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Lists of Attachments

October 26, 2018

Jinnifer Mariman
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345 First Avenue East
Kalispell, MT 59901

Dear Jinnifer,

I have reviewed materials pertaining to the Libby Plaintiffs' actions against the BNSF Railway Company, with specific focus on the concentrations of asbestos in dust created by BNSF activities including those concentrations at the respective residences of the Plaintiffs in *Barnes et al. v. BNSF Railway Company*, Lincoln County Cause No. DV-16-111. My analysis and opinions regarding Plaintiffs' lifetime exposure to asbestos resulting from BNSF activities in the Libby area follows.

I have been asked to comment on these questions, to a reasonable degree of scientific probability:

- What were the lifetime concentrations of asbestos in the air at the respective residences of Tracie Barnes, Rhonda Braaten, and Gerrie Flores?
- Are lifetime concentrations of asbestos in the dust created by BNSF activities substantial relative to those created by W.R. Grace activities?
- Are lifetime concentrations of asbestos in the dust created by BNSF activities substantial relative to reference concentrations?

My conclusions regarding both latter questions is "yes", lifetime exposure concentrations of LA dust created by BNSF operations were substantial. My conclusion is based on calculations (described below) that include estimating emissions from specific sources, and then using air dispersion modeling to predict concentrations at Plaintiffs' homes,

which answers the first question. The sources I investigated and modeled related to W.R. Grace activities are the Grace Mine Site (stack and non-stack) and the River Loading Site; sources related to BNSF activities are the railroad between the River Loading Site and Libby, and the Libby Railyard. To provide predictions and modelling on a more-probable-than-not basis, I have conservatively underestimated emissions from BNSF activities, and conservatively overestimated emissions from W.R. Grace activities. For each emission source, I look at its separate impact on the lifetime-average exposure concentration for each Plaintiff, based on that person's residential location over time.

Estimates provided here reflect reasonable engineering calculations using generally accepted scientific methods, and are within a reasonable degree of scientific probability. I reserve the option to alter my opinion based on additional information obtained through discovery or otherwise.

I. Qualifications

1. **General**: I hold a B.S.E. in Chemical Engineering and a Ph.D. in Energy and Resources. I am a Professor of Civil and Environmental Engineering at the University of Washington in Seattle. I have taught courses in Environmental Engineering and Air Quality Management. I am familiar with air pollution modeling and with exposure assessment, and I have published or submitted more than 100 scientific articles in peer-reviewed journals. My Curriculum Vitae is attached as Appendix H of this report.

2. **Libby-Specific**: I have visited Libby and the BNSF[1] facilities, including the downtown railyard and river loading site. I have reviewed records from BNSF, W.R. Grace, Asbestos Remediation Contractors, and governmental agencies including United States Environmental Protection Agency ("US EPA") records, State of Montana agency records, and records of third parties. I have carried out model runs and calculations to further understand and quantify the emissions and concentrations of concern. All opinions, predictions, and modelling offered are provided on a more-probable-than-not basis, reflect reasonable engineering calculations using generally accepted scientific methods, and are within a reasonable degree of scientific probability. I retain the option to alter my opinions as additional information becomes available.

[1] Unless more specifically referenced, the term "BNSF" refers to the Burlington Northern Santa Fe Railway along with its predecessor railroads including but not limited to the Great Northern Railroad, the Chicago, Burlington & Quincy Railroad Company (Burlington Railroad), and the Atchison, Topeka and Santa Fe Railroad Company (Santa Fe Railroad).

II. Introduction

3. **Background on Vermiculite Mining Operations in Libby**: Libby is a community of about 2,700 people in northwestern Montana; approximately 12,000 people live within a 10 mile radius (US EPA 2014a, pg. 1-3). A mountaintop vermiculite mine located approximately 7 miles northeast of Libby operated from the 1920s until 1990. Most of the vermiculite mining and milling activity during this period was conducted by the Zonolite Company[2] (1939 to 1963) and the W.R. Grace Company (1963 to 1990), with the majority of production occurring during the ownership of W.R. Grace (US EPA 2015b). The processed vermiculite material was shipped out of the downtown Libby railyard by BNSF and its predecessor railroads from the 1920s until 1993. The vermiculite ore and concentrate that was mined, milled, and transported in and around the Libby area contained a highly toxic form of asbestos, known as Libby Amphibole Asbestos (LA) (US EPA 2014b). In 2002, the Libby Asbestos Superfund Site was added to the National Priorities List, with the aim of reducing health risk of LA to the Libby community. In 2009, the EPA declared the first and only Public Health Emergency in agency history to address asbestos-related issues in Libby (US EPA 2015b).

4. **Overview of Study Areas**: The mining, milling, processing, and transport of vermiculite and related materials released LA into the atmosphere over several decades and represent the original source of atmospheric LA emissions in the Libby area. Mining and milling activities occurred at the Libby Asbestos Superfund Operable Unit 3 (OU3), which is located approximately 7 miles northeast of Libby and includes Vermiculite Mountain and the Rainy Creek drainage (Libby Asbestos Superfund Site Map). Vermiculite concentrate was trucked down Vermiculite Mountain to a screening and storage facility on the

[2] Formerly the Universal Zonolite and Insulation Company.

northern bank of the Kootenai River (Libby Asbestos Superfund Operable Unit 2 [OU2]), where concentrate was stored in silos, and then conveyed across the river and into awaiting railcars at the Grace River Loading Site. At this River Loading Site, the conveyed vermiculite concentrate was dumped into railcars located on a spur of the BNSF mainline track that runs along the Kootenai river. Loaded railcars were then transported from the River Loading Site 5 miles into the downtown Libby Railyard, an operation known as the Libby Log Job. At the Libby Railyard, loaded vermiculite cars were inspected, weighed, and stored before eventually being shipped out of town. The mainline track and downtown Libby Railyard have been designated Libby Asbestos Superfund Operable Unit 6 (OU6).

5. **Scope of Study**: The Libby Plaintiffs lived in and around Libby from 1955-present. In light of the Plaintiffs' proximity to the railway and Libby Railyard, I have been asked to investigate their lifetime exposure to airborne LA from fugitive dust sources from railway and yard activities. I have applied generally accepted scientific methods to model the relative contributions to airborne LA in historical Libby air from the (1) Libby Railyard (LR), (2) Libby Log Job (LLJ), (3) River Loading Site (RLS), (4) W.R. Grace Mine Site dry mill stack (GMS-stack) and (5) W.R. Grace Mine Site fugitive dust emissions (GMS-fugitive). To provide predictions and modelling on a more-probable-than-not basis, I have conservatively underestimated emission from BNSF activities (LR+LLJ), and conservatively overestimated emissions from W.R. Grace activities (RLS+GMS). I characterized LA concentration at Plaintiffs' residential locations for the years they lived in Libby during vermiculite mining and transport activities (i.e., up to 1993). I then used those values to calculate Plaintiffs' lifetime-average (70-year) exposure concentrations from BNSF and W.R. Grace activities. For years Plaintiffs did not live in Libby, and from 1994 onward, emissions and exposures are assumed to be zero.

6. **Proximity and Exposure**: Three important factors that typically affect the emission-to-inhalation relationship are the size of the exposed population, the proximity of the exposed population to the emission source, and the persistence of the pollutant in the environment (Marshall and Nazaroff 2004). These three factors are known as the "three P's": population, proximity, and persistence.

   For example, a unit emission in an urban area will expose more people than the same emission in a rural area with much lower population density. Similarly, a small emission within an urban area may have the same total impact to health as a much larger emission in a rural area. When considering the impact of several emission sources on an individual, as done here, both the proximity and the amount emitted will impact the individual's exposure. Additionally, long-lived pollutants may remain in the environment and expose individuals for a longer period of time than pollutants that rapidly transform, degrade, or decay. Asbestos is not known to undergo any significant transformations or degradations in air or soil, therefore, when it is released into the air, the only means of removal is dispersion and deposition to surfaces (ATSDR 2001). Once deposited, asbestos may become resuspended (ATSDR 2001).

   As discussed below, when comparing the impacts of emissions by BNSF and W.R. Grace, a critical aspect is proximity. Emissions from BNSF are closer to town than are emissions from the Grace mine. The BNSF railyard is in town, and there are many Libby homes within only a few blocks from the railroad, whereas the Grace mine is many miles from Libby. BNSF's proximity to the Libby community means BNSF's emissions can have a substantial impact on the community of Libby.

III. Asbestos Emissions in the Libby Area

7. **Asbestos Content in Mining-Related Materials**: The vermiculite ore mined and milled at the GMS and the resulting vermiculite concentrate were heavily contaminated with LA. A 1982 EPA analysis of mine materials found that the vermiculite ore contained 21-26% respirable asbestos by weight (Atkinson et al. 1982). Sampling of airborne dust in the GMS mill found 40% asbestos (Vermiculite Dust Sampling – February 1962), however, that value is based on a single sample and it is unclear whether it represents total or respirable fibers. I use 24% respirable LA for emissions from disturbances and processing of vermiculite ore and waste product (Atkinson et al. 1982). Vermiculite concentrate from W.R. Grace was separated into five grades, by size; analysis of these materials found respirable LA content of 0.3-7% by weight, with a mean of 3.5% respirable LA by weight (Atkinson et al. 1982). I use 3.5% respirable LA for emissions from disturbances of vermiculite concentrate.

8. **Grace Mine, Mill, and River Loading Operations**:

    a. **Overview of GMS Emissions**: Raw ore was mined at the top of Vermiculite Mountain for approximately 70 years. During that time, the top several hundred feet of the mountain was excavated, processed and either dumped as waste or transported into Libby. There were several sources of airborne LA emissions on the mine site, including dust emissions from excavation and blasting of the mountain, transportation and disposal of material around the mine site, windblown dust from storage and waste piles, and emissions from the milling processes. For most years of operation, including during the Plaintiffs' exposure window, milling of the vermiculite ore occurred at the mine site. Prior to 1975, most of the ore was

processed at the mining site via a dry milling process that created extremely dusty conditions and emitted several tons of LA-laden dust every day. (Grace Dry Mill Dust Memo – February 1969). The US EPA estimates that "the [dry] milling process released more than 5,000 lbs of asbestos into the atmosphere every day" (US EPA 2015a, pg. 1-4). In 1975 the dry mill and a smaller wet mill were replaced by a large wet mill that significantly reduced dust emissions at the mine site from milling. (Spear- Relative contributions to airborne dust; Grace Mine Production Report – April 1979).

b. **Overview of RLS Emissions**: Starting in 1949, processed vermiculite was trucked down to the river storage facility (OU2) and stored in large silos sorted by grade. (12/15/1949 Western News Article). Daily orders of vermiculite concentrate were prepared for shipment by releasing concentrate into tunnels below the storage bins and onto a conveyer belt that transported concentrate across the Kootenai River to a rail site (the RLS) where the concentrate was loaded into railroad cars. The RLS rail site was constructed by BNSF for the exclusive use of Zonolite (later W.R. Grace) to load vermiculite concentrate into railroad cars. The RLS operations were dusty: large clouds of dust were generated during the loading of railcars that covered the cars and RLS building. A 1971 United States Department of the Interior, Bureau of Mines Report notes the dust problems at the RLS (US Bureau of Mines Report 1971):

> *"The car loader, located in a control booth alongside the railroad tracks, filled cars with concentrate. Although protected in the booth, and although the loading equipment was provided with a Pangborn dust-collecting system, the exposure appeared high … Settled dust was noted above the railroad car roof slots."*

The RLS operations continued on a daily basis, loading an average of 10-16 cars per day, until the last shipment of vermiculite concentrate in 1993.

c. **Specification of GMS Dry Mill Emissions**: The dry mill operated from 1937-1975. The dry mill is an important source of emissions, yet little documentation is available regarding those emissions. A 1969 W.R. Grace memo from Chief Mining Engineer Ray Kujawa to Assistant Manager Earl Lovick details efforts to measure dust emissions from the dry mill (Grace Dry Mill Dust Memo – February 1969). The memo states that 24,000 pounds of dust per day were emitted from the "600 fan" (the largest fan system in the dry mill) and that an additional 1,300 pounds of dust per day were emitted from the north ventilation system. Assuming 24% respirable LA by weight (Atkinson et al. 1982), this amounts to 25,300 lbs/day × 24% = 6072 lb/day (31.9 g/s) respirable LA. I assume dry mill emissions of 31.9 g/s emissions for all years prior to the closing of the dry mill in 1975. Ventilation systems in the dry mill released LA laden dust via the "600 fan" and a small number of additional ventilation stacks on top of the dry mill building, with large clouds of dust visible from historical photographs. (see Dry Mill Photo 1; Dry Mill Photo 2.) For simplicity, all dry mill emissions were assumed to occur from a single stack, with the location and size estimated from historical photos. Details are provided in Appendix A.

d. **Specification of GMS and RLS Fugitive Dust Emissions**: Dust emissions related to the mine that did not occur during the dry milling operation are considered fugitive dust emissions. Fugitive dust emissions occur from the disturbance of mining-related materials from a wide variety of activities, including overburden removal, blasting, shovels/truck loading, haul roads, truck dumping, crushing, transfer/conveying, material storage, and waste disposal. Using a range of historic emission factors for these mining

activities (US EPA 1976, 1977) and W.R. Grace production statistics, Dr. Spear estimated fugitive dust emissions from operations at the GMS and RLS, excluding windblown dust (Spear- Relative contributions to airborne dust). For simplicity, the dispersion modeling considers the emission location to be either (1) at the GMS on Vermiculite Mountain, or (2) at the RLS. I assign the screening plant (OU2) and the RLS emissions to be at the RLS. Sources of dust included both vermiculite ore and concentrate. Consistent with values above, Dr. Spear uses 24% respirable LA by weight for ore-related operations, and 3.5% respirable LA by weight for concentrate-related operations. The milling process is what concentrates the ore; therefore, for modeling done here, materials handled upstream of milling are considered vermiculite ore; post-milling, materials are considered concentrate. For each process, Dr. Spear provides a range of estimated emissions; to conservatively over-estimate emissions from the GMS and RLS, I use the highest number in his range.

Dr. Spear's calculations indicate that prior to 1975, fugitive dust emissions, excluding windblown dust, at the GMS and RLS totaled 731-4040 lbs/day of respirable LA (Spear- Relative contributions to airborne dust). (After 1975, owing to elimination of some operations associated with the dry mill, fugitive dust emissions were estimated to be slightly reduced: 647 – 3956 lbs/day.) To conservatively over-estimate these emissions, I used the highest number in each of his ranges of values.

Some of the emission factors that Dr. Spear used to calculate daily dust emissions account for suppressed dust emissions on days with precipitation (US EPA 1976); other emission factors do not. For consistency, for values from Dr. Spear that did not account for precipitation, I added a factor to account for precipitation. Specifically, for activities that did not yet include

climatic adjustments, I adjust emissions to exclude days with precipitation using a value of 120 days per year with at least 0.01 inches of precipitation, as given in Figure 4-4 of Cowherd et al. (1985) (See Table A1 in Appendix A for details).

Three exceptions to dust-suppression due to precipitation are transfer/conveying at the Dry Mill, material storage at the River Silos, and transfer/conveying to rail cars at the RLS. These three sources are partially enclosed and so would not be directly wetted by precipitation; for that reason I have not applied the climatic adjustment for those three sources. Some of the emissions at the River Silos were from the bulldozing of vermiculite piles into the elevator mechanism that lifted the concentrate into the silos. These piles were exposed to the environment and consequently to dust-suppression from precipitation. Here I assume that all of the River Silo storage emissions are enclosed, which would conservatively overestimate W.R. Grace's emissions. Additionally, if the enclosures did not provide full protection from moisture – for example, if the enclosures leaked, or if vehicles tracked water inside that reached the vermiculite – my approach of excluding the climatic factor for these three sources would conservatively overestimate W.R. Grace's emissions.

After applying those climatic adjustments, I estimate 3164 lbs/day (16.6 g/s) of respirable LA fugitive dust, excluding windblown dust, combined from the GMS and RLS. That value reflects the upper end of the range from Dr. Spear (after accounting for precipitation) and so is likely to over-estimate emissions from W.R. Grace. For comparison, if I were to use the midpoint of each range instead of the upper bound, estimated emissions would be 1895 lbs/day (9.9 g/s) (after accounting for precipitation).

Of the 3164 lbs/day from the two sites, 462 lbs/day are associated with storage at the screening plant, and 31.5 lbs/day are associated with transfer and conveying to railcars. For dispersion modeling, I assign both these sources to the RLS: 493.5 lbs/day (2.6 g/s) combined total. The remaining 2670.5 lbs/day (14.0 g/s) of respirable LA fugitive dust was assigned to the GMS. Of these 14.0 g/s fugitive dust emissions, 7.9 g/s are from waste, tailings, and storage areas; the remainder (6.1 g/s) are from overburden removal, blasting, and crushing (see Table A1 in Appendix A).

Dr. Spear's fugitive dust emissions estimates include dust generated during specific activities, but exclude general windblown dust. To conservatively over-estimate windblown dust, I assume it is equal to all fugitive dust at the mine site from waste, tailings, and storage areas (i.e., 7.9 g/s). Thus, the total fugitive emissions of respirable LA at the mine site, including windblown dust, is 14.0+7.9=21.9 g/s. The value for windblown dust is meant to be a conservative over-estimate of windblown dust emissions. This value (7.9 g/s for windblown dust) is larger than an estimate from US EPA (1976), which states that total fugitive emissions from storage areas are estimated as 33% windblown dust. (My approach implies that windblown dust emissions are 50% of total fugitive emissions from storage, waste, and tailings areas; again, I have conservatively overestimated emissions relative to the EPA value.)

To confirm that the approach given here yields a conservative over-estimate for wind-blown dust emissions, I also identified and employed four other windblown dust emission factors for open storage piles or un-reclaimed land (US EPA 1976; Western Governers' Association 2006). In applying these four approaches (see Appendix A for details), I calculated emissions using the entire mine site area, 1200 acres, as a conservatively high

estimate of the area of storage or un-reclaimed land. The results are in the range 1.8-5.3 g/s, all of which are less than the windblown dust value used here (7.9 g/s), further supporting that the estimate given here for windblown dust is a conservative overestimate of the actual emissions of windblown dust from GMS.

In summary, I estimate that the total amount respirable LA in fugitive dust, including windblown dust, is 2.6 g/s at the RLS and 21.9 g/s at the GMS. For modeling, RLS emissions were assumed to occur over a square area (9 m^2) near the river loading point, with a release equal to train height (assumed 4.5 m); GMS fugitive emissions were assumed to occur at ground level over a rectangular area (2 km × 1.3 km) encompassing the disturbed mining area. (Map of Study Area). Details are provided in Appendix A.

9. **Libby Log Job**:

   a. **Overview of Libby Log Job Emissions**: As part of the "Libby Log Job", BNSF employees picked up, on average, 10-16 loaded vermiculite cars per day at the RLS and pushed them ~5 miles southwest along the mainline track to the Libby Railyard for eventual shipment outside of Libby. At the RLS, while loading railcars, the conveyor would deliver vermiculite concentrate into cars – in earlier years from the side (box cars), then in later years via hatch openings in the roof of the train car (C6 cars) (Hart 2018). During this loading process, the conveyor belt would not be stopped while the train was being pushed from loading one opening to loading the next opening, causing loose vermiculite to accumulate on top of the cars and spill onto the tracks. Workers at the RLS reported regular buildup of spilled vermiculite concentrate to above the level of the tracks; this spilled vermiculite had to be removed with a front-end loader and later with a

vacuum truck (Hart 2018). Workers reported loose vermiculite concentrate on top of the railcars, and BNSF employees reported large clouds of dust during the entire Log Job trip, as the vermiculite railcars were pushed back into the Libby Railyard (Hart 2018).

While pushing loaded vermiculite cars back to Libby "we had to keep the windows and doors closed in the engine to try to keep the vermiculite out because it created an awful dust inside the cab"

Deposition of Bruce Carrier, pg. 13

"Dust would be blowing right in your face, and I had my head out [off] the engine because that's our responsibility and job as an engineer, to keep constant visual contact with that head brakeman." "Dust looked like black smoke" or "charcoal".

Deposition of James Kampf, pg. 50-51

b. Specification of Log Job Emissions: Based on worker testimony, Dr. Hart estimates that the typical amount of vermiculite concentrate on the top of railcars was 6 – 8 inches when leaving RLS and 1/8 – 3 inches when arriving at Libby Railyard (Hart 2018). The difference in those amounts is how much vermiculite concentrate was lost (emitted into the air) during the trip from RLS to Libby Railyard. From that range of values (6 – 8 inches before the Log Job run; 1/8 – 3 inches after), the smallest difference in heights is 6 inches – 3 inches = 3 inches (i.e., 0.25 ft) of vermiculite concentrate lost (i.e., emitted) from the tops of each car. Using mid-range heights (7 inches before; 1.56 inches after) would yield a difference in heights (5.44 inches) that is more than 80% larger than the minimum value

(3 inches). To conservatively underestimate emissions, I will use this smallest value (0.25 ft) for the height of vermiculite concentrate that is lost to emissions during the train ride from RLS to Libby trainyard.

A 1962 newspaper article states that the hopper cars are 55 ft long (Hopper Car - February 1962). Based on the worker testimony, I assume 13 railcars loaded and transported per day, and that 49% of each car-length (estimated from a photograph of River Loading Vermiculite Hopper Car, showing that ~51% of the train-car roof is covered by hatches or other openings) contained vermiculite concentrate on the roof. I assume a density of vermiculite concentrate of 3 g/cc and that 3.5% of vermiculite concentrate is respirable LA (Atkinson et al. 1982). Worker testimony indicates that most days involved one Log Job run, but some days involved two Log Job runs. Here, I have assumed only one Log Job run per day, to conservatively underestimate total emissions.

To estimate the volume of material lost requires an estimate of the width of the vermiculite strip on top of the train car. I assumed a strip of 1 ft wide and that the shape of the cross-section is a triangle (so, cross-section area = ½ × width × height). Those values provide a reasonable engineering estimate, and also aim to conservatively underestimate the emissions: because worker testimony describes accumulated vermiculite concentrate on the roof in general, without mentioning it as a "strip", it seems unlikely that the width would be less than the value assumed (1 foot) and it seem likely that the width would be more than the value assumed (1 foot).

The volume of vermiculite concentrate lost is therefore 44 cu ft per day (i.e., ½ × 1 foot × 0.25 feet × 55 feet/train-car × 49% × 13 train-cars/day). This value is reasonable in light of the loading rate and the rate at which

material would be coming off the conveyor. Converting to respirable LA yields 1.5 g/s (i.e., 44 cu ft/d × [28317 cc/cu ft] × [3 g/cc] × [d/ 86400 s] × 3.5%). For modeling, these emissions get distributed equally among ten equally spaced points located along the Libby Log Job route between RLS and the railyard (1.5 g/s ÷ 10 locations = 0.15 g/s at each location) and using the same emission parameters as the RLS (9 m^2 square area and 4.5 m release height). Details are provided in Appendix B.

10. Downtown Libby Railyard:

a. **Overview of Libby Railyard Emissions**: Libby Railyard cuts through the town of Libby and is directly north of downtown at the end of Mineral Avenue, Libby's main street. During the relevant years (1955-1993) the Libby Railyard was surrounded by residential neighborhoods, businesses, parks, baseball fields, and a public swimming pool. As mentioned above, a major factor in the health impact of emissions is the proximity between the emissions and the exposed population. Given the proximity of the Libby Railyard to homes in Libby, even comparatively small emissions from the railyard could have a substantial contribution to concentrations in Libby. W.R. Grace estimated that daily average production of vermiculite concentrate was between 500-1000 tons in the late 1960s and 1970s, and between 800-1000 tons in the 1980s. (W.R. Grace Response to EPA - February 2000, pg. 8-9). Using the 3.5% respirable LA for vermiculite concentrate and a daily average of 750 tons, BNSF carried an estimated 52,500 pounds of LA into and out of downtown Libby per day in the late 1960s and 1970s (750 tons × 2000 lbs/ton × 3.5% LA = 52,500 lbs LA). Table 1 summarizes total LA shipments in during the 1970s and 1980s.

Table 1: Summary of LA Hauled by BNSF into Libby During the 1970s and 1980s

	Mine and Mill daily production of vermiculite concentrate (tons)[a]	Mid-range value for daily vermiculite production (tons)	Daily respirable LA hauled into the Libby Railyard (lbs/day)[b]	Total respirable LA hauled into the Libby Railyard for the time period (lbs)[c]
1970s (10 years)	500-1000	750	52,500	18,375,000
1980s (10 years)	800-1000	900	63,000	22,050,000

[a] From W.R. Grace Response to EPA - February 2000, pg. 8-9.
[b] Using 3.5% respirable LA by weight from Atkinson et al. (1982).
[c] Assuming 350 days of production per year

As mentioned above, loaded vermiculite cars were pushed into the Railyard, creating a dust cloud that was reported to persist into the Libby railyard (Hart 2018). As described above, worker testimony also indicates that between 1/8 and 3 inches of vermiculite remained on top of the cars that arrived in the yard (Hart 2018). Once at the railyard, cars were typically moved, uncoupled, weighed, recoupled, moved again, and eventually stored in the railyard on tracks #1 and #2 near the main line before being coupled to eastbound or westbound trains. While in the railyard, each car would be weighed, which accounts for some of the bumping and jostling, as each car in the train was moved onto the scale, one at a time. Workers report falling vermiculite and dust clouds as cars were bumped into each other and as air hoses between cars were buckled and unbuckled during the process of uncoupling, weighing, and recoupling vermiculite cars (Hart 2018). Workers estimate that a single car would be

moved several times, often being uncoupled/recoupled each time (Hart 2018). In addition to loose vermiculite on the cars, workers reported that it was common for vermiculite cars to leak, creating piles of vermiculite concentrate in the railyard that would be need to be kicked down or regularly spread throughout the yard (Hart 2018). Worker depositions describe constant sources of vermiculite and vermiculite dust in the railyard:

Workers "moved [vermiculite cars] from three to four different locations in the yard" and "as they switched them they actually hit them together with the knuckles, and a lot of them hit pretty damn hard and that stuff was coming off of them all the time." The amount of vermiculite falling off bumped cars "could vary anywhere from inch to maybe as deep as ten inches or a foot in places"

Deposition of Bill Obermayer, pg. 17-19,

"On certain parts of the yard you have the vermiculite that leaked out of cars, and when they hit each other, they would drop the vermiculite down. It was pretty bad as far as vermiculite in the yard"

Deposition of Donald Erickson, pg. 30

"constant" vermiculite and dust on the ground in the Libby Railyard.

Deposition of James Kampf, pg. 55

"The ore went on the ground; and any dust that was connected with it – Whatever went up in the air would gradually, eventually settle back down on the ground." Piles "would just be leveled out, and it would be out there in the railroad yard."

Deposition of Robert Barnes, pg. 70

"[Vermiculite] was scattered all over the yard."

Deposition of Robert Barnes, pg. 105

These quotes highlight multiple sources of vermiculite concentrate emissions in the railyard that are not modeled here: leaks from holes in train-cars, dust generated or knocked off the tops and sides from the constant banging of cars during coupling/uncoupling, dust blown off the tops of cars when moving the cars, dust created by air hoses, windblown dust from the piles of concentrate, movement of foot traffic and truck traffic around the railyard, and physical interactions with the concentrate such as sweeping and people knocking down piles by kicking them (Hart 2018). In addition, there would be general windblown dust from throughout the yard, and entrained dust from regular maintenance activities (Hart 2018). My approach here ignores those many sources of emissions. Ignoring those many sources of emissions further suggests that emission estimates here conservatively underestimate total emissions from the railyard.

To my knowledge, soil sampling was not conducted in the yard while vermiculite was actively being shipped out of Libby. The first soil sampling I know of occurred in 2001, which is after vermiculite production and shipping had stopped but prior to the EPA-directed cleanup efforts in the

yard (US EPA 2014a). During this sampling period, which was many years after the last vermiculite shipment through Libby Railyard, a large portion of the railyard was flagged as having visible vermiculite, marked on a map for removal, and not sampled (US EPA 2014a). (See grey shaded area in Map of Flagged Vermiculite in Libby Railyard.) On August 13, 2003, initial cleanup in the yard began: the area of visible vermiculite was loosened with an excavator and the top two inches of soil were removed via a vacuum truck (US EPA 2014a). Composite clearance samples taken after initial cleanup showed 2% LA in the remaining soil (see EMR Fax – August, 20 2003); after consultation with EPA, cleanup efforts were suspended (US EPA 2014a). A September 2003 Initial Pollution Report for OU6 submitted to the EPA states:

"Visible vermiculite has been found along the tracks and within the railyard and analytical results have shown asbestos levels in soil from 2-5%"

"Asbestos contaminated materials were hauled and shipped through the railyard, and spilled into the soil for decades. The soil around the tracks and under the ballast is contaminated and needs to be removed."

The reported 2-5% LA content in railyard soil (which was measured after the initial cleanup) is consistent with the 3.5% LA found in vermiculite concentrate, and also consistent with worker testimony that the railyard was covered in visible vermiculite (Hart 2018). The prevalence of vermiculite in the railyard was also confirmed by BNSF Manager of Industrial Hygiene, Gerald McCaskill, who recalled the yard sparkling with vermiculite. (1/24/2007 Deposition of Gerald McCaskill, pg. 55). Likely owing to the practice of spreading spilled and leaked vermiculite around the yard, this

area was essentially vermiculite concentrate in 2001, despite being many years after the last vermiculite shipment, and undergoing years of regular yard maintenance and ballast cleaning. EPA-directed cleanup in the railyard continued into 2011, resulting in the removal of over 18,000 tons of LA contaminated soil, and the removal or capping of soil in nearly every part of the railyard (Hart 2018; US EPA 2014a).

During the period of vermiculite shipments out of the Libby Railyard, the mainline track that ran through the yard was an active line. Freight trains regularly sped through the Libby yard, generating dust clouds. Railroad workers estimate that 20 to 30 trains per day would pass through the yard, and that a visible cloud of vermiculite would occur every time a train passed by as long as the ground was dry (Hart 2018). The occurrence of dust with every passing train and the lightweight nature of the material is consistent across worker testimonies:

Passing trains created a "dust storm you wouldn't believe" that was visible "all the way from the east end of the yard clear to the west end" containing "lots of dust, and wood chips"

Deposition of Bruce Carrier, pg. 21-22

It was "like a mini cyclone with every train that went by"

Deposition of Bruce Carrier, pg. 69

"every time a train would go by there was lots of dust"

Deposition of Bill Obermayer, pg. 18

"when it was dry, there was dust all the time" when main line trains came in.

Deposition of Donald Erickson, pg. 24

"Every time that I saw a freight coming through there at 50, I'd notice some dust." Dust kicked up from trains looked like "charcoal" with "diamonds in it". The dust "was like your first snowfall", "really light and snow that is cold", like "small, little, teeny ice chips."

Deposition of James Kampf, pg. 58-59

"Every time a mainline train went through there at 55 mile an hour" it would kick up dust. "It'd take 15 minutes after a train went by" for the dust to dissipate.

Deposition of Robert Barker Jr., pg. 84

"When the train goes by, it always kicks up dust, especially in dry weather." For example, "watch a train go by in the wintertime when there's been a light snow, and that train picks that snow up and just whirls it." That "gives you a good idea what dry dust will do."

Deposition of Robert Barnes, pg. 45

"You always got [dust and dirt] in your eyes when they'd go through if you were standing out on the platform or in the yard"

Deposition of Robert Barnes, pg. 80

Worker testimony is clear and consistent: emissions from passing trains happened consistently, with every passing train, and the resulting dust emissions were substantial.

b. Specification of Railyard Emissions: When trains traveled through the Libby Railyard on the mainline tracks at high speed, the turbulent wake from their movement was one source of wind that could kick up LA-laden vermiculite dust. As described above, worker testimony emphasizes that this type of local dust-storm would happen for every passing train when the weather was dry. In order to estimate these dust emissions, I follow an approach outlined in the environmental impact report for a proposed California high-speed train (California High-Speed Rail Authority and Federal Railroad Administration 2012). This approach involves two main steps: (1) estimating the windspeed from the air turbulence caused by passing trains, and (2) using those windspeeds to estimate the amount of dust that would be kicked up by passing trains. Both of these steps follow generally accepted scientific methods; their inclusion in the final report prepared for the California High Speed Rail Authority and the U.S. Department of Transportation Federal Railroad Administration supports their usage here (CHSRA/FRA 2012).

The first step is to estimate windspeed induced by a passing train. That windspeed is a function of the train speed and the distance from the train

(induced windspeeds are generally faster close to the train than further from the train). The bluff body shape of the freight trains typically passing on the mainline would tend to induce higher airflows than would an aerodynamically shaped train going the same speed (Soper 2014). I use measurements of induced windspeed relative to train speed to estimate the induced windspeed from mainline trains (Liao et al. 1999). Figure 2-1 from Liao et al. (1999) shows the relationship between distance from train and the induced windspeed relative to train speed, for a range of measurements. I estimate a lower and upper bound induced windspeed from this figure and then use the midpoint (Liao et al., 1999 Figure 2-1 Induced Windspeed). Based on the bluff body shape of the trains passing through the railyard, the high induced airflow (i.e., the upper end of the range of data) is likely more accurate for conditions in Libby, but I employ the midpoint to conservatively underestimate emissions from the railyard. The majority of railroad worker firsthand observations indicate a train speed of 55 mph in the Libby Railyard for mainline trains (Hart 2018). Assuming 55 mph trains, and values obtained from measured windspeeds (see above – Liao et al, 1999, Figure 2-1), I can estimate the induced windspeed from trains passing through the Libby Railyard. I assume estimated induced windspeeds on either side of the train are for train half-height (½ * 4.5 m = 2.25 m), and that induced windspeed underneath the train is equal to windspeed at the edge of the train.

As mentioned above, following the calculation approach laid out by the California High-Speed Rail Authority and Federal Railroad Administration (2012) ("CHSRA/FRA"), the second step is to estimate fugitive dust emissions from the induced windspeed obtained above. The CHSRA/FRA approach uses the AP-42 Chapter 13.2.5 Industrial Wind Erosion guidance document, a generally accepted scientific method to estimate wind erosion

emissions in industrial settings (US EPA 2006). Equations from this guidance calculate suspended particle emissions per unit area based on a fluid mechanics parameter called "surface friction velocity," which is the shear stress at the erodible soil surface caused by the wind. Emissions are a function of (1) the surface friction velocity (estimated from train speed, using a common fluid mechanics equation for windspeed vertical profile), (2) a threshold friction velocity needed to entrain dust, and (3) the number of disturbances (US EPA 2006). Threshold friction velocity depends on the nature of the soil being entrained. For the vermiculite concentrate and dust covering the yard I employ a value of 30 cm/s, which is a published threshold for "strip mines, quarries, and barrow pits" (Gillette and Passi 1988). Based on the dry and lightweight nature of the vermiculite concentrate and LA, and the description from workers comparing the dust clouds from passing trains to a light powdery snow, the true threshold velocity for the material in the railyard is likely lower than the 30 cm/s value employed here. The use of this value (30 cm/s) is to conservatively underestimate emissions from passing trains in the railyard.

I assume 20 trains per day, using the low end of the 20 – 30 trains from worker testimony, to conservatively underestimate emissions. I also assume that the area along the mainline containing exposed vermiculite material available to be entrained by passing trains is approximately 550 m, the length of mainline track adjacent to the area flagged with visible vermiculite during 2001 sampling. (See grey shaded area in Map of Flagged Vermiculite in Libby Railyard; Map of Study Area – Libby Railyard). Since this length (550m) reflects areas that were still contaminated many years after the last vermiculite shipment, one would expect that the area of land that was contaminated when the railyard was active with vermiculite shipments would be the same or more, so the 550m

likely underestimates the amount of contamination and emissions. Finally, I adjust emissions to exclude days with significant precipitation, using a value of 120 days with at least 0.01 inches of precipitation from Figure 4-4 of Cowherd et al. (1985). Based on these assumptions, the induced windspeed, using the AP-42 Industrial Wind Erosion equation, and 3.5% respirable LA by weight, I estimate 119 lbs/day (0.6 g/s) of respirable LA. I assign emissions as a line source along the 550 m section of mainline track with initial plume dimensions based on US EPA Haul Road Workgroup recommendations (US EPA 2011). Details are provided in Appendix C.

During the relevant years (1955-1993), the Libby Railyard was an active yard, and there are many other activities that could release LA-laden dust into the air that are not included in this estimate (Hart 2018). In addition to typical daily activities in the railyard, maintenance activities like monthly sweeping and annual ballast removal and spot tamping could create significant dust clouds in the railyard (Hart 2018). I do not include these emissions to ensure that Libby Railyard emissions are conservatively underestimated.

IV. Model Description

11. The AERMOD Model: Air dispersion modeling is needed to convert estimates of emissions into estimated concentrations in the air at residential locations. The EPA's American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) is employed here to quantify the relative impact from W.R. Grace mine-related operations (i.e., GMS-stack, GMS-fugitive, RLS) and BNSF vermiculite transport operations (i.e., Log Job, Libby Railyard) (US EPA 2018).

AERMOD is the EPA's preferred regulatory dispersion model. It is a generally accepted scientific method for an analysis of this nature. According to the EPA's Guideline on Air Quality Models, "the AERMOD modeling system has been extensively evaluated across a wide range of scenarios based on numerous field studies" (US EPA 2017, pg. 5210). AERMOD was used by consultants representing W.R. Grace and the EPA to model deposition of LA from milling operations to soil near the W.R. Grace mine site (US EPA 2016, pg. 38).

12. **Meteorological Data**: The AERMOD model uses meteorological data, including windspeed and direction, to estimate the extent and location of LA particle transport in the air. Two types of meteorological data are needed: upper air data and surface data (US EPA 2004). These data typically come from the nearest National Weather Service (NWS) observations, or on-site measurements (US EPA 2004). I use the nearest NWS upper air station, located in Spokane, WA, and the nearest NWS surface station, located in Kalispell, MT.

Spokane NWS upper air data
https://www1.ncdc.noaa.gov/pub/data/igra/igra2-station-list.txt
Available: 1926-present

Kalispell NWS surface data
https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/WBAN:24146/detail
Available: 1957-present

The dispersion modeling therefore uses meteorological monitors located away from the emission source; that outcome is common in dispersion modeling and is a generally accepted scientific method.

I note that the study area contains two non-NWS monitors, which are part of the Remote Automated Weather Station (RAWS) network (https://raws.dri.edu). One monitor is located on top of Zonolite Mountain; the other is located ~1 mile northeast of downtown Libby (see map in Libby and Zonolite Mountain RAWS Station). The Zonolite Mountain monitor is not suitable for modeling conducted here, owing to its high elevation compared to the Plaintiff home locations in Libby. The Libby monitor is located in a small clearing surrounded by forested area, with the windspeed and wind direction sensors positioned below the tree line, therefore, despite being listed in the RAWS database, it does not meet the RAWS siting recommendations for wind sensors to be placed at least 20 feet above nearby obstructions (National Wildfire Coordinating Group 2005) (see zoom-in map and photo in Libby and Zonolite Mountain RAWS Station). Furthermore, neither of the two non-NWS monitors have data for the years that are relevant to the Plaintiffs' exposures. For these reasons, the two non-NWS monitors are less suitable for modeling than the NWS station in Kalispell. However, to test the impact of this aspect on the results, I also ran models using the non-NWS monitor in Libby. Results using the non-NWS data and the NWS data are similar (see Appendix F), indicating that the core conclusions are not strongly sensitive to this choice.

13. **Model Configuration**: To capture conditions over the relevant years (1955-1993), the AERMOD model was run at 5-year intervals from 1960-1990 (i.e., for 1960, 1965, 1970, 1975, 1980, 1985, and 1990). To quantify the impact of individual emission sources, the model was run separately for each of the five emission sources: GMS-stack, GMS-fugitive, RLS, LLJ (as described above, this source is modeled as 10 separate source locations along the route of the railroad track from RLS to LR), and the LR. GMS-stack emissions are modeled as a point source; all other emissions are modeled as area sources, which means that emissions are distributed over a pre-defined area. Respirable LA concentrations from each

source were estimated by AERMOD (in μg/m^3 of respirable LA) for 24 receptor locations representing residential locations. Further details on emission rate calculations and source parameters for the five sources are provided in Appendixes A-C, and summarized in Appendix D.

V. Fiber Concentration and Health Risk

14. **EPA Lung Cancer and Asbestos Related Disease Risk**: Given the particularly toxic nature of LA and the need for a reference concentration to assess exposure in the Libby area, the EPA undertook a toxicity assessment of LA (US EPA 2014b). In doing so, a lifetime (i.e., 70 years) reference concentration (RfC) for LA asbestos related disease (ARD) was set as 0.00009 fibers/cc (90 fibers/m^3). This value is an estimated concentration "that is likely to be without an appreciable risk of deleterious effects during a lifetime." (US EPA 2014b). In addition to the RfC for ARD, an inhalation unit risk (IUR) of 0.169 fibers/cc was set for the combined mortality risk from either mesothelioma or lung cancer (US EPA 2014b). The IUR, when multiplied by a lifetime exposure, gives the lifetime mortality risk for mesothelioma and lung cancer. Conversely, one can obtain a lifetime exposure concentration corresponding to an acceptable risk. Assuming a 1:10,000 ("one in ten thousand") acceptable risk, one can obtain an acceptable lifetime exposure concentration of 0.00059 fibers/cc (590 fibers/m^3). I will use these risk values to compare the health risk from the five emission sources (GMS-stack, GMS-fugitive, RLS, Log Job, Railyard).

Reference concentration for asbestos related disease (RfC ARD): **90 fibers/m^3**
1:10,000 risk concentration for mesothelioma and lung cancer (RfC to IUR): **590 fibers/m^3**

15. **Estimated Plaintiff Lifetime LA Exposure**: Respirable LA concentrations from each source were estimated by AERMOD (in µg/m^3 of respirable LA) for the 24 residential locations throughout Libby at 5-year intervals from 1960-1990. Concentrations were converted from LA mass to LA fiber count using the conversion factor given by the Agency for Toxic Substances & Disease Registry (ATSDR 2001): 1 µg/m^3 = 0.033 fibers/cc = 33,000 fibers/m^3. A 70-year lifetime respirable LA exposure concentration was then estimated, following a similar methodology as the EPA's site-wide LA risk assessment for Libby (US EPA 2015, pg. ES-2), for each of the three Plaintiffs and the five emission sources, given their residential history, the nearest modeled year, and assuming all LA exposures were zero for years lived outside of Libby and after 1993 (when vermiculite shipments stopped). (See Plaintiff Residential History and Model Assignment Timeline.) Details are provided in Appendix E. Lifetime (70-year) exposure concentration and the ratio of lifetime concentration to emission for the three Plaintiffs are shown in Table 2.

Table 2. Summary of Lifetime Respirable LA Exposure by Source

		Emissions (g/s)[a]	Ratio of Lifetime concentration to emission[a] (µg/m^3 per g/s), based on AERMOD modeling	Lifetime Concentration (µg/m^3)	Lifetime Concentration (fibers/m^3)[b, c]
GMS stack emissions (600-fan & other stacks)	W.R. Grace	32	Barnes: 0.005 Braaten: 0.008 Flores: 0.0[d]	0.16 0.24 0.0[d]	5,200 8,000 0.0[d]
GMS fugitive dust	W.R. Grace	28	0.020 0.020 0.002	0.44 0.43 0.04	14,500 14,100 1,400
RLS fugitive dust	W.R. Grace	2.6	0.045 0.027 0.005	0.12 0.07 0.01	3,800 2,300 400
Dust from Libby Log Job	BNSF	1.5	0.193 0.055 0.024	0.29 0.08 0.04	9,500 2,700 1,200
Dust from Libby Railyard	BNSF	0.63	2.176 0.423 0.011	1.36 0.26 0.01	44,900 8,700 200

[a] During relevant years while source was active (GMS-stack: 1955-1975; GMS-fugitive: 1955-1990; all others: 1955-1993)

[b] Conversion factor (from ATSDR, 2001): 1 µg/m3 = 0.033 fibers/cc = 33,000 fibers/m^3

[c] Reference concentrations (from US EPA 2014b):

- RfC to IUR: 590 fibers/m^3 (i.e., 0.00059 fibers/cc)
- RfC ARD: 90 fibers/m^3 (i.e., 0.00009 fibers/cc)

[d] Plaintiff did not live in Libby area during the operation of the dry mill

A summary of each Plaintiff's lifetime respirable LA exposure by BNSF and W.R. Grace activities is provided below:

Tracie Barnes

BNSF: 9,500 fibers/m^3 + 44,900 fibers/m^3 = **54,400 fibers/m^3**

Grace: 5,200 fibers/m^3 + 14,500 fibers/m^3 + 3,800 fibers/m^3 = **23,500 fibers/m^3**

Ratio of BNSF to Grace contribution: **2.31**

Rhonda Braaten

BNSF: 2,700 fibers/m^3 + 8,700 fibers/m^3 = **11,400 fibers/m^3**

Grace: 8,000 fibers/m^3 + 14,100 fibers/m^3 + 2,300 fibers/m^3 = **24,400 fibers/m^3**

Ratio of BNSF to Grace contribution: **0.47**

Geri Flores

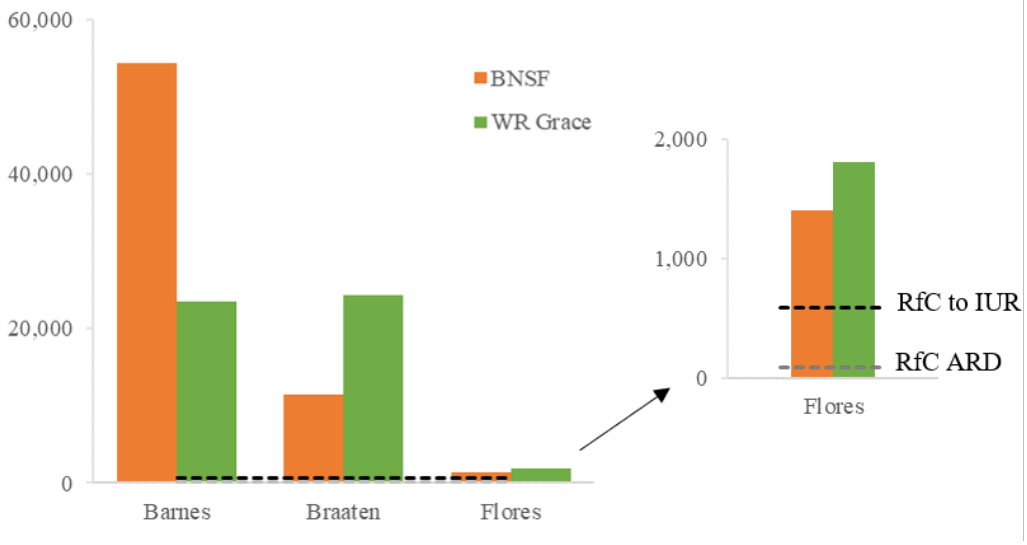
BNSF[3]: 1,200 fibers/m^3 + 200 fibers/m^3 = **1,400 fibers/m^3**

Grace: 0 fibers/m^3 + 1,400 fibers/m^3 + 400 fibers/m^3 = **1,800 fibers/m^3**

Ratio of BNSF to Grace contribution: **0.78**

[3] This value is based on BNSF emissions from the LLJ and from the LR. LR ("Libby Railyard") is a line source along 550 m of mainline track located in the Libby railyard (adjacent to downtown Libby). For 8 of 12 years that she resided in Libby, Ms. Flores lived adjacent to the railroad tracks, two miles west of LR. We have not accounted for BNSF emissions west of LR, which means that our estimate ignores emissions from the railroad tracks closest to the house where she lived for those 8 years. Workers reported spilled vermiculite from leaking rail cars along the mainline track leading out of Libby, as well as loose vermiculite on rail cars shipped out of the Libby Railyard (Hart 2018).

Figure 1: 70-year Lifetime LA Exposure Concentration (fibers/m^3)



Emissions from both BNSF and W.R. Grace each had significant contributions to Plaintiffs' lifetime exposures, approximately 2-92× higher than the RfC to IUR (590 fibers/m^3) and approximately 16-600× higher than the RfC ARD (90 fibers/m^3).

These results indicate that the proximity of BNSF activities to residential locations was a substantial contributor in determining total exposures. (See the ratio of lifetime concentration to emissions, Table 2.)

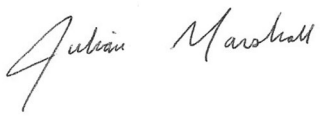
As stated above, I have been asked to comment on these questions, to a reasonable degree of scientific probability:

- What were the lifetime concentrations of asbestos in the air at the respective residences of Tracie Barnes, Rhonda Braaten, and Gerrie Flores?
- Are lifetime concentrations of asbestos in the dust created by BNSF activities substantial relative to those created by W.R. Grace activities?
- Are lifetime concentrations of asbestos in the dust created by BNSF activities substantial relative to reference concentrations?

My calculated values in answer to the first question are given in Table 2, immediately below Table 2, and in more detail in Appendix E. As described in detail throughout this report, I conservatively overestimate impacts from W.R. Grace and conservatively underestimate impacts from BNSF.

Lifetime LA exposure concentrations from BNSF activities were approximately 0.5-2.3× the lifetime LA exposure concentrations from W.R. Grace activities. In answer to question 2, my results indicate that lifetime exposure concentrations of LA from dust created by BNSF activities are substantial relative to those created by W.R. Grace activities.

Finally, lifetime LA exposure concentrations from BNSF activities were approximately 2-92× higher than the RfC to IUR (590 fibers/m^3) and approximately 16-600× higher than the RfC ARD (90 fibers/m^3). Thus, with regards to question 3, I find that lifetime exposure concentrations of LA from dust created by BNSF activities are substantial relative to reference concentrations.



Julian Marshall

10/26/2018

VI. Appendix A: GMS and RLS Emissions Calculations

16. **Dry Mill (GMS-stack)**: From approximately 1937-1975, vermiculite ore was processed in a dry mill on Vermiculite Mountain to produce vermiculite concentrate. Dust from the dry mill was exhausted via ventilation systems. A 1969 W.R. Grace memo from Chief Mining Engineer Ray Kujawa to Assistant Manager Earl Lovick states that 24,000 pounds of dust per day were emitted from the "600 fan" (the largest fan system in the dry mill), and an additional 1,300 pounds of dust per day were emitted from the north ventilation system (Grace Dry Mill Dust Memo – February 1969). Assuming 24% respirable LA by weight (Atkinson et al. 1982), one can calculate the total emissions of respirable LA from the dry mill stacks.

Total dust (lb/day) = 24,000 lb/day + 1,300 lb/day = 25,300 lb/day
Respirable LA dust (lb/day) = 25,300 lb/day × 24% = 6072 lb/day
Respirable LA dust (g/s) = 6072 lb/day × 453.592 g/lb ÷ 86,400 s/day = **31.9 g/s**

I assume dry mill emissions of 31.9 g/s emissions for all years prior to the closing of the dry mill in 1975, after which dry mill emissions are assumed to be 0 g/s.

AERMOD source parameters needed to model the GMS-stack are stack location, stack height, stack diameter, exit velocity, and temperature. Ventilation systems in the dry mill released LA laden dust via the "600 fan" and a small number of additional ventilation stacks on top of the dry mill building, with large clouds of dust visible from historical photographs. For simplicity, all dry mill emissions were assumed to occur from a single stack (see 1963 GMS Aerial Photo and 1995 Google Earth Imagery of GMS used to estimate GMS-stack location).

The height and diameter of the stack were estimated from two historical photos of the mill, using a door as reference height (assuming a door height of 7 ft). The dry mill is located on a hill; therefore, I estimated an upper and lower height from each of the two photos and used the average of all four values. (Grace Dry Mill – Stack Height and Diameter).

Stack diameter = 1.5 ft = **0.5 m**
Stack height = (46 ft + 37 ft + 50 ft + 40 ft) ÷ 4 = 43.2 ft = **13 m**

The stack temperature was ambient, and a value of 298 K (25° C or 77° F) was used. The stack exit velocity was estimated using the midpoint of minimum design velocity values for "fine dry dust, or powder" (3000 ft/s) and "industrial dust" (3500 ft/s) obtained from a 1988 Dust Control Handbook, with a safety factor of two (i.e., two times 3250 ft/s), based on the opinion of Dr. Spear on the nature of the dry mill dust (Spear- Relative contributions to airborne dust).

Stack temperature = **298 K**
Stack velocity = 3250 ft/s × 2 = 6500 ft/s = **33 m/s**

17. **Fugitive Dust (GMS-fugitive and RLS)**: Dr. Spear estimated fugitive dust emissions from operations at the GMS and RLS, excluding windblown dust (Spear- Relative contributions to airborne dust). For simplicity, the dispersion model employs two locations: (1) at the GMS on Vermiculite Mountain, or (2) at the RLS. Screening plant (OU2) and RLS emissions are assigned to RLS. Sources of dust included both vermiculite ore and concentrate. Consistent with values above, Dr. Spear assumes 24% respirable LA by weight for ore-related operations, and 3.5% respirable LA by weight for concentrate-related operations. For each process, Dr. Spear provides a range of estimated emissions; to conservatively

over-estimate emissions from the GMS and RLS, I use the highest number in his range.

As described in the main text, for values from Dr. Spear that did not yet include climatic adjustments, I added a factor to account for precipitation (except for sources that are enclosed or covered).

After applying those climatic adjustments, I estimate 3164 lbs/day (16.6 g/s) of respirable LA fugitive dust, excluding windblown dust, combined from the GMS and RLS. That value reflects the upper end of the range from Dr. Spear (after accounting for precipitation) and so is likely to over-estimate emissions from W.R. Grace. For comparison, if I were to use the midpoint of each range instead of the upper bound, estimated emissions would be 1895 lbs/day (9.9 g/s). A summary of these values is provided in Table A1 below.

Table A1: Upper-End Estimate of Fugitive Dust Emissions from GMS and RLS by Activity

Process	Location	Respirable LA by weight	Upper-end estimate of total dust emissions (lbs/day)[a]	Upper-end estimate of respirable LA dust emissions (lbs/day)	GMS Storage/ Waste/ Tailings[b]
Overburden Removal	Mine/Mill	24%	4320	696[c]	
Truck Dumping Overburden	Mine/Mill	24%	384	62[c]	W/T
Haul Roads (mine to waste)	Mobile	24%	1491.6	358[d]	W/T
Blasting	Mine/Mill	24%	2192	353[c]	
Shovels/Truck Loading	Mine/Mill	24%	1370	221[c]	W/T
Haul Roads (mine to crusher)	Mobile	24%	118.8	29[d]	S
Haul Roads (mine to tailings)	Mobile	24%	466.4	112[d]	W/T
Haul Roads (lower ore bins to river silos)	Mobile	24%	660	158[d]	S
Haul Roads (mill to river silos)	Mobile	24%	594	143[d]	S
Truck Dumping (mine to crusher)	Mine/Mill	24%	40	6[c]	S
Truck Dumping (mine to tailings)	Mine/Mill	24%	120	19[c]	W/T
Truck Dumping (lower ore bins to river silos)	Mine/Mill	3.5%	30	0.7[c]	S
Crusher	Mine/Mill	24%	700	113[c]	
Transfer/conveying Transfer Point	Mine/Mill	24%	1500	242[c]	S
Transfer/conveying Dry Mill	Mine/Mill	3.5%	2400	84[c]	S
Material Storage Mill	Mine/Mill	24%	420	68[c]	S
Material Storage Skip Cars	Mine/Mill	3.5%	315	7[c]	S
Material Storage River Silos	Screening Plant	3.5%	13200	462[e]	
Transfer/Conveying to Rail cars	River Loading	3.5%	900	32[e]	

[a] Values taken as the upper end of the range reported by Spear- Relative contributions to airborne dust.

[b] Processes identified as occurring in storage (S) and waste/tailings (W/T) areas; these values are used to estimate windblown dust emissions at the mine site.

[c] Values from Dr. Spear were adjusted here to account for days with significant precipitation (n=120 days).

[d] Haul road emission factors include a climatic adjustment (US EPA 1976).

[e] Enclosed or partially enclosed sources; no climatic adjustment.

Excluding windblown dust, fugitive respirable LA dust totals are as follows:
(GMS + RLS) = 3164 lb/day × 453.592 g/lb ÷ 86,400 s/day = 16.6 g/s
RLS-only = (462 lb/day + 32 lb/day) × 453.592 g/lb ÷ 86,400 s/day = 2.6 g/s
GMS-only = 16.6 g/s – 2.6 g/s = 14.0 g/s

Storage at the RLS is contained within silos, and the remaining RLS processes (dumping and conveying) account for windblown losses (US EPA 1976). I therefore assume no additional windblown dust fugitive emissions at the RLS.

RLS respirable LA dust = 2.6 g/s

To conservatively over-estimate windblown dust at the mine site, I assume it is equal to all fugitive dust at the mine site from waste, tailings, and storage areas. From Dr. Spear's report and Table A1 below:

GMS waste/tailings/storage = 1509 lb/day × 453.592 g/lb ÷ 86,400 s/day = 7.9 g/s

The value for windblown dust is meant to be a conservative over-estimate of windblown dust emissions.

US EPA (1976, pg. 57) states that total fugitive emissions from storage areas are estimated as 33% windblown dust. The approach taken here implies that windblown dust emissions are even greater: 50% of total fugitive emissions from storage, waste, and tailings areas.

To further confirm that the estimate here (7.9 g/s) is an over-estimate, I compared it with four other estimates of windblown dust emissions:

First, Table 3.2 on pg. 58 of US EPA (1976) provides an emission factor of 3.5 lb/acre of storage/day for storage piles. Applying this emission factor to a conservative overestimate of mine area, 1200 acres, yields:

3.5 lb/acre/day × 1200 acre × 24% LA × 453.592 g/lb ÷ 86,400 s/day = 5.3 g/s

Second, US EPA (1976, pg. 59) provides an estimate of 428 lb/acre/yr based on wind erosion rates for arid portions of the Great Plains. Applying this emission factor to 1200 acres yields:

428 lb/acre/yr × 1200 acre × 24% LA × 453.592 g/lb ÷ 365 days/yr ÷ 86,400 s/day = 1.8 g/s

Third, US EPA (1976, pg. 68) has an equation to estimate windblown dust from reclaimed and un-reclaimed former mining areas. This equation provides an emission factor (in tons/acre/yr) based on the following formula:

EF = aIKCL'V' = 0.04 × 134 tons/acre/yr × 1 × 0.1 × 1 × 1 = 0.54 tons/acre/yr

a = 0.04 (highest value in table on pg. 69)
I = 134 tons/acre/yr (highest value in table on pg. 69)
K = 1 (both the highest value and the suggested value on pg. 69)
C = 10 × 0.01 = 0.1 (method on pg. 69 and value of 10 from pg. 70)
L' = 1 (both highest value and suggested value on pg. 69)
V' = 1 (both highest value and suggested value on pg. 69)

Applying this emission factor of 0.54 tons/acre/yr yields:

0.54 tons/acre/yr × 1200 acre × 24% LA × 907184.74 g/ton ÷ 365 days/yr ÷ 86,400 s/day = 4.4 g/s

Fourth, Table 11-6 of the Western Governers' Association (2006) Fugitive Dust Handbook provides an emission factor of 0.38 tons/acre/yr from exposed areas. Applying this emission factor yields:

0.54 tons/acre/yr × 1200 acre × 24% LA × 907184.74 g/ton ÷ 365 days/yr ÷ 86,400 s/day = 3.1 g/s

The four results calculated above are in the range 1.8-5.3 g/s, all of which are less than the windblown dust value used here (7.9 g/s), further supporting that the estimate used here for windblown dust is a conservative overestimate of the actual emissions of windblown dust from GMS.

Total GMS-fugitive = 14.0 g/s + 7.9 g/s = 21.9 g/s

AERMOD source parameters needed to model area emission sources are the location of the SW corner of the area, width and length of a rectangular area of emissions, release height, and an initial vertical dimension of the emission plume. The location of the RLS was determined from historical photos of the site and Google Earth imagery (see River Loading Photo; Map of Study Area). The RLS emissions were assumed to be released at approximately train height (4.5 m) during loading with no initial vertical dimension of the plume, and initial horizontal dimensions equal to a square area with sides equal to approximately the

width of a train car (3 m). The input emission rate for area sources in AERMOD is per area, therefore, one must divide the 2.6 g/s by the source area:

RLS emission rate = 2.6 g/s ÷ (3 m × 3 m) = **0.29 g/s-m^2**

The location and horizontal dimensions of GMS-fugitive emissions was determined from historical aerial photography of the site and Google Earth imagery (1963 GMS Aerial Photo; 1992 GMS Aerial Photo; Map of Study Area). Horizontal dimensions of 2000 m by 1300 m was chosen. Emissions were assumed to be released at ground level with no initial vertical dimension of the plume. Because topography is incorporated into the model, assuming ground-level emissions accounts for the GMS emissions being on a mountain-top.

GMS-fugitive emission rate = 21.9 g/s ÷ (2000 m × 1300 m) = **8.42×10^{-6} g/s-m^2**

A summary of the fugitive dust emission rates is provided in Table A2 below.

Table A2: Fugitive Dust Emissions from GMS and RLS

	GMS	RLS	Total
Fugitive dust (excluding windblown)	14.0 g/s	2.6 g/s	16.6 g/s
Windblown dust	7.9 g/s	0 g/s	7.9 g/s
Total	21.9 g/s	2.6 g/s	24.5 g/s

VII. Appendix B: Libby Log Job Emissions Calculations

Worker testimony suggests that typically 6-8 inches of vermiculite was on top of loaded railcars when leaving RLS and 1/8 – 3 inches when arriving at Libby Railyard (Hart 2018). The difference in the amount of vermiculite concentrate at RLS and LR is how much was lost (emitted) during the trip. To conservatively underestimate how much vermiculite is emitted along the route I assume the minimum depth at RLS and maximum depth at LR.

Depth of vermiculite emitted from tops of cars = 6 in – 3 in = 3 in = 0.25 ft

(Assuming midrange values [i.e., 7 in – 1.56 in = 5.44in] would increase the emission estimate by more than 80%.) Vermiculite hopper cars are assumed here to be 55 ft long (see Hopper Car - February 1962). Based on worker testimony I assume 13 railcars loaded and transported per day. To account for areas along the top of the car that have hatches or other types of openings that would not support piles of vermiculite, I estimate the fraction of the hopper car top that has a solid flat surface (49%) from a historical photograph (River Loading Vermiculite Hopper Car). To estimate the volume of material lost, one must know the width of the vermiculite pile on top of the train car. I assumed a strip of 1 ft wide and that the shape of the cross-section is a triangle (cross-section area = ½ × width × height). One can then estimate the volume of vermiculite concentrate lost.

Volume vermiculite lost per day = 13 cars × 55 ft/car × 49% × ½ × 1 ft × 0.25 ft = 44 ft^3.

I assume an approximate density of vermiculite concentrate of 3 g/cc based on Tables 11 and 12 of Atkinson et al. (1982), and the 3.5% respirable LA by weight of vermiculite concentrate (Atkinson et al. 1982, pg. 4). The emission rate of respirable LA dust from the top of the hopper cars is then estimated as follows.

Emission rate = 44 ft^3/day × 28317 cc/ft^3 × 3 g/cc × 3.5% LA ÷ 86400 s/day = 1.5 g/s

For modeling, these emissions are divided equally among ten equally spaced points located along the Libby Log Job route between RLS and the eastern most portion of the railyard (Map of Study Area - Libby Log Job). I use the same AERMOD emission source parameters as RLS (9 m^2 square area; 4.5 m release height with no initial vertical plume dimension).

LLJ emission rate per location = 1.5 g/s ÷ 10 locations ÷ 9 m^2 = **0.017 g/s-m^2**

VIII. Appendix C: Libby Railyard Emissions Calculations

18. **Overview of Libby Railyard Emission Approach**: Trains traveling through the Libby Railyard on the mainline tracks at high speed created turbulent wake that would kick up vermiculite dust in the railyard. Worker testimony consistently describes a local dust-storm that would happen with every passing train when the ground was dry. In order to estimate these dust emissions, I follow an approach outlined in the environmental impact report for a proposed California high-speed train (California High-Speed Rail Authority and Federal Railroad Administration 2012). This approach involves two key steps: (1) estimating the windspeed from the air turbulence caused by passing trains, and (2) using those windspeeds to estimate the amount of dust that would be kicked up by passing trains. These two steps are independent of each other and use generally accepted scientific methods.

19. **Induced Winds from Passing Trains**: Windspeed induced by a passing train is a function of the train speed and the distance from the train. The bluff body shape of the freight trains, like those typically passing on the mainline, will induce higher airflows than aerodynamically shaped trains going the same speed (Soper 2014). Most studies on induced windspeed from passing trains focus on high speed passenger trains, where train velocities can be very high. The California High-Speed Rail Authority and Federal Railroad Administration (2012) ("CHSRA/FRA") uses theoretical equations for induced winds from a high speed train. The airflow around a bluff body, such as a freight train, is more complex than an aerodynamicly shaped passenger train, and is not as easily approximated with a theoretical equation (Soper 2014). As a result, I use measurements of induced windspeed relative to train speed to estimate the induced windspeed from mainline trains (Liao et al. 1999). Figure 2-1 from Liao et al. (1999) shows the relationship between distance from train and the induced windspeed relative to train speed, for a range of measurements. I estimate a lower and upper bound

relative induced windspeed from this figure (see Liao et al., 1999 Figure 2-1 Induced Windspeed) and use the midpoint of these values. Table C1 shows the lower and upper bound relative windspeeds as a function of distance from train. Using the midpoint of the upper and lower bound relative induced windspeed, and an assumed train speed of 55 mph based on worker testimony, one can estimate the induced windspeed from trains passing through the Libby Railyard. For example, the induced windspeed for the third observation in Table C1 (0.06 m from edge of train) would be calculated as:

Induced windspeed = (0.61 + 0.95) ÷ 2 × 55 mph × 0.447 m/s per mph = 19.2 m/s

Table C1. Induced Windspeed and PM Emissions by Distance from Train

Distance from side of train (m)	Lower bound ratio of induced windspeed to train speed[a]	Upper bound ratio of induced windspeed to train speed[a]	Midpoint induced windspeed (m/s) for 55 mph train	Midpoint surface friction velocity (m/s) for 55 mph train	Midpoint erosion potential (g/m^2) for 55 mph train
Underside	1.00	1.00	24.6	1.13	61.3
0.00	1.00	1.00	24.6	0.98	44.0
0.06	0.61	0.95	19.2	0.77	24.3
0.10	0.58	0.92	18.5	0.74	22.0
0.13	0.56	0.90	17.9	0.71	20.3
0.17	0.53	0.87	17.3	0.69	18.5
0.21	0.51	0.85	16.6	0.66	16.7
0.25	0.49	0.82	16.1	0.64	15.3
0.30	0.46	0.80	15.5	0.62	13.8
0.36	0.44	0.77	14.9	0.60	12.4
0.41	0.43	0.74	14.4	0.57	11.2
0.46	0.41	0.72	13.9	0.55	10.1
0.52	0.39	0.70	13.4	0.53	9.0
0.58	0.38	0.68	12.9	0.52	8.1
0.63	0.37	0.66	12.6	0.50	7.4
0.69	0.36	0.63	12.2	0.49	6.6
0.74	0.35	0.61	11.8	0.47	5.9
0.81	0.34	0.59	11.4	0.45	5.2
0.87	0.33	0.57	11.0	0.44	4.5
0.92	0.32	0.55	10.6	0.42	4.0
0.99	0.31	0.53	10.2	0.41	3.3
1.06	0.30	0.50	9.8	0.39	2.8
1.12	0.29	0.49	9.5	0.38	2.4
1.18	0.28	0.47	9.2	0.37	2.0
1.24	0.28	0.45	8.9	0.36	1.6
1.30	0.27	0.44	8.7	0.35	1.3
1.37	0.26	0.42	8.4	0.33	0.9
1.44	0.26	0.41	8.1	0.32	0.7
1.51	0.25	0.40	7.9	0.32	0.4
1.58	0.25	0.39	7.8	0.31	0.2
1.66	0.24	0.38	7.6	0.30	0.1
1.74	0.23	0.37	7.4	0.30	0.0
1.81	0.23	0.37	7.3	0.29	0.0
1.87	0.22	0.36	7.2	0.29	0.0
1.95	0.22	0.36	7.1	0.28	0.0
2.02	0.21	0.36	7.0	0.28	0.0

[a] Estimated from Figure 2-1 in Liao et al. (1999)

20. **Fugitive Dust Emissions from Induced Windspeed**: The CHSRA/FRA approach uses the AP-42 Chapter 13.2.5 Industrial Wind Erosion guidance to estimate fugitive dust emissions from train induced winds (US EPA 2006). In addition to this method being supported by CHSRA/FRA and the EPA (the method is from EPA's emission factor handbook, AP-42), the Western Governors' Association (WGA) also endorses it as the primary methodology for estimating wind erosion from open areas and storage piles, as described in the WGA Fugitive Dust Handbook (2006, pg. 8-2 and pg. 9-2).

    Equations from this guidance provide suspended particle emissions per unit area based on a fluid mechanics parameter called "surface friction velocity" (i.e., the shear stress at the erodible soil surface due to wind). Equation 1 from AP-42 13.2.5 is a common fluid mechanics equation for windspeed vertical profile, and is used to calculate the surface friction velocity from a windspeed above the soil surface.

AP-42 13.2.5 Equation 1:

$$u^* = \frac{0.4 u_{max}}{\ln \frac{z}{z_0}}$$

Parameter	Units	Definition
u^*	m/s	Surface friction velocity
u_{max}	m/s	Maximum windspeed (use induced train windspeed)
z	m	Height above surface for u_{max} windspeed
z_0	m	Surface roughness height

I assume estimated induced windspeeds on either side of the train are for the train half-height (½ × 4.5 m = 2.25 m), and that induced windspeed underneath the train

is equal to windspeed at the edge of the train (assume 1 m above track). I assume a surface friction velocity of 0.01 cm, following CHSRA/FRA (2012). Continuing with the example calculation for the third observation in Table C1 (0.06 m from edge of train), the surface friction velocity would be calculated as:

$$u^* = \frac{(0.4)(19.2\,m/s)}{\ln\left(\frac{2.25\,m}{0.01\,cm\,\times\,0.01\,m/cm}\right)} = 0.77\,m/s$$

Particle emissions owing to wind erosion are given by equations 2 and 3 from AP-42 13.2.5. Together these equations give emissions as a function of the surface friction velocity, a threshold friction velocity needed to entrain dust, and the number of disturbances (US EPA 2006).

AP-42 13.2.5 Equation 2:

$$EF = k\sum_{i=1}^{N} P_i$$

Parameter	**Units**	**Definition**
EF	g/m^2	Emission factor
k	unitless	Particle size multiplier (value of 1 assumes TSP or PM_{30})
N	#	Number of disturbances
P_i	g/m^2	Erosion potential for the i^{th} period between disturbances

AP-42 13.2.5 Equation 3:

$$P = 58(u^* - u_t{}^*)^2 + 25(u^* - u_t{}^*)$$

$$P = 0 \ for \ u^* \leq u_t{}^*$$

Parameter	Units	Definition
P	g/m^2	Erosion potential
u^*	m/s	Surface friction velocity
$u_t{}^*$	m/s	Threshold friction velocity

Threshold friction velocity varies by soil type, with lower values indicating more easily entrained material. The CHSRA/FRA (2012) approach uses a value of 19 cm/s, a minimum value found in literature for arid desert dust, in order to conservatively over-estimate fugitive dust emissions from the proposed high-speed rail for the environmental impact report. I use a value of 30 cm/s (0.3 m/s) for the vermiculite concentrate and dust covering the yard. This a published threshold friction velocity for "strip mines, quarries, and barrow pits" (Gillette and Passi 1988). Based on the dry and lightweight nature of the vermiculite concentrate and LA (workers describe the dust clouds caused by passing trains as comparable to a light powdery snow), the threshold velocity is likely lower than the 30 cm/s employed here; by using this value I conservatively underestimate emissions from passing trains in the railyard. Note that with Equation 3, erosion potential (P) is zero when the surface friction velocity is below the threshold. Again, continuing with the example calculation from Table C1 (0.06 m from edge of train), the erosion potential would be calculated as:

$P = 58 \times (0.77 \text{ m/s} - 0.3 \text{ m/s})^2 + 24 \times (0.77 \text{ m/s} - 0.3 \text{ m/s}) = 24.3 \text{ g/m}^2$

Once one has calculated the erosion potential under the train and for the distance from the edge of the train to the point where the induced surface friction velocity

is below the threshold friction velocity (~1.7 m, as seen in Table C1), the next step is to calculate the erosion potential for a 1 m length of mainline track. To do this I integrate the erosion potential from the edge of the train to a distance 1.7 m away from the train. This was done using the trapezoidal rule for numerical integration. For example, the unit erosion potential for the area on one side of the train, from the edge of the train to 0.06 m can be calculated as:

$$P_{1m,\ 0\text{-}0.06m} = (24.3\ m/s + 44.0\ m/s) \div 2 \times (0.06\ m - 0.00\ m) = 2.05\ g/m$$

Doing this calculation from the edge of the train to 1.7 m and multiplying by two, to account for emissions on both sides of the train, yields a unit erosion potential of 25.3 g/m. One must also account for the erosion potential underneath the train. Assuming the width of a train is 3 m, using the erosion potential underneath the train from Table C1 yields:

$$P_{1m,\ under\ train} = 61.3\ g/m^2 \times 3\ m = 183.9\ g/m$$

The total erosion potential for a 1 m length of track from the induced winds of a train passing at 55 mph is 25.3 g/m + 183.9 g/m = 209.2 g/m.

Using AP-42 13.2.5 Equation 2 one can convert the erosion potential into a particulate matter emission. I use a value of k=1 for total suspended particulates or PM_{30} (particles less than 30 microns in diameter); as with other calculations in this document, the proportion that is respirable LA is 3.5% LA by weight for vermiculite concentrate, based on Atkinson et al. (1982). The other key parameter for Equation 2 is the frequency of disturbances. A disturbance restores the erosion potential of the surface, and is defined as any action that exposes fresh material, including any time that new material is added to the exposed area or whenever the surface is overturned (US EPA 2006; Watson et al. 1996). When surfaces are continually disturbed they may become what such models refer to as “unlimited

reservoirs that emit dust whenever winds exceed threshold suspension velocities" (Watson et al. 1996). I assume the railyard is such a reservoir owing to (1) the constant activities in the railyard, including the coupling and uncoupling of railcars that released clouds of vermiculite dust, the leak from rail cars, and frequent disturbances to piles; (2) the dry and lightweight nature of the vermiculite concentrate; and, (3) clear, consistent testimony from railyard workers that every passing mainline train created substantial clouds of dust. Therefore, calculations here are based on every passing train during dry weather conditions entraining dust.

I assume 20 trains per day, using the low end of the 20-30 trains from worker testimony, to conservatively underestimate emissions. I also assume that the area along the mainline containing exposed vermiculite material available to be entrained by passing trains covers 550 m of mainline track, adjacent to the area flagged with visible vermiculite during 2001 sampling. (See grey shaded area in Map of Flagged Vermiculite in Libby Railyard; Map of Study Area – Libby Railyard.) Finally, I adjust emissions to exclude days with precipitation, using a value of 120 days with at least 0.01 inches of precipitation from Figure 4-4 of (Cowherd et al. 1985). Using these values, the emission rate can be calculated as:

Per train emission = 209.2 g/m × 550 m × 3.5% LA = 4027 g respirable LA

Emission rate = 4027 g/train × 20 trains/d × (365–120) d/y = 19,732,300 g/y = 0.63 g/s

I model the fugitive dust from passing mainline trains as a line source, with a length equal to the 550 m section adjacent to flagged vermiculite, and assume that the initial plume dimensions and release height are approximated using source parameter guidelines for modeling fugitive dust emissions on haul roads (US EPA

2011). These guidelines provide suggested best practices for characterizing the initial dimensions and release height of the emissions plume, rather than the emissions themselves. The Haul Road Guidelines for modeling as a line source are as follows:

- Initial emission width = 6 m + vehicle width = 6 m + 3 m = 9 m
- Plume height = 1.7 × vehicle height = 1.7 × 4.5 m = 7.65 m
- Release height = 0.5 × plume height = 0.5 × 7.65 m = 3.83 m
- Initial vertical dimension = plume height ÷ 2.15 = 7.65 m ÷ 2.15 = 3.56 m

LR emission rate = 0.63 g/s ÷ (9 m × 550 m) = 1.26×10^{-4} g/s-m^2

IX. Appendix D: Summary of AERMOD Model Inputs

A summary of the AERMOD input parameters for the five emission sources are provided below. Emissions are input as points (e.g., stack emissions), areas (i.e., emissions distributed over a specified area), or lines (i.e., a special type of area emission). As is common practice, area sources are represented as rectangles with horizontal dimensions over which emissions occur (i.e., Xinit, Yinit). The location of area source rectangles is specified by the southwest corner and an orientation angle (no rotation was necessary for the three area sources here). An initial vertical dimension of the source plume (Szinit) may also be specified for area and line sources. This is typically done when emissions may be turbulently mixed near the source (US EPA 2018).

W.R. Grace Activities:

GMS: Dry Mill Stack

Source type: point

Stack height: 13 m

Stack diameter: 0.5 m

Exit velocity: 33 m/s

Exit temp: 298 K

Location: 617012.07 E, 5366222.53 N

Emission rate: 31.9 g/s (from 1975 onward, emission rate is 0 g/s)

GMS: Fugitive Dust Area

Source type: area

Location of SW corner of area: 616682 E, 5365090 N

Release height: 0 m

Xinit: 2000 m

Yinit: 1300 m

Szinit: 0 m

Angle: 0

Emission rate: 8.42×10^{-6} g/s-m^2 (from 1991 onward, emission rate is 0 g/s-m^2)

RLS

Source type: area

Location of SW corner of area: 613872.74 E, 5363154.75 N

Release height: 4.5 m

Xinit: 3 m

Yinit: 3 m

Szinit: 0 m

Angle: 0

Emission rate: 0.29 g/s-m^2 (from 1994 onward, emission rate is 0 g/s-m^2)

BNSF Activities:

Log Job (LJ) locations 1-10

Source type: area (specifically, ten area sources equally spaced along the railroad tracks between RLS and LR).

Location of SW corner of area:

LJ1: 613349.15 E, 5363531.29 N

LJ2: 612687.49 E, 5363560.82 N

LJ3: 612051.45 E, 5363364.99 N

LJ4: 611418.37 E, 5363163.20 N

LJ5: 610784.56 E, 5362967.77 N

LJ6: 610324.44 E, 5362490.35 N

LJ7: 609908.91 E, 5361970.88 N

LJ8: 609491.88 E, 5361451.56 N

LJ9: 609066.02 E, 5360937.32 N

LJ10: 608449.67 E, 5360792.52 N

Release height: 4.5 m

Xinit: 3 m

Yinit: 3 m

Szinit: 0 m

Angle: 0

Emission rate: 0.017 g/s-m^2 (for each of the 10 locations; from 1994 onward, emission rate is 0 g/s-m^2)

Railyard

Source type: line

Line start location: 607241.86 E, 5361304.93 N

Line end location: 607739 E, 5361082 N

Width: 9m

Release height: 3.83 m

Szinit: 3.56 m

Emission rate: 1.26×10^{-4} g/s-m^2 (from 1994 onward, emission rate is 0 g/s-m^2)

X. Appendix E: Calculations of Lifetime Fiber Concentration

Respirable LA concentrations from each of the five sources were estimated by AERMOD (in $\mu g/m^3$ of respirable LA) for the 24 residential locations throughout Libby at 5-year intervals from 1960-1990. In this manner, a total of 9 model-year configurations were considered: 1960, 1965, 1970, 1975 with GMS-stack, 1975 without GMS-stack, 1980, 1985, 1990 with GMS-area, 1990 without GMS-area. A residential history for each of the three Plaintiffs was constructed based on their reported home locations and dates of residence (Plaintiff Fact Sheets; Plaintiff Residential History and Model Assignment Timeline). For each of the five sources, I estimated lifetime (70-year) average concentrations for each Plaintiff, based on year-by-year concentration estimates at residential locations.

The year-by-year estimates employ the following approach:

(1) If a Plaintiff did not live in Libby in a given year, he/she is assigned a concentration of zero for that year.

(2) For years after 1993, concentrations equal zero because vermiculite was no longer being mined or shipped.

(3) If a Plaintiff lived at one residence in Libby for a given year, their exposure for that year is based on that residential location and the nearest-year model run (e.g., for exposures in 1964, the nearest year model run is 1965).

(4) If a Plaintiff lived at multiple residences for a given year, we take the average concentration at those locations for that year. For example, if a person lived at three locations in 1964, we would use the average concentration at those three locations (and based on the nearest model year: 1965).

The total time lived in Libby is 38 years for Barnes, 32 years for Braaten, and 12 years for Flores. Thus, my approach assumes that none of the three Plaintiffs were exposed to ambient LA from the five sources considered here for an entire 70-year lifetime. If we

reported concentrations that were average over only the years when people were exposed, rather than averaging over 70 years, results would be ~2-6× higher (specifically, 70/38 = 1.8× higher for Barnes, 70/32 = 2.2× higher for Braaten, and 70/12 = 5.8× higher for Flores); those higher values, which are not reported here, would represent each Plaintiffs' average exposure while she/he lived in Libby during BNSF and W.R. Grace operations.

Plaintiff lifetime exposure concentrations were converted from LA mass to LA fiber count using the conversion factor of 1 $\mu g/m^3$ = 0.033 fibers/cc = 33,000 fibers/m^3, given by the Agency for Toxic Substances & Disease Registry (ATSDR 2001). Lifetime (70-year) exposure concentrations for the three Plaintiffs are reported in Section 15 of the main report (see Table 2).

Table E1: Annual Respirable LA Concentration (µg/m^3) – Tracie Barnes

Year	GMS-Stack LA Exposure (µg/m^3)	GMS-Fugitive LA Exposure (µg/m^3)	River Loading Site LA Exposure (µg/m^3)	Libby Log Job LA Exposure (µg/m^3)	Libby Railyard LA Exposure (µg/m^3)	Basis	
						Model-year run	Location
Before 1955	0.000	0.000	0.000	0.000	0.000	NA	NA
1955	0.079	0.128	0.003	0.103	2.693	1960	1
1956	0.079	0.128	0.003	0.103	2.693	1960	1
1957	0.079	0.128	0.003	0.103	2.693	1960	1
1958	0.079	0.128	0.003	0.103	2.693	1960	1
1959	0.079	0.128	0.003	0.103	2.693	1960	1
1960	0.079	0.128	0.003	0.103	2.693	1960	1
1961	0.079	0.128	0.003	0.103	2.693	1960	1
1962	0.079	0.128	0.003	0.103	2.693	1960	1
1963	0.793	1.642	0.670	1.188	3.154	1965	1
1964	0.793	1.642	0.670	1.188	3.154	1965	1
1965	0.793	1.642	0.670	1.188	3.154	1965	1
1966	0.793	1.642	0.670	1.188	3.154	1965	1
1967	0.793	1.642	0.670	1.188	3.154	1965	1
1968	0.778	1.160	0.202	1.048	3.880	1970	1
1969	0.778	1.160	0.202	1.048	3.880	1970	1
1970	0.778	1.160	0.202	1.048	3.880	1970	1
1971	0.778	1.160	0.202	1.048	3.880	1970	1
1972	0.778	1.160	0.202	1.048	3.880	1970	1
1973	0.677	0.947	0.248	0.766	3.176		1
	1.427	1.603	0.230	0.172	0.064	1975 w/ Dry Mill	2
	1.052	1.275	0.239	0.469	1.620		avg. of 1 & 2

1974	1.427	1.603	0.230	0.172	0.064	1975 w/ Dry Mill	2
1975	0.000	1.603	0.230	0.172	0.064	1975 w/o Dry Mill	2
1976	0.000	1.603	0.230	0.172	0.064	1975 w/o Dry Mill	2
1977	0.000	1.603	0.230	0.172	0.064	1975 w/o Dry Mill	2
1978	0.000	1.136	0.179	0.162	0.072	1980	2
	0.000	1.136	0.179	0.162	0.072		2
1979	0.000	0.313	0.045	0.059	0.090	1980	3
	0.000	0.725	0.112	0.111	0.081		avg. of 2 & 3
1980	0.000	0.313	0.045	0.059	0.090	1980	3
1981	0.000	0.313	0.045	0.059	0.090	1980	3
1982	0.000	0.313	0.045	0.059	0.090	1980	3
	0.000	0.621	0.219	0.313	0.740		4
1983	0.000	0.726	0.211	0.450	2.487	1985	5
	0.000	0.673	0.215	0.382	1.614		avg. of 4 & 5
	0.000	0.621	0.219	0.313	0.740		4
1984	0.000	0.726	0.211	0.450	2.487	1985	5
	0.000	0.673	0.215	0.382	1.614		avg. of 4 & 5
	0.000	0.621	0.219	0.313	0.740		4
1985	0.000	0.726	0.211	0.450	2.487	1985	5
	0.000	0.673	0.215	0.382	1.614		avg. of 4 & 5
1986	0.000	0.000	0.000	0.000	0.000	NA	NA
1987	0.000	0.858	0.270	0.799	4.399	1985	6
1988	0.000	0.789	0.205	0.782	4.489	1990 w/ GMS	6
1989	0.000	0.789	0.205	0.782	4.489	1990 w/ GMS	6
1990	0.000	0.789	0.205	0.782	4.489	1990 w/ GMS	6
1991	0.000	0.000	0.205	0.782	4.489	1990 w/o GMS	6

1992	0.000	0.000	0.205	0.782	4.489	1990 w/o GMS	6
1993	0.000	0.000	0.205	0.782	4.489	1990 w/o GMS	6
After 1993	0.000	0.000	0.000	0.000	0.000	NA	NA

Table E2: Annual Respirable LA Concentration (µg/m^3) – Rhonda Braaten

Year	GMS-Stack LA Exposure (µg/m^3)	GMS-Fugitive LA Exposure (µg/m^3)	River Loading Site LA Exposure (µg/m^3)	Libby Log Job LA Exposure (µg/m^3)	Libby Railyard LA Exposure (µg/m^3)	Basis	
						Model-year run	Location
Before 1960	0.000	0.000	0.000	0.000	0.000	NA	NA
1960	0.076	0.181	0.006	0.070	2.166	1960	8
1961	0.076	0.181	0.006	0.070	2.166	1960	8
1962	0.076	0.181	0.006	0.070	2.166	1960	8
1963	0.712	1.548	0.683	0.899	2.508	1965	8
1964	0.712	1.548	0.683	0.899	2.508	1965	8
1965	0.712	1.548	0.683	0.899	2.508	1965	8
	0.749	0.715	0.097	0.056	0.027		9
	0.730	1.132	0.390	0.477	1.268		avg. of 8 & 9
1966	0.749	0.715	0.097	0.056	0.027	1965	9
1967	0.749	0.715	0.097	0.056	0.027	1965	9
1968	2.119	1.965	0.113	0.044	0.018	1970	9
1969	2.119	1.965	0.113	0.044	0.018	1970	9
1970	2.119	1.965	0.113	0.044	0.018	1970	9
1971	2.119	1.965	0.113	0.044	0.018	1970	9
1972	2.119	1.965	0.113	0.044	0.018	1970	9
1973	1.243	1.252	0.057	0.048	0.011	1975 w/ Dry Mill	9
1974	1.243	1.252	0.057	0.048	0.011	1975 w/ Dry Mill	9
1975	0.000	1.252	0.057	0.048	0.011	1975 w/o Dry Mill	9
1976	0.000	1.252	0.057	0.048	0.011	1975 w/o Dry Mill	9
1977	0.000	1.252	0.057	0.048	0.011	1975 w/o Dry Mill	9
1978	0.000	0.898	0.074	0.049	0.019	1980	9

	0.000	0.149	0.066	0.059	0.045		10
	0.000	0.524	0.070	0.054	0.032		avg. of 9 & 10
1979	0.000	0.149	0.066	0.059	0.045	1980	10
	0.000	0.192	0.074	0.070	0.061		13
	0.000	0.170	0.070	0.065	0.053		avg. of 10 & 13
1980	0.000	0.192	0.074	0.070	0.061	1980	13
1981-1982	0.000	0.000	0.000	0.000	0.000	NA	NA
1983	0.000	0.953	0.076	0.049	0.016	1985	9
1984	0.000	0.953	0.076	0.049	0.016	1985	9
	0.000	0.604	0.282	0.404	1.612		11
	0.000	0.875	0.041	0.036	0.015		12
	0.000	0.811	0.133	0.163	0.548		avg. of 9, 11 & 12
1985	0.000	0.604	0.282	0.404	1.612	1985	11
	0.000	0.797	0.193	0.386	1.390		14
	0.000	0.813	0.252	0.589	0.483		15
	0.000	0.738	0.242	0.460	1.162		avg. of 11, 14 & 15
1986	0.000	0.813	0.252	0.589	0.483	1985	15
	0.000	1.188	0.174	0.159	0.055		16
	0.000	1.001	0.213	0.374	0.269		avg. of 15 & 16
1987	0.000	1.188	0.174	0.159	0.055	1985	16
	0.000	0.844	0.391	0.459	0.274		17
	0.000	0.764	0.190	0.394	1.424		18
	0.000	0.932	0.252	0.337	0.585		avg. of 16, 17 & 18
1988	0.000	0.616	0.152	0.379	1.668	1990 w/ GMS	18
1989	0.000	0.616	0.152	0.379	1.668	1990 w/ GMS	18
	0.000	0.936	0.125	0.126	0.058		19

	0.000	0.776	0.139	0.252	0.863		avg. of 18 & 19
1990	0.000	0.936	0.125	0.126	0.058	1990 w/ GMS	19
1991	0.000	0.000	0.125	0.126	0.058	1990 w/o GMS	19
1992	0.000	0.000	0.190	0.149	0.047	1990 w/o GMS	20
	0.000	0.000	0.190	0.149	0.047		20
1993	0.000	0.000	0.140	0.140	0.162	1990 w/o GMS	21
	0.000	0.000	0.165	0.144	0.104		avg. of 20 & 21
After 1993	0.000	0.000	0.000	0.000	0.000	NA	NA

Table E3: Annual Respirable LA Concentration (µg/m^3) – Geri Flores

Year	GMS-Stack LA Exposure (µg/m^3)	GMS-Fugitive LA Exposure (µg/m^3)	River Loading Site LA Exposure (µg/m^3)	Libby Log Job LA Exposure (µg/m^3)	Libby Railyard LA Exposure (µg/m^3)	Basis	
						Model-year run	Location
Before 1979	0.000	0.000	0.000	0.000	0.000	NA	NA
	0.000	1.109	0.494	3.921	0.134		22
1979	0.000	0.164	0.015	0.022	0.027	1980	23
	0.000	0.636	0.255	1.971	0.080		avg. of 22 & 23
1980	0.000	0.164	0.015	0.022	0.027	1980	23
1981	0.000	0.164	0.015	0.022	0.027	1980	23
1982	0.000	0.164	0.015	0.022	0.027	1980	23
1983	0.000	0.169	0.068	0.057	0.041	1985	23
1984	0.000	0.169	0.068	0.057	0.041	1985	23
1985	0.000	0.169	0.068	0.057	0.041	1985	23
1986	0.000	0.169	0.068	0.057	0.041	1985	23
	0.000	0.169	0.068	0.057	0.041		23
1987	0.000	0.179	0.066	0.060	0.055	1985	24
	0.000	0.174	0.067	0.058	0.048		avg. of 23 & 24
1988	0.000	0.339	0.064	0.059	0.032	1990 w/ GMS	24
1989	0.000	0.339	0.064	0.059	0.032	1990 w/ GMS	24
1990	0.000	0.339	0.064	0.059	0.032	1990 w/ GMS	24
After 1990	0.000	0.000	0.000	0.000	0.000	NA	NA

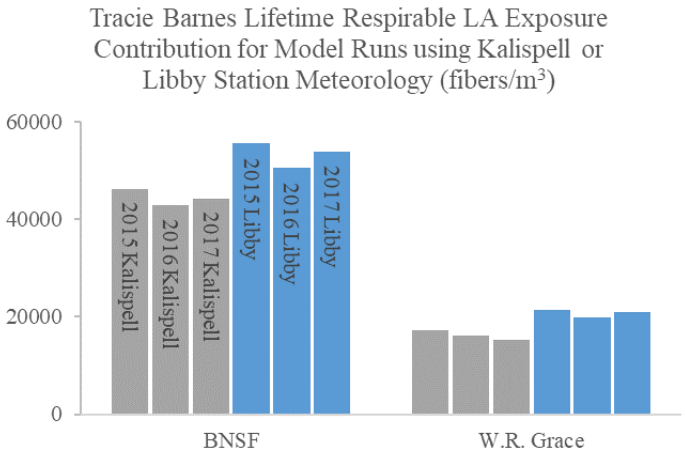
XI. Appendix F: Libby Meteorology Sensitivity Analysis

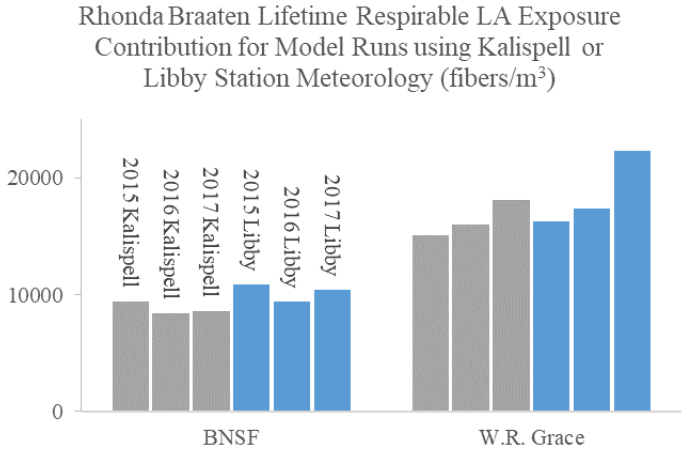
For surface air meteorology, we used available data for the relevant years (1960 – 1990) from the National Weather Service (NWS) database (https://www.ncdc.noaa.gov). The NWS station is located in Kalispell. There also are two non-NWS monitors located in the study area; these monitors are part of the Remote Automated Weather Station (RAWS) network (https://raws.dri.edu/). One monitor is located on top of Zonolite Mountain; the other is located ~1 mile northeast of downtown Libby (see map in Libby and Zonolite Mountain RAWS Station). The Zonolite Mountain monitor is not suitable for modeling conducted here, owing to its high elevation compared to the Plaintiffs' home locations in Libby. The Libby monitor is located in a small clearing surrounded by forested area, with the windspeed and wind direction sensors positioned below the tree line; therefore, despite being listed in the RAWS database, it does not meet the RAWS siting recommendations for wind sensors to be placed at least 20 feet above nearby obstructions (National Wildfire Coordinating Group 2005) (see zoom-in map and photo in Libby and Zonolite Mountain RAWS Station).

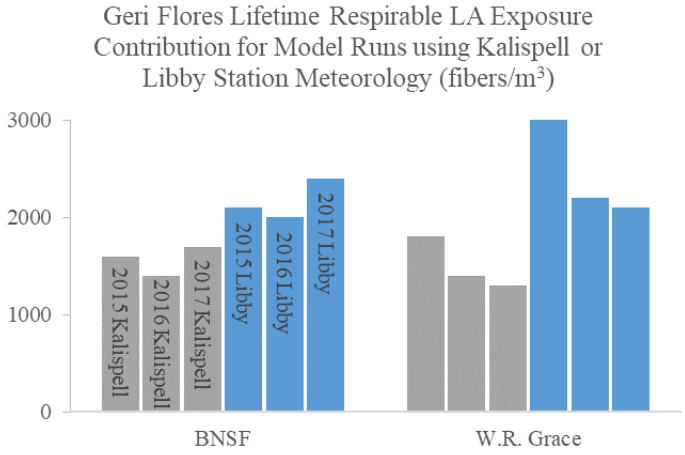
Neither of the two non-NWS monitors have data for the years that are relevant to the Plaintiffs' exposures.

For these reasons, I believe at this time that the two non-NWS monitors are less suitable for modeling than the NWS station in Kalispell. However, to test the impact of meteorology monitor location on the results, I also ran models using the non-NWS monitor in Libby.

Respirable LA concentrations from each of the five sources were estimated by AERMOD for the three most recent years (2015-2017) using meteorological data from either the Kalispell NWS station or the Libby RAWS station. Specifically, in each of the six sensitivity analyses, I simulate year-to-year variability in emissions (e.g., LA concentration from GMS-Stack is zero from 1975 onward), but use a single year's meteorology (six simulations: Kalispell 2015, 2016, or 2017, or Libby 2015, 2016, or 2017). Tables F1-F5 summarize modeled LA concentrations from these six runs for the five sources. The 70-year lifetime respirable LA exposures for each of the six sensitivity analyses is shown for each of the Plaintiffs below.


Tracie Barnes Lifetime Respirable LA Exposure Contribution for Model Runs using Kalispell or Libby Station Meteorology (fibers/m³)
60000
40000
20000
0
2015 Kalispell
2016 Kalispell
2017 Kalispell
2015 Libby
2016 Libby
2017 Libby
BNSF
W.R. Grace


Rhonda Braaten Lifetime Respirable LA Exposure Contribution for Model Runs using Kalispell or Libby Station Meteorology (fibers/m³)
20000
10000
0
2015 Kalispell
2016 Kalispell
2017 Kalispell
2015 Libby
2016 Libby
2017 Libby
BNSF
W.R. Grace


Geri Flores Lifetime Respirable LA Exposure Contribution for Model Runs using Kalispell or Libby Station Meteorology (fibers/m³)
3000
2000
1000
0
2015 Kalispell
2016 Kalispell
2017 Kalispell
2015 Libby
2016 Libby
2017 Libby
BNSF
W.R. Grace

Modeled lifetime LA concentrations are slightly higher using the Libby station than using the Kalispell station (see summary figures above). This finding suggests that the calculated impact of BNSF emissions would be higher if using meteorological data from Libby rather than from Kalispell. This outcome is consistent with our aim to conservatively underestimate impacts from BNSF. As mentioned above, meteorological data for Libby are unavailable for the years being modeled and the Libby station location does not follow RAWS siting recommendations.

The relative contributions to lifetime LA exposure from BNSF (i.e., relative to that from W.R. Grace) is relatively similar when using meteorological data from Libby as from Kalispell (see figure below). This finding suggests that my core conclusion about relative contributions (BNSF versus W.R. Grace) is not strongly sensitive to the choice of weather station (Kalispell versus Libby) used in AERMOD.

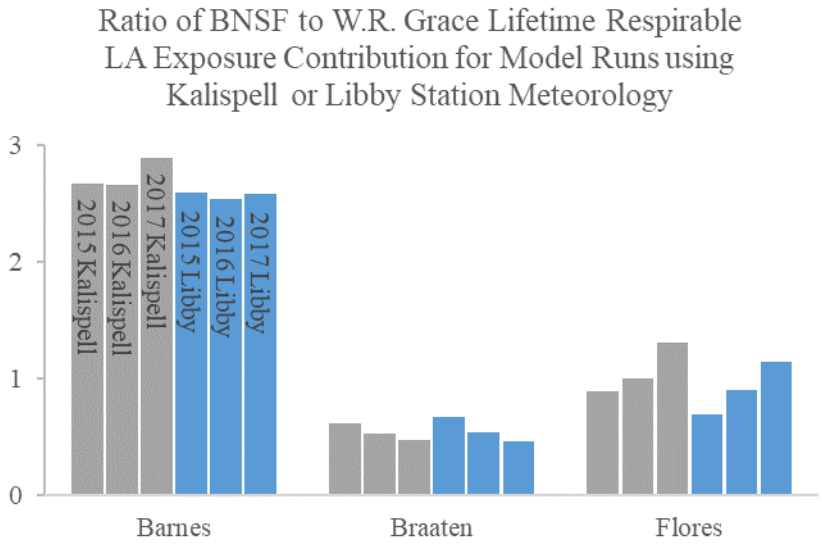


Table F1: Respirable LA Concentration (µg/m^3) from Grace Mine Site Dry Mill by Sensitivity Model Run and Location

	Location ID	2015 Kalispell Station	2015 Libby Station	2016 Kalispell Station	2016 Libby Station	2017 Kalispell Station	2017 Libby Station
Barnes	1	0.544	0.572	0.414	0.543	0.396	0.640
	2	1.228	1.233	1.191	1.136	1.301	1.334
	3	0.397	0.543	0.311	0.411	0.353	0.452
	4	0.445	0.499	0.378	0.487	0.335	0.549
	5	0.441	0.582	0.471	0.518	0.385	0.544
	6	0.480	0.620	0.522	0.569	0.420	0.623
	7	3.207	3.036	3.999	3.473	3.174	3.483
Braaten	8	0.595	0.601	0.438	0.579	0.445	0.710
	9	0.901	0.846	1.048	0.993	1.052	1.215
	10	0.354	0.452	0.322	0.530	0.258	0.331
	11	0.417	0.497	0.438	0.513	0.337	0.556
	12	0.970	1.002	0.974	0.972	1.105	1.165
	13	0.393	0.498	0.357	0.552	0.284	0.367
	14	0.412	0.588	0.403	0.455	0.396	0.520
	15	0.469	0.583	0.535	0.611	0.590	0.724
	16	1.134	1.196	1.163	1.173	1.317	1.379
	17	0.792	0.812	0.570	0.525	0.694	0.805
	18	0.417	0.582	0.423	0.471	0.389	0.516
	19	1.147	1.204	1.173	1.177	1.324	1.384
	20	1.249	1.230	1.173	1.090	1.271	1.286
	21	0.393	0.530	0.315	0.418	0.343	0.436
Flores	22	0.662	1.028	0.725	0.812	0.679	1.131
	23	0.257	0.444	0.170	0.301	0.192	0.291
	24	0.286	0.446	0.213	0.341	0.176	0.288

Table F2: Respirable LA Concentration (µg/m^3) from Grace Mine Site Fugitive Dust by Sensitivity Model Run and Location

	Location ID	2015 Kalispell Station	2015 Libby Station	2016 Kalispell Station	2016 Libby Station	2017 Kalispell Station	2017 Libby Station
Barnes	1	0.444	0.611	0.435	0.554	0.266	0.428
	2	1.249	1.425	1.221	1.347	1.290	1.491
	3	0.284	0.394	0.263	0.454	0.265	0.339
	4	0.403	0.568	0.427	0.525	0.250	0.384
	5	0.341	0.523	0.391	0.465	0.554	0.732
	6	0.420	0.637	0.479	0.574	0.633	0.836
	7	4.845	5.282	4.928	5.227	5.577	6.599
Braaten	8	0.442	0.590	0.395	0.524	0.264	0.442
	9	0.605	0.645	0.744	0.773	1.041	1.255
	10	0.268	0.407	0.146	0.355	0.187	0.253
	11	0.377	0.559	0.440	0.513	0.339	0.466
	12	0.876	1.013	0.855	0.956	0.924	1.069
	13	0.293	0.440	0.180	0.413	0.209	0.278
	14	0.342	0.510	0.376	0.490	0.584	0.768
	15	0.526	0.623	0.412	0.534	0.746	0.985
	16	1.151	1.306	1.091	1.186	1.071	1.223
	17	0.435	0.544	0.459	0.537	0.794	1.005
	18	0.333	0.502	0.370	0.465	0.577	0.760
	19	1.166	1.324	1.109	1.207	1.096	1.252
	20	1.272	1.450	1.244	1.377	1.359	1.578
	21	0.274	0.380	0.250	0.441	0.239	0.304
Flores	22	1.196	1.751	1.050	1.636	1.327	1.755
	23	0.209	0.347	0.134	0.233	0.130	0.222
	24	0.280	0.429	0.230	0.331	0.107	0.227

Table F3: Respirable LA Concentration (μg/m^3) from River Loading Site by Sensitivity Model Run and Location

	Location ID	2015 Kalispell Station	2015 Libby Station	2016 Kalispell Station	2016 Libby Station	2017 Kalispell Station	2017 Libby Station
Barnes	1	0.131	0.198	0.166	0.197	0.159	0.210
	2	0.101	0.098	0.152	0.154	0.196	0.215
	3	0.145	0.200	0.030	0.077	0.071	0.111
	4	0.083	0.134	0.114	0.123	0.161	0.218
	5	0.135	0.199	0.084	0.189	0.091	0.134
	6	0.209	0.303	0.091	0.225	0.129	0.192
	7	0.301	0.287	0.320	0.200	0.193	0.153
Braaten	8	0.153	0.219	0.179	0.213	0.121	0.173
	9	0.102	0.083	0.114	0.096	0.096	0.090
	10	0.090	0.143	0.049	0.091	0.082	0.125
	11	0.119	0.181	0.118	0.170	0.200	0.259
	12	0.044	0.038	0.046	0.042	0.038	0.033
	13	0.098	0.161	0.056	0.104	0.091	0.140
	14	0.173	0.252	0.055	0.143	0.104	0.154
	15	0.135	0.179	0.147	0.179	0.281	0.361
	16	0.145	0.134	0.172	0.162	0.179	0.168
	17	0.192	0.212	0.176	0.142	0.269	0.326
	18	0.151	0.223	0.060	0.154	0.095	0.140
	19	0.138	0.125	0.166	0.159	0.188	0.177
	20	0.096	0.103	0.173	0.168	0.217	0.246
	21	0.137	0.192	0.028	0.073	0.067	0.107
Flores	22	0.922	1.585	0.555	0.885	0.740	1.036
	23	0.027	0.048	0.024	0.036	0.022	0.057
	24	0.017	0.036	0.034	0.049	0.021	0.050

Table F4: Respirable LA Concentration (µg/m^3) from Libby Log Job by Sensitivity Model Run and Location

	Location ID	2015 Kalispell Station	2015 Libby Station	2016 Kalispell Station	2016 Libby Station	2017 Kalispell Station	2017 Libby Station
Barnes	1	0.408	0.523	0.348	0.450	0.384	0.556
	2	0.149	0.135	0.159	0.145	0.141	0.132
	3	0.116	0.178	0.058	0.115	0.080	0.137
	4	0.199	0.257	0.160	0.213	0.174	0.253
	5	0.261	0.414	0.215	0.322	0.265	0.407
	6	0.628	0.861	0.743	0.926	0.793	1.005
	7	0.176	0.161	0.133	0.126	0.155	0.131
Braaten	8	0.419	0.493	0.324	0.421	0.464	0.642
	9	0.045	0.038	0.051	0.043	0.043	0.036
	10	0.103	0.158	0.053	0.093	0.071	0.120
	11	0.304	0.428	0.183	0.294	0.207	0.317
	12	0.044	0.035	0.059	0.047	0.042	0.036
	13	0.132	0.205	0.064	0.114	0.091	0.147
	14	0.252	0.396	0.181	0.295	0.228	0.340
	15	0.490	0.489	0.534	0.534	0.542	0.606
	16	0.137	0.123	0.153	0.138	0.132	0.124
	17	0.420	0.417	0.427	0.409	0.381	0.399
	18	0.231	0.367	0.170	0.272	0.232	0.349
	19	0.138	0.124	0.155	0.137	0.133	0.123
	20	0.153	0.141	0.163	0.149	0.144	0.133
	21	0.105	0.161	0.050	0.103	0.071	0.123
Flores	22	5.396	7.091	4.656	6.305	5.346	7.550
	23	0.028	0.049	0.026	0.040	0.034	0.053
	24	0.029	0.047	0.028	0.042	0.036	0.052

Table F5: Respirable LA Concentration (µg/m^3) from Libby Railyard by Sensitivity Model Run and Location

	Location ID	2015 Kalispell Station	2015 Libby Station	2016 Kalispell Station	2016 Libby Station	2017 Kalispell Station	2017 Libby Station
Barnes	1	2.604	2.749	2.479	2.549	2.314	2.537
	2	0.033	0.035	0.029	0.024	0.023	0.024
	3	0.135	0.211	0.092	0.146	0.111	0.189
	4	0.659	0.637	0.658	0.623	0.723	0.740
	5	2.089	3.181	1.358	2.322	1.617	2.532
	6	4.465	6.079	4.022	5.459	4.660	6.042
	7	0.036	0.045	0.018	0.029	0.021	0.023
Braaten	8	1.971	2.079	1.861	1.909	1.725	1.862
	9	0.009	0.007	0.009	0.006	0.012	0.012
	10	0.055	0.097	0.062	0.089	0.055	0.102
	11	1.279	1.378	1.132	1.196	1.351	1.587
	12	0.015	0.011	0.019	0.014	0.014	0.010
	13	0.133	0.225	0.075	0.121	0.106	0.144
	14	0.844	1.493	0.652	0.995	0.728	1.168
	15	0.263	0.283	0.303	0.314	0.389	0.373
	16	0.032	0.028	0.034	0.027	0.043	0.039
	17	0.147	0.149	0.181	0.179	0.248	0.228
	18	1.003	1.651	0.755	1.188	0.764	1.441
	19	0.029	0.028	0.033	0.025	0.041	0.038
	20	0.031	0.035	0.027	0.022	0.019	0.020
	21	0.115	0.179	0.089	0.134	0.094	0.159
Flores	22	0.237	0.337	0.195	0.270	0.242	0.321
	23	0.017	0.021	0.031	0.043	0.040	0.048
	24	0.023	0.028	0.017	0.024	0.029	0.032

XII. Appendix G: References

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XIII. Appendix H: Marshall CV

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Current position

John R. Kiely Professor, Department of Civil and Environmental Engineering, University of Washington (UW).
February 2016–present.

Research area: **Exposure to air pollution**, especially (1) mechanistic and empirical modeling of air pollution; (2) measuring and modeling air pollution exposures in developing countries; (3) environmental justice.

Citation impact (as of October 2018), by database:

Research ID / Web of Science (based on the 30 articles they index): 1661 citations; h-index: 23; average citations per article: 55.
Scopus / Elsevier: 3227 citations; h-index: 35.
Google Scholar: 5168 citations; h-index: 41.

Associate Editor, *Development Engineering* (2015–current).
Associate Editor, *Environmental Health Perspectives* (2016–current).

Education

Post-doctoral Fellow	2005–2006	**University of British Columbia**, School of Environmental Health Mentor: Professor Michael Brauer
Ph.D.	2005	**University of California Berkeley**, Energy and Resources Group Dissertation: "Inhalation of Vehicle Emissions in Urban Environments" Mentor: Professor William Nazaroff
M.S.	2002	**University of California Berkeley**, Energy and Resources Group
B.S.E.	1996	**Princeton University**, Chemical Engineering, with High Honors

Honors

- One article (Apte et al., 2017) declared "Best Environmental Technology Paper of 2017" from *Environmental Science & Technology*
- Charles E. Bowers Teaching Award, UMN, 2014
- C. Eugene Allen Award for Innovative International Initiatives (awarded to the Acara program), UMN, 2014
- Joan M. Daisey Outstanding Young Scientist Award, International Society of Exposure Science, 2013

- McKnight Land-Grant Professorship, UMN, 2009–2011
- Young Engineer of the Year, American Society of Civil Engineers, Minnesota Section, 2009
- One article (Ji et al., 2012) on the "most read" list from *Environmental Science & Technology*
- One article (Marshall and Toffel, 2005) on the "most downloaded" list from *Environmental Science & Technology*
- Two articles (Marshall, McKone, et al., 2005; Marshall, Nethery, et al., 2008) on the "most downloaded" list from *Atmospheric Environment*
- Post-doctoral research fellowships from the School of Environmental Health and from the Bridge Program in engineering, policy, and health, UBC, 2005–2006
- Outstanding Graduate Student Instructor Award, U.C. Berkeley, 2005. Award states: "Each year, fewer than 10% of GSIs earn this distinguished award"
- Fellowship, U.C. Toxic Substances Research & Teaching Program, 2003–2005
- Dissertation Fellowship, U.C. Transportation Center, 2003–2004
- Graduate Research Fellowship, National Science Foundation (NSF), 2000–2003

Articles submitted for peer review

Articles are numbered in chronological order, and listed in reverse chronological order. To help clarify my role in multi-author papers, the right column indicates my contributions: lead, major, or minor. "Lead" indicates my being first or corresponding author, reflecting my role as leader or principal investigator. "Major" indicates a large contribution, equivalent to a co-principal investigator or senior advisor; my contribution is less than the principal investigator but is second or third in importance. "Minor" denotes all other articles; my contribution is not among the top three investigators for that article.

J Hill, A Goodkind, C Tessum, S Thakrar, D Tilman, S Polasky, T Smith, N Hunt, K Mullins, M Clark, J Marshall. Air-quality Related Health Damages from Maize Production in the United States. Submitted.	Minor
SY Kim, C Olives, N Fann, CA Pope III, JD Marshall, L Sheppard. Estimation of long-term area-average PM2.5 concentrations and new insights into its association with life-expectancy. Submitted.	Minor
D Paolella, C Tessum, P Adams, J Apte, S Chambliss, J Hill, N Muller, J Marshall. Effect of Model Spatial Resolution on Estimates of Fine Particulate Matter Exposure and Exposure Disparities in the United States. Submitted.	Lead
V Sreekanth, C Tonne, M Salmon, S Arulselvan, J Marshall. Sensitivity of transmissometer measurement of black carbon to reference filter. Submitted. Submitted.	Major
A Goodkind, C Tessum, J Coggins, J Hill, J Marshall. Fine-scale, spatially-explicit economic damages of fine particulate matter and its precursors in the United States. Submitted.	Major
TW Aung; J Baumgartner; G Jain; K Sethuraman; C Reynolds; JD Marshall; M Brauer. Blood Pressure and Eye Health Symptoms from a Randomized Cookstove Intervention in Rural India. Submitted.	Minor

M Salmon, C Mila, S Bhogadi, S Addanki, P Madhira, N Muddepaka, A Mora, M Sanchez, S Kinra, V Sreekanth, A Doherty, JD Marshall, C Tonne. Personal exposure to PM2.5 in relation to wearable camera-derived microenvironments. Submitted.	Minor
E Gilmore, J Heo, N Muller, C Tessum, J Hill, JD Marshall, P Adams. An Inter-Comparison of Air Quality Social Cost Estimates from Reduced-Complexity Models. Submitted.	Minor
MM Kelp, AP Grieshop, J Baumgartner, CC Reynolds, K Sethuraman, G Jain, JD Marshall. Real-time indoor measurement of health and climate-relevant air pollution concentrations during a carbon-finance-approved cookstove intervention in rural India. Submitted.	Lead
H Xu, M Bechle, M Wang, A Szpiro, S Vedal, Y Bai, JD Marshall. National PM2.5 and NO2 Exposure Models for China Based on Land Use Regression, Satellite Measurements, and Universal Kriging. Submitted.	Lead
L Liu, T Hwang, S Lee, Y Ouyang, B Lee, SJ Smith, CW Tessum, JD Marshall, F Yan, K Daenzer, TC Bond. Health and climate impacts of future U.S. freight transportation assessed with linked global, regional, and urban models. Submitted.	Minor
V Menghwani, H Zerriffi, P Dwivedi, JD Marshall, AP Grieshop, R Bailis. Freedom of choice and household aspirations: Determinants of cookstoves and fuel choice among rural households in India. Submitted.	Minor

Peer-reviewed journal articles

The right column indicates my contribution to each article: lead, major, or minor. Those terms are defined above.

92.	MK Kumar, S Vakacherla, M Salmon, C Tonne, JD Marshall. Use of spatiotemporal characteristics of ambient PM2.5 in rural South India to infer local versus regional contributions. *Environmental Pollution*. Accepted.	Lead
91.	M Sanchez, A Ambros, C Mila, M Salmon, K Balakrishnan, S Sambandamm, V Sreekanth, JD Marshall, C Tonne. Development of land-use regression models for fine particles and black carbon in peri-urban South India. *Science of the Total Environment*. DOI: 10.1016/j.scitotenv.2018.03.308.	Minor
90.	LD Knibbs, CP Coorey, MJ Bechle, JD Marshall, MG Hewson, B Jalaludin, GG Morgan, AG Barnett. Long-term nitrogen dioxide exposure assessment using back-extrapolation of satellite-based land-use regression models for Australia. *Environmental Research*. DOI: 10.1016/j.envres.2018.01.046. 2018.	Minor
89.	D Donaire-Gonzalez, J Barrera-Gómez, JD Marshall, MJ Nieuwenhuijsen, GA Wellenius, C Tonne. Performance of low-cost monitors to assess household air pollution. *Environmental Research*. DOI: 10.1016/j.envres.2018.01.024. 2018.	Minor

88.	NP Nguyen, JD Marshall. Impact, efficiency, inequality, and injustice of urban air pollution: variability by emission location. *Environmental Research Letters*. 13 024002. 2017.	Lead
87.	S Thakrar, A Goodkind, C Tessum, J Marshall, J Hill. Life cycle air quality impacts on human health from potential switchgrass production in the United States. *Biomass and Bioenergy.* DOI: 10.1016/j.biombioe.2017.10.031. 2017.	Major
86.	MPS Thind, EJ Wilson, IL Azevedo, JD Marshall. Marginal Emissions Factors for Electricity Generation in the Midcontinent ISO. *Environmental Science & Technology*. DOI: 10.1021/acs.est.7b03047. 2017.	Lead
85.	S Hankey, JD Marshall. Urban Form, Air Pollution, and Health. *Current Environmental Health Reports*. DOI: 10.1007/s40572-017-0167-7. 2017.	Major
84.	M Bechle, D Millet, JD Marshall. Does urban form affect urban NO_2? Satellite-based evidence for more than 1,200 cities. *Environmental Science & Technology*. 51 (21), 12707-12716. 2017.	Lead
83.	AP Grieshop, G Jain, K Sethuraman, JD Marshall. Emission factors of health- and climate-relevant pollutants measured in-home during a carbon-finance-approved cookstove intervention in rural India. *GeoHealth,* 1(5), 222–236. 2017.	Major
82.	LP Clark, DB Millet, JD Marshall. Changes in transportation-related air pollution exposures by race-ethnicity and socioeconomic status: outdoor nitrogen dioxide in the United States in 2000 and 2010. *Environmental Health Perspectives,* 125(9):097012. 2017.	Lead
81.	M Sanchez, A Ambros, M Salmon, S Bhogadi, RT Wilson, S Kinra, JD Marshall, C Tonne. Predictors of daily mobility of adults in peri-urban South India. *Environmental Research & Publich Health*, DOI: 10.3390/ijerph14070783. 2017.	Minor
80.	J Apte, K Messier, S Gani, M Brauer, T Kirchstetter, M Lunden, J Marshall, C Portier, R Vermeulen, S Hamburg. High-resolution air pollution mapping with Google Street View cars: exploiting big data. *Environmental Science & Technology*, 51 (12), 6999–7008. 2017. *Listed as the 'Best Environmental Technology Paper of 2017' from *Environmental Science & Technology*	Minor
79.	CW Tessum, JD Hill, JD Marshall. InMAP: a model for air pollution interventions. *PLoS ONE*, 12(4): e0176131. 2017.	Lead
78.	A Larkin, J Geddes, R Martin, Q Xiao, Y Liu, J Marshall, M Brauer, P Hystad. A global land use regression model for nitrogen dioxide air pollution. *Environmental Science & Technology*, 51 (12), 6957–6964. 2017.	Minor
77.	C Tonne, M Salmon, M Sanchez, V Sreekanth, S Bhogadi, S Sambandam, K Balakrishnan, S Kinra, JD Marshall. Integrated assessment of exposure to PM2.5 in South India and its relation with cardiovascular risk: design of the CHAI study. *International Journal of Hygiene and Environmental Health*, 220(6), 1081-1088. 2017.	Major

76.	P Pant, G Habib, JD Marshall, RE Peltier. PM 2.5 exposure in highly polluted cities: A case study from New Delhi, India. *Environmental Research*, 156, 167-174. 2017.	Minor
75.	MC Turner, D Krewski, WR Diver, CA Pope III, RT Burnett, M Jerrett, JD Marshall, SM Gapstur. Ambient air pollution and cancer mortality in the cancer prevention study-II. *Environmental Health Perspectives*, DOI: 10.1289/EHP767. 2017.	Minor
74.	E Carter, C Norris, KL Dionisio, K Balakrishnan, W Checkley, ML Clark, S Ghosh, DW Jack, PL Kinney, JD Marshall, LP Naeher, JL Peel, S Sambandam, JJ Schauer, KR Smith, BJ Wylie, J Baumgartner. Assessing exposure to household air pollution: a systematic review and pooled analysis of carbon monoxide as a surrogate measure of particulate matter. *Environmental Health Perspectives*, DOI: 10.1289/EHP767. 2017.	Minor
73.	M Jerrett, R Brook, L White, RT Burnett, J Yu, J Su, E Seto, JD Marshall, J Palmer, L Rosenberg. Ambient ozone and incident diabetes: a prospective analysis in a large cohort of African American women. *Environment International,* Accepted. 2017.	Minor
72.	S Hankey, G Lindsey, JD Marshall. Population-Level exposure to particulate air pollution during active travel: planning for low-exposure, health-promoting cities. *Environmental Health Perspectives*, DOI: 10.1289/EHP442. 2016.	Major
71.	L Knibbs, C Coorey, M Bechle, C Cowie, M Dirgawati, J Heyworth, G Marks, J Marshall, L Morawska, G Pereira, M Hewson. Independent validation of national satellite-based land-use regression models for nitrogen dioxide using passive samplers. *Environmental Science & Technology*, 50(22). 2016.	Minor
70.	H Vreeland, JJ Schauer, AG Russell, JD Marshall, A Fushimi, G Jain, K Sethuraman, V Verma, SN Tripathi, MH Bergin. Chemical characterization and toxicity of particulate matter emissions from roadside trash combustion in urban India. *Atmospheric Environment*, 147. 2016.	Minor
69.	S Zhu, JD Marshall, D Levinson. Population exposure to ultrafine particles: size-resolved and real-time models for highways. *Transportation Research Part D: Transport and Environment*, 49. 2016.	Major
68.	BL Keeler, JD Gourevitch, S Polasky, F Isbell, CW Tessum, J Hill, JD Marshall. The social cost of nitrogen. *Science Advances,* DOI: 10.1126/sciadv.1600219. 2016.	Minor
67.	K de Hoogh, J Gulliver, A van Donkelaar, RV Martin, JD Marshall, MJ Bechle, G Cesaroni, MC Pradas, A Dedele, M Eeftens, B Forsberg, C Galassi, J Heinrich, B Hoffmann, B Jacquemin, K Katsouyanni, M Korek, N Kunzli, SJ Lindley, J Lepeule, F Meleux, A de Nazelle, M Nieuwenhuijsen, W Nystad, O Raaschou-Nielsen, A Peters, VH Peuch, L Rouil, O Udvardy, R Slama, M Stempfelet, EG Stephanou, MY Tsai, T Yli-Tuomi, G Weinmayr, B Brunekreef, D Vienneau, G Hoek. Development of West-European PM2.5 and NO2 land use regression models incorporating satellite-derived and chemical transport modelling data. *Environmental Research*, 151. 2016.	Minor

66.	TW Aung, G Jain, K Sethuraman, J Baumgartner, C Reynolds, AP Grieshop, JD Marshall, M Brauer. Health and climate-relevant pollutant concentrations from a carbon-finance approved cookstove intervention in rural India. *Environmental Science & Technology*, 50(13). 2016.	Major
65.	P Coogan, LF White, J Yu, RT Burnett, JD Marshall, E Seto, RD Brook, JR Palmer, L Rosenberg, M Jerrett. Long Term Exposure to NO2 and Diabetes Incidence in the Black Women's Health Study. *Environmental Research*, 148. 2016.	Minor
64.	C Norris, MS Goldberg, JD Marshall, MF Valois, T Pradeep, M Narayanswamy, G Jain, K Sethuraman, J Baumgartner. A panel study of the acute effects of personal exposure to household air pollution on ambulatory blood pressure in rural Indian women. *Environmental Research*, 147. 2016.	Major
63.	LF White, M Jerrett, J Yu, JD Marshall, L Rosenberg, PF Coogan. Ambient air pollution and 16 year weight change in African American women. *American Journal of Preventive Medicine,* 51(4). 2016.	Minor
62.	MT Young, MJ Bechle, PD Sampson, AA Szpiro, JD Marshall, L Sheppard, JD Kaufman. Satellite-Based NO2 and Model Validation in a National Prediction Model Based on Universal Kriging and Land-Use Regression. *Environmental Science & Technology*, 50(7). 2016.	Minor
61.	MC Turner, M Jerrett, CA Pope III, D Krewski, SM Gapstur, WR Diver, BS Beckerman, JD Marshall, J Su, DL Crouse, RT Burnett. Long-term ozone exposure and mortality in a large prospective study. *American Journal of Respiratory and Critical Care Medicine*, Accepted.	Minor
60.	S Ji, C Cherry, W Zhou, R Sawhney, Y Wu, S Cai, S Wang, JD Marshall. Environmental justice aspects of exposure to PM2.5 emissions from electric vehicle use in China. *Environmental Science & Technology*, 49(24). 2015.	Minor
59.	JD Marshall, JS Apte, JS Coggins, AL Goodkind. Blue Skies Bluer? *Environmental Science & Technlogy,* 49(24). 2015.	Lead
58.	MJ Bechle, DB Millet, JD Marshall. A national spatiotemporal exposure surface for NO2: monthly scaling of a satellite-derived land-use regression, 2000-2010. *Environmental Science & Technology*, 49(20). 2015.	Major
57.	S Hankey, JD Marshall. On-bicycle exposure to particulate air pollution: particle number, black carbon, PM2.5, and particle size. *Atmospheric Environment*, 122. 2015.	Lead
56.	S Hankey, JD Marshall. Land use regression models of on-road particulate air pollution (particle number, black carbon, PM2.5, particle size) using mobile monitoring. *Environmental Science & Technology*, Accepted.	Lead
55.	JS Apte, JD Marshall, AJ Cohen, M Brauer. Addressing global mortality from ambient PM2.5. *Environmental Science & Technology,* 49(13). 2015. Listed as a "most-downloaded article."	Major

54.	SH Chan, VC Van Hee, S Bergen, AA Szpiro, JD Marshall, JD Kaufman, DP Sandler. Long-term air pollution exposure and blood pressure in the Sister Study. *Environmental Health Perspectives*, 123. 2015.	Minor
53.	S Hankey, G Lindsey, JD Marshall. Day-of-year scaling factors and design considerations for non-motorized traffic monitoring programs. *Transportation Research Record,* 2468. 2015.	Major
52.	CW Tessum, JD Hill, JD Marshall. Twelve-month, 12 km resolution North American WRF-Chem air quality simulation: performance evaluation. *Geoscientific Model Development*, 8. 2015.	Lead
51.	S Hankey, K Sullivan, A Kinnick, A Koskey, K Grande, JH Davidson, JD Marshall. Using objective measures of stove use and indoor air quality to evaluate a cookstove intervention in rural Uganda. *Energy for Sustainable Development*, 25. 2015.	Major
50.	L Hu, DB Millet, M Baasandorj, TJ Griffis, KR Travis, CW Tessum, JD Marshall, WF Reinhart, T Mikoviny, M Müller, A Wisthaler, M Graus, C Warneke, J de Gouw. Emissions of C6-C8 aromatic compounds in the United States: constraints from tall tower and aircraft measurements. *Journal of Geophysical Research*, 120(2). 2015.	Minor
49.	L Dekoninck, D Botteldooren, LI Panis, S Hankey, G Jain, K Sethuraman, JD Marshall. Applicability of a noise-based model to estimate in-traffic exposure to black carbon and particle number concentration in different cultures. *Environment International*, 74. 2015.	Major
48.	CW Tessum, JD Hill, JD Marshall. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proceedings of the National Academy of Sciences*, 111(52). 2014.	Lead
47.	AL Goodkind, JS Coggins, JD Marshall. A spatial model of air pollution: the impact of the concentration-response function. *Journal of the Association of Environmental and Resource Economists*, 1(4). 2014.	Major
46.	P Fantke, O Jolliet, JS Apte, AJ Cohen, JS Evans, OO Hänninen, F Hurley, MJ Jantunen, M Jerrett, JI Levy, MM Loh, JD Marshall, BG Miller, P Preiss, JV Spadaro, M Tainio, JT Tuomisto, CJ Weschler, TE McKone, 2014. Health effects of fine particulate matter in life cycle impact assessment: conclusions from the Basel guidance workshop. *The International Journal of Life Cycle Assessment*, DOI 10.1007/s11367-014-0822-2. 2014.	Minor
45.	LD Knibbs, MG Hewson, MJ Bechle, JD Marshall, AG Barnett. A national satellite-based land use regression model for air pollution exposure assessment in Australia. *Environmental Research*, 135. 2014.	Minor
44.	LP Clark, DB Millet, JD Marshall. National patterns in environmental injustice and inequality: outdoor NO_2 air pollution in the United States. *PLOS One*, 9(4). 2014.	Lead
43.	JD Marshall, KR Swor, NP Nguyen. Prioritizing environmental justice and equality: diesel particles in California's South Coast. *Environmental Science & Technology*, 48(7). 2014.	Lead

42.	DPdL Barido, JD Marshall. The relationship between urbanization and CO_2 emissions depends on income level and policy. *Environmental Science & Technology*, 48(7). 2014.	Lead
41.	D Vienneau, K de Hoogh, MJ Bechle, R Beelen, A van Donkelaar, RV Martin, DB Millet, G Hoek, JD Marshall. Western European land use regression incorporating satellite- and ground-based measurements of NO_2 and PM_{10}. *Environmental Science & Technology*, 47(23). 2013.	Major
40.	A Saraswat, JS Apte, M Kandlikar, M Brauer, SB Henderson, JD Marshall. Spatiotemporal land use regression models of fine, ultrafine and black carbon particulate matter in New Delhi, India. *Environmental Science & Technology*, 47(22). 2013.	Lead
39.	MJ Bechle, DB Millet, JD Marshall. Remote sensing of exposure to NO_2: satellite versus in situ measurement in a large urban area. *Atmospheric Environment*, 69. 2013.	Lead
38.	AF Both, D Westerdahl, S Fruin, B Haryanto, JD Marshall. Exposure to carbon monoxide, fine particle mass, and ultrafine particle number in Jakarta, Indonesia: effect of commute mode. *Science of the Total Environment*, 443. 2013.	Lead
37.	CW Tessum, JD Marshall, J Hill. A spatially and temporally explicit life cycle inventory of air pollutants from gasoline and ethanol in the United States. *Environmental Science & Technology*, 46(20). 2012.	Major
36.	DB Millet, E Apel, DK Henze, J Hill, JD Marshall, HB Singh, CW Tessum. Natural and anthropogenic ethanol sources in North America and potential atmospheric impacts of ethanol fuel use. *Environmental Science & Technology,* 46(15). 2012.	Major
35.	JS Apte, E Bombrun, JD Marshall, WW Nazaroff. Global intraurban intake fractions for primary air pollutants from vehicles and other distributed sources. *Environmental Science & Technology,* 46(6). 2012.	Lead
34.	S Ji, C Cherry, MJ Bechle, Y Wu, JD Marshall. Electric vehicles in China: emissions and health impact. *Environmental Science & Technology,* 46(4). 2012. Listed as a "most-read article."	Major
33.	S Aggarwal, R Jain, JD Marshall. Real time prediction of size resolved ultrafine PM on freeways. *Environmental Science & Technology,* 46(4). 2012.	Lead
32.	S Hankey, JD Marshall, M Brauer. Health impacts of the built environment: within-urban variability in physical inactivity, air pollution and ischemic heart disease mortality. *Environmental Health Perspectives*, 120(2). 2012.	Lead
31.	AP Grieshop, JD Marshall, M Kandlikar. Health and climate benefits of cook-stove replacement options. *Energy Policy,* 39(12). 2011.	Major
30.	LP Clark, DB Millet, JD Marshall. Air quality and urban form in US urban areas: evidence from regulatory monitors. *Environmental Science & Technology,* 45(16). 2011.	Lead

29.	JS Apte, TW Kirchstetter, AH Reich, SJ Deshpande, G Kaushik, A Chel, JD Marshall, WW Nazaroff. Exposure concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. *Atmospheric Environment,* 45(26). 2011.	Lead
28.	A Both, A Balakrishnan, B Joseph, JD Marshall. Spatiotemporal aspects of real-time $PM_{2.5}$: low- and middle-income neighborhoods in Bangalore, India. *Environmental Science & Technology,* 45(13). 2011.	Lead
27.	MJ Bechle, DB Millet, JD Marshall. Effects of income and urban form on urban NO_2: global evidence from satellites. *Environmental Science & Technology,* 45(11). 2011.	Lead
26.	S Humbert, JD Marshall, S Shaked, J Spadaro, Y Nishioka, P Preiss, TE McKone, A Horvath, O Jolliet. Intake fractions and characterization factors for particulate matter: review and recommendations for life cycle assessment. *Environmental Science & Technology,* 45(11). 2011.	Major
25.	EV Novotny, MJ Bechle, DB Millet, JD Marshall. National satellite-based land-use regression: NO_2 in the United States. *Environmental Science & Technology,* 45(10). 2011.	Lead
24.	A de Nazelle, MJ Nieuwenhuijsen, JM Antó, M Brauer, D Briggs, C Braun-Fahrlander, N Cavill, AR Cooper, H Desqueyroux, S Fruin, G Hoek, LI Panis, N Janssen, M Jerrett, M Joffe, ZJ Andersen, E van Kempen, S Kingham, N Kubesch, K Leyden, JD Marshall, J Matamala, G Mellios, M Mendez, H Nassif, D Ogilvie, R Peiró, K Pérez, A Rabl, M Ragettli, D Rodríguez, D Rojas, P Ruiz, JF Sallis, J Terwoert, JF Toussaint, J Tuomisto, M Zuurbier, E Lebret. Improving health through policies to promote active travel: a review of evidence to support integrated health impact assessment. *Environment International,* 37(4). 2011.	Minor
23.	NL Boeke, JD Marshall, S Alvarez, KV Chance, A Fried, TP Kurosu, B Rappenglück, D Richter, J Walega, P Weibring, DB Millet. Formaldehyde columns from the Ozone Monitoring Instrument: urban versus background levels and evaluation using aircraft data and a global model. *Journal of Geophysical Research,* 116(D05303). 2011.	Major
22.	E Setton, JD Marshall, M Brauer, KR Lundquist, P Hystad, P Keller, D Cloutier-Fisher. The impact of mobility on exposure to traffic-related air pollution and health effect estimates. *Journal of Exposure Science and Environmental Epidemiology,* 21(1). 2011.	Major
21.	EJ Wilson, JD Marshall, KJ Krizek, R Wilson. School choice and children's school commuting. *Environment and Planning A,* 42(9). 2010.	Major
20.	JD Marshall, R Wilson, KL Meyer, SK Rajangam, N McDonald, E Wilson. Vehicle emissions during children's school commuting: impacts of education policy. *Environmental Science & Technology,* 44(5). 2010.	Lead
19.	S Hankey, JD Marshall. Impacts of urban form on future U.S. passenger-vehicle greenhouse gas emissions. *Energy Policy,* 38(9). 2010.	Lead
18.	A Boies, S Hankey, D Kittelson, JD Marshall, P Nussbaum, W Watts, E Wilson. Reducing motor vehicle GHG emissions in a non-California state: a case study of Minnesota. *Environmental Science & Technology,* 43(23). 2009.	Lead

17.	JD Marshall, M Brauer, LD Frank. Healthy neighborhoods: walkability and air pollution. *Environmental Health Perspectives,* 117(11). 2009.	Lead
16.	FJ Ries, JD Marshall, M Brauer. Intake fraction of urban wood smoke. *Environmental Science & Technology,* 43(13). 2009.	Lead
15.	JD Marshall. Environmental equality: air pollution exposures in California's South Coast Air Basin, *Atmospheric Environment,* 42(21). 2008.	Sole author
14.	JD Marshall. Energy-efficient urban form. *Environmental Science & Technology,* 42(9). 2008.	Sole author
13.	JD Marshall, E Nethery, M Brauer. Within-urban variability in ambient air pollution: comparison of estimation methods. *Atmospheric Environment,* 42(6). 2008.	Lead
12.	JD Marshall. Urban land area and population growth over time: a new scaling relationship. *Urban Studies,* 44(9). 2007.	Sole author
11.	PJ Marcotullio, JD Marshall. Potential futures for road transportation CO_2 emissions in the Asia Pacific. *Asia Pacific Viewpoint,* 48(3). 2007.	Major
10.	JD Marshall, PW Granvold, AS Hoats, TE McKone, E Deakin, WW Nazaroff. Inhalation intake of ambient air pollution in California's South Coast Air Basin. *Atmospheric Environment*, 40(23). 2006.	Lead
9.	JD Marshall, E Behrentz. Vehicle self-pollution intake fraction: children's exposure to school bus emissions. *Environmental Science & Technology*, 39(8). 2005. Widely reported in news media, including *New York Times* and *Los Angeles Times*.	Lead
8.	JD Marshall, TE McKone, EA Deakin, WW Nazaroff. Inhalation of motor vehicle emissions: effects of urban population and land area. *Atmospheric Environment*, 39(2). 2005. Listed as a "most-downloaded article."	Lead
7.	JD Marshall, SK Teoh, WW Nazaroff. Intake fraction of nonreactive vehicle emissions in US urban areas. *Atmospheric Environment*, 39(7). 2005.	Lead
6.	JD Marshall, MW Toffel. Framing the elusive concept of sustainability: a sustainability hierarchy. *Environmental Science & Technology*, 39(3). 2005. Listed as a "most-downloaded article."	Lead
5.	PJ Marcotullio, E Williams, JD Marshall. Faster, sooner, and more simultaneously: how recent road and air transportation CO_2 emission trends in developing countries differ from historic trends in the United States. *Journal of Environment and Development*, 14(1). 2005.	Major
4.	MW Toffel, JD Marshall. Comparative analysis of weighting methods used to evaluate chemical release inventories. *Journal of Industrial Ecology*, 8(1-2). 2004. Chosen as the issue's "sample article."	Major

3.	JD Marshall, WJ Riley, TE McKone, WW Nazaroff. Intake fraction of primary pollutants: motor vehicle emissions in the South Coast Air Basin. *Atmospheric Environment*, 37(24). 2003.	Lead
2.	JD Marshall, BW Shimada, PR Jaffe. Effect of temporal variability in infiltration on contaminant transport in the unsaturated zone. *Journal of Contaminant Hydrology*, 46(1-2). 2000.	Lead
1.	SR Hayes, JD Marshall. Designing optimal strategies to attain the new US particulate matter standards: some initial concepts. *Journal of the Air & Waste Management Association*, 49(SI). 1999.	Major

Book chapters and other peer-reviewed publications

D Philippon, B Colombo, F Rose, J Marshall. Translating Knowledge to Engage Global Grand Challenges: A Case Study. (Peer reviewed.) In *Innovative Learning and Teaching: Experiments Across the Disciplines*, ID Alexander, RK Poch, (eds). 2017; University of Minnesota libraries publishing: Minneapolis, MN.

KJ Krizek, E Wilson, JD Marshall, R Wilson. Transport Costs of School Choice. (Peer reviewed.) In *Education, Land, and Location*, GK Ingram, DA Kenyon (eds). 2014; Lincoln Institute LPS: Cambridge, MA.

FJ Ries, JD Marshall, M Brauer. Wood Energy: The Dangers of Combustion. Letter to the editor (peer reviewed), *Science*, 324(5933). 2009.

M Brauer, B Ainslie, M Buzzelli, S Henderson, T Larson, JD Marshall, E Nethery, D Steyn, J Su. Models of Exposure for Use in Epidemiological Studies of Air Pollution Health Impacts. In *Air Pollution Modeling and Its Application XIX (NATO Science for Peace and Security Series C: Environmental Security)*, C Borrego, AI Miranda (eds). 2008; Springer: Dordrecht, The Netherlands.

JD Marshall, WW Nazaroff. Intake Fraction. (Peer reviewed.) In *Exposure Analysis*, WR Ott, A Steinemann, L Wallace (eds). 2007; CRC Press: Boca Raton, FL.

Reports and other publications

C Tessum, JD Marshall, J Hill. Tank-to-Wheel Emissions of Ethanol and Biodiesel Powered Vehicles as Compared to Petroleum Alternatives. Report to the Center for Transportation Studies, University of Minnesota, Minneapolis, MN. March 2010.

C Cherry, S Ji, JD Marshall, Y Wu. Emissions and Public Health from Electric Vehicles in China. Report to the Energy Foundation, Beijing, China. September 2009.

C Tessum, A Boies, J Hill, JD Marshall. Assessing the Sustainability of Biofuels: Metrics, Models, and Tools for Evaluating the Impact of Biofuels. In *Expanding Biofuel Production and the Transition to Advanced Biofuels*. National Research Council, 2009: 117-140.

M Brauer, SB Henderson, JD Marshall. A Land Use Regression Road Map for the Burrard Inlet Area Local Air Quality Study. Report to the Greater Vancouver Regional District (GVRD), Vancouver, BC. December 2006.

B Haryanto, JD Marshall, D Westerdahl, S Fruin, I Trihandini. Personal Exposure Measurements of PM2.5 and Carbon Monoxide in Jakarta, Indonesia. Report to US Agency for International Development, and US Asia Environmental Partnership (USAID, USAEP), Jakarta, Indonesia. October 2005.

JD Marshall, WW Nazaroff. Using Intake Fraction to Guide ARB Policy Choices: the Case of Particulate Matter. Report to the Research Division of the California Air Resources Board (ARB), Sacramento, CA. October 2004.

MW Toffel, JD Marshall. Assessing Environmental Performance with Chemical Release Inventories. In *Proceedings of the 11th International Conference of the Greening of Industry Network*. October 2003.

JD Marshall. Exposure to Motor Vehicle Emissions: an Intake Fraction Approach. Report LBL-51854, Lawrence Berkeley Laboratory, Berkeley, CA. December 2002.

JD Marshall, WW Nazaroff. Health Risk Assessment of Diesel-fired Back-up Generators Operating in California. Report to Environmental Defense, Oakland, CA. August 2002. Presented to the California Air Resources Board, Sacramento, CA, May 2002.

Invited presentations

JD Marshall. "Air pollution and environmental justice", iCOMOS (International Conference on One Medicine One Science), University of Minnesota, April 25, 2016. Minneapolis, MN.

JD Marshall. "Air pollution and environmental justice", Big Ideas, Better Cities conference, McMaster Institute for Transportation & Logistics, April 20, 2016. Hamilton, Ontario.

JD Marshall. "Air pollution kills! So what? Air quality engineering to improve public health", Energy and Resources Group, UC Berkeley, February 12, 2014. Berkeley, CA.

JD Marshall. " Environmental-justice & -equality in the U.S.: Quantifying and addressing regional variability", USC Program for Environmental and Regional Equity, University of Southern California February 8, 2014. Los Angeles, CA.

JD Marshall. "Air pollution kills! So what? Air quality engineering to improve public health", Keck School of Medicine, University of Southern California, February 7, 2014. Los Angeles, CA.

JD Marshall. "Air pollution kills! So what? Air quality engineering to improve public health", Center for Research in Environmental Epidemiology, October 5, 2012. Barcelona, Spain.

JD Marshall. “Urban sustainability: Designing cities for human health and the environment”, Geography Department, University of Minnesota, February 10, 2012, Minneapolis, MN.

C Tessum, K Wagstrom, J Hill, JD Marshall. “Air quality and public health impacts of biofuel production and use in the United States”, Peking University, August 15, 2011, Beijing, China.

JD Marshall, “Urban sustainability: Designing cities for human health and the environment”, Civil Engineering Department, École Polytechnique Fédérale de Lausanne, June 9, 2011, Lausanne, Switzerland.

JD Marshall, “Exposure to PM in a low-income country: Real-time measurements in India”, Swiss Tropical & Public Health Institute, June 7, 2011, Basel, Switzerland.

JD Marshall, “Satellite-based land-use regression”, Institute for Risk Assessment Sciences, Utrecht University, February 11, 2011, Utrecht, The Netherlands.

JD Marshall, “Mobility-based exposure assessment”, VITO, the Flemish Institute for Technological Research [Vlaamse Instelling voor Technologisch Onderzoek], February 2, 2011, Mol, Belgium.

JD Marshall, R Wilson, KL Meyer, SK Rajangam, N McDonald, E Wilson, “Active travel & children: Effects of education policy”, Transportation, Air Pollution, and Physical Activities International Workshop (TAPAS), November 9–10, 2009, Barcelona, Spain.

JD Marshall, S Hankey, M Brauer, LD Frank, “Healthy neighborhood design: Exposure to air pollution and physical inactivity”, TAPAS, November 9–10, 2009, Barcelona, Spain.

C Tessum, J Hill, JD Marshall, “Spatially and temporally explicit life-cycle analysis of biofuels”, First Annual Fulbright US-Brazil Biofuels Short Course, July 27-August 7, 2009, Sao Paulo, Brazil.

JD Marshall. “Incorporating environmental justice into air quality management.” 2nd Colombian Congress on Air Quality & Public Health. Inter-university Group for Research on Air Quality & Health. July 14–17, 2009. Manizales, Colombia.

JD Marshall. “Urban land-use and transportation-GHG: Minnesota”. How Land Use Can Help Minnesota Reach Its Greenhouse Gas Reduction Goals (Workshop held at University of Minnesota). January 5, 2009. Minneapolis, MN.

JD Marshall. "Urban sustainability engineering". Minnesota Pollution Control Agency, December 4, 2008. St Paul, MM.

JD Marshall. "Urban sustainability engineering". Center for Urban Environmental Research and Education, University of Maryland Baltimore County. November 7, 2008. Baltimore, MD.

JD Marshall. "Urban sustainability engineering". Liu Institute for Global Issues, University of British Columbia. October 31, 2008. Vancouver, BC.

JD Marshall. "Urban Health: Walkability and Air Pollution". 7th International Conference on Urban Health. October 30, 2008. Vancouver, BC.

JD Marshall. "Fine particles and haze: Reductions and resulting benefits." Minnesota Air, Water, and Waste Environmental Conference. February 26–28, 2008. Bloomington, MN.

JD Marshall. "Energy efficient urban form: Carbon implications of reducing urban sprawl in United States." International Workshop on Urban Energy and Carbon Modeling. Global Carbon Project. February 4–6, 2008, Asian Institute of Technology, Pathumthani, Thailand.

JD Marshall. "Intake fraction: a new tool for air quality management." 20th Annual Research Symposium, UC Toxic Substances Research & Teaching Program. April 20–21, 2007. Santa Cruz, CA.

JD Marshall. "Incorporating exposures into air quality management." 1st Colombian Congress on Air Quality & Public Health. Inter-university Group for Research on Air Quality & Health. March 14–16, 2007. Manizales, Colombia.

JD Marshall. "Intake fraction: a new tool for air quality management." 4th Annual Workshop on Air Pollution & Public Health. British Columbia Lung Association. March 7, 2007. Vancouver, BC.

JD Marshall. "Mobility-based estimates of inhalation of vehicle emissions." Symposium on Current Advances in Exposure and Health Effect Assessment of Traffic Exhaust. International Society of Exposure Analysis and International Society for Environmental Epidemiology (ISEA/ISEE) Joint Annual Meeting. September 2–6, 2006. Paris, France. Abstract published in *Epidemiology*, 17(6): S53. November 2006.

JD Marshall. "Applying New Exposure Tools to ARB Efforts: Mobility-Based Exposure Modeling and Intake Fraction." California Air Resources Board's Chairman's Air Pollution Seminar Series. January 30, 2006. Sacramento, CA.

JD Marshall. Panel discussion on effective library research techniques for graduate students. Spring 2004. California Clearinghouse on Library Instruction. May 17, 2004. Fremont, CA.

JD Marshall. "Making Choices in Local Air Quality Management: Emissions vs. Exposures." Workshop by the Institute for Global Environmental Strategies: "Policy Integration towards Sustainable Energy Use for Asian Cities: Integrating Local Air Pollution and Greenhouse Gas Emissions Concerns." January 28–30, 2004. Hayama, Japan.

JD Marshall. "Making Sense of Sustainability" United Nations University. January 27, 2004. Tokyo, Japan.

WW Nazaroff, GA Heath, AS Hoats, JD Marshall. "Environmental Health Implications of Electricity Generation Choices: Pollutants of Concern and Exposure Issues." California Air Resources Board Haagen-Smit Symposium. April 9–12, 2002. Lake Arrowhead, CA.

Conference presentations

J Apte, K Messier, S Chambliss, M Brauer, J Caubel, S Gani, S Hamburg, TW Kirchstetter, JD Marshall, B LaFranchi, MM Lunden, CV Preble, AA Presto, C Portier, A Robinson, ES Robinson, R Shah, K Tuxen-Bettman, R Vermeulen, R Alvarez. "Early Lessons from New Air Pollution Exposure Science: High-resolution Mapping of Urban Air Quality using Google Street View Cars, Low-cost Samplers, and Aerosol Mass Spectrometry", American Association for Aerosol Research (AAAR) International, September 2-7, 2018. St. Louis, MO.

MM Islam, R Wathore, G Jain, K Sethuraman, H Zerriffi, JD Marshall, R Bailis, AP Grieshop. "Emission Factors and Optical Properties of Health and Climate Relevant Pollutants Measured in a Multi-year

Cookstove Intervention Study in Rural India", American Association for Aerosol Research (AAAR) International, September 2-7, 2018. St. Louis, MO.

MM Islam, R Wathore, G Jain, K Sethuraman, H Zerriffi, JD Marshall, R Bailis, AP Grieshop. "Linking PM 2.5 Indoor Air Quality and Emission Factors Measured during a Cookstove Intervention Trial in Rural India", American Association for Aerosol Research (AAAR) International, September 2-7, 2018. St. Louis, MO.

J Apte, K Messier, S Chambliss, M Brauer, J Caubel, S Gani, S Hamburg, TW Kirchstetter, J Marshall, B LaFranchi, MM Lunden, CV Preble, AA Presto, C Portier, A Robinson, ES Robinson, R Shah, K Tuxen-Bettman, R Vermeulen, R Alvarez. "Early lessons from new air pollution exposure science: High-resolution mapping of urban air quality using Google Street View cars, low-cost samplers, and aerosol mass spectrometry", American Association for Aerosol Research (AAAR) International, September 2-7, 2018. St. Louis, MO.

JS Apte, JD Marshall. "Addressing Global Mortality from PM2.5", Art Rosenfeld Symposium, December 1, 2017. Berkeley, CA.

TW Aung, AP Grieshop, M Kelp, JD Marshall. "Emission and Concentration Linkages from a Cookstove Intervention Trial in India", International Society of Exposure Science (ISES) Annual Meeting, October 15-19, 2017. Research Triangle Park, NC.

M Sanchez, A Ambros, M Salmon, C Mila, V Sreekanth, JD Marshall, C Tonne. " Development of land use regression model for fine particles in peri-urban South India", International Society for Environmental Epidemiology (ISEE) Annual Meeting, September 24-28. Sydney, Australia.

JD Marshall, L Clark, MJ Bechle, N Nguyen, K Swor, C Tessum, JD Hill, DB Millet. "Environmental justice aspects of transportation-related air pollution in the United States: evidence from national-scale longitudinal analyses, case studies, and life cycle assessment", Health Effects Institute Annual Conference, May 1–3, 2016. Denver, CO.

L Clark, MJ Bechle, JD Marshall. "National Patterns in Environmental Injustice Over Time: Outdoor NO_2 Air Pollution in United States Urban Areas, 2000-2010", International Society for Environmental Epidemiology (ISEE) Annual Meeting, August 30 - September 3, 2015. São Paulo, Brazil.

S Hankey, G Lindsey, JD Marshall. "Active Travel and Exposure to Air Pollution: Implications for Planning Healthy Cities", ISEE Annual Meeting, August 30 - September 3, 2015. São Paulo, Brazil.

S Hankey, JD Marshall. "Exposure to On-Road Particulate Air Pollution ($PM_{2.5}$, Black Carbon, Particle Number, Particle Size) While Cycling", ISEE Annual Meeting, August 30 - September 3, 2015. São Paulo, Brazil.

S Hankey, JD Marshall. "Land Use Regression Models of Particulate Air Pollution ($PM_{2.5}$, Black Carbon, Particle Number, Particle Size) Using Mobile Monitoring", ISEE Annual Meeting, August 30 - September 3, 2015. São Paulo, Brazil.

N Nguyen, JD Marshall. "Addressing Environmental Justice: Importance of Spatially-Targeted Emission-Reductions", ISEE Annual Meeting, August 30 - September 3, 2015. São Paulo, Brazil.

MJ Bechle, JD Marshall. "Use of LUR Models to Cover a Large Spatial Scale: Integration with Satellite Data", International Society of Exposure Science Annual Meeting, October 12–16, 2014. Cincinnati, Ohio.

S Hankey, JD Marshall, G Lindsey. "Modeling Spatial Patterns of Bicycle and Pedestrian Traffic to Estimate Exposure to Hazards", International Society for Environmental Epidemiology (ISEE) Annual Meeting. August 24–28. Seattle, Washington.

S Hankey, K Sullivan, A Kinnick, A Koskey, K Grande, J Davidson, JD Marshall. "Using Objective Measures of Stove Use and Indoor Air Quality to Evaluate a Cookstove Intervention in Rural Uganda", ISEE Annual Meeting. August 24–28. Seattle, Washington.

MT Young, MJ Bechle, PD Sampson, JD Marshall, LA Sheppard, JD Kaufman. "A National Prediction Model Based on Universal Kriging and Land-Use Regression Using Satellite-Based NO2 Measurements for Epidemiological Analysis of Long-Term Health Effects", ISEE Annual Meeting. August 24–28. Seattle, Washington.

T Aung, JD Marshall, J Baumgartner, B Alexander, G Ramachandran, A Grieshop, C Reynolds, M Brauer, S Narayanswami, T Pradeep, G Jain, K Sethuraman. "Air Quality and Health Evaluation of a Climate-Financed Cookstove Intervention. Institute for Resources", Environment and Sustainability (IRES) Seminar (University of British Columbia), January 7, 2014. Vancouver, Canada.

T Aung, JD Marshall, J Baumgartner, B Alexander, G Ramachandran, A Grieshop, C Reynolds, M Brauer, S Narayanswami, T Pradeep, G Jain, K Sethuraman. "Air Pollution and Blood Pressure Outcomes from a Cookstove Intervention", Occupational and Environmental Health (OEH) Seminar (University of British Columbia), October 25, 2013. Vancouver, Canada.

J Apte, JD Marshall. "Addressing Global Mortality from PM2.5", American Association for Aerosol Research Annual Meeting, October 20-24, 2013. Orlando, FL.

J Apte, JD Marshall, WW Nazaroff. "Inhalation Intake of Urban Emissions of Semivolatile Organic Compounds from Vehicles", American Association for Aerosol Research Annual Meeting, September 30–October 4, 2013. Portland, OR.

J Apte, JD Marshall. "Addressing Global Mortality from PM2.5", International Society for Environmental Epidemiology Annual Meeting, August 25-28, 2013. Seattle, WA.

J Apte, A Goodkind, J Coggins, JD Marshall. "Blue Skies Bluer? Puzzling Implications of a Possible Supra-Linear Relationship Between PM Exposure and Mortality", International Society of Exposure Science, International Society for Environmental Epidemiology, and International Society of Indoor Air Quality and Climate (ISES/ISEE/ISIAQ) Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

T Aung, JD Marshall, T Pradeep, S Narayanswami, G Jain, K Sethuraman, A Grieshop, J Baumgartner, C Reynolds, M Brauer. "Air Quality and Health Evaluation of a Climate Financed Cookstove Intervention in Rural India", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

MJ Bechle, DB Millet, JD Marshall. "Monthly National Satellite-Based Land-Use Regression of NO_2 in the United States for 2000-2010", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

MJ Bechle, DB Millet, JD Marshall. "Remote Sensing of Exposure to NO_2: Satellite Versus Ground Based Measurement in a Large Urban Area", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

L Clark, DB Millet, MJ Bechle, JD Marshall. "Environmental Injustice and Inequality: NO_2 Air Pollution in the United States", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

S Hankey, M Brauer, G Lindsey, JD Marshall. "Neighborhood Walkability and Air Pollution Exposure", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

S Hankey, G Lindsey, JD Marshall. "Comparing Spatial Patterns of Non-Motorized Traffic and Particulate Air Pollution in Minneapolis, MN", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

S Hankey, G Lindsey, JD Marshall. "Measuring and Modeling Particulate Air Pollution Using a Mobile, Bicycle-Based Platform", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

JD Marshall, K Swor, N Nguyen. "Measuring and Improving Environmental Equality and Justice: Diesel Particles in California's South Coast", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

C Tessum, J Hill, JD Marshall. " Air Pollution, Health, and Environmental Justice Implications of Shifting Transportation Fuels", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

D Vienneau, K de Hoogh, MJ Bechle, R Beelen, RV Martin, A van Donkelaar, EV Novotny, DB Millet, G Hoek, JD Marshall. "High Resolution NO_2 and PM_{10} Models for Europe Using Satellite-Derived Measurements", ISES/ISEE/ISIAQ Joint Annual Meeting, August 19–23, 2013. Basel, Switzerland.

T Aung, G Jain, K Sethuraman, A Greishop, T Pradeep, S Narayanswami, JD Marshall, M Brauer. "Air Quality and Health Evaluation of a Climate Financed Cookstove Intervention in Rural India", Institute for Heart + Lung Health FEST, February 19–23, 2013. Vancouver, Canada.

T Aung, G Jain, K Sethuraman, A Greishop, T Pradeep, S Narayanswami, JD Marshall, M Brauer. "Evaluating Climate Financed Cookstove Intervention in Rural Karnataka, India", Symposium on Atmospheric PM Research in British Columbia, December 10, 2012. Vancouver, Canada.

J Apte, JD Marshall, WW Nazaroff. "Intraurban Intake Fraction of Vehicle Emissions: Asian Cities in Global Context." Better Air Quality 2012 Meeting, December 5-7, 2012. Hong Kong, China.

G Jain, K Sethuram, T Aung, MJ Bechle, A Grieshop, J Baumgartner, T Pradeep, M Narayanswamy, C Reynolds, M Brauer, JD Marshall. "Stove Emissions and Indoor and Outdoor Pollution Levels from a Randomized Cook-stove Exchange in Karnataka, India", International Society of Exposure Science (ISES) Annual Meeting, October 28–November 1, 2012. Seattle, WA.

T Aung, JD Marshall, J Baumgartner, B Alexander, G Ramachandran, A Grieshop, C Reynolds, M Brauer, S Narayanswami, T Pradeep, G Jain, K Sethuraman. " Emissions, Health, and Livelihood Impacts of a Randomized Cookstove Exchange in Karnataka, India", International Society for Environmental Epidemiology (ISEE) Annual Meeting, August 26–30, 2012. Columbia, SC.

JD Marshall. "Experiential Education: Designing Solutions to Global Grand Challenges", American Association for the Advancement of Science (AAAS) Annual Meeting, February 16–20, 2012. Vancouver, Canada.

JD Marshall. "Verifying Health and Emission Improvements from a Stove Change-Out", AAAS Annual Meeting, February 16–20, 2012. Vancouver, Canada.

JD Marshall, LP Clark, DB Millet, MJ Bechle. "Environmental Justice and Equality in NO2 Air Pollution in the United States", AAAS Annual Meeting, February 16–20, 2012. Vancouver, Canada.

K Wagstrom, C Tessum, J Hill, JD Marshall. "Air Pollution Impacts of Conventional and Alternative Transportation Fuels", AAAS Annual Meeting, February 16–20, 2012. Vancouver, Canada.

C Tessum, K Wagstrom, J Hill, JD Marshall. "Air Quality and Public Health Impacts of Biofuel Production and Use in the United States", Initiative for Renewable Energy and the Environment E3 Conference. November 7, 2011. St Paul, MN.

C Tessum, K Wagstrom, J Hill, JD Marshall. "Air Quality and Public Health Impacts of Biofuel Production and Use in the United States", Student Sustainability Symposium. October 26, 2011. St Paul, MN.

K Wagstrom, C Tessum, J Hill, JD Marshall. "Air Quality Impacts of Achieving U.S. Renewable Fuels Mandates", American Institute of Chemical Engineers Annual Meeting. October 16–21, 2011. Minneapolis, MN.

J Apte, JD Marshall, WW Nazaroff. "Inhalation Intake Fraction for Vehicle-Attributable Organic PM2.5", American Association for Aerosol Research Annual Meeting. October 8–12, 2011. Minneapolis, MN.

J Apte, E Bombrun, JD Marshall, WW Nazaroff. "Intake Fraction of Nonreactive Ground-Level Pollutant Emissions in 3,646 Global Urban Areas", American Association for Aerosol Research (AAAR) Annual Meeting. October 3–7, 2011. Orlando, FL.

K Wagstrom, C Tessum, J Hill, JD Marshall. "Air Quality Impacts of Achieving U.S. Renewable Fuel Mandates", AAAR Annual Meeting. October 3–7, 2011. Orlando, FL.

C Tessum, K Wagstrom, J Hill, JD Marshall. "Air Quality and Public Health Impacts of Biofuel Production and Use in the United States", American Center for Life Cycle Analysis. October 3–6. 2011, Chicago, IL. Won "Third Place Student Poster" award.

K Lundquist, JD Marshall. "Air Quality Modeling and Exposure Analysis for Environmental Justice Opportunities", Promoting Healthy Communities: Developing and Exploring Linkages Between Public Health Indicators, Exposure and Hazard Data. September 26–27, 2011. Washington, DC.

K Lundquist, JD Marshall. "Effect of Emission Reductions by Source or Location", Promoting Healthy Communities: Developing and Exploring Linkages Between Public Health Indicators, Exposure and Hazard Data. September 26–27, 2011. Washington, DC.

J Apte, JD Marshall, W, Nazaroff. Transient Exposure to Vehicle Exhaust Plumes Inside New Delhi Auto-rickshaws", International Society for Environmental Epidemiology (ISEE) Annual Meeting. September 13–16, 2011. Barcelona, Spain.

S Hankey, JD Marshall, M Brauer. "Health Impacts of the Built Environment: Physical Inactivity, Exposure to Air Pollution, and Ischemic Heart Disease", ISEE Annual Meeting. September 13–16, 2011. Barcelona, Spain.

D Martinez, A De Nazelle, S Fruin, D Westerdahl, JD Marshall, J Matamala, N Kubesch, A Ripoll, M Nieuwenhujsen. "Relation Between Commuter and Exposure to Pollution Related to Traffic in Barcelona", ISEE Annual Meeting. September 13–16, 2011. Barcelona, Spain.

C Tessum, K Wagstrom, J Hill, JD Marshall. "Air quality and public health impacts of biofuel production and use in the United States", ISEE Annual Meeting, September 13-16, 2011. Barcelona, Spain.

D Vienneau, K de Hoogh, G Hoek, MJ Bechle, EV Novotny, DB Millet, JD Marshall. "European NO_2 Land Use Regression Incorporating Satellite- and Ground-based Measurements", ISEE Annual Meeting. September 13–16, 2011. Barcelona, Spain.

K Wagstrom, C Tessum, J Hill, JD Marshall. "Air Pollution Impacts of Conventional and Alternative Transportation Fuels". 22nd Annual CTS Transportation Research Conference. May 24–25, 2011. Portland, OR.

LP Clark, DB Millet, JD Marshall. "Air pollution and urban form in US urban areas", University of Minnesota Center for Transportation Studies Research Conference. May 24, 2011. St. Paul, MN.

C Tessum, K Wagstrom, J Hill, JD Marshall. "Air Quality Implications of Alternative Fuels: A spatially, Temporally Explicit Life Cycle Modeling Approach", Minnesota Supercomputing Institute Research Exhibition. April 25, 2011, Minneapolis, MN.

A de Nazelle, E Seto, D Donaire, M Mendez, D Rodriguez, L Maurer, J Matamala, M Portella, JD Marshall, M Nieuwenjuisen, M Jerret. "Ubiquitous Sensing Technology: A Tool to Understand and Promote Bicycling Behavior". X Fòrum TIG SIG. March 15–16, 2011. Barcelona, Spain.

NL Boeke, JD Marshall, S Alvarez, K Chance, A Fried, T Kurosu, B Rappenglück, D Richter, J Walega, P Weibring, DB Millet. "Formaldehyde Columns from the Ozone Monitoring Instrument: Urban vs. Background Levels and Evaluation Using Aircraft Data and a Global Model". American Geophysical Union Fall Meeting. December 13–17, 2010. San Francisco, CA.

C Tessum, K Wagstrom, J Hill, JD Marshall. "Air Quality Implications of Alternative Fuels: A Spatially, Temporally Explicit Life Cycle Modeling Approach". Initiative for Renewable Energy and the Environment E3 Conference. November 30, 2010. Saint Paul, MN.

J Apte, TW Kirchstetter, JD Marshall, WW Nazaroff. "An Instrumentation Package for Measuring Commuter Exposure to Vehicle Exhaust Pollutants in New Delhi, India". AWMA Symposium on Air Quality Measurement Methods and Technology. November 2–4, 2010. Los Angeles, CA.

K Wagstrom, C Tessum, J Hill, JD Marshall. "Air Pollution Impacts of Conventional and Alternative Fuels". American Association for Aerosol Research Annual Meeting. October 25–29, 2010. Portland, OR.

NL Boeke, S Alvarez, K Chance, A Fried, T Kurosu, B Rappenglück, D Richter, P Weibring, J Walega, JD Marshall, DB Millet. "Formaldehyde Columns From the Ozone Monitoring Instrument: Urban vs. Background Levels and Evaluation Using Aircraft Data and a Global Model". NASA Aura Science Team Meeting. September 27–29, 2010. Boulder, CO.

JD Marshall. "Exposure Assessment for Improved Air Quality Management". International Society of Exposure Science and International Society for Environmental Epidemiology (ISES/ISEE) Joint Annual Meeting. August 28–September 1, 2010. Seoul, Korea.

JD Marshall. "Is Epidemiology Important for Environmental Sustainability?" ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

JD Marshall, P Hystad, EV Novotny, M Brauer. "Challenges and Next Steps for LUR Models". ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

S Aggarwall, R Jain, JD Marshall. “Real Time, Size-resolved Prediction of Ultrafine and Accumulation-mode Particle Concentrations on Freeways”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

JS Apte, E Bombrun, WW Nazaroff, JD Marshall. “Intake Fractions for Vehicle Emissions in 88 Worldwide Urban Areas”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

JS Apte, TW Kirchstetter, JD Marshall, WW Nazaroff. “Commuter Exposure to Vehicle Exhaust Plumes in New Delhi, India”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

NL Boeke, B Rappenglück, A Fried, JD Marshall, DB Millet. “Satellite-derived NO_2 and HCHO: Comparison to in Situ Measurement and Application to Air Quality Management”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

S Hankey, JD Marshall, M Brauer, LD Frank. “Within-city Variation in Exposures to Air Pollution and Physical Inactivity”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

KR Lundquist, JD Marshall. “Intake and Exposure Effects of Reducing Diesel PM in the South Coast”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

EV Novotny, MJ Bechle, DB Millet, JD Marshall. “National Satellite-based Land Use Regression: NO_2 in the United States”. ISES/ISEE. August 28–September 1, 2010. Seoul, Korea.

NL Boeke, A Fried, P Weibring, J Walega, D Richter, B Rappenglück, S Alvarez, T Kurosu, K Chance, JD Marshall, DB Millet. “Investigating Ozone Chemistry with Measurements of HCHO and NO_2 from the Ozone Monitoring Instrument and GEOS-Chem”. International Commission on Atmospheric Chemistry and Global Pollution and International Global Atmospheric Chemistry (CACGP/IGAC). July 11–16, 2010. Halifax, Canada. Won a “Best Student Poster” award at this international conference.

K Wagstrom, C Tessum, J Hill, JD Marshall. “Air Pollution Impacts of Conventional and Alternative Fuels”. Initiative for Renewable Energy and the Environment E3 Conference. November 17, 2009. Saint Paul, MN.

KR Lundquist, JD Marshall. "Exposure to Diesel Particulate Matter in the South Coast". International Society of Exposure Science (ISES) Annual Meeting. November 1–5, 2009. Minneapolis, MN.

A Both, B Joseph, JD Marshall. "PM2.5 in Low- and Middle-income Neighborhoods in Bangalore, India". ISES. November 1–5, 2009. Minneapolis, MN.

MJ Bechle, LC Ohman, KR Lundquist, DB Millet, JD Marshall. “Within-urban Variability in Outdoor NO_2 Concentrations: Satellite versus Ground-based Estimates”. ISES. November 1–5, 2009. Minneapolis, MN.

S Hankey, JD Marshall. “Impacts of Urban Form on Passenger-vehicle CO_2 Emissions”. Transportation, Planning, Land Use and Air Quality (TPLUAQ) Conference 2009. July 28–29, 2009. Denver, CO.

JD Marshall, E Setton, M Brauer. “Enhancing Spatiotemporal Aspects of Air Pollution Epidemiological Studies”. International Society of Exposure Analysis and International Society for Environmental Epidemiology (ISEA/ISEE) Joint Annual Meeting. October 12–16, 2008. Pasadena, CA.

KL Lundquist, JD Marshall. “Strategies for Improving Exposure and Exposure Distributions: Air Pollution and Environmental Justice in the South Coast”. ISEA/ISEE. October 12–16, 2008. Pasadena, CA.

S Humbert, S Shaked, Y Nishioka, P Preiss, JD Marshall, *et al*. “Development of Consensus Characterization Factors for Primary and Secondary Particulate Matter”. Society of Environmental Toxicology and Chemistry (SETAC) North America Annual Meeting. November 11–15, 2007. Milwaukee, WI. And, SETAC Europe Annual Meeting, May 25–29, 2008.Warsaw, Poland.

M Brauer, C Lencar, L Tamburic, JD Marshall, *et al*. “The Impact of Woodsmoke, Point Sources and Traffic-related Air Pollution on Intrauterine Growth Retardation (IUGR)”. ISEE Annual Meeting. September 5–9, 2007. Mexico City, Mexico.

JD Marshall. “Environmental Equality and Environmental Justice: Exposure to Air Pollution in California’s South Coast”. ISEE. September 5–9, 2007. Mexico City, Mexico.

JD Marshall, E Nethery, C Lencar, M Brauer. “Accounting for Intra-urban Variability in Outdoor Air Concentrations: Estimating Exposures Using Monitoring Station Data and Land-Use Regression

Models". ISEA/ISEE. September 2–6, 2006. Paris, France. Abstract published in *Epidemiology*, 17(6): S473–474. November 2006.

JD Marshall. "U.S. Urban-scale Intake Fraction of Motor Vehicle Emissions: Trends During 1950 – 2000". ISEA/ISEE. September 2–6, 2006. Paris, France. Abstract published in *Epidemiology*, 17(6): S31. November 2006.

D Westerdahl, S Fruin, JD Marshall, PL Fine, *et al.* "Fine and Ultrafine Particles in Jakarta, Indonesia." Asian Aerosol Conference. December 13–16, 2005. Mumbai, India.

D Westerdahl, JD Marshall, S Fruin, B Haryanto. "Assessing Micro-environmental and Personal Exposures to Carbon Monoxide and Fine and Ultrafine Particles in Jakarta, Indonesia." Asian Aerosol Conference. December 13–16, 2005. Mumbai, India.

JD Marshall, PW Granvold, AS Hoats, TE McKone, *et al.* "Mobility, Demographics, and Air Pollutant Exposure." Coordinating Research Council Mobile Source Air Toxics Workshop. December 1–2, 2004. Scottsdale, AZ.

JD Marshall, PW Granvold, AS Hoats, TE McKone, *et al.* "Mobility, Demographics, and Air Pollutant Exposure." ISEA. October 18–21, 2004. Philadelphia, PA.

JD Marshall. "'Smart Growth,' Infill Development, and Health." U.C. Toxic Substances Research & Teaching Program Annual Conference. April 23–24, 2004. San Diego, CA.

MW Toffel, JD Marshall. "Assessing Environmental Performance with Chemical Release Inventories." International Conference of the Greening of Industry Network. October 12–15, 2003. San Francisco, CA.

JD Marshall, TE McKone, EA Deakin, WW Nazaroff. "The Relationship between Land Use Patterns and Human Exposure to Motor Vehicle Emissions." ISEA. September 21–25, 2003. Stressa, Italy.

MC DeSimone, TE McKone, JD Marshall. "How Source Location, Population Distribution, and Pollutant Travel Distance Affect Exposure Estimates for Pollution Prevention." August 11–15, 2002. Vancouver, Canada. ISEA/ISEE. Abstract published in *Epidemiology*, 13(4): 204. July 2002.

JD Marshall, WJ Riley, TE McKone, WW Nazaroff. "Population, Proximity, and Persistence: Incorporating Exposure into Life-cycle Assessment." (LBNL-53038 Abs.). August 11–15, 2002. Vancouver, Canada. ISEA/ISEE. Abstract published in *Epidemiology*, 13(4): 205. July 2002.

MC DeSimone, TE McKone, JD Marshall. "Health Impact Calculations for Life-cycle Impact Assessment Based on Source Location, Population Distribution, and Characteristic Travel Distance." SETAC Europe Annual Meeting. May 12–16, 2002. Vienna, Austria.

JD Marshall, T Kyosai, C Poomontree, M Kane, *et al.* "The 10 or 20 Million Dollar Question: Can Airlines Recycle Their Aluminum Beverage Cans?" International Society for Industrial Ecology. November 12–14, 2001. Leiden, the Netherlands.

JD Marshall, WJ Riley, TE McKone, WW Nazaroff. "Exposure to Motor Vehicle Emissions: a Dose Fraction Approach." ISEA. November 4–8, 2001. Charleston, SC.

SR Hayes, JD Marshall, "Designing Optimal Strategies to Attain the New US Particulate Matter Standards: Some Initial Concepts." Air & Waste Management Association International Specialty Conference on PM2.5. January 28–30, 1998. Long Beach, CA.

JD Marshall, BW Shimada, PR Jaffe, "Effect of Temporal Variability in Infiltration on Contaminant Transport in the Unsaturated Zone." Spring meeting of the American Geophysical Union. May 20–24, 1996. Baltimore, MD.

Teaching: classes taught

University of Minnesota, Minneapolis, MN.

CSE1905: Design for Grand Challenge Innovation (1 credit, undergrad), Fa2013, Fa2014.

CE3501: Intro to Environmental Engineering (3 credits, undergrad), Fa2007, Sp2008, Sp2012, Sp2013.

CE5561: Air Quality Engineering (3 credits, grad), Fa2008, Fa2009, Sp2012, Sp2013.

CE4011/5570: Design for Sustainable Development: Discovery India, Study Abroad in India (3 credits, grad + undergrad, 3 weeks), January 2013, May 2014, scheduled: May 2015.
CE5571: Design for Sustainable Development: Innovate (4 credits, grad + undergrad), Sp2010, Fa2011, Fa2013, Fa2014.
CE8490: Technologies for Sustainable Societies (2 credits, grad), Sp2007, Fa2007.

University of California, Berkeley, CA. Teaching Assistant, 2004–2005. Civil & Environmental Engineering Department.

Temasek Polytechnic, Singapore. Lecturer, 1998–1999. Chemical Technologies Department.

Teaching: curriculum development and collaborative efforts

- Developed and taught new graduate course in air quality engineering (CE5561).
- In 2013, I "flipped" the CE5561 course: lectures were online, class-time was used for discussion and problem solving.
- Developed and taught graduate- and freshman-level course in innovation for environmental solutions (CSE1905, CE5571). These classes are taught collaboratively with the business school (Carlson School of Management).
- Contributed to the Acara Summer Institute, a class (2 weeks, full-time) in Bangalore, India, to help students launch a social venture to solve an environmental or health problem in India.
- Co-developed and taught a grad/undergrad learning abroad class on civil engineering in developing countries. This 3-week class (CE 4011/5011) was co-taught in Delhi, India, in January 2013 with instructors from Minnesota and India. In May 2014, I co-taught this class in Bangalore, India.
- At Temasek Polytechnic (1998–1999), developed and taught an introductory math class for students majoring in Chemical Technologies.

Advising and mentoring

Undergraduate Student Activities

Undergraduate research projects (UROPs, directed research, or lab participation) [7]

- Matthew Bechle (CE, UMN)
- Sean DeBruzzi (CE, UMN)
- Adam Heinzen (Mechanical Eng., UMN)
- Aditya Kumar (Civil Eng., India Institute of Technology – Kanpur)
- Laura Ohman (CE, UMN)
- Diego Ponce de Leon Barido (CE, UMN)
- Bernardo Villalba Cahue (CE, UMN)

Undergraduate theses or honors projects directed [1]

- Diego Ponce de Leon Barido (CE, UMN). Honors project: "CO_2 and Growth Patterns: Will Cities Lead the Way?", May 2009. 111 pp. (Research later published in *Environmental Science & Technology*.)

Graduate Student Activities

Master's student advisees: past [9]

Research-based Masters [6]:

- Ryan Wilson, "Effect of Education Policy and Urban Form on Elementary-age School Travel," 2008.

- Katie Lundquist, “Air Quality Engineering to Reduce Environmental Injustice: Diesel PM2.5 in Southern California,” 2010.
- Adam Both, “PM2.5 Concentration in Low- and Middle-Income Neighborhoods in Bangalore, India,” 2012.
- Nik Boeke, 2012.
- Nam Nguyen, 2014.
- Srinidhi Murali, 2014.

Masters International (coursework-based) [6]:
- Nathan Warner, 2014
- Eric Svingen, 2014
- Kathleen Thurmes, 2014
- Ethan Lipscomb, 2014
- K Brook Johnson, 2014
- Jamie Strandemo, 2014

Master’s student advisees: current [7]

Masters International (coursework-based) [7]:
- Makenzie Dixon
- Adam Iversen
- Bushra Jawaid
- Matthew Simon
- Malcolm Smith
- Sarah Walsh
- Gareth Westler

Doctoral student advisees: past [3]
- Steve Hankey, “Exposure to Particulate Air Pollution During Active Travel”, 2014. Job after graduation: Assistant Professor, Virginia Tech.
- Chris Tessum, “Life cycle air quality and climate impacts of conventional and alternative light-duty transportation in the United States”, 2014. Job after graduation: Post-doc, U Minnesota.
- Joshua Apte, “Human Exposure to Urban Vehicle Emissions”, 2014. [UC Berkeley]. Job after graduation: post-doc, followed by Assistant Professorship, UT Austin.

Doctoral student advisees: current [4]
- Matthew Bechle
- Lara Clark
- Maninder Thind
- Ther Aung [U British Columbia]

Post-doctoral Student Activities

Post-doctoral researchers supervised [5]
- Kristina Wagstrom, 7/2009–8/2012. Job after post-doc: Assistant Professor, U Connecticut
- Eric Novotny, 9/2009–11/2010. Job after post-doc: Environmental Engineer, Barr Engineering
- Jill Baumgartner, 9/2010–10/2011. Job after post-doc: Assistant Professor, McGill University
- Conor Reynolds, 1/2011–1/2012. Job after post-doc: Environmental Engineer, MetroVancouver

- Chris Tessum, 1/2015–1/2016. Job after post-doc: Staff research scientist, University of Washington

Professional experience

Professor, Department of Civil and Environmental Engineering, University of Washington (UW). 2/2016–present. John R. Kiely Professorship, 2/2016–present.

Adjunct Associate Professor, Department of Civil, Environmental, and Geo- Engineering, University of Minnesota, Minneapolis, MN. 2/2016 – present.

Associate Professor, Department of Civil, Environmental, and Geo- Engineering, University of Minnesota, Minneapolis, MN. 5/2013–2/2016. **Assistant Professor**, 1/2007–5/2013.

Visiting Researcher, UC Berkeley, CA, 1/2014–5/2014; focus: air pollution impacts of transportation.

Visiting Researcher, Centre de Recerca en Epidemiologia AmbientaL [CREAL], Barcelona, Spain, 8/2010–5/2011; focus: spatiotemporal variability of air pollution, interactions between air pollution and physical activity.

Post-doctoral Research Fellow, University of British Columbia, Vancouver, BC. 2005–2006.

Independent Contract Researcher, Berkeley, CA. 2001–2005.
Designed and performed contract research on energy and the environment, including health risk assessments. Clients: California Air Resources Board (Sacramento, California), Environmental Defense Fund (Oakland, California), United Nations University (Tokyo, Japan), and the United States Agency for International Development (Jakarta, Indonesia).

Graduate Student Researcher, Lawrence Berkeley National Laboratory, Berkeley, CA. 2001–2005.

Graduate Student, University of California, Berkeley, CA. 2000–2005.

Volunteer, Ladakh Ecological Development Group, Kashmir, India. 1999.

Lecturer and International Fellow, Chemical Technologies Department, Temasek Polytechnic, Singapore. 1998–1999.

Air Sciences Consultant. Environ Corporation, Emeryville, CA. 1996–1998.

Environmental Security Intern, The Pentagon, Washington, DC. Summer 1995.

Professional service

University of Minnesota

- **Director, Master's International (1/2010–1/2016)**
  Co-founded a new Master's program in my department. Students complete 2–3 semesters of coursework in residence at UMN, then earn experiential credits via (option 1) 27 months service

in the Peace Corps while working on water and sanitation projects or, alternatively (option 2) 10 months service in the Acara program. After 2-3 years (~1 year at UMN, plus either ~1 year in Acara or ~2 years in the Peace Corps), students earn an MS with a focus in environmental engineering or water resources engineering. With Professor Gulliver, I initiated the program, including defining policies governing student activities and writing the agreement between UMN and the Peace Corps. I currently co-oversee day-to-day management of the program and student recruitment and advising. Program size: 3–5 incoming students per year.

- **co-Director, Acara (1/2008–1/2016)**
  Acara offers classes in Minnesota, India, and Africa for students to identify an environmental or health problem, propose a sustainable local solution, and launch a for-profit or not-for-profit organization to address the problem. External judges evaluate teams' ideas; Acara and outside groups fund students to test and launch their ideas. I co-founded and co-direct the program with Mr. Fred Rose, including teaching classes in Minnesota and in India, mentoring student teams, and helping winning teams develop their ideas and find funding. We have had several students travel to India to test their ideas or to start new projects in existing organizations. One team has received venture funding ($100k–$1million) and is a growing business employing >20 people in Madurai, India; their focus is drip-irrigation and other agricultural technologies for small-plot farmers.

- **Chair (2014-1/2016) and Member (2009–1/2016), Curriculum Committee, Sustainability Studies Minor**
  This committee provides oversight and assists with decisions for academic requirements associated with the Sustainability Studies Minor at UMN.

- **Faculty advisor, UMN Chapter of Engineers Without Borders (2007–2013)**
  Advised a student group that designs and builds drinking water, wastewater, and sanitation projects in low-income communities overseas. EWB-UMN has multiple active projects overseas (e.g., Guatemala, Honduras, Uganda), with about 100 student members actively participating.

- **Chair, Department of Civil Engineering Scholarship Committee (2008–2012)**
  Oversaw a $100,000 annual budget for undergraduate student scholarships.

- **Member, Sustainability Goals and Outcomes Committee (2008–2010)**
  Provided guidance and assistance to UMN Vice President O'Brien regarding how UMN can chart a path towards measuring and reducing its environmental impact.

Other

- Associate Editor, *Development Engineering* (2015–).
- Associate Editor, *Environmental Health Perspectives* (2016–).
- Reviewer for *Atmospheric Environment, Aerosol Science and Technology, Environmental Science and Technology, Environmental Health Perspectives, Indoor Air*, *Journal of the American Planning Association, Journal of Infrastructure Systems, Science of the Total Environment,* and *Journal of Transport and Land Use*
- Member, United Nations Environmental Program advisory group (UNEP/SETAC Life Cycle Initiate - Task Force 4, Particulate Matter sub-group), 2006–2011
- Testified three times to Minnesota State Legislature regarding transportation greenhouse gas emissions.
- Technical (content) advisor for two children's books: *Awesome Air* (ABDO Publishing Group, Edina, MN. 2008) and *Let it Blow! Learn about Air* (The Children's World, Mankato, MN. 2010).

- Organized multiple sessions for International Society for Environmental Epidemiology annual conferences.

Pending research support

(Federal grants are underlined.)

"Air Pollutants and Cardiovascular Risk: Investigating Thresholds with Pooled Cohorts and Electronic Health Records", NIH, 2016-2020, **co-Investigator, $3 million.**

Objective: Investigate the shape of the concentration-response function for outdoor air pollution, based on datasets covering millions of residents in the U.S.

Current research support

(Federal grants are underlined.)

"SRN: Integrated Urban Infrastructure Solution for Sustainable, Healthy and Livable Cities", NSF, 2014–2018, **co-Investigator, $12 million.**

Objective: multi-university research network on sustainable cities.
Status: recommended for funding

"Center for Air, Climate, and Energy Solutions", US EPA, 2015–2020, co-lead **(dual-PI), $10 million.**

Objective: Investigate regional differences, multiple pollutants, and development and dissemination of tools for addressing air quality & climate.
Status: passed peer review; currently in programmatic review

"Cardiovascular health effects of particulate air pollution in Andhra Pradesh, India", European Research Council, 2014–2018, **collaborator, €1.4 million.**

Objective is to quantify the association between exposure to air pollution and biomarkers of cardiovascular disease. Exposure estimates are derived from models and measurements.

"Experimental interventions to facilitate clean cookstove adoption, promote clean indoor air, and mitigate climate change", US EPA, 2013–2017, **co-Principal Investigator, $1.5 million.**

Objective is in situ measurement of emissions from a cookstoves change-out in rural India.

Previous grants

(Federal grants are underlined.)

"Air pollution, environmental justice, and urban form", National Science Foundation, 2013–2016, **Principal Investigator, $310,000.**

Objective is to use panel data (time series data for many cities) to explore empirical evidence of how changes in urban form relate to air pollution and environmental justice. Pollution estimates are from nationwide satellite-based land-use regression models.

"Urbanization and exposure to air pollution (Hyderabad, India)", Global Programs and Strategies Alliance, University of Minnesota, 2012–2014, **Principal Investigator, $75,000.**

Objective is to measure air pollution in communities along a rural-to-urban gradient in and around Hyderabad, India to explore the effect of urbanization on air pollution.

"Stove change-out: A 'win-win-win' for development, environment, and health?", Discovery Grant, Institute on the Environment, University of Minnesota, 2011–2013, **Principal Investigator, $300,000.**

Objective is to measure air pollution and health impacts of a stove change-out in rural India, while exploring opportunities for financially sustainable businesses.

"Air pollution impacts of conventional and alternative fuels: a spatial and temporal life cycle analysis decision support tool", UMN Institute for Renewable Energy and the Environment, 2009–2014, **Principal Investigator, $599,786.** Co-PI: J Hill, Ecology / Applied Economics, University of Minnesota

Objective is to compare air pollution and health impacts of fossil fuels versus bio-fuels, considering the lifecycle of fuels (production plus consumption) and environmental justice (how pollution exposures change for specific groups).

"The Bridge Program: CIHR Strategic Training Program bridging public health, engineering and policy research", Canadian Institutes of Health Research (CIHR), Ottawa, 2009–2014, **Co-Investigator, CND$19 million.** (2 PIs, 53 co-Investigators.)

Objective is interdisciplinary training program in environment and health, University of British Columbia.

"Smartphone-based travel experience sampling (UbiHappy Phase I): Transportation, health, and happiness", SLPP TechPlan, ITS Institute, University of Minnesota, 2011–2012, **Co-Investigator, $578,000.**

Objective is to develop a smartphone application prototype to investigate travel behavior patterns and travel-related health and well-being impacts.

"Air pollution and urban form: evidence from satellite data", NSF. 2009–2011, **Principal Investigator, $199,970.**

Using satellite data for several cities internationally, the objective is to obtain cross sectional empirical evidence as to how urban form (e.g., sprawl versus infill development) influences air pollution concentrations.

"The Acara Summer Institute for High Impact Businesses", National Collegiate Inventors and Innovators Alliance, 2009–2011, **Principal Investigator, $20,500.**

Objective is to develop and offer a two-month summer program for intensive incubation of selected social venture teams from the Acara Challenge.

"Impact of emission reductions on exposures and exposure distributions: application of a geographic exposure model", EPA. 2007–2011, **Principal Investigator, $459,276.**

Objectives include calculating intake fraction for several sources in California's South Coast Air Basin, and exploring how various emission reduction options would impact average exposures and exposure distribution (environmental justice).

"Decision tools for assessing transportation impacts of school policy and school choice", University of Minnesota Intelligent Transportation Systems / State and Local Policy Program / Center for Transportation Studies. 2008–2010. **Co-Investigator, $78,400.**

Objective is to determine the impact of school policy on environmental and health impacts of children's school commutes, and to develop a software tool to allow schools to explore this issue on their own.

"Comparing GHG emissions and health impacts of emissions of traditional pollutants from electric and traditional motorized transport modes in China", The Energy Foundation, Beijing, 2008–2009, **Co-Principal Investigator, $78,812.** PI: C Cherry, Civil & Environmental Engineering, University of Tennessee.

Objective is to compare environmental impacts of fossil fuel versus electric vehicles.

"Urban environmental health: air pollution in Bangalore, India", University of Minnesota Grant-in-Aid. 2008–2009, **Principal Investigator, $39,898.**

Objective is to measure air pollution in a low- and a medium-income neighborhood in Bangalore, to understand how exposure concentrations change over time as a result of rural-to-urban migration.

"Assessment of transportation policy and technology options to reduce greenhouse gas emissions in Minnesota", Minnesota State Legislature. 2007–2008. **Co-Principal Investigator, $300,000.**

Objectives include estimating potential reductions in climate-change emissions based on three policy strategies: changes to fuels; changes to motor-vehicle; and, 'smart growth' and other land-use planning options.

"School travel and the implications for advances in transportation related technology", University of Minnesota Intelligent Transportation Systems / State and Local Policy Program / Center for Transportation Studies. 2007–2008. **Co-Investigator, $97,400.**

Objective is to survey elementary-school parents to understand which travel modes they choose for their children and why. Based on those results, we will estimate impacts of shifts in school policies such as modifying busing or school-choice rules.