wave of asbestos disease was later recognized in workers, including insulators, pipefitters, boilermakers, machinists, electricians, carpenters, and sheet metal workers who use asbestos products in industry, or encounter asbestos-containing materials (ACM) in their work.[8] The aging and deterioration of buildings and homes constructed with asbestos-containing materials creates the potential for a third wave of asbestos disease among workers, or the public, engaged in the maintenance, renovation and demolition of buildings and homes, or contacting asbestos sources through accidental disturbances. Because asbestos-containing materials were used extensively wherever heat shielding, fire proofing, and corrosion proofing was required, today's risk of asbestos exposure comes from asbestos "in place" in structures built before the mid-1980's. This includes industrial facilities, private and public buildings, personal residences, and public infrastructure. It has been reported that the most important non-occupational asbestos exposure is from the release of fibers from asbestos-containing surfacing materials in schools, auditoriums, public buildings, or from sprayed asbestos-containing fireproofing in high-rise office buildings, and the maintenance, repair, and removal of these materials creates a high potential for exposure.[9]

Asbestos-Related Disease

Asbestos is the cause of an international public health problem, and male mesothelioma mortality rates have been increasing in industrialized countries by 5 to 10 per cent per year since the 1950s.[7,10] Exposure to asbestos can cause asbestosis, mesothelioma, and cancer of the lung, larynx, and ovary.[11] Epidemiologic studies conducted worldwide have established that all forms of asbestos have the capacity to cause these illnesses. Asbestos is the principal carcinogen associated with malignant mesothelioma, which was rare before the widespread use of asbestos. Mesothelioma is a global health issue with an increasing incidence worldwide. While most asbestos-related diseases (ARDs), including mesothelioma, have been associated with occupational exposure to asbestos, investigations from different countries have identified mesotheliomas due to possible domestic or neighborhood asbestos exposure.[9,12,13, 14]

The Center for Disease Control and Prevention (CDC) released a public report on malignant mesothelioma mortality in the U.S. between 1999 to 2015 which showed a steady increase in the number of deaths throughout the period.[15] Between 1999 and 2015, mesothelioma was noted on death certificates of 45,221 people as a cause of death. These recorded mesothelioma deaths are substantially greater than risk assessments predicted by the U.S. Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA). The authors reported that despite regulatory actions of OSHA and the EPA, "the continuing occurrence of mesothelioma deaths among persons aged < 55 years suggests ongoing occupational and environmental exposures to asbestos fibers." Asbestos products remain in use and new asbestos-containing products continue to be manufactured and/or imported into the United States, and new cases of mesothelioma may result from exposure to asbestos fibers during maintenance, remediation and demolition activities.[15]

In France, asbestos is responsible for some 2,000 deaths per year, including 750 deaths from mesothelioma.[7] The number of asbestos-linked occupational diseases for which compensation was paid (mesothelioma, lung cancer, asbestosis, pleural abnormalities) increased fourfold between 1985 and 1995. Both amphibole and chrysotile asbestos cause mesothelioma, with amphiboles reported to be somewhat more carcinogenic in the case of mesothelioma, but not lung cancer. According to WTO (2000)[7], "This cancer occurs mostly as a result of occasional low-intensity exposure. After a long latency period (lasting for 30 years on average), this cancer enters the terminal phase, which lasts for one year on average. There is as yet no curative treatment with any effect." Approximately 200,000 mesothelioma deaths have been estimated in the six European countries (Great Britain, France, Germany, Italy, the Netherlands, Switzerland) over the period 1995-2029.[16] Between the periods 1990-1994 and 2015-2019, the number of deaths will at least double, resulting in 6,700 deaths per annum. If deaths from lung cancer and mesothelioma are tabulated for all the countries of Western Europe, approximately 500,000 deaths from cancer will have been caused by exposure to asbestos by the year 2029.[7]

There is no established threshold of occupational asbestos exposure below which mesothelioma will not occur and there is overwhelming evidence and consensus of the medical and scientific community that the inhalation of asbestos fibers of any type (chrysotile, amosite, crocidolite, tremolite, anthophyllite, and actinolite), from any source or product, causes all of the asbestos-related diseases, including mesothelioma.[7,11,17,18,19,20,21]

Scope of the Problem

More than 30 million metric tons of asbestos was used in the United States since 1900. The annual use of asbestos peaked at approximately 800,000 metric tons in 1973, and decreased to approximately 250,000 metric tons in 1982. This accounted for about 6% of world production.[22] Much of this asbestos is still present in its original application and provides a potential for exposure. Environmental contamination from asbestos-containing materials can occur not only during construction and demolition, but also throughout the life of the structure.[23] The U.S. Environmental Protection Agency (EPA, 1988) found that “friable” (easily crumbled) asbestos-containing materials (ACM) can be found in an estimated 700,000 public and commercial buildings.[24] About 500,000 of those buildings are believed to contain at least some damaged asbestos, and some areas of significantly damaged ACM can be found in over half of them. Some form of servicing work (i.e., electrical, plumbing) is highly likely to be performed on or around any installation of ACM in a building or structure during its life cycle, creating the potential for the release of and exposure to asbestos fibers. Chrysotile has been reported to constitute approximately 95 percent of the asbestos used in the United States, but building surveys have shown the amphiboles of amosite and, to a lesser extent, crocidolite, to have been used with greater frequency in buildings than the total consumption figures would suggest.[25] All asbestos-containing products may release asbestos fibers to some extent. As long as the fibers are at the surface of the product when manufactured, fibers can be released to the environment. Even products containing bound or embedded asbestos can release fibers to the environment when the surface is worn, broken, damaged, or deteriorated.

Asbestos products remain in use, and new asbestos-containing products continue to be manufactured in or imported into the United States. Approximately 340 metric tons of asbestos were imported in 2016 for use in manufacture of semipermeable diaphragms by the chloralkali industry. An unknown quantity of asbestos was imported within manufactured products, including brake linings and pads, building materials, gaskets, millboard, and yarn and thread, among others.[15,26] EPA issued a final rule banning most asbestos-containing products on July 12, 1989. Many components of this standard were set aside by the U.S. Fifth Circuit Court of Appeals in 1991. The regulation continues to ban the use of asbestos in products that have not historically contained asbestos, referred to as “new uses” of asbestos. The asbestos-containing products that remained banned include flooring felt, rollboard, and corrugated, commercial, or specialty paper.[27] Asbestos-containing products that are no longer subject to the 1989 ban include asbestos-cement corrugated sheet, asbestos-cement flat sheet, asbestos clothing, pipeline wrap, roofing felt, vinyl-asbestos floor tile, asbestos-cement shingle, millboard, asbestos-cement pipe, automatic transmission components, clutch facings, friction materials, disc brake pads, drum brake linings, brake blocks, gaskets, non-roofing coatings, and roof coatings. In their clarification of the asbestos materials ban, EPA stated that they do not track the manufacture, processing, or distribution in commerce of asbestos-containing products, and left it up to the consumer or other buyer to inquire as to the presence of asbestos in particular products.

A strong correlation has been demonstrated between cases of mesothelioma and consumption of asbestos per inhabitant, measured by the amount of imports, for ten Western countries.[28] The number of cases of cancer increases proportionally with the increase of imports of asbestos into each country. Since the end of the World War II, the vast majority of the asbestos used throughout the world has been chrysotile, which correlates with the very high incidence of mesothelioma among building workers.[7,29]

Most deaths from malignant mesothelioma are the result of asbestos exposures that occurred 20–40 years prior. If controls are not instituted to protect workers, new cases might result from occupational and nonoccupational exposures to asbestos fibers during maintenance, remediation, and demolition activities in structures, installations, and buildings containing ACM. In the report of the Panel on European Communities – Measures Affecting Asbestos and Asbestos – Containing Products,[7] the World Trade Organization stated: "It cannot be asserted that there is an "absence of scientific proof of the health risks posed by modern products containing chrysotile" and "the large majority of cancers due to asbestos are the result of such work (servicing and maintenance) on materials containing chrysotile."[7] Workers performing servicing or maintenance of asbestos-containing products or equipment, including plumbers, electricians, or other tradesmen involved in construction finishing work, are at serious risk of ARDs. If ACM in a structure is unknown to servicing or maintenance workers performing work in the structure, they may be at risk of high peak exposures. The same would be true for homeowners performing home renovations and maintenance.

Peto et al. reported in 1995 that that mesothelioma deaths would continue to increase in construction and building maintenance workers for the next 15 to 25 years.[30] The authors reported a continuing increase in the death rate among men under 50 years of age who began work in the mid-1960s or later, and the worst effects have been experienced by men who began work after this date. The authors explained that "most exposures (not the most intense, but affecting large numbers) occurred in occupational settings, particularly in the building industry, which were and still are largely unmonitored."[30] In European Union countries the annual raw asbestos imports peaked in the early to mid-1970's and remained above 800,000 tons per year until 1980, and falling to about 100,000 tons by 1993. Substantial exposure to chrysotile and amphibole asbestos may occur during maintenance or demolition work on older buildings.[16] Primary releases from impact and abrasion of ACM have been reported to result in elevated level airborne fiber levels during maintenance and removal activities[31,32,33,34,35,36,37,38]

ACM in good repair and undisturbed within buildings is unlikely to give rise to airborne asbestos fiber concentrations above the levels found outside those buildings, but building maintenance, remodeling, or asbestos removal can result in elevated asbestos fiber concentrations in buildings. Janitorial, custodial, maintenance, and renovation personnel may disturb or damage ACM, and subsequent fiber levels may persist for varying lengths of time, potentially exposing other building occupants.[25] Exposures to maintenance personnel can be maintained below 0.1 fiber per milliliter (f/mL) in building with an Operations & Maintenance Program, but exposures can exceed 10 f/mL during some removal and repair work without adequate controls. Potential asbestos exposures of 10 to 100 f/mL can occur during dry asbestos removal with air exhaust. Due to episodic high exposure concentrations, the added life-time cancer risk in such workers may be appreciably higher than the risk to general building occupants.[25]

Studies have been conducted to determine airborne concentrations of asbestos in buildings containing ACM.[24,31,32,39,40,41] From these studies, mean airborne asbestos concentrations ranged from 0.0007 to 0.0245 asbestos structures per cubic centimeter (s/cc).

EPA (1988)[24] collected 387 air samples for asbestos in 49 government-owned buildings. Six of the buildings had no ACM (Category 1), six buildings had ACM in generally good condition with limited areas with moderate damaged ACM (Category 2), and 37 buildings had at least one area with significantly damaged ACM and numerous other areas containing moderately damaged ACM (Category 3). In buildings with ACM, airborne asbestos levels were elevated and buildings with damaged ACM demonstrated the highest airborne asbestos levels.[41]

An early study[31] of asbestos fiber release from a building containing ACM reported that occupant exposure to asbestos fibers under all conditions of usual activity resulted from the ceiling material in the building which was a spray-applied mixture of asbestos and fibrous glass. Measured asbestos fiber concentrations by phase contrast microscopy (PCM) were above the ambient city levels and exceeded Occupational Safety and Health Administration (OSHA) permissible exposure limits in some situations. Sampling performed in 1971 found a maximum level of 0.5 f/cc. Ceiling deterioration was visible and the contamination of the building with ceiling material resulting from continuous low-level fallout from the ceiling (mean of 0.02 f/cc quiet conditions), occasional heavy loss by contact (mean of 17.1 f/cc mechanics removing 1 x 2 foot ceiling section), and re-entrainment from surfaces such as floors, desks, and shelves (mean of 0.2 f/cc). The mean airborne fiber concentrations during custodial dry sweeping and dusting were 1.6 and 4.0 f/cc, respectively. The mean airborne fiber concentrations for electricians installing track lighting and dry removal of an 8 x 12 foot ceiling section were 7.7 and 82.2 f/cc, respectively.[31] In a report on asbestos-related maintenance work performed within the framework of an Operations and Maintenance Program (OMP) and utilizing both personal protective equipment and controls against fiber release/dispersion, the highest mean 8-hour time weighted average exposure was 0.030 fibers per cubic centimeter (f/cc) > 5 micron (um) for ceiling tile replacement. The OSHA 30-minute excursion limit of 1.0 f/cc > 5um length was exceeded during ceiling tile replacement three times in a five-year period. The maximum asbestos concentration for environmental samples was 0.027 f/cc > 5 micron. Eight-hour time weighted average exposures for personal sampling for each task category were all below the OSHA permissible exposure level of 0.1 fibers f/cc > 5 micron.[42]

In a study providing estimates of the airborne asbestos exposure of workers engaged in routine maintenance and repair work and by other building occupants, annual exposure levels ranging from a median value of 0.002 f/cc per year to 0.02 f/cc per year at the 90th percentile were reported for maintenance and repair workers in buildings with ACM. Average exposure levels ranging from 0.00003 f/cc to 0.0005 f/cc were reported for building occupants not involved in maintenance and repair work.[43] Another study reported that workers performing renovation or maintenance activities in buildings containing sprayed fireproofing material are frequently exposed to asbestos. During renovation activities, carpenters, electricians, and sheet-metal workers were exposed to average airborne fiber concentrations exceeding 0.1 f/cc.[34] Burdett and Jaffrey (1986)[39] measured airborne concentrations of asbestos and other fibers in 39 buildings containing asbestos materials used in their construction or present in warm-air heating systems and in four buildings without asbestos materials. The authors reported that most of the fibers were not asbestos when analyzed by transmission electron microscopy (TEM). Asbestos fiber concentrations exceeded 0.001 f/ml > 5 um at only one site. The highest concentration of 0.012 chrysotile f/ml was in a room with a visibly damaged sprayed asbestos ceiling. Of the 43 sites sampled, the authors noted that chrysotile fibers were detected at 24, amosite fibers were detected at 22, and crocidolite fibers were detected at 2 of the sites.[39] Nurminen et al. (2003)[44] reported that "the effects of asbestos exposure in the maintenance, removal, and demolition work of older buildings during the 1980s and 1990s, although not yet apparent, could prove considerable" in relation to the incidence of mesothelioma, and "prolong the asbestos epidemic long after some 35 to 40 years have elapsed from the cessation of all manufacture and installation of asbestos products in a society." [44]

Building owners are governed by a variety of federal, state, and local regulations which influence the way they must deal with ACM in their facilities. Both EPA and OSHA have published regulations to reduce asbestos exposure. EPA regulations pertain to the application and removal of ACM in new or remodeled buildings, and the identification of friable asbestos in schools. If ACM is present, building owners must have plans for controlling ACM and initiate special operations and maintenance (O&M) to (1) maintain ACM in good condition, (2) ensure proper cleanup of asbestos fibers previously released, (3) prevent further release of asbestos fibers, and (4) monitor the condition of ACM. OSHA addresses worker protection in the workplace and specifies airborne exposure standards for asbestos workers, engineering and administrative controls, workplace practices, and medical surveillance and worker protection requirements. OSHA regulates asbestos exposure of building maintenance personnel under the OSHA Construction Standard for Asbestos designated a Class III activity (USDOL, 1994).[45] OSHA's worker exposure standards are inappropriate for nonindustrial settings, and home owners are generally not aware of ACM in their homes, and would not have, or be required to have, an O&M Program.

Nonoccupational Asbestos Exposure

Nonoccupational asbestos exposure can be grouped in the following categories: (1) in areas where studies of the geological structure have shown the presence of naturally occurring asbestos; (2) neighborhood exposure due to the proximity of an asbestos source (i.e., a mine, factory or building); (3) household exposure for family members of occupationally exposed workers (para-occupational); and (4) other nonoccupational exposures, including home-related domestic exposure during home maintenance and renovations or hobby/leisure activities. Asbestos-related diseases have been associated with exposure to naturally occurring mineral fibers in Turkey, Finland, Bulgaria, the United States.[46,47,48,49] The majority of studies associated with residential living space asbestos contamination have focused on exposure and related disease among household members of occupationally exposed workers,[50,51,52,53,54,55,56,57,58] or residential exposure in areas near asbestos-related industries or naturally occurring asbestos deposits.[13,49,59,60] A study of 42 mesotheliomas cases occurring from a geographical area of approximately 30,000 square miles reported six of the cases clustered in and around an insulation plant.[13] Perhaps the best examples disease associated with living near asbestos sources include the vermiculite mine in Libby, Montana, USA, and the Wittenoom crocidolite mine in Western Australia.[57,59,61]

Other nonoccupational exposures, including home-related domestic exposure during home maintenance and renovations, hobby/leisure activities, or accidental disturbances are largely unmeasured and the risk of disease associated with domestic asbestos exposure, aside from para-occupational exposure, is unclear. The extensive use of asbestos products in buildings has raised concerns about the widespread exposure of the general public to asbestos in nonoccupational settings. A wide variety of asbestos can be found in older homes, including thermal insulation products on boilers and high temperature water lines, furnace ducts, wall and ceiling sprayed-on decorative or soundproofing material, wallboard and joint compounds, resilient floor tiles, vinyl sheeting and adhesives, cement sheeting, millboard, paper, gaskets used around furnaces and stoves, roofing cement, shingles, and siding, automobile brake pads, clutch facings and gaskets. Fiber release from floor tile would be minimal unless the tile is sanded or physically abraded during home renovations. During home alterations, either by the owner or outside contractors, asbestos fibers can be released from subflooring or walls with ACM. Measurements of asbestos air concentrations in homes using asbestos paper air ducts for air conditioning demonstrated a significant difference between the concentrations of all indoor samples and those taken outdoors for control purposes. Most of the homes also had chrysotile-containing textured paint in all living areas. Homeowners may disturb the painted surfaces during renovations because they are unaware of the presence of asbestos content.[62] It has been reported that work on old asbestos-containing floor tile can be an important source of asbestos exposure.[63,64,65,66,67] In 1976, flooring materials represented about 15 percent of the total U.S. market for asbestos.[68] Asbestos fibers are released when floor tile is broken and/or abraded during removal procedures, and airborne asbestos concentrations ranging from 0.15 to 6.9 total asbestos structures/cc have been reported.[67] Dust concentrations of 1.2 and 1.3 f/cc during simulated sanding of floor tile using a belt sander with a coarse grit have been reported.[69]

Asbestos was used drywall or joint compound until the late 1970's, when it was banned by the Consumer Product Safety Commission. Asbestos-containing drywall may still be present in older homes. An evaluation of ten industrial drywall taping (spackling) compounds found that nine of the taping compounds contained chrysotile ranging from 5 to 12 percent. A mean airborne asbestos concentration of 5.3 f/cc was reported for hand sanding of taping compounds, with mean asbestos background concentrations of 2.3 and 4.3 f/cc in the same room and in an adjacent room, respectively. The authors reported that home repair work involving sanding and clean of drywall taping compounds creates the possibility of asbestos exposure during home construction and repair.[70]

A review of epidemiological studies and quantitative meta-analysis of pleural mesothelioma and household and neighborhood exposure to asbestos reported that the most common source of household exposure was the installation, degradation, removal or repair of asbestos-containing products.[12] An additional source of household exposure was asbestos dust brought home from the workplace on the clothes of family members. A strong relationship between pleural mesothelioma and high environmental asbestos exposure from domestic or neighborhood sources was found. For all studies evaluated, the relative risk for pleural mesothelioma and neighborhood exposure was 7.0 (4.7-11 95% CI). For household exposure, the relative risk was 8.1 (5.3-12 95% CI), but para-occupational exposure was not separated from other domestic exposures.[12] In a study of 42 mesothelioma cases that worked in asbestos plants, lived close to an asbestos industry, or were family members of asbestos workers, no history of asbestos exposure could be obtained in 11 cases.[13] Asbestos exposure was assumed in 10 other cases after prolonged questioning. Of these 10 cases, one was 14 year-old boy who had helped his father replace most of the plaster board during extensive remodeling of his house. No other occupational asbestos exposure was identified. Another case with no identified occupational exposure had mixed asbestos cement and applied asbestos insulation to boilers in his home. Another case involved the son of his father who sawed asbestos pipe insulation material and installed it on pipes in the basement. The authors acknowledged that the minimal dose-effect relationship and duration of a latent period were unknown, and their study presented many unanswered questions.[13]

The Australian Mesothelioma Registry (AMR, 2015)[71] became operational in 2011 and has a voluntary component that enables the collection of asbestos exposure information directly from people who have been diagnosed with mesothelioma. On May 31, 2016, the AMR had received 650 notifications of people newly diagnosed with mesothelioma between January 1 and December 31, 2015. Of these people, 505 were males and 145 were females. Six hundred and fifty one people (520 males and 131 females) with mesothelioma completed the asbestos exposure questionnaire, and 582 (89.4%), representing 464 males and 118 females also completed the telephone interview. Of the 582 people who were interviewed, 351 (60.3%) (343 males and 8 females) provided information indicating 'possible' or 'probable' occupational asbestos exposure, and 483 (82.9%) people (377 males and 106 females) provided information indicating 'possible' or 'probable' asbestos exposure in non-occupational settings.[71] The Australian Housing Survey (1999)[72] found 23% of households reporting that alterations and additions had been carried out to their current dwelling within the last two years, which included alterations and additions to kitchens (6%), bathrooms (6%) or to outdoor living areas such as pergolas or decks (6%). Fifty-five per cent of households reported that repairs or maintenance, including painting (31%), plumbing (24%) and electrical work (17%), had been carried out to their current dwelling within the last twelve months.[72] In an investigation in New South Wales, Australia,[73] self-reported non-occupational asbestos exposure during home renovation was obtained from a mailed questionnaire examining renovation activity and tasks performed during renovation. From a random survey of 10,000 adults, 3612 responses were received. The authors reported that 1597 participants (44.2%) had renovated their home and among these, 858 participants (53.7%) self-reported as do-it-yourself (DIY) renovators. Asbestos exposure during home renovations was reported in 527 (61.4%) of the responses. Types of exposure identified included contact with asbestos fibro sheeting, insulation and other ACM. Home renovations tasks included cutting, drilling, and sanding of asbestos building materials with hand and power tools. The authors concluded that self-reported asbestos exposure during home renovation is common, potentially placing residents at risk of asbestos exposure.[73]

Olsen, et al. (2011)[14] reviewed all cases of malignant mesothelioma diagnosed from 1960 through 2008 in Western Australia to determine the primary source of exposure using 29 exposure codes, including five non-occupational codes and "unknown" or "no known" codes. Exposure sources coded as "handyman, home maintenance and DIY were for cases where no other source of exposure could be identified, and exposure occurred during participation in home renovation or maintenance or as a bystander during these activities. The authors reported that 195 mesothelioma cases involved non-occupational exposure, 6.8% for men and 44.4% for women. The authors coded 87 cases of mesothelioma since 1981 attributed to home renovation or maintenance, 55 men and 32 women. Incidence rates for the last two periods, 200-2004 and 2005-2008, were reported to be significantly higher than the period 1980-1984. The authors reported that home renovation and maintenance now made up the largest portion of non-occupational cases for both men and women.[14] Due to the extensive use of asbestos throughout the country, Australia has the highest reported per capita incidence of asbestos-related disease in the world. According to the Asbestos Management Review (2012),[74] "Of particular concern are recent studies that indicate the incidence of mesothelioma is increasing. Asbestos related diseases have traditionally been linked to workers who have had direct contact with the material, either through mining or working with asbestos in manufacturing processes. A developing demographic whom asbestos related diseases affect is appearing in the population, and includes DIY home renovators and their families. In the absence of timely and decisive intervention, many more people for generations to come will continue to contract these avoidable incurable fatal illnesses."[74]

It has been reported that only 40% of mesothelioma cases in women can be related to occupational exposure.[75] Lifetime non-occupational asbestos exposure was also assessed using information reported by subjects on the use of asbestos-containing materials or performed tasks. Do-it-yourself activities that potentially involved asbestos-containing products in home improvements or brake and clutch repairs were used to define domestic exposure. Para-occupational exposure was also evaluated as well as self-reported environmental exposure of living near an industrial source of asbestos. For subjects never occupationally exposed to asbestos, the authors reported an asbestos population-attributable risk (ARp) of 20.0% (99% CI −33.5% to 73.5%) in men and 38.7% (99% CI 8.4% to 69.0%) in women due to non-occupational asbestos exposure. The authors concluded that the overall ARp in women is largely driven by non-occupational asbestos, which could explain the observed difference in ARp between men and women because of the difficulty in assessing domestic or environmental exposure to asbestos.[75]

In addition to asbestos containing building products in homes, exposures to asbestos may also result from the use of products in which asbestos occurs as a contaminant. Asbestos-related diseases have been associated with exposure to mineral fibers which may occur as contaminants in other minerals used commercially (e.g. talc and vermiculite). Asbestos minerals are present in many areas where the original rock mass has undergone metamorphism.[4,76] Contact metamorphic talcs are likely to contain amphiboles, and regional metamorphic talc bodies often contain amphiboles with asbestiform habits.[77] Talc is widely used as a pigment, extender, or processing aid in ceramic tile, paint, paper, plastics, and, in smaller quantities, as a component of cosmetic powders, foods, drugs, pesticides, and many other products.[11] Some talcum powder products have been reported to contain asbestos,[11,78,79,80,81,82] and mesothelioma and ovarian cancer have been reported in relation to the use of talcum powders.[83,84] In a report on 75 mesothelioma cases whose only known exposure to asbestos was repeated exposures to cosmetic talcum powders, most of the cases were women, and several cases occurred in hairdressers and barbers.[83] The authors attributed the asbestos exposure to the presence of anthophyllite and tremolite contaminants in cosmetic talcum powder, and tissue examinations by analytical transmission electron microscopy (ATEM) were found to be comparable to laboratory testing of cosmetic talc. The authors stated that exposure through the use of cosmetic talc may account for an uncertain percentage of mesothelioma cases in women previously reported as "idiopathic" with no known source of asbestos exposure. [83]

Another commercially important natural substance that could potentially be contaminated with asbestos is vermiculite. Vermiculite mined from Libby, Montana, USA, was contaminated with asbestiform amphiboles originally described as tremolite-actinolite,[85] but later described as approximately 84% winchite, 11% richterite, and 6% tremolite, and referred to as Libby amphibole (LA).[86] Of these three amphibole minerals, only asbestiform tremolite is regulated. A common commercial use for exfoliated or expanded vermiculite from Libby was loose-fill insulation with the brand name Zonolite. The precise number of homes in the U.S. containing Zonolite brand vermiculite attic insulation (VAI) originating from the Libby mine is unknown, however nearly 80% of the world's vermiculite produced from the 1920s to 1990 originated from this mine. Vermiculite has also been used in horticultural additives, packaging materials, fire-resistant coatings, aggregates for insulation plasters, fire-resistant insulating wall-boards and acoustic tile.[87] From the period when W.R. Grace owned the Libby mine (1964-1990), an analysis of shipping invoices reported that a total of approximately 6,109,000 tons of vermiculite were shipped to 245 sites in the U.S. from 1964 to the early 1990's.[88] The report estimated that exfoliation, or expansion, facilities received over 95% of the vermiculite shipped from the Libby mine during the same period. The Libby mine began operations in the 1920s, and limited information is available about production and shipping of vermiculite before 1964. Consequently, more than 40 years of shipping/distribution data are not available for analysis. Of the 245 sites that received vermiculite, 145 non-exfoliation sites received less than 5% of the vermiculite shipped from the Libby mine and included various industries such as gypsum wallboard manufacturing, agricultural product manufacturing, shipping, and mining.[88] Facilities such as the Western Mineral Products Site in Minneapolis, Minnesota produced additional products such as Monokote, a fire proofing material that combined vermiculite and chrysotile asbestos.[88]

While the presence of Libby amphibole asbestos in source media such as vermiculite is an important factor in assessing probable health risks, the potential for Libby amphibole fibers to be released from vermiculite and become airborne is equally important. Disturbances of source media such as soil or vermiculite insulation have revealed hazardous air concentrations, even when asbestos concentrations in source media were below 1% asbestos by weight.[87,89,90,91,92] The most critical determining factors in the level of airborne concentrations are the degree of disturbance and the presence of complete exposure pathways. Epidemiologic studies of workers, family members of workers, and other residents of Libby, Montana exposed to LA fibers indicate increased lung cancer and mesothelioma cases, as well as asbestosis and other nonmalignant respiratory diseases.[61,93,94,95,96,97,98,99,100,101,102,103,104]

A study was conducted for the EPA[105] to (1) estimate of amount of asbestos in attics having vermiculite attic insulation; and (2) obtain an estimate of a person's exposure to asbestos while performing common household activities. Bulk sampling of vermiculite attic insulation in five occupied Vermont houses found the asbestos content in vermiculite as high as two percent. Simulations were conducted to evaluate exposure to asbestos during scenarios which disturbed vermiculite attic insulation. Vermiculite bulk analysis reported as non-detect for asbestos still generated airborne asbestos concentrations when disturbed. During the Phase 1 simple simulation, the range of potential passive exposures associated with living in a house where vermiculite attic insulation is installed once in a lifetime was 0.0078 f/cc to 0.011 f/cc in the stationary monitors.

Using asbestos concentrations detected from personal and stationary monitors in the attic space during the Phase 1 simulation of residential activities to estimate the range of potential exposure associated with using an attic with vermiculite insulation as a storage space, the highest asbestos concentration of 0.25 f/cc was detected in a personal air monitor (PAM). The minimum asbestos concentration of 0.0079 f/cc was detected in a stationary monitor.[105] Simulations were also conducted in a containment system and one in an unoccupied Vermont house to estimate potential exposures to asbestos during the removal of dry vermiculite by a homeowner who is replacing vermiculite attic insulation. The asbestos concentrations in the containment system ranged from 0.21 to 0.40 actinolite f/cc, and asbestos concentrations detected during the relevant activity conducted in the unoccupied Vermont house ranged from 0.043 to 0.30 actinolite f/cc. The range of potential exposure associated with installing vermiculite attic insulation once in a lifetime was evaluated using simulations including installation, disturbance, and removal of vermiculite attic insulation. The maximum and minimum asbestos concentrations detected were 2.6 actinolite f/cc in a PAM and 0.023 actinolite f/cc respectively. Simulations conducted in a containment system and in the unoccupied Vermont house to estimate potential exposures to asbestos during the disturbance of dry vermiculite during the installation of a ceiling fan and associated wiring activities found maximum and minimum asbestos concentrations of 2.6 actinolite f/cc in a PAM and 0.028 actinolite f/cc respectively. The asbestos concentrations detected during the simulations conducted in the unoccupied Vermont house ranged from 0.013 to 0.41 actinolite f/cc.[105]

An activity-based air and surface sampling study was performed in three homes containing vermiculite attic insulation.[92] During cleaning activities consisting of dusting of stored items, sweeping, and vacuuming of rugs with a standard upright vacuum cleaner in an attic with Zonolite only at the top of wall cavities, an average exposure of 0.12 asbestos structures/cc (s/cc) was reported during cleaning. During cleaning with a broom in a storage area in an attic fully insulated with Zonolite, 16-minute time-weighted average (TWA) asbestos concentrations of 0.88 s/cc > 0.5 um and 0.61 s/cc > 5 um were found in area samples closest to the cleaning activity. Prior to cutting a hole in the ceiling of a living space below Zonolite Attic Insulation, average airborne asbestos concentrations of 0.023 s/cc > 0.5 um 0.017 s/cc for structures > 5 µm in length were found. During the cutting process, the TWA exposure for 26-minutes was 1.32 s/cc > 5 µm). Peak exposures of 4.98 s/cc > 0.5 um and 2.85 s/cc > 5 µm were found during the last five minutes of cutting the hole. Bulk samples of the Zonolite Attic Insulation contained less than 1% amphibole asbestos by polarized light microscopy (PLM). Chrysotile asbestos (~ 7%) by PLM was also found in the finish coat of the wood lathe, plaster, and gypsum wallboard ceiling material. The study reported that asbestos exposures greater than 1 f/cc during 30-minute activities can occur during cleaning, maintenance, and remodeling activities that disturb vermiculite attic insulation.[92]

In 2007 research began to confirm the presence of vermiculite attic insulation or other asbestos-containing materials (ACM) in selected homes in southwest Montana and to assess the potential for living space contamination associated with asbestos sources. The aim of this research was to develop, test, and refine draft protocols for safely weatherizing homes based on extensive testing and monitoring of homes that contained vermiculite attic insulation (VAI) and other ACM.[106,107] In Phase I of this research, the presence of asbestos was confirmed via bulk sampling in individual homes, and the presence of asbestos fibers in the living spaces was evaluated through high-volume air sampling, and surface dust samples were collected from numerous room surfaces via wet wipe and micro-vacuum techniques prior to any activities being conducted in the home. Air and surface concentrations of 0.01 f/mL (70 structures per square millimeter [s/mm^2]) (confirmed by TEM analysis) and 10,000 structures per square centimeter (s/cm^2), respectively, were adopted for this project as values, that if exceeded, required the home to be cleaned by a state licensed asbestos abatement contractor (LAAC) and cleared via air sampling prior to the home being considered for the Phase II component of our research.[109]

Of the 46 homes evaluated in the baseline assessment (Phase 1),[107] 40 homes contained VAI which revealed the presence of amphibole asbestos in bulk samples. Asbestos (primarily chrysotile) was confirmed in bulk samples of suspect asbestos-containing materials (ACM) collected from 18 homes. Fourteen homes contained both VAI and other ACM, while four homes contained only ACM other than VAI. Of the 158 high-volume air samples analyzed by TEM, 15 (9.5%) samples collected in 11 separate homes revealed detectable levels of asbestos. One sample analyzed exceeded the clearance concentration of 0.01 s/mL (or 70 s/mm^2). Of the 134 micro-vacuum samples collected in the 46 homes, 23 (17%) revealed detectable asbestos concentrations, and four samples (3%) collected in four separate homes revealed chrysotile asbestos concentrations greater than the background surface concentration of 10,000 s/cm^2. Of the 244 surface wipe samples collected, 134 (55%) of these samples revealed detectable levels of asbestos while 38 (16%) of the total wipe samples collected revealed asbestos concentrations greater than the background surface concentration of 10,000 s/cm^2. All 38 of these samples greater than the adopted background surface concentration were due to chrysotile contamination and were collected in 27 separate homes. Amphibole asbestos was detected in the living space of 12 (26%) homes, and chrysotile asbestos was detected in the living space of 45 (98%) homes prior to weatherization activities being performed. Sixteen homes were weatherized without the need for prior cleaning, and 21 homes were cleaned and cleared by air sampling prior to weatherization. The occupants and owners were informed of the bulk sample test results and a summary of asbestos-safe weatherization practices were discussed with the client.[107]

The initial baseline data were then used to develop sampling strategies, personal protective equipment (PPE) selections, and exposure control strategies for the second phase of the research. The aim of the second research phase was to determine the impact of weatherization activities in homes with asbestos sources (VAI and/or other ACM) on potential living space contamination, as well as weatherization worker exposure to asbestos. The ultimate goal of this research was to develop asbestos-safe weatherization protocols.[108] Of the initial 46 homes evaluated in Phase I,[106] 37 underwent weatherization protocols during the second research activity (phase II).[108] Prior to home weatherization activities, the weatherization crew leader met with the home occupant(s) and explained the weatherization process. The home occupant(s) were instructed to remain out of the home until the home was cleared via sample results. A stipend check was issued to the home occupant(s) to minimize the economic hardship associated with this requirement. VAI containing Libby amphibole asbestos was present in 32 of the 37 homes and one of the homes without VAI contained vermiculite insulation in two walls. Twenty-six samples of bulk ACM were also collected in these homes. Seventeen of these samples contained greater than one percent asbestos. The majority of positive bulk ACM samples were collected in basement areas and were chrysotile-based thermal system insulation (TSI) materials. Seven homes contained both VAI and other ACM, while four homes contained ACM with no vermiculite insulation identified.[107]

Airborne asbestos was detected in high-volume air samples in 28 of the 37 homes during weatherization activities.[106] Of these, chrysotile asbestos was detected in the air samples in 26 homes, and LA was detected in

14 homes. Eleven homes had both LA and chrysotile asbestos detected in air samples during weatherization activities. Of the 509 high volume air samples collected in home living spaces during weatherization activities and analyzed by TEM, 107 (21%) revealed detectable levels of asbestos, and 14 samples (2.8%) exceeded the clearance level of < 0.01 f/cc adopted for this research. For total asbestos structures (< and > 5 um), the mean high volume air sample concentration was 0.0059 s/cc, and the mean high volume air sample concentration for asbestos structures > 5 um was 0.0011. Due to the required air volume for the high-volume samples (1200 liters), several weatherization activities often were performed during the collection of individual high-volume air samples. Therefore, the results from the high-volume samples may be influenced by more than one weatherization activity, in addition to building-specific random variables. Based on a review of high-volume air sampling results and field notes, the weatherization activities that were most likely to generate airborne asbestos fibers were attic blow-in, sealing penetrations in attics, drilling holes in interior walls, interior wall blow-in, and basement batting installation. A total of 216 surface wipe samples were collected at the conclusion of the weatherization activities in the 37 homes. Asbestos structures were detected in 14.0%, or in 30 of the 216 surface wipe samples. Of the 213 personal samples collected on weatherization workers and analyzed by TEM, 71 samples (33%) showed detectable asbestos concentrations. For total asbestos structures, the mean personal sample concentration outside of the respirator worn by the worker was 0.372 s/cc, and the mean personal sample concentration for asbestos structures > 5 um was 0.078. This research revealed that performing weatherization measures has the potential to disturb asbestos-containing materials and disperse asbestos fibers into the living space. Airborne asbestos was detected during numerous weatherization measures, suggesting that weatherization practices as a whole, not single weatherization activities, may contribute to the disturbance and dispersal of asbestos fibers into the air. [106]

Discussion

The mechanisms by which fibers are released from ACM include impact, abrasion, fallout, vibration, air erosion, and emergency situations such as fire damage or natural disasters. Asbestos fibers released from ACM and then deposited on surfaces can be resuspended by human activities, i.e., sweeping or dusting. Once fibers are released into a structure, they will persist and potentially expose all occupants of the structure. In the home environment, ordinary vacuum cleaning is not effective in removing asbestos fibers, and fibers released into the home can remain for years and repeatedly become airborne again whenever they are disturbed. Resuspension of dust containing asbestos is an important consideration for persons living in the home and performing routine cleaning operations.[108] Disturbance of ACM by impact and abrasion occurring during activities such as construction, demolition, renovation; maintenance, and accidental disturbance can lead to fiber release and an increase in airborne fiber concentrations. Fallout, vibration, and air erosion could result in fiber release from damaged or friable ACM such as sprayed asbestos insulation materials. The release of asbestos fibers from the surfaces of asbestos building products was evaluated using test methods consisting of air erosion and light brush contact.[109] The asbestos building products tested were classified as sprayed insulations, building sheet products, and weatherized asbestos cement claddings. The authors reported that for sprayed insulation with soft, fluffy surfaces, air erosion fiber release was measurable, but fiber release from other products was below detection. For most asbestos products, fiber release from brush erosion was measurable.[109] Aging and degradation of ACM can eventually lead to fiber release through fallout which would be expected to increase with the age of the structure.[108]

The hazard of indoor asbestos pollution or contamination is enhanced because of the durability and aerodynamic properties of asbestos fibers.[108] Asbestos fibers exhibit low settling velocities, and a 1.0 um fiber with a 5:1 aspect ratio falling from three meters with a variable axis attitude will have a settling velocity of 10^3 cm/second and will remain airborne for 80 hours.[23] The persistence and durability of asbestos fibers, their low settling velocity, combined with the fact that the asbestos fibers can be easily re-suspended into air by activities such as dusting or sweeping, means that fibers either brought into a home, or released within a home, can repeatedly present an inhalation exposure pathway.

The potential for the development of asbestos-related diseases is a public health issue that extends beyond the workplace. Historically, it has been demonstrated that 'primary' workers, and workers who perform renovation and maintenance activities involving ACM, are at risk of developing an ARD. In the United States, 1.3 million workers in general industry continue to be exposed to asbestos, and an estimated 125 million people worldwide are exposed to asbestos in the workplace.[110,111] Regulations in Europe and recommendations in the U.S. since the 1930's [112,113] have failed to eliminate the risk of cancer from asbestos exposure. OSHA's risk assessment showed that reducing exposure to 0.1 f/cc, the current permissible exposure limit, would further reduce, but not eliminate, significant risk. The excess cancer risk at that level would be reduced to a lifetime risk of 3.4 per 1,000 workers.[114]

Public awareness of asbestos exposure and the associated health risks is limited when compared to other public health threats such as smoking and excess sun exposure. Latency periods of several decades for the development of ARDs contributes to lower public awareness. Government sponsored health campaigns regarding asbestos have been largely limited to particular occupational groups at risk such as brake mechanics, etc. Home owners or tenants sometimes carry out similar tasks with ACMs (e.g. DIY home renovations or maintenance), without the same risk mitigation measures that are mandated in the occupational setting, thus putting them at risk of developing an ARD. A study commissioned by the Asbestos Safety and Eradication Agency (ASEA) found that low levels of risk literacy relating to products containing asbestos was a barrier to informed decision-making regarding asbestos removal in the residential and commercial sectors in Australia, and a need was identified to improve homeowners' literacy in relation to the risks associated with asbestos in different forms, locations and conditions.[115]

The Australian government established the Asbestos Management Review (2012) [74] "... to make recommendations for the development of a national strategic plan to improve asbestos awareness and management." This review proposed the following: "A requirement that an asbestos content report (ACR) be undertaken by a competent assessor to determine and disclose the existence of ACMs in residential properties constructed prior to 1987 at the point of sale or lease, and prior to renovation, together with a property labelling system to alert workers and potential purchasers and tenants to the presence of asbestos." The proposal also included an evaluation of the feasibility of a removal program for residential properties.[74] Approximately one third of all homes in Australia contain asbestos products, and a house built prior to 1990 is likely to have some asbestos-containing materials.[115] The most common types of ACM used throughout Australia are asbestos cement sheeting and corrugated roofing which subject to the effects of constant weathering. The study reported that asbestos is commonly found in flooring material like vinyl floor tiles and sheeting, in wet areas such as around sinks and in bathrooms, and along the eaves. Management practices relating to asbestos awareness, identification and removal were identified as key issues in the study.[115]

Home owners are generally not aware of ACM in their homes and are therefore unlikely to be aware of the hazards. Industrial or occupational use of asbestos requires control measures prescribed by law. Occupational exposure standards for asbestos are not generally applicable or protective for domestic environments containing ACM because occupational standards are intended to protect presumed healthy workers who are aware of the hazards in the workplace, have specific training and access to personal protective equipment, and can actively participate in medical monitoring programs.[116] Currently, there are no exposure standards for asbestos in nonindustrial settings, and no regulations requiring corrective actions in homes with ACM. Additionally, domestic exposures can be long duration exposures to young and old individuals, people with pre-existing medical conditions such as asthmatic individuals, pregnant women, and other individuals sensitive to chemical exposures. Because of their long-life expectancy, children exposed at younger ages may be more susceptible.[9] Low socioeconomic status of some household members may affect access to health care and increase their vulnerability to ARD.

The Workers' Family Protection Act (Public Law 102–522) (29 USC 671), required the National Institute for Occupational Safety and Health (NIOSH) to conduct a study on workers' home contamination, and potential sources of asbestos home contamination that exist due to the widespread use of asbestos-containing building materials over many decades.[56] There are no surveillance systems in place for tracking or monitoring health conditions relating to domestic asbestos exposure, and health effects associated with homes with asbestos containing materials is unknown. In the U.S., the Residential Lead-Based Paint Hazard Reduction Act of 1992 has provisions to protect workers' families in their homes from dust contaminated with lead which includes the development of a health standard for lead-contaminated household dust, a lead exposure abatement program, and studies of sources of lead exposure in children [56] (NIOSH, 1995). The same approach could be used to analyze the living conditions and activities of homeowners in relation to the risk of asbestos exposure.[56]

The global mesothelioma burden has been estimated in the range of 36,300 to 38,400 annual deaths and remains an ongoing global health threat.[117] Epidemiological studies have found that even at the lowest levels of asbestos exposure, there have been increases in the incidence of mesotheliomas.[118,118,120] National mesothelioma incidence rates for large countries can mask high incidence and mortality rates clustering in small areas associated with past asbestos mines or industries.[121]

Conclusion

The world-wide human and economic impacts of asbestos are immeasurable. Despite the fact that more than 55 countries have banned asbestos, ACM is still present in public and private building and residences and its use continues in a large part of the world. The impacts of asbestos will continue to be felt during the third wave of asbestos disease. Greater policy efforts are needed eliminate further production and use of asbestos, increase the public health awareness of threat posed by asbestos, and facilitate asbestos testing and abatement.

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