# Real-time monitoring of arsenic, cadmium, copper and lead concentrations in workplace smelter particulates using a TSI 8520 DustTrak

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## ABSTRACT

*Exposure to particulates containing metals and metal fumes (PCMMF) is a potential concern in ore refining and smelting. Some metals of primary interest are arsenic, cadmium, copper and lead, which have been linked to various adverse health effects. The current National Institute for Occupational Safety and Health (NIOSH) sampling method for metals in particulates requires the use of a filter, precision airflow pump and laboratory analysis. A major concern with this method is the one-to-two weeks' wait before laboratory results are available for use in determining if additional controls are needed to assure adequate exposure protection for workers.*

*Particulates containing these metals were sampled during sixteen sampling events at a copper smelter using the traditional NIOSH methods. Monitoring of particulates was simultaneously conducted using a TSI 8520 DustTrak real-time aerosol monitor with a 10-µm-cutpoint sampling inlet. NIOSH analytical methods related to particulates and metals (methods 0500, 0600 and 7300) were used to determine particulate mass and individual mass contributions of metals on sample filters.*

*Linear regressions with y-intercepts forced to zero were developed to determine the relationship between the* $PM_{10}$ *measurements recorded by the DustTrak and laboratory-reported total particulate mass,* $PM_{10}$ *and respirable arsenic, cadmium, copper and lead concentrations. These linear regressions yielded correction factors that can be applied to DustTrak readings to obtain total particulate mass,* $PM_{10}$ *and respirable concentration estimates for each of the four metals. The* $R^2$ *(coefficient of determination) values from the linear regressions ranged from 0.65 for total lead to 0.91 for total copper. These results suggest that the DustTrak may produce real-time data useful in providing estimates for airborne concentrations of arsenic, cadmium, copper and lead in copper smelter particulates.*

Key words: Lead, Arsenic, Copper, Particulate control, Health and safety

## Introduction

Exposure to particulates containing metals and metal fumes (PCMMF) is a concern in metal refining and smelting operations. Recent data from the U.S. Bureau of Labor Statistics indicates that of the estimated 699,720 U.S. workers currently employed in the smelting and refining of ferrous and nonferrous metals, 394,380 have occupational exposures to metals (Bureau of Labor Statistics, 2009). A variety of acute and chronic health effects associated with human exposures to arsenic (Enterline et al., 1987; Enterline et al., 1995; Lee-Feldstein, 1986; NIOSH, 2007; Rossman, 1998), cadmium (Chalkley et al., 1998; Newman-Taylor, 1998; NIOSH, 2007), copper (Madden, 1998; NIOSH, 2007) and lead (Chalkey et al., 1998; Fischbein, 1998; NIOSH, 2007; Roels et al., 1994) have been documented, making these metals of significant concern. Most notably, acute arsenic exposure may cause profound gastrointestinal inflammation, constriction of the throat, paralysis and coma. Chronic arsenic exposure may increase risk of lung and lymphatic cancer. Acute cadmium exposure may cause pulmonary edema and chronic cadmium exposure may damage the liver and kidneys and increase the risk of prostate and lung cancer. Acute exposure to copper fumes may cause metal fume fever and chronic copper exposure may be damaging to the respiratory system, liver and kidneys. Acute lead exposure may cause convulsions, coma, encephalopathy and kidney damage. Chronic lead exposure may contribute to the onset of kidney disease. In addition, epidemiological studies have shown that metal smelting and refining workers are at a higher risk for lung cancer than the general population (Lubin et al., 2000; Ades and Kazantzis,

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1988; Jarup et al., 1989). The Occupational Safety and Health Administration (OSHA) has set the permissible exposure limit (PEL) for arsenic at 10 $\mu$g/m$^3$ (29 CFR 1910.1018), cadmium at 5 $\mu$g/m$^3$ (29 CFR 1910.1027), copper at 1,000 $\mu$g/m$^3$ for dusts/mists and 100 $\mu$g/m$^3$ for fumes (29 CFR 1910.1000) and lead at 50 $\mu$g/m$^3$ (29 CFR 1910.1025).

The current National Institute for Occupational Safety and Health (NIOSH) sampling and analytical methods for metals in particulates require laboratory analysis that typically takes one to two weeks before results are available. Therefore, there is a one-to-two-week time period between the samples being collected and the sampling data being available for use in assessing worker exposures. Other disadvantages of the standard sampling methodology include: 1) the necessity to sample for several hours, in most instances, to accumulate sufficient particulate matter mass for accurate analysis, 2) the lack of data provided on concentration fluctuations within a sampling period, 3) the relatively high amount of labor required for both sampling and analysis and 4) the relatively high long-term expense when detailed analysis and/or frequent monitoring is necessary. Although having relatively high initial costs (~$5,000-$30,000), the use of real-time aerosol monitors such as the TSI 8520 DustTrak (TSI Inc., Shoreview, MN), hereafter referred to as "DustTrak," eliminates these disadvantages. However, there is currently no OSHA or NIOSH standardized sampling method to provide real-time data on concentrations of PCMMF.

The DustTrak, in conjunction with carefully determined site-specific correction factors, has been previously demonstrated to be effective in providing relative concentration estimates of airborne diesel particulate matter (Stephenson et al., 2006), respirable coal dust (Lehocky and Williams, 1996), metalworking fluids (Verma et al., 2006), environmental tobacco smoke, cooking oil fumes, cedar-wood smoke (Jenkins et al., 2004), welding fumes and residual fuel oil ash in the boilermaker industry (Kim et al., 2004), and PM$_{2.5}$ particulate matter (Yanosky et al., 2002; Ramachandran et al., 2000; Chang et al., 2001). An advantage of real-time monitors, such as the DustTrak, that detect scattered light, rather than transmitted light, is that they exhibit higher sensitivity at lower concentrations (Vincent, 2007). A disadvantage of the DustTrak and other real-time monitors operating on the light scattering principle to measure aerosols is that the response of the instrument is affected by particle shape, particle density, particle size and the refractive index of the aerosol (Rader and O'Hern, 2001; Chen et al., 1990; Görner et al., 1995). Cheng (2008) and Chan et al. (2002) found, specifically, that the response of the DustTrak decreases as particle size increases.

The purpose of this study was to determine if the DustTrak with an inlet cutpoint of 10 µm, in conjunction with site-specific correction factors for total, PM$_{10}$ and respirable fractions of each metal of concern, can provide an approximation of results obtained using current arsenic, cadmium, copper and lead sampling techniques. If proven effective, real-time monitoring of PCMMF would provide instantaneous information on the airborne concentration level of particulate matter, which could then be quickly extrapolated to determine an accurate estimate for the concentration of each metal of concern in air. This does require site-specific information on the normal concentration of each metal in the airborne particulates to be measured. This information would allow for a prompt evaluation of area concentrations and potential employee exposures. Availability of this data could allow for the swift implementation, if necessary, of any appropriate controls for assuring worker exposures remain within acceptable levels.

## Methods

Air sampling for PCMMF was performed during 16 sampling events (two sampling events per day for eight non-consecutive sampling days) at a single location inside of a copper smelter. The sampling location was a platform approximately three meters above and directly between two refining furnaces that were approximately 10 m apart. This location was chosen for its proximity to potential emission sources for airborne particulates, lack of significant ventilation, suitable representation of the working area and noninterference with normal work processes. The sampling days were selected based on scheduling convenience and avoidance of days when the smelter was not in operation. The eight days are representative of normal operations at this smelter.

During each sampling event, samples were collected using three SKC 37 mm styrene cassettes (SKC Inc., Eighty Four, PA) coupled with SKC Respirable Dust Aluminum Cyclones (SKC Inc., Eighty Four, PA) for respirable samples, three SKC Thoracic Parallel Particle Impactors (SKC Inc., Eighty Four, PA) for PM$_{10}$ samples and three total dust cassettes, all containing SKC 37 mm matched weight Mixed Cellulose Ester (MCE) filters with a pore size of 0.8 $\mu$m (SKC Inc., Eighty Four, PA). All equipment and sampling media were assembled per manufacturer instructions and were colocated with a DustTrak on a 1.2-by-1.2-m sampling table with its surface positioned approximately 1.0 m above the platform. The inlets for all samples, except the DustTrak, were secured to a horizontal string approximately 0.5 m above the table. For discussion purposes, when referring to samples collected using the SKC cyclones, the term "respirable samples" will be used and, when referring to the samples collected using the SKC thoracic impactors, the term "PM$_{10}$ samples" will be used. The DustTrak was set to log the detected mass concentrations per unit volume every one second during sampling. For quality control purposes, two total dust samples, collected directly outside of the smelter, and one blank sample were obtained during each sampling event.

The DustTrak is a solid-state laser photometer, which operates on the principle of light scattering. An internal precision-flow pump is used to draw a continuous airstream through an impaction inlet, which removes particles with an aerodynamic diameter greater than 10 µm (1 µm and 2.5 µm cut-point inlets are also available for use with this instrument). The sampled air is then passed through a sensing chamber, where light from a laser diode oriented at 90° intersects it. When the light hits a particle, it is scattered and reflected onto a silicon detector. The amount of light measured by the detector is internally extrapolated into a particulate mass concentration using a calibration factor. The default calibration factor is based on the International Organization for Standardization (ISO) 12103-1 A1 test dust (Arizona Test Dust), which has a density of 2.65 g/cm$^3$. Any monitoring of aerosols with densities differing from this standard requires an altered calibration factor. The DustTrak can detect particles between 0.1 and 10 µm in size and has a mass per unit volume detection range of 0.001 to 100 mg/m$^3$.

For each sampling period, pre- and post airflow calibrations were performed on all SKC AirChek 2000 air sampling pumps (SKC Inc., Eighty Four, PA), as well as the DustTrak, using a DryCal Model DC-Lite (BIOS International, Pompton Plains, NJ). The DustTrak was calibrated to the manufacturer's recommended flow rate of 1.7 L/min. The precision air sampling pumps associated with the collection of both total dust samples and PM$_{10}$ samples were calibrated to 2.0 L/min and the sampling pumps associated with the respirable samples were calibrated to 2.5 L/min, all per NIOSH or manufacturer instructions. Pump calibrations were performed with appropriate surrogates of actual sampling trains in place. Sampling pumps were allowed to run continuously throughout the entire sampling day, but were recalibrated between sampling periods. All DustTrak and pump postcalibrations were found to be within 5% of pre-calibrations. The averages of pre- and post-calibration flow rates were then used in the calculation of total air volumes for each sample collected. In addition, the DustTrak was zeroed before each sampling period, using an attachable high-efficiency particulate air (HEPA) filter supplied by the manufacturer.

| | | **Traditional sampling shows concentration to be above PEL** | |
|---|---|---|---|
| | | **Yes** | **No** |
| **DustTrak predicts concentration to be above PEL** | **Yes** | A | B |
| | **No** | C | D |

Sensitivity = A / (A + C)
Specificity = D / (B+ D)
Positive predictive value (PPV) = A / (A + B)
Negative predictive value (NPV) = D / (C + D)

**Figure 1** — Contingency table methodology.

Following equipment setup, all sample-collecting devices were simultaneously placed into operation and allowed to sample for approximately three hours. Exact run times varied slightly but specific start and stop times were recorded for use in calculation of accurate sample volumes for each sample. During the sampling period, the research team remained on-site to observe sample collection and record relevant smelter activities that could potentially affect results. At the end of each sample period, samples were simultaneously disconnected from pumps. The sampling media was then taken into a reasonably clean environment and prepared for transport to the laboratory. The subsequent sampling period was then prepared for and sample collection was performed identically to the previous sampling period.

Following each sampling day, the sampling media were transported to an American Industrial Hygiene Association (AIHA)-accredited laboratory, where NIOSH analytical method 0500 procedures were followed to gravimetrically determine particulate mass collected on both $PM_{10}$ and total dust sample filters. NIOSH analytical method 0600 was used to gravimetrically determine particulate mass collected on the respirable sample filters. NIOSH analytical method 7300 procedures were then followed to analyze all samples for individual mass contributions of arsenic, cadmium, copper and lead using inductively coupled plasma, atomic emission spectroscopy (ICP-AES). The sampling data logged by the DustTrak was downloaded to a computer hard drive using TrakPro v3.32 software (TSI Inc., Shoreview, MN).

After results were received from the laboratory, the reported concentrations from each set of three samples from a single sampling period (e.g., the three respirable samples) were averaged to give a single estimate of metal concentration. Samples below the laboratory detection limit for a metal were given a value of half of the detection limit and used for mathematical computation purposes. The detection limits were 1 $\mu$g for arsenic, copper and lead and 0.5 $\mu$g for cadmium.

STATA version 10.1 (STATA Corp., College Station, TX) was used for statistical analysis. Pearson's correlation coefficient (*r*) was used to assess the strength of association between the average $PM_{10}$ concentrations reported by the DustTrak for each sampling period and the corresponding total particulate, $PM_{10}$ and respirable metal concentrations determined by laboratory analysis of sample filters. Individual least squares linear regressions were then performed to assess the linear relationship between $PM_{10}$ measurements recorded by the DustTrak (the independent variable) and laboratory-reported arsenic, cadmium, copper and lead concentrations (the dependent variables). Each linear regression model was assessed independently by its $R^2$ (coefficient of determination) value. For these calculations, it was assumed that when concentrations on the sampling media analyzed by the laboratory were zero, particulate concentrations detected by DustTrak would also be zero. Therefore, the intercept of each regression was forced to zero, as was done by Lehocky and Williams (1996) in a study on respirable coal dust. The slope of the regression equation for each metal was then used as the correction factor for that metal. For example, the slope of the regression equation for respirable copper multiplied by the reported reading of the DustTrak resulted in the predicted respirable copper concentration.

Contingency tables were developed to assess the sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of the DustTrak in terms of predicting whether or not the airborne concentration of each metal in a particular situation was above or below the PEL for that metal. Only total dust metal concentrations were used in this analysis, since the PEL for each metal is based on total concentration. Figure 1 demonstrates the methodology used to calculate these values.

Sensitivity in this case is defined as the probability the DustTrak predicted the concentration of a metal to be above the PEL when the laboratory analysis of the sampling media showed the concentration of that metal to be above the PEL. Conversely, specificity in this case is defined as the probability the DustTrak predicted the concentration of a metal to be below the PEL when the laboratory analysis of the sampling media showed the concentration of that metal to be below the PEL. The PPV in this case is defined as the proportion of DustTrak-predicted concentrations above the PEL that are truly above the PEL, as determined by the laboratory analysis of the sampling media. The NPV in this case is defined as the proportion of DustTrak-predicted concentrations below the PEL that are truly below the PEL, as determined by the laboratory analysis of the sampling media.

## Results

A total of seven samples (five respirable samples and two $PM_{10}$ samples) were voided due to problems with pumps or errors made during sample handling. All sample sets (e.g., three respirable samples collected during one sampling period) had a minimum of two usable samples. Of all samples collected in this study, two out of 43 respirable samples, seven out of 46 $PM_{10}$ samples and four out of 48 total dust samples yielded cadmium contributions below the detection limit. No samples yielded contributions of arsenic, copper or lead below detection limits, other than the blanks and controls.

Metal concentration results for respirable samples, $PM_{10}$ samples and total dust samples are listed in Tables 1, 2 and 3. In each table, metal concentrations represent the average concentrations from a particular sample set. For example, the respirable arsenic concentration for sample period 1 is the arithmetic average of the laboratory-reported arsenic concen-

**Table 1** — Respirable sample results.

| Date sampled | Sample period | Arsenic concentration, µg/m$^3$ | Cadmium concentration, µg/m$^3$ | Copper concentration, µg/m$^3$ | Lead conc., µg/m$^3$ | Total respirable concentration, µg/m$^3$ | DustTrak reading, µg/m$^3$ |
|---|---|---|---|---|---|---|---|
| 1/5/09 | 1* | 68.7 | 2.56 | 80.7 | 200 | 767 | 295 |
| 1/5/09 | 2 | 44.0 | 4.05 | 46.0 | 60.0 | 917 | 264 |
| 1/7/09 | 3 | 14.0 | 1.60 | 88.7 | 25.7 | 329 | 522 |
| 1/7/09 | 4 | 39.7 | 4.70 | 51.3 | 73.7 | 786 | 696 |
| 1/9/09 | 5 | 48.7 | 2.13 | 31.7 | 187 | 901 | 335 |
| 1/9/09 | 6* | 28.0 | 1.10 | 40.0 | 65.0 | 323 | 148 |
| 1/12/09 | 7 | 48.7 | 6.73 | 71.0 | 197 | 580 | 325 |
| 1/12/09 | 8* | 12.0 | 0.68 | 34.5 | 39.5 | 285 | 86.0 |
| 1/16/09 | 9 | 45.3 | 5.30 | 49.3 | 103 | 551 | 371 |
| 1/16/09 | 10 | 54.3 | 4.10 | 55.3 | 120 | 601 | 472 |
| 1/19/09 | 11 | 77.3 | 6.83 | 59.3 | 69.0 | 672 | 718 |
| 1/19/09 | 12* | 31.0 | 1.95 | 39.0 | 48.0 | 146 | 364 |
| 1/23/09 | 13* | 71.5 | 1.80 | 61.0 | 115 | 662 | 564 |
| 1/23/09 | 14 | 66.0 | 2.73 | 78.7 | 143 | 707 | 470 |
| 1/26/09 | 15 | 12.3 | 0.88 | 97.7 | 18.3 | 783 | 445 |
| 1/26/09 | 16 | 39.3 | 2.77 | 140 | 88.7 | 671 | 482 |
| Average | | 43.8 | 3.12 | 64.0 | 97.1 | 605 | 410 |

* denotes sample periods in which the results of only two samples were averaged due to third sample being voided

trations for the three respirable samples that were collected during that sample period.

Correlation coefficients from the Pearson's correlations and coefficients of determination, slopes of regression and *p*-values from the linear regressions comparing DustTrak predicted metal concentrations with reported laboratory measured metal concentrations from sampling media are summarized in Table 4. Copper exhibited the highest Pearson's correlation coefficients for PM$_{10}$ and total dust particulates at 0.64 and 0.67, respectively, while cadmium had the highest Pearson's correlation coefficient for respirable particulates at 0.42. The correlations involving lead displayed the lowest Pearson's

**Table 2** — PM$_{10}$ sample results.

| Date sampled | Sample period | Arsenic concentration, µg/m$^3$ | Cadmium concentration, µg/m$^3$ | Copper concentration, µg/m$^3$ | Lead conc., µg/m$^3$ | Total pm10 concentration, µg/m$^3$ | DustTrak reading, µg/m$^3$ |
|---|---|---|---|---|---|---|---|
| 1/5/09 | 1 | 63.3 | 2.37 | 90.7 | 190 | 1020 | 295 |
| 1/5/09 | 2* | 35.5 | 4.80 | 70.5 | 69.0 | 274 | 264 |
| 1/7/09 | 3 | 18.3 | 2.57 | 120 | 34.0 | 1880 | 522 |
| 1/7/09 | 4 | 34.3 | 5.00 | 72.0 | 65.0 | 1120 | 696 |
| 1/9/09 | 5 | 52.7 | 2.53 | 42.0 | 170 | 596 | 335 |
| 1/9/09 | 6 | 22.7 | 0.25 | 41.3 | 51.0 | 396 | 148 |
| 1/12/09 | 7 | 55.0 | 7.37 | 87.0 | 200 | 1440 | 325 |
| 1/12/09 | 8 | 9.97 | 0.25 | 34.0 | 35.0 | 320 | 86 |
| 1/16/09 | 9 | 49.7 | 6.13 | 66.0 | 112 | 669 | 371 |
| 1/16/09 | 10 | 49.7 | 6.13 | 66.0 | 112 | 671 | 472 |
| 1/19/09 | 11 | 110 | 9.43 | 127 | 93.7 | 867 | 718 |
| 1/19/09 | 12* | 30.5 | 1.90 | 50.0 | 45.5 | 654 | 364 |
| 1/23/09 | 13 | 110 | 2.70 | 107 | 170 | 1010 | 564 |
| 1/23/09 | 14 | 81.0 | 3.40 | 120 | 173 | 1100 | 470 |
| 1/26/09 | 15 | 14.7 | 1.28 | 123 | 23.7 | 234 | 445 |
| 1/26/09 | 16 | 37.7 | 2.77 | 140 | 86.0 | 841 | 482 |
| average | | 48.4 | 3.68 | 84.8 | 102 | 818 | 410 |

* denotes sample periods in which the results of only two samples were averaged due to third sample being voided

**Table 3** — Total dust sample results.

| Date sampled | Sample period | Arsenic concentration, µg/m$^3$ | Cadmium concentration, µg/m$^3$ | Copper concentration, µg/m$^3$ | Lead conc., µg/m$^3$ | Total dust concentration, µg/m$^3$ | DustTrak reading, µg/m$^3$ |
|---|---|---|---|---|---|---|---|
| 1/5/09 | 1 | 64.0 | 2.43 | 103 | 193 | 1710 | 295 |
| 1/5/09 | 2 | 48.7 | 4.40 | 62.7 | 63.3 | 791 | 264 |
| 1/7/09 | 3 | 17.0 | 2.33 | 120 | 29.3 | 850 | 522 |
| 1/7/09 | 4 | 30.3 | 4.43 | 79.3 | 50.3 | 1180 | 696 |
| 1/9/09 | 5 | 53.3 | 2.77 | 46.7 | 180 | 1120 | 335 |
| 1/9/09 | 6 | 29.7 | 1.02 | 53.7 | 63.7 | 430 | 148 |
| 1/12/09 | 7 | 42.3 | 6.00 | 71.7 | 170 | 950 | 325 |
| 1/12/09 | 8 | 11.0 | 0.25 | 39.7 | 36.7 | 529 | 86 |
| 1/16/09 | 9 | 52.3 | 6.67 | 81.3 | 110 | 1040 | 371 |
| 1/16/09 | 10 | 56.7 | 4.30 | 98.0 | 120 | 1630 | 472 |
| 1/19/09 | 11 | 103 | 9.23 | 160 | 87.0 | 1340 | 718 |
| 1/19/09 | 12 | 35.3 | 2.30 | 62.3 | 51.0 | 1140 | 364 |
| 1/23/09 | 13 | 100 | 2.77 | 103 | 163 | 1660 | 564 |
| 1/23/09 | 14 | 83.7 | 3.53 | 130 | 183 | 1920 | 470 |
| 1/26/09 | 15 | 16.3 | 2.07 | 130 | 24.3 | 892 | 445 |
| 1/26/09 | 16 | 47.3 | 3.77 | 167 | 98.7 | 866 | 482 |
| Average |  | 49.4 | 3.64 | 94.3 | 102 | 1130 | 818 |

correlation coefficients at -0.08, 0.06 and 0.01 for respirable, PM$_{10}$ and total dust, respectively.

The linear regressions for copper also yielded the highest coefficient of determination values for PM$_{10}$ and total dust, with $R^2$ values of 0.90 and 0.91, respectively. These values indicate that 90% of the variability between sample periods in sampled PM$_{10}$ copper concentrations and 91% of the variability between sample periods in sampled total dust copper concentrations is explained by their respective regression models. Arsenic produced the highest respirable $R^2$ value at 0.82. Lead again displayed the lowest values for all three sample types, with $R^2$ values of 0.61, 0.66 and 0.65 for respirable, PM$_{10}$ and total dust, respectively. All linear regressions were statistically significant, with *p*-values below 0.001. Figure 2 displays regression plots for respirable, PM$_{10}$ and total dust copper concentrations. Similar plots for arsenic, cadmium and lead were developed but not included for brevity. It is assumed that homoscedasticity has been achieved, meaning there is a random distribution of residual errors (differences between predicted values and actual values) across all predicted metal concentrations, although this is difficult to determine with a small sample size.

Contingency tables for total concentrations of each metal are displayed in Fig. 3. Sampling results from traditional sampling and analytical methods indicated that 16 of 16 arsenic concentrations, 3 of 16 cadmium concentrations, 0 of 16 copper concentrations and 13 of 16 lead concentrations exceeded the PEL. Similarly, the DustTrak predicted that 15

**Table 4** — Summary of results from Pearson's correlation and linear regression.

| Metal | Sample type | Pearson's correlation coefficient (*r*) | Coefficient of determination ($R^2$) | Slope of regression (correction factor) | *p*-value |
|---|---|---|---|---|---|
| Arsenic | respirable | 0.40 | 0.82 | 0.098 | < 0.00001 |
|  | PM$_{10}$ | 0.51 | 0.79 | 0.114 | < 0.00001 |
|  | total dust | 0.46 | 0.80 | 0.114 | < 0.00001 |
| Cadmium | respirable | 0.42 | 0.76 | 0.007 | < 0.00001 |
|  | PM$_{10}$ | 0.54 | 0.77 | 0.009 | < 0.00001 |
|  | total dust | 0.56 | 0.82 | 0.009 | < 0.00001 |
| Copper | respirable | 0.33 | 0.81 | 0.142 | < 0.00001 |
|  | PM$_{10}$ | 0.64 | 0.90 | 0.195 | < 0.00001 |
|  | total dust | 0.67 | 0.91 | 0.219 | < 0.00001 |
| Lead | respirable | -0.08 | 0.61 | 0.199 | < 0.00001 |
|  | PM$_{10}$ | 0.06 | 0.66 | 0.216 | < 0.00001 |
|  | total dust | 0.01 | 0.65 | 0.213 | < 0.00001 |

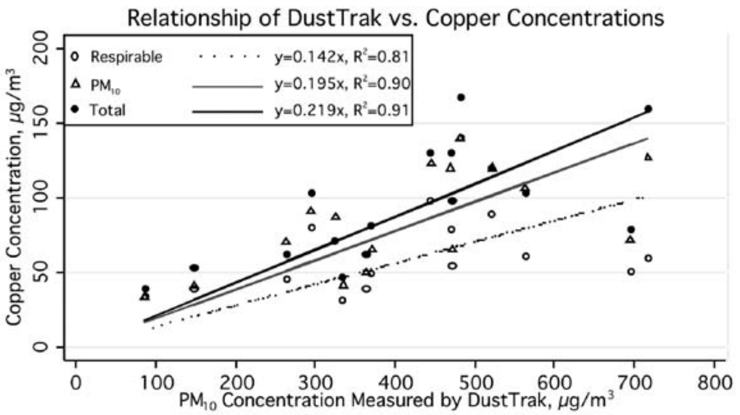

**Figure 2** — Regression plots for respirable, $PM_{10}$ and total dust copper.

of 16 arsenic concentrations, 2 of 16 cadmium concentrations, 0 of 16 copper concentrations and 14 of 16 lead concentrations exceeded the PEL.

A summary of sensitivity, specificity, PPV and NPV for each metal is provided in Table 5. The following example demonstrates the appropriate interpretation of the information contained in Table 5. When the cadmium concentration was above the PEL, the DustTrak accurately predicted concentrations to be above the PEL 33% of the time and when the cadmium concentration was below the PEL, the DustTrak accurately predicted concentrations to be below the PEL 92% of the time. When the DustTrak predicted cadmium concentrations to be above the PEL, they were truly above the PEL 50% of the time and when it predicted cadmium concentrations to be below the PEL, they were truly below the PEL 86% of the time. The Table 5 values for arsenic, copper, and lead are interpreted in the same fashion. The zeros in the table occur due to the lack of recorded concentrations either above or below the PEL for a given metal. For example, the sensitivity and PPV for copper are zero simply because there is no data for copper concentrations above the PEL.

## Discussion

For the smelter environment in which the study was conducted, the Pearson's correlation analyses suggest that DustTrak $PM_{10}$ readings are more highly correlated overall with copper concentrations than concentrations of the other metals evaluated. Arsenic and cadmium show an intermediate level of correlation with the DustTrak, while lead monitoring results exhibit a poor correlation. However, the Pearson's correlation is useful only to obtain a preliminary overview of the strength of association. The linear regression is a better measure of the relationship between DustTrak readings and actual metal concentrations.

The linear regression analyses and Pearson's correlations agree and suggest that, for the smelter environment in which the study was conducted, there is a strong correlation between DustTrak readings and copper concentrations, a lower level of correlation between DustTrak readings and arsenic and cadmium concentrations and a low level of correlation between DustTrak readings and lead concentrations. The high level of correlation exhibited between the DustTrak readings and copper, arsenic and cadmium concentrations suggests that any necessary action (such as increased exposure control) could be identified based on the concentrations predicted by the DustTrak. It is not recommended that action take place based on predicted lead concentrations, due to the low level of correlation. These varying correlations indicate that the percent compositions of some metals, such as copper, in the smelter particulates were more consistent than others, such as lead. This may have been caused by a variety of factors, such as the feedstock that was used and smelter activities that were taking place at any given time. Another source of potential error is the differing densities of the metals. It should be noted that any estimation of future concentrations of these four metals is limited by the statistical error associated with sampling and analysis, the particular location and environment in which this sampling was conducted and the relatively small sample size of the study.

As was previously mentioned, the DustTrak is factory-

| **Arsenic** | | Traditional sampling shows arsenic concentration to be above PEL | |
|---|---|---|---|
| | | Yes | No |
| DustTrak predicts arsenic concentration to be above PEL | Yes | 15 | 0 |
| | No | 1 | 0 |

| **Cadmium** | | Traditional sampling shows cadmium concentration to be above PEL | |
|---|---|---|---|
| | | Yes | No |
| DustTrak predicts cadmium concentration to be above PEL | Yes | 1 | 1 |
| | No | 2 | 12 |

| **Copper** | | Traditional sampling shows copper concentration to be above PEL | |
|---|---|---|---|
| | | Yes | No |
| Dusttrak predicts copper concentration to be above PEL | Yes | 0 | 0 |
| | No | 0 | 16 |

| **Lead** | | Traditional sampling shows lead concentration to be above PEL | |
|---|---|---|---|
| | | Yes | No |
| Dusttrak predicts lead concentration to be above PEL | Yes | 12 | 2 |
| | No | 1 | 1 |

**Figure 3** — Contingency tables for arsenic, cadmium, copper and lead.

**Table 5** — Summary of contingency table statistics.

| Metal | Sensitivity | Specificity | PPV | NPV |
|---|---|---|---|---|
| Arsenic | 0.94 | 0 | 1 | 0 |
| Cadmium | 0.33 | 0.92 | 0.5 | 0.86 |
| Copper | 0 | 1 | 0 | 1 |
| Lead | 0.92 | 0.33 | 0.86 | 0.5 |

calibrated with Arizona Test Dust. Therefore, to provide more accurate real-time data on smelter particulate concentrations, the internal calibration factor (factory default of 1.0) may be adjusted based on the gravimetric results of particulates in the environment. In this study, no alteration was made to the instrument's internal calibration factor, as the scope of the study did not require it. An advantage to retaining the factory default calibration factor is that data from the DustTrak requires less manipulation and is, therefore, a simpler exposure assessment tool for use in the smelting industry. It should be noted that if the calibration factor were adjusted for one metal of concern, external calculations would still be required to determine concentration estimates for the other metals present.

The difference between the airflow rate used by the DustTrak and those used in the collection of samples using the pump-and-filter method may also have contributed to the difference in results returned by the two methods. Sampling conducted via the traditional method (using sample pumps calibrated at 2.0-to-2.5 L/min and filter media) would likely collect more, and larger, particles than the DustTrak (with an air collection flow rate of 1.7 L/min). The higher airflow rates used in the pump-and-filter method likely also caused particles located further from the sample port to be collected compared to the DustTrak. This would explain, to some extent, the increase in mass per unit volume results, observed in the large majority of sample periods, when comparing filter sample data to DustTrak data. The differing positions of the DustTrak and the other collection media, and the variation in actual particulate densities between and within sampling periods, could also have contributed to differences in the data from the different monitoring methods. While the particulates are physically collected and weighed on the sample filters, allowing actual particulate densities to be taken into account, the DustTrak estimates the mass of each particle based on its size and a fixed assumed density.

Although sensitivity, specificity, PPV and NPV can be useful tools in this type of study for determining the capability of the DustTrak for predicting conditions that may be above or below the PEL for certain metals, the range of metal concentrations recorded in this study reduces their applicability. For these statistics to be effective in assessing the predictive capabilities of the DustTrak, it is necessary to have sample results in a range of concentrations both above and below the PEL. In this study, all measured arsenic concentrations represented conditions where the concentration was above the PEL; 13 of 16 measured lead concentrations represented conditions above the PEL. Conversely, all measured copper concentrations represented conditions below the PEL, while 13 of 16 measured cadmium concentrations represented conditions below the PEL. The sensitivity and PPV of the cadmium analysis and specificity and NPV of the lead analysis suggest that when concentrations of these metals approach the PEL (from below for cadmium and from above for lead) the capability of the DustTrak to predict concentrations to be above or below the PEL becomes imprecise. This could most likely be improved with a larger sample size, more distribution of measured concentrations around the PEL and/or information on the composition or changes in composition of the feedstock used in the smelter.

It should be noted that this study is not meant to demonstrate that the DustTrak can be used as a true indicator of compliance with PELs for arsenic, cadmium, copper and lead. OSHA's PELs for these metals are all based on personal eight-hour time weighted average (TWA) samples, whereas this study used only area samples for less-than-eight-hour periods. This study is meant only to determine if the DustTrak, in conjunction with site-specific correction factors for each metal of concern, can be used as a tool to provide real-time estimates of area airborne concentrations of arsenic, cadmium, copper and lead. This information would allow for real-time evaluation of metal concentrations, which may then assist management in determining if any additional emission or exposure controls need to be promptly implemented to maintain acceptable levels of potential worker exposure to these metals.

## Conclusions

The results of this study suggest that the DustTrak may be used to provide usable real-time estimates of arsenic, cadmium, copper and lead concentrations compared to measurements by standard methods, although percent compositions of these metals in smelter particulates appear to be variable, due to differences in ore supplied for smelting. As this is the first study to assess the capability of the DustTrak to predict concentrations of specific metals in airborne particulates from smelter operations, further research is necessary to confirm the results. In future studies, the addition of other explanatory variables, such as feedstock, environmental conditions and specific smelter activities, to regression models should be performed to assess the impact each of these factors may have on the relationship between DustTrak readings and actual arsenic, cadmium, copper and lead concentrations.

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