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Michael J. McCoy,[1] *Matthew E. Wolter,*[2] *and Kim E. Anderson*[3]

Mesothelioma in Drywall Finishing Workers

ABSTRACT: In this manuscript, we evaluate the context in which workers were exposed to drywall joint compound based on the state-of-the-art of the construction industry during the post-World War II era through the 1970s and conduct a review of the scientific literature associated with the drywall trade and occupational exposure to airborne asbestos from drywall finishing work practices. Specifically, this manuscript evaluates the epidemiologic literature describing the apparent lack of association of mesothelioma to asbestos fibers utilized in drywall finishing materials in workers who were potentially occupationally exposed to short-fiber chrysotile asbestos contained in some drywall joint compound products during the post-World War II era through the early to mid-1970s. This manuscript also provides an understanding of the state-of-the-art in drywall joint compound manufacturing during this period.

KEYWORDS: chrysotile, asbestos, mesothelioma, drywall joint compound, drywall tapers, short-fiber

Introduction

The health effects of occupational exposure to asbestos are well documented in the scientific literature. The significant sequelae of asbestos exposure include asbestosis, lung cancer, and pleural and peritoneal malignant mesothelioma. Between 2500 and 3000 new cases of malignant mesothelioma are diagnosed annually in the United States, with malignant mesothelioma responsible for 15 000–20 000 deaths annually worldwide [1,2]. Mossman and Gee [3] reported that over 80 % of these malignant mesothelioma cases were caused by occupational exposure to asbestos-containing materials (ACMs) in the workplace, and other researchers have reported that asbestos is the leading cause of mesothelioma in the United States and the western world [1]. According to Ismail-Khan et al., the worldwide incidence of mesothelioma is increasing and it is expected to peak in 2020 [4]. Recent research also suggests that these tumors may have also been related to the SV40 virus used in the manufacture of polio vaccines in the 1950s, therapeutic radiation and the genetic predisposition in the absence of asbestos exposure [2,5]. This may be reflected in the fact that 10–20 % of mesothelioma cases are not associated with known asbestos exposure [6]. It should also be noted that a recent review article by Price and Ware found that for mesothelioma cases estimated to be diagnosed in 2008, 42 % of those cases will have a "cause" other than asbestos exposure [7]. In fact, Price and Ware stated, "The number of background mesothelioma cases projected for 2008, slightly more than 1000 or 42 %, is notable and growing as a percentage of all cases" [7]. In addition, fluoroedenite, erionite, zeolite, and single-wall carbon nanotubes are all suspected agents of mesothelioma [6,8–11]. With a latency of 20–40 years from asbestos exposure, mesothelioma often impacts workers and spouses in their retirement, at least a minimum of 10 years, if not multiple decades after their exposure [12].

In this manuscript, we evaluate the context in which workers were exposed to drywall joint compound based on the state-of-the-art of the construction industry during the post-World War II era through the 1970s and conduct a review of the scientific literature associated with the drywall trade and occupational exposure to airborne asbestos from drywall finishing work practices. This manuscript provides a comprehensive review of the epidemiologic literature associated with drywall finishing workers who were potentially occupationally exposed to short-fiber chrysotile asbestos contained in some drywall joint compound products during the post-World War II era through the early to mid-1970s. Specifically, this manuscript

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[1] Environmental Health and Safety, GZA GeoEnvironmental, Inc., Waukesha, WI 53186.
[2] Environmental Health and Safety, GZA GeoEnvironmental, Inc., Waukesha, WI 53186.
[3] Senior Principal/Director of Toxicology, Environmental Health and Safety, GZA GeoEnvironmental, Inc., Waukesha, WI 53186 (Corresponding author), e-mail: kim.anderson@gza.com

reviews the available epidemiologic literature and the apparent lack of association between drywall finishing work and the development of mesothelioma in drywall workers. This manuscript also provides an understanding of the state-of-the-art in drywall joint compound manufacturing during this time period and the manufacturer's lack of information and knowledge related to the potential adverse health effects of worker exposures to asbestos-containing joint compounds prior to the late 1970s.

The Construction Industries' Work with Asbestos-Containing Building Materials

For over 50 years, the construction industries' workforce had performed work practices that resulted in exposure to ACMs, including asbestos-containing building materials (ACBMs). ACBMs were often supplied by pass-through suppliers to construction company contractors. These products included insulation, spray fireproofing, cements, roofing materials, gaskets, caulks, joint compounds, vinyl floor tile, mastics, pipes, plasters, and many other materials. Construction workers may have also utilized or been exposed to fire-resistant clothing, including gloves and blankets, during construction and may have been exposed to other ACBMs, including but not limited to firebricks, lagging, and insulation on heating systems and ductwork installed during construction. According to the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA), "…an estimated 1.3 million employees in the construction and general industry face significant asbestos exposure on the job. Heaviest exposures occur in the construction industry, particularly during the removal of asbestos during renovation or demolition" [13].

Drywall Installers and Tapers (Finishers)

According to the U.S. Department of Labor, Bureau of Labor Statistics (BLS), the construction industry employed an average of 1.19 million people in the United States in 1945 [14]. In the U.S. post-World War II era, drywall installers and tapers (finishers) made up a small portion of the overall construction workforce, many of which may have been exposed to asbestos while performing their work practices.

According to the BLS, a drywall taper or finisher is defined as a worker in the North American Industry Classification System grouping 238310, Construction and Extraction Operations, Standard Occupational Classification (SOC) subgroup 47-2082, which "seal(s) joints between plasterboard or other wallboard to prepare (the) wall surface for painting or papering" [14]. Logically, drywall tapers' work practices included the use of drywall joint compound, of which most, if not all, contained a small percentage of short-fiber Grade 7 chrysotile asbestos for a defined time period [14]. The BLS estimated that drywall installers, ceiling tile installers and drywall tapers, SOC 47-2080, which included drywall tapers (SOC 47-2082), totaled 160 590 workers in May 2008, which is the most recent data available from the BLS [14]. Occupational-specific data is not available from the BLS prior to 2003 to define the number of drywall finishers and tapers (SOC 47-2082) working in the United States in the post-World War II era. However, the BLS reported that of the 160 590 drywall installers employed in May 2008, ceiling tile installers and tapers in May 2008, ~128 740 workers were employed and categorized as drywall and ceiling tile installers, and 31 850 were employed and categorized specifically as drywall tapers [14]. The total number of construction workers in 2008 was ~7.215 million workers according to the BLS.

Assuming the percentage of drywall tapers has remained as a consistent proportion of the total construction industry from the post-World War II era to present, or ~0.44 % of the total workers in the construction industry, ~5236 drywall tapers would have been in the workforce in 1945. In 1970, there were ~3.654 million workers employed in the construction industry, again with 0.44 % being drywall tapers, ~16 077 workers would have been employed as drywall tapers in 1970. If these estimations are considered, then the number of workers coded as SOC 47-2082 would have increased by ~10 841 employees from 1945 to 1970, with an increase of ~15 773 drywall tapers between 1970 and May 2008. While this is clearly a retrospective estimation of the BLS data, these estimates provide an overview of the approximate number of workers in the United States performing drywall work as compared to the overall number of workers in the construction trades in the United States during the post-World War II era.

The advent of gypsum wallboard (GWB) occurred in the mid-to late 1940s. The rapid demand for post-World War II homes necessitated the transition from the labor-intensive plaster finish work to the more rapid installation of GWB and subsequent finishing that utilized a variety of joint compounds and finishing compound. Eventually, by the late 1960s, the drywall installation and finishing trades were performed by the rough carpentry unions and construction trade groups, while plasterers worked more commonly with plasters, stuccos, and specialty finishes.

Short-Fiber Chrysotile Asbestos Utilized in Drywall Joint Compound

Due to its physical properties, including thermal stability and flexibility, short-fiber chrysotile serpentine mineral fibers were used as a component in hundreds if not thousands of building products. These short-fiber chrysotile fibers were also incorporated into selected manufacturers' drywall joint compound beginning in the early 1950s to mid-1960s or later depending on the manufacturer [15]. Chrysotile asbestos is a hydrated magnesium silicate, which has unique chemical characteristics and structures such that it remains pliable and strong for many years (or decades). Due to chrysotile's high tensile strength and thermal resistance, chrysotile was utilized to stabilize, fireproof, and insulate a wide variety of construction products. Chrysotile was generally used more frequently than the other commercial asbestos fiber types in construction products, particularly after the 1960s [16].

Background on chrysotile mining and milling provides an understanding of the chrysotile asbestos content and mineralogy contained in drywall joint compound and its potential toxicological impact on drywall workers. Chrysotile asbestos of the serpentine crystalline structure was historically, and is currently, mined in Canada, mainly in the eastern townships of Quebec. Historically, asbestos was mined in Zimbabwe, Russia (Ural Mountains), China, Italy, Brazil, and United States (California and Vermont). In 1955, more than half of the chrysotile produced in the world came from Canada and Russia [17]. In the Quebec chrysotile mining district, the primary chrysotile mines extended from the southern town of Asbestos (Jeffrey Mine) in Black Lake, Thetford, and East Broughton to the northeastern operation of the Carey Canadian operations where the bulk of Canadian chrysotile fiber was produced [17]. For decades, the Carey Canadian operation supplied an extensive volume of chrysotile asbestos, which was imported into the United States for incorporation into construction products, including joint compounds. At one time, the amphibole tremolite was considered a contaminant in chrysotile ACBMs, including some joint compounds. The tremolite content, if any, varied widely across building products based on the source of origin of the chrysotile ore.

Researchers have found that several sources of chrysotile used in joint compound did not contain tremolite. Specifically, Butler, Pooley and Gunter et al. independently found no detectable amphibole tremolite fibers in chrysotile asbestos mined in the Canadian Carey operations [18–20]. Williams-Jones et al. found similar results in the Jeffrey Pitt mine where selected chrysotile deposits are tremolite-free [21]. Mining occurred at Jeffrey Pitt outside of silica-rich intrusion bodies which differ from tremolite-containing chrysotile deposits found in the Thetford, Bells, and other asbestos area mines [17,22]. Langer and Nolan reported that tremolite asbestos was present in chrysotile ore from the Bell Mine in Thetford, Quebec [17]. Other studies have revealed that tremolite contamination in Thetford was two to three times higher than that of tremolite found in chrysotile mined in and around the Asbestos, Quebec region [23]. Addison and Davies found a presence of tremolite in 28 of 81 samples, which were examined from the Quebec mining region, excluding the Carey Canadian and Jeffrey Pitt mines at an average concentration of 0.09 % tremolite for both mines [24].

In the United States, the majority of chrysotile mining occurred in California, although chrysotile was historically mined in Vermont as part of the southern extension of the Quebec deposits [25]. Bernstein et al. and Gibbs reported in 2005 that no tremolite was present in "Calidra" chrysotile mined from the Coalinga mine in New Idria, California [26,27].

Drywall joint compounds historically contained calcite, quartz (silica), talc, mica, gypsum, clays (attapulgite and kaolinite), polyvinyl alcohol, and perlite in addition to short-fiber chrysotile asbestos [27,28]. While tremolite is a naturally occurring constituent of some talc based on the mines' geographic origin, talc can be identified in both its asbestiform and non-asbestiform geologic habits. In addition, Rohl et al. identified some consumer products that contained small quantities of tremolite as a component of talc, ranging from 0.1 % to 10.3 % [29]. However, talc processing, including crushing and grinding, resulted in talc cleavage fragments with lower aspect ratios as compared to commercial amphiboles. Initial talc content and subsequent tremolite content in joint compound likely varied significantly between manufacturers' formulae. The resulting tremolite content in joint compounds, which in many brands of joint compound was below the level of detection, would have been determined by the mining origin of the talc, the type of natural tremolite (asbestiform or non-asbestiform), if any, found in the talc. In addition, the final aspect ratio of asbestiform tremolite fibers found in some brands of joint compound after final processing, would likely be significantly shortened.

Bernstein and Hoskins provided a comprehensive review of the health effects of chrysotile asbestos and noted that chrysotile is mineralogically and structurally unique from amphiboles [30]. Chrysotile is a "sheet silicate" and due to mismatched magnesium and silicate ions within its crystal structure, it forms a curled and flexible, thin-rolled sheet [30]. The disassociation of chrysotile through the loss of magnesium ions, in which the silica matrix is broken, is significantly different from that of amphiboles. When amphiboles lose magnesium ions, which loosely hold together its crystal structure, rod-like, inflexible needles are liberated. Unlike the commercially used amphiboles, amosite and crocidolite, which contain roughly 29–39 % iron, respectively, chrysotile contains no iron in its crystal structure and minimal iron, if any, as a surface contaminant [31,32]. Iron plays a key role in the generation of the reactive oxygen and nitrogen species on the surface of the fiber and is also seen in amphibole-induced oxidant release from phagocytic cells [33].

The inclusion of chrysotile asbestos in the composition of ACBM, including joint compound, enhanced the function and performance of the product. Drywall joint compound products typically utilized a uniform grade of chrysotile and had these selected grades of asbestos, specifically Grade 7 chrysotile, added to its composition based on the desired physical characteristics of the final product. Drywall joint compound, toppings, coatings, and other compounds that required hydration by water, or contained water or other dilutants as a component, were often challenging to formulate. Chrysotile, particularly short-fiber Grade 7 chrysotile, prevented cracking and shrinking in drywall joint compound and provided stability and appropriate texture [15]. After the removal of short-fiber chrysotile asbestos from joint compound in the mid- to late 1970s, manufacturers received both customer complaints due to physical limitations and experienced internal challenges in reformulating products. Therefore, the addition of a particularly fine-grade or short-fiber Grade 7 chrysotile and consistent production formulation were necessary in order to maintain product consistency in the competitive building products market of the 1960s and 1970s. Most, if not all, companies that manufactured joint compounds in the 1950s through the early 1970s included short-fiber chrysotile asbestos in their formulations [15]. The chrysotile asbestos acted as a binder to the other minerals in the compound and made the compounds "workable" and smooth.

Several national construction material manufacturers dominated the production of drywall joint compound during the Post-World War II era. Each manufacturer, sometimes within the same company, maintained numerous formulas with varying composition of short-fiber chrysotile content based on application and specific use of the product, with some of these joint compounds containing no asbestos. Furthermore, most regionally-based joint compound manufacturers had little or no in-house industrial hygiene staff and relied on information proved by the mining operations that supplied the asbestos, regulatory agencies, and other trade organizations for guidance on the safe use of asbestos in their products.

Review of the Epidemiologic and Toxicological Literature Related to Short-Fiber Chrysotile Utilized in Drywall Joint Compound

As previously discussed in this manuscript, while in excess of 16 000 people were likely employed as drywall tapers in 1970 and that many of the drywall joint compounds with which these drywall tapers worked contained short-fiber chrysotile asbestos during this time, a review of the scientific literature revealed scant epidemiologic evidence of mesothelioma in this worker population. When the scientific literature is reviewed, several epidemiological studies are available, which found no mesothelioma deaths in drywall workers in their historical cohort studies (see Table 1) [34–39]. The occupational cohort studies of drywall finishing workers to date contain limited numbers of workers, which potentially decrease the power of these studies to determine risk of mesothelioma in drywall workers. Due to the unique challenges of historical cohort studies and limited worker records, the studies reviewed were the most comprehensive available that discusses and defines the risk of mesothelioma for drywall workers.

Fischbein et al. and Robinson et al. reported no mesothelioma in drywall workers in their respective studies [34,35]. Specifically, Fischbein et al., in their cross-sectional study of 114 drywall workers in the New York City area, found increases in the prevalence of asbestosis and pleural thickening yet did not report any cases of mesothelioma in historical cohort studies [34]. Some investigators contend that Fisch-

TABLE 1—*Epidemiologic studies associated with drywall finishing work.*

			Independent Variables		Dependent Var.=Outcome	Threats to Internal Validity			
Author	Study Design	Sample (*n*)	Exposure(s)	Adjustment Factors	Measure of Effect	Bias	Uncontrolled Confounding	Chance	Comments /Overall Quality
Fischbein et al. [34]	Cross-sectional study of drywall workers	114	Drywall joint compound	None	Asbestosis=26.3–51.4 % [a] and pleural thickening=0.0–14.3 % [a]	Healthy worker effect, selection bias	Smoking, potential asbestos exposures other than joint compound	Possible due to low *N*; chest films read by five readers	Small sample size, no mesothelioma cases despite 31.6 % of cases 20+ year exposures
Robinson et al. [35]	Cohort of white, male construction workers, including drywall workers who died between 1984 and 1986	61 682 (355 drywall workers/320 plasterers)	Construction-related materials including asbestos	None	Zero cases of mesothelioma in this cohort for drywall installers and plasterers	Healthy worker effect, death certificate mis-classification	Smoking	None	Large sample size
NIOSH [39]	Mortality study	1 713 413 (3580 drywall workers)	Varied by occupation	Age and sex	Zero cases of mesothelioma in this cohort for drywall workers	Death certificate mis-classification	Smoking	None	Excellent, large sample size
Lipscomb and Dement [36]	Cohort of union carpenters, including drywall workers who died between 1989 and 1992; nested case control for asthma	10 938 (1525 drywall workers)	Multiple construction materials including asbestos and drywall joint compound.	Age, sex, time in union and ever/never smoking for nested-case control; none for mesothelioma	Zero cases of mesothelioma reported in this cohort for drywall workers	Healthy worker effect, death certificate mis-classification	Smoking	None	Good; study not designed to directly measure drywall workers
Wang et al. [37]	Cohort of male construction workers, including drywall workers in North Carolina who died between 1988 and 1994	29 554	Multiple construction materials including asbestos and drywall joint compound	None	Zero cases of mesothelioma reported in this cohort for drywall workers	Healthy worker effect, death certificate mis-classification	Smoking	None	Good
Stern et al. [38]	Cohort of Unionized Construction Plasterers and Cement Masons who died between 1972 and 1996	12 873	Included drywall joint compound and also asbestos-containing fireproofing, plasters (until 1960) and thermal system insulation	Proportionate cancer mortality rates utilized	Four observed mesothelioma deaths, PMR=188 [b]	Healthy worker effect, potential misdiagnosis of mesothelioma	Smoking, amphibole ACBMs	None	Plasterers are responsible for preparation, installation, and repair of all interior and exterior insulation and fireproofing of steel beams and columns

[a] From zero to 20+ years since on-set of exposure to drywall joint compound.

[b] Expected rates for mesothelioma were unavailable. PMR was not statistically significant. Two of the four mesothelioma deaths were in plasterers.

bein et al.'s study revealed no mesothelioma in drywall workers due to the long latency of the disease and that their cohort had not yet reached that latency threshold for development of mesothelioma. However, it is important to note that short-fiber chrysotile was included by some companies in their products as early as the late 1950s, and, as reported by Stern et al., some plaster products contained asbestos prior to the advent of joint compound [38]. Robinson et al. evaluated occupation and industry codes on death certificates from 19 states to evaluate the mortality risk among men and women employed in construction occupations who died during 1984–1986 [35]. Malignant mesothelioma or any combinations of pleural or peritoneal carcinoma were not reported in this evaluation of 61 682 death certificates [35].

Wang et al. also found no mesothelioma deaths in a cohort of 29 554 male construction workers, including drywall workers in North Carolina who died between 1988 and 1994. Wang et al. confirmed the findings of previous investigators that increased mortality risk exists among construction workers [37]. A study by Lipscomb and Dement, which evaluated a cohort of 10 938 active union carpenters that had worked at least three months between 1989 and 1992, determined the odds ratios for lung diseases defined by ICD-9 codes [36]. This study also identified no cases of pleural neoplasms in this cohort of union carpenters, which included 1525 carpenters whose predominant type of carpentry work was classified as "drywall" workers.

Stern et al.'s study of the Operative Plasterers' and Cement Masons' (OPCM) Association of the United States and Canada, which was comprised of 36 000 members including 12 960 plasterers, revealed four cases of mesothelioma in the overall cohort [38]. In Stern et al.'s report, plasterers were defined as "…generally responsible for all interior and exterior plastering of drywall, cement, stucco, and stone imitation as well as taping and pointing of all joints, nail holes and bruises on wallboard and drywall" [38]. It is important to note that plasterers in the OPCM union were involved with work activities that were not included in the BLS's description of a "drywall taper." Stern et al. noted that plasterers in the OPCM often installed structural fireproofing and other ACBM, which contained amphibole asbestos, in addition to short-fiber chrysotile, making evaluation of this occupational cohort challenging based on the variety of ACBMs, including amphiboles, to which they worked with and were exposed [38]. Beginning in the early 1960s, the drywall installation and finishing trades were performed by the rough carpentry unions and then by specific construction trade groups by the late 1960s, while plasterers worked more commonly with plasters, stuccos and specialty finishes during that time.

In June 1997, the U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH) published a mortality study stratified by occupation, industry and cause of death in 24 reporting states from 1984 to 1988 [39]. The measure of association utilized in this study was the proportionate mortality ratio (PMR), which was age-adjusted for four race-sex groups, which included male, female, African-American, and Caucasian. All occupations were included, except for housewives or homemakers, with a total of 1 713 413 decedents in the study. There was a total of 3580 deaths in drywall workers, with no deaths reported in this cohort for pleural or peritoneal mesothelioma. NIOSH currently maintains the National Occupational Mortality Surveillance System (NOMS) data of death certificate data with coded occupational and industry information, including 28 states that have participated from 1984 through 1998. When evaluating the NOMS database for white male drywall workers, coded as "Drywall Installers" under the U.S. Census Bureau occupation code 573, the database revealed 3173 total deaths occurring in drywall workers, with an undefined number, but less than three, of those deaths attributed to pleural or peritoneal mesothelioma. While this most recent NIOSH data is exclusively available by electronic media, it suggests similar results as the 1997 NIOSH occupational mortality study [40].

It is important to note that epidemiologic studies, based on death certificate analyses, may have inherent error by incorrectly reporting the decedent's occupation and under-reporting co-morbid diseases, which may be important when evaluating mortality in an occupational population. Studies of mortality using death certificates are important surveillance tools for identifying potentially hazardous occupations and industries. Wang et al. noted that the data may lack occupational exposure histories, as well as information on non-occupational risk factors, such as smoking and diet, which may be important in evaluating mortality rates from all diseases [37]. However, Wang et al.'s study confirmed previous findings of increased mortality risks among construction workers, revealed statistically significant work-related increases in the PMR for malignant neoplasm of the buccal cavity, pharynx, and lung, as well as pneumoconiosis, transportation accidents, and accidental falls, yet did not indicate an increase in mesothelioma in drywall workers above that of all other workers [37].

It is also important to consider that occupational coding at death may not reflect the patient's true long-term occupational exposure to ACBM. As noted by Stern et al., there is always the potential for underdiagnosis of mesothelioma due the fact that the International Classification for Disease (ICD) code for mesothelioma does not include all sites where mesothelioma can occur [38]. While misdiagnosis may result in a feasible bias in these mortality studies, due to the low incidence of mesothelioma, clinical progression, and the histologically unique nature of mesothelioma, a "large undercount of mesothelioma deaths," as identified in Stern et al.'s study of plasterers who died from 1972 to 1996 is generally unsupported. In summary, the preceding epidemiologic studies utilizing death certificates revealed a lack of association between drywall workers and the development of malignant mesothelioma above that of the general population and workforce.

Recently published research on asbestos-related disease, fiber type and dimension indicated that amphibole asbestos, not serpentine asbestos, is the causative agent of mesothelioma. In fact, Berman and Crump, in performing a meta-analysis of asbestos-related cases, including the mesothelioma risk, found that "for mesothelioma, the hypothesis that chrysotile and amphibole are equally potent was strongly rejected by every metric and the hypothesis that (pure) chrysotile is non-potent for mesothelioma was not rejected by any metric" [41]. Numerous scientific studies have been conducted which show that the short-fiber chrysotile asbestos utilized in joint compounds, termed Grade 7 chrysotile, is neither a causative agent nor is it associated with pleural or peritoneal mesothelioma from the inhalation of this fibrous material [26,35,42–47].

Short-fiber Grade 7 chrysotile, which was used in drywall joint compound, has also been studied for its biopersistence, or biologic half-life, in the lung. Bernstein et al. extensively published on their research on the biopersistence of chrysotile asbestos compared with that of amphibole tremolite [48]. They found that clearance of these shorter chrysotile fibers was either similar to or faster than the clearance of insoluble nuisance dusts. Bernstein et al. also reported that fibers less than 5 μm in length are effectively no different from non-fibrous particles and are cleared with similar kinetics and mechanisms as particles [48]. The World Health Organization (WHO) confirmed that chrysotile is more rapidly cleared form the lung than are amphiboles and reported that the fiber length is an important determinant of alveolar clearance of chrysotile fibers [49]. WHO reported that evidence from animal studies confirmed that short-fibers (less the 5 μm long) are cleared more rapidly than long fibers (longer than 5 μm long) [49]. The National Institute of Environmental Health Sciences, in its Annual Report on Carcinogens, 11th Edition, reported that "ninety-one percent of the chrysotile used in 2002 was categorized as Grade 7 asbestos (with fiber lengths less than 3 mm) followed by Grades 4, 5, 6 and 3" [50]. The U.S. Environmental Protection Agency technical support document assigned zero risk to fibers less than 5 μm in length and panelists concurred that fibers shorter than 5 μm in length and more likely 10 μm in length should be assigned "zero potency" [51].

Hodgson and Darton also concurred that in humans, the short-fiber chrysotile utilized in drywall joint compound is cleared from the lung in months, which might have less biological effect than amphibole fibers, which are typically cleared in years [47]. Pistolesi and Rusthoven reported that amphiboles appear to be more carcinogenic and mutagenic in animal models and tissue cultures than those that are curled and more pliable, such as chrysotile [52]. Roggli et al., in a clinicopathological correlation of 1445 pleural mesothelioma cases, reported that commercial amphiboles are responsible for most of the mesothelioma cases observed in the United States [53]. These studies provided additional mechanistic and biologic plausibility to the epidemiologic data which suggests a lack of mesothelioma development in drywall finishing workers.

Airborne Exposure to Short-Fiber Chrysotile During Drywall Finishing Activities

While both toxicological and epidemiologic literature support that short-fiber chrysotile found in joint compound products is not causative of mesothelioma, the scientific literature described the fiber types and sizes observed during drywall finishing activities. Significant work has been performed to evaluate the airborne chrysotile fiber concentrations measured during typical drywall finishing work activities [54–56]. In 2008, Brorby et al. characterized the distribution of primary size and bundles in historical joint system cement (joint compound) and three samples of Grade 7 chrysotile [57]. Brorby et al. reported that 90.5 % of all fibers were less than 10 μm in length in a historical joint compound and that 96.3 % and 98.4 % of all fibers were less than 10 μm for Johns Manville JM7RF3 and JM7R05, respectively [57]. In the historical joint system cement, 81.1 % of the fibers were less than 5 μm in length [57]. However, in the work by Fischbein et al. on unspecified brands of asbestos-containing drywall joint compounds in 1979, they noted that optical microscopy failed to identify the majority of asbestos fibers less than 5 μm in length [34]. They stated, "electron microscopic analysis of these air samples showed a large proportion of smaller fibers (less than 1 μm) too fine to be seen by optical microscopy" [34].

Phase-contrast microscopy (PCM) analysis of air samples in these preceding studies failed to identify if fibers longer than 5 μm were actually asbestos fibers and not a non-asbestos fiber. Specifically, non-asbestos fiber types, including gypsum and cellulose fibers, are a likely source of fiber contamination in these samples [28]. Transmission electron microscopy (TEM) is capable of not only evaluating the length and aspect ratio of a fiber, but also identifying its chemical and structural composition to identify it as an asbestos fiber, specifically differentiating serpentine and amphibole fibers. It is important to note that in PCM gross fiber analysis, any fibrous structure with a length greater than 5 μm with an aspect ratio (length to width) of greater than 3:1 is included. NIOSH Method 7402 is used to determine asbestos fibers in the optically visible range and may complement the results obtained by PCM (NIOSH Method 7400). Perkins and Hargesheimer reported in their study of chrysotile asbestos fibers released during actual field demolitions of GWB finished with chrysotile asbestos-containing joint compound, that less that 4 % of the fibers counted by PCM were actually chrysotile asbestos fibers. The authors continued, "The fact that gypsum fibers interfere with the proper counting of asbestos fibers is well known" and "PCM, which counts all fibers, yielded fiber counts 10–50 times higher than TEM reported asbestos fibers" [58].

Several non-published studies evaluated airborne exposure to asbestos during drywall taping and finishing work activities. An unpublished study performed by the National Loss Control Service Corporation of Long Grove, Illinois, reported to the United States Gypsum Co. in Des Plaines, Illinois, that airborne asbestos concentrations by PCM ranged from 0 fibers of asbestos per cm^3 of air (f/cm^3) to 55.7 f/cm^3 with sampling times of 1.5–30 min under a variety of working conditions [55]. Other similar studies were conducted by George D. Clayton & Associates, Inc., for the Gypsum Association, a consortium of the national manufacturers of joint compound products, also reported similar findings. During work activities, such as mixing and sanding, airborne asbestos concentrations ranged from 3.7 to 43.6 f/cm^3 [56]. These sampling results again measured any fiber that was greater than 5 μm long with an aspect ratio of 3:1. The sampling times for these airborne asbestos measurements where also very short in duration, typically less than 30 min. This data, while quantifying the maximal or peak airborne asbestos concentrations during selected work activities, primarily including the mixing or sanding of dry powder joint compound, is not reflective of a worker's eight-hour time-weighted average (TWA) exposure.

The study conducted by Verma and Middleton provided the most comprehensive evaluation of airborne exposure to asbestos and evaluated the drywall worker's exposure as an eight-hour TWA during specific work activities utilizing the applicable work practices required to utilize dry powder and pre-mixed joint compound, separately [59]. The TWA airborne asbestos (chrysotile) concentration for a 40-h workweek for drywall/taping workers using dry powder joint compound and hand-sanding techniques was 4.5 f/cm^3 [59]. The TWA airborne asbestos (chrysotile) concentration for a 40-h workweek for drywall/taping workers using pre-mixed compound and pole sanding techniques was 2.1 f/cm^3 [59].

The state-of-the-art knowledge of the joint compound manufacturers during the post-World War II era through the 1970s is paramount of importance including when the applicable scientific and medical literature provided a basis for understanding the potential exposures to drywall finishing workers during this period. The evaluation of the available medical, toxicological and scientific literature pertaining to joint compound in order to evaluate the state-of-the-art knowledge by joint compound manufacturers during the post-World War II era through the 1970s provides an understanding of the potential knowledge of drywall joint compound manufacturers.

State-of-the-Art for Drywall Joint Compound Manufacturing

In order to understand the state-of-the-art regarding joint compound during this time, an understanding of the composition of joint compound, along with the typical work practices performed by a drywall taper and finisher, is required. Significant research has been conducted to elucidate the mineralogical types and concentrations of asbestos in drywall joint compound as well as its inert material composition [15,25,57]. As discussed previously, drywall joint compound, which historically contained a small percentage of Grade 7 short-fiber chrysotile, was a widely used building product to finish joints and nail or screw holes within and in between GWB. Some drywall installers were involved in hanging and fastening drywall to wood or metal framework. As described previously, others, known as drywall tapers or finishers, taped joints between sheets of drywall, mixed in some instances, and applied joint compound, as well as sanded the finished seams and nail or screw holes. Selected drywall tapers also performed cleanup following their work. Verma et al., in 1980, described the duration of a variety of drywall installation and finishing work practices [59].

In the post-World War II era and extending into the early 1970s, the relevant scientific and medical literature did not show that anyone would be harmed by performing work with or around others using drywall joint compound. In 1930, Merewether and Price published one of the first studies that showed that asbestos textile workers in the United Kingdom who were exposed to excessively high airborne asbestos concentrations for extended durations were at a risk above that of the general population for contracting asbestosis [60]. This study also noted that asbestos exposures lower than the airborne concentrations found in the textile industry's spinning rooms would not cause asbestosis even if the exposure occurred for the working lifetime [60]. In 1946, Fleischer et al. published a study of shipyard workers, including pipe covering workers (insulators), in the naval shipyards which stated in part that pipe covering was "a relatively safe occupation" [61]. In the late 1950s to mid-1960s, other limited research was published that suggested that raw asbestos fibers either mined, manufactured, or used in insulation products were related to selected physical anomalies [62–64]. No discussion, or for that matter any reference to joint compound materials, were included in any of these studies.

The first studies that demonstrated the possibility of significant asbestos illnesses resulting from the use of any construction products that contained asbestos appeared as early as 1964, when studies began appearing regarding asbestos illnesses from the use of asbestos-containing thermal insulation by the Asbestos Workers' Union. In 1964, Marr published a study entitled "Asbestos Exposure During Naval Vessel Overhaul" [65]. Also in 1964, Irving Selikoff, M.D. started publishing articles concerning the illnesses that he was finding in insulators. Also, by the mid-to late 1960s, Dr. Selikoff was presenting the findings of his research at meetings and symposia of trade organizations, including insulators. In 1965, the New York Academy of Science symposium on "Biologic Effects of Asbestos" and research in the late 1960s, noted that asbestos insulation workers were experiencing asbestos-related diseases at work sites where the average airborne concentrations of asbestos dust were below the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) in effect at that time of 5 million particles per cubic foot (mppcf), or $\sim 30\ f/cm^3$ [66]. This was followed in 1968 by two studies entitled "The Work Environment of Insulating Workers" by Balzer and Cooper [67] and "Asbestos Hazards in Naval Dockyards" by Harries [68]. In 1969, the ACGIH recommended revising the TLV of 5 mppcf for asbestos that had been in effect since 1946. By the early 1970s, OSHA's permissible exposure limit (PEL) was established as $5\ f/cm^3$ longer than $5\ \mu m$ with a peak exposure level of $10\ f/cm^3$. OSHA, in 1976, further revised the asbestos PEL to $2\ f/cm^3$.

It was not until 1973, that researchers from Mt. Sinai School of Medicine began to study union workers in the International Brotherhood of Painters and Allied Trades [69]. Thereafter, the National Resources Defense Council contacted the U.S. Consumer Product Safety Commission to raise concerns about the use of asbestos products [70]. In August 1975, the information contained in a *Wall Street Journal* article provided the initial discussion in a widely disseminated medium regarding the use of asbestos in building products. The article stated, "various spackling compounds used for home repair contains concentrations of asbestos sufficient to cause disease" [71]. By the mid- to late 1970s, for the first time, several authors, trade associations and companies started evaluating exposures of asbestos related to the use of joint compounds in the workplace [34,72,73].

Thus, until the early to mid-1970s, during the time that an estimated 16 077 drywall tapers may have used asbestos-containing joint compounds while performing construction jobs, a joint compound manufacturer had no reason to believe that there were any hazards related to the use of joint compound that contained asbestos. Most manufactures had no information related to their products and asbestos exposures much less related to the potential hazards of working with or around their joint compound. Further, there were no federal regulations which required any special requirements for the use of asbestos-containing products until late 1971.

Generally, joint compound manufacturers learned that potential asbestos exposure existed that might be harmful in the early 1970s, before any questions had been raised regarding the evidence of disease from exposures to joint compounds. Studies by industry in 1973 indicated that airborne asbestos concentrations associated with the mixing and sanding of drywall joint and spackling compounds were generally within the OSHA PELs but could occasionally approach or exceed them [74]. Further monitoring, dust control measures, or respirators, as required by OSHA, were recommended [74,75].

The first case report in the medical literature of lung cancer and asbestosis in a drywall worker was reported by Fischbein et al. in 1978 [76]. Fischbein et al. published a study in 1979, demonstrating that selected, but unnamed, brands of drywall joint compounds contained asbestos, whose peak concentrations associated with their use could exceed the applicable OSHA PELs and that irregular radiographic opacities were seen in some drywall workers with several years of exposure [34]. To reiterate, in 1980, Verma and Middleton conducted the initial and only study to measure the airborne asbestos concentrations during the use of both dry powder and pre-mix drywall joint compound while defining the 8-h TWA exposure concentrations for each [59]. Prior to this study, other research had only presented peak and short-term air sampling results, not eight-hour TWAs [72,77–79].

Some joint compound manufacturers had begun developing asbestos-free joint compound before there were any published reports suggesting any potential health hazard with the use of asbestos-containing joint compounds and some placed warning labels on their joint compounds in 1972. It should be noted that on Jan. 12, 1972, OSHA proposed a revised asbestos standard that was promulgated in July 1976. This 1972 proposed standard required the initial warning labels for joint compound that contained asbestos that was distributed outside of the factories that manufactured the product. Following the January 1972 proposal, OSHA established an Advisory Committee on Asbestos Dust to make recommendations regarding a permanent asbestos standard and to receive oral and written comments from the public.

Summary

It should be noted that the scientific and epidemiological journals in which the few studies that were published regarding what were essentially new toxicological findings of asbestos prior to the early 1970s were scientific with limited distribution in medical and epidemiologic journals and, in general, obscure to most of those in the general population. Generally, joint compound manufacturers became aware in the late 1960s of potential health hazards of asbestos to persons exposed in mines, factories, and textile mills with products other than joint compound. For example, few individuals or companies had ready access to the *British Journal of Industrial Medicine* or the *Annals of Occupational Hygiene*. Obviously, the 1960s were long before the advent of the internet or any method to obtain these studies other than a company or individual conducting frequent library research. Further, in the United States, there were no federal safety and health regulations for individual facilities until the implementation of OSHA in 1971. However, there is no doubt that selected workers in the construction industry were exposed to asbestos and contracted asbestos-related diseases, including mesothelioma.

Currently, research is on-going to define the cellular basis for causation of mesothelioma. Regardless, the scientific literature for drywall tapers is strongly suggestive in conferring the lack of a relationship to their work assignments, which may have used drywall accessory products that contained small concentrations of chrysotile asbestos and the epidemiologic evidence of mesothelioma in drywall workers. While lung cancer and asbestosis have been well described in drywall worker cohorts, mesothelioma development has not been definitely associated with drywall finishing work in the scientific literature. The current literature's lack of epidemiologic relationship between drywall finishing workers and mesothelioma may be in part due to the unique biopersistence, limited toxicity, fiber dimensions and structure and morphology of short-fiber chrysotile, which was historically used in some joint compound systems. Despite the limited number of workers in the epidemiologic studies reviewed in the manuscript, the available evidence shows that the majority of asbestos fibers in ACBMs contain chrysotile fibers of less than 5 μm in length. Toxicological data suggests that these asbestos fibers are less carcinogenic than amphibole fibers. Therefore, in comparison to other occupationally exposed workers, drywall finishing workers have a reduced risk of developing mesothelioma. Future research, particularly in areas of genetic causation of mesothelioma, additional epidemiologic studies of drywall finishing worker cohorts, and advanced survey methods for historic joint compound exposure assessment, would contribute to the body of knowledge on this consistently fatal disease process.

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