

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>

FEATURE

Field-portable methods for monitoring occupational exposures to metals[☆]

Millions of workers are employed in manufacturing, mining, construction, and other industries where significant amounts of airborne metals and metal compounds are generated. Depending on the work practices, processes, techniques, and locations, exposures to airborne and surface sources of a variety of metals can cause occupational illness. These exposures can lead to a plethora of adverse health effects such as lung disease, anemia, cancer, asthma, dermal sensitization, dermatitis and neurological damage. The ability to monitor worker exposures to metals on-site in the field has been a goal of the National Institute for Occupational Safety and Health (NIOSH) since the early 1990s. In the last 15 years or so, several field-portable procedures for metals have been developed, evaluated and published as NIOSH methods. These methods, published in the *NIOSH Manual of Analytical Methods*, describe field screening tests and on-site analysis for lead, hexavalent chromium and beryllium. Some of these methods have also been published in the form of ASTM International voluntary consensus standards. This paper gives an overview of NIOSH research and development efforts on field screening and portable analytical methods for metals in the workplace. The goal of such efforts has been to provide screening and analytical tools that can be used on-site in the field to aid in the prevention of excessive exposures to toxic metals in the workplace.

By Kevin Ashley

INTRODUCTION

Millions of workers in the United States are exposed to inorganic toxic

Kevin Ashley, Ph.D., is a research chemist with the US Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Mail Stop R-7, Cincinnati, OH 45226-1998, USA (Tel.: +513 841 4402; e-mail: KAshley@cdc.gov). Dr. Ashley serves as chair of ASTM International Subcommittee D22.04 on Workplace Air Quality.

[☆] This article was prepared by US Government employees as part of their official duties and legally may not be copyrighted in the United States of America. Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention. The findings and conclusions in this article are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

substances in myriad occupations.¹ Depending on the work practices, processes, techniques, and locations, workers may be exposed to airborne concentrations of a wide variety of metals and metalloids that may have toxic effects. Laborers in construction and mining are exposed to high concentrations of airborne heavy metals,² and workers in some industries suffer exposures from toxic elements such as beryllium³ and hexavalent chromium⁴ on surfaces as well. In the U.S. alone, occupational lead exposures continue to result in high blood lead levels in hundreds of thousands of workers.⁵ Exposures to aerosols and vapors containing inorganic toxic agents can lead to numerous deleterious health effects, such as lung disease and damage to other organs, anemia, asthma, cancer, and neurological effects, to cite a few examples.^{6,7}

In 1970, the Occupational Safety and Health Act (Public Law 91-596) gave the National Institute for Occupational Safety and Health (NIOSH) responsibility for the development and evaluation of sampling and analytical methods for workplace exposure monitoring. Occupational exposure monitoring to toxic substances is conducted by public

health professionals in order to determine whether exposures are in excess of pertinent occupational exposure limits (OELs), e.g., NIOSH Recommended Exposure Limits (RELs).⁸ Presently, the most commonly used method for assessment of worker exposures entails collection of air samples, which is followed by subsequent laboratory analysis. Generally speaking, metallic aerosols are collected onto filters⁹ which are subsequently analyzed in order to obtain an estimate of exposure.¹⁰ For aerosol collection, there has been recent interest towards the use of inhalable samplers, rather than 'total' aerosol samplers.^{11,12} Sampling of smaller size fractions, e.g., respirable or thoracic, may also be pertinent for exposure assessment involving metallic aerosols.¹³ Apart from air samples, in recent years there has been increased interest in monitoring of surface dust,¹⁴ since occupational exposures to toxic materials can sometimes occur via worker contact with contaminated surfaces. New work activities and processes have also resulted in a desire for novel industrial hygiene sampling and analysis techniques.¹⁵ All of these scenarios present new analytical challenges that need to be addressed.

To this end, much of the research effort in our laboratory has been directed towards the development, evaluation and validation of user-friendly procedures that can be employed for on-site monitoring of toxic metals in occupational environments. Construction and mining industries have been the primary targets of application for field-portable monitoring methods, but such procedures can be taken to other workplace environments as well, notably manufacturing. On-site methods for the determination of lead^{16,17} and hexavalent chromium^{18,19} in filter samples collected from workplace air have been used successfully in field studies. In addition to air filter samples, portable anodic stripping voltammetry (ASV) has also been shown to perform well for measuring lead in surface dust samples collected using wipes.²⁰ Portable X-ray fluorescence (XRF) can provide on-filter quantitative measurement of a number of heavy metals in samples collected from workplace atmospheres.²¹ In other work, a molecular fluorescence method for the determination of trace beryllium in workplace air and wipe samples has been developed and validated.²² In several instances, field methods have been shown to meet NIOSH criteria for method accuracy.²³

The aim of this paper is to provide an overview of the available field-portable methods for metals that have been published as NIOSH methods and/or as ASTM International (formerly American Society for Testing and Materials) voluntary consensus standards. Depending on the specific application, definitive (quantitative), semi-quantitative and screening methods are all useful in the industrial hygiene field. Portable methods offering desired performance characteristics are available for some metals, notably lead, beryllium and chromium. Field screening test method performance has been treated in a general fashion using a rigorous statistical protocol,²⁴ with applications having been demonstrated for examples entailing lead monitoring in the workplace.²⁵ Using a statistical formalism to treat collected data, performance criteria and characteristics of field-portable methods can be estimated for qualitative, semi-

quantitative, and quantitative measurement procedures. The application is general for any analyte, and allows for results from screening tests to be used in making defensible decisions concerning potential human exposures to toxic substances. This research provides a basis for investigations on the evaluation of field screening methods for toxic inorganic species of interest in occupational safety and health.

NIOSH METHODS

Field-portable analytical methods for metals that have been approved and published in the *NIOSH Manual of Analytical Methods* include examples of qualitative, semi-quantitative and quantitative procedures. Qualitative screening methods have been described by NIOSH for detecting lead in air filters, as well as for the detection of lead or hexavalent chromium in wipe samples. A semi-quantitative NIOSH method for estimating lead loadings in air filter samples, based on the use of portable XRF, has also been promulgated. Quantitative measurement procedures for metals that have been approved as NIOSH methods include: (a) lead determination in air samples by portable ASV; (b) determination of hexavalent chromium in air by portable spectrophotometry; and (c) on-site determination of beryllium in air filters or wipe samples by a molecular fluorescence technique. Salient details regarding these methodologies are provided in the following paragraphs.

A screening technique for testing for the presence of lead in air filter samples, NIOSH Method 7700,²⁶ entails the use of a colorimetric chemical spot-test kit applied to the particulate matter collected on the filters. A characteristic color change on the filter (i.e., from yellow/orange to pink/red hues) indicates the presence of lead in the collected aerosol. To evaluate the method, a commercial rhodizonate-based spot test kit was evaluated for its potential use in the detection of lead in airborne particulate matter.²⁷ Battery-powered personal sampling pumps were used to collect over 370 air samples on cellulose ester mem-

brane filters at various worksites where lead was a suspected air contaminant. Each filter sample was tested with an individual chemical spot test, and the samples (test kit materials included) were then analyzed using reference measurement of lead by graphite furnace atomic absorption spectrometry (GFAAS) as described by NIOSH Method 7105.²⁸ The experimental data were statistically modeled in order to estimate the performance parameters of the spot test kit. A positive reading was found at 95% confidence for lead mass values above about 10 µg Pb per filter, while 95% confidence of a negative reading was found for lead masses below ≈0.6 µg Pb per filter.²⁷ Given these performance measures, in the field the spot test screening technique can be used to estimate, using short- or medium-term sampling, whether lead exposures will be expected to exceed applicable OELs, e.g., the Occupational Safety and Health Administration (OSHA) Personal Exposure Limits (PELs) for lead. Tl⁺, Ag⁺, Cd²⁺, Ba²⁺, and Sn²⁺ also form colored compounds with rhodizonate ion, but with less sensitivity than that of Pb²⁺, and only the lead-rhodizonate complex gives the characteristic pink or red color.²⁹

A similar colorimetric screening method for the presence of lead in wipe samples has been described in a NIOSH procedure.³⁰ The method was designed as a handwipe method for detecting lead collected from human skin,³¹ but it is also applicable to wipe samples obtained from various nondermal surfaces including floors, walls, equipment, furniture, etc. The method has been evaluated preliminarily using commercial wipes spiked with certified reference materials (CRMs), and has been found to give a positive response for at least 10 µg of lead per wipe. The method has also been subjected to limited field testing, and shows a positive response for at least a few tens of micrograms of lead per wipe. Extremely heavy soiling on the wipe could interfere with visualization of the red color change due to darkening of the wipe, but the pink or red hues should still be visible around the area of the heaviest soiling, provided lead is present. Difficult matrices (e.g., dust wipes

containing paint chips) may require leaching in dilute nitric acid before spot testing. In addition to the metallic interferences mentioned above for air filter samples screened using rhodizionate-based test kits, interferences from the wipe medium, e.g., surfactants, are also possible.

Hexavalent chromium, Cr(VI), can be detected colorimetrically at trace levels using diphenylcarbazide, and this chemistry has been applied to the detection of Cr(VI) in wipe samples.³² The method reportedly can detect masses as low as a microgram of Cr(VI) per sample, but unfortunately no evaluation data are available. In any case, a qualitative screening procedure could be useful to detect traces of Cr(VI) in surface dust collected using wipes. Follow-up analysis with more definitive methods is recommended.

Portable XRF measurement of lead in aerosols collected onto air filters has been described in a NIOSH method.³³ This methodology was validated on field samples by collecting lead particulate samples from bridge lead abatement projects.³⁴ Airborne concentrations of lead within the containment area of a sand blasting bridge lead abatement project ranged from 1 to 10 mg/m³. Area and personal samples were collected for periods of time ranging from 15 s to 2 hours. This sampling protocol yielded 65 filter samples with lead loadings ranging between 0.1 and $\approx 1,500$ μg of lead per sample. The filter samples obtained were first analyzed using a non-destructive, field-portable XRF method, and the samples were subsequently subjected to reference analysis by the laboratory-based NIOSH Method 7105.²⁸ The portable XRF method was statistically evaluated in accordance with NIOSH guidelines.²³ The overall precision of the portable XRF method was calculated at 0.054 (95% confidence interval (CI) = 0.035–0.073), and the bias was 0.069 (95% CI = 0.006–0.152). The portable XRF method accuracy was determined to be $\pm 16\%$; however, at the upper 90% CI, the accuracy is $\pm 27\%$. Since the confidence interval exceeds $\pm 25\%$, meeting the NIOSH accuracy criterion²³ is inconclusive; hence, this measurement technique

may be regarded as “semi-quantitative”.²⁴ However, it is noted that the samples used to evaluate the portable XRF method were field samples; laboratory-prepared aerosol samples give better precision.²¹ Additionally, it should be pointed out that the portable XRF method is non-destructive; if required, samples analyzed on-site in the field can subsequently be transported and analyzed in a fixed-site laboratory using a method with greater accuracy. Portable XRF may also be extendable to the detection of lead on surfaces after collection using wipe media.³⁵

Quantitative on-site analysis of air filter samples for the determination of lead by field-based ultrasonic extraction with ASV measurement has been published as a NIOSH method.³⁶ This method was evaluated with lead aerosol samples generated in the laboratory (≈ 40 to ≈ 80 μg Pb per filter),³⁷ and with air particulate samples collected from workplaces where abrasive blasting of leaded paint on highway bridges was being conducted.³⁸ For the latter, lead masses covered the range from below the detection limit of 0.09 μg Pb per filter to loadings in excess of 1,500 μg Pb per filter. The method also has been evaluated with performance evaluation materials and by interlaboratory testing.³⁹ Lead recoveries from CRMs were found to be quantitative ($>90\%$) and equivalent to recoveries obtained using confirmatory analytical methods (e.g., NIOSH 7105²⁸). Thallium is a known interferant, but its presence is unlikely in the vast majority of occupational air samples. Extremely high concentrations of copper may cause a positive bias. Surfactants can poison electrode surfaces, so if the presence of surfactants is suspected, such interferences must be eliminated during sample preparation.

A quantitative method describing the trace determination of beryllium in air samples by field-based extraction and fluorescence measurement has been published in the most recent edition of the *NIOSH Manual of Analytical Methods*.⁴⁰ The method entails extraction of beryllium in air filter samples for 30 min using dilute (1%, aqueous) ammonium bifluoride, with subsequent fluorescent measurement

after reaction of dissolved beryllium with the high-quantum yield fluorophore, hydroxybenzoquinoline sulfonate.²² Experiments were conducted using several commercial portable fluorescence devices. The method was evaluated using beryllium oxide spiked onto mixed-cellulose ester (MCE) filters at various levels (0, 0.02, 0.1, 0.2, 0.3, 0.4, 1.5, 3.0, and 6.0 μg ; five samples at each level). Long-term stability of samples was verified from spikes (number [n] = 30) of 0.1 μg Be on MCE filters. Samples were analyzed at day one ($n = 12$) and then 1 week ($n = 6$), 10 days ($n = 3$), 2 weeks ($n = 3$), 3 weeks ($n = 3$), and 1 month ($n = 3$) after spiking. No diminution of fluorescence signal was observed from samples prepared and analyzed after having been stored for up to 30 days. Interference tests were carried out using solutions of 0 nmol/L, 100 nmol/L, and 1.0 $\mu\text{mol/L}$ Be in the presence of 0.4 mmol/L of Al, Ca, Co, Cu, Fe, Ti, Li, Ni, Pb, Sn, U, V, W, or Zn (separate experiments were carried out for each potential interferant). Minor interference from iron can result if iron concentrations are high (e.g., $\approx 100\times$ the beryllium concentration). Samples high in iron demonstrate a yellow or gold coloration. This interference can be minimized by allowing the solution to sit for 4 hours or more, during which time the solution clears, and then filtering the sample extract before use. Interlaboratory evaluations of the method were also performed on both soluble and refractory beryllium compounds.^{22,41} When high-temperature (≈ 90 °C) extraction is employed, the method is effective for quantitative dissolution and determination of high-fired (calcined) beryllium oxide in aerosol samples. Ultra-trace determination of beryllium in air samples has been achieved, with attainable method detection limits of less than a nanogram of beryllium per sample.⁴¹ It is pertinent to note that the method detection limit of the portable fluorescence method for beryllium is comparable to that of inductively coupled plasma mass spectrometry (ICP-MS).⁴²

A companion NIOSH method for determining beryllium in surface wipe

Table 1. NIOSH field-portable methods for metals measurement in samples collected in occupational settings.^{26,30,32,33,36,40,43,45}

Method number	Sample medium	Element/species	Sample preparation	Detection method	Estimated MDL ^a
7700	Air filters	Pb	Extraction (weak acid)	Colorimetry (chemical spot test)	<10 µg/sample
7701	Air filters ^b	Pb	Ultrasonic extraction (dilute HNO ₃)	Anodic stripping voltammetry	0.09 µg/sample
7702	Air filters ^c	Pb	None	X-ray fluorescence	6 µg/sample
7703	Air filters	Cr(VI)	Ultrasonic extraction (sulfate or carbonate buffer) ^d ; SPE ^e	Spectrophotometry	0.08 µg/sample
7704	Air filters	Be	Extraction (dilute NH ₄ HF ₂)	Fluorescence	0.0008 µg/sample
9101	Wipes	Cr(VI)	Extraction (dilute H ₂ SO ₄); pH adjustment (carbonate buffer)	Colorimetry (chemical spot test)	1 µg/sample
9105	Wipes	Pb	Extraction (weak acid)	Colorimetry (chemical spot test)	~10 µg/sample
9110	Wipes	Be	Extraction (dilute NH ₄ HF ₂)	Fluorescence	0.0008 µg/sample

^a Method detection limit. ^b With minor modification, method is also applicable to wipe samples. ^c With modification, method may also be applicable to wipe samples. ^d For soluble or insoluble Cr(VI) compounds, respectively; addition of phosphoric acid is recommended for samples high in iron. ^e Solid-phase extraction; for many sample matrices, this step can be omitted.

samples has also been promulgated.⁴³ Method evaluation and validation on cellulosic filter materials were carried out in a similar fashion as described above for air filter samples. Trace²² and ultra-trace⁴¹ quantitative determination of beryllium in wipe samples has been demonstrated, along with excellent intra- and inter-laboratory reproducibility. A modification of the procedure, in which longer-term extraction (4 hours) is carried out in a slightly higher concentration (3%) of aqueous ammonium bifluoride, enables quantitative extraction of larger particle sizes (up to >200 microns aerodynamic diameter) of high-fired beryllium oxide.⁴⁴ The method yielded acceptable recoveries from refractory BeO in several different sampling media tested.

A field-portable spectrophotometric NIOSH method for determining Cr(VI) in air filter samples entails field-based ultrasonic extraction in basic buffer, followed by measurement of the chromium–diphenylcarbazide adduct.⁴⁵ Strong anion-exchange solid-phase extraction (SAE-SPE)^{46,47} enables isolation of Cr(VI) from other metallic interferents such as trivalent iron, manganese and mercury. This method was evaluated in the laboratory with spiked filters^{47,48} and with a CRM containing a certified loading of Cr(VI).⁴⁷ (This European CRM, consisting of Cr(VI) and Cr(total) in welding dust loaded on a glass fiber filter,⁴⁹

is no longer available.) The NIOSH portable method for Cr(VI) has also been evaluated in the field, where samples collected during aircraft maintenance and painting operations were analyzed on-site.^{18,19} Filters used for sample collection can be pretreated with base to minimize Cr(VI) reduction during sampling in high-iron or acidic environments.⁵⁰ SAE-SPE can be omitted if suspected metallic interferences are not present, or can be minimized by other means, e.g., with inclusion of phosphoric acid during extraction.⁵¹ Recent studies have extended applications of the method to extraction of insoluble Cr(VI) compounds⁵² and sequential extraction of soluble and insoluble Cr(VI) species.⁵³

Table 1 summarizes the NIOSH field-portable methods for metals measurement described above.

ASTM METHODS

Voluntary consensus standards such as those published by ASTM International are considered by many to be the most technically sound and most credible documents for use in their particular fields of application. This was recognized by the U.S. Congress through passage of the National Technology Transfer and Advancement Act of 1995 (Public Law 104-113), which directs federal agencies to: (a) rely on consensus standards in their guidelines

and activities, and (b) participate in the consensus standards development process. Experts from relevant federal agencies have contributed significantly to the development of numerous ASTM standards that apply to the field of industrial hygiene chemistry. Within ASTM International Committee D22 on Air Quality, Subcommittee D22.04 on Workplace Air Quality produces standards that describe methods to collect and measure chemical hazards in the workplace.⁵⁴ This subcommittee has been active for decades, and its members have developed many needed standards consisting of test methods, practices, and guides. These consensus standards are meant for use by industrial hygienists, chemists, engineers, health physicists, toxicologists, epidemiologists, and myriad other professionals. Experts from private industry, government, and academia have all contributed extensively to the development of standards for workplace contaminant monitoring. One of the voluntary consensus standards produced by ASTM International Subcommittee D22.04 describes field-portable procedures for trace beryllium monitoring. Also, ASTM International Subcommittee E06.23 on Mitigation of Lead Hazards has published several standards pertaining to on-site measurement of lead in occupational environments.⁵⁵ Pertinent details on specific ASTM standards describing on-site sample preparation

Table 2. ASTM standards pertaining to on-site metals determination in samples collected in occupational settings. ^{56,58-61,63,64}

Standard number	Type of standard	Sample media	Element(s)/ species	Comments
D6966	Practice	Wipes	Metals	Collected samples can be analyzed on-site (e.g., for Be, Pb)
D7144	Practice	Micro-vacuum sample	Metals	Collected samples can be analyzed on-site (e.g., for Be, Pb, Cr(VI))
D7202	Test method	Air filters or wipes	Be	Based on NIOSH methods 7704/9110
E1775	Guide	Air filters, wipes, paint, soil	Pb	Outlines performance criteria for field-portable measurement by electroanalysis or spectrophotometry
E1792	Specification	Wipes	Pb ^a	Describes required characteristics of wipe media to be used for collection of Pb on surfaces
E1979	Practice	Air filters, wipes, paint, soil	Pb	Ultrasonic extraction in dilute HNO ₃ ; can be followed by electroanalysis (e.g., using ASTM E2051)
E2051	Practice	Air filters, wipes, paint, soil	Pb	Samples previously extracted (e.g., using ASTM E1979)

^a Also applicable to other elements.

and analysis of beryllium and lead in occupational environments are given below.

ASTM D7202 describes a test method that is intended for use in the determination of beryllium by sampling workplace air or surface dust.⁵⁶ The method assumes that air and surface samples are collected using appropriate and applicable ASTM International standard practices for sampling of workplace air and surface dust. These samples are typically collected using air filter sampling,⁵⁷ vacuum sampling⁵⁸ or wiping⁵⁹ techniques. The method includes a procedure for on-site extraction (dissolution) of beryllium in weakly acidic medium (pH of 1% aqueous ammonium bifluoride is 4.8), followed by field analysis of aliquots of the extract solution using a beryllium-specific fluorescent dye, hydroxybenzoquinoline sulfonate. The procedure is targeted for on-site use in the field for occupational and environmental hygiene monitoring purposes, and can be used to determine as low as a few nanograms of beryllium in collected samples. This voluntary consensus standard method was developed based on the aforementioned NIOSH procedures^{40,43} for on-site determination of beryllium in the workplace.

Lead contamination in paint, dust, soil and air represents a potential health hazard to people, and field-portable analytical methods for the determination of this toxic metal in environmental samples are desired

for the on-site assessment of lead hazards. On-site determination of lead in occupational hygiene samples obtained using consensus standard sampling techniques is described in ASTM procedures for field-based ultrasonic extraction⁶⁰ and electroanalysis (e.g., ASV),⁶¹ respectively. These ASTM standards were developed based on the NIOSH method³⁶ described earlier. Compared to traditional digestion methods that employ hot plate^{57,62} or microwave digestion⁵⁷ with concentrated acids, ultrasonic extraction using dilute nitric acid⁶⁰ is a simple, yet effective, method for extracting lead from air filter and wipe samples. Hence, ultrasonic extraction may be used in lieu of the more rigorous strong acid/high-temperature digestion methods, provided that the overall method performance is demonstrated using acceptance criteria as delineated in ASTM Guide E1775.⁶³ In contrast with hot plate and microwave digestion techniques, the equipment required for ultrasonic extraction is field-portable, which allows for on-site sample analysis.

Field-portable techniques (such as ASV) for the determination of lead in environmental and occupational hygiene samples, notably air filters and wipe samples, may allow for rapid assessments of lead hazards and corresponding cost reductions compared to traditional fixed-site laboratory-based analyses. Prior to analysis in accordance with ASTM standard protocols,

the use of standardized sampling techniques for lead in air⁵⁷ and on surfaces^{58,59} is highly recommended. Moreover, for leaded dust wipe sampling, it is urged to use a standardized wipe material.⁶⁴ Standardization of sampling materials, sample collection procedures, sample preparation protocols, and analytical methods is meant to optimize overall analytical performance and interlaboratory comparability. Using these ASTM standard methods, practices, guides and specifications, on-site measurement of lead content in workplace samples may be used for compliance with applicable federal, state, and local regulations and guidelines, providing accepted performance criteria are demonstrated to be met.

Table 2 provides an overview of the ASTM standards relating to the field-portable methods for metals described in this section.

CONCLUDING REMARKS

Traditionally, workplace samples for subsequent metals determination have been sent away to fixed-site laboratories for analysis. In some cases, the analytical results can take many weeks to be reported. Such delays can compromise worker health if exposures are excessive. The use of field-portable methods and instrumentation for on-site metals monitoring is meant to alleviate such problems that may be

brought on by delayed analytical results. Methods relying on field-portable instruments and tests allow for screening and/or analysis of occupational hygiene samples on location with same-day speed.⁶⁵ While most of the methods described in this paper do not rely on direct-reading monitoring techniques, they are nonetheless invaluable for obtaining rapid analysis results. Additionally, samples that are analyzed non-destructively in the field can be sent for confirmatory analysis if exposures appear to approach or exceed applicable OELs. This can reduce the number of samples that are conveyed to fixed-site laboratories and makes the overall exposure assessment process more cost-effective. Use of field-portable methods can also facilitate the proper selection and evaluation of exposure controls to reduce the potential for adverse health effects among workers. The NIOSH and ASTM International methods and standards highlighted in this article represent accepted government and consensus standard procedures for on-site monitoring of metals, notably lead, beryllium and hexavalent chromium.^a While there is redundancy between some of the NIOSH and ASTM field-portable analytical methods discussed here, the availability of voluntary consensus standards is often desired by potential users. Also, reliance on consensus standards may be required by accreditation and certification bodies.

ACKNOWLEDGMENTS

Appreciation is extended to Leroy Dobson of the Wisconsin Occupational Health Laboratory, as well as Yvonne Gagnon, Bob Streicher and Dave Utterback of NIOSH, for reviewing the draft manuscript.

REFERENCES

1. U.S. Census Bureau. *Statistical Abstract of the United States-2000, 20th ed.* U.S. Census Bureau; Washington, 2000.
2. King, R. W.; Hudson, R. *Construction Safety Handbook*; Butterworths; London, 1985.
3. Berlin, J. M.; Taylor, M. S.; Sigel, M. E.; Bergfeld, W. F.; Dweik, R. A. *J. Am. Acad. Dermatol.* **2003**, *49*, 939-941.
4. Flint, G. N.; Carter, S. V.; Fairman, B. *Cont. Derm.* **1998**, *39*, 315-316.
5. Alarcón, W. A.; Roscoe, R. J.; Calvert, G. M.; Graydon, J. R. *Morbid. Mortal. Wkly. Rpt.* **2009**, *58*, 365-369.
6. Ruegger, M. *Schweiz Med. Wschr.* **1995**, *125*, 467-474.
7. Hathaway, G. J.; Proctor, N. H.; Hughes, J. P.; Fischman, M. L. *Chemical Hazards in the Workplace, 3rd ed.* Van Nostrand Reinhold; New York, 1991.
8. National Institute for Occupational Safety and Health (NIOSH). *Recommendations for Occupational Safety and Health-Compendium of Policy Documents and Statements*; NIOSH; Cincinnati, 1992.
9. Lee, K. W.; Ramamurthi, M. Filter collection, In P. A. Baron, & K. Willeke (Eds.), *Aerosol Measurement-Principles, Techniques, and Application*. Van Nostrand Reinhold: New York, 1992 Chapter 10.
10. Beliles, R. P. The metals, In G. D. Clayton, & F. E. Clayton (Eds.), *Patty's Industrial Hygiene and Toxicology, Vol. II, Part C.* (4th ed.). Wiley: New York, 1994.
11. Kenny, L. C.; Aitken, R.; Chalmers, C.; Fabries, J. F.; Gonzalez-Fernandez, E.; Kromhout, H.; Lidén, G.; Mark, D.; Riediger, G.; Prodi, V. *Ann. Occup. Hyg.* **1997**, *41*, 135-153.
12. Harper, M.; Demange, M. *J. Occup. Environ. Hyg.* **2007**, *4*, D81-D86.
13. Maynard, A. D.; Jensen, P. A. Aerosol measurement in the workplace, In P. A. Baron, & K. Willeke (Eds.), *Aerosol Measurement-Principles, Techniques, and Application*. Van Nostrand Reinhold: New York, 1992 Chapter 25.
14. Wheeler, J. P.; Stancliffe, J. D. *Ann. Occup. Hyg.* **1998**, *42*, 477-488.
15. Draper, W. M.; Ashley, K.; Glowacki, P. R.; Michael, C. R. *Anal. Chem.* **1999**, *71*, 33R-60R.
16. Sussell, A.; Ashley, K. *J. Environ. Monit.* **2002**, *4*, 156-161.
17. Drake, P. L.; Lawryk, N. J.; Ashley, K.; Sussell, A. L.; Hazelwood, K. J.; Song, R. *J. Hazard. Mater.* **2003**, *102*, 29-38.
18. Marlow, D.; Wang, J.; Wise, T. J.; Ashley, K. *Am. Lab.* **2000**, *32*(15), 26-28.
19. Boiano, J. M.; Wallace, M. E.; Sieber, W. K.; Groff, J. H.; Wang, J.; Ashley, K. *J. Environ. Monit.* **2000**, *2*, 329-333.
20. Ashley, K.; Wise, T. J.; Mercado, W.; Parry, D. B. *J. Hazard. Mater.* **2001**, *83*, 41-50.
21. Lawryk, N. J.; Feng, H. A.; Chen, B. T. *J. Occup. Environ. Hyg.* **2009**, *6*, 433-445.
22. Agrawal, A.; Cronin, J.; Tonazzi, J.; McCleskey, T. M.; Ehler, D. S.; Minoque, E. M.; Whitney, G.; Brink, C.; Burrell, A. K.; Warner, B.; Goldcamp, M. J.; Schlecht, P. C.; Sonthalia, P.; Ashley, K. *J. Environ. Monit.* **2006**, *8*, 619-624.
23. Kennedy, E. R.; Fischbach, T. J.; Song, R.; Eller, P. M.; Shulman, S. *Guidelines for Air Sampling and Analytical Method Development and Evaluation*; NIOSH; Cincinnati, 1995.
24. Song, R.; Schlecht, P. C.; Ashley, K. *J. Hazard. Mater.* **2001**, *83*, 29-39.
25. Ashley, K.; Song, R.; Schlecht, P. C. *Am. Lab.* **2002**, *34*(12), 32-39.
26. NIOSH. *Method 7700: Lead in air by chemical spot test*, NIOSH Manual of Analytical Methods. *4th ed. (Suppl. I)* NIOSH; Cincinnati, 1996.
27. Ashley, K.; Fischbach, T. J.; Song, R. *Am. Ind. Hyg. Assoc. J.* **1996**, *57*, 161-165.
28. NIOSH. *Method 7605: Lead by GFAAS*, NIOSH Manual of Analytical Methods. *4th ed.* NIOSH; Cincinnati, 1994.
29. Feigel, F.; Anger, V. *Spot Tests in Inorganic Analysis*; Elsevier; Amsterdam, 1972, pp. 282-287, 564-566, 569.
30. NIOSH. *Method 9105: Lead in dust wipes by chemical spot test (colorimetric screening method)*, NIOSH Manual of Analytical Methods. *4th ed. (Suppl. IV)* NIOSH; Cincinnati, 2003.
31. Esswein, E. J.; Boeniger, M. F.; Ashley, K. *Handwipe Disclosing Method for the Presence of Lead*. U.S. Pat. 6,248,593 (2001).
32. NIOSH. *Method 9101: Chromium, hexavalent, in settled dust samples*, NIOSH Manual of Analytical Methods. *4th ed. (Suppl. I)* NIOSH; Cincinnati, 1996.
33. NIOSH. *Method 7702: Lead by field-portable XRF*, NIOSH Manual of Analytical Methods. *4th ed. (Suppl. II)* NIOSH; Cincinnati, 1998.
34. Morley, J. C.; Clark, C. S.; Deddens, J.; Ashley, K.; Roda, S. *Appl. Occup. Environ. Hyg.* **1999**, *14*, 306-316.
35. Harper, M.; Hallmark, T. S.; Bartolucci, A. A. *J. Environ. Monit.* **2002**, *4*, 1025-1033.
36. NIOSH. *Method 7701: Lead by field-portable ultrasonic extraction/ASV*, NIOSH Manual of Analytical Methods. *4th ed. (Suppl. II)* NIOSH; Cincinnati, 1998.
37. Ashley, K. *Electroanalysis*, **1995**, *7*, 1189-1192.

^aNIOSH methods and ASTM standards are available online at www.cdc.gov/niosh/nmam and www.astm.org, respectively.

38. Ashley, K.; Mapp, K. J.; Millson, M. *Am. Ind. Hyg. Assoc. J.* **1998**, *59*, 671–679.
39. Ashley, K.; Song, R.; Esche, C. A.; Schlecht, P. C.; Baron, P. A.; Wise, T. *J. Environ. Monit.* **1999**, *1*, 459–464.
40. NIOSH. *Method 7704: Beryllium in air by field-portable fluorometry*, NIOSH Manual of Analytical Methods. 5th ed. NIOSH; Cincinnati, 2007.
41. Ashley, K.; Agrawal, A.; Cronin, J.; Tonazzi, J.; McCleskey, T. M.; Burrell, A. K.; Ehler, D. S. *Anal. Chim. Acta*, **2007**, *584*, 281–286.
42. Ashley, K.; Brisson, M. J.; Howe, A. M.; Bartley, D. L. *J. Occup. Environ. Hyg.*, in press, doi:10.1080/15459620903022605.
43. NIOSH. *Method 9110: Beryllium in surface wipes by field-portable fluorometry*, NIOSH Manual of Analytical Methods. 5th ed. NIOSH; Cincinnati, 2007.
44. Goldcamp, M. J.; Goldcamp, D. M.; Ashley, K.; Fernback, J. E.; Agrawal, A.; Millson, M.; Marlow, D.; Harrison, K. *J. Occup. Environ. Hyg.*, in press, doi:10.1080/15459620903012044.
45. NIOSH. *Method 7703: Chromium, hexavalent, by field-portable spectrophotometry*, NIOSH Manual of Analytical Methods. 4th ed. (Suppl. IV) NIOSH; Cincinnati, 2003.
46. Wang, J.; Ashley, K.; Marlow, D.; England, E. C.; Carlton, G. *Anal. Chem.* **1999**, *71*, 1027–1032.
47. Wang, J.; Ashley, K. *Method for the Determination of Hexavalent Chromium using Ultrasonic Extraction and Strong Anion Exchange Solid Phase Extraction*. U.S. Pat. 6,808,931 (2004).
48. Wang, J.; Ashley, K.; Kennedy, E. R.; Neumeister, C. *Analyst*, **1997**, *122*, 1307–1312.
49. Commission of the European Communities, Institute for Reference Materials and Measurements (EC/IRMM). *Certificate of Analysis, CRM 545–Cr(VI) and Total Leachable Cr in Welding Dust Loaded on a Filter*; EC/IRMM; Brussels, 1997.
50. Ashley, K.; Howe, A. M.; Demange, M.; Nygren, O. *J. Environ. Monit.* **2003**, *5*, 707–716.
51. Deutsche Forschungsgemeinschaft (DFG). *Methods for the determination of hexavalent chromium—Cr(VI) method no. 3*, Kettrup, A. Ed., *Analysis of Hazardous Substances in Air*, vol. 4, Wiley-VCH: Weinheim, 1993.
52. Hazelwood, K. J.; Drake, P. L.; Ashley, K.; Marcy, D. J. *Occup. Environ. Hyg.* **2004**, *1*, 613–619.
53. Ashley, K.; Applegate, G. T.; Marcy, A. D.; Drake, P. L.; Pierce, P. A.; Carabin, N.; Demange, M. *J. Environ. Monit.* **2009**, *11*, 318–325.
54. Ashley, K.; Harper, M. *J. Occup. Environ. Hyg.* **2005**, *2*, D44–D47.
55. ASTM International. *ASTM Standards on Lead Hazards Associated with Buildings*; ASTM International; West Conshohocken, PA, 1998.
56. ASTM International. *ASTM D7202, Standard Test Method for the Determination of Beryllium in the Workplace using Field-based Extraction and Fluorescence Detection*; ASTM International; West Conshohocken, PA, 2006.
57. ASTM International. *ASTM D7035, Standard Test Method for the Determination of Metals and Metalloids in Workplace Air by Inductively Coupled Plasma Atomic Emission Spectrometry*; ASTM International; West Conshohocken, PA, 2004.
58. ASTM International. *ASTM D7144, Standard Practice for Collection of Surface Dust by Micro-vacuum Sampling for Subsequent Metals Determination*; ASTM International; West Conshohocken, PA, 2005.
59. ASTM International. *ASTM D6966, Standard Practice for Wipe Sampling of Surfaces for Subsequent Determination of Metals*; ASTM International; West Conshohocken, PA, 2003.
60. ASTM International. *ASTM E1979, Standard Practice for Ultrasonic Extraction of Paint, Dust, Soil, and Airborne Particles for Subsequent Determination of Lead*; ASTM International; West Conshohocken, PA, 2003.
61. ASTM International. *ASTM E2051, Standard Practice for the Determination of Lead in Paint, Settled Dust, Soil, and Air Particles by Field-Portable Electroanalysis*; ASTM International; West Conshohocken, PA, 2001.
62. ASTM International. *ASTM E1644, Standard Practice for Hot Plate Digestion of Dust Wipe Samples for the Determination of Lead*; ASTM International; West Conshohocken, PA, 2004.
63. ASTM International. *ASTM E1775, Standard Guide for Evaluating the Performance of On-Site Extraction and Electrochemical or Spectrophotometric Determination of Lead*; ASTM International; West Conshohocken, PA, 2007.
64. ASTM International. *ASTM E1792, Standard Specification for Wipe Sampling Materials for Lead in Surface Dust*; ASTM International; West Conshohocken, PA, 2003.
65. Lawryk, N. J.; Ashley, K.; Drake, P. L. *Synergist*, **2005**, *16*(5), 54–61.