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Characteristics of Beryllium Oxide and Beryllium Metal Powders for Use as Reference Materials

ABSTRACT: Laboratory evaluations of commercially available powders of beryllium oxide (BeO) and beryllium metal, with special emphasis on type UOX-125 BeO and type I-400 beryllium metal, are ongoing to develop reference materials for evaluating analytical chemistry digestion methods and facilitating occupational health studies. Measured properties of the powders include morphology, size, density, specific surface area (SSA); crystalline and elemental composition; surface chemistry, and *in vitro* dissolution in hydrochloric acid (HCl) (pH 1), phagolysosomal simulant fluid (PSF) (pH 4.5), and serum ultrafiltrate (pH 7.3). The powders were also used to evaluate the digestion and recovery efficiencies for commonly used U.S. Environmental Protection Agency (EPA), National Institute for Occupational Safety and Health (NIOSH), and Occupational Safety and Health Administration (OSHA) standard analytical methods. UOX-125 BeO powder has high-purity and aggregate cluster morphology with SSA independent of aerodynamic particle cluster size, which results in dissolution kinetics that are independent of cluster size. I-400 beryllium metal powder has high-purity and compact particle morphology with SSA that increases as particle size decreases, which causes size-dependent dissolution kinetics (i.e., smaller particles dissolve more quickly than larger particles). The PSF and HCl chemical dissolution rate constants ($g \cdot cm^{-2} \cdot day^{-1}$) for the BeO powder were a factor of 10 lower than for the metal powder. Concomitantly, the EPA and NIOSH analytical methods, which used aggressive digestion procedures (e.g., microwave-assisted sample digestion or perchloric acid), gave more complete recovery of beryllium from BeO compared to the OSHA analytical method. Our characterization data suggest that these BeO and metal powders hold promise for use as analytical reference materials. We recommend continued laboratory collaborations to evaluate and apply these BeO and beryllium metal powders as analytical reference materials.

KEYWORDS: beryllium oxide, beryllium metal, reference material, digestion, particle

Introduction

Exposure to beryllium particles is associated with development of chronic beryllium disease (CBD) [1–4], a progressive lung disease characterized by non-caseating granulomas and fibrosis that occurs in individuals who are sensitized to beryllium [5]. The National Institute for Occupational Safety and Health (NIOSH) has estimated that as many or more than 130 000 workers in the United States are potentially exposed to beryllium under a wide variety of circumstances [6], making determination of beryllium levels in the environment of significant interest to the public health community.

Methods for quantifying levels of elements in environmental samples can be divided into two sequential steps: sample preparation (digestion) and sample analysis (determination of elemental mass). During sample preparation, an environmental sample and its associated matrix are digested to ensure the analyte is completely dissolved prior to analysis. For particulate samples,

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if a fraction of the analyte remains in undissolved particulate form after digestion, underestimation of mass will occur during analysis. If a digestion procedure is not sufficient to completely solubilize all forms and sizes of particles in a sample, the analytical method will fail to measure the elemental mass contribution of the incompletely dissolved particles. In the case of poorly soluble metals, complete digestion of all particulate to their dissolved form during sample preparation is therefore necessary to yield accurate and precise determinations of elemental mass levels in samples.

Quantitative analytical methods for beryllium are validated using standard reference materials containing beryllium. Existing beryllium standard reference materials are prepared using beryllium acetate, a soluble and easily digested compound that is either analyzed directly or applied to a sampling substrate such as a paper or membrane cellulose filter. In contrast, particulate beryllium in the form of beryllium oxide (BeO) and metal is poorly soluble [7–9] and can therefore be more difficult to digest completely. This difference in dissolvability is not assessed by the existing soluble beryllium standard reference material. As illustrated in the work reported here, recovery of beryllium from samples that contain particulate BeO and metal may not be fully known for methods that rely on the existing, soluble beryllium standard reference material to assess method recovery. Therefore, particulate beryllium reference materials are needed to supplement validation of a beryllium analytical method.

Currently, there is no standard reference material of high-purity particulate beryllium in any chemical form. Achieving and maintaining proficiency for analysis of all forms of beryllium material will require a suite of beryllium standard reference materials ranging from solutions to insoluble particulate forms. The existing beryllium acetate standard reference material could be used to evaluate instrument analysis accuracy (without concerns for digestion efficiency errors), and new particulate beryllium standard reference materials could be used to evaluate digestion and instrument analysis accuracy. The availability of BeO and metal powder reference materials in a range of particle sizes representative of what is encountered in the workplace, as powder or suspended in an appropriate matrix, would also permit industrial hygienists and chemists to assess the accuracy of beryllium analytical method and laboratory procedures by preparing and submitting spike samples blind with their environmental samples. Well-characterized and readily available reference materials of beryllium powders, having a range of particle sizes of concern for adverse health effects, could also be used to study the influences of beryllium physicochemical form and to eliminate material properties as a source of variability in inhalation toxicology, dermal exposure investigations, molecular biology, and immunology studies.

The purpose of this paper is to report our efforts to improve the scientific basis for quantification of beryllium in environmental samples and beryllium occupational health studies by conducting laboratory evaluations of commercially available powders of BeO and beryllium metal as reference materials, with special emphasis on type UOX-125 BeO and type I-400 beryllium metal powders (Brush Wellman Inc., Elmore, OH) that have been aerodynamically size-separated in the laboratory. Results from our characterization of these bulk powders, and aerodynamically size-separated subsets of these powders, suggest that these BeO and metal powders hold promise for use as analytical reference materials.

Materials and Methods

Size Separation of Beryllium Powders

Bulk samples of BeO (product type UOX-125) and beryllium metal (product type I-400) powder were obtained from Brush Wellman Inc. (Elmore, OH). Note that numerical designations refer to mesh sizes of screens through which powders were sieved by the manufacturer. These powders were chosen for study because they are primary feed materials for manufacturing beryllium metal and oxide ceramic parts, and CBD has been found in workers who form or machine these parts [10–12].

Details of the aerosol generation and aerodynamic size separation procedure for the powders have been described [13–15]. Briefly, bulk powders were aerosolized using a dry powder blower (Model 175, DeVilbiss, Somerset, PA) and the aerosol aerodynamically size-separated using a 5-stage aerosol cyclone [16] operated at 24 L min^{-1} and 20ºC, followed by an electrostatic precipitator (ESP) (Mine Safety Appliances, Pittsburgh, PA). The aerodynamic cutoff diameters for the 5-stage aerosol cyclone and ESP used to size-separate the beryllium aerosols were >6, 2.5, 1.7, 0.9, 0.4, and ≤0.4 μm for stages 1 to 5 and the ESP, respectively.

Particle Physicochemical Characterization Techniques

A suite of analytical techniques was used to characterize physicochemical properties of the BeO and metal powders [9,14,15] (Table 1). Transmission electron microscopy (TEM) (Model CM30, Philips Electron Optics, Eindhoven, Netherlands) was used to assess particle morphology and size from samples prepared on 300-mesh copper grids coated with a lacey carbon substrate (Ted Pella Inc., Redding, CA). Nitrogen gas adsorption (Monosorb Model MS-16 Automated Direct-Reading Surface Area Analyzer, Quantachrome Corp., Syossett, NY) was used to determine powder specific surface area (SSA).

TABLE 1—*Beryllium powder characterization techniques.*

Technique[A]	Objective	Comments	Mass[B]
TEM	Morphology, size	Properties of individual or multiple particles	pg
Gas adsorption	Surface area	Total surface area of particle sample by gas adsorption	mg
XRD	Crystalline composition	Bulk analysis of constituents at 1 % or more by weight	mg
TEM-SAD	Crystalline composition	Properties from a selected viewing area; typically multiple particles	ng
TEM-μD	Crystalline composition	Properties of individual particles	pg
TEM-EDS	Elemental composition	Elements from C to U in a selected viewing area; typically multiple particles	ng
TEM-EELS	Elemental composition	Properties of individual particles	pg
XPS	Elemental composition	Surface analysis of chemical composition	mg
Pycnometry	Density	Density size by gas adsorption or gradient ultracentrifugation	mg
NAA	Oxide surface layer	Estimated thickness of the BeO surface layer on metal particles	mg
In vitro	Solubility	Quantification of chemical dissolution rate constant	mg

[A] TEM = Transmission electron microscopy.
XRD = X-ray diffraction.
TEM-SAD = Transmission electron microscopy-selected area electron diffraction.
TEM-μD = Transmission electron microscopy-micro electron diffraction.
TEM-EDS = Transmission electron microscopy-energy dispersive spectrometry.
TEM-EELS = Transmission electron microscopy-electron energy loss spectrometry.
XPS = X-ray photoelectron spectroscopy.
NAA = Neutron activation analysis.

[B] Mass indicates approximate amount required for an individual analysis.

X-ray diffraction (XRD) (Model XDS2000 powder diffractometer, Scintag, Inc., Sunnyvale, CA), TEM-selected area electron diffraction (TEM-SAD) (Philips Electron Optics), and TEM-microelectron diffraction (TEM-μD) (Philips Electron Optics) were used to qualitatively identity crystalline chemical constituents of samples. Note that XRD and TEM-SAD were used to determine constituents on powder samples and subsets of powder samples, whereas TEM-μD was used to determine constituents of individual particles. TEM-SAD and TEM-μD analyses were performed using the same grid samples prepared for TEM morphology and size analyses.

TEM-energy dispersive x-ray spectrometry (TEM-EDS) (germanium detector, Princeton Gamma-Tech, Princeton, NJ), TEM-electron energy loss spectrometry (TEM-EELS) (Model 766 DigiPEELS, Gatan, Pleasanton, CA), and x-ray photoelectron spectroscopy (XPS) (Model PHI 5600, Perkin-Elmer Corp., Eden Prairie, MN) were used to qualitatively identify elemental constituents of powder samples. TEM-EDS and TEM-EELS analyses were performed using the same grid samples prepared for the previously described TEM analyses. Note that elemental beryllium (atomic number 4) could not be detected using our TEM-EDS system, but elements in the sample having an atomic number greater than carbon (atomic number 6) could be identified. XPS is a surface technique that was used to determine the chemical composition and relative percent abundance of elements on the outer 50 to 75 Å-thick surface layer of powder sample subsets. The presence and estimated thickness of an oxide layer on the surface of I-400 beryllium metal particles, as a function of particle size, was previously evaluated by a combination of density measurements (gas pycnometry and gradient ultracentrifugation), SSA determinations, and oxygen-content determination by neutron activation analysis (NAA) [13].

Values of the chemical dissolution rate constant (k) for the powders were assessed *in vitro* using a static dissolution technique [17]. Rates of BeO and metal powder dissolution were previously determined in a range of solvents at 37°C, including 0.1 N hydrochloric acid (pH 1), phagolysosomal simulant fluid (pH 4.5), and serum ultrafiltrate (pH 7.3) [7–9].

Mercer Dissolution Theory

The dissolution theory of Mercer [18] was used to evaluate the comparative solubility and particle dissolution lifetimes of the BeO and metal powders. From Mercer's dissolution theory, the initial fractional dissolution rate at which a single particle suspended in a liquid medium dissolves is:

$$\left.\frac{df}{dt}\right]_{t=0} = -k\frac{6}{\rho D_0} \tag{1}$$

where, k = chemical dissolution rate constant $\left[\frac{\text{mass}}{\text{area} \cdot \text{time}}\right]$

ρ = particle density

D_0 = initial particle diameter

It follows that a particle is completely dissolved when:

$$t = \frac{3\alpha_v \rho D_0}{\alpha_s k} \tag{2}$$

where, t = time

α_v = volume shape factor, *e.g.* $\frac{\pi}{6}$ for a sphere

α_s = surface shape factor, *e.g.* π for a sphere

Evaluation of Digestion and Recovery Efficiencies of Commonly Used Analytical Methods

The BeO and metal powders were used to evaluate the recovery of beryllium digested by several standard analytical methods:

- U.S. Environmental Protection Agency (EPA) SW-846 Method 3051: Microwave assisted acid digestion of sediments, sludges, soils and oils [19],
- U.S. Occupational Safety and Health Administration (OSHA) method 125G: Metal and metalloid particulates in workplace atmospheres [20], and
- NIOSH method 7300: Elements by ICP [21].

In addition, for comparison, an aqueous beryllium standard reference material was used to evaluate the recovery of beryllium digested by:

- EPA SW-846 Method 3015: Microwave assisted acid digestion of aqueous samples and extracts [19].

Note that all spiked samples used to evaluate the recovery of beryllium from powders digested by these standard analytical methods contained mass levels that, at a minimum, exceeded the respective method reporting limit for beryllium by a factor of two. Spike sample matrices were varied among analytical laboratories, permitting challenge with several different matrices that were representative of those commonly used during environmental monitoring.

Modified EPA Method 3051—Recovery of beryllium from BeO and metal powder digested by a modified EPA Method 3051 was performed by a commercial laboratory. Suspensions of known concentration were prepared by adding phosphate buffered saline (PBS) solution to known masses of powder in glass scintillation vials and subjecting the vials to ultrasonic sonication for 15 min. Each suspension was occasionally shaken by hand to break apart agglomerates and was shaken vigorously immediately prior to pipetting a known amount of suspension (50–850 μg BeO collected in stage 2, 3, or 4 of the aerosol cyclone, 60–2300 μg metal powder collected in stage 2, 3, or 4 of the aerosol cyclone) onto 37-mm diameter cellulose filter support pads (stock number AP10, Millipore, Bedford, MA) [8]. Each aliquot used to prepare a spike sample was drawn from the center of the suspension, and any liquid remaining on the pipette tip was removed with a lint-free wipe prior to dispensing the material. Spike samples were submitted blind to the laboratory for quantification.

Spiked filter samples were generally prepared in replicates of 3–5 at each mass level. Each spiked sample (n = 49 BeO, n = 34 metal powder) was placed in a Teflon microwave digestion vessel. Ten mL of concentrated nitric acid and 2.5 mL of concentrated hydrochloric acid were added to each sample. The vessels were sealed, heated in a microwave for 30 min, cooled, transferred to 50-mL centrifuge cones, and diluted to 50 mL with ultrapure water (ASTM Type I). All samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) (Elan 6000, Perkin Elmer, Wellesley, MA).

Modified OSHA Method 125G—Recovery of beryllium from BeO powder digested by a modified OSHA Method 125G was performed by a private laboratory. A suspension of known concentration was prepared by adding PBS to BeO powder in a glass scintillation vial and subjecting the vial to ultrasonic sonication for 15 min. The suspension was shaken vigorously by hand immediately prior to pipetting a known amount of suspension (0.05–10.0 μg bulk BeO powder) onto Whatman 41 (42.5 mm diameter) cellulose filters (catalog number 1441-042, Whatman International Ltd., Maidstone, England).

Each spiked filter sample (n = 1 at 6 different mass levels) was hot-plate digested with 1 mL 50 % sulfuric acid and 1 mL concentrated nitric acid with addition of 30 % hydrogen peroxide until a white vapor was produced. The solution was cooled, 1 mL hydrochloric acid added, and then reheated to near boiling. Next, the solution was diluted to 10 mL with ASTM Type I water (resultant matrix 10 % hydrochloric acid, 4 % sulfuric acid) and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Optima 4300DV, Perkin Elmer) at the 313.107 nm beryllium emission line.

Modified NIOSH Method 7300—Recovery of beryllium, from BeO powder digested by a modified NIOSH Method 7300, was performed by a private laboratory (different from the laboratory that performed analyses according to OSHA Method 125G). Spiked samples were prepared for the purpose of digesting and analyzing samples known to contain large quantities of organic material. Method 7300 was modified by using large quantities of acid (40 to 60 mL nitric, 5 mL perchloric acid) to fully digest thin cotton gloves (Lisle 3301, Johnson Wilshire Inc., Downey, CA) spiked with BeO. A suspension of known concentration was prepared by adding 10.2 mg bulk BeO powder to 1 L n-propanol, then subjecting to ultrasonic sonication for 30 min. To prepare a spike sample, a known volume of suspension that contained 10.2 μg BeO was pipetted onto a cotton glove. One mL aliquots of the suspension itself were also analyzed.

Each spiked cotton glove sample (n = 6) and each suspension sample (n = 5) was hot-plate digested in a beaker with 25 mL concentrated nitric acid at 100ºC for 2 h to break the integrity of the glove matrix. Two mL of perchloric acid were then added to each beaker, the beaker covered, and the sample refluxed at 150ºC for 48 h. The cover was then removed and the sample taken to dryness at the same temperature. This digestion procedure was repeated with two additional aliquots of nitric acid (5 mL) and perchloric acid (1 mL). The resultant residue was dissolved in 25 mL of 4 % nitric/1 % perchloric acid, filtered through a 0.45 μm pore size polytetrafluoroethylene filter, and analyzed by ICP-AES (Spectro EOP, Spectro Analytical Instruments, Kleve, Germany) at the 313.107 nm beryllium emission line. All sample results were background-corrected for levels of beryllium in propanol and in the cotton glove matrix.

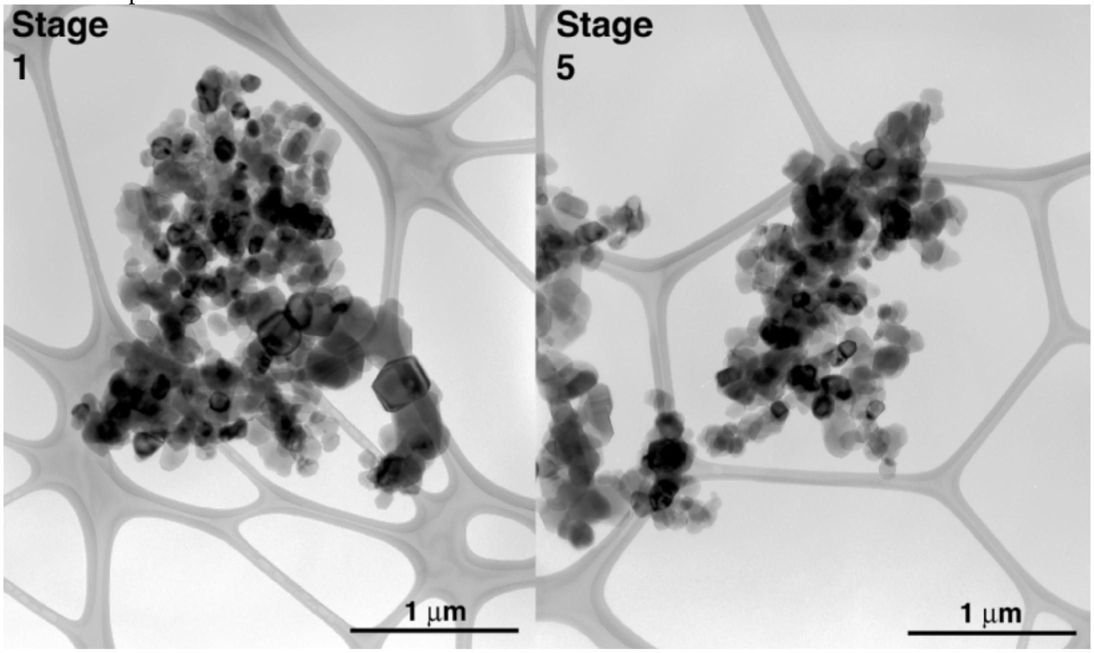
EPA Method 3015—Recovery of beryllium from the soluble beryllium standard reference material digested by EPA Method 3015 was performed by the same commercial laboratory as described for modified EPA Method 3051. Liquid spike samples (n = 77) were prepared gravimetrically (0.1 to 25 μg beryllium) from a working solution of liquid beryllium standard reference material (SRM3105a, National Institute of Standards and Technology, Gaithersburg, MD) in phagolysosomal simulant fluid [8] and submitted blind to the laboratory for quantification. For each aqueous sample, 45 mL of well-mixed sample were measured into a clean microwave vessel. Five milliliters of high-purity concentrated nitric acid were added and the vessel swirled to mix. Vessels were sealed and heated in a microwave for 30 min, cooled, transferred to 50 mL centrifuge cones, and analyzed without further dilution by ICP-MS.

Results

BeO and Beryllium Metal Properties

Morphology and size of UOX-125 BeO powder and I-400 metal powder collected in stage 1 and 5 of the aerosol cyclone are shown in Fig. 1 (note that the scale used for the BeO powder images differed from the scale used for the beryllium metal powder images, precluding direct comparison of particle size between materials). UOX-125 BeO powder had aggregate cluster morphology; the average primary particle size, 0.19 ± 0.42 µm, was independent of cluster size. Metal powder had compact morphology and size that decreased with aerodynamic cutoff diameters of the cyclone. The SSA of the BeO was independent of aerodynamic particle cluster size, but dependent upon average BeO primary particle size, while SSA of metal powder increased as aerodynamic particle size decreased (Fig. 2).

(a) UOX-125 BeO powder



(b) I-400 metal powder

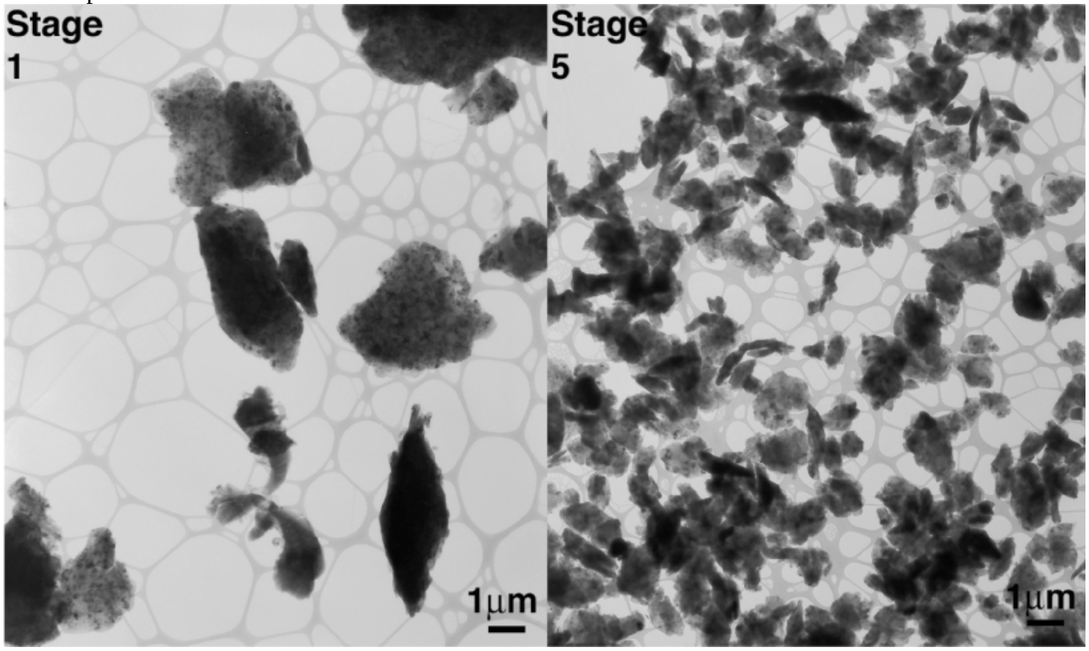


FIG. 1—*Transmission electron micrographs of (*a*) UOX-125 BeO powder and (*b*) I-400 metal powder collected in stage 1 and stage 5 of the aerosol cyclone. The micrographs illustrate that BeO consists of agglomerate clusters of uniform diameter primary particles (0.19 ± 0.42 µm), and metal powder consists of compact particles of decreasing size.*

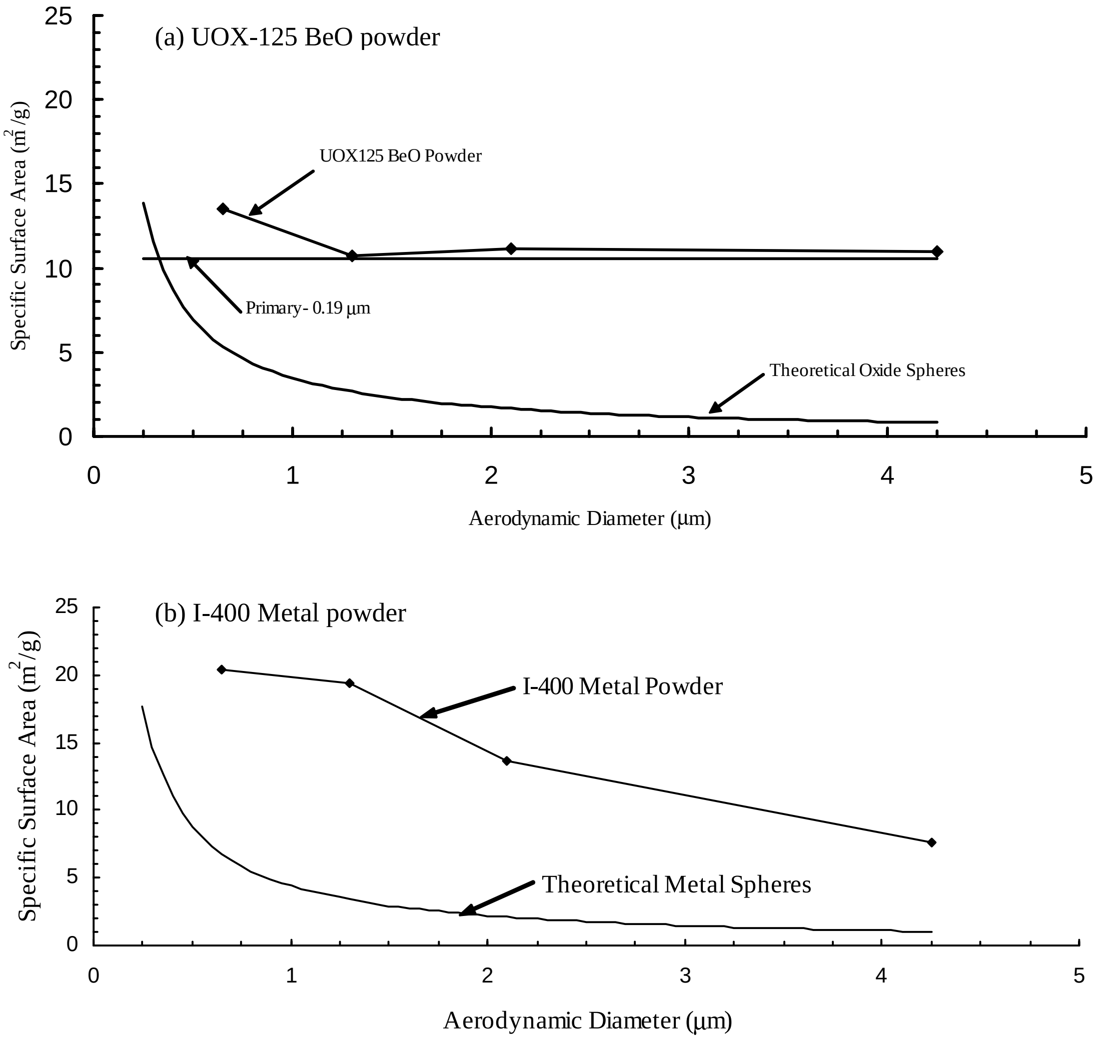


FIG. 2—*Specific surface area (SSA) of (*a*) UOX-125 BeO powder is independent of cluster size but depends on primary particle size. SSA of (*b*) I-400 metal powder is dependent on particle size.*

Analysis of crystalline composition by XRD, TEM-SAD, and TEM-μD identified only BeO in UOX-125 BeO powder and only beryllium metal in I-400 metal powder (i.e., both materials were high-purity). Analysis of elemental composition by TEM-EDS and TEM-EELS identified beryllium, oxygen, and silicon in both powders. X-ray photoelectron spectroscopy analysis identified only BeO on the surface of the BeO powder. Beryllium oxide and beryllium metal were identified on the surface of the metal powder. From the XPS data, the thickness of the BeO layer on the surface of metal powder was estimated to be 42 Å thick.

Powder Dissolution Behavior

Values of k (g•cm^{-2}•day^{-1}) determined for BeO powder and metal powder in 0.1 N hydrochloric acid, phagolysosomal simulant fluid, and serum ultrafiltrate are summarized in Table 2. The k values for BeO powder were about a factor of 10 lower than for metal powder in acidic solvents. Figure 3 is a plot of both the theoretical initial fractional particle dissolution rate and particle dissolution lifetime for compact smooth spheres of BeO powder (density 3.0 g•cm^{-3}) having initial diameters (D_0) of 0.1, 1, 10, and 100 μm and k values ranging from 10^{-10} to 10^{-1} g•cm^{-2}•day^{-1}. In accordance with Eq 1 and Eq 2, dissolution rate and dissolution lifetime are observed to vary proportionally with particle diameter.

TABLE 2—*Estimated values of k for BeO powder and metal powder in 0.1 N hydrochloric acid, phagolysosomal simulant fluid (pH 4.5), and simulated lung fluid (pH 7.3).*

Powder	Solvent[A]	pH	k, g·cm^{-2}·day^{-1}
UOX-125 BeO	HCl	1	6.1 ± 2.2 x 10^{-8}
	PSF	4.5	1.2 ± 1.4 x 10^{-8}
	SUF	7.3	3.7 ± 1.2 x 10^{-9}
I-400 metal	HCl	1	4.1 ± 0.2 x 10^{-7}
	PSF	4.5	1.1 ± 1.4 x 10^{-7}
	SUF	7.3	1.5 ± 0.8 x 10^{-9}

[A] HCl = hydrochloric acid [7].
PSF = phagolysosomal simulant fluid (model of pulmonary alveolar macrophage phagolysosome fluid) [9].
SUF = serum ultrafiltrate (model of extracellular lung fluid) [7].

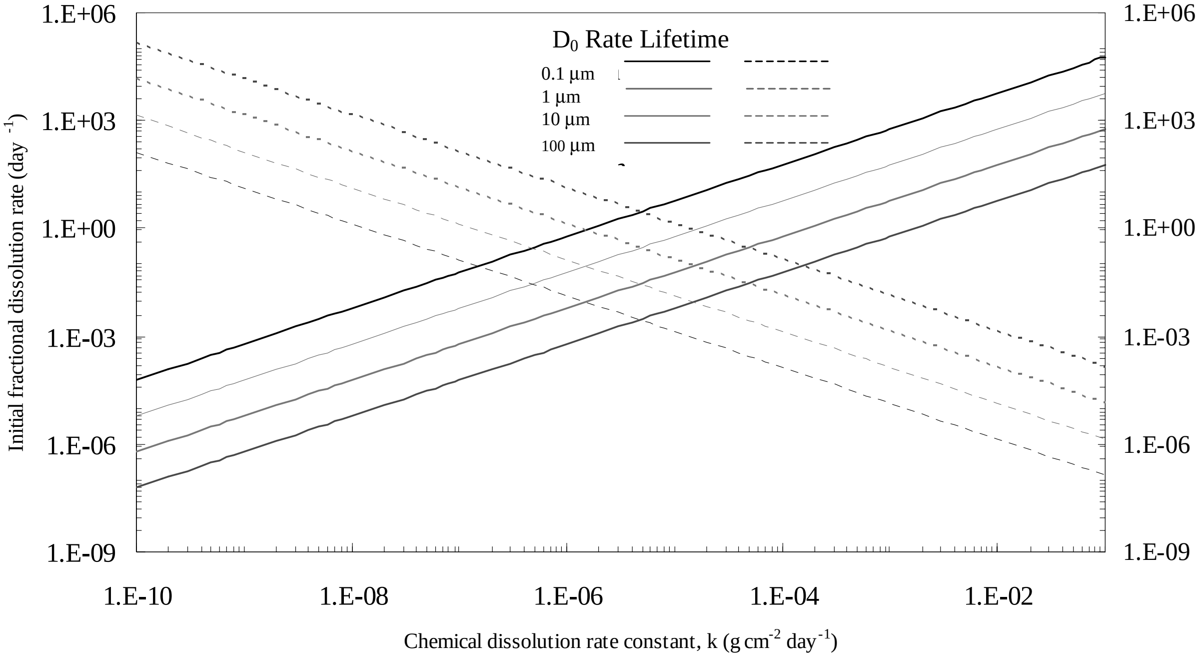


FIG. 3—*Comparison of initial fractional dissolution rates and times needed to completely dissolve BeO particles having initial particle diameters of 0.1, 1, 10, and 100 μm and chemical dissolution rate constants (k) of 10^{-10} to 10^{-1} g•cm^{-2}•day^{-1}.*

Digestion and Recovery Efficiencies

Digestion and recovery efficiencies for the beryllium powders by commonly used standard analytical methods are summarized in Table 3. Greater than 90 % of BeO was digested and recovered by EPA Method 3051 and NIOSH Method 7300. In contrast, less than 77 % of BeO was digested and recovered by OSHA Method 125G. For I-400 metal powder, 89 % (coefficient of variation, CV = 8.9 %) was digested and recovered by EPA Method 3051. Recovery of the aqueous standard reference material digested by modified EPA Method 3015 was complete (100.4 %) but tended to be more variable (CV = 14 %) than observed for powder samples.

TABLE 3—*Recovery of beryllium from UOX-125 BeO and I-400 metal powders digested and analyzed using modified versions of standard analytical methods.*

Modified Method[A]	Treatment	Powder	N	Recovery Mean (CV)[B], %
EPA 3051	Microwave	Metal	34	88.6 (8.9)[C]
EPA 3051	Microwave	BeO	49	93.7 (9.8)[C]
OSHA 125G	Hot plate	BeO	6	76.6 (5.7)[D]
NIOSH 7300	Hot plate	BeO	5	95.9 (1.0)[E]
NIOSH 7300	Hot plate	BeO	6	94.6 (0.9)[F]

[A] Standard analytical methods were modified as follows:

EPA 3051: A 4:1 concentrated HNO_3 to concentrated HCl solution, rather than 10 mL concentrated HNO_3 was used to digest the sample; sample solution was microwave-heated for 30 min, rather than 10 min.

OSHA 125G: A 2.5:1 50 % H_2SO_4 to concentrated HNO_3 solution, rather than a 1:2 ratio of these acids was used to ash the sample; the sample solution was placed on a hotplate straight away rather than let sit for 1 h at ambient temperature; and 1 mL rather than 4 mL concentrated HCl was used to reheat the sample to near boiling.

NIOSH 7300: 25 mL HNO_3, rather than 4:1 HNO_3 to $HClO_4$ solution was used to ash; the sample solution was placed on a hotplate straight away, rather than let sit at ambient temperature for 0.5 h; 2 mL $HClO_4$, rather than 4:1 HNO_3 to $HClO_4$ solution was added to the ashing solution; this solution was refluxed for 48 h, then taken to dryness; next 5:1 HNO_3 to $HClO_4$ was added to the solution and refluxed to near dryness twice more, rather than adding 4:1 HNO_3 to $HClO_4$ solution and heating repeatedly until the solution turns clear; finally, solid debris from cotton gloves were removed by filtering digestate through a 0.45 μm pore size polytetrafluoroethylene filter.

[B] CV = coefficient of variation.

[C] Powder suspended in PBS and spiked onto 37-mm diameter cellulose filter support pads.

[D] BeO powder suspended in PBS and spiked onto 42.5-mm diameter Whatman cellulose filters.

[E] BeO powder suspended in n-propanol.

[F] BeO powder suspended in n-propanol and spiked onto cotton gloves.

Discussion

Fundamental to the assessment of the performance of any analytical method is the existence of accurate standard reference materials. Standard reference materials must be: 1) independently validated, 2) representative of both the chemical form of the material in the actual samples and matrices in which that material will be found, and 3) sufficiently robust to ensure complete digestion of the most insoluble chemical form. We used a suite of analytical techniques to assess the properties of particulate BeO and beryllium metal powder materials and analyzed the same materials by spectroscopic analysis. Two forms of beryllium with toxicological significance were evaluated for a range of sample matrices, including suspension of particles in n-propanol or PBS and application to mixed cellulose ester filters or thin cotton gloves.

The UOX-125 BeO powder had aggregate cluster morphology with SSA independent of particle cluster size. In turn, dissolution kinetics of the BeO powder was independent of cluster size but dependent on primary particle size (0.19 μm) [9]. However, to fully evaluate the robustness of a digestion procedure for BeO, compact particles from machining or other comminution of sintered BeO that have a range of physical particle sizes are also needed. I-400 beryllium metal powder had compact particle morphology with SSA that increased as particle size decreased, which, as previously shown [7], caused size-dependent dissolution kinetics (i.e., smaller particles dissolved more quickly than larger particles). Note that digestion of bulk samples of metal powder may differ from that observed for the size-selective materials (<10 μm aerodynamic diameter) used in our studies. I-400 metal powder consisted of particles that had passed through a 400 mesh screen (i.e., nominal particle diameter less than 38 μm). Beryllium metal particles collected on substrate during air or swipe sampling could contain particles with diameters larger than 38 μm. In this case, a standard reference material of metal powder with particle diameter greater than 38 μm would be needed to fully evaluate the robustness of a digestion procedure. Successful digestion of metal particles of these sizes would ensure complete digestion of smaller metal particles.

Both beryllium powder materials were high purity. The estimated oxide layer thickness on the surface of metal powder (42 Å) was in excellent agreement with 52 Å that was previously determined for this same size of metal powder using NAA [13]. Note that there is a significant difference in dissolution of BeO and metal even though the metal powder had a 42 Å oxide coating (Table 2). This difference in k values has implications for complete digestion of beryllium-containing particles, which may include intentional oxides (e.g., UOX-125 BeO powder) or incidental oxides (e.g., BeO formed under ambient conditions on the surface of a beryllium material). Note that for intentional oxides, calcine (heat-treatment) temperature influences particle physicochemical properties, which in turn influences solubility [7]. Given the k values in acid solvents (Table 2), the time required to completely dissolve a particle of intentionally formed UOX-125 BeO is more than a factor of 10 longer than for the same size particle of I-400 beryllium metal that has a thin surface coating of incidental oxide (Eq 2). A given k value for digestion is related to the chemical properties of the particle, the chemical activity of the solvent, and thermal conditions of the digestion procedure. Thus, it is not just the chemical form of material and the solvent or solvent/temperature combination used in the digestion procedure that determines digestion efficiency; time is also a factor. For a given chemical activity and set of thermal conditions of a digestion procedure, the larger the particle, the longer the time needed for complete digestion. Digestion procedures used in EPA Method 3051, NIOSH Method 7300, and OSHA Method 125G may dissolve nanometer-scale beryllium-containing particles, but above a certain particle size (which is currently not known), digestion is not complete. The time required to completely dissolve the largest particle of a given chemical form within a sample (and all particles of the same chemical form of smaller sizes), under the solvent and temperature conditions of a given digestion procedure, can be estimated using Eqs 1 and 2. UOX-125 BeO particles with diameters equal to or less than 100 μm are completely dissolved in 1.2 h when $k = 10^{-1}$ $g \bullet cm^{-2} \bullet day^{-1}$. When $k = 10^{-5}$ $g \bullet cm^{-2} \bullet day^{-1}$, UOX-125 BeO particles with diameter equal to or less than 100 μm are completely dissolved in 12 000 h (Fig. 3). In general, the time needed to completely dissolve a particle of a given size and chemical form will increase by an order of magnitude for each order of magnitude lowering of k value.

The ranking of digestion efficiency for beryllium from UOX-125 BeO by method was (from highest to lowest recovery): NIOSH Method 7300 ≈ EPA Method 3051 > OSHA Method 125G. Many factors can influence the digestion efficiency of these analytical methods, including the suspension preparation technique and the selection of sample media, mass level, and digestion procedure. Variability in the chemical composition and particle size of the BeO digested can be excluded as factors to explain differences in digestion efficiency among these common analytical methods.

Suspensions analyzed by EPA Method 3051 and OSHA Method 125G were prepared by the same person in the same laboratory under similar conditions of temperature and low humidity (note that BeO and metal are not hygroscopic), and techniques for agitation of suspensions and dispensing onto sample media were, by design, very similar. PBS was used to suspend BeO for analysis by EPA Method 3051 and OSHA Method 125G, while n-propanol was used to suspend particles for analysis by NIOSH 7300. Phosphates in PBS could cause spectral interference, but similar levels of beryllium were recovered by EPA Method 3051 and NIOSH Method 7300. These data indicate that variation in suspension preparation techniques may explain a portion, but not all, of the observed difference in beryllium recovery among techniques.

Cellulose filters were used to prepare spike samples for analysis by EPA Method 3051, Whatman cellulose filters were used to prepare spike samples for analysis by OSHA Method 125G, while cotton gloves were used as the sample media to prepare spike samples for analysis by NIOSH Method 7300. Beryllium recovery from EPA Method 3051 was similar to NIOSH 7300, indicating that differences between the spike sample media probably do not fully explain the low recovery by OSHA Method 125G.

Beryllium oxide mass levels were highest on spike samples digested by EPA Method 3051 (50 to 850 μg BeO) and were similar for spike samples analyzed by NIOSH Method 7300 (10.2 μg BeO) and OSHA Method 125G (0.05 to 10.0 μg BeO). Despite the fact that BeO masses differed by up to a factor of 80 between spiked samples digested by EPA Method 3051 and NIOSH Method 7300, beryllium recovery levels were proportionally similar. The low recovery of beryllium from BeO by OSHA Method 125G cannot be explained by differences between spike sample mass levels. Note that the influence of mass level on spike sample recovery by OSHA Method 125G could be assessed by successive digestions (e.g., digestion for 10 min, 100 min, and 1000 min). Particles would be completely dissolved by the method when element level results remained unchanged between successive digestion durations.

The relatively small contributions of suspension preparation techniques, sample media, and sample mass levels to observed differences in recovery efficiencies suggest that differences in digestion procedures used by EPA Method 3051, NIOSH Method 7300, and OSHA Method 125G were important for dissolution of beryllium particles. Our data indicate that the use of perchloric acid or a microwave digestion step was needed to nearly completely dissolve 0.2-μm diameter BeO primary particles. Note that microwave digestion did not completely dissolve all sizes of metal powder in samples. With respect to UOX-125 BeO, even though a digestion procedure can completely dissolve 0.2 μm diameter BeO particles, it may not completely dissolve a larger (e.g., 1 μm) BeO particle. For larger BeO particles, a longer digestion time may be needed to completely dissolve the particles prior to measurement. Note that other digestion procedures, e.g., ASTM D 7035-04 [22] or International Standards Organization 15202-2 [23], and other digestion solvents (e.g., hydrofluoric acid) exist but were not evaluated in this study to determine if they could completely dissolve BeO and metal particles.

Beryllium samples for proficiency testing programs are often prepared using a soluble beryllium acetate standard reference material, rather than a poorly soluble particulate beryllium metal and BeO powder. Analytical laboratory methods currently considered proficient in beryllium analysis based on the results of proficiency testing using beryllium acetate may, in fact, not be completely digesting particulate BeO and metal. A test program to evaluate the robustness of the digestion method and the accuracy of the instrument analysis would include a suite of standard reference materials consisting of soluble beryllium salts and poorly soluble particulate beryllium metal and oxide in a range of particle sizes.

Implications of Lower-Than-Expected Recovery Efficiency

If beryllium recovery efficiency by an analytical method is not accurately known, routine analysis of environmental samples may be in error when estimating beryllium levels in samples.

For example, if complete recovery by a method was assumed, but actual recovery was 77 %, then the estimated beryllium levels may be lower than actual levels. Our results indicate that spike samples can be prepared from suspensions of beryllium powder in PBS or n-propanol and used for blind assessment of method digestion and recovery efficiency. Note that use of the UOX-125 BeO powder or I-400 metal powder as a reference material cannot help to speciate (identify) the chemical form(s) of beryllium that may be present in an environmental sample. Speciation can be important for discriminating forms of beryllium in the workplace and can aid in identifying sources of exposure. Speciation can also help discriminate between beryllium from naturally occurring minerals in the soil and beryllium from man-made sources. Various techniques to speciate forms and sources of beryllium have been proposed, including serial digestion [24] and elemental ratios in local soils [25,26].

Summary and Recommendations

We characterized two candidate analytical reference materials for analytical chemistry and occupational health studies: aerodynamically size-separated type UOX-125 BeO powder and type I-400 beryllium metal powder. Each high-purity material presented a unique challenge for digestion. Beryllium oxide powder has aggregate cluster morphology with SSA independent of particle cluster size, resulting in dissolution kinetics that is independent of aerodynamic cluster size. I-400 beryllium metal powder has compact particle morphology with SSA that increased as particle size decreased, resulting in size-dependent dissolution kinetics. Use of the BeO material in evaluation of the recovery efficiencies of 3 United States governmental standard analytical methods demonstrated that not all methods provide quantitative recovery for BeO particles. Perchloric acid or a microwave-assisted digestion nearly completely dissolved 0.2 μm diameter BeO primary particles. Microwave-assisted digestion did not completely dissolve all sizes of metal powder in spiked samples.

Based on the results of this study, the following recommendations are made:

- In addition to the chemical form of beryllium, a sample preparation procedure must consider the digestion solvent, solvent temperature, particle size, and time.
- Mercer single-particle dissolution theory could be used to determine the time needed to completely dissolve the largest particle in a sample (Eq 2).
- To fully evaluate the robustness of a digestion procedure, reference materials of compact particles from machining or other comminution of sintered BeO that have a range of physical particle sizes are needed, as are particles of metal powder with particle diameter greater than 38 μm.
- Upon being validated, BeO powder and metal powder standard reference materials should be incorporated into proficiency testing programs.
- Laboratory collaborations should continue to evaluate (e.g., round-robin testing) and apply these BeO and beryllium metal powders as analytical reference materials.

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