

THESIS

INHALABLE HEAVY METALS AND RESPIRABLE SILICA DUST EXPOSURES AT A
MUNICIPAL LANDFILL

Submitted by

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ABSTRACT

FEASIBILITY STUDY FOR INHALABLE HEAVY METALS AND RESPIRABLE SILICA DUST EXPOSURES AT A MUNICIPAL LANDFILL

Occupational respiratory exposures are a significant exposure route in the United States, with millions of workers in required respiratory protection programs, due to workplace exposures to fumes, dusts, bioaerosols, particles, and other respiratory hazards. Exposure to excessive workplace respiratory hazards may lead to occupational diseases such as silicosis, heavy metals poisoning, or impacts to various organs including the lungs, liver, and kidneys. One work sector that has not been evaluated for respiratory workplace exposures are landfill workers. There are 22,302 municipal landfill workers in the United States across. Landfill worker exposures are of concern since this population operates heavy machinery like construction operations, potentially exposing the workers to airborne hazards. This study was conducted to quantify airborne exposures to landfill workers and to identify the risks that are associated with their daily tasks. The researchers aimed to (1) determine airborne heavy metal particles to which landfill workers are exposed; (2) determine the exposure to respirable silica particles; and (3) identify current worker protections and their effectiveness based on the study results. Nine silica and nine heavy metal personal airborne samples were taken on seven landfill workers during their normal workday tasks. Worker exposure concentrations were compared to occupational exposure limits published by the US Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH) when there was no OSHA exposure limit. Of the seven workers sampled, one worker had a single sample in

exceedance of the OSHA Action Limit for silica at 31.1 ug/m^3 while the overall 95th percentile of all samples was at 28.89 ug/m^3 . Many of the heavy metal samples were non-detectable which limited the statistical analysis. All iron sample results were less than 1% of the OSHA Permissible Exposure Limit (PEL) of 10 mg/m^3 and manganese samples were at 12% of the ACGIH Threshold Limit Value of 0.01 mg/m^3 . Sample analytical detections did occur for aluminum, magnesium, and zinc, but the metals had less than 50% detection rate. These samples were statistically analyzed but none showed any substantial levels of exposure, all within the American Industrial Hygiene Association's Category 0, meaning that the concentrations were less than 1% of their respective occupational exposure limits. Mitigations in exposure with a focus on silica have been considered for the landfill site, including emphasis on the effectiveness of proposed and existing engineering controls and assuring that these controls are able to operate at their designed efficiency. Workers exposed above the action limit for silica have an increased risk of respiratory disease. As noted in a National Institute for Occupational Safety and Health (NIOSH) action limit publication, "The action limit is set to minimize the probability of even a low percentage of daily employee exposure exceed the standard" which confirms that exceedances at or above the action limit should initiate careful attention to monitor for the potential of day-to-day overexposures to workers. Worker exposure to heavy metals should be investigated further, since this was a feasibility study with a small sample size, but collected data has variability in whether there was an elevated risk to respiratory health.

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CHAPTER 1: INTRODUCTION

Landfilling work is a hazardous occupation, including physical, chemical, biological and thermal stresses. In the United States, solid waste landfills are categorized under 562212 of the North American Industry Classification System (NAICS), and the 2020 US Census reports 22,302 workers in this sector across 1501 establishments.^[1] NAICS code 562212 specifically includes only solid waste landfill workers and does not include other types of waste management, such as hazardous waste. While this is a smaller occupation, it is the belief of the researchers that the health of all workers is valuable, and every worker deserves quality work to quantify and protect their health. Silica and heavy metals particles present a concerning risk to acute and chronic worker health since these agents may be found in the landfill soil and in the waste materials. Minimal research on landfill workers has been performed to quantify their occupational exposures, therefore the focus of this research project was to quantify silica and heavy metal airborne exposures to these workers.

Within a landfilling operation there are many potential sources of contaminants brought in with waste materials to which workers could be exposed. Potential contaminants include silica, metals, and biologicals, such as pathogenic microbes. When receiving waste, the landfill employees direct trucks with waste to the current area being landfilled, where they dump the contents of the truck. The waste content is then compacted and moved by the heavy equipment on site. In addition, landfill personnel may use water trucks as dust suppression method on site.. After the daily waste is received, workers cover the waste-dumping area with topsoil to cover and bury the waste. The waste materials may contain a variety of contaminants, and the process of moving and manipulating the soil and waste materials with heavy machinery generates particulate.^[2] These trucks haul waste to the landfill from residential, agricultural, industrial and

construction/demolition sites. Collectively, these waste sources may contribute to worker exposures, yet those potential exposures have not been evaluated to determine if landfill workers are at increased risk of occupational disease.

The research team of the current study prioritized the assessment of airborne silica and heavy metals at landfilling operations based on the limited studies that focused on landfilling operations. Researchers found that heavy machine operations at a soil excavation site, heavy machine work similar to landfilling operations, created significant silica-containing dust based on samples from the ambient environment, in heavy machinery, and on personnel.^[3] In addition, researchers in Poland found that many landfill sites have variable heavy metal concentrations in soil samples, however the metals could not be correlated specifically to the waste received.^[4] Given the limited research for this work sector, the current study was performed to evaluate the risk of occupational exposure to silica and heavy metals exposures to workers at a public landfill.

CHAPTER 2: LITERATURE REVIEW

Silica and heavy metals in municipal landfill settings are potential respiratory exposures for workers based on the job tasks and material wastes that are introduced to the worksite daily in large quantities. Occupational silica exposure causes one of the most dangerous and damaging respiratory occupational diseases, per the United States Centers for Disease Control (CDC): “Silicosis, an irreversible but preventable lung disease, is caused by inhalation of respirable crystalline silica (RCS). Work exposures to RCS also cause other serious diseases, including lung cancer.”^[5] Studies relating to silica exposure from heavy machine operations provide the basis for investigating silica exposure at landfills where heavy machinery is used. In 2000, Pannell and Grogin^[3] demonstrated that heavy equipment (e.g., scrapers, dozers, and backhoes) generates high concentrations of silica on the exterior of cabins and that cabin air filtration had varying levels of efficacy on reducing airborne concentrations to safe levels when sampling directly on workers. Their research was conducted at a soil excavation operation, which is not a landfilling operation, however the type of work is similar to work conducted at the landfill. Podlasck et al.,^[4] showed that heavy metals were deposited in the soil at municipal landfills, and that metal concentrations varied between sites. The authors’ findings demonstrated that landfill waste is a source of heavy metal contamination, in addition to naturally occurring heavy metals in soil. Further, data on heavy metals in Colorado soil samples were compiled by the United States Geological Survey, USGS, in a 2006 report,^[6] indicating high concentrations of heavy metals in soil which may be a health concern for workers that disturb the soil. In addition, vehicle traffic generates airborne particles especially on dirt roads, which may expose workers in the landfill that are working around constant truck traffic. Wagner et al.,^[7] analyzed road dusts that can be generated from vehicles as both a method of suspension and a source of metals

exposure. To reduce worker and public exposure to airborne contaminants from unpaved roads, United States Department of Agriculture (USDA) Code 373^[8] provides guidelines for mitigating dust generation from unpaved roads as a method of exposure prevention from emissions of particulate matter. However, the Code emphasizes the likelihood of particulate generation. In the current study, the sampling site included the use of heavy truck traffic on unpaved roads, which was not being mitigated by any dust controls.

Landfills receive an abundance and variety of waste to which workers may be exposed during landfill operations, however, there are no studies that have characterized landfill worker exposure to airborne silica or heavy metals. Exposures to silica and heavy metals can be introduced from waste as well as environmental sources based on where the site is located. Waste characterization data are available from the United States Environmental Protection Agency, where studies are compiled from States in the US that have conducted surveys of waste volume received, waste types, and waste origin (e.g., residential, construction and demolition, and industrial).^[9] Larimer County, CO performed a waste characterization study in 2016 that specified the types of waste that were received at the Larimer County landfill, which receives all waste from the county. This report provides in-depth analysis of waste delivered to the Larimer County landfill, which is in Northern Colorado, similar to the landfill in the current study. Relevant to the current study, the authors specified categories for Aluminum UBC's (used beverage can), Mixed Ferrous Metals, Mixed Non-Ferrous Metals, and Inert Materials (e.g., dirt, rock, sand, and brick).^[10] In 2015 there were 356,912 tons of waste delivered to the Larimer County landfill,^[10] and the percentages of the materials relevant to the current study are: 0.5% or 1784 tons of Aluminum UBC's, 4.0% or 14276 tons of Ferrous Metals, 0.4% or 1427 tons of Non-Ferrous Metals, 10.9% or 38903 tons of Inert Materials. These waste material amounts

demonstrate that there are considerable sources of metallic wastes disposed in Northern Colorado, which the authors of the current study extrapolated to the current study site. The Larimer County landfill additionally reported a high volume of steel. According to the EPA, “ferrous metals (iron and steel) are the largest category of metals in municipal solid waste”^[11] emphasizing the potential exposure to workers. Steel waste also causes concern of worker exposure to manganese in landfilling operations since manganese is a component of steel. “Average world unit consumption of manganese in steel is estimated at 11 kg/t” as reported by the International Manganese Institute.^[12] Although the Larimer Country landfill characterization does not specify tons for iron and steel individually, the number is large enough to assume there could be substantial sources of manganese from steel waste present in landfills. Corrosion of steel is a common occurrence, both through contact with acids and rust on non-stainless steels. Additionally physical impacts on steel in waste, which may occur from the hardened steel blade of a bulldozer, can scrape and gouge materials from steel waste items. Physical impacts on the wastes may generate particles, but that generation may be elevated by weakened metals that have been corroded; however, the metal corrosion is not a necessary component for particle generation from physical impacts on steels in waste.^[13]

The composition of Non-Ferrous Metal waste includes lead, copper and zinc as reported by the EPA,^[14] creating a potential source of worker exposures to these metals. However, these metals are highly recycled in the United States, with 1,770 thousand tons recycled of 2,510 thousand tons produced in 2018, with the remaining 740 thousand tons landfilled.^[14] Comparatively, 19,200 thousand tons of ferrous materials with 8,670 thousand tons recycled and 10,530 thousand tons landfilled.

Chromium is used in products in a variety of industries, though some products only use trace amounts for processes like tanning or pigmentation of paints. However, the increased use of stainless-steel products in daily life has increased overall chromium consumption,^[15] as a component of stainless steel.

Arsenic, a highly toxic metal, may also be of concern at landfills since it is commonly found in soils. The Colorado Department of Public Health and Environment (CDPHE) has published guidance for risk management of arsenic-containing soils. The reference authors note that arsenic is a naturally occurring mineral that has higher concentrations in highly mineralized areas that have been mined, as well as many different anthropogenic sources from multiple industries.^[16] Since arsenic commonly occurs in Colorado soils, worker exposure to arsenic due to soil disturbance may be a concern that should be quantified given that the current study is in Colorado.

CHAPTER 3: PURPOSE AND SCOPE

Purpose

The purpose of this study is to determine the worker airborne exposures to respirable silica particles and inhalable heavy metal particles during specific occupational tasks at a Colorado municipal landfill. The sampling data will be used to provide an estimated contaminant exposure level for specific job tasks performed at the landfill.

Scope

This project will be performed at a Colorado municipal landfill that has approximately ten employees on-site that do a variety of tasks in mechanical equipment and on foot throughout the site. All employees who consent to participate will be sampled so that the researchers may understand where exposures may occur and what tasks and work zones present the most risk, if any, to worker health. If warranted, based on the sampling results, worker protection strategies may be developed to protect worker health.

Hypotheses and Research Questions

- H1: Workers are not overexposed to airborne silica dust as compared to established exposure limits from OSHA and ACGIH.
- H1 Alternative: Workers are overexposed to airborne silica dust as compared to established exposure limits from OSHA and ACGIH.
- H2: Workers are not overexposed to airborne heavy metals as compared to established exposure limits from OSHA and ACGIH.
- H2 Alternative: Workers are overexposed to airborne heavy metals as compared to established exposure limits OSHA and ACGIH.

CHAPTER 4: METHODS AND MATERIALS

Site Identification

The research was performed at a Colorado municipal landfill from June 20-26, 2025 (weather conditions found in Appendix A) and included two job categories that were evaluated: heavy machine operators, and spotters for traffic direction. The month of June was identified for sampling based on the site supervisor's observation of maximum dust generation during May and June, and dust mitigation was not used during the sampling campaign due to staffing shortages. The site did not receive hazardous waste and was reported by the site supervisor to be in compliance with the Resource Conservation and Recovery Act (RCRA) standards. There were a total number of 12 employees at the site, which limited the sample size number for this study. Work shifts were 10 hours in duration. The site in the receives 300-400 truckloads of waste material per day, including residential garbage trucks, long bed haul trucks, and dump trucks.

Recruitment of Participants

The Colorado State University Institutional Review Board approved all aspects of this research. Informed consent was obtained from all study subjects prior to the execution of the study. Workers at the landfill were the only group of individuals solicited for participation.

Sampling Procedures

Sampling media were obtained from the Wisconsin Occupational Health Laboratory and included SKC Parallel Particle Impactors (PPI) (Model 225-385A) for silica and Zefon AA MCE 37-mm cassette filters for heavy metals. SKC AirChek TOUCH air-sampling pumps (Model 220-5000TC) were used with both the PPI and Zefon filters, calibrated to a flowrate of two liters

per minute in accordance with NIOSH Method 7500^[17] for silica and NIOSH Method 7303^[17] for heavy metals.

On each sampling day, the sampling pumps were attached to the workers on their hip, clipped into their belt or waistband of their pants. The flexible tubing that connects the pump and the sampling filter was secured on the back of the workers and over the shoulder to attach the sampling filter to the lapel of the worker. Sampling filters were attached to the open end of the tubing, which was secured in the breathing zone of the worker, defined as, “a hemispheric area forward of the shoulders within a 6-to-9-inch radius of a worker’s nose and mouth”.^[18] All air sampling pumps that were used in this study were calibrated in the morning prior to their use and then post-calibrated each day after use.

Samples were taken across a variety of times on site, but each sample was taken during a 10-hour shift. The earliest shift and samples began at 0530 running to 1530, with other samples starting at 0600, and 0830. Some workers had an occasional extended shift and others needed to end sampling early due to personal reasons, ranging from 12-hour shifts to 6.5-hour shifts, but most samples were 10-hours in duration. Most employees were sampled four times, but not all workers completed four full sampling days due to personal reasons resulting in nine silica samples and nine heavy metal samples. Across the four sampling days, workers were sampled for silica twice and heavy metals (HM) twice, switching each day resulting in a sampling order of HM, silica, HM, silica. The workers were categorized into two similar exposure groups on their sampling day: operator or spotter. Operators controlled heavy machinery and spotters directed incoming traffic and helped guide in trucks as needed; however, both tasks were within the area that was actively being landfilled. At the completion of the work shift, the sampling media/pumps were collected, and the sampling filters were then sealed, packaged, and shipped to

the Wisconsin Occupational Health Laboratory (WOHL) in Madison, Wisconsin for analysis. The samples were analyzed using NIOSH method 7500 for silica and NIOSH method 7303 for a suite of ten common heavy metals on the MCE filters.

Data Analysis

The reported sample concentrations were adjusted to 8-hour samples for comparison to the 8-hour OSHA PEL or the 8-hour American Conference of Governmental Industrial Hygienists' Time Weighted Average, ACGIH TLV. The adjustment to 8-hour exposures was performed using Equation 1.

$$8\text{-Hr AEC} = (T_s/480 \text{ min}) \times (C) \quad \text{Equation 1}$$

Where,

8-Hr AEC = the 8-hour adjusted exposure concentration

T_s = Time sampled in minutes

C = Sample concentration in $\mu\text{g}/\text{m}^3$

The adjusted 8-hour TWA data were entered into IHStats®, a Microsoft Excel application developed by the American Industrial Hygiene Association (AIHA) for analyzing occupational health data and providing the probability of overexposure by generating 95th percentiles and checking for lognormality of data.

The IHStats® application provided the probability of multiple sampling events occurring within the same area, such as the current study worksite. IHStats® presents the sampling data with a 95th percentile confidence interval, which is the upper limit of possible results, and the 95th percentile point estimate is compared to occupational exposure limits (OEL). The 95th percentile

was reported in ug/m^3 which compares directly to the OEL, and this comparison then provides the percent dose of the OEL. The calculated OEL percentages were reported in five exposure categories that are defined in “*A Strategy for Assessing and Managing Occupational Exposures*”^[19]: Category 0, less than 1% of the OEL; Category 1, 1-10% of the OEL; Category 2, 10-50% of the OEL; Category 3, 50-100% of the OEL; and Category 4, Greater than 100% of the OEL. These exposure categories were used to determine the probability of exposure for a similar exposure group based on the collected samples and provided recommended controls for each exposure category.

CHAPTER 5: RESULTS

Silica

The workers at the landfill in the current study used multiple types of heavy equipment, which contributed to the generation of airborne particulate. The machines included an excavator, sheepsfoot roller, two bulldozers, and two haul trucks. These machines all had enclosed cabs and were pressurized, but the specifics of the filtration systems, or equipment models, were not disclosed to the research team. These machines were operated by the operators and were ~100 yards (91.4 meters) from the on-site spotters, potentially exposing them to airborne particulate. Due to worker job rotation during the day, it was assumed that all machines were used and contributing to the generation of dust collected in samples. Nine silica samples were collected and the sample concentrations ranged from 6.2-26 ug/m³ (average = 11.8 ug/m³) for the full shifts or 5.8-31.1 ug/m³ (average = 13.53 ug/m³) when adjusted to an 8-hour shift using Equation 1 (Table 1). The average silica sample concentrations for operators were 15.68 ug/m³ and the average silica sample concentrations for spotters was 10.87 ug/m³. As shown in Table 1, there were no sample concentrations above the OSHA PEL of 50 ug/m³, but there was a single sample that exceeded the OSHA action limit of 25 ug/m³.

Table 1: Silica sampling results for full shift time-weighted averages and adjusted 8-hour time weighted averages.

Job Task	Volume Sampled (L)	Time Sampled	Total Weight in ng	Full Shift Conc. in ug/m³	8-hour Adjusted in ug/m³
Operator	1158	579	12000	10	12.1
Operator	1149.55	577	9200	8	9.6
Operator	1148.42	574	30000	26	31.1
Operator	1171.82	585	16000	14	17.1
Operator	1137.67	572	8200	7.2	8.6
Spotter	1065.15	533	6600	6.2	6.9
Spotter	742.12	409	5100	6.9	5.9
Spotter	1149.94	575	9100	7.9	9.5

Spotter	1021.86	510	20000	20	21.3
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The silica sample concentrations were lognormally distributed as reported by IHStats®, with a geometric standard deviation (GSD) of 1.727, which indicated relatively low variability between samples. A GSD less than 3 does not require further categorization of similar exposure groups for data analysis in IHStats®. These silica sample data are displayed in Figures 1-4, using all data in Figures 1 and 2, and then categorizing by job task in Figures 3 and 4.

The probability density curve for all 8-hour adjusted silica samples is found in Figure 1, using the OSHA PEL of 50 ug/m³ for comparison. The X-axis is the sampled percentage of the PEL with an overlay of the AIHA exposure categories ranging from 0-4. The 95th percentile line (yellow) indicates a sample concentration point estimate of 28.89 ug/m³, below which 95% of the samples occurred. Compared to the OSHA PEL of 50 ug/m³, this exposure data set is a Category 3 exposure, meaning that 95% of the samples are estimated to be at 50-100% of the PEL. However, because the 95% upper tolerance limit point estimate exceeded the PEL, it could not be concluded with 95% confidence that the 95th percentile point estimate of 28.89 ug/m³ is the true point estimate.

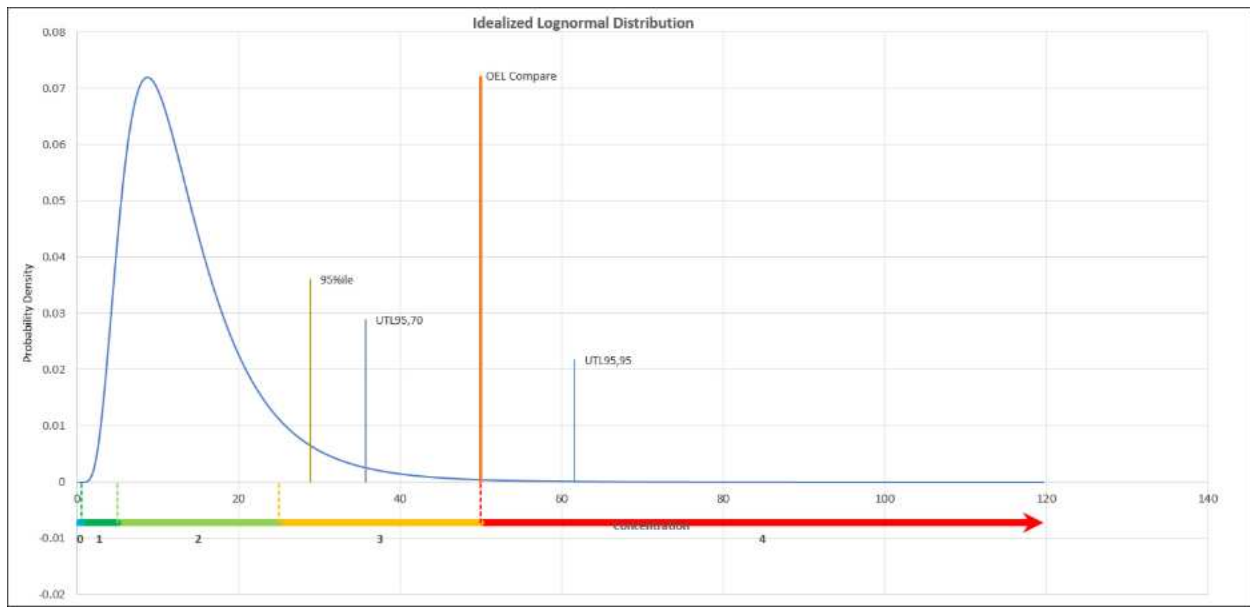


Figure 1: Probability Density Curve for all 8-hour adjusted Silica Samples Compared to the OSHA PEL.

The probability density curve for all 8-hour adjusted silica samples using the OSHA Action Limit of 25 ug/m^3 for comparison is shown in Figure 2. The 95th percentile line (in yellow) indicates a sample concentration point estimate of 28.89 ug/m^3 , below which 95% of the samples occurred. Compared to the OSHA Action Limit, this exposure would be an AIHA Category 4 exposure, which means that the 95th percentile was above the action limit, and this is an unacceptable exposure that needs to be addressed immediately through resampling, medical surveillance programs and prompt remediation.

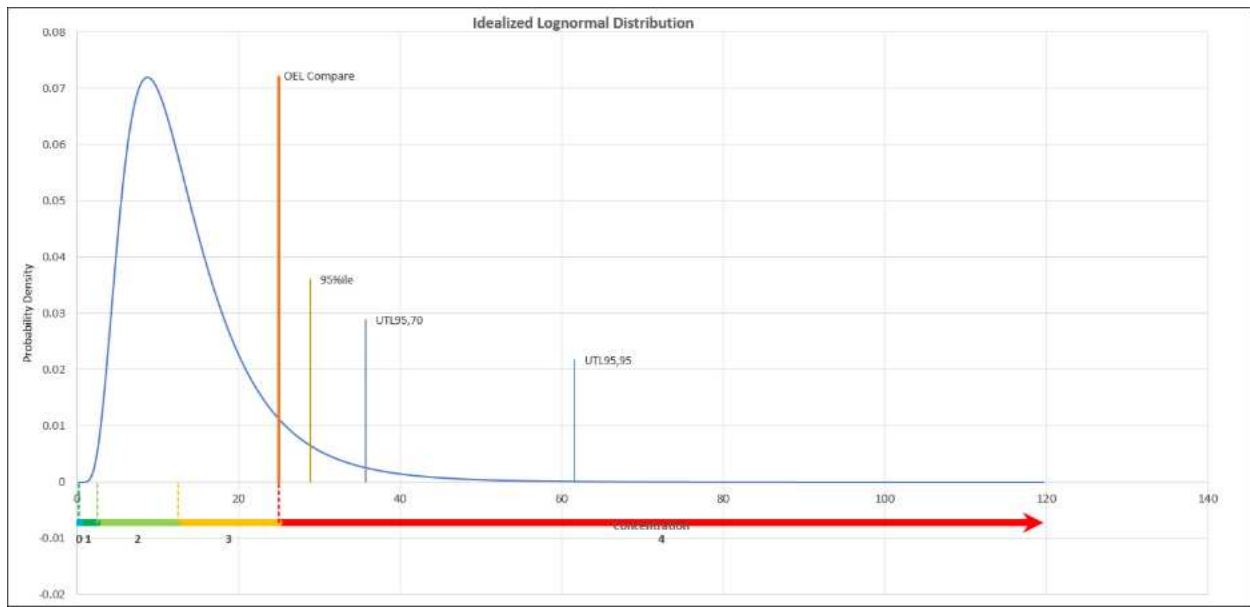


Figure 2: Probability Density Curve for all 8-hour adjusted Silica Samples Compared to the OSHA Action Limit.

The silica samples collected from operators are displayed in Figure 3. This dataset was examined as a subset of the entire silica dataset to determine if there were observable variations between the two onsite job tasks. The x-axis is the sampled percentage of the OEL with an overlay of the AIHA Exposure Categories ranging from 0-4. The 95th percentile line (in yellow) demonstrates the upper limit for exposure which was 32.77 $\mu\text{g}/\text{m}^3$. Compared to the OSHA Action Limit of 25 $\mu\text{g}/\text{m}^3$, this exposure would be an AIHA Category 4 exposure, meaning that there is an unacceptable immediate risk that must be remediated promptly with sampling and efforts to remediate the burden of exposure.

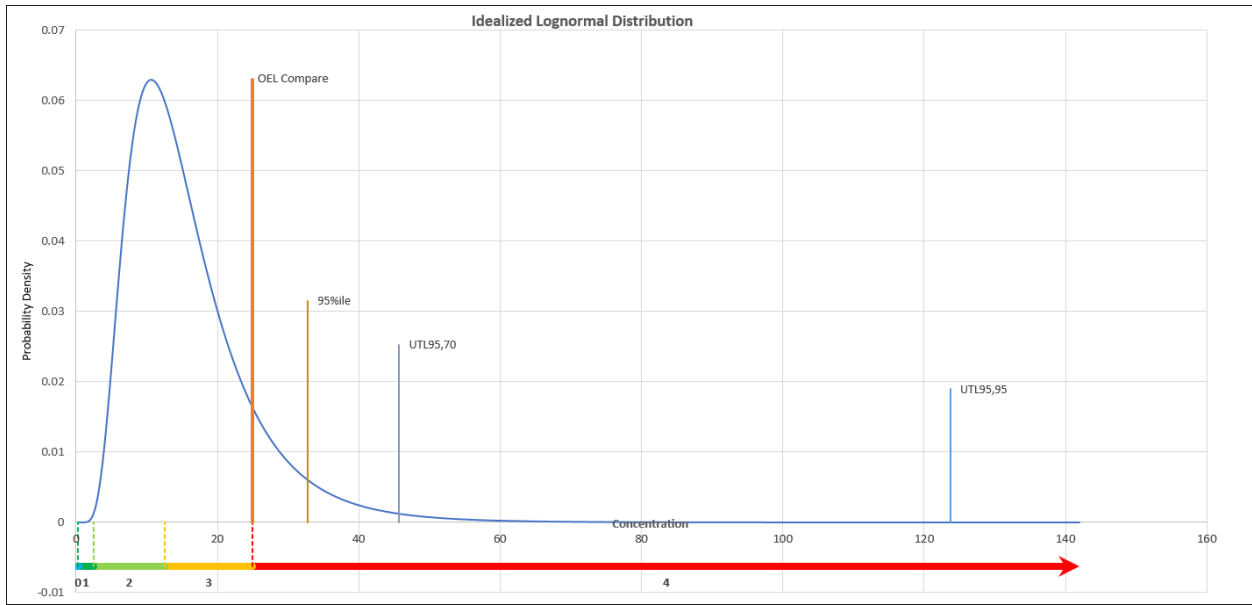


Figure 3: Probability Density Curve for Operator 8-hour Adjusted Silica Samples Compared to the OSHA Action Limit.

Figure 4 is representative of the silica sampling data that were collected on spotters. This dataset was examined as a subset of the entire silica dataset to determine if there were observable variations between the two onsite job tasks. The x-axis is the sampled percentage of the OEL with an overlay of the AIHA Exposure Categories ranging from 0-4. The 95th percentile line (in yellow) demonstrates the upper limit for exposure which was 24.35 $\mu\text{g}/\text{m}^3$. Compared to the OSHA Action Limit of 25 $\mu\text{g}/\text{m}^3$, this exposure would be an AIHA Category 4 exposure, meaning that there is an unacceptable immediate risk that must be remediated promptly with sampling and efforts to remediate the burden of exposure.

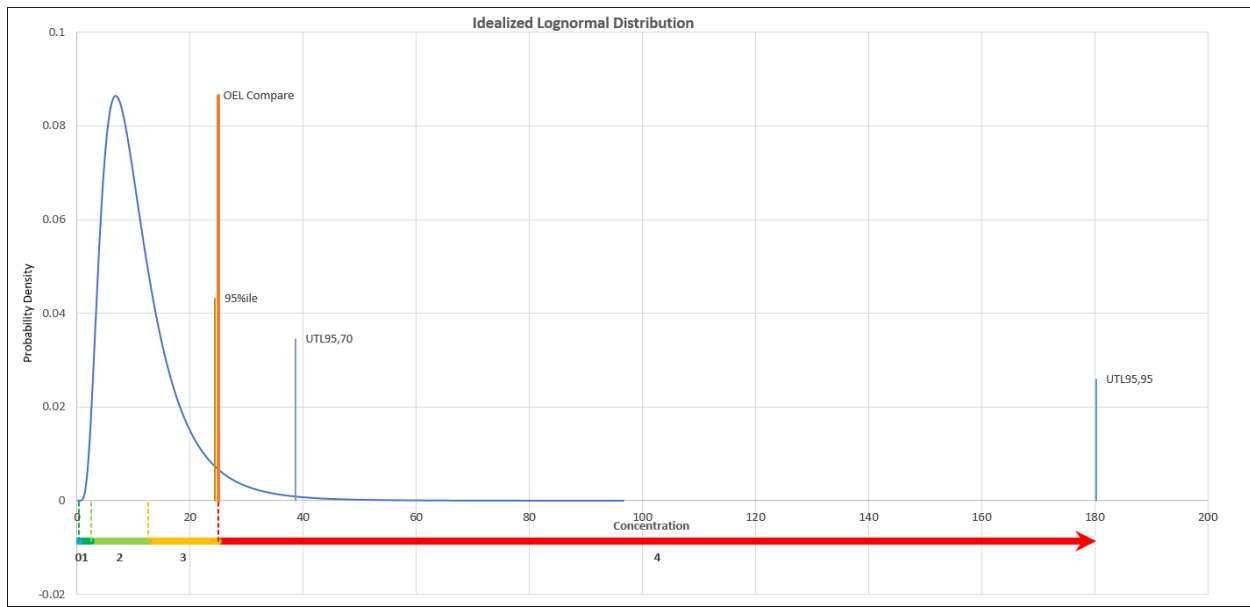


Figure 4: Probability Density Curve for Spotter 8-hour Adjusted Silica Samples Compared to the OSHA Action Limit.

In comparing the two job categories of operators and spotters, it was noted that there were observational differences between the exposures. The spotters had a smaller 95th percentile point estimate exposure of 24.35 ug/m³, whereas the operators had a similar 95th percentile point estimate 32.55 ug/m³ as compared to the average 95th percentile for all the exposures (31.1 ug/m³). These results lack statistical power, based on the low sample numbers, which is shown in the spotters dataset having a much higher UTL around 180 ug/m³ as compared to the operators dataset UTL of approximately 125 ug/m³.

Heavy Metals

Nine personal airborne respirable dust samples were collected and analyzed for ten metals (Table 2) that were adjusted to 8-hour time-weighted averages for comparison to OELs using Equation 1. None of the metal sample concentrations exceeded the OSHA PELs or ACGIH TLVs.

Table 2: Heavy Metals Sample Results

Job Task	Volume (L)	Aluminum (mg/m³)	Arsenic (mg/m³)	Chromium (mg/m³)	Copper (mg/m³)	Iron (mg/m³)	Lead (mg/m³)	Magnesium (mg/m³)	Manganese (mg/m³)	Nickel (mg/m³)	Zinc (mg/m³)
Operator	1158.45	<0.0086	<0.00065	<0.0035	<0.0013	0.0045	<0.0016	<0.0043	<0.00022	<0.00086	<0.0016
Operator	1473.1	<0.0068	<0.00051	<0.0027	<0.0010	0.0048	<0.0012	<0.0034	<0.00017	<0.00068	<0.0012
Operator	163.01	<0.061	<0.0046	<0.025	<0.0092	<0.031	<0.011	<0.031	<0.0015	<0.0061	<0.011
Spotter	1135.77	0.011	<0.00066	<0.0035	<0.0013	0.023	<0.0016	0.0069	0.00041	<0.00088	<0.0016
Spotter/ Hauler	747.33	<0.013	<0.0010	<0.0054	<0.0020	0.01	<0.0024	<0.0067	<0.00033	<0.0013	<0.0024
Operator	1228.54	0.015	<0.00061	<0.0033	<0.0012	0.035	<0.0015	0.0081	0.0006	<0.00081	0.0034
Operator	1107	<0.009	<0.00068	<0.0036	<0.0014	0.013	<0.0016	<0.0045	0.00023	<0.0009	<0.0016
Spotter	934.12	<0.011	<0.0008	<0.0043	<0.0016	0.019	<0.0019	0.0058	0.00034	<0.0011	<0.0019
Spotter/ Hauler	1024.67	0.012	<0.00073	<0.0039	<0.0015	0.023	<0.0018	0.0072	0.0005	<0.00098	<0.0018

As seen in Table 2, arsenic, chromium, copper, lead, and nickel were not detected above the limit-of-detection (LOD) and were eliminated from further analyses. Eight of the nine iron sample concentrations were above the LOD, and five of the nine manganese samples were above the LOD. The aluminum, magnesium, and zinc sample concentrations included several samples above the LOD and were analyzed using IHStats®. All heavy metals were compared to OSHA PELs when available, but when there was no OSHA standard, ACGIH TLVs were used as a comparison.

Figure 5 is the probability density curve for the iron samples that were collected, and these samples had a GSD of 2.122 which indicated that no further categorization of exposure groups was necessary. It was also verified that the data were lognormally distributed. The OSHA PEL for iron is 10 mg/m³ and eight of nine iron samples had detectable concentrations for comparison. However, the exposure limit for iron is relatively high compared to the detectable iron concentrations, therefore the statistical data demonstrated minimal exposure risk. The 95th percentile point estimate was 0.0502 mg/m³ or 0.5% of the PEL which is an AIHA Category 0, meaning that there is no need to conduct any further actions or implementation of controls for less than 1% of the PEL. The UTL was less than the PEL of 10 mg/m³, meaning that it can be concluded with 95% confidence that the 95th percentile point estimate of 0.0502 mg/m³ is the true point estimate.

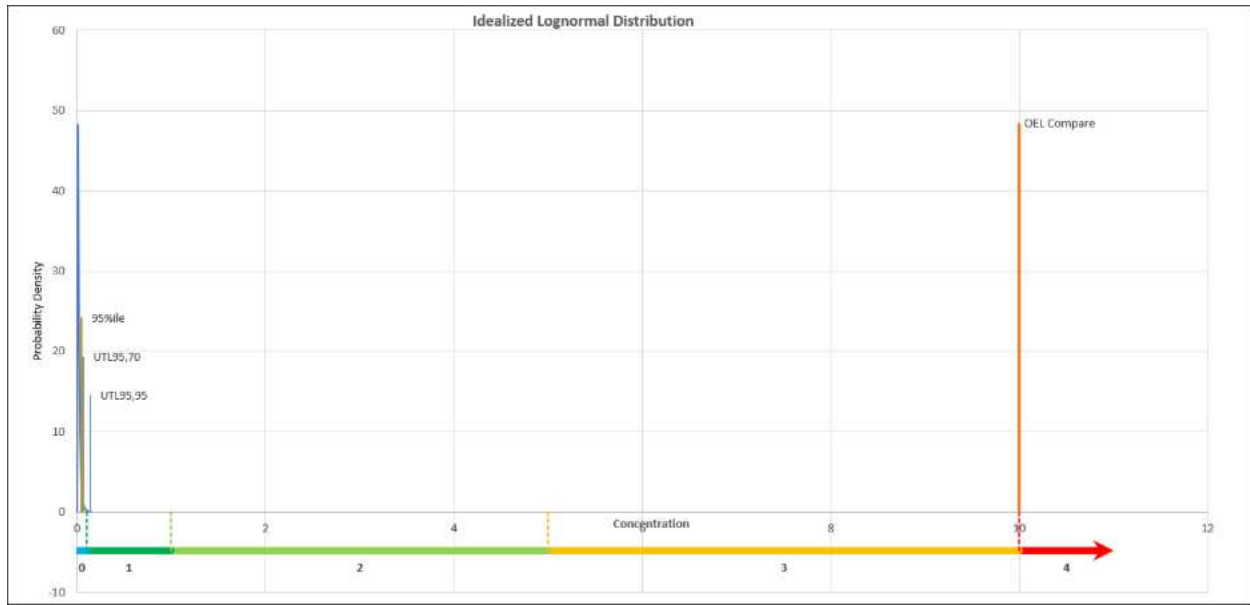


Figure 5: Iron Probably Density Curve OSHA PEL.

Figure 6 is the probability density curve for the manganese samples, with a GSD of 1.943 which indicated that no further categorization of exposure groups was necessary. It was also verified that the data were lognormally distributed. The OSHA manganese PEL of $5\text{mg}/\text{m}^3$ is a ceiling (C) limit, meaning that this concentration level should not be exceeded at any time during the workday. None of the manganese sample concentrations exceeded the OSHA ceiling limit. However, the ACGIH TLV for manganese is $0.01\text{mg}/\text{m}^3$ as an 8-hour TWA to which the data set was compared. The manganese sample concentrations resulted in a 95th percentile point estimate of $0.0012\text{mg}/\text{m}^3$ or 12% of the TLV which resulted in an AIHA Category 2 exposure (10% to 50% of the TLV). The UTL was less than the TLV of $0.01\text{mg}/\text{m}^3$, meaning that there is 95% confidence that the 95th percentile point estimate is less than the TLV.

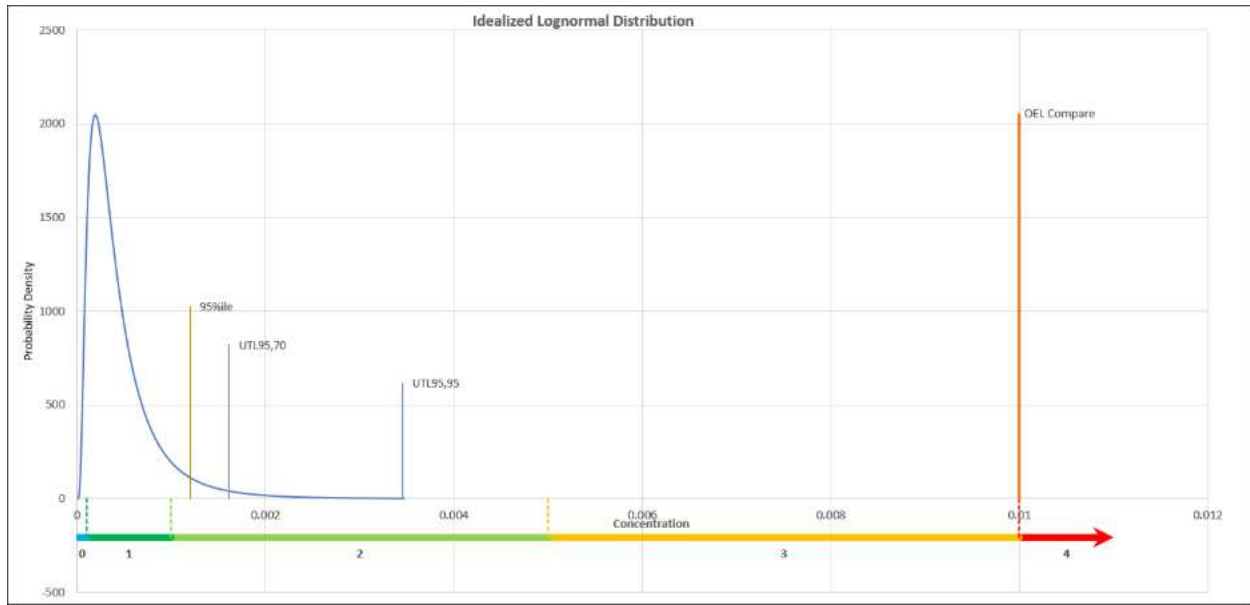


Figure 6: Manganese Exposure Banding ACGIH TLV.

Figure 7 is the probability density curve for the aluminum samples, including the majority that were under the LOD. The GSD for these samples was 2.289 which indicated that no further categorization of exposure groups was necessary. It was also verified that the data were lognormally distributed. The OSHA PEL for aluminum is 5 mg/m^3 . The analytical method has a limit-of-detection (LOD) of 10 ug which was important since most of these samples were under the LOD. Three of the nine samples had detectable concentrations. Sample concentrations that were under the limit of detection (LOD) were still used for statistical comparisons of the 95th percentile. The 95th percentile point estimate was 0.047 mg/m^3 . Given that the 95th percentile point estimate and the 95th percentile UTL were both below the PEL, it can be concluded with 95% confidence that the true 95th percentile point estimate is below the PEL. This was an AIHA Category 0 exposure which is under 1% of the OEL.

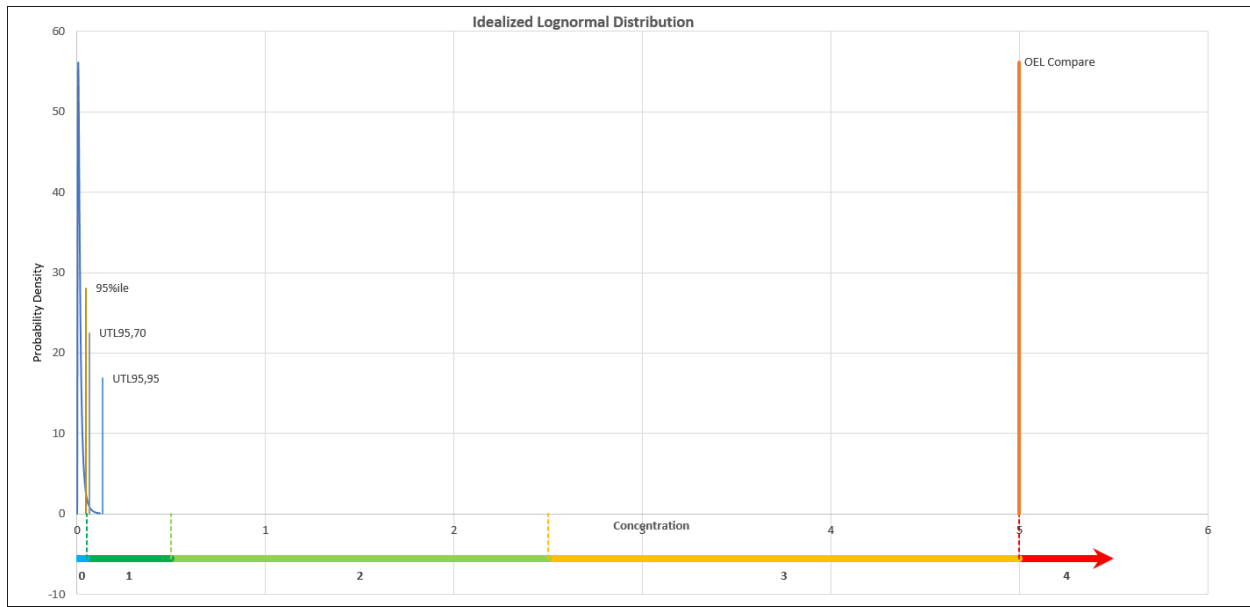


Figure 7: Aluminum Probability Density Curve OSHA PEL.

Figure 8 is the probability density curve for the magnesium samples, including the majority of the samples that were under the LOD. These data had a GSD of 1.933 which indicated that no further categorization of exposure groups was necessary. It was also verified that the data were lognormally distributed. The OSHA PEL for magnesium is 15 mg/m³, and the analytical method had a LOD of 5 ug. The upper 95th percentile point estimate for these samples was 0.006 mg/m³ which places this dataset as an AIHA Category 0 exposure, less than 1% of the OEL. Given that the 95th percentile point estimate and the 95th percentile UTL were both below the PEL, it can be concluded with 95% confidence that the true 95th percentile point estimate is below the PEL.

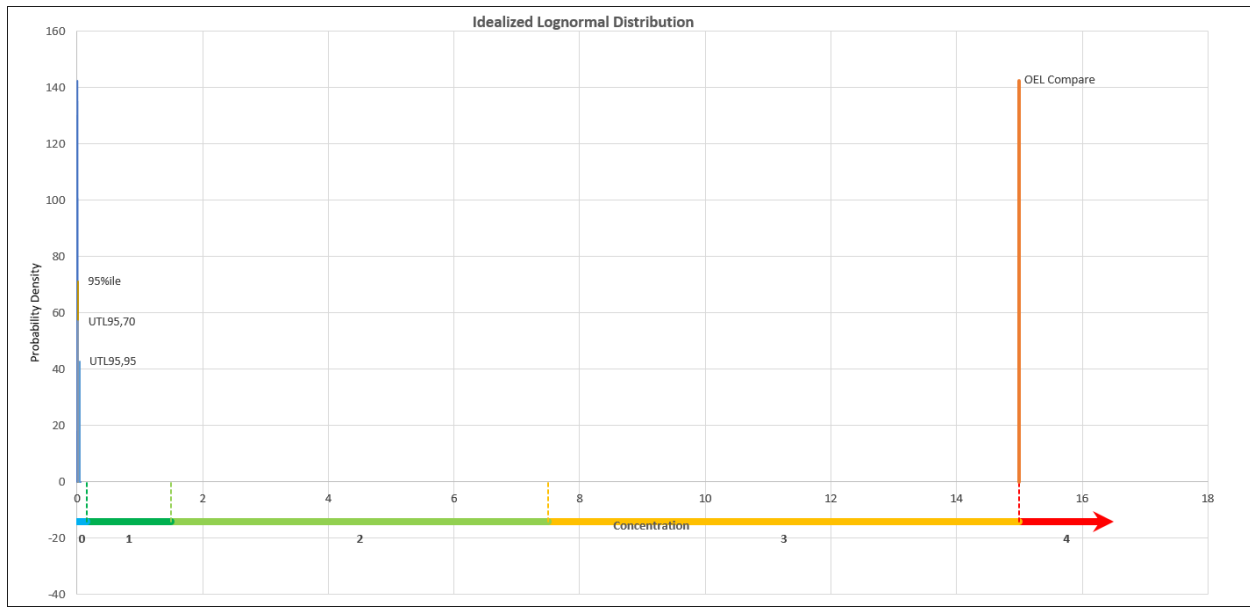


Figure 8: Magnesium Probability Density Curve OSHA PEL.

The data for zinc were analyzed statistically using IHStats®, but the data were not lognormally distributed, therefore, the probability density curve is not provided. The OSHA PEL for zinc is 15 mg/m³, and the analytical method had an LOD of 1.8 ug. Only one of nine samples had a detectable concentration of 0.0034 mg/m³, well less than the OSHA PEL of 15 mg/m³.

CHAPTER 6: LIMITATIONS

Sample Size

A limitation of this study was that the landfilling operation did not employ a large workforce (12 total), meaning that the number of samples was limited to nine per sample type. In addition, five of the 12 did not consent to participate as they did not want to know their exposure levels and were concerned about job security if results demonstrated over-exposure. However, the small sample size was ideal for using IHStats® to represent many real-life industrial hygiene sampling campaigns for small- to medium-sized organizations. Further, it was determined that the samples would be unique each sampling day because of job rotation. Given that this study was exploratory in landfilling operations exposures, the IHStats® results can be used to determine if future exposure studies for airborne respiratory hazards are warranted.

Worker Shifts

Some of the worker exposure samples were conducted longer than the scheduled 10-hour shifts and other samples were less than 10 hours in duration because the subject did not work a full-shift. In addition, because the researcher performing the sampling was not allowed in the landfilling work zone, the employees were not observed 100% of the sampling time to verify if they spent their entire shift within the landfilling area.,

Dust Generation and Mitigation

Because of personnel shortages during the sampling campaign, there may have been a reduction in the amount of water applied to the soil to mitigate dust in the work area. Additionally, worker shortages limited the amount of soil excavation to cover the landfill materials. Both events could have impacted the amount of dust that was generated during the sampling days. Further, the site

supervisor reported that the summer months were the landfill's busiest season, and that hot, dry conditions may contribute to a higher rate of dust generations on site. In addition, more landfilling occurs during the summer season because of longer working daylight time. Seasonal summer monsoons also brought heavy rain to the site one day during the sampling campaign for three hours, which could have impacted the sampling results.

CHAPTER 7: DISCUSSION

Respirable Crystalline Silica Exposure

As indicated in Figure 2, the respirable silica exposure concentrations for all workers had an upper 95th percentile point estimate exposure at 28.89 ug/m³ for an adjusted 8-hour TWA. In addition, the maximum exposure concentration for one worker was 26 ug/m³ or 31.1 ug/m³ when adjusted to an 8-hour exposure, exceeding the 8-hour OSHA Action Limit of 25 ug/m³ for silica. Pannell and Grogan^[3] found that in similar pressurized cabs, though with more intensive soil work contributing to exposure, the average silica exposure was 72 ug/m³. The silica exposure data set is categorized by the AIHA exposure categories as problematic when compared to the OSHA PEL and would require additional monitoring. Further, the overall 95th percentile point estimate in Figure 2 was above the silica OSHA action limit, meaning that OSHA requires the employer to perform additional monitoring and the establishment of a program to monitor employee health. Given the small sample size, it would be valuable to establish industrial hygiene monitoring programs onsite to understand seasonal exposure variations.

When all sample concentration results were combined, regardless of task, and compared to the OSHA OEL, this sample set was an AIHA Category 3 exposure at 58% of the OEL. AIHA recommendations categorize this exposure set as a problematic exposure, where there is a greater than 30% chance that 5% of the population will be overexposed. Recommendations from the AIHA exposure categories include increased monitoring, workplace inspections, and the development of further controls.^[19] However comparison of silica sampling results to the OSHA silica action limit has an overexposure to the action limit at 115%. Based on the AIHA recommendations^[20], this as an unacceptable exposure and requires immediate review and implementation of the hierarchy of controls, leading with attempts to eliminate the sources of

exposure. Additionally, with overexposure to the silica action limit, the OSHA silica standard requires that a medical surveillance program be established as per 29 CFR 1910.1053(i).^[21]

The average silica concentration from the operators in the current study was 15.68 ug/m³, which was substantially less than the average silica concentration of 72 ug/m³ as reported by Pannell and Grogin^[3] for the similar types of heavy equipment operation. Both the Pannell & Grogin^[3] study and the current study included soil excavation, however, the landfilling operations in the current study were not solely soil excavation operations.

It was determined in the current study that the rate of exposure for all workers was consistent due to the GSD being less than 3. Additionally, the probability density curves (Figures 3 & 4) based on the separation of the job tasks, lead the researchers to conclude that these groups had a close to equal burden of silica exposure due to the 95th percentiles of 24.35 ug/m³ for spotters and 32.77 ug/m³ for operators both at or exceeding the OSHA action limit of 25 ug/m³. However the sample size was small, and it was also determined that neither the operators nor spotters were likely exposed above the OSHA silica PEL since the 95th percentile point estimate was below the OSHA PEL of 50 ug/m³ (Figure 1). However, since the UTL for the Figure 1 data set exceeded the OSHA PEL, it cannot be assured with 95% confidence that the 95th percentile point estimate is the true estimate. To reduce the uncertainty of this data set, additional sampling would be warranted.

Heavy Metals Exposure

Results from Podlasck^[4] indicated that heavy metals were present in landfill soils and that the concentrations varied by landfill site. However, based on the heavy metals airborne exposure concentrations in the current study, it was determined that the risk of adverse health outcomes

from these elements was minimal, with below detection limits for five of the ten metals analyzed. Three of the ten metals, aluminum, magnesium, and zinc had detectable levels, but the reported concentration levels were well below published exposure limits. Likewise, the iron and manganese exposure results were relatively low as compared to published occupational exposure limits. The iron exposure concentrations had a 95th percentile point estimate of 0.0502 mg/m³ (Figure 5) which was less than 1% of the OSHA PEL of 10 mg/m³ demonstrating that while there were airborne iron particles, the exposure concentrations were negligible when compared to exposure limits. The manganese exposure concentrations were compared to the ACGIH TLV of 0.01 mg/m³, which resulted in a 95th percentile point estimate of 0.0012 mg/m³ which was 12% of the TLV. While there were detectable heavy metal airborne exposures in the current study, they were at relatively low concentrations that would not seem to increase the risk of occupational disease.

Possible Exposure Pathways

When considering how landfill workers may be exposed to airborne contaminants from landfill wastes and naturally occurring elements during their work shifts, there are two possible variables to consider. Workers on site are exposed to hot and windy conditions that may facilitate suspension of particles, increasing the risk of respiratory inhalation of contaminants. Daytime weather conditions are detailed in Appendix A. Additionally, faulty seals within the cab of the machine, or poorly functioning filtration and ventilation systems, could enable leakage to occur into the cab to increase the risk of respiratory hazards.

CHAPTER 8: RECOMMENDATIONS

With a complex site that covers a wide range of equipment and area, as in the current study, recommendations for controls are limited. However, recommendations include:

(1) Maintenance: ensure that built-in systems in heavy equipment are functional, such as the seal in machine cabins, filter upkeep, and general maintenance of supplied air systems within the vehicle.

(2) Manufacture or purchase a sealed work environment with a filtration system for the spotter, so that these workers can retreat to a clean area when they are not actively directing traffic.

Given the various responsibilities of the spotter, it is difficult to ascertain the reduced exposure time, however any reduction in exposure is to the benefit of the worker. This option could additionally include a plug-in HEPA filtered unit located in the enclosure.

(3) Emphasis on dust suppression methods, such as the use of the water truck and making that a core daily task. This is a common industry practice, and wet methods are often used as industrial hygiene control methods for dust suppression.

(4) Use ambient air monitors to indicate high dust concentrations. Note however, that given the size of the site, the monitors would have to be located in strategic positions. In addition, the use of windsocks would help workers determine the direction of wind so that, when possible, workers could work upwind.

Further, since several non-consenting workers at the study site stated that they did not want to know their exposure levels and were concerned about job security, it is recommended to include the development of an additional background information package for workers to explain the benefits of knowing their occupational exposure results.

CHAPTER 9: CONCLUSION

Respiratory exposures to airborne contaminants are one of the most common and most dangerous occupational exposures. The researchers in the current study aimed to identify potential respiratory exposures at landfilling operations and concluded that there was a risk to operators and spotters to exceed OSHA's action level of 25 ug/m³ for silica. This conclusion is based on calculated 95th percentile confidence intervals that exceeded the action limit and UTLs for spotters and operators that also far exceeded action limits. The researchers also concluded that there was not an increased risk of occupational exposure to heavy metals. Null Hypothesis 1, that workers are not overexposed to airborne silica dust as compared to published exposure limits, was rejected since there is a probability that the workers were overexposed to the OSHA AL. Null Hypothesis 2, that workers are not overexposed to heavy metals was accepted since the data did not support overexposure for any of the 10 metals analyzed. However, given the low sample number and the number of tasks performed at the site, the results from this study cannot be generalized to other landfills. Further, additional sampling should be performed at landfills to better estimate risk of respiratory exposure.

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APPENDIX A

Date	Sample Type	High/Low in F°	Rain (Yes or No)	Mean Wind Speed /Gusts
2025-06-20	Metals	95/55	No	6/10 mph
2025-06-24	Silica	79/57	Yes @ 3pm	9/18 mph
2025-06-25	Metals	79/60	Yes @ 4pm	7/30 mph
2025-06-26	Silica	51/84	No	6/20 mph