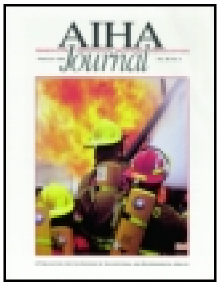

AIHA Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uaih20

Exposures to Quartz, Diesel, Dust, and Welding Fumes During Heavy and Highway Construction

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Version of record first published: 04 Jun 2010

To cite this article: Susan R. Woskie, Andrew Kalil, Dhimiter Bello & M. Abbas Virji (2002): Exposures to Quartz, Diesel, Dust, and Welding Fumes During Heavy and Highway Construction, AIHA Journal, 63:4, 447-457

To link to this article: http://dx.doi.org/10.1080/15428110208984733

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Personal samples for exposure to dust, diesel exhaust, quartz, and welding fume were collected on heavy and highway construction workers. The respirable, thoracic, and inhalable fractions of dust and quartz exposures were estimated from 260 personal impactor samples. Respirable quartz exposures exceeded the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) in 7–31% of cases for the trades sampled. More than 50% of the samples in the installation of drop ceilings and wall tiles and concrete finish operations exceeded the NIOSH REL for quartz. Thoracic exposures to quartz and dust exceeded respirable exposures by a factor of 4.5 and 2.8, respectively. Inhalable exposures to quartz and dust exceeded respirable exposures by a factor of 25.6 and 9.3, respectively. These findings are important due to the identification of quartz as a carcinogen by the National Toxicology Program and the International Agency for Research on Cancer. Fourteen percent of the personal samples for EC (n=261), collected as a marker for diesel exhaust, exceeded the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV®) for diesel exhaust. Seventeen of the 22 (77%) samples taken during a partially enclosed welding operation reached or exceeded the ACGIH TLV of 5 mg/m^3 for welding fume.

Keywords: construction, diesel exhaust, quartz, silica, size-selective sampling, welding

Construction is a substantial part of the U.S. economy, employing more than 6.8 million workers. The focus of this article is heavy construction, represented by Standard Industrial Code (SIC) group 16, which includes highway, bridge, tunnel, water, sewer, and pipeline construction. This sector accounts for about 14% of the workers employed in construction.[1]

The construction industry is unique in that it is dominated by work organized along trade lines. Each trade has a set of skills and phases of construction with which it is associated. Although the tasks performed by workers in the construction trades remain fairly constant from contract to contract, the exposures in these operations may vary because the location, duration of the tasks, and environmental conditions will vary. Thus, construction is quite different from manufacturing and presents a unique set of challenges for the identification and prevention of health and safety hazards.

Construction work is by nature a constantly changing set of phases and operations. The exposures of workers vary within each construction phase and operation as well as between the trades present at the time. The work described here is a sample (snapshot in time) of the heavy and highway construction activities that have taken place over several years on the largest and most complex infrastructure project in U.S. history. The Boston Central Artery/Tunnel Project (CAT) began in 1991 and is scheduled for completion in 2004. The project includes construction of 7.5 miles of highway, much of it underground through the center of Boston, with two bridges and two immersed tube tunnels. The estimated cost is more than $11 billion.

Although several authors[2,3] have grappled with how to define tasks in construction, no universal definitions of construction activities have been developed to date. As part of the authors' work on the CAT project they have developed a taxonomy to describe construction work using field observations and input from workers and management. In this taxonomy a construction

This study was funded by NIOSH (#60/CCU317202-01) through a cooperative agreement with the Center to Protect Workers' Rights, Washington, DC.

phase is the largest organizational unit. Each phase includes a number of *operations* that are integral parts of the phase. For example, the phase of utility relocation may include the operations of demolition, excavation, laying of conduit/pipe in trenches, and site support. An operation can last multiple days and phases often last weeks or months. Each operation can further be described by the *procedures* used by individual workers. A procedure is a series of tasks that a worker will complete as part of an operation.

The phases covered in this article include: build road; build supported excavation; tunnel finish; cut and cover construction; general work site infrastructure; roadway demolition; slurry wall construction; utility relocation; jet grouting; and caisson work. Some of the results from the tunnel finish and cut and cover construction phases were reported previously[4] and the results for the other phases are reported elsewhere.[5] Exposures during construction operations are the focus of this article. The 12 operations covered are described in Appendix B and include: build concrete forms; concrete finish work; concrete pouring; demolition; excavation; excavation support work; installing drop ceilings and wall tiles; laying conduit/pipe in trenches; pipejacking; site support; slurry/grout plant operation; specialized foundation operations. Operations such as build concrete forms or concrete finish work may occur in multiple phases (e.g., tunnel finish, caisson work, vertical building construction, cut and cover construction).

SILICA EXPOSURES IN CONSTRUCTION

In new construction, common sources of silica are soil and concrete. Trenching, excavation, and earthmoving will produce exposures that, in part, depend on the quartz content of soil. The quartz content varies depending on the region of the country and whether the soil is sandy or clay based. A recent study of farm soils in North Carolina found that the percentage of quartz in the large particle size fraction was greater than in the respirable size particles (for sandy soil 70 ± 10% for large particles, 29± 11% for respirable size particles).[6] The major component of all the excavated material on the Boston "Big Dig" highway construction project is Boston blue clay. Boston blue clay is a marine sediment rich in minerals. An X-ray diffraction analysis of the Boston blue clay revealed the presence of feldspars (30%), mica (20%), kaolinite (20%), quartz (15%), and chlorite (8%).[7]

Steel reinforced concrete is a major component of new construction. Concrete is made up of aggregate (crushed stone, gravel), sand, portland cement, and water. Fly ash may also be added. The formulations vary based on the use, and the quartz content varies mostly with the composition of the aggregate. Crushed stone from the New England area is likely to contain large amounts of granite and other quartz-containing minerals. Concrete bulk samples from the present study were analyzed by Fourier transform infrared (FTIR) spectroscopy and were found to contain an average of 3.1% quartz, a little lower than expected. During underground highway or building construction, jet grouting using cement-based grouts and slurry excavations using bentonite may occur. According to product material safety data sheets, bentonite may contain up to 6% quartz and the grout may contain fly ash with about 3% quartz. Production of slurry, mortar, grout, and concrete can generate exposures during dry powder mixing, during excavation of the grouted soil, or during finishing procedures on the cured concrete or slurry wall (drilling, grinding, cutting, shotblasting). Exposures can also occur in repair, renovation, and retrofitting construction when silica-containing materials are disrupted.

Silica has long been associated with respiratory disease. It is known to cause progressive fibrosis that is identifiable by chest X-ray and pulmonary function tests. In addition to scarring that can produce cough and shortness of breath, silica exposures have been associated with other diseases such as bronchitis, tuberculosis, and chronic obstructive pulmonary disease. The International Agency for Research on Cancer (IARC) has determined that there is sufficient animal and human evidence to support the finding that crystalline silica is a carcinogen, and has designated it a Group I carcinogen.[8] The National Toxicology Program, in its *9th Report on Carcinogens,* lists respirable crystalline silica in the category of "known to be a human carcinogen."[9] Despite the well-known health effects of silica exposure, silicosis is still prevalent in the United States. It has been estimated that nearly 2 million workers are exposed to silica (quartz, cristobalite, and amorphous).[10]

Relatively little attention has been paid to silica hazards in construction until recently. In the seven states with silicosis surveillance programs, 9.3% of the confirmed silicosis cases are among construction workers, with an additional 13.3% of the cases among manufacturers of stone, clay, glass, and concrete products.[11] In 1993 and 1994, 26% of the Occupational Safety and Health Administration (OSHA)-collected samples in construction exceeded the OSHA permissible exposure limit (PEL) for crystalline silica.[12]

DUST EXPOSURES IN CONSTRUCTION

Construction work can be extremely dusty. Little work has been done to characterize the full extent of the problem. However, elevated ambient particulate air pollution has been associated in the general population with declines in lung function,[13,14] increases in respiratory hospitalizations,[15,16] and increases in mortality from respiratory and cardiovascular causes.[17,18] Little is known about the effects on the respiratory system or clearance mechanisms of long-term exposure to unclassified dust. It has been hypothesized that some changes in pulmonary function associated with the development of chronic obstructive pulmonary disease, and some carcinogenic effects, may be due, in part, to an overloading of the respiratory clearance system.[19]

DIESEL EXHAUST EXPOSURES IN CONSTRUCTION

Another source of particulate exposure in construction is diesel exhaust. Most construction equipment, including fixed location equipment like compressors and pumps, use diesel engines as their power source. Examination of the respiratory effects of diesel particulate have been limited. Most studies have found increased morbidity and mortality associated with the potential for diesel particulate exposure but they have not actually measured diesel exposure levels. For example, when compared with controls, bus drivers and mechanics have been shown to have decreased pulmonary function and increased respiratory tract symptoms.[20,21] Chronic bronchitis and airway resistance changes suggestive of obstructive airway disease have been noted in bridge and tunnel workers.[22] Among railroad workers and truckers, diesel exhaust exposure has been associated with an increase in lung cancer.[23–25]

METAL FUME EXPOSURES IN CONSTRUCTION

In heavy and highway construction most of the welding is done on mild steel using manual metal arc (shielded metal arc or stick welding) methods. Welding fume consists of the oxides or salts of the base metal, filler metal, or the electrode coating materials. In addition, ozone and nitrogen oxides are formed and the process emits both infrared and ultraviolet radiation.

IARC has placed welding fume in Group 2B as a possible human carcinogen.[26] Cancer mortality studies of mild steel welders have shown mixed results. In some cases no elevation in risk has been found[27] and in others a significant elevation in risk occurs after long duration (> 20 years) or long latency (> 20 years since first exposure).[28] Sheet metal workers with greater than 4 years of welding exposure had a significantly elevated risk of obstructive lung disease after controlling for potential asbestos exposure and cigarette smoking.[29] Neurotoxic effects also have been reported among manganese exposed welders.[30]

METHODS

With the exception of a few area samples taken in the cabs of operating engineers, personal samplers covering approximately 6 hours of a typical 8-hour workday were used in this study. The Construction Occupational Health Program's sampling strategy requires researchers to collect data as randomly as possible, by choosing operations within a site and randomly sampling workers in those operations at the work site. Therefore, the collected samples cover a wide range of construction phases, operations, and exposure levels.

Samples were collected with a number of aerosol collection devices. The first was a BGI-4 respirable cyclone (BGI, Waltham, Mass.) run at 2.2 L/min. The cyclone sampler with a heat treated quartz filter (Gelman Sciences Pallflex, Ann Arbor, Mich.) was used to collect samples for elemental and organic carbon analysis (diesel particulate). In high silica exposure operations that would overload the impactor, the cyclone was used with a 5-μm PVC filter (SKC, Eighty-Four, Pa.). The second aerosol sampler was an IOM inhalable sampler (SKC) with a 5-μm PVC filter, run at 2 L/min. This sampler was used to collect welding fume particulate when placed near the breathing zone outside the welding hood. A third sampler was used to collect fluoride samples in the breathing zone outside the welding helmet. This was a 37-mm closed-face cassette with a 0.8 μm cellulose ester membrane filter and a sodium carbonate treated cellulose backup pad (National Institute for Occupational Safety and Health [NIOSH] method 7902).[31] The fourth sampler was a Marple 290 series personal four-stage cascade impactor with sampling cowl and visor, which was run at 2 L/min.[32] Personal impactor samples were collected to estimate exposures to construction dust and crystalline silica (quartz). The impactor stages used a mylar substrate (Grasby Anderson, Atlanta, Ga.) coated with less than 1 mg of Apezion L grease (Supelco, Bellefonte, Pa.) applied in a toluene solution using an artist's air brush.

Use of the personal impactor permitted estimation of the inhalable, thoracic, and respirable size-selective particulate fractions. The method uses Simpson's rule in a tabular-graphical approach to estimating the contribution of each impactor stage to the overall particle size fraction of interest.[33] Due to the relatively wide range of particle sizes represented on each stage, this approach may contain some error; however, it represents a reasonable estimate of these biologically relevant size fractions.[5] Appendix A contains the correction factor, particle size range, and midpoint and fraction of each stage used to estimate the respirable, thoracic, and inhalable particulate mass concentrations.

Sample Analysis

All particulate samples, except the diesel samples, were analyzed gravimetrically using a Cahn C-30 microbalance after equilibrating the filters for at least 3 hours in a temperature (21±1°C) and humidity (50±3% relative humidity) controlled environmental chamber. The limit of detection for the gravimetric analysis was 14 μg for Mylar® filters and 12 μg for PVC filters. Quartz analysis was done using a micropellet technique (5 mm) and an FTIR spectrophotometer. Spectral manipulations such as Fourier self-deconvolution and derivatizations were performed on the averaged spectrum to improve quantification. Peak height for quartz was measured at 798 cm^{-1} and 696 cm^{-1}.[34] Separate calibration curves were generated for each stage of the four-stage personal impactor, by using the impactor to sample quartz dust (Min-U-Sil 5 and Min-U-Sil 30) in an aerosol-generating loop.[5] The limit of detection for the quartz analysis is 1 μg for respirable particles and 3 or 4 μg for thoracic and inhalable particles, respectively.

Diesel particulate samples were analyzed by evolved gas analysis using a thermal-optical analyzer (NIOSH method 5040).[31] Analysis was done by either the DataChem Laboratories (Salt Lake City, Utah) or the Sunset Laboratory (Forest Grove, Ore.) The resultant elemental and organic carbon levels are reported.

Analysis for metals and elements in the welding samples was done using ICP-AES and NIOSH method 7300[31] (Liberty Mutual Labs, Hopkington, Mass.). Fluoride samples were analyzed using ion chromatography and NIOSH method 7906[31] (ESA labs, Chelmsford, Mass.).

Data Analysis

Personal exposures for construction workers were grouped by trade union of the subject and by the construction operation being performed. The trades included operating engineers who operate heavy equipment; laborers who do manual tasks throughout all phases of construction; and miscellaneous trades including iron workers, carpenters, plumbers, electricians, tile setters, piledrivers, and boilermakers who were put together because of an insufficient number in any one group.

The data were examined for the underlying distribution using the Shapiro-Wilks statistic and by graphing probability plots and histograms using the SAS System for the PC (Chapel Hill, N.C.). The data fit the lognormal distribution better than the normal distribution. Hence, the natural logarithms of the measured exposures were used for all analyses. Although it is common to use the geometric mean (GM) and geometric standard deviation (GSD) to describe lognormal exposure distributions, for epidemiologic purposes it is often desirable to estimate the mean exposure of an exposure group.[35] However, the simple arithmetic mean is a poor estimator of the population mean when the distribution is lognormal. Hence, the minimum variance unbiased estimator (MVUE) of the population mean was calculated for each operation.[36] When analytical results were less than the limit of detection (LOD) for a method, the LOD/square root of 2 was used to permit these samples to be included in the data analysis.[37] To calculate the fraction of respirable dust that was quartz, the samples that were less than the LOD for respirable dust were excluded (n=14). There were 170 paired personal respirable dust

TABLE I. Personal Exposures to Respirable Dust and Quartz (mg/m³) During Heavy and Highway Construction by Trade

Trade	N	MVUE Respirable Dust (mg/m³)	GM Respirable Dust (mg/m³)	GSD Respirable Dust	Max Respirable Dust (mg/m³)	Mean Elemental Carbon Fraction (%)	MVUE Respirable Quartz (mg/m³)	GM Respirable Quartz (mg/m³)	GSD Respirable Quartz
Laborer	146	1.098	0.402	4.2	21.767	5.2	0.122	0.026	5.9
Misc. trades[C]	26	0.946	0.366	4.2	6.260	2.4	0.021	0.013	2.8
Operating engineer	88	0.163	0.106	2.5	3.946	11.3	0.012	0.007	2.8

[A]10 mg/% quartz + 2.
[B]0.05 mg/m³.
[C]Miscellaneous trades includes carpenters (9), iron workers (6), piledrivers (4), plumbers (2), tile setters (2), electrician (1), boilermaker (1), personal area (1).

and elemental carbon (EC) samples used to calculate the fraction of respirable dust that was diesel.

RESULTS

Samples for this study were collected during 113 site visits between June 1994 and April 1999. Examination of 260 respirable dust and respirable quartz concentrations by trade found them to be more lognormal than normal. Nevertheless, the distributions were highly skewed, with large GSDs in many cases (Table I). There were 206 workers sampled for respirable dust and silica. The laborers had the highest mean exposures to respirable dust and to respirable quartz. The laborers and operating engineers had the highest percentages of quartz as part of their respirable dust exposures. The operating engineers had the highest percentage of EC in their particulate and the lowest percentage of samples over either the federal OSHA PEL or the NIOSH REL for quartz. Conversely, the laborers had the highest percentage of samples over these occupational exposure limits (Table I).

Examination of the distributions of respirable dust and respirable quartz concentrations by operation also found them to be more lognormal than normal. Many operations, like trades, had highly skewed exposure distributions (Table II and III). The operations with the highest mean respirable dust exposures were found in concrete finish work, excavation support work, and installation of drop ceilings and wall tiles. The highest percentages of quartz in the respirable dust were found in concrete finish work operations, demolition, and installation of drop ceilings and wall tiles. The highest percentages of EC particulate in the respirable dust were found in the excavation and concrete pouring operations (Table II).

The operations with the highest mean respirable quartz exposures were found in concrete finish work, demolition, and installation of drop ceilings and wall tiles. More than 30% of the samples taken in the operations of concrete finish work, pipejacking, and installation of drop ceilings and wall tiles exceeded the federal OSHA PEL for quartz exposure. More than 50% of the samples in the installation of drop ceilings and wall tiles and concrete finish operations exceeded the NIOSH REL for quartz (Table III).

Thoracic exposures were estimated for both dust and quartz in a variety of construction operations (Table IV). In the thoracic dust samples, the highest percentage of quartz was found in the samples from concrete pouring and demolition work, followed by pipejacking and site support operations. The highest mean thoracic dust exposures were found in installation of drop ceilings and wall tiles, excavation support work, pipejacking, and laying conduit/pipe in trenches. The highest mean thoracic quartz exposures were found in pipejacking, installation of drop ceilings and wall tiles, laying conduit/pipe in trenches, and concrete finish work (Table IV).

Inhalable exposures were estimated for both dust and quartz in a variety of construction operations (Table V). In the inhalable dust samples, as with the thoracic samples, the highest percentage of quartz was found in the samples from concrete pouring and

TABLE II. Personal Exposures to Respirable Dust (mg/m³) During Heavy and Highway Construction Operations

Operations	N	MVUE Respirable Dust (mg/m³)	GM Respirable Dust (mg/m³)	GSD Respirable Dust	Maximum Respirable Dust (mg/m³)	Mean Quartz Fraction of Dust (%)	Mean Elemental Carbon Fraction (%)	Average Sample Time (Minutes)
Build Concrete Forms	26	0.499	0.268	3.2	1.817	5.4	2.7	304
Concrete Finish Work	37	1.642	0.666	4.0	14.730	10.8	3.6	309
Concrete Pouring	3	0.105	0.104	1.2	0.121	5.1	11.1	293
Demolition	31	0.689	0.227	4.7	18.166	15.4	4.4	334
Excavation	42	0.224	0.121	3.1	7.281	6.4	10.8	341
Excavation Support Work (Steel Crossbeam Attachment)	14	2.240	0.713	5.1	6.349	6.3	3.8	265
Install Drop Ceiling & Wall Tiles	21	1.294	0.803	2.8	21.767	9.9		315
Laying Conduit/Pipe in Trenches	7	0.637	0.356	3.3	4.819	8.1	2.5	324
Pipejacking	8	0.924	0.359	4.7	2.725	7.5	6.9	283
Site Support	24	0.145	0.104	2.3	0.959	8.3	6.1	350
Slurry/Grout Plant Operation	13	0.802	0.315	4.3	4.240	3.2	4.1	370
Specialized Foundation[A]	34	0.194	0.122	2.7	3.929	6.6	8.2	356

[A]Specialized Foundation includes the operations of Jet Grouting, Slurry Wall Excavation, Caisson Placement, and Piledriving.

TABLE I. Extended

Trade	Max Respirable Quartz (mg/m³)	Mean Quartz Fraction of Dust (%)	% Samples Over the OSHA Quartz PEL[A]	% Samples Over the NIOSH Quartz REL[B]
Laborer	3.000	9.0	22.6	30.8
Misc. trades[C]	0.134	5.2	11.5	11.5
Operating engineer	0.093	8.8	2.3	6.8

demolition work, followed by site support and pipejacking operations. The highest mean inhalable dust exposures were found in installation of drop ceilings and wall tiles, laying conduit/pipe in trenches, pipejacking, as well as concrete finish work and excavation support work. The highest mean inhalable quartz exposures were found in pipejacking, laying conduit/pipe in trenches, concrete pouring, and concrete finish work (Table V).

For both dust and quartz, thoracic exposures exceeded respirable exposures. In the case of dust it was by a factor of almost three (Table VI). In the case of quartz, thoracic exposures exceeded respirable exposures by a factor of more than 4.5. It is also important to note that the regression coefficient (R^2) between the thoracic and respirable concentrations was less than 0.90 (0.83 for quartz and 0.76 for dust) (Table VI). An R^2 of more than 0.90 has been suggested as the value indicating potential collinearity among predictors in multiple regression analysis.[38] Another way to state this is that the thoracic concentration is not a simple linear function of the respirable concentration or the regression coefficient (squared correlation coefficient) would be greater than 0.90.

Inhalable exposures greatly exceeded respirable exposures for both dust and quartz. For dust, the mean ratio of inhalable to respirable dust was more than 9 (Table VI). For quartz, on average, the inhalable concentration exceeded the respirable quartz concentration by almost 26 fold (Table VI). As with the thoracic data, the regression coefficient (R^2) between the inhalable and respirable concentrations was less than 0.90 (Table VI). The relatively low regression coefficients (0.42 for quartz and 0.48 for dust) suggest that these are not a simple linear function of each other (Table VI).

EC levels were measured as an indication of diesel particulate concentrations. There were 261 diesel particulate samples collected, representing 204 workers. The miscellaneous trades group had the highest mean exposure to EC, followed by the operating engineers (Table VII). The operations with the highest EC concentrations were the installation of drop ceilings and wall tiles, concrete pouring, concrete finish work, laying conduit/pipe in trenches, and excavation work (Table VII). The percentage of samples exceeding the American Conference of Governmental Industrial Hygienists (ACGIH) proposed threshold limit value (TLV®) for diesel exhaust of 20 μg/m³ EC was calculated. The miscellaneous trade group had the highest percentage of samples over the proposed TLV. The operations with the highest percentage of samples over the TLV included installing drop ceilings and wall tiles and concrete pouring. The miscellaneous trades group and the laborers had the highest mean exposures to organic carbon. Operations with the highest mean organic carbon exposures were installation of drop ceilings and wall tiles, pipejacking, and laying conduit/pile in trenches (Table VII).

Welding exposures primarily occurred in the excavation support operation when steel crossbeams are welded in place (Table VIII). Seventeen of the 22 (77%) samples taken during welding operations reached or exceeded the 5 mg/m³ ACGIH TLV for welding fume.[39] Eleven percent (2) of the fluoride samples exceeded the 2.5 mg/m³ fluoride TLV.[39] Sixteen percent (3) of the manganese samples reached the level of the ACGIH TLV of 0.2 mg/m³.[39] For the remaining elements, none of the samples reached or exceeded their respective TLVs.

DISCUSSION

Construction dust has historically been considered a "nuisance dust," "particulate not otherwise classified" or "particulate not otherwise regulated." Data show that, in fact, it does not meet the basic criterion of a dust in that category (i.e., a crystalline silica content of less than 1%). Rather, the present data show an average quartz content of 8.6% in the respirable samples from the current study. Although little research has been performed to characterize the other airborne constituents of general construction particulate, the present research suggests that in addition to quartz, the respirable fraction of construction dusts contain, on average, 6.5% EC.

TABLE III. Personal Exposures to Respirable Quartz (mg/m³) During Heavy and Highway Construction Operations

Operations	N	MVUE Respirable Quartz (mg/m³)	GM Respirable Quartz (mg/m³)	GSD Respirable Quartz	Max Respirable Quartz (mg/m³)	% Samples Over the OSHA PEL[A]	% Samples Over the NIOSH REL[B]
Build Concrete Forms	26	0.022	0.012	3.0	0.096	7.7	15.4
Concrete Finish Work	37	0.266	0.061	5.9	2.505	32.4	51.4
Concrete Pouring	3	0.008	0.007	1.5	0.012	0.0	0.0
Demolition	31	0.124	0.029	5.9	3.000	22.6	25.8
Excavation	42	0.014	0.007	3.2	1.134	2.4	2.4
Excavation Support Work (Steel Crossbeam Attachment)	14	0.087	0.026	5.4	1.016	28.6	28.6
Install Drop Ceiling & Wall Tiles	21	0.143	0.045	4.9	1.487	33.3	52.4
Laying Conduit/Pipe in Trenches	7	0.051	0.026	3.7	0.304	14.3	28.6
Pipejacking	8	0.100	0.021	7.6	0.333	37.5	37.5
Site Support	24	0.010	0.008	2.2	0.036	0.0	0.0
Slurry/Grout Plant Operation	13	0.009	0.006	2.6	0.059	7.7	7.7
Specialized Foundation[A]	34	0.009	0.006	2.4	0.085	0.0	2.9

[A]10 mg/% quartz + 2.
[B]0.05 mg/m³.
[C]Specialized foundation includes the operations of Jet Grouting, Slurry Wall Excavation, Caisson Placement, and Piledriving.

TABLE IV. Personal Exposures to Thoracic Dust and Quartz (mg/m³) During Heavy and Highway Construction Operations

Operations	N	MVUE Thoracic Dust (mg/m³)	GM Thoracic Dust (mg/m³)	GSD Thoracic Dust	Max Thoracic Dust (mg/m³)	MVUE Thoracic Quartz (mg/m³)	GM Thoracic Quartz (mg/m³)	GSD Thoracic Quartz	Max Thoracic Quartz (mg/m³)	Mean Quartz Fraction of Dust (%)
Build Concrete Forms	26	1.477	0.732	3.4	5.162	0.085	0.048	3.0	0.616	7.7
Concrete Finish Work	12	1.530	1.006	2.6	3.606	0.143	0.099	2.5	0.363	10.0
Concrete Pouring	3	0.326	0.325	1.1	0.348	0.049	0.046	1.6	0.077	15.3
Demolition	17	0.595	0.352	2.9	6.512	0.102	0.054	3.2	1.788	17.1
Excavation	40	0.469	0.289	2.7	3.742	0.040	0.027	2.5	0.170	10.7
Excavation Support Work (Steel Crossbeam Attachment)	12	2.618	1.097	4.1	7.796	0.090	0.057	2.8	0.273	6.9
Install Drop Ceiling & Wall Tiles	6	3.733	3.020	2.1	9.081	0.171	0.071	4.7	1.202	4.0
Laying Conduit/Pipe in Trenches	7	1.900	1.084	3.3	8.356	0.178	0.092	3.6	0.650	9.2
Pipejacking	7	2.424	0.883	5.1	7.462	0.472	0.089	8.7	1.483	12.4
Site Support	21	0.378	0.262	2.4	1.649	0.037	0.029	2.0	0.152	12.4
Slurry/Grout Plant	11	0.727	0.401	3.2	2.678	0.027	0.020	2.2	0.082	7.2
Specialized Foundation[A]	32	0.411	0.279	2.5	5.020	0.030	0.023	2.1	0.171	9.9

[A]Specialized Foundation includes the operations of Jet Grouting, Slurry Wall Excavation, Caisson Placement, and Piledriving.

Evidence is mounting that, in addition to respiratory tract irritation, high particulate exposures can overload the clearance mechanisms of the lung, producing a cascade of responses that may culminate in chronic lung injury.(19) These responses include release of mediators and antiproteases, depressed macrophage mobility, attraction of polymorphonuclear cells (neutrophils), reduced integrity of the alveolar epithelial barrier, and increased particle interstitialization.(40) It has been suggested that this cascade of effects can also result in epithelial hypertrophy/hyperplasia and bronchiolization/squamous metaplasia with subsequent tumor development.(41) Other possible effects of decreased clearance include increased toxicity of other exposures, and even an increased susceptibility to bacterial or viral respiratory infections.(42) In animals, it appears that the effects of overload persist long after exposure ceases, suggesting that it is not simply a reversible, transitory phenomenon.(43,44)

A recent model for particulate overload in the human lung has been developed from animal data.(45) The authors suggest that at exposures of 5 mg/m³ of respirable particulate for 40 hours a week, it would take 1 month to reach a lung burden of dust that would result in clearance overload and 6–7 months to accumulate sufficient lung burden to commence fibrosis. On the other hand, if exposures were only 0.5 mg/m³, it would take 1 year to reach overload and about 2 years before fibrosis would commence. Because construction workers may frequently have particulate exposures in these ranges, they may be susceptible to a clearance overloading phenomenon and subsequent pulmonary fibrosis, independent of any specific health effect associated with concurrent silica or other particulate exposures.

Exposures to silica have long been associated with silicosis. Construction is the most frequently recorded industry on death certificates for individual's dying from silicosis.(46) From 1987–1996, 30% of the OSHA samples collected for silica exposures in construction exceeded the OSHA PEL. These samples were, on average, 11 times higher than the standard.(46) In the present study, 15% of the samples exceeded the PEL and 21% exceeded

TABLE V. Personal Exposures to Inhalable Dust and Silica (mg/m³) During Heavy and Highway Construction Operations

Operations	N	MVUE Inhale Dust (mg/m³)	GM Inhale Dust (mg/m³)	GSD Inhale Dust	Max Inhale Dust (mg/m³)	MVUE Inhale Quartz (mg/m³)	GM Inhale Quartz (mg/m³)	GSD Inhale Quartz	Max Inhale Quartz (mg/m³)	Mean Quartz Fraction of Dust (%)
Build Concrete Forms	26	4.210	1.987	3.5	25.561	0.315	0.168	3.2	2.184	10.3
Concrete Finish Work	12	5.532	3.584	2.7	12.882	0.655	0.484	2.3	1.596	14.1
Concrete Pouring	3	2.549	2.548	1.0	2.633	0.709	0.700	1.2	0.821	27.8
Demolition	17	1.430	0.931	2.6	12.557	0.297	0.188	2.7	2.383	22.5
Excavation	40	1.244	0.742	2.8	7.673	0.201	0.115	2.9	0.883	19.5
Excavation Support Work (Steel Crossbeam Attachment)	12	5.590	2.678	3.7	14.438	0.589	0.329	3.2	1.045	16.0
Install Drop Ceiling & Wall Tiles	6	7.875	5.989	2.3	23.945	0.380	0.148	5.0	3.125	4.0
Laying Conduit/Pipe in Trenches	7	6.459	3.487	3.5	19.100	0.843	0.360	4.4	1.865	11.6
Pipejacking	7	6.635	2.740	4.5	21.053	1.802	0.495	6.5	6.792	20.1
Site Support	21	1.074	0.812	2.2	3.677	0.191	0.146	2.1	0.518	22.2
Slurry/Grout Plant	11	2.199	0.940	4.1	10.424	0.193	0.085	4.0	2.018	15.7
Specialized Foundation[A]	32	1.243	0.833	2.5	9.028	0.182	0.123	2.5	0.822	16.5

[A]Specialized Foundation includes the operations of Jet Grouting, Slurry Wall Excavation, Caisson Placement, and Piledriving.

TABLE VI. Mean Ratio of Thoracic and Inhalable Concentration to Respirable Concentration During Heavy and Highway Construction by Trade/Squared Correlation Coefficient (R^2)

Trade	Thoracic to Respirable Quartz	Inhalable to Respirable Quartz	Thoracic to Respirable Dust	Inhalable to Respirable Dust
Overall	4.5/0.83	25.6/0.42	2.8/0.76	9.3/0.48
Laborer	4.7/0.83	29.0/0.40	3.0/0.74	10.9/0.48
Misc. trades[A]	4.8/0.84	29.5/0.38	2.8/0.84	10.0/0.52
Operating engineer	4.1/0.90	20.2/0.59	2.6/0.85	7.0/0.71

[A]Miscellaneous trades includes plumbers, electricians, tile setters, surveyors.

the NIOSH REL of 0.05 mg/m³, with the highest respirable quartz sample being 60 times the REL. Recent work on the exposure-response relationship between silica exposures and silicosis has suggested that a standard of less than 0.01 mg/m³ would be necessary to adequately lower the lifetime risk of silicosis.(47)

The designation of crystalline silica as a human carcinogen by IARC(8) and the National Toxicology Program(9) suggests the cancer experience of construction workers should be more closely examined. Some studies have found an association between the exposure to crystalline silica, construction or excavation dusts, and cancers of either the lungs, the colon, or the stomach.(48) Elevated standardized mortality ratios for cancers of the lung and throat, other digestive organs, and urinary tract have also been found among California construction workers.(49) Among Japanese construction workers proportional mortality rates (PMRs) for cancers of the trachea, bronchus, and lung were elevated.(50) Likewise, among North Carolina construction workers, PMRs for malignant neoplasms of the buccal cavity, pharynx, and lung were also significantly elevated.(51) Among unionized construction operating engineers, PMRs for lung cancer were significantly elevated.(52)

The concern for cancers of the respiratory tract and the gastrointestinal and urinary systems suggests that it is time to broaden the traditional focus on the respirable fraction of crystalline silica, which was based on the association with silicosis. The current movement in the occupational hygiene arena is toward the development of particle size-selective standards for aerosols. ACGIH, in coordination with the International Organization for Standardization and the European Standardization Committee, has developed a set of sampling criteria based on particle penetration into various regions of the respiratory tract.(39) Use of particle size-selective sampling based on these criteria and the development of a thoracic and inhalable standard for crystalline silica would be an important step in protecting worker health. Data from the current study suggests that thoracic quartz exposures are 4.5 times higher than respirable quartz and that inhalable exposures are 25.6 times higher than respirable exposures. However, the relationship between the respirable and thoracic or respirable and inhalable concentration is not a simple linear function. Poor correlation between the more biologically relevant metrics and respirable silica measurements in other silica using industries may help explain the difficulty in finding an exposure-response relationship between respirable quartz exposures and systemic or respiratory cancers.

There are several aspects of construction that may be important in evaluating crystalline silica exposures in construction. These

TABLE VII. Personal Exposures to Elemental Carbon (EC) and Organic Carbon (OC) (mg/m³) During Heavy and Highway Construction Operations

Categories	N EC	MVUE EC Conc (mg/m³)	GM EC Conc (mg/m³)	GSD EC Conc	Max EC Conc (mg/m³)	MVUE OC Conc (mg/m³)	GM OC Conc (mg/m³)	GSD OC Conc	% > 20 μg/m³ EC
Overall	261	0.013	0.008	2.7	0.176	0.064	0.046	2.3	14
Operations									
Build Concrete Forms	38	0.009	0.007	2.0	0.040	0.065	0.054	1.9	5
Concrete Finish Work	23	0.015	0.011	2.1	0.057	0.070	0.061	1.7	17
Concrete Pouring	6	0.023	0.020	1.8	0.052	0.047	0.042	1.7	33
Demolition	21	0.008	0.007	2.0	0.032	0.057	0.033	3.0	5
Excavation	56	0.012	0.008	2.6	0.165	0.060	0.043	2.3	11
Excavation Support Work (Steel Crossbeam Attachment)	12	0.011	0.006	3.4	0.059	0.085	0.072	1.8	17
Install Drop Ceiling & Wall Tiles	20	0.054	0.031	3.0	0.176	0.104	0.091	1.7	75
Laying Conduit/Pipe in Trenches	6	0.014	0.008	3.4	0.072	0.100	0.072	2.5	17
Pipejacking	7	0.007	0.006	2.1	0.014	0.105	0.077	2.4	0
Site Support	30	0.006	0.005	2.0	0.029	0.038	0.030	2.0	3
Slurry/Grout Plant	9	0.008	0.006	2.3	0.016	0.050	0.041	2.0	0
Specialized Foundation[A]	33	0.011	0.007	2.6	0.101	0.045	0.031	2.4	6
Trade									
Laborer	116	0.011	0.007	2.4	0.101	0.073	0.051	2.3	11
Misc. trades[B]	32	0.018	0.009	3.5	0.175	0.078	0.063	2.0	22
Operating Engineer	113	0.014	0.009	2.6	0.169	0.049	0.037	2.2	14

[A]Specialized Foundation includes the operations of Jet Grouting, Slurry Wall Excavation, Caisson Placement, and Piledriving.
[B]Miscellaneous Trades includes iron workers (15), carpenters (9), piledrivers (5), boilermakers (1), plumbers (1), surveyors (1).

TABLE VIII. Welding Fume Particulate, Fluoride and Element Exposures During Heavy and Highway Construction Welding (mg/m³)

Elements	N	Mean	SD	Max	N LOD[A]
Zinc	8	0.014	0.020	0.062	2
Manganese	19	0.100	0.055	0.196	
Iron	19	0.767	0.436	1.448	
Copper	8	0.006	0.007	0.019	3
Titanium	11	0.009	0.007	0.024	1
Calcium	11	0.404	0.261	0.917	
Aluminum	15	0.109	0.098	0.379	
Silicon	11	0.007	0.008	0.028	2
Antimony	18	0.094	0.103	0.304	3
Magnesium	15	0.037	0.041	0.145	
Sodium	11	0.169	0.201	0.676	
Potassium	12	0.446	0.167	0.727	5
Welding fume particulate	22	9.325	6.680	21.070	
Fluoride	19	0.726	1.130	3.343	5

[A]N LOD = number of sample less than the limit of detection for the method.

have to do with the evolving understanding of the mechanism of crystalline silica induced lung disease. It has been proposed that the biological effect of quartz is based on the mineral's surface reactivity. Quartz has the ability to generate free radicals and cause oxidative stress in cells. This oxidative stress can result in mutations and inflammatory responses. Thus, the more reactive the surface of the quartz dust is, the more damage it may cause. It has been noted that exposures to freshly fractured quartz produces more cytotoxic and inflammatory effects in rats than exposures to aged quartz.(53) On the other hand, the presence of iron and aluminum ions can, in some cases, reduce the toxicity of quartz.(54) So, for example, researchers would like to know whether when concrete is drilled, ground, or broken up during construction it produces more hazardous quartz or whether the quartz neutralized during the concrete curing process. In addition, exposures to quartz in soils during excavation also include exposures to clays. A common clay constituent is feldspar, which is a noncrystalline silicate. It has been suggested that when exposures to quartz are concurrent with feldspar exposure, the feldspar may provide a neutralizing effect.(55)

EC exposures, as an indicator of diesel exhaust particulate, averaged 13 μg/m³ for all samples in the present study. Average EC concentrations for rural and urban sites are around 1.3 and 3.8 μg/m³ respectively.(56) NIOSH monitored local and highway truck drivers and found their EC exposures averaged about 5 μg/m³. (57) At these exposure levels, it has been estimated that a truck driver would have a lifetime excess risk of lung cancer of 1–2% above background.(58) Exposures to EC were high in some enclosed operations such as using diesel lifts to install drop ceilings and wall tiles in a submerged highway tunnel. In these environments EC exposures averaged 54 μg/m³. It should be noted, however, that even in the tunnel the exposures were less than those measured for underground mine workers exposed to diesel (130–240 μg/m³).(59)

The only guideline regarding occupational exposure to diesel exhaust comes from the ACGIH proposed TLV of 20 μg/m³ as EC.(39) Using this value, 14% of all of the samples collected were over this concentration. Also, for the operating engineers who run the heavy equipment, 14% of the samples were over 20 μg/m³. Certain operations did have higher exposures. The installation of drop ceilings and wall tiles resulted in 75% of the 20 samples being over 20 μg/m³.

Organic carbon exposures in the present study had a mean of 64 μg/m³. In the NIOSH truckers study, measurements of submicrometer organic carbon levels for truck drivers had a mean of about 34 μg/m³. However, in that study only samples from nonsmokers were analyzed for organic carbon, because cigarette smoke consists mainly of organic carbon. In the present study, the mean organic carbon exposure of nonsmokers was slightly higher than that of smokers 68 versus 55 μg/m³. It is difficult to interpret the organic carbon measurements because workers who smoked on the day they were sampled may have been more likely to work outdoors or in a less confined areas. Also, other possible sources of organic carbon include nondiesel vehicle exhaust, solvents, oils and greases, and stationary source fuel combustion.

Previous work on welding exposures in construction operations have found 31–100% of the samples from boilermakers, pipefitters, and ironworkers exceeding the ACGIH TLV for respirable particulate (3 mg/m³).(60) In the present study, more than three-quarters (77%) of the samples taken exceeded the ACGIH TLV for welding fume (5 mg/m³). Susi et al.(2) also found that 7–72% of the samples from these trades exceeded the TLV for manganese (0.02 mg/m³), whereas in the present study 16% of the samples exceeded this level. Manganese exposures in welders have been associated with neurotoxic effects resulting in decreased motor function.(30) Little work has been done to evaluate fluoride exposures in construction. An early NIOSH criteria document discusses skeletal effects including osteosclerosis and increased bone density as well as pulmonary fibrotic changes from exposures to inorganic fluorides.(61) In this study 11% of the samples exceeded the current TLV for fluoride.

CONCLUSION

Given the high variability in exposure levels within construction operations it will be important to evaluate the determinants of dust, quartz, and diesel exposures using statistical modeling methods. By using the time variant exposure analysis method developed by the UMass Lowell Construction Occupational Health Program, it will be possible to distinguish the important exposure modifiers in the construction environment for each of these agents.(62) This will greatly assist in identifying and prioritizing potential exposure control interventions.

ACKNOWLEDGMENTS

Thanks to the contractors, construction workers, and local unions who participated in the sampling and to students and staff who assisted in data collection and analysis, including Nicole Blute; Cathy Greenspan; Susan Moir; Dana Hanson; Bernie Mizula; Mary Sobolefski; Heather Lyons; Todd Burnham; X. Michael Liu; Michael Landadio; and Jeffrey Vardis. Thanks also to Pam Susi and Jim Platner from CPWR for their assistance and support.

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APPENDIX A

The tabular-graphical procedure was used to calculate the size-selective fractions from impactor data. The major advantage of this procedure is that no underlying distribution of the data need be assumed. First, the mass on each impactor stage is corrected for entry and internal losses. Then, for each size-selective fraction the portion of each stage contributing to the fraction is determined using Simpson's rule. This calculation uses the size-selective fraction for the upper and lower range and midpoint of particle sizes collected on a stage.

	Cutpoint (μm)[A]	Inlet and Internal Correction	Particle Size Range (μm)[A]	Particle Size Midpoint (μm)[A]	Respirable Fraction	Thoracic Fraction	Inhalable Fraction
1	21.1	0.52	21.1–42	31.55	0	0.01	0.58
2	15	0.61	15.0–21.1	18.05	0	0.096	0.677
3	9.8	0.78	9.8–15.0	12.3	0.005	0.338	0.617
5a	3.5	0.875	3.5–9.8	7.4	0.152	0.711	0.74
filter	0	0.9	0–3.5	1.75	0.895	0.951	0.951

[A]Aerodynamic mass median diameter.

APPENDIX B

Description of Heavy Construction Operations Covered by This Study

Build Concrete Forms

This includes any of the activities surrounding the building of forms to hold the wet concrete.

Concrete Finish Work

Unlike demolition, this operation involves the finishing of new concrete structures that typically have defects and voids to be repaired. Known as Point and Patch activities with some workers. This operation is necessary after most large concrete forms are poured. In addition, after the slurry wall is completed, the top of the wall has to be finished by chipping away to bring the wall to specified height and remove substandard concrete. Usually additional rebar and concrete is then added to "cap" the wall.

Concrete Pouring

This is thee actual process of pouring the wet concrete into a completed form.

Demolition

This is the removal of old concrete using pneumatic or electric chipping tools or hammers if by hand or using hoe-rams and/or other heavy equipment if done by operating engineers.

Excavation

This includes any earth-moving operation involving heavy equipment and/or hand tools where the end-goal is an excavation of some sort. Includes process of filling in (backfilling) a trench or other excavation after necessary work has been completed. Includes grading, which mostly applies to front-end loaders and bulldozers, which grade the roads and work areas as needed.

Excavation Support Work (Steel Crossbeam Attachment)

This operation is also called placing struts and wales. This operation includes placement of bracing for the supported excavation at specified intervals as earth removal proceeds. This operation includes welding and cranework to put the struts and wales in place or removal of struts and wales prior to backfilling.

Installing Interior Drop Ceilings and Wall Tiles

After the tunnel is completed, large porcelain ceiling panels are hung to create and air the plenum/drop ceiling after holes are drilled in the concrete ceiling to hold anchor bolts. For one of the tunnels alone, 26,000 anchor bolt holes were drilled. The side walls of the tunnel are covered by ceramic tiles during the tunnel finish phase.

Laying Conduit/Pipe in Trenches

This is a subpart of the utility relocation phase in which the pipe or conduit is placed in the trench.

Pipejacking

Pipejacking operations have a sending pit and receiving pit. The objective is to lay utilities without having to disturb the surface above the line except at the two pits using some sort of hydraulic excavating equipment or if precluded by pipe diameter hand tools.

Site Support

This includes functions such as directing traffic, power washing trucks, and distributing water jugs related to the general support of a construction site and not to any specific activity occurring on site.

Slurry/Grout Plant Operation

This includes any work at the central location where new slurry is pumped out to the active slurry panels and old slurry is returned for recycling or disposal. Slurry is typically a water and bentonite (2–4% crystalline silica) or a polymer mixture that stabilizes soil. This also may be work at a central location where grout (cement or cement and fly ash) is stored, mixed, and pumped out to a drill rig for jet grouting.

Specialized Foundation Operations

These include the following: Excavate Slurry Panel—Excavation of the slurry panel using clamshell excavators to remove earth and slurry (bentonite or polymer and water) to stabilize the walls.

Jet Grouting—Any of the work at the drill rig where grout is injected into the soil.

Caisson Placement—As used on the CAT, a caisson is a cast-in-place pile generally having a diameter of 2.5 feet or greater. Caisson techniques may be used in place of pile-driving equipment to minimize disturbance of surrounding soil and clay substrate. All caisson work takes place at the surface using mostly mechanized equipment to excavate the hole.

Pile Driving—Pertains to all of the activities surrounding the pile-driving operation.