

A comparison of direct-reading instruments for the measurement of hexavalent chromium during stainless steel welding

Hexavalent chromium (Cr(VI)), a known human carcinogen, is a potential exposure concern for workers performing tasks such as welding, soldering or brazing. Traditional monitoring methods for Cr(VI) require the use of a closed-face cassette with a polyvinyl chloride filter, followed by analysis using high-performance liquid chromatography with an ultraviolet and visible light detector, to measure an 8-hr time weighted average (TWA). Utilizing this method can produce a substantial lag time between sampling and results. The use of a direct-reading instrument would provide a useful tool to enable real-time estimation of Cr(VI) for rapid assessment of exposure controls. For this study, three direct-reading instruments were compared with the traditional sampling method: the TSI DustTrak 8520, the HazDust EPAM 5000 and the GRIMM 1.109. A total of 10 side-by-side sampling events were carried out in three different workplaces where welding of stainless steel was being performed. Results from all three instruments found they performed well when compared to the traditional method based on linear regression modeling, and with all R^2 greater than 0.80. This study demonstrated potential value for using direct-reading instruments to quickly estimate Cr(VI) in air during welding operations.

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INTRODUCTION

Epidemiological studies have found a relationship between cumulative hexavalent chromium Cr(VI) exposure among workers and increased risk for lung cancer compared with the general population.^{1–10} As such, Cr(VI) has been listed as a known human carcinogen by the International Agency for Research in Cancer¹¹ and is considered a potential occupational carcinogen by the National Institute for Occupational Safety and Health (NIOSH).¹² Workers performing stainless steel welding are particularly at risk of developing lung cancer from airborne Cr(VI) exposures,^{4,13,14} up to a 2.4-fold higher risk.¹⁵ According to the Bureau of Labor Statistics, in 2012 there were 357,400 welders, cutters, solderers and brazers in the US.¹⁶

The US Occupational Safety and Health Administration (OSHA) have set a Permissible Exposure Limit (PEL) of $5 \mu\text{g}/\text{m}^3$, as an 8 hr time-weighted average (TWA).¹⁷ The OSHA Standard (29 CFR 1910.1026) specifically requires monitoring of employees

with possible exposure to hexavalent chromium.

The current sampling methods for Cr(VI) used by both the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) require the use of a 37-mm closed-face cassette with a polyvinyl chloride (PVC) filter with a $5 \mu\text{m}$ pore size for sampling over a 4–8 hr period.^{18,19} Laboratory analysis is performed using high performance liquid chromatography (HPLC), with an ultraviolet and visible light detector (UV-VIS) to determine the concentration of Cr(VI) in air over the entire sampling period.¹⁸ Use of this methodology can take from days to weeks before results are available. This lag time in receiving sampling results delays verification of the acceptability of the existing exposure controls or determination of the need for additional or modified exposure controls that may need to be considered or implemented to assure continued protection of workers. Therefore, the availability of a direct-reading aerosol monitoring

instrument, validated to rapidly provide usable estimates of Cr(VI) concentrations in air during stainless steel welding activities, would be beneficial in helping to ensure exposure levels are being adequately controlled. This tool would be a valuable supplement to required personal monitoring for Cr(VI).

Therefore, the purpose of this study was to determine if direct-reading aerosol monitoring instruments can provide acceptable estimates of Cr(VI) concentrations in air during stainless steel welding operations.

METHODS

Sampling instruments

Three direct-reading instruments were chosen for this study: TSI DustTrak 8520, HazDust EPAM 5000, and GRIMM 1.109, described in detail below. As a reference, three 37-mm closed-face cassettes containing 5 μm pore size pre-weighed PVC filters (“cassettes”) were used simultaneously. Although a 2 L/min flow rate is typically used for these samples, due to the different flow rates used by the direct-reading instruments (between 1.2 and 1.7 L/min), cassette samples were also collected at pump flow rates of 1 L/min. This is within the purview of the relevant method, NIOSH 7600 (hexavalent chromium).¹⁸ After sample collection, the cassette filters were desiccated and then weighed using a microbalance to determine the total particulate mass. The samples were then analyzed using HPLC equipped with a UV-VIS detector to separate, identify and quantify the Cr(VI) on the filter. Samples were analyzed by an American Industrial Hygiene Association (AIHA) accredited laboratory, certified for the analytical methods specified in NIOSH Method 7600. This method has an accuracy of $\pm 18.58\%$ and an overall precision of 0.084 mg/m^3 .¹⁸

The TSI DustTrak Model 8520 (TSI Inc., Shoreview, MN) is a direct-reading aerosol monitoring instrument that utilizes light-scattering technology to provide real-time estimates of particulate matter (PM) of various size ranges, including PM_{10} , $\text{PM}_{2.5}$, PM_1 , and

respirable particulate matter. According to the manufacturer calibration documentation, this instrument has an accuracy of $\pm 1\%$ relative to Arizona road dust, although that accuracy will change depending on the dust being sampled and the particle size distribution. Previous studies have found a strong correlation in monitoring results between gravimetric sampling results and the DustTrak sampling results for measuring welding fumes and for residual fuel oil ash in the boilermaker industry,²⁰ as well as diesel particulate matter in underground hard rock mines²¹ and oil- and water-based metalworking fluid aerosols.²² The DustTrak has also been used to study aerosols such as environmental tobacco smoke, fumes from cooking oil, and smoke emissions from combustion of cedar-wood.²³ It has been reported that the accuracy of the DustTrak increased as the particle size got smaller (e.g., $\text{PM}_{2.5}$ vs. PM_{10}).²⁴ For this study, the DustTrak was operated at 1.7 L/min to provide an estimate of PM_{10} concentration, with data logging every second.

The HazDust EPAM 5000 (Environmental Devices Corporation, Plaistow, NH) is a portable aerosol monitor, with data logging capability, which uses light-scattering technology to provide mass concentrations of airborne particles. According to the manufacturer, the accuracy of this device is $\pm 10\%$ of a gravimetric fine test dust filter measurement, with a precision of $\pm 0.003 \text{ mg/m}^3$. Different size-selective inlets are available for measuring particulate matter less than 10 μm (PM_{10}), $\text{PM}_{2.5}$, PM_1 , and total suspended particles (TSP). It has been used by the United States Environmental Protection Agency (EPA) for ambient air quality surveys.²⁵ It has also been used to quantify seasonal changes in indoor and outdoor levels of PM_{10} in high-rise apartment buildings.²⁶ For this study, the HazDust was set to data log for PM_{10} concentrations every second.

The GRIMM 1.109 (GRIMM Technologies, Douglasville, GA) is a portable aerosol spectrometer that uses light scattering technology to detect airborne particles in a sample air stream, operating at 1.2 L/min. This instrument is capable of detecting particles

ranging in 31 size ranges (bins) that measure aerosols from 0.22 to 32 μm in aerodynamic diameter. This capability allows for detailed size distributions that can be displayed in number of particles per cubic meter or in mass concentration ($\mu\text{g/m}^3$). For the mass concentration mode used in this study, the manufacturer certifies the accuracy as $\pm 5\%$. Previous studies have shown that, compared to standard gravimetric methods, the GRIMM 1.109 can provide acceptably accurate estimates of airborne metal concentrations in a smelter environment²⁷ and for diesel particulate matter from use of diesel engines in an underground mine.²⁸ For this study, the GRIMM logged data in mass concentration per unit volume (every $\mu\text{g/m}^3$) every 6 s.

Sampling set-up

Sampling was conducted at three separate welding sites, resulting in a total of 10 sampling events. Each of the three sampling sites used arc welding equipment and welded on type 304 stainless steel materials, which contain 18.0–20.0% chromium.²⁹ Two of the sites used flux-cored arc welding (FCAW) with DW-308LP flux-cored wire, which contains 19.1% chromium.³⁰ The third site used arc welding without a wire-feed mechanism.

Figure 1 shows the sampling chamber that was constructed to facilitate simultaneous measurements with the direct-read aerosol monitoring instruments and filter cassette samples equidistant from the welding site. The chamber was constructed of 4 m of galvanized duct, approximately 15 cm (6 in.) in diameter. A Fantech model FR150 (Fantech, Lenexa, KS) variable speed exhaust fan was positioned on one end of the duct to provide air movement and a rectangular capture hood, approximately 30 cm (12 in.) by 11 cm (4.4 in.), was positioned on the opposite end, close to the source of welding fume. The inlets to the direct-read instruments and filter cassettes were placed perpendicular to the airflow through holes drilled through the sampling chamber 1 m upstream of the exhaust fan and 3 m from the hood, as shown in Figure 2. The inlets to the direct-read instrument and cassettes were sealed to the duct to



Figure 1. Specially constructed chamber for enabling simultaneous measurements of welding fumes.

prevent air leakage. The flow rate of air through the duct was maintained between 3.8 and 4.3 m/s (750 and 850 fpm), as measured by a TSI 8345 VelociCalc thermal anemometer (TSI Inc., Shoreview, MN).

One control and one blank cassette sample were collected and analyzed for each of the three sampling locations. Control samples were taken outside of the welding facilities in an area away from any welding sources of Cr(VI). Blank cassettes were open for

<1 min at each of the welding facilities before being resealed and submitted for analytical testing.

Data analysis

All data were evaluated using descriptive statistics and linear regression analyses using Microsoft Excel 2010 (Microsoft Corp., Redmond, WA) and SigmaPlot 12.0 (Systat Software Inc., San Jose, CA). The mean aerosol concentration from each direct-reading instrument was calculated for the

same time period of each sampling event. For the GRIMM 1.109 data, which are separated into 31 bins based on particle size range, dust concentrations were averaged for each sampling event by taking the mean value from each size bin and then calculating the total concentration across all the size bins. Data from each direct-read instrument were blank adjusted using 1 min samples of background dust concentrations collected in an adjacent work area where welding was not being performed.

A least-squares regression line was fit to determine the slope and intercept of the relationship between the Cr(VI) air concentration and the mean aerosol concentration measured separately by each instrument. A coefficient of determination (R^2) was assessed from the least-squares line to explain the total variance of the model. To determine a simple correction factor, the regression lines were also forced through the origin and the change in R^2 was assessed. The relationship between each instrument and the total dust concentration was also examined to further validate the use of the direct-reading instruments for comparison to a more comparable gravimetric measurement. For values of Cr(VI) obtained by the filter cassettes that were below the limit of detection (LOD = 0.05 μg), one half the LOD was used for statistical analysis.

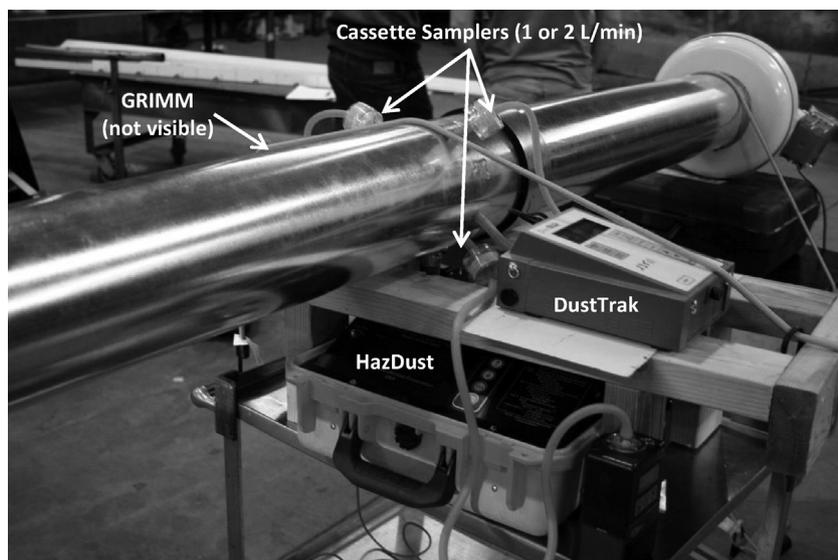


Figure 2. Configuration of measurement devices used to assess air concentrations of Cr(VI).

RESULTS

Table 1 shows the data from all sampling events, including the filter cassette data for total mass concentration and Cr(VI) mass concentration for both 1 L/min and 2 L/min air samplers. The Cr(VI) mass concentration results ranged from 1.6 up to 120 $\mu\text{g}/\text{m}^3$ for sampling periods between 13 and 57 min. Although many of these values are above the OSHA PEL of 5 $\mu\text{g}/\text{m}^3$, these measurements were taken inside of a local exhaust ventilation system and are not representative of results that would be obtained from personal samples.

The mass concentration data from the three direct-reading instruments are provided in Table 1 as well. All

Table 1. Results for Filter Cassette Samples of Total Dust and Cr(VI) Taken Simultaneously with Three Different Direct-reading Aerosol Monitoring Instruments.^a

Sampling Event	Sampling Time (min)	1 L/min		2 L/min		DustTrak Conc.	HazDust Conc.	GRIMM Conc.
		Total Dust	Cr(VI)	Total Dust	Cr(VI)			
1	48	2,200	2.6	4,400	5.7	1,200	330	372
2	57	18,000	79	17,000	80	17,500	6,270	764
3	30	13,000	41	13,000	42	10,700	1,420	475
4	16	5,300	5.1	4,200	5.7	3,600	180	341
5	20	140,000	30	12,000	36	12,300	3,190	528
6	26	12,000	43	13,000	42	10,100	4,030	486
7	21	7,800	13.7	<LOD	<LOD	4,600	740	538
8	13	28,000	120	18,000	103.5	17,700	6,440	991
9	38	<LOD	<LOD	<LOD	<LOD	300	70	154
10	35	1,600	1.6	<LOD	<LOD	300	120	170

^a All concentration values are in $\mu\text{g}/\text{m}^3$.

Table 2. Linear Regression Results for Comparison of Three Different Direct-read Instruments with Hexavalent Chromium Results Collected at Two Different Sampling Flow Rates.

Instrument	Cassette Flow Rate (L/min)	Regression Equation	R^2
DustTrak	1	With intercept: $y = 0.0054x - 8.37$ No intercept: $y = 0.0047x$	0.84 0.82
	2	With intercept: $y = 0.0051x - 8.55$ No intercept: $y = 0.0045x$	0.90 0.87
HazDust	1	With intercept: $y = 0.0145x + 0.596$ No intercept: $y = 0.0146x$	0.87 0.87
	2	With intercept: $y = 0.0137x + 0.376$ No intercept: $y = 0.0138x$	0.91 0.91
GRIMM	1	With intercept: $y = 0.1443x - 35.88$ No intercept: $y = 0.847x$	0.86 0.68
	2	With intercept: $y = 0.1294x - 30.73$ No intercept: $y = 0.0784x$	0.81 0.65

blank samples measured concentrations below the limit of detection. Table 2 provides the results of the linear regressions comparing each of the direct reading instruments to the Cr(VI) measurements using both 1 L/min and 2 L/min samplers, including where the linear regressions were forced through the origin (no y-intercept).

DustTrak

Figure 3 shows the relationship between mass concentrations measured by the DustTrak and the Cr(VI) on the cassette filters. The linear regression analysis showed a coefficient of determination (R^2) of 0.84 for 1 L/min cassette samples and 0.89 for 2 L/min cassette samples. Forcing the regression line through the origin (in order to provide a simple correction factor)

produced R^2 of 0.82 and 0.87, respectively, and showed a slope of 0.0047 for the 1 L/min sample comparison and 0.0045 for the 2 L/min comparison. This corresponds to a nearly 200 fold difference in concentration measurements; for example, a DustTrak reading of 2000 $\mu\text{g}/\text{m}^3$ would correspond to a Cr(VI) concentration in air of approximately 9 $\mu\text{g}/\text{m}^3$.

HazDust

Figure 4 shows the relationship between the mass concentrations measured by the HazDust and the Cr(VI) on the cassette filters. The linear regression analysis showed an R^2 of 0.87 for 1 L/min cassette samples and 0.91 for 2 L/min cassette samples. In this case, forcing the regression line through the origin did not change the R^2 (0.87 and 0.91, respectively),

implying minimal impact on the ability of the HazDust to predict Cr(VI) concentrations. The linear regression also showed a slope of 0.015 for the 1 L/min sample comparison and 0.014 for the 2 L/min comparison. In this case, a HazDust reading of 700 $\mu\text{g}/\text{m}^3$ would correspond to a Cr(VI) concentration in air of approximately 10 $\mu\text{g}/\text{m}^3$.

GRIMM

Figure 5 shows the relationship between the mass concentrations measured by the GRIMM and the Cr(VI) on the cassette filters. The linear regression analysis showed an R^2 of 0.86 for 1 L/min cassette samples and 0.81 for 2 L/min cassette samples. Forcing the regression lines through the origin reduced the predictive ability of the model, with R^2 of 0.68 and 0.65, respectively, and showed a slope of 0.085

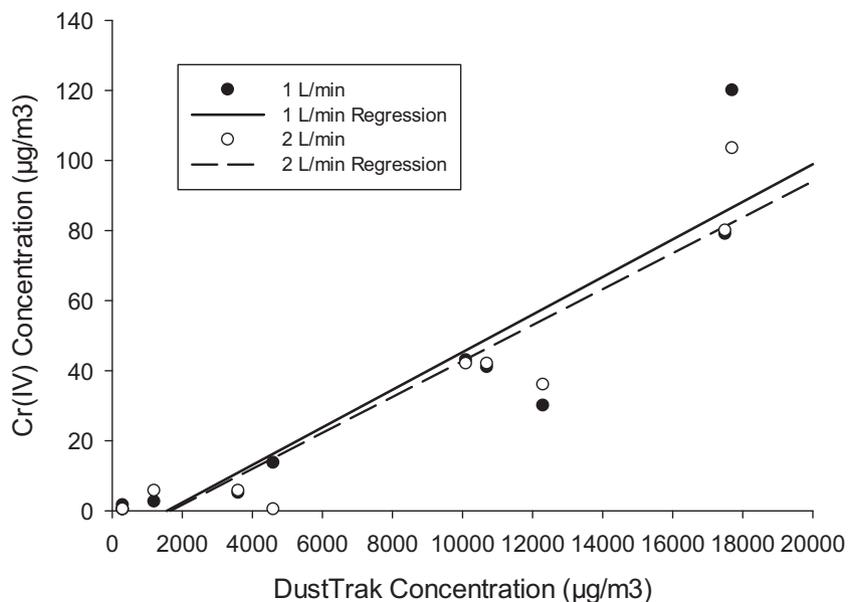


Figure 3. Comparison of the DustTrak direct-reading monitoring instrument to concentrations of Cr(VI) obtained by traditional sampling methods at both 1 L/min (black dots, solid line) and 2 L/min (white dots, dashed line) sampling flow rates. Linear regression equations and R^2 are shown in Table 2.

for the 1 L/min sample comparison and 0.078 for the 2 L/min comparison. Therefore, a GRIMM reading of $100 \mu\text{g}/\text{m}^3$ would correspond to a Cr(VI) concentration in air of approximately $8 \mu\text{g}/\text{m}^3$, however, in this case

that prediction has much higher variability based on the lower R^2 .

Total dust

As a validation of this exercise, it is also of interest to investigate how each of

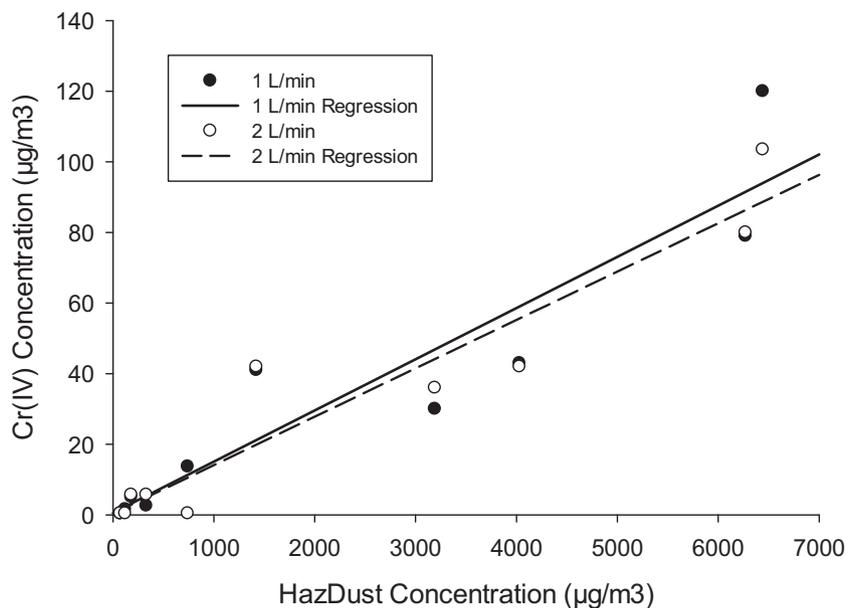


Figure 4. Comparison of the HazDust EPAM 5000 direct-reading monitoring instrument to concentrations of Cr(VI) obtained by traditional sampling methods at both 1 L/min (black dots, solid line) and 2 L/min (white dots, dashed line) sampling flow rates. Linear regression equations and R^2 are shown in Table 2.

the direct-reading instruments estimated the total dust concentration as measured by the filter cassette samplers. Figure 6 shows this comparison for all three direct-reading instruments for the 2 L/min cassette samples, with the linear regression statistics shown in Table 3. In that case, forcing the regression lines through the origin produced strong relationships for both the DustTrak ($R^2 = 0.91$) and the HazDust ($R^2 = 0.74$) with respect to estimating total dust concentrations, with the GRIMM providing a moderate estimate of total dust ($R^2 = 0.64$). Looking at the slopes of those linear regression lines shows that the DustTrak had the most accurate estimate of total dust (slope = 1.03) compared to the HazDust (slope = 3.04) and the GRIMM (slope = 18.3). A slope of 1.0 would be perfect agreement between the instrument and the cassette sample.

DISCUSSION

The results of this study found that, with the application of a simple correction factor, direct-reading instruments may provide acceptable estimates of Cr(VI) emitted during welding of stainless steel. Although each of the three direct-reading instruments provides a slightly different measure of airborne particles, the predictive strength of the three different direct-reading monitoring instruments were similar for Cr(VI), with all R^2 greater than 0.80. These relationships were similar for filter cassettes sampling at both 1 L/min and 2 L/min, suggesting that the pump flow rate might not have a substantial impact on these comparisons.

Based on these results, it may be of interest to establish a simple correction factor that could be applied to measurements obtained by the direct-reading instruments to estimate Cr(VI) concentrations during stainless steel welding. Ideally, this would involve forcing the linear regressions (see Figures 2–4) through the origin, as was done for Figure 6. For the DustTrak and Hazdust this is straightforward, and the R^2 values were only minimally affected (<5% change). For the GRIMM, however, it is not

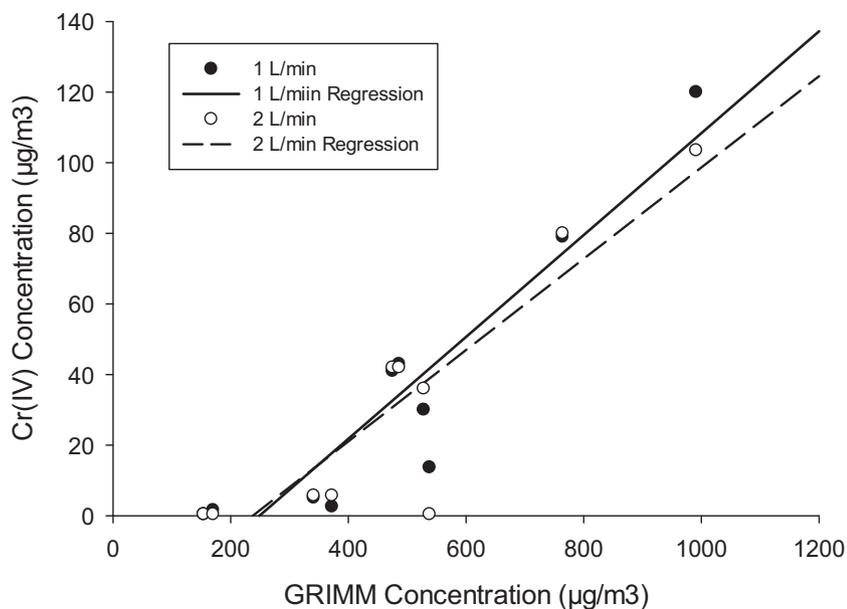


Figure 5. Comparison of the GRIMM 1.109 aerosol spectrometer to concentrations of Cr(VI) obtained by traditional sampling methods at both 1 L/min (black dots, solid line) and 2 L/min (white dots, dashed line) sampling flow rates. Linear regression equations and R^2 are shown in Table 2.

recommended to force the line through the origin, as this substantially decreases the predictive ability of that correction factor by about 20%. For this study, it should also be noted that all 31 bins of the GRIMM were used for comparison. Although welding fume is anticipated to be composed

primarily of small particles ($<10 \mu\text{m}$), potentially there are larger particles present and this may skew these results. The GRIMM also logged data every 6 s, compared to 1 s sampling by the DustTrak and HazDust. For the short sampling time periods used in this study (between 13 and 57 min),

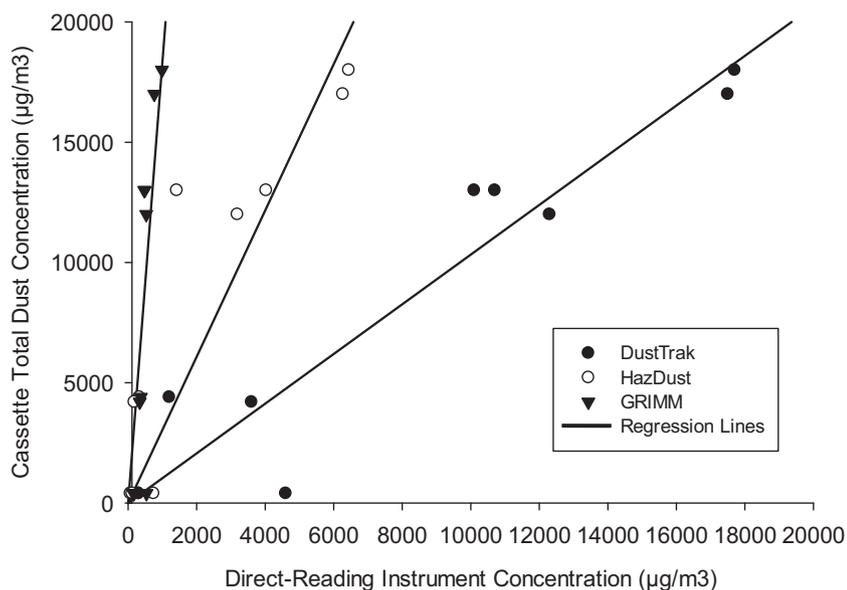


Figure 6. Comparison of all three direct-reading instruments to the total dust concentrations measured by the 2 L/min cassette samples (linear regression equations and R^2 are shown in Table 3).

Table 3. Linear Regression Results for Comparison of Three Different Direct-read Instruments with Total Dust Concentrations Measured by Cassettes Sampling at 2 L/min Flow Rate.

Instrument	Regression Equation	R^2
DustTrak	$Y = 1.03x$	0.91
HazDust	$Y = 3.04x$	0.74
GRIMM	$Y = 18.3x$	0.64

this difference in data logging could have resulted in comparatively lower resolution for peak concentrations.

One limitation of this study was that all sampling inlets (i.e., all simultaneously sampling direct-reading instruments and cassette samplers) were placed perpendicular to the air flow instead of directly facing the air stream. This configuration was utilized in order to provide simultaneous measurement from six different devices (three cassette samples and three direct-reading instruments) without significant blockage of the airflow through the duct. Although typical personal sampling methods cannot control the relationship between the sampling inlet and the air stream, it is possible this configuration could lead to sampling bias. With that in mind, future research should utilize personal sampling to confirm the results of this study. Another limitation of this study was that all welding facilities were only performing MIG welding. Therefore, the results of this study may not apply to other types of welding operations. Lastly, the small sample size, as well as several measurements below the limit of detection, may also be limitations that need to be addressed in future studies.

CONCLUSION

Hexavalent chromium is a potential health concern for workers who perform welding, soldering, or brazing of stainless steel. Rapid assessment of controls and exposure potential would be especially useful for this task-based activity. This study demonstrated the potential for using direct-reading instruments to quickly provide acceptably accurate estimates of Cr(VI) air

concentrations during welding operations.

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