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# Comparative Risks of Cancer from Drywall Finishing Based on Stochastic Modeling of Cumulative Exposures to Respirable Dusts and Chrysotile Asbestos Fibers

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Sanding joint compounds is a dusty activity and exposures are not well characterized. Until the mid 1970s, asbestos-containing joint compounds were used by some people such that sanding could emit dust and asbestos fibers. We estimated the distribution of 8-h TWA concentrations and cumulative exposures to respirable dusts and chrysotile asbestos fibers for four worker groups: (1) drywall specialists, (2) generalists, (3) tradespersons who are bystanders to drywall finishing, and (4) do-it-yourselfers (DIYers). Data collected through a survey of experienced contractors, direct field observations, and literature were used to develop prototypical exposure scenarios for each worker group. To these exposure scenarios, we applied a previously developed semi-empirical mathematical model that predicts area as well as personal breathing zone respirable dust concentrations. An empirical factor was used to estimate chrysotile fiber concentrations from respirable dust concentrations. On a task basis, we found mean 8-h TWA concentrations of respirable dust and chrysotile fibers are numerically highest for specialists, followed by generalists, DIYers, and bystander tradespersons; these concentrations are estimated to be in excess of the respective current but not historical Threshold Limit Values. Due to differences in frequency of activities, annual cumulative exposures are highest for specialists, followed by generalists, bystander tradespersons, and DIYers. Cumulative exposure estimates for chrysotile fibers from drywall finishing are expected to result in few, if any, mesothelioma or excess lung cancer deaths according to recently published risk assessments. Given the dustiness of drywall finishing, we recommend diligence in the use of readily available source controls.

**KEY WORDS:** Chrysotile asbestos fibers; cumulative exposure risk; drywall finishing; respirable dusts; stochastic modeling

## 1. INTRODUCTION

Construction of interior walls using drywall (wallboard or gypsum board), a cost-effective and time-saving substitute to lath and plaster, became standard practice after World War II. Installation involves affixing sheets of drywall to a wooden or metal frame. Drywall finishing involves applying tape and joint compound to seams, joints, nail or screw dents, and then sanding the surface to the desired texture.

Current joint compounds are formulated with talc, silica, calcite, gypsum, and/or mica.[1–4] Until the mid–1970s, however, some joint compounds contained chrysotile asbestos as a filler in the range of 5–15% by weight.[1,5] Amphibole mineral fragments, most commonly in the tremolite series, were reported as sometimes present in concentrations of 2–12%, likely as a contaminant in the chrysotile or talc,[1,6] but neither amphibole mineral fragments

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nor talc were found in the joint compound formulations reported by Brorby *et al.*[5] Published historical data on amphibole mineral contaminants in joint compound, however, do not provide sufficient information to conclude that the minerals were amphibole asbestiform fibers and not elongate tremolite cleavage fragments.[7] Until the characteristics of the mineral being studied are clearly determined, there will be confusion as to the biological effect of asbestos and nonasbestos amphibole minerals.[8] Exposure monitoring in the 1970s reported peak asbestos fiber concentrations (as total fibers) in excess of the then Threshold Limit Value (TLV) of 5 fibers longer than 5 $\mu$m per cc (5 f/cc) during the mixing of dry-mix joint compound with water,[9] sanding of joint compound, and clean-up activities.[1,6,10]

Mesothelioma and excess lung cancer deaths have been reported among drywall construction workers based on death certificates listing drywall construction as usual occupation.[11] The number of mesotheliomas reported has been few and may reflect asbestos exposures received in other occupations or as bystander exposure to insulators. Studies identifying excess lung cancer deaths have been limited by a lack of information on smoking habits.[12,13] Radiologic findings of pleural thickening and parenchymal abnormalities among drywall workers are nonspecific.[1] These studies also lack information on measured or estimated asbestos exposure concentrations.[14,15]

Because limited exposure monitoring data exist for exposure reconstruction and risk characterization of drywall workers, additional data and new methods are needed to support retrospective exposure assessment. Here we integrate previous work to characterize cumulative exposures to dusts and asbestos fibers resulting from the sanding of joint compound during drywall finishing. Specifically, we apply a semi-empirical mathematical model to predict 8-h TWA respirable dust concentrations from joint compound sanding activities.[16] These predictions are coupled with an empirical factor that relates chrysotile asbestos fiber to respirable dust concentrations to predict 8-h TWA asbestos fiber concentrations.[17,18] We present data about time-activity patterns of drywall construction, including finishing activities, obtained through a survey of drywall construction business owners and direct observation of drywall construction workers at active job sites. These data are used to develop prototypical exposure scenarios for workers categorized according to their time-activity patterns and skill sets.

## 2. METHODS

Our approach was to use a survey instrument and field observations to collect data regarding time-activity patterns, work practices, and skill sets. These data were used to classify workers and create exposure scenarios, which were modeled to calculate the 8-h TWA and, subsequently, cumulative exposures.

### 2.1. Survey Instrument

The survey instrument addressed work practices that may influence exposure to dusts. Potential participants were identified through professional contacts and randomly from the California Drywall Information Trust Fund and the Chicago Plastering Institute directories. Sixteen contractors were contacted, and 11 agreed to participate (69%). All were interviewed in person or over the telephone during March or April 2008.

### 2.2. Field Observations

Three drywall construction job sites were identified for observation between 2008 and 2009 based on job size and type, and work crew characteristics (Table I). Site 1 was an addition to a church. Workers had dedicated tasks (bifurcated crew), and the finishing worker was a union member. Site 2 (Study A in Jones *et al.*[16]) was a two-room area in a storage building/garage. Drywall was installed and finished by three workers in a general contracting crew (nonunion). Site 3 was a floor in a high-rise commercial building with a bifurcated crew comprised of up to 30 union workers. We observed one week of this 14-week drywall construction project. The contractor at Site 3 also completed the survey instrument.

In addition, Site 4 (Study B in Jones *et al.*[16]) was a residential bathroom built in an isolation testing facility to simulate a do-it-yourself project (Table I). The drywall finisher was unskilled in the trade.

Team members observed and documented activities using field logs and photography at all sites and videography at Sites 2 and 4. The time each worker spent on the following activities was recorded in field logs: framing walls (if applicable), hanging drywall, applying tape and joint compound, and sanding joint compound. Time using each tool and time at rest was also recorded.

The protocols and methods used for the survey and the field observations were approved by the Copernicus Group Institutional Review Board.

**Table I.** Observed Time-Activity Breakdown at Each Job Site by Hours and Percent of Job Time

| Variable | Site 1 | Site 2 North room | Site 2 South room | Site 3[a] | Site 4 1st sanding[d] | Site 4 2nd sanding[d] | Site 4 Total |
|---|---|---|---|---|---|---|---|
| Floor area in $m^2$ | 92.9 | 69.0 | 58.3 | 2675.6 | | 3.3 | |
| Drywall area in $m^2$ | 194.3 | 165 | 157 | 867.6[b] | | 21.6 | |
| Ceiling included | N | Y | Y | N | | N | |
| Hours in installing drywall (%) | 18.0 (44%) | 123 (55%) | | 43 (44%) | | 18.2 (50%) | |
| Hours in applying tape and joint compounds (%) | 10.1 (24%) | 64 (29%) | | 31 (32%) | | 9.7 (27%) | |
| Hours in other activities[c] (%) | 10.1 (24%) | 26 (12%) | | 13 (13%) | | 4.2 (12%) | |
| Hours in sanding (%) | 3.3 (8%) | 2.4 (1%) | 7 (3%) | 11 (11%) | 1.7 (5%) | 2.1 (6%) | 3.8 (11%) |
| Sanding rate in $m^2$ per person-hour | 58.9 | 68.6 | 22.4 | 78.8 | 12.6 | 10.4 | 5.7 |
| Person(s) who performed the sanding | specialist | generalist[e] | generalists | specialist | | DIYer | |
| Tools[f] | b, bh, c, cr, em, mm, m, mr, p, pb, s, sp(150), t | br, d, e, l, m, p, pb, s, sc, sf, sg(med./fine), sp(150), ss(180), t | | b, bh, c, cr, em, m, p, pb, sg(med./fine),sp (120/150), st, t | br, ct, d, l, m, mm, s, ss(120), t, v, w | | |

[a]Total hours of work observed was approximately one week of 14-week project.
[b]Total drywall surface area observed during sanding activities.
[c]Other activities: mixing, setup, cleanup, break, etc.
[d]On Site 4, the first sanding was performed after the second coat of joint compounds, and the second sanding occurred after the third and the final coating.
[e]This worker is a generalist with technical training in drywall construction.
[f]Drywall and cleaning tools observed at each worksite: b-bazooka, bh-box handle, br-broom, c-corner angle, cr-corner roller, ct-corner trowel, d-dust pan, e-electric drill w/mixing attachment, em-electric mixer, l-ladders, m-mud pan, mm-mud masher, mr-mud runner, p-pole sander, pb-push broom, s-sanding block, sc-long handle scraper, sf-scaffold, sg-sanding sponge, sp-sand paper, ss-sanding screen, st-stilts, t-taping knife, v-vacuum, w-wet mop, (###)-abrasive grit rating.

### 2.3. Classification of Workers

To describe reported and observed differences among skill levels, work practices, and work frequency, we classified professional drywall workers into two categories: drywall specialists and generalists. In addition, we identified two more categories: other tradespersons who may receive exposure as bystanders to professional drywall finishing, and do-it-yourselfers (DIYers). The latter category describes individuals who occasionally engage in home renovation projects, similar to the unskilled worker at Site 4. These classifications reflect likely differences in exposure determinants on a daily basis and over a working lifetime.

### 2.4. Exposure Model and Simulation

Jones *et al.* developed and confirmed the reasonableness of a semi-empirical mathematical model using extrapolation factors to predict surrounding area and breathing zone dust concentrations during sanding of drywall joint compound.[(16)] This semi-empirical model was used here with two modifications. First, we combined the task-duration TWA concentrations during sanding and postsanding to estimate 8-h TWA concentrations of respirable dust. Second, we applied an empirical factor to estimate the 8-h TWA concentrations of asbestos fiber. The empirical factor, $F_{CH\text{-}rd}$, relates chrysotile (CH) asbestos fiber concentrations emitted during sanding reformulated asbestos-containing joint compound to respirable dust (rd) concentrations emitted during sanding of modern asbestos-free joint compound.[(17)] The factor has a median value of 0.044 f/cm$^3$ per mg/m$^3$, and a central 95% range of 0.039–0.050 f/cm$^3$ per mg/m$^3$.[(17)] We represented $F_{CH\text{-}rd}$ as normally distributed with mean and standard deviation of 0.044 and 0.0028 f/cm$^3$ per mg/m$^3$. The asbestos-free joint compound used to develop $F_{CH\text{-}rd}$ was also used in the experiments upon which the exposure model is based.[16]

The exposure model estimated the probability distribution of 8-h TWA concentrations to respirable dust ($mg/m^3$) and asbestos fibers ($f/cm^3$) for each worker category in stochastic projections with 100,000 iterations in the R Project for Statistical Computing. Our model took into consideration variability in sanding duration, emission frequency, postsanding duration, ventilation rate, and room volume for specialists, generalists, and DIYers. Bystander tradesperson 8-h TWA concentrations were calculated assuming that the concentration during the bystander period equaled the 8-h TWA concentrations estimated for the area of sanding around a drywall specialist; and no exposure for the remainder of the 8-h period. The sensitivity of predictions to model inputs was evaluated using the Spearman's correlation coefficient between inputs and predicted 8-h TWA respirable dust concentrations.

Cumulative exposures were subsequently estimated by simulation, with 100,000 iterations. Given a worker who finished drywall or worked near drywall finishing for D days per year (Table II) over Y years, $N = \sum_{n=1-1}^{Y} (D_n)$ values were drawn with replacement from the probability distribution of 8-h TWA for the respective worker category. These values were then summed and divided by 250 days per year to calculate cumulative exposure in $mg/m^3$-years for dust and $f/cm^3$-years for asbestos over the worker's exposure history.

### 2.5. Reconstruction Algorithm

The approach to exposure reconstruction is:

(1) Obtain the individual's work history, with preference for empirical rather than anecdotal information.
(2) Match the individual to one or more worker classification(s).
(3) Integrate the individual's work history with general work characteristics for each worker classification (Table II) to select model input parameters.
(4) Apply the exposure model to estimate 8-h TWA concentrations of respirable dust and fibers emitted during joint compound sanding.
(5) Estimate the cumulative exposures to respirable dust and fibers based on work history and 8-h TWA for the respective worker classification.

## 3. RESULTS

### 3.1. Initial Results Based on Survey Instrument

Eleven persons who had worked in the drywall construction trade for 22 to 49 years (median = 30 years) were surveyed. The median year of first employment in the business was 1976. Respondents worked in rehabilitation construction projects ($n = 6$, 55%), or solely on new construction sites ($n = 5$, 45%). Typical size of work crews varied between commercial (typically 8, range 2–30) and residential construction (typically 3, range 1–6), but had remained the same over the careers of the majority of respondents (55%).

The amount of drywall with applied joint compound sanded on a per person-hour basis varied from 8.2 $m^2$ to 92.9 $m^2$ (median = 66.9 $m^2$) ($n = 9$). The amount of time spent sanding per sanding event ranged from 20 to 480 minutes (median = 90 minutes) ($n = 4$). Three specialists estimated time spent on finishing tasks, and noted that applying tape and joint compound occupied a greater proportion of finishing time (65–75%, 80%, 85%) than sanding (10–15%, 15%, 20%).

Respondents reported anecdotally that plumbers and electricians worked frequently in proximity to drywall installers, while painters, millwork installers, and carpenters worked occasionally in proximity to drywall installers.

The survey results indicated that the techniques, tools, and activities were relatively standard and changed little over time. Joint compound may be purchased as dry-mix powder or as ready-mix paste and mixed or thinned with water, respectively, before use. Respondents identified the transition from dry-mix to ready-mix joint compounds in the late 1970s, due to cost and convenience. Exposures during dry-mix joint compound preparation were not considered in this analysis, although these potential exposures may have relevance in other contexts.

### 3.2. Results from Field Observations

The proportion of time spent on each activity by a work crew was consistent across the field sites, with workers spending 4–11% of project time sanding joint compounds (Table I), and was within

**Table II.** Prototypical Exposure Scenarios

| Variable | Unit | Distribution[a] | Worker Categories | | | |
|---|---|---|---|---|---|---|
| | | | Drywall Specialists | Generalists | DIYers | Bystander Trades |
| Sanding frequency, D | Description | | Frequent | Occasional | Sporadic | Occasional |
| | # days/year | Uniform | [52, 104] | [12, 36] | [0, 4][b] | [12, 36] |
| Sanding rate, $S_A$ | $m^2$/hour | Triangular | 69, [41, 97] | 23, [8, 69] | 11, [5, 23] | NA[c] |
| Sanding duration, $T_s$ 5 $m^2$ | Hours[d] | Triangular | 0.25, [0.18, 0.43] | 0.76, [0.25, 2.19] | 1.59, [0.76, 3.5] | NA |
| 12 $m^2$ | | Triangular | 0.61, [0.43, 1.02] | 1.83, [0.61, 5.25] | 3.82, [1.83, 8.4] | |
| 50 $m^2$ | | Triangular | 2.54, [1.80, 4.27] | 7.61, [2.54, 10][e] | | |
| 100 $m^2$ | | Triangular | 5.07, [3.61, 8.54] | Unlikely | | |
| Overall[f] | | Non-parametric | [0.18, 8.54] | [0.25, 10][e] | [0.76, 8.4] | |
| Emission frequency, $f_{emit}$ | Unitless | Normal | $\mu = 0.80, \sigma = 0.043$ | $\mu = 0.80, \sigma = 0.043$ | $\mu = 0.60, \sigma = 0.043$ | NA |
| Post-sanding duration, $T_{ps}$ | Description | | Cleaning tools | Cleaning tools or general cleanup | Cleaning tools or general cleanup | NA |
| | Hours | Uniform | [0.25, 0.75] | [0.5, 4] | [0.25, 1.25] | NA |
| Duration as bystander | Hours | Uniform | | NA | | [0.5–6] |
| Ventilation rate | ACH (h-1) | Lognormal | GM = 0.8, GSD = 1.47 | | | |
| Room volume, V | m3 | | (Sanding rate mode × $T_s$ / 3.5) × Ceiling height, where ceiling height is 2.44 m | | | |
| $C_{R,\ 1h\text{-}twa,\ PBZ}$[g] | Description | | Respirable dust $C_{twa}$ measured in the PBZ during 1 hr sanding in testing events | | | |
| | mg/$m^3$ | Lognormal | GM = 3.74, GSD = 2.20 | | | |
| $F_{R,\ Area\text{-}to\text{-}PBZ}$[h] | Description | | Ratio of respirable dust $C_{twa}$ in area surrounding sanding to that in PBZ | | | |
| | Unitless | Lognormal | GM = 0.51, GSD = 1.59 | | | |
| $F_{fiber\text{-}to\text{-}dust}$[i] | Description | | Conversion factor from respirable dust conc. to airborne PCM fiber conc. | | | |
| | $(f \times cm^{-3})/(mg \times m^{-3})$ | Normal | $\mu = 0.044, \sigma = 0.00281$ | | | |

[a]For a uniform distribution, [range] is given; for a triangular distribution, mode, [range] is given.
[b]The cumulative annual exposure was estimated based on 1–4 days of sanding per year.
[c]NA = not applicable.
[d]Hours = Floor area × 3.5 ÷ Sanding rate.
[e]The upper bound is determined to be a reasonable shift of 10 hours although the calculated value is greater than 10.
[f]The sampling of sanding duration for specialists is based on 1% of work in a room of 5 $m^2$, 5% in 12 $m^2$, 24% in 50 $m^2$, and 70% in 50 $m^2$. That for generalists is based on 33% of work in rooms of 5, 12, and 50 $m^2$ each. That for DIYers is based on 50% of work in both 5 and 12 $m^2$ rooms.
[g]Measured in isolation chamber testing events by Simmons *et al.*(4) PBZ = personal breathing zone.
[h]Values based on chamber test and field observations,(15) rather than chamber tests alone.(4)
[i]Developed by Sheehan *et al.*(16)

the reported range of Fischbein *et al.*[1] However, productivity ($m^2$ of drywall sanded per person-hour) varied among crews, and was highest at Sites 1 and 3 with bifurcated work crews (Table I).

At Site 3, drywall finishers were brought onsite after drywall installation along the perimeter area was complete. The finishers applied tape and joint compound and sanded, moving from the perimeter inwards. At both Sites 1 and 3 after the second coat, workers sanded briefly (0.6 h at Site 1; not quantified at Site 3); and after the third coat, workers sanded more thoroughly (3.3 h at Site 1 and 11 h at site 3).

At Site 2, three members of a general contracting crew finished 322 $m^2$ of drywall including the ceiling. Sanding rates varied substantially between workers (Table I): one worker who had received training on drywall finishing sanded three times more drywall surface area per hour (north room) than the two workers in the south room. All workers sanded only after the final coat of joint compound was applied.

At Site 4, a nonprofessional with no previous drywall experience sanded as per the manufacturer's recommendations after the second and third (final) joint compound application. The sanding durations were similar in the two events (1.7 and 2.1 h). While that time was sufficient to complete the sanding task for the small room, the nonprofessional reported fatigue.

We observed the use of tools mentioned by survey respondents (Table I). Not surprisingly, professional crews applied joint compound with techniques and a level of skill that ultimately minimized the overall time needed for sanding. At every work site, workers chose to wear their own filtering facepiece N95 respirators during sanding.

### 3.3. Prototypical Exposure Scenarios

We integrated survey results, direct observations, and a literature review to develop prototypical exposure scenarios and model parameters for each worker classification (Table II). The prototypical exposure scenarios define model inputs, and identify work practices and characteristics critical to exposure reconstruction that should be obtained with preference to empirical sources over anecdotal recollections.

In general, when drywall finishing work is ongoing, building envelopes have typically been closed in and mechanical ventilation systems are turned off. Thus, the ventilation rate may be lower during drywall finishing than during human occupancy. At Site 2, we measured the air exchange rate to be 0.43–1.2 $h^{-1}$. We represent the distribution of air exchange rates during drywall finishing with a log-normal distribution with geometric mean (GM) and geometric standard deviation (GSD) of 0.8 $h^{-1}$ and 1.47, respectively. The 5th and 95th percentiles of the distribution correspond to 0.4 $h^{-1}$ and 1.5 $h^{-1}$. These values are similar to, but somewhat lower than, surveys of occupied residences[19] and commercial buildings.[20]

#### *3.3.1. Drywall Specialist*

Drywall specialists perform drywall finishing—taping, joint compound application, and sanding—to the exclusion of most other construction tasks. Specialists may work in crews with multiple workers, and be exposed to dusts and fibers as bystanders of other workers.

The mean sanding rate for drywall specialists was equated with the observed mean, 69 $m^2$ drywall per hour (Table I). We applied a triangular distribution with range equal to the central 95th percentile range of the observed sanding rate (standard deviation 14 $m^2$/h). At field sites, we observed, on average, specialists to spend approximately 80% of their sanding time actually sanding and emitting dust. Assuming 10% (0.08) variation, the proportion $f_{emit}$ can be represented by a normal distribution with mean 0.80 and standard deviation 0.043, such that $f_{emit} = 0.7$ and $f_{emit} = 0.9$ correspond to the 1st and 99th percentiles, respectively.

The duration of sanding in a work shift may vary widely, and depends upon the sanding rate, $S_A$ ($m^2$ drywall per hour), and drywall area to be sanded, $D_A$ ($m^2$ drywall). The duration of sanding, $T_s$ (hours), may be estimated by $T_S = D_A \div S_A$. Alternatively, the drywall surface area may be estimated from the floor area, $F_A$ ($m^2$ floor): in homes with 8-ft ceilings, $D_A \sim 3.5 \times F_A$.[21] In Table II, the sanding duration is estimated for rooms with floor areas of 5 $m^2$ (bathroom), 12 $m^2$ (bedroom or office), 50 $m^2$, and 100 $m^2$: for most sanding rates, specialists are estimated to complete these room areas in 0.18 to 8.54 h. We represented the overall distribution of $T_s$ as nonparametric, ranging from 0.18 to 8.54 h based on 1% of work in a room of 5 $m^2$, 5% in 12 $m^2$, 24% in 50 $m^2$, and 70% in 100 $m^2$.

Drywall specialists are likely to be union members, such that clean-up activities would be limited to the cleaning of their personal tools. Thus, we assume the duration of time spent on site after sanding, $T_{ps}$ (hours), is limited to 0.25–0.75 hours.

Sanding joint compound is likely to be frequent for specialists as such activities are part of their profession. Joint compound is applied in three or more layers, with at least overnight drying between applications. Sanding occurs after complete drying of the final layer, such that we would anticipate that specialists sand joint compound during portions of 1–2 days each week. This is consistent with the observation that specialists spend approximately 10% of their time at a project sanding joint compound (Table I).

### *3.3.2. Generalist*

A generalist performs a variety of construction tasks, including drywall finishing, such that a generalist likely spends fewer workdays in a year doing drywall finishing than a specialist. The skill level of generalists will depend upon training and work experience.

We observed the sanding rate of generalists at Site 2 to vary (Table I) between 69 and an average of 22 $m^2$ drywall per hour in the two rooms, respectively. We represent the sanding rate using a triangular distribution, with the mode equal to the average sanding rate observed for two workers, 22 $m^2$/h. The upper bound was equated with the rate observed for the third worker, 69 $m^2$/h, while the lower bound was equated with the minimum sanding rate reported by survey respondents, 8 $m^2$/h. We observed generalists to spend approximately the same proportion of sanding time actively sanding and emitting dusts ($f_{emit}$) as drywall specialists.

The duration of sanding in a workday depends upon the sanding rate and drywall area to be sanded. For rooms of 5, 12, and 50 $m^2$, the range of sanding rates indicates that generalists will complete sanding in 0.25–10 h (Table II). Given the duration of sanding estimated for a 50 $m^2$, we considered it unlikely that generalists would undertake larger rooms in a single workday. We represented the overall distribution of $T_s$ as a nonparametric distribution ranging from 0.25 to 10 h, developed under the assumption that a generalist spends one-third of his or her time in 5 $m^2$, 12 $m^2$, and 50 $m^2$ rooms.

Generalists may participate in general cleaning tasks like debris removal and sweeping, in addition to cleaning personal tools. Thus, we assume that the duration of time spent on site after sanding, $T_{ps}$, is 0.25–4 hours, though measurements at Site 2 indicate that respirable dust concentrations decrease substantially in the first 2 hours after sanding ceases.[16]

The frequency of joint compound sanding is likely to vary between generalist workers and over time because it depends upon time spent on other construction tasks. Based on our observation that 4% of the total job time at Site 2 was spent sanding (all on one work day), and the work spanned several weeks during which the same 2–3 workers participated in a variety of construction tasks, we characterize the frequency of joint compound sanding by generalists to occur during portions of 1–3 days per month, or occasionally.

### *3.3.3. Tradesperson Bystanders*

Drywall finishing is one of the last construction tasks at a job site, as the installation of drywall closes walls containing mechanical, electrical, and plumbing (MEP), and the finishing prepares the surface for painting. Nevertheless, survey respondents indicated that other tradespersons may be present during drywall finishing. We considered these tradesmen to be bystanders to finishing work, and exposed to dusts and fibers at some distance from the site of emission—that is, to concentrations in the area of sanding, not in the breathing zone of the sander. For the reconstruction of exposures to specific tradesperson, tradesperson bystanders would identify: (1) whether they worked near drywall specialists, generalists, or DIYers; (2) the frequency with which they were bystanders to finishing work; and (3) the duration of time spend in proximity to ongoing sanding or recently completed sanding. For the simulations herein, we assume the tradespersons are occasionally (portions of 1–3 days per month) bystanders to drywall specialists for 0.5–6 h per day (Table II).

### *3.3.4. Do-It-Yourself Nonprofessional Worker (DIYer)*

A DIYer performs drywall installation and finishing sporadically, and on projects of limited scope, such as patching damaged drywall or renovation of a residential room. Product manufacturers and training materials for DIYers recommend sanding joint compound separately after the second and third (final) joint compound application. This additional sanding is recommended to combat a tendency for excessive and uneven joint compound application.

We observed a DIYer at Site 4. The DIYer sanded after the second and third joint compound application, at the rate of 11 $m^2$ drywall per person-hour (Table I). We assumed that the sanding rate

**Table III.** Distribution of 8-h TWA Concentrations of Respirable Dusts ($mg/m^3$) and Chrysotile Fibers ($f/cm^3$) for Each Worker Category

| | Respirable Dust ($mg/m^3$) | | | | Chrysotile Fibers ($f/cm^3$) | | | |
|---|---|---|---|---|---|---|---|---|
| Worker Category | GM | GSD | Mean | Central 90% | GM | GSD | Mean | Central 90% |
| Specialists | 3.77 | 3.14 | 6.40 | 0.45–19.5 | 0.17 | 3.15 | 0.28 | 0.020–0.86 |
| Generalists | 2.31 | 3.67 | 5.02 | 0.26–18.5 | 0.10 | 3.68 | 0.22 | 0.011–0.81 |
| Bystander Trades | 0.72 | 3.83 | 1.56 | 0.068–5.51 | 0.032 | 3.84 | 0.069 | 0.0030–0.24 |
| DIYers | 1.95 | 2.85 | 3.32 | 0.34–10.8 | 0.086 | 2.85 | 0.15 | 0.015–0.48 |

has a triangular distribution, which ranges from 5 to 22 $m^2$ drywall per person-hour, where the maximum value is the averaged observed rate of the slower generalists.

The physical demands of sanding drywall joint compound, coupled with relatively small-scale drywall installation and finishing projects, may limit the duration of time a DIYer sands in any single day. We estimated that a DIYer could sand a 5 or 12 $m^2$ room in 0.76–8.4 h (Table II). Sanding would be repeated for this duration twice—after a second and third joint compound application. We represented the overall distribution of $T_s$ as a nonparametric distribution ranging from 0.76 to 8.4 h, developed from the assumption that DIYers equally split time between 5 and 12 $m^2$ rooms.

Inefficient sanding practices may also slow the sanding rate of DIYers. At Site 4 we observed that while sanding, the DIYer was actually emitting dust approximately 60% of the time. Short breaks were taken to rest and inspect the surface finish. Assuming that the proportion varies plus or minus 10%, the proportion $f_{emit}$ can be represented by a normal distribution with mean 0.60 and standard deviation 0.043, such that $f_{emit} = 0.50$ and $f_{emit} = 0.70$ correspond to the 1st and 99th percentiles of the distribution.

The amount of time DIYers remain in the area of sanding may vary widely based on personal preference for immediate or delayed cleanup. Thus, we consider a range of 0.25–1.5 hours, with a uniform distribution.

DIYers perform drywall finishing work infrequently, even though sanding may consume a larger proportion of finishing time for DIYers than it does for generalists and specialists. We assumed that DIYers perform drywall sanding during portions of 0–4 days per year. Persons performing occasional drywall finishing more frequently may be more accurately classified as generalists.

**Table IV.** Selected Sensitivity Analysis Results for Predicted 8-h TWA Concentrations of Respirable Dusts ($mg/m^3$) for Each Worker Category

| | Spearman's Correlation Coefficient | | | | |
|---|---|---|---|---|---|
| Worker Category | ACH | $f_{emit}$ | $T_s$ | $T_{ps}$ | V |
| Specialists | −0.161 | 0.0493 | 0.545 | 0.0217 | 0.545 |
| Generalists | −0.132 | 0.0310 | 0.774 | 0.0509 | 0.774 |
| Bystander Trades | −0.130 | 0.0335 | 0.428 | 0.0290 | 0.428 |
| DIYers | −0.133 | 0.0549 | 0.627 | 0.0600 | 0.627 |

### 3.4. Eight-Hour TWA Concentration Estimates

The mean respirable dust and asbestos fiber 8-h TWA concentrations are numerically highest for specialists, followed by generalists, DIYers, and bystander tradespersons (Table III). This ordering reflects the time and motion relationship among sanding duration, sanding rate, and job size. The other tradespersons were assumed to be bystanders of drywall specialists, and the dust and fiber concentrations estimated for this group reflect those in the sanding area of specialists. The distributions of 8-h TWA concentrations have GSD in the range of 2.85–3.83 (Table III), which is consistent with the magnitude of within-worker variability in similar exposure groups.[22] The similarity in GSD values between the respirable dust and asbestos fiber concentrations indicates that the variability introduced to the fiber-to-dust ratio, $F_{CH\text{-}rd}$, is relatively small. The $F_{CH\text{-}rd}$ ratio, however, was developed for one joint compound formulation and could be different for other joint compound formulations or manufacturers.

The sensitivity of predictions to model inputs was evaluated using the Spearman's correlation coefficient between inputs and predicted 8-h TWA respirable dust concentrations (Table IV). Predicted 8-h TWA concentrations were positively correlated with the sanding duration, and less correlated with postsanding duration. Predicted 8-h TWA concentrations were negatively correlated with air exchange rate, but positively correlated with room volume. The correlation with room volume (V) reflects the influence of sanding duration on the 8-h TWA because the V was calculated from the sanding duration and sanding rate (mode of the worker classification) (Table II).

### 3.5. Cumulative Exposure Estimates

Cumulative exposures over 1 year and 10 years follow normal distributions, and the estimates are summarized in Table V. Mean cumulative exposures for specialists are four-fold greater than those of generalists, due to more frequent sanding in a calendar year (Table II). The annual cumulative exposure of DIYers is low, relative to the other groups. Owing to the infrequency of the activity by DIYers, the 10-year cumulative exposure was not estimated. The cumulative exposures of bystanders are about one-tenth of those of drywall specialists because they have occasional exposure and are at some distance from the emission point.

## 4. DISCUSSION

Drywall is the primary construction material used for interior walls in the United States, which means that numerous workers finish drywall by sanding joint compound. Nevertheless, little information exists to characterize exposures to dust and, separately, asbestos fibers, for the period before the mid 1970s when chrysotile asbestos was used as filler in some joint compounds.

We initially characterized the range of work practices in drywall construction by surveying 11 persons who had worked in the drywall construction trade for 22 to 49 years. While our characterization involved relatively small numbers of participants, the survey respondents had extensive experience. Separately, we observed work practices directly of drywall workers at four job sites. Survey respondents consistently identified work activities, tools, and supplies, which were also observed in the field. In addition, the self-reported sanding rates from survey respondents compared well with the observed sanding rates.

We observed that the rate of drywall sanding and the amount of time spent sanding varied among workers. These differences are likely attributable to skill level and work specialization. Therefore, we classified workers who may be exposed to dusts and fibers emitted during joint compound sanding into one of four categories: (1) drywall specialists, (2) generalists, (3) other tradespersons incidentally exposed as bystanders, (4) and DIYers. A worker may move between categories over his or her working lifetime, due to improved skills and/or employment changes. The relationship among skill, productivity, sanding duration, job size, and exposures is understandably complex. The exposure model does not explicitly consider skills, such that DIYers are not predicted to have higher 8-h TWA concentrations than generalists or specialists for the same sanding duration (Table III). However, the cumulative exposure estimates consider frequency of tasks, such that DIYers are estimated to have lower cumulative exposures (Table V).

Bystanders—including other drywall finishing workers and other tradespersons—may be present during drywall finishing. Jones *et al.* accounted for bystander exposure simultaneous to sanding by summing the dust concentration estimated in the personal breathing zone of a sander with that estimated for the area around the second sander nearby.[16] In our study, we have only considered bystander exposures for tradespersons working near drywall finishing: these workers are exposed to the lowest 8-h TWA concentrations to respirable dusts and asbestos fibers (Table III). The 8-h TWA concentrations and cumulative exposures estimated for specialists, generalists, and DIYers are attributable to their own sanding activities. Thus, if multiple workers are sanding joint compound in the same general area, the concentrations of dusts and fibers may be somewhat higher than the estimated 8-h TWA concentrations (Table III); however, the breathing zone concentration is not additive between workers.

We observed visible dust in the air during sanding, and dust and debris on the floor after sanding. When joint compound is sanded, the predicted 8-h TWA concentrations of respirable dusts (Table III) suggest that all groups of workers may be exposed to respirable dust concentrations above the TLV of 3 $mg/m^3$.[23] This is consistent with measurements at Sites 2 and 4 in Jones *et al.*[16] and with Miller *et al.*[2] who measured 8-h TWA respirable dust concentrations ($n = 15$) and calculated an arithmetic mean of 2.09 $mg/m^3$ (GM = 1.52 $mg/m^3$ and GSD = 2.40). In contrast, Epling *et al.* measured 8-h TWA respirable

**Table V.** Distribution of Cumulative Annual and 10-Year Exposures to Respirable Dusts ($mg/m^3$-years) and Chrysotile Fibers (f/cc-years) for Each Worker Category

| Worker Category | Respirable Dust ($mg/m^3$-years) | | | | Chrysotile Fibers ($f/cm^3$-years) | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | *SD* | GM | Central 90% | Mean | *SD* | GM | Central 90% |
| 1-Year Cumulative Exposure | | | | | | | | |
| Specialists | 2.00 | 0.46 | 1.94 | 1.28–2.78 | 0.088 | 0.020 | 0.085 | 0.056–0.12 |
| Generalists | 0.48 | 0.2 | 0.44 | 0.19–0.85 | 0.021 | 1.58 | 0.0090 | 0.0085–0.037 |
| Bystander Trades | 0.15 | 0.065 | 0.14 | 0.060–0.27 | 0.0066 | 0.0029 | 0.0060 | 0.0026–0.012 |
| DIYers | 0.033 | 0.03 | 0.023 | 0.0039–0.089 | 0.0015 | 0.0013 | 0.0010 | 0.00017–0.0039 |
| 10-Year Cumulative Exposure[a] | | | | | | | | |
| Specialists | 20.0 | 3.92 | 19.6 | 13.9–26.1 | 0.88 | 1.22 | 0.17 | 0.61–1.15 |
| Generalists | 4.82 | 1.48 | 4.58 | 2.56–7.19 | 0.21 | 0.065 | 0.20 | 0.11–0.32 |
| Bystander Trades | 1.50 | 0.46 | 1.43 | 0.79–2.24 | 0.066 | 0.020 | 0.063 | 0.035–0.099 |

[a]Ten-year cumulative exposure estimates were not calculated for DIYers because they may not sand every year.

dust concentrations to be on average lower than 1 $mg/m^3$, though instantaneous concentrations of the thoracic fraction were reported to have ranged from 3.82–20.7 $mg/m^3$.[24] The magnitude of these respirable dust exposures is consistent with exposures by drywall workers who reported respiratory symptoms: phlegm production, morning or day cough, and shortness of breathing. These symptoms improved with time away from work.[2]

The estimated 8-h TWA concentrations of chrysotile fibers (Table III) are in excess of the current TLV of 0.1 $f/cm^3$, but within the TLV at the time asbestos-containing joint compounds were used.[25] The modeled mean 8-h TWA concentrations are 0.28 and 0.22 $f/cm^3$ for drywall specialists and generalists, respectively. Previously, asbestos fiber concentrations (as total fibers $> 5\ \mu m$ in length) were measured in the breathing zone of workers during sanding of asbestos-containing joint compound; peak or task-duration total fiber concentrations were measured in the range of 1.2–24.2 $f/cm^3$.[1,6,10] Peak concentrations are typically greater than 8-h TWA concentrations. In addition, Brorby *et al.* have described a joint compound matrix effect that may have positively biased fiber counts in the P&CAM 239 method used in the 1970s.[26]

Few published epidemiological studies of drywall workers exist and these have reported modest excess proportionate mortality from lung cancer: proportionate mortality ratio (PMR) = 1.39 ($p < 0.01$),[15] PMR = 1.21, 95% confidence interval (CI) 0.82–1.71,[12] and PMR = 1.40, 95% CI 1.26–1.56.[11] PMR studies have well-recognized limitations. Reliance upon "usual" occupation or industry as reported by next-of-kin for the death certificate may not represent accurately relevant job history as a proxy for exposure. By nature of the study design, the sum of all proportionate causes in a PMR analysis equals 1, and therefore some categories of death must show excess mortality to offset other categories of death that show deficit mortality. Also, the pattern of excess or deficit mortality does not necessarily reflect mortality patterns that can only be accurately described using death rates for a population at risk. These studies are further limited by the absence of quantitative exposure information regarding dusts and asbestos fibers, or surrogates such as duration of employment, as well as information on potential confounders, especially smoking habits. Nelson *et al.* reported the smoking prevalence among drywall installers as 55% based on data from National Health Interview Surveys from 1987 to 1990.[27]

Risks of asbestos-related cancers have not been reported in relation to cumulative exposure measures in published studies of drywall workers. However, risks in relation to cumulative exposures have been reported for other classifications of workers exposed to asbestos.[28–30] There may be important risk differences between drywall workers and non-drywall workers at the same estimated cumulative exposure. Therefore, it may be inappropriate to compare risks from non-drywall workers with drywall workers.

Nevertheless, asbestos-related cancer risks have been summarized in recent years[31–33] and a risk comparison with our quantified cumulative exposure estimates for drywall workers is offered. For drywall specialists exposed to an annual cumulative exposure of 0.088 $f/cm^3$, a specialist would accrue approximately 3.5 f/cm$^3$-years over a career of 40 years, assuming it is even possible to have worked with asbestos-containing joint compound for 40 years. It is important to note that asbestos-containing joint compound has not been manufactured in the United States for nearly 40 years.(5) Since drywall became common only after World War II, the maximum period for use of asbestos-containing joint compound is 25 to 30 years (post-World War II through the mid 1970s). Consequently, a 40-year cumulative exposure to asbestos-containing drywall compounds is a conservative high end estimate. With an annual exposure of 0.088 f/cm$^3$, a specialist would more likely accrue a maximum of 2.2–2.6 f/cm$^3$-years over a 40-year career, assuming that 40-year career spanned the time period of post-World War II through the mid 1970s.

For chrysotile, a cumulative exposure in the low single digits has been estimated by modeling, with the assumption of no lower threshold, to produce 5 mesothelioma deaths (range 1–20) per 100,000 exposed and 2 extra lung cancer deaths per 100,000 exposed.(32) Van der Bij *et al*. reported a lung cancer relative risk of 1.013 (95% CI 0.791–1.296) to 1.027 (95% CI 1.020–1.034) for cumulative exposures of 4 f/cm$^3$-years (all types of asbestos) by fitting flexible meta-regression models to the data from existing cohort studies reporting cumulative exposure data.(34) Fitting these same models to data stratified by fiber type resulted in lung cancer relative risks of 1.006 (95% CI 0.848–1.194) to 1.013 (95% CI 0.999–1.028) for cumulative chrysotile exposures of 4 f/cm$^3$-years.(34)

Pierce *et al.* have suggested that cumulative "no-effects" exposure thresholds of 15–500 f/cm$^3$-years and 25–1,000 f/cm$^3$-years exist for chrysotile asbestos-related mesothelioma and lung cancer, respectively.(35) Cumulative exposures estimated herein (Table V) indicate that most drywall workers would not reach these cumulative exposures over a 40-year working lifetime. Our estimates of cumulative fiber exposure for specialists and generalists are an order of magnitude lower than the 12–26 f/cm$^3$-years estimated by Phelka and Finely.(7) The 12–26 f/cm$^3$-years estimate was developed from the analysis by Verma and Middleton,(10) which assumed that 25% of time each week is spent sanding joint compound and equated exposures with peak fiber concentrations. This activity duration is not consistent with our survey results and observations (Table I).

Nevertheless, the magnitude of estimated respirable dust concentrations (Tables III and V) indicate the continued need for diligence in the use of source controls and personal protective equipment for drywall finishing activities. At all job sites, we observed workers chose to wear their own filtering facepiece N95 respirators during sanding. We did not factor the use of respiratory protection into our modeled cumulative exposures. A variety of commercial dust control technologies are available for drywall finishing, including sanders fitted with vacuum systems,(3,36–38) and vacuum or wet-cleaning methods.

A potential limitation for the generalization of the exposure modeling is that the empirical factor $F_{CH\text{–}rd}$ is specific to one particular asbestos–free joint compound and a reformulated chrysotile–containing joint compound(5) and the exposure model was developed based on experiments and observations with the same asbestos–free joint compound.(16) Differences in joint compound formulation may influence the amount of dusts and the amount and type of asbestos fibers emitted during sanding. Over their careers, workers may have used different joint compounds, each having different formulations. By the mid 1970s, asbestos was no longer added to joint compound.

The prototypical exposure scenarios were developed from our survey results and observations, and designed to capture the range of time-activity patterns in the industry. The exposure estimates are not intended to reflect the exposure history of any single individual. Exposure reconstruction for an individual should consider his or her specific history of work practices, preferentially relying on empirical rather than anecdotal data, supplemented by our observations as needed to fill in data gaps.

## 5. CONCLUSIONS

Uncontrolled sanding of drywall joint compound is a dusty activity. In addition to dust, workers employed before the mid 1970s may have been exposed to asbestos fibers. Through survey and field observations, we identified four worker classifications to differentiate exposure based on drywall finishing activities and subsequently developed prototypical exposure scenarios. We then estimated 8-h TWA concentrations and cumulative exposures to respirable dust and chrysotile fiber for each work category. The predicted 8-h TWA concentrations of respirable dusts for drywall specialists are, on average, above the TLV of 3 mg/m$^3$ for days with sanding. Cumulative estimated exposures to chrysotile fibers are not in the range associated with elevated rates of lung cancer or mesothelioma. Continued diligence in the use of source controls and personal protective equipment for drywall finishing activities is recommended. Due to the predominance of chrysotile fibers in joint compounds, epidemiological study of this population may inform the relative potency of fiber types.

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