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## Interlaboratory evaluation of trace element determination in workplace air filter samples by inductively coupled plasma mass spectrometry†,‡

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### Abstract

Inductively coupled plasma mass spectrometry (ICP-MS) is becoming more widely used for trace elemental analysis in the occupational hygiene field, and consequently new ICP-MS international standard procedures have been promulgated by ASTM International and ISO. However, there is a dearth of interlaboratory performance data for this analytical methodology. In an effort to fill this data void, an interlaboratory evaluation of ICP-MS for determining trace elements in workplace air samples was conducted, towards fulfillment of method validation requirements for international voluntary consensus standard test methods. The study was performed in accordance with applicable statistical procedures for investigating interlaboratory precision. The evaluation was carried out using certified 37-mm diameter mixed-cellulose ester (MCE) filters that were fortified with 21 elements of concern in occupational hygiene. Elements were spiked at levels ranging from 0.025 to 10  $\mu\text{g filter}^{-1}$ , with three different filter loadings denoted “Low”, “Medium” and “High”. Participating laboratories were recruited from a pool of over fifty invitees; ultimately twenty laboratories from Europe, North America and Asia submitted results. Triplicates of each certified filter with elemental contents at three different levels, plus media blanks spiked with reagent, were conveyed to each volunteer laboratory. Each participant was also provided a copy of the test method which each participant was asked to follow; spiking levels were unknown to the participants. The laboratories were requested to prepare the filters by one of three sample preparation procedures, *i.e.*, hotplate digestion, microwave digestion or hot block extraction,

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which were described in the test method. Participants were then asked to analyze aliquots of the prepared samples by ICP-MS, and to report their data in units of  $\mu\text{g filter}^{-1}$ . Most interlaboratory precision estimates were acceptable for medium- and high-level spikes (RSD <25%), but generally yielded greater uncertainties than were anticipated at the outset of the study.

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## Introduction

The health of workers in many industries is at risk through exposure by inhalation to toxic metals and metalloids.<sup>1,2</sup> Industrial hygienists and other public health professionals must determine the effectiveness of measures taken to control and minimize occupational exposures, and this is generally achieved by monitoring workplace air quality.<sup>3-5</sup> Estimation of workers' exposures to airborne metals and metalloids by inhalation requires the ability to measure target elements at very low levels in workplace atmospheric samples.<sup>6</sup> Traditionally, atomic spectrometric techniques have been used to determine metals and metalloids in occupational air samples, especially flame and graphite furnace atomic absorption spectrometry (FAAS and GFAAS, respectively) and inductively coupled plasma atomic emission spectrometry (ICP-AES).<sup>7,8</sup> Efforts are underway to obtain yet lower detection limits for toxic elements in workplace atmospheres than those offered by atomic absorption, atomic emission and other trace analytical methods. This is driven in part by reduced occupational exposure limits (OELs) for some metals, such as beryllium. One of the most promising techniques for ultra-trace multi-element analysis is inductively coupled plasma mass spectrometry (ICP-MS), which is becoming more widely used in the occupational health field.<sup>9-11</sup>

To address the need for harmonized ICP-MS methods for use by occupational hygiene laboratories, international voluntary consensus standard ICP-MS test methods have been recently developed and promulgated by ASTM International<sup>12</sup> and the International Organization for Standardization (ISO).<sup>13</sup> These consensus standard methods describe aspects of sampling and sample preparation as well as analysis by ICP-MS. Compared to FAAS, GFAAS and ICP-AES techniques, ICP-MS offers lower detection limits for most elements,<sup>14</sup> offering ultra-trace analysis capabilities that are often required for short-term workplace air measurements, reduced OELs, measurements of ultrafine particles and nanomaterials, *etc.* ICP-MS offers parts-per-trillion detection capability, which is 3 orders of magnitude or better than ICP-AES for most analytes.<sup>14,15</sup> Also, a noteworthy advantage of ICP-MS is that it suffers from fewer spectral interferences when compared to atomic spectrometric methods such as ICP-AES.<sup>14,15</sup>

The primary objective of this investigation was to conduct an interlaboratory evaluation of the ASTM International ICP-MS consensus standard test method, ASTM D7439,<sup>12</sup> with a goal of obtaining estimates of method performance for elemental analysis based on a collaborative trial. To date there is a paucity of validation data for ICP-MS analysis of occupational air samples, and it was our desire to endeavor to fill this data void. It was intended that the performance data obtained could also be used to assess the parallel ISO standard, ISO 30011.<sup>13</sup> The inter-laboratory study (ILS) was carried out in consideration of an applicable ASTM International standard practice, ASTM E691,<sup>16</sup> which describes

statistical procedures for investigating interlaboratory precision of ASTM standard test methods. In efforts to address multiple outliers that were observed, additional statistical analyses were carried out in accordance with robust multivariate methods.<sup>17</sup>

The ILS was carried out so as to provide ICP-MS performance data for a maximum number of elements of interest in the occupational hygiene field. Cellulosic air filter samples including metals and metalloids that were distributed in the ILS contained elements for which OELs have been established.<sup>18–20</sup> The ILS evaluated aspects of sample transport, sample preparation and ICP-MS analysis. Precision and bias estimates from performance evaluation samples containing certified levels of 21 elements from 20 volunteer participating laboratories (12 North American, 7 European, 1 Asian) are reported herein.

## Experimental

### Interlaboratory study

The evaluation materials used in the interlaboratory comparison consisted of 37-mm diameter mixed-cellulose ester (MCE) filters which were spiked with 21 elements of interest (Al, Ag, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, Sb, Se, Sn, U, V, Zn) at certified levels of 0.025 to 100 µg per filter (High Purity Standards, Charleston, SC, USA); see Table 1. Media blanks consisted of MCE filters that were spiked with the solution reagent containing no added metals and metalloids. The as-received filters were mailed in sets of five within sealed plastic containers and were isolated from one another by non-absorbent separator pads. The levels selected were based on applicable OELs in consideration of typical sampling times and air sampling rates (*e.g.*, full-shift 8-hr time-weighted average sampling at  $\approx 2 \text{ l min}^{-1}$ ), as well as practical considerations in producing the performance evaluation samples.

Laboratories possessing ICP-MS instrumentation and having experience in environmental elemental analysis were solicited to participate in the ILS. Performance evaluation samples, *i.e.*, the spiked MCE filters, were mailed in triplicate to each volunteer laboratory; spiking levels were unknown to the participants. The volunteer laboratories were requested to carry out sample preparation and ICP-MS analysis in accordance with the procedures described in ASTM D7439.<sup>12</sup> Participants were able to choose from one of three sample preparation procedures described in the ASTM standard, *i.e.*, hotplate or microwave acid digestion or hot-block acid extraction. After ICP-MS analysis, participants were requested to report their results to the coordinator of the study in units of micrograms of each element per filter sample. A list of the twenty volunteer laboratories that participated in the ILS and returned results is presented in Table 2. For purposes of data presentation, laboratories were identified by number to guarantee confidentiality of the reported results.

A summary of sample preparation methods used by the participating laboratories in the ILS is given in Table 3. Hotplate digestion, microwave digestion and hot block extraction procedures that the laboratories were asked to follow are described in A2, A3 and A4 of ASTM D7439, respectively. All laboratories employed HNO<sub>3</sub> in their sample dissolution procedures, and most participants (14) used HNO<sub>3</sub> in combination with HCl (Table 3). Final

solution volumes after sample preparation were 10 ml, 25 ml or 50 ml, with most laboratories (14) reporting 25 ml final volumes and typical dilution factors of 10 to 100×.

ICP-MS analysis instrumentation used by the volunteer laboratories is summarized in Table 4. The ICP-MS instruments employed came from four manufacturers: Agilent (Santa Clara, CA, USA), Perkin Elmer (San Jose, CA, USA), Thermo Fisher (Waltham, MA, USA) and Varian (Palo Alto, CA, USA); they were predominantly quadrupole devices. A variety of sample introduction systems was reported, with most laboratories reporting the use of platinum and/or nickel cones. Seven of the twenty laboratories relied on collision/reaction cells for certain elements (*e.g.*, As, Cr, Se, V), normally with He and H<sub>2</sub> as collision and reaction gases, respectively. A variety of elements were used as internal standards (Table 2 of ASTM D7439); their concentrations ranged from 1 to 100 µg l<sup>-1</sup>, depending on the particular laboratory. Only one laboratory carried out analyses in a clean room, although two other participants used a localized ventilated cabinet to cover the ICP-MS sample introduction system.

### Statistical analysis

Variability of the reported ILS results was initially investigated using the statistical analysis procedures described in ASTM E691.<sup>16</sup> In accordance with this consensus standard practice, repeatability and reproducibility of the results reported were calculated for each element. Repeatability (*r*) is an estimate of within-laboratory variability, which was computed by averaging the squares of the standard deviations of within-laboratory results for each sample, and taking the square root of this average. Thus, the average within-laboratory standard deviation for each reported result is expressed by the repeatability standard deviation, *s<sub>r</sub>*. Reproducibility (*R*) is an estimate of the variability of both within-laboratory and between-laboratory results. The reproducibility standard deviation is expressed

$$S_R = \{(S_x)^2 + [(S_r)^2(n-1)n^{-1}]\}^{1/2},$$

where *s<sub>x</sub>* is the standard deviation of the mean value as estimated by the average of all interlaboratory results for a given spiked sample and *n* is the number of test results at a particular spiking level.

For each element, estimates of absolute bias were calculated by dividing the difference between the mean of the laboratory-reported triplicate results and the reference value by the reference value:<sup>10,21</sup>

$$B_i = (\mu_i - R_i)R_i^{-1},$$

where *B<sub>i</sub>*, *μ<sub>i</sub>* and *R<sub>i</sub>* are the bias, mean measured value and reference value, respectively, for the *i*<sup>th</sup> laboratory-reported value. Where blank correction was done, the relative bias *B'<sub>i</sub>* was obtained from:

$$B'_i = (\mu_i - b_i - R_i) R_i^{-1},$$

where  $b_i$  is the average blank value for the  $i^{\text{th}}$  reported result.

For an alternative investigation there were some decisions that had to be made about inclusion of data. When laboratories did not provide method detection limit (MDL) values for given elements, measurements reported as zeros were dropped from subsequent statistical calculations. (See ESI appendix for additional discussion.) Also, at the low level, for many metals, there were a few laboratories that reported values less than the MDL, in addition, to values less than the MDL for the blanks. These laboratories were removed from the blank-corrected statistical analysis at the low level for the metals for which this occurred. If MDLs were reported, results below the MDL were substituted as  $\text{MDL} \times 2^{-1/2}$ . In addition, the robust models used required that each lab have the same number of analyses. In the revised data, an average value is used if there were just two measurements. If the laboratory reported measurements and “0” for the blanks, 0 was substituted for “0”, in computing the average for blank correction. Because of the above considerations, the number of labs used for each metal at each level was quite variable, ranging between 6 and 19.

Statistical analyses then produced estimates of average bias as well as estimates of standard deviation relative to the target (spike) value, assuming normally distributed data. Expressed in terms of relative standard deviations (RSDs), this is referred to by NIOSH as  $\text{RSD}_{\text{true}}$ .<sup>22</sup>

note that estimated  $\text{RSD} = \text{RSD}_{\text{true}} \times (B'_i + 1)^{-1}$ . For both non-robust and robust analyses, within-laboratory, between-laboratory, and total relative standard deviations ( $\text{RSD}_w$ ,  $\text{RSD}_b$ ,  $\text{RSD}_{\text{tot}}$ , respectively; note that  $\text{RSD}_{\text{tot}} = (\text{RSD}_w^2 + \text{RSD}_b^2)^{1/2}$ ) were estimated for each element at each spike level.

For non-robust estimates of variance (where statistical outliers are included and given equal weights as non-outliers), linear mixed models were fitted to the relative bias data (the  $B'_i$  values) in order to obtain estimates of the relative bias and estimates of  $\text{RSD}_{\text{true}}$  via restricted maximum likelihood.<sup>22,23</sup>

Alternatively, computation of robust statistics by means of “constrained M estimates” (see appendix as ESI), as implemented in an applicable statistical package,<sup>17</sup> was used to arrive at interlaboratory estimates of precision and bias. (Several alternative robust methods were also used for comparison, and these are discussed in the appendix; see ESI.) The variance output of the statistical program is a  $3 \times 3$  variance-covariance matrix, corresponding to the three samples each participating lab analyzed. The between lab variance is estimated as the average of the off-diagonal covariances in the variance-covariance matrix. By subtracting this average from the average of the diagonal elements, the within laboratory variance is obtained. The estimated bias is a weighted average bias for all labs. The robust methods considered here are intended to protect against contamination of the data from outliers. Box plots in the appendix (ESI) make it clear that there are many potential outliers in these data. Because these robust methods do not work well with very small data sets, for the four metals

with 8 or fewer qualifying labs, the (h,k) statistics of ASTM E691<sup>16</sup> are used (see appendix in ESI). For comparison the chosen robust method was also used for these four metals; the robust estimates are close to the (h,k)-based estimates, except for silver.

## Results

### Non-robust statistics

Overall interlaboratory ICP-MS results, in terms of average percent recoveries (and with standard deviations in percents, as represented by error bars), are summarized in Fig. 1 and Fig. 2 for elements having negligible and significant blank levels reported, respectively. Overall mean values were calculated based on the pooled means for the average of the three results reported by each laboratory for each element; however, it is noted that some laboratories did not report results for all elements. Percent recoveries were determined based on the spiking levels listed in Table 1, and standard deviations (as values of  $s_R$ <sup>16</sup>) were correspondingly normalized to percents. The data summarized in Fig. 1 and 2 are uncorrected for blanks and statistical outliers, with the following exceptions: In six cases (one value each for: Ag, Pb and U at low loading; Ag and Mn at medium loading; and Ag at high loading), obvious outliers (single reported values that differed from the remainder by >2 orders of magnitude) were discarded.

For the nine elements with negligible blank values reported (Fig. 1), ILS mean recoveries for low loadings (refer to Table 1 for elemental spiking levels) ranged from 104% for Co to 130% for Cd. However, for the eleven elements with significant blanks reported (Fig. 2), most ILS elemental measurements of low loadings were positively biased. With exception of the elements As and Sb (for which mean recoveries of 100% and 104%, respectively, were obtained), mean recoveries ranged from 144% for Ag to 395% for Mg. In general, interlaboratory precision showed high variability for low-level spiked filters: for elements having negligible blanks reported,  $s_r$  ranged from 17% for Ba to 64% for Be and V, while for elements with significant blanks,  $s_r$  values ranged from 36% for As to 190% for Se. For low loadings, the best ILS results were obtained from As, Ba, Co, Cu and Pb, with generally acceptable recoveries ( $100\% \pm 20\%$ ) and better precision than for other elements at these loadings ( $RSD_{tot} < 0.35$ ). Only one element at low loading, *i.e.*, Ba, had  $RSD_{tot} < 0.20$ . For these spiking levels the poorest ILS data were reported for Al, Be, Cr, Fe, Mg, Mn, Ni, Se, V and Zn, which demonstrated high bias (mean recovery >150%) and/or high imprecision ( $RSD_{tot} > 0.35$ ).

Mean recoveries for medium loadings (again, see Table 1 for spiking levels) were close to quantitative ( $100\% \pm 15\%$ ) for nearly all (20/21) elements,<sup>10</sup> whether the reported elemental blank values were significant or not (Fig. 1 and 2): mean recoveries ranged from 97% for Ba to 120% for Fe. ILS precision estimates for medium-level spiked samples were much better than for low loadings;  $s_r$  ranged from 8% for Ba and Cd to 38% for V. For medium loadings, two-thirds of the elements (14 of 21) yielded interlaboratory RSDs (as  $RSD_{tot}$ ) of #0.25. For medium loadings, acceptable interlaboratory results were obtained for the elements As, Ba, Be, Cd, Co, Cr, Cu, Mn, Ni, Pb and U, with good recoveries ( $100\% \pm 10\%$ ) and precision ( $RSD_{tot} < 0.20$ ). At these loading levels, the most imprecise ILS results were obtained for Ag, Sb and V ( $RSD_{tot} > 0.30$ ).

Mean recoveries for ILS samples spiked at high levels (once again, refer to Table 1) were less than 100% for all elements (Fig. 1 and 2); means ranged from 78% for Ni to 99% for Sn, with recoveries for most elements between 80-90%. ILS precision estimates for high-spiked samples were generally acceptable, with 20 of 21 elements yielding values of  $RSD_{tot} < 0.2$ . For high loadings, the best ILS results were reported for As, Fe, Sb and Sn: these elements yielded acceptable recoveries (90-100%) and precision ( $RSD_{tot} < 0.2$ ). The poorest ILS results at this loading level were reported for Ag with  $RSD_{tot} > 0.4$ , and Ni and V, both with mean recoveries  $< 80\%$ .

### Robust analysis results

ICP-MS interlaboratory precision statistics for blank-corrected low-level spikes, based on results reported by the twenty participating laboratories and treated statistically in accordance with non-robust<sup>16,22</sup> as well as robust<sup>17</sup> techniques, are summarized in Table 5. (Because the observed interlaboratory precision estimates were especially variable for low-level spikes (Fig. 1 and 2), robust statistics were applied to these results in an effort to further investigate ILS variability for these loading levels.) It is shown for most elements that blank correction significantly reduces the absolute value of the bias (recall Fig. 1 and 2), although almost all blank-corrected bias estimates are negative. After blank adjustment and correction for outliers (Table 5), a third of the elements (7/21) have biases  $< 10\%$  (absolute value). For blank-corrected, robust estimates (Table 5), 33% (7/21) of the values for within-laboratory RSDs ( $RSD_w$ ) are  $> 0.40$ , and, similarly, 33% (7/21) of the values for between-laboratory RSDs ( $RSD_b$ ) are  $> 0.40$ . Also, for about one-quarter (5/21) of the elements at this loading level,  $RSD_w$  exceeds  $RSD_b$  (Table 5); it is uncommon for within-laboratory variability to exceed between-laboratory variability. However, the medium and low levels also had labs with  $RSD_w$  exceeding  $RSD_b$ . The difference is that the size of the exceedances was much larger at the low level. (See aluminum, iron, and silver in Table 5). For blank-corrected robust estimates of low loadings, about 40% (8/21) of the elements have  $RSD_{tot} > 0.50$ . Thus, even after correction for potential outliers, there remains high variability in the ILS data from low-level spikes; only 8 out of 21 elements yielded  $RSD_{tot} < 0.25$ .

Blank-corrected ILS results for medium and high loadings are shown in Tables 6 and 7, respectively. Only non-robust statistical treatments were applied to these data sets, *i.e.*, outliers were not removed. For results from medium loadings (Table 6), 16 of 21 elements have  $RSD_w < RSD_b$ , while for high spikes (Table 7), 17 of 21 elements yielded  $RSD_w < RSD_b$ . After blank subtraction of medium level spike values (Table 6), 16 of 21 elements gave absolute value of bias  $\#0.1$ ; for blank-corrected high loadings, only 6 of 21 elements demonstrated absolute value of bias  $\#0.1$ . Medium-level estimates of  $RSD_{tot}$  for Al is very high (0.95: Table 6), and the high-loading value of  $RSD_{tot}$  for Ag is also quite high (0.51: Table 7).

### Discussion

The significantly biased ILS results for Al, Fe, Mg, Se, and Zn at low loading levels (Fig. 2) are not entirely unexpected, as MCE filters spiked with reagent have been shown to contain significant background levels of these elements;<sup>24</sup> nevertheless, the magnitudes of the some

of the bias estimates are surprisingly high. Metals contamination from sources such as water, acids, laboratory ware and equipment has been documented<sup>25</sup> and can be a serious problem for ultra-trace elemental analysis techniques like ICP-MS. Also for low loadings, numerous elements (notably Al, Fe, Mg, Mo, Ni, Se, Zn) yielded very high imprecision (Table 5), which is suggestive of contamination problems. Multiple participating laboratories did not report results for low level samples, suggesting frequent over-dilution of low-level spiked filters after extraction or digestion. A number of participants reported method detection limits (MDLs) of  $0.5 \mu\text{g sample}^{-1}$  for several elements; in practice, much lower MDLs should be accessible when using ICP-MS.<sup>12,13</sup> Robust statistical treatment of low-level spike samples (Table 5) still results in high imprecision for most elements: thus even when correcting for outliers, there is still high variability. The results from the present investigation suggest that numerous occupational hygiene laboratories need to do more to prevent metals contamination, especially when conducting elemental measurements at sub-microgram per sample levels.

The low loading results for elements with significant blanks may be high for the following reasons: for Cr because of uncorrected or poorly corrected  $\text{ArC}^+$ ; for Se due to uncorrected or poorly corrected  $\text{Ar}_2^+$ ; for Mg, Mn, Ni and Zn due to contamination. Besides contributions from contamination, polyatomic interferences that could have given rise to the observed positive bias for iron, if no interference correction was applied, are  $^{40}\text{Ar}^{16}\text{O}^+$  and  $^{40}\text{Ar}^{16}\text{OH}^+$  for  $^{56}\text{Fe}^+$  and  $^{57}\text{Fe}^+$  isotopes, respectively.<sup>14,26</sup> The high interlaboratory RSD observed for vanadium (with monitoring of the  $^{51}\text{V}^+$  isotope) could be ascribed to variability in correction interference from  $^{35}\text{Cl}^{16}\text{O}^+$ <sup>15,26</sup> for those laboratories using aqua regia (or reverse aqua regia) sample dissolution methods. It is emphasized that the biases and variabilities concerned are almost certainly not attributed to contamination of the sampling media in many, if not all, instances. They are elements that are ubiquitous in the laboratory environment. Al, Fe, Mg and Zn are commonly present in background, and even elements like Ni are often leachable from disposable labware at parts-per-billion levels. On top of this there is the potential for carryover from digestion vessels used to prepare samples at higher levels of the elements of interest and, of course, uncorrected or partially corrected interferences.<sup>27</sup> Nevertheless, as a practical point, in normal occupational hygiene practice it is probably rare that elements such as Al, Mg and Zn will be measured at sub-mg levels per filter sample, in consideration of their rather high OELs (Table 1).

Generally, blank-corrected data for medium-level spiked filters demonstrated mostly negative biases and significantly better precision than low-level spikes (Table 6). Nevertheless, many elements yielded precision estimates greater than the target value of 0.20. It is relevant to point out that applicable proficiency testing programs typically investigate only a few metals (such as As, Cd, Cr, Cu, Pb),<sup>28,29</sup> thus sample preparation and analysis procedures in many laboratories will normally have been optimized for particular target elements.

For high loading ILS samples, the negative biases observed for most elements (Table 7) can be attributed to material losses from the filters during transport. Many laboratories reported discoloration of the separator pads between the spiked filters for the high-loading samples, indicating that spiking material had transferred from the spiked filters to the separator pads.

Most of the precision estimates are  $<0.20$  for the high-spiked filters, which were loaded at levels commonly investigated in proficiency testing schemes for elemental analysis.

In summary, the results from this ILS generally demonstrated measures of significant bias and precision for trace elemental analysis by ICP-MS, especially for low loadings ( $<0.25 \mu\text{g filter}^{-1}$ ). While some laboratories obtained results that were largely unbiased and precise, others reported values that were highly biased and variable. Appreciable contribution to bias and interlaboratory uncertainty could be due to a number of the participants having limited experience in ICP-MS analyses. It is expected that ICP-MS laboratory performance will improve as more experience is gained by laboratories performing trace analysis of occupational hygiene samples. Proficiency testing schemes typically show improved overall interlaboratory performance with succeeding rounds as laboratories obtain experience with new analytical techniques and sample matrices.<sup>30</sup> Additional work is currently underway that is hoped will fulfill requirements for performance data of fully validated international standard ICP-MS procedures for workplace air measurements, in analogous fashion to investigations involving ambient air and emissions monitoring.<sup>31–33</sup>

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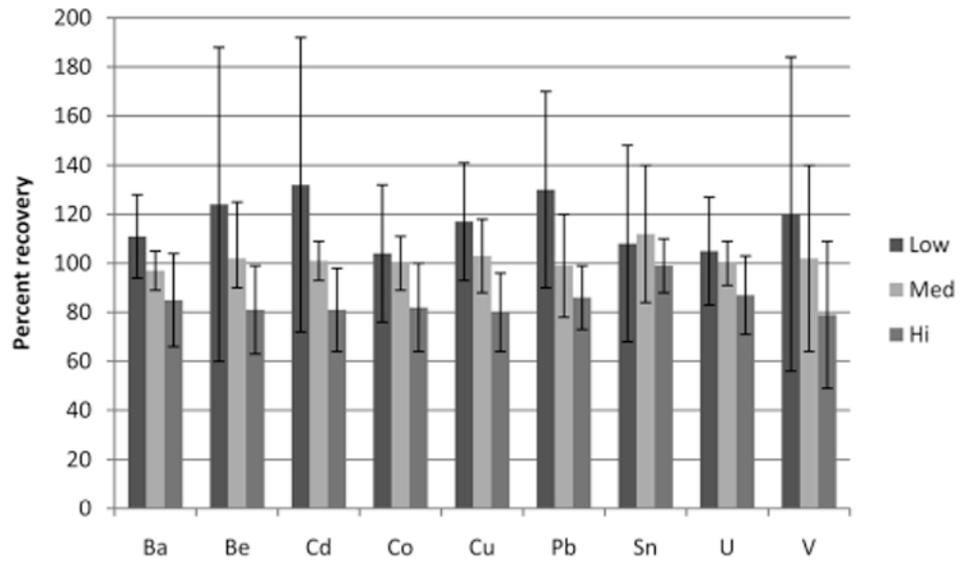
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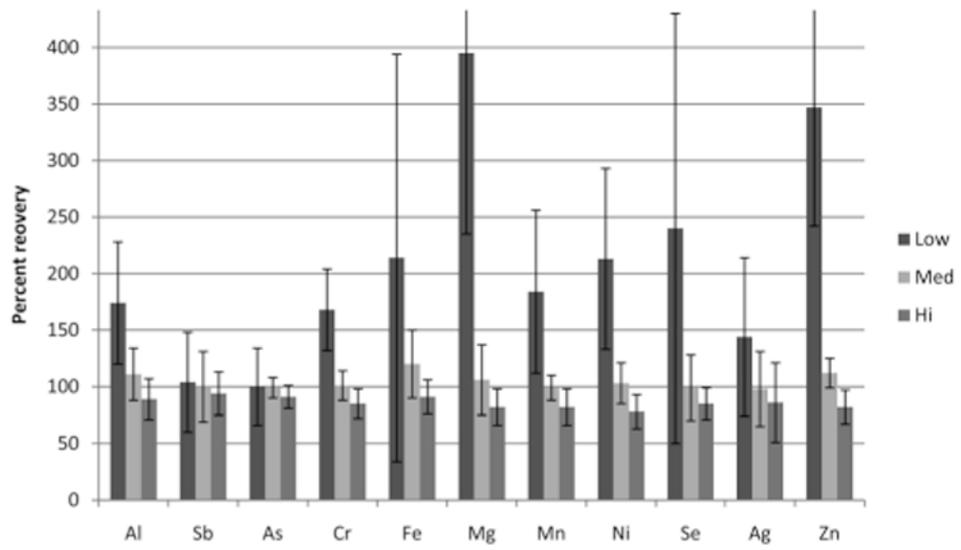
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### Environmental impact

This research is significant because it investigates the performance of laboratories that analyze occupational hygiene samples for their trace elemental content, with a goal of estimating workers' occupational exposures. Reductions in occupational exposure limits (OELs) for metals and metalloids present significant analytical challenges relating to ultra-trace elemental measurement by atomic spectrometric techniques such as inductively coupled plasma mass spectrometry (ICP-MS). Knowledge garnered from this inter-laboratory study can assist in understanding and addressing analytical challenges involving ultra-trace elemental determinations. Laboratories can use this knowledge to take corrective actions to improve performance and ensure accurate trace analyses.



**Fig. 1.** ICP-MS ILS results – Elements with negligible blank levels reported; error bars are standard deviations. (“Low,” “Med” and “Hi” refer to Low, Medium and High filter loading levels, respectively.)



**Fig. 2.** ICP-MS ILS results – Elements with significant blank levels reported; error bars are standard deviations. (“Low,” “Med” and “Hi” refer to Low, Medium and High filter loading levels, respectively.)

**Table 1**  
**Certified trace metal spike levels on MCE filters and their OEL rationale; values for Low, Medium and High levels are  $\mu\text{g filter}^{-1}$**

Element	Low level, $\mu\text{g} (\pm 15\%)$	Medium level, $\mu\text{g} (\pm 1\%)$	High level, $\mu\text{g} (\pm 1\%)$	OEL ( $\mu\text{g m}^{-3}$ )	OEL Basis
Aluminum	0.250	5.0	100	5000	US DOL/OSHA <sup>18</sup> (respirable)
Antimony	0.025	0.5	10	500	US DOL/OSHA <sup>18</sup>
Arsenic	0.250	5.0	100	10	US DOL/OSHA <sup>18</sup>
Barium	0.250	5.0	100	500	US DOL/OSHA <sup>18</sup> (soluble)
Beryllium	0.025	0.5	10	0.2	US DOE <sup>19</sup>
Cadmium	0.025	0.5	10	10	ACGIH <sup>20</sup>
Chromium	0.250	5.0	100	50	ACGIH <sup>20</sup> ( $\text{Cr}^{3+}$ )
Cobalt	0.025	0.5	10	20	ACGIH <sup>20</sup>
Copper	0.250	5.0	100	1000	US DOL/OSHA <sup>18</sup> (dusts/mists)
Iron	0.250	5.0	100	1000	ACGIH <sup>20</sup> (oxide dust)
Lead	0.025	0.5	10	50	US DOL/OSHA <sup>18</sup>
Magnesium	0.250	5.0	100	10 000	ACGIH <sup>20</sup> (oxide fume)
Manganese	0.025	0.5	10	200	ACGIH <sup>20</sup>
Molybdenum	0.025	0.5	10	10 000	ACGIH <sup>20</sup> (insoluble)
Nickel	0.025	0.5	10	200	ACGIH <sup>20</sup> (insoluble)
Selenium	0.025	0.5	10	200	US DOL/OSHA <sup>18</sup>
Silver	0.025	0.5	10	10	US DOL/OSHA <sup>18</sup>
Tin	0.025	0.5	10	2000	US DOL/OSHA <sup>18</sup> (inorganic)
Uranium	0.025	0.5	10	200	ACGIH <sup>20</sup>
Vanadium	0.025	0.5	10	50	ACGIH <sup>20</sup> ( $\text{V}_2\text{O}_5$ )
Zinc	0.250	5.0	100	10 000	ACGIH <sup>20</sup> (ZnO dust)

**Table 2**  
**Participants in the ICP-MS interlaboratory study**

Laboratory	Location
ALS Laboratory Group <sup>a</sup> (ALS)	Salt Lake City, Utah, United States
Bureau Veritas North America (BVNA)	Novi, Michigan, United States
BWXT Y-12 National Security Laboratory (Y-12)	Oak Ridge, Tennessee, United States
Environmental Resource Associates (ERA)	Arvada, Colorado, United States
Eurofins Environnement (Eurofins)	Saverne, France
Health and Safety Laboratory (HSL)	Buxton, England, United Kingdom
Hungarian Institute of Occupational Health (HIOH)	Budapest, Hungary
Institut de Recherche Robert Sauvé et en Sécurité du Travail (IRSST)	Montréal, Québec, Canada
Institut National de Recherche et de Sécurité (INRS)	Vandoeuvre-lès-Nancy, France
Institut Technique des Gaz de l'Air (ITGA)	Saint-Etienne, France
Japan National Institute of Occupational Safety and Health (JNIOSH)	Kawasaki, Japan
Laboratoire Central de la Préfecture de Police (LCPP)	Paris, France
Navy Central Industrial Hygiene Laboratory (CIHL)	San Diego, California, United States
Occupational and Environmental Safety Laboratory (OESL), Institute of Naval Medicine	Gosport, England, United Kingdom
Occupational Safety and Health Administration (OSHA), Salt Lake Technical Center	Sandy, Utah, United States
Research Triangle Institute International (RTI)	Research Triangle Park, North Carolina, United States
Savannah River Nuclear Solutions (SRNS), Savannah River Site	Aiken, South Carolina, United States
United States Geological Survey (USGS)	Denver, Colorado, United States
University of Cincinnati (UC), Department of Chemistry	Cincinnati, Ohio, United States
US Army Public Health Command <sup>b</sup> (USAPHC)	Aberdeen Proving Ground, Maryland, United States

<sup>a</sup>Formerly DataChem Laboratories.

<sup>b</sup>Formerly US Army Center for Health Promotion and Preventive Medicine (USACHPPM).

**Table 3**  
**Summary of sample preparation methods used by participating laboratories**

<b>Acid mixture + Heating technique used</b>	<b>No. of laboratories</b>
HNO <sub>3</sub> /HCl + hot block	8
HNO <sub>3</sub> /HCl + microwave	4
HNO <sub>3</sub> /HCl + hot plate	2
HNO <sub>3</sub> /H <sub>2</sub> O <sub>2</sub> + hot block	1
HNO <sub>3</sub> /H <sub>2</sub> O <sub>2</sub> + microwave	1
HNO <sub>3</sub> /HCl/H <sub>2</sub> O <sub>2</sub> + microwave	1
HNO <sub>3</sub> /H <sub>2</sub> O + microwave	1
HNO <sub>3</sub> /HF + microwave	1
HNO <sub>3</sub> /HClO <sub>4</sub> /HCl/H <sub>2</sub> O <sub>2</sub> + hotplate	1

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**Table 4**  
**ICP-MS analysis instrumentation used by participating laboratories**

<b>ICP-MS instrumentation</b>	<b>No. of laboratories</b>
Agilent 7500 series	7
Thermo VG	5
Perkin Elmer 6000 series	4
Varian 820 series	2
Varian 700	1
Thermo Elemental	1

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Table 5

Interlaboratory bias and precision estimates for ICP-MS elemental measurements from non-robust and robust statistical analyses of low-level filter spikes, after blank correction. (n = number of reporting laboratories;  $RSD_w$ ,  $RSD_b$ , and  $RSD_{tot}$  are within-laboratory, between-laboratory, and total relative standard deviations, respectively.)

Element	Non-robust <sup>a</sup>						Robust <sup>b</sup>								
	n	Bias	$RSD_w$	$RSD_b$	$RSD_{tot}$	n	Bias	$RSD_w$	$RSD_b$	$RSD_{tot}$	n	Bias	$RSD_w$	$RSD_b$	$RSD_{tot}$
Aluminum	14	-4.78	10.68	27.18	29.20	14	0.20	1.28	0.60	1.41	14	0.20	1.28	0.60	1.41
Antimony	11	2.28	4.88	4.52	6.65	11	-0.22	0.11	0.40	0.41	11	-0.22	0.11	0.40	0.41
Arsenic	11	-0.21	0.28	0.16	0.32	11	-0.13	0.03	0.08	0.09	11	-0.13	0.03	0.08	0.09
Barium	16	-0.08	0.05	0.25	0.26	16	-0.05	0.04	0.11	0.12	16	-0.05	0.04	0.11	0.12
Beryllium	11	-0.66	0.15	1.80	1.81	11	-0.19	0.05	0.24	0.25	11	-0.19	0.05	0.24	0.25
Cadmium	11	-0.03	0.16	0.24	0.29	11	-0.13	0.12	0.30	0.32	11	-0.13	0.12	0.30	0.32
Chromium	17	-0.16	0.39	0.62	0.74	17	-0.09	0.14	0.15	0.20	17	-0.09	0.14	0.15	0.20
Cobalt	11	-0.93	0.12	2.95	2.95	11	-0.04	0.04	0.10	0.11	11	-0.04	0.04	0.10	0.11
Copper	17	-0.09	0.32	0.43	0.54	17	-0.04	0.08	0.14	0.16	17	-0.04	0.08	0.14	0.16
Iron	12	-0.21	1.84	1.33	2.27	12	0.21	1.37	0.00	1.37	12	0.21	1.37	0.00	1.37
Lead	12	0.94	0.85	3.09	3.21	12	0.01	0.07	0.18	0.19	12	0.01	0.07	0.18	0.19
Magnesium	14	0.49	1.27	0.77	1.49	14	0.04	0.59	0.42	0.72	14	0.04	0.59	0.42	0.72
Manganese	11	0.34	0.39	1.12	1.19	11	0.12	0.16	0.21	0.26	11	0.12	0.16	0.21	0.26
Molybdenum	13	-1.07	2.39	5.87	6.34	13	-0.28	0.18	0.72	0.74	13	-0.28	0.18	0.72	0.74
Nickel	12	-0.65	1.08	1.06	1.51	12	-0.20	0.34	0.80	0.87	12	-0.20	0.34	0.80	0.87
Selenium	8	0.61	6.12	0.00	6.12	7	-0.08	0.50	0.68	0.84	7	-0.08	0.50	0.68	0.84
Silver	7	-10.85	42.89	15.43	45.58	6	0.18	0.93	0.00	0.93	6	0.18	0.93	0.00	0.93
Tin	10	0.59	1.85	2.44	3.06	10	-0.37	0.15	0.44	0.47	10	-0.37	0.15	0.44	0.47
Uranium	6	-0.22	0.04	0.24	0.24	6	-0.22	0.04	0.24	0.24	6	-0.22	0.04	0.24	0.24
Vanadium	7	-1.11	3.25	1.36	3.52	6	-0.24	0.42	0.17	0.45	6	-0.24	0.42	0.17	0.45
Zinc	19	-1.44	0.79	3.51	3.60	19	-0.34	0.51	1.02	1.14	19	-0.34	0.51	1.02	1.14

<sup>a</sup>Includes outliers.

<sup>b</sup>Outliers treated in accordance with ref. 17.

**Table 6**

Interlaboratory bias and precision estimates for ICP-MS elemental measurements from non-robust statistical analyses of medium-level filter spikes, after blank correction. ( $n$  = number of reporting laboratories;  $RSD_w$ ,  $RSD_b$ , and  $RSD_{tot}$  are within-laboratory, between-laboratory, and total relative standard deviations, respectively.)

Element	n	Bias	$RSD_w$	$RSD_b$	$RSD_{tot}$
Aluminum	18	-0.14	0.74	0.60	0.95
Antimony	14	-0.08	0.10	0.28	0.30
Arsenic	15	-0.02	0.04	0.08	0.09
Barium	17	-0.04	0.02	0.07	0.07
Beryllium	15	-0.09	0.03	0.19	0.19
Cadmium	14	-0.03	0.03	0.08	0.08
Chromium	20	-0.04	0.04	0.09	0.10
Cobalt	15	-0.03	0.04	0.10	0.11
Copper	18	0.00	0.03	0.09	0.10
Iron	14	0.00	0.18	0.16	0.24
Lead	16	-0.04	0.05	0.18	0.19
Magnesium	15	-0.04	0.09	0.27	0.28
Manganese	15	-0.03	0.04	0.11	0.12
Molybdenum	15	-0.11	0.04	0.33	0.34
Nickel	16	-0.12	0.08	0.18	0.19
Selenium	15	-0.19	0.30	0.16	0.34
Silver	8	-0.09	0.34	0.33	0.47
Tin	13	-0.07	0.02	0.16	0.16
Uranium	9	-0.06	0.02	0.05	0.05
Vanadium	9	-0.19	0.18	0.14	0.23
Zinc	19	-0.08	0.06	0.18	0.19

**Table 7**

Interlaboratory bias and precision estimates for ICP-MS elemental measurements from non-robust statistical analyses of high-level filter spikes, after blank correction. ( $n$  = number of reporting laboratories;  $RSD_w$ ,  $RSD_b$ , and  $RSD_{tot}$  are within-laboratory, between-laboratory, and total relative standard deviations, respectively.)

Element	n	Bias	$RSD_w$	$RSD_b$	$RSD_{tot}$
Aluminum	18	-0.14	0.14	0.13	0.19
Antimony	15	-0.05	0.05	0.14	0.14
Arsenic	15	-0.06	0.04	0.06	0.07
Barium	17	-0.14	0.13	0.10	0.16
Beryllium	16	-0.19	0.10	0.11	0.14
Cadmium	15	-0.17	0.09	0.10	0.13
Chromium	20	-0.16	0.07	0.08	0.11
Cobalt	16	-0.18	0.10	0.11	0.15
Copper	18	-0.20	0.09	0.09	0.13
Iron	15	-0.10	0.07	0.12	0.13
Lead	17	-0.15	0.08	0.11	0.14
Magnesium	15	-0.18	0.09	0.14	0.16
Manganese	16	-0.22	0.09	0.13	0.16
Molybdenum	17	-0.08	0.05	0.13	0.14
Nickel	19	-0.25	0.09	0.13	0.16
Selenium	16	-0.17	0.07	0.08	0.10
Silver	9	-0.26	0.21	0.46	0.51
Tin	14	-0.01	0.04	0.10	0.11
Uranium	9	-0.08	0.08	0.11	0.13
Vanadium	14	-0.26	0.20	0.15	0.25
Zinc	19	-0.20	0.09	0.11	0.14