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CHAPTER 1

Overview of Beryllium Sampling and Analysis^{*,‡}

Occupational Hygiene and Environmental Applications

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Abstract

Because of its unique properties as a lightweight metal with high tensile strength, beryllium is widely used in applications including cell phones, golf clubs, aerospace, and nuclear weapons. Beryllium is also encountered in industries such as aluminium manufacturing, and in environmental remediation projects. Workplace exposure to beryllium particulates is a growing concern, as exposure to minute quantities of anthropogenic forms of beryllium may lead to sensitization and to chronic beryllium disease, which can be fatal and for which no cure is currently known. Furthermore, there is no known

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exposure-response relationship with which to establish a “safe” maximum level of beryllium exposure. As a result, the current trend is toward ever lower occupational exposure limits, which in turn make exposure assessment, both in terms of sampling and analysis, more challenging. The problems are exacerbated by difficulties in sample preparation for refractory forms of beryllium, such as beryllium oxide, and by indications that some beryllium forms may be more toxic than others. This chapter provides an overview of sources and uses of beryllium, health risks, and occupational exposure limits. It also provides a general overview of sampling, analysis, and data evaluation issues that will be explored in greater depth in the remaining chapters. The goal of this book is to provide a comprehensive resource to aid personnel in a wide variety of disciplines in selecting sampling and analysis methods that will facilitate informed decision-making in workplace and environmental settings.

1.1 Introduction

Control of occupational exposure in the workplace, characterization of environments or legacy areas, and management of environmental or workplace remediation projects, all require careful planning and execution, including development of appropriate sampling plans, up-front understanding of laboratory capabilities, and proper evaluation of analytical data. This involves a number of disciplines, including industrial hygienists, laboratory personnel, statisticians, and line management. Even before a sampling plan is developed, additional disciplines such as medicine, immunology, toxicology, and epidemiology, are involved to tell us the health risks of the material we are trying to control. Additional disciplines, such as engineering, assist us with implementing the full hierarchy of controls,¹ of which sampling and analysis are a part, to minimize exposure to toxic substances in workplace and environmental settings. All of these disciplines must work closely together, beginning with the design phases of a project or facility, through the end of a project’s lifecycle, to ensure an outcome that protects workers but also avoids unnecessary costs to the project.

Perhaps nowhere is this more true than with beryllium. Because beryllium exposure must be managed at ultra-trace levels (with the trend being toward even lower levels), the sampling and analytical challenges associated with measuring beryllium are greater than for most other metal or metalloid particulates. This includes workplaces actively using beryllium, legacy areas where beryllium was used in the past, and environmental remediation projects. New facilities where beryllium will be used also need to be designed not only with appropriate engineering controls, but also with consideration of beryllium sampling and analytical requirements.

This book provides information on sampling and analysis techniques that have been developed to ensure that beryllium particulate (whether in natural or anthropogenic forms) can be effectively sampled and analyzed, and the resulting data properly evaluated for sound decision-making in workplace and environmental settings. This book is not intended to provide detailed medical

or toxicological information, nor does it discuss engineering controls. It is focused primarily on the sampling and analytical state-of-the-art.

This chapter provides background information on beryllium sources, uses, health risks, and exposure limits. It then provides an overview of sampling and analysis issues to set the stage for the detailed discussion of these issues and techniques in the chapters to follow.

1.2 Goals of this Book

The primary goal of this book is to be a resource that can be used by all of the disciplines involved in beryllium health and safety management, to enable the best possible sampling and analytical decision-making so that workers are better protected from the risks of beryllium in the workplace. Its primary users would include industrial hygiene practitioners, analytical laboratory personnel, statisticians, and managers of projects or processes that either utilize beryllium or characterize beryllium in legacy or environmental settings. This book should help such users understand current capabilities and limitations in beryllium sampling and analysis, both in their own disciplines and in the others, and the need for good communication with other disciplines to assure success. It is also hoped that this book will be useful in academic, research and development settings to encourage additional research to address the many limitations in our current understanding and capabilities.

It is not the intention of this book to tell users to sample or analyze by some prescribed method(s). There is no “one size fits all” approach to beryllium sampling and analysis, but it is important that selected methods be fit for purpose and be defensible (as applicable) to customers, regulators, accrediting agencies, managers, and perhaps most importantly, to workers whose beryllium exposures are being characterized and managed.

1.3 Background

Beryllium (atomic number 4) is a lightweight metal (density 1.85) with a high melting point (1287 °C), stiffness (Young’s modulus 287 GPa) and thermal conductivity ($190 \text{ W m}^{-1} \text{ K}^{-1}$).^{2,3} These properties make beryllium a highly desirable component for a wide variety of applications.

1.3.1 Beryllium Sources

Beryllium occurs naturally in some 30 different mineral species.³ In the Earth’s crust, beryllium content is estimated at 2–5 parts per million (ppm) overall, with specific rocks having up to 15 ppm.⁴ For the extraction of elemental beryllium, the species of importance are the beryllium alumino-silicate mineral beryl ($\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$) and the beryllium silicate hydroxide mineral bertrandite [$\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$], with bertrandite as the principal mineral mined in the United States, and beryl the principal mineral in other countries.⁴ Beryl is roasted with

Table 1.1 Beryllium content in various substances⁴

<i>Substance</i>	<i>Beryllium Content</i>
Coal	1.8–2.2 E + 06 $\mu\text{g kg}^{-1}$
Coal ash	4.6 E + 07 $\mu\text{g kg}^{-1}$
Stack emissions from coal-fired power plants	0.8 $\mu\text{g m}^{-3}$
Cigarettes	ND–0.74 μg per cigarette
Fertilizers	< 200–13 500 $\mu\text{g kg}^{-1}$
US drinking water	0.5 $\mu\text{g L}^{-1}$
Air (US average)	< 3 E-05 $\mu\text{g m}^{-3}$
Kidney beans	2200 $\mu\text{g kg}^{-1}$
Crisp bread	112 $\mu\text{g kg}^{-1}$
Garden peas	109 $\mu\text{g kg}^{-1}$

sodium hexafluorosilicate to form beryllium fluoride, which is water-soluble. From the fluoride, beryllium may be precipitated as beryllium hydroxide by adjusting the pH to 12, or may be obtained by reduction of the fluoride with magnesium.² For bertrandite, the ore is leached with sulfuric acid; solvent extraction of the sulfate solutions ultimately produces beryllium hydroxide.⁵ In 2007, active mine production was principally in the United States, China, and Mozambique, with minor amounts elsewhere.⁶

Beryllium also is found in bauxite ore used in the manufacture of aluminium. The amount of beryllium varies with the source of the bauxite. While bauxite is not a beryllium source for production purposes, aluminium smelter workers can be exposed to beryllium in pot emissions.^{7,8} Table 1.1 contains additional data on beryllium in a variety of materials based on information from the US Agency for Toxic Substances and Disease Registry (ATSDR).⁹

1.3.2 Beryllium Uses

1.3.2.1 Beryllium metal

Beryllium metal is used in nuclear weapons, aircraft brake parts, spacecraft structures, navigation systems, X-ray windows, mirrors, and audio components.⁹ The metal is also a neutron reflector used in nuclear reactors.

1.3.2.2 Beryllium alloys

Beryllium alloys represent the largest use of beryllium. Copper–beryllium alloys typically have 0.15–2.0% beryllium content,⁵ and are widely used because they exhibit good conductivity, are resistant to corrosion, have high hardness, and are non-magnetic. Copper–beryllium alloys are used for applications such as coaxial connectors in cell phones, computers, aircraft bushings, non-sparking tools, automotive switches and sensors, and plastic injection molds.^{5,9} Aluminium–beryllium alloys, such as Brush-Wellman's AlBeMet[®], are used as optical substrates for night vision systems and avionics applications.¹⁰ Nickel–

beryllium alloys have good spring characteristics and are used in applications such as thermostats and bellows.¹¹

1.3.2.3 Beryllium oxide

Beryllium oxide is used in a variety of ceramics applications such as medical laser bores, integrated circuits, electronic heat sinks and insulators, microwave oven components, gyroscopes, and thermocouple tubing.⁹

1.3.3 Health Risks

The most noticeable adverse health effects from beryllium exposure are those affecting the respiratory system; however, effects on the lymph nodes, skin, and other target organs have been documented.¹²

Acute beryllium disease is an inflammation of the entire respiratory tract caused by exposure to high levels of soluble beryllium.⁹ Symptoms may range from mild nasopharyngitis to severe pneumonitis, which could be fatal. These effects were reported in the US in the 1940s.^{13,14} All cases in the 1948 study¹³ involved exposures greater than 0.1 mg m^{-3} . Imposition of exposure limits after 1950 all but eliminated acute beryllium disease.

At significantly lower levels, exposure to airborne beryllium particulate can cause an immune system response known as *beryllium sensitization* (BeS).¹² Estimates of BeS range from 0.9% to 21.4% of those exposed,¹⁵ with some industrial processes having a higher prevalence of BeS than others. There is no established dose–response relationship, but BeS has been attributed in some studies to exposures below $0.2 \text{ } \mu\text{g m}^{-3}$ (mean daily lifetime weighted average).^{16–18} Studies are ongoing as to the mechanism by which sensitization occurs, but genetic susceptibility is believed to be a factor.^{18,19}

Sensitized individuals may go on to develop *chronic beryllium disease* (CBD), a debilitating and potentially fatal lung disease characterized by lesions in the lung known as granulomas.²⁰ Because the mechanism of progression from exposure to BeS to CBD is not well understood, it is possible that once an individual is sensitized, a risk of developing CBD exists even if there is no further exposure to beryllium.²⁰ Also, recent studies suggest that dermal exposure, in addition to causing contact dermatitis in some workers,^{15,21} may also be a pathway to BeS,^{22,23} although CBD appears to require some pulmonary exposure.¹² Controlling workplace exposures to prevent BeS and/or CBD is the primary driver for the sampling and analysis activities described in this book.

Thus far, cases of CBD have involved exposure to anthropogenic forms of beryllium, *i.e.* metal, alloy, or oxide. Exposure to natural forms of beryllium (beryl or bertrandite) has not been shown to result in CBD, although BeS has been reported from such exposure.¹²

Additionally, the International Agency for Research on Cancer (IARC) has determined that there is sufficient evidence that beryllium and compounds are

human carcinogens.²⁴ The US National Toxicology Program has reached a similar conclusion.²⁵ Alternative conclusions have been presented in the literature, and discussion of the differing positions was ongoing at the time of writing.^{26–29}

1.3.4 Occupational Exposure Limits

In the US, initial exposure limits were established based on studies in the late 1940s by the Atomic Energy Commission.³⁰ By this point, the existence of CBD and the need to protect against it, as well as acute beryllium disease, had been established. Additionally, instances of CBD were reported among residents near the beryllium plant in Lorain, Ohio. The initial proposal was for a peak exposure limit of $25 \mu\text{g m}^{-3}$, intended as protection against acute disease. Next, an ambient air limit of $0.01 \mu\text{g m}^{-3}$ was adopted for community protection. Finally, a limit value of $2 \mu\text{g m}^{-3}$ was proposed as an eight-hour time-weighted average to protect against CBD. This proposal was based on an extrapolation of the prevailing limit value for heavy metals such as arsenic and lead, accounting for the lower atomic weight of beryllium.

Within the US, two of the three original limits remain in place at the time of writing. The limit value of $2 \mu\text{g m}^{-3}$ (eight hour time-weighted average) remains in place as the threshold limit value (TLV[®]) of the American Conference of Governmental Industrial Hygienists (ACGIH[®])³¹ and it is also the permissible exposure limit (PEL) of the US Occupational Safety and Health Administration (OSHA).³² This limit value is also in use in many other countries. The ambient air quality standard of $0.01 \mu\text{g m}^{-3}$ also remains.³³ In 1997, ACGIH[®] adopted a short-term exposure limit (STEL) of $10 \mu\text{g m}^{-3}$; ³¹ at the US national level, that is the only change from the original standards. Additional discussion on limit values in air can be found in Chapter 2.

A number of studies have established that the current $2 \mu\text{g m}^{-3}$ limit, as well as the current STEL, are not adequately protective.^{16–18,34–35} As a result, proposals to lower these limits are currently pending. ACGIH[®] has issued notices of intended change several times (1999, 2005, 2006, and 2007), including the most recent proposal for a TLV[®] of $0.05 \mu\text{g m}^{-3}$ and a STEL of $0.2 \mu\text{g m}^{-3}$.³⁶ None of these has been adopted, but the 2007 proposals remained pending at the time of writing. OSHA has also begun the process to lower its PEL, possibly to as low as $0.1 \mu\text{g m}^{-3}$.³⁷ A listing of occupational exposure limits for selected countries is provided in Table 1.2.

1.3.5 Impact of US Department of Energy Regulation

In 1999, the US Department of Energy (DOE) promulgated a regulation known formally as the Chronic Beryllium Disease Prevention Program (informally the Beryllium Rule),³⁸ which established three action levels for

Table 1.2 International occupational exposure limits for beryllium and compounds⁴⁰

Country	Limit Value ($\mu\text{g}/\text{m}$) Eight-Hour Time-Weighted Average	Short Term
Austria	2	8
Belgium	2	
Canada (Quebec)	0.15	
Denmark	1	2
France	2	
Hungary		2
Japan	2	
Poland	1 (inorganic compounds)	
Spain	2 ^a	
Sweden	2	
Switzerland	2 (inhalable aerosol)	
United Kingdom	2	
United States (OSHA) ^b	2	5

^aSpain has a separate limit for beryllium oxide (same Limit Value as above).

^bChanges to the US OSHA limits have been proposed and were pending at the time of writing.

DOE facilities:

- (a) An airborne beryllium limit of $0.2 \mu\text{g m}^{-3}$
- (b) A housekeeping limit of $3.0 \mu\text{g}$ per 100 cm^2 for surfaces within beryllium work areas
- (c) A limit of $0.2 \mu\text{g}$ per 100 cm^2 for release of equipment to the public or to “non-beryllium” work areas

All of these action levels are empirical, as DOE recognized that the existing PEL was not adequately protective and, while wanting to take some steps to improve worker protection, did not have an exposure–response relationship on which to base any action levels.

At the time of writing, there is still no exposure–response relationship. DOE did not wait for such a relationship, and its action appears to be part of a trend toward lower empirical exposure limits and action levels. As noted previously, ACGIH[®] also acted in 1999, issuing the first of several notices of intended change. The 1999 proposal was in fact for a TLV[®] at the DOE action level of $0.2 \mu\text{g m}^{-3}$,³⁶ with subsequent proposals even lower. In North America, the state of California³⁹ and the province of Quebec⁴⁰ have also lowered their workplace air exposure limits to $0.2 \mu\text{g m}^{-3}$ and $0.15 \mu\text{g m}^{-3}$, respectively. Finally, in OSHA’s report on its preliminary draft standard, options it has considered include essentially adopting the DOE Beryllium Rule.³⁷

The DOE Beryllium Rule is presently the only regulation with specific action levels for contaminated surfaces. However, others may soon follow. Studies of surface sampling have been performed in Quebec and at some US Department of Defense sites. OSHA has indicated that a surface PEL is a possible option for its new standard.³⁷ Finally, a recent US National Academy of Sciences

report commissioned by the US Air Force suggests that surface and skin contamination correlate with airborne contamination, and suggests that the Air Force perform surface sampling consistent with the DOE standard.⁴¹

Thus, it is clear that the DOE Beryllium Rule has had appreciable impact within the US, and it appears reasonable, based on studies such as Day *et al.*²³ and the National Academy of Sciences (NAS) report,⁴¹ to predict that both surface and dermal sampling for beryllium will increase, at least within the US. Even in the absence of specific numerical surface standards, some degree of surface sampling may be appropriate as part of an overall beryllium house-keeping program. Thus, the discussion in Chapter 3 of techniques for sampling and analysis of surfaces should be beneficial.

1.3.6 Environmental Beryllium and Soil Remediation

Another provision of the DOE Beryllium Rule is that, for purposes of complying with action levels, background beryllium levels from soil, if known, may be subtracted.³⁸ This has led to a need for a reliable method to measure beryllium levels in soil. In addition, environmental remediation at sites where beryllium was used in the past have included cleanup goals for beryllium, requiring the ability to measure beryllium levels in soil.⁴² A reliable method has been recently developed⁴³ and is described in Chapter 7.

1.3.7 Beryllium in Water

Sampling and analysis of beryllium in water are outside of the scope of this book. The reader is referred to published sampling and analysis methods such as those published by ASTM International,⁴⁴ the US Environmental Protection Agency (USEPA),⁴⁵ or *Standard Methods*⁴⁶ for more information. For data on levels of beryllium found in ambient water, refer to the ATSDR toxicological profile⁹ for more information.

1.4 Sampling Overview

1.4.1 Air Sampling

Workplace atmosphere sampling for beryllium has been taking place for over 60 years. The background, technical basis, and current issues associated with beryllium air sampling are described in detail in Chapter 2, although some of the key issues are given here.

First, it is often challenging to obtain a sample of sufficient air volume. It is typically necessary to sample the breathing zone of the worker, using air pumps that sample at a relatively low rate. For short-duration jobs (less than an hour), the available volume is often less than 0.1 m³. When air volume is low, analytical sensitivity must be greater to obtain a meaningful result in relation to an action level or exposure limit.

A second issue is size-selective sampling. In the US, closed face cassette (CFC) sampling is commonly used.⁴⁷ This method is ostensibly for “total” dust, although as noted in Chapter 2, larger aerosol particulate is not sampled particularly well with the CFC. Outside the US, the inhalable sampling fraction of ISO 7708⁴⁸ is more widely used. ACGIH[®], in its 2007 notice of intended change,³⁶ proposes adopting the inhalable convention for beryllium as part of a general move in that direction for its TLVs[®]. If adopted, this would require a re-evaluation of current sampling techniques for those who choose to utilize the ACGIH[®] TLV[®] and are not using an inhalable sampling method.

Finally, it is necessary to note that some beryllium particulate may deposit on interior walls of samplers. There is currently no consensus on whether such wall deposits need to be included in the sample that is analyzed by the laboratory. Subsequent chapters elaborate on this issue as well as on techniques to include wall deposits for those who choose to do so.

As noted previously, the focus of this book is on beryllium sampling and analysis in workplaces, not on environmental beryllium sampling. However, the first ambient air standard adopted in the US was in fact for beryllium.³⁰ There is, therefore, regular air monitoring across the US for beryllium. ATSDR reports the ambient levels in the US to be 0.03–0.2 ng m⁻³, with higher levels in urban areas due to the burning of coal and fuel oil.⁹ Comparable results have been obtained in studies in Germany and Japan.⁴⁹

1.4.2 Surface Sampling

Background, technical basis, and current issues associated with beryllium air sampling are described in detail in Chapter 3. Some of the key issues are given here.

Proper planning is essential for successful surface sampling. It is necessary to understand both the nature of the surfaces being sampled (for characteristics such as roughness and porosity) and the characteristics of the dust on the surface (such as oiliness and thickness of dust) to select the correct sampling technique (such as vacuum sampling or surface wiping). It is also necessary to understand the end purposes for the sampling campaign, including required data quality objectives. This information aids in selection of the appropriate number of samples and sampling points. The capabilities of the laboratory performing the analyses must be understood so that the results can be used as intended. Finally, how the data will be evaluated and communicated to the end user (discussed in Chapter 8) should be understood prior to commencing of sampling. In addition to Chapter 3, resources such as the American Industrial Hygiene Association’s *A Strategy for Assessing and Managing Occupational Exposures*⁵⁰ are useful for planning. While these criteria are also useful for planning air sampling campaigns, they are of particular importance for surface sampling.

Collection efficiency of surface wipes is another important factor. For beryllium surface wiping, there is limited information available in the published literature; one of the few published studies was by Dufay and Archuleta.⁵¹ The prevailing view is that wetted wipes have better collection efficiency than dry wipes, though

some unpublished studies have questioned that view. A DOE study showed that selection of wetting agent is important (*e.g.* alcohol-wetted wipes may be better for oily surfaces than water-wetted wipes).⁵² Also, some surfaces may be damaged by wet wiping; for these, dry wiping may be the best method available.

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Finally the ability of the laboratory to handle the surface wiping matrix should be verified before collecting samples using that matrix. Additional details on effective sample preparation techniques can be found in Chapter 4.

1.4.3 Dermal and Soil Sampling

As noted previously, dermal exposure to beryllium has been recently identified as a potential route to BeS,^{22,23} and some studies have suggested a correlation between dermal exposure and airborne beryllium levels.⁴¹ The European Committee for Standardization (CEN) has issued a report and a technical specification on dermal sampling.^{53,54} The CEN technical standard describes generic techniques for dermal sampling; however, specific methods for beryllium are not currently available. Task groups have been formed within ASTM International and the International Standards Organization (ISO) to develop dermal sampling methods for beryllium and other contaminants.

Detailed information on soil sampling is outside of the scope of this book. The user is referred to standard methods such as those issued by ASTM International⁵⁵ for soil sampling guidance.

1.5 Analysis Overview

1.5.1 Summary of Current Techniques

Analytical techniques commonly used in the US and Europe include inductively coupled plasma atomic emission spectroscopy (ICP-AES), inductively coupled plasma mass spectroscopy (ICP-MS), and atomic absorption spectroscopy (AAS).⁵⁶ Additionally, a molecular fluorescence method for beryllium has been recently developed in the US and has demonstrated sensitivity comparable to ICP-MS. These techniques are described in Chapters 6 and 7.

A variety of alternative techniques have been attempted. These include laser-induced breakdown spectroscopy (LIBS),⁵⁷ microwave-induced plasma spectroscopy (MIPS),^{58,59} aerosol time-of-flight mass spectroscopy (TOFMS),⁶⁰ and surface-enhanced Raman spectroscopy.⁶¹ In general, these techniques require significantly less sample preparation than those described in Chapters 6 and 7. However, due to issues with lack of precision at lower analyte levels and with ability to process surface wipes, these methods have not gained wide acceptance.

1.5.2 Sample Preparation

A key consideration in effective analysis of beryllium at trace levels is sample preparation for subsequent analysis by ICP-AES, ICP-MS, AAS, or

fluorescence. Sample preparation techniques are described in Chapters 4 and 5. Since analytical techniques used for trace-level beryllium analysis require the beryllium to be in solution, it is of paramount importance that the selected sample preparation method digests or extracts all of the beryllium into the solution used for analysis. As noted in Chapter 4, a number of standard sample preparation techniques are available. A survey of 16 laboratories (primary US DOE) conducted in 2004 indicated not only that a wide variety of methods were being used, but also that most labs found it necessary to modify a “standard” method in some fashion.⁶²

Of the forms of beryllium typically encountered in workplace air and surface samples, beryllium oxide (BeO) is the most difficult to bring into solution. Issues affecting the ability of a sample preparation method to dissolve or extract BeO include particle size distribution and BeO firing temperature.^{63,64} Until recently, the lack of a BeO reference material hindered the ability to provide a definitive evaluation of digestion and extraction protocols for effectiveness with BeO.⁶⁵ In spring 2008, however, the US National Institute of Standards and Technology (NIST) released a BeO Standard Reference Material (SRM).⁶⁶ It is hoped that this material will make possible a more effective validation of beryllium sample preparation methods. It is also hoped that the BeO reference material can be used in proficiency testing programs, such as that conducted by the American Industrial Hygiene Association (AIHA), to provide a more robust test of digestion and extraction methods. The current AIHA program is based on beryllium acetate, which is water-soluble and thus easy to bring into solution. A BeO-based proficiency testing program would provide greater assurance that participating laboratories are effective in bringing the various forms of beryllium in workplace samples into solution.

Sample preparation for beryllium in soil is also described in Chapter 4. Beryllium silicates and aluminosilicates typically require a more robust preparation method than does BeO; however, these forms are not typically encountered by industrial hygiene laboratories.

1.5.3 Data Evaluation and Reporting

Another issue that has gained increased attention in recent years is that of statistical evaluation of beryllium analytical data. This is the focus of Chapter 8. In many instances, a majority of data in many datasets consist of non-detects, or values that fall below the laboratory’s reporting limit (RL). Such results are typically reported as “<RL”, often referred to as “censored data”. This form of data censoring is required by accreditation bodies such as AIHA. In these instances, proper evaluation of a dataset can be very difficult. If accredited data are not required, reporting of data below the laboratory limit, with appropriate caveats, is one option discussed in Chapter 8. This chapter also discusses issues with reporting data to downstream customers, stakeholders, and affected workers.

1.5.4 Future Analytical Challenges

As mentioned previously, the trend toward lower occupational exposure limits for beryllium will create greater challenges for sample preparation and analysis. Already, the current DOE action levels for airborne and surface contamination are pushing the limits of techniques such as ICP-AES, which is the most commonly used in US industrial hygiene laboratories. Proposals from ACGIH[®], in particular the Short Term Exposure Limit (STEL) of $0.2 \mu\text{g m}^{-3}$, may bring about requirements for sensitivity beyond the reach of ICP-AES. As an example, a 15-minute air sample using a 2 L min^{-1} personal air pump would provide 30 L, or 0.03 m^3 , of air. Multiplying the STEL by this volume results in a *de facto* sensitivity requirement of 6 ng per sample. However, it is considered good laboratory practice to have a reporting limit of one-tenth the action level, which in this case translates to 0.6 ng per sample. For soluble forms of beryllium, requiring only small amounts of solution, analysis at these levels by ICP-AES has been reported,⁶⁷ but for non-soluble forms of beryllium, analysis at these levels is likely beyond the reach of ICP-AES due to the higher dilution factors required.

An additional challenge is the need for faster analysis, preferably in or near real time, while retaining excellent sensitivity. Most laboratories can analyze “rush samples” within a few hours; however, for routine samples, a time of 24 hours or longer is more typical. This lag time is driven by competition from other samples and, in many cases, by the sheer volume of beryllium samples, which for some labs is in the tens of thousands per year.⁶² Radiologically contaminated samples, which represented 19% of the total in the 2004 survey, take longer and are more expensive. The expense (millions of US dollars for DOE alone) is another reason why real-time, or near real-time, beryllium monitoring would be desirable.

In the first few years following implementation of the DOE Beryllium Rule,³⁸ several attempts were made, focusing on direct-solids measurement techniques that did not require solubilization of the beryllium and thus could be expected to provide faster results and could be deployed closer to field locations. However, when these initial efforts were not successful, it became evident that more costly and time-consuming research and development would be necessary to develop suitable (near) real-time monitoring equipment. To date, this level of resource commitment has not been available. Optimization of existing sampling and analysis methods seems the principal path in the near term for improving our existing capabilities.

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