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A review of workplace aerosol sampling procedures and their relevance to the assessment of beryllium exposures†‡

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Standardized conventions governing the fractions of airborne particles that can penetrate the human head airways, the thoracic airways and the alveolar spaces have been internationally (although not universally) adopted. Several agencies involved in setting limit values for occupational exposure concentrations have taken these conventions into account when considering the appropriate standard for specific chemicals, in order to ensure the standards are biologically relevant. A convention is selected based on the characteristic health effects, and forms the basis of measurement against the limiting concentration value. In order to assess exposure for comparison to this metric or any other purposes, it is necessary to choose a sampler whose performance matches the convention, and protocols have been developed and used to test sampler performance. Several aerosol sampling devices are available, nominally at least, for each of the conventions. Some considerations important to the sampling of airborne particles containing beryllium with regard to the sampling conventions, the test protocols and sampler performance are discussed.

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‡ Disclaimer: The findings and conclusions in this report are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of sampling devices does not constitute an endorsement, and does not imply that other devices are not fit for the same purpose. Discussion of the draft ACGIH TLV documentation does not imply acceptance or endorsement by the U.S. Federal Government.

Introduction

The history of dust sampling for occupational hygienic purposes has not been well covered in recent reviews, and it is often necessary to refer back to textbooks published around the time of each technological development in order to obtain an accurate picture. The best of the modern reviews is that of Walton and Vincent, published in 1998 and based on a presentation to American Association for Aerosol Research in 1996.[1] Walton and Vincent's review summarizes the discussions over the years concerning how best to measure particles in the air, of which the most important debate has been between particle mass *vs.* number. South Africa, a country for which mine dust exposure has always been of the greatest significance, made mass measurements from about 1900. However, in the USA and the UK particle number measurements were more popular in the early days of modern occupational hygiene (konimeter, 1916; Greenburg–Smith impinger 1922; thermal precipitator, 1935).[1] Size-selection was introduced when it was recognized that fine silica particles in mines could penetrate to the alveolar region of the lung and cause fibrotic disease; the horizontal elutriator was added to the thermal precipitator used in the UK in 1954, in order to separate the numbers of fine particles from coarse.[1] In the USA, cyclones replaced impingers in the late 1960s and early 1970s, and standards changed from counts to mass. The use of personal, miniaturized cyclones was facilitated by the concurrent development of a personal sampling pump.[2] Currently, the methods used by practically all relevant agencies worldwide are mass-based and particles are collected on filters housed in filter holders, with or without a size pre-selector, and weighed or analyzed chemically to provide a result in units of airborne mass concentration. Other than for fibers which are traditionally measured as number per unit volume, the

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U.S. Occupational Safety and Health Administration (OSHA) retains today only a very few Permissible Exposure Limits, or PELs, couched in number/volume units (millions of particles per cubic foot). In the USA, probably the commonest chemical hygienic measurement taken is for "total" dust (also known as Particulates Not Otherwise Regulated (Total) [U.S. National Institute for Occupational Safety and Health, or NIOSH, by Method 0500],[3] or Particles Not Otherwise Regulated (Total) [U.S. OSHA, IMIS 9135, by partially validated method PV2121][4]). Both methods use a 37 mm poly(styrene/acrylonitrile) closed-face cassette (CFC) which holds and supports a polyvinylchloride (PVC) filter of 5 μm nominal pore size (note that the pore size is not representative of the actual ability of the membrane to filter airborne particles; depending on the manufacturer, 5 μm PVC filters can collect >99% of particles 0.3 μm aerodynamic equivalent diameter, AED[5]). In other methods specific to the analysis of metals, which require the sample to be brought into solution the PVC filter usually is replaced by a 0.8 μm pore size mixed cellulose ester (MCE) filter that can be digested in acid. PVC filters have also been used for metals, and other filters (*e.g.* Teflon®) are available for specific purposes.

The word "total" appears in the title of both NIOSH and OSHA gravimetric methods. No-one today should believe that the CFC is capable of collecting every particle present in the air pulled into the orifice, since all tests of aspiration efficiency have shown an efficiency of collection significantly less than 100% for particles larger than 20 μm AED.[6,7] The misnomer came about because industrial hygienists did not immediately recognize the significance of very large particles in the workplace or inlet effects on the sampling of large particles. Recent studies have shown the presence of large airborne particles in many workplaces, and have demonstrated their ability to travel to the worker's breathing zone.[8] The concepts relating to the size distributions of aerosols and the process of sampling have been discussed to some extent within the U.S. government agencies (*e.g.* Chapter O, Part 2 of the Chapter section of the NIOSH Manual of Analytical Methods[3]). The magnitude of the bias for the CFC increases with particle size, but the bias may be constant across similar workplaces. There would not be a problem in continuing to use the CFC in this case when exposure limit values are based on epidemiological studies whose exposure axis consists of historical results obtained with the same sampler type. Unfortunately, this is not the case for many limit values, which are instead based either on a mixture of studies using different sampler types, some of which may have an aspiration efficiency different from the CFC, or on extrapolation from animal dose–response experiments, where the dose is not commonly presented to the animal in a form fully relevant to the typical particle size distributions present in real workplace environments.

Inhalable sampling

A convention to describe the aspiration efficiency of the entry to the human airways system has been agreed internationally (ISO 7708), and is termed the inhalable (once "inspirable") convention.[9] This convention has a curve that essentially becomes flat at 50% aspiration efficiency for particles between 50 and 100 μm AED. The American Conference of Governmental Industrial Hygienists (ACGIH) recognizes this convention for substances such as those which can be absorbed anywhere within the respiratory or gastro-intestinal system and which have a systemic toxicity (*e.g.* pesticides, metals), or those which have a mode of action in the head airways (*e.g.* wood dust). According to the ACGIH, these substances should be sampled using a sampler whose performance matches the inhalable convention, as discussed in their method for Particles (Insoluble or Poorly Soluble) Not Otherwise Specified.[10] The ACGIH Threshold Limit Value Notice of Intended Change (NIC) for beryllium published in 2004 includes sampling in accordance with the inhalable convention, and this has been continued in the latest draft documentation.[11,12] The NIC is mostly founded on epidemiological data using a dose–response model based on workplace exposure measurements, but these measurements were not made with CFC samplers since their operational flow rate is too low to allow sufficient sensitivity of analysis. Instead, measurements used in setting the draft TLV were taken using high volume samplers whose size selection characteristics were considered to be "unknown". The recommendation for an inhalable particulate value was based on an assumption that these high volume samplers collected some of the larger particles that would also be collected by an inhalable dust sampler. However, this recommendation is open to re-assessment (*until more definitive data become available…*).[11] If the NIC is adopted in its current form, beryllium would join the company of other important chemicals where the ACGIH has recommended measurement of the inhalable dust fraction, including metals like nickel and molybdenum and their compounds, organic dusts such as flour and wood, many pesticides, asphalt fume (benzene-soluble), diatomaceous earth and single-filament glass fiber.[10]

Large particles do not remain suspended in air for long periods of time under normal conditions of generation and air movement. Settling rates for large particles under gravity are fast; for example, a particle of 100 μm AED has a settling rate of 26 cm s^{-1} at equilibrium, while a for a particle of 10 μm AED the settling rate is 0.3 cm s^{-1}. However, large particles can be given momentum by a high-speed generation process. The stopping distance for the same 100 μm particle given a thrust of 10 m s^{-1}, by, for example, a grinding wheel is approximately 13 cm.[13] Larger particles can travel even further, and this does not even take into account buoyancy effects of a surrounding sheath of moving air. Particles that are even larger than 100 μm AED have been shown to exist in many workplace atmospheres, and they can be projected into the workers breathing zone. The cube relationship between diameter and mass ensures that such "ultra-large" particles are a significant part of the total aerosol mass. Then the question arises as to whether these particles can be inhaled. Studies have shown that workers can inhale large particles, particularly in fast-moving air and when breathing through the mouth.[15,16]

As noted previously, in wind tunnel tests, the traditional U.S. "total" dust sampler, the CFC, has not been shown to sample all particle sizes with 100% efficiency. In addition, the same studies have shown the CFC significantly under-samples large particles in comparison to the proportion it should

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sample were it to meet the inhalable convention,[6,7] although it an important point, to be considered later, that these studies have assumed only the filter deposit to constitute the sample. In a collaborative European study,[7] and a subsequent analysis of the data, it has been possible to provide quantitative estimates of the maximum bias magnitude for several different sampler types (at the 95% confidence level) for a broad range of size distributions.[17] Sampler calibration factors were estimated for minimizing the bias extremes with AED up to 50 μm for use in wind speeds up to 1 m s^{-1}. The graphical displays of sampler performances are convenient for a quick visual comparison of samplers, so that, for example, regions where filter capture by the CFC sampler may or may not be adequate are clearly identified. One example of a sampler with identified performance in accord with the inhalable convention is the Institute of Occupational Medicine (UK), or IOM, sampler. The IOM sampler was designed *a priori* to meet the inhalable convention, and prototypes were further improved through a series of iterations comparing their performance to that of a breathing manikin in a wind-tunnel.[18] Hence, it is no surprise that the IOM sampler performed the best of all samplers tested in the European performance study.[7] The IOM sampler operates at 2 l min^{-1}, as does the CFC, and therefore suffers the same potential problem of significantly poor analytical sensitivity as the CFC for chemicals, such as beryllium, with low reference exposure limit concentrations.[19] Many studies, for example both in the laboratory[20] and in the field,[8] have shown that the IOM collects a greater mass of particulate than the CFC sampler from the same atmosphere, particularly when particles are large, and that the discrepancy increases with particle size. Based on a compilation of studies from many different industries, Werner *et al.* suggested that the results were equivalent when the particle size was small, as with welding fume.[21] However, the same analysis suggested it would be necessary to increase CFC results from hot processes such as smelting and refining in foundries by about 50% (*i.e.* ×1.5), and to increase CFC results from mechanical processing such as crushing or grinding by as much as an additional 150% (*i.e.* ×2.5), in order to match the corresponding result from an IOM sampler. Note that these values represent the aggregated results of many trials, and there are often large variations in individual pairs of sampler comparisons. It is also necessary to keep in mind that, while most of these studies have only measured material collected on the filter of the CFC (and the inner surfaces of the CFC are also sites of potential aerosol deposition), any deposits on internal surfaces of the IOM are considered an integral part of the sample and are added to the analysis. This is usually accomplished by rinsing the inner parts of the inner capsule, although there is some evidence to suggest that mechanical means such as sonication or wiping is required to remove all deposited particles from internal surfaces, at least in the case of the CFC.[22]

Wall deposition

When the performance of the CFC and IOM samplers is examined in detail, the major difference between them appears to be whether the internal catch that does not reach the filter is included in the sample. As noted above, the particulate deposited on the internal walls of the IOM sampler is considered part of the sample, but there is an ambivalence concerning the inclusion of material deposited on the internal walls of the CFC. The NIOSH Manual of Analytical Methods[3] discusses the issue in Chapter. O, part 7, but no standard method is provided, and accounting for wall deposits is not mentioned in any specific method. The main difference between the NIOSH and OSHA gravimetric methods is that the OSHA gravimetric analyses for PNOR routinely use an internal capsule within the CFC, weighed in its entirety to include wall deposits.[4] The U.S. Mines Safety and Health Administration (MSHA) uses a similar capsule for coal mine dust sampling. A similar capsule is also in use within the pharmaceutical industry in the USA for the same purpose, which is to capture the wall deposits as part of the sample.[23] OSHA metals procedures do not use the internal capsule, but some, although not all, procedures, call for a fabric material (such as a polyvinyl acetate "Ghost Wipe™" or smear tab) to be used to wipe internal surfaces, and for this wipe to be digested or extracted along with the sample filter. For example, OSHA ID 125G, a general procedure for inductively-coupled spectroscopic (ICP) analysis of metals, including beryllium, does include this procedure, but ID 206, a method specifically for beryllium, does not.[4] Certain U.S. Department of Energy facilities, such as the Lawrence Livermore National Laboratory (Procedure HCL-I-2010, R. Shah, LLNL, personal communication), include a wipe of internal deposits as part of their standard procedures for the analysis of CFC samples. A French national method calls for acid digestion within the cassette which also accounts for wall deposits.[24]

When samples taken in typical metals industries using the CFC and IOM samplers are compared on an equal basis (*i.e.* filter-only to filter-only, or total catch to total catch), there is found to be little difference between them in practice. For example, in a recent NIOSH study in the froth-flotation concentrate mill of a lead mine, where particles are likely to be coarse, both samplers had similar filter deposits and the CFC samples had a mean wall deposition of 19% of the total sample (maximum of 35%) while IOM samples had a mean wall deposition of 17% of the total sample (maximum of 30%), indicating their total catches were also similar.[25] Modeling suggests the main mechanism of deposition to the walls for coarse particles is gravitational settling through the main flow stream into areas of more turbulent flow.[26] The percentage of wall deposited sample gets lower as particle size decreases, although for the finest particles wall deposition may increase again in response to electrostatic effects.[17] However, inclusion of fine particles will not have as significant an impact on the total mass collected as would the inclusion of large particles. In the NIOSH studies mentioned above, variations in wall losses were found by industrial site, ranging from sites where the larger proportion of samples had no detectable wall deposits to sites where the wall deposits comprised as much as 70% of the total sample collected.[27] Although wall deposits were not measured for every sampler in every site in these studies, confirmation comes from similar studies that have been carried out in France, which showed that when the total catches are compared (*i.e.* using their *in situ* dissolution method), results for the CFC and IOM are

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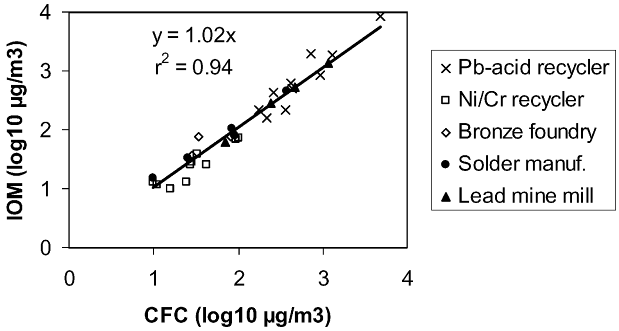

Fig. 1 Combined side-by-side lead concentration data from IOM (filter-only) and CFC (filter-only) samples from five different industrial locations (data in process of publication).

similar.[28] These observations are to some extent at odds with the results from studies used to support the Werner *et al.* conclusions,[21] many of which were in comparable industries, and which suggested a larger bias towards the IOM. If this bias was to hold true for the NIOSH studies, then given the almost perfect 1 : 1 correlation between IOM and CFC filter-only results shown in Fig. 1, more than half of the IOM sample would necessarily have to be on the walls. Such a high proportion was not seen in either the NIOSH or the French studies, and no explanation for the difference is currently available (further studies on the NIOSH samples will include SEM analyses of the filter and wall deposits).

Other issues regarding the IOM sampler

For testing samplers to the current inhalable convention, the standard protocol defines a minimum and maximum wind speed of 1 m s^{-1} and 4 m s^{-1}, respectively (based mainly on concerns of the mining industry), and any possible orientation bias is lost in a requirement for direction-averaging. The size selection characteristics of the IOM sampler are known to be dependent on wind speed and orientation, and to a greater extent than other samplers,[29] probably because of the larger inlet (13 mm *vs.* 4 mm for the CFC). The collection efficiency of the IOM at low wind speeds (*i.e.* $\ll 1$ m s^{-1}) does not match the inhalable convention well,[30] and such low wind speeds are more common than was once thought. Recently completed studies have demonstrated indoor wind speeds typically less than 0.1 m s^{-1} and only rarely do they exceed 0.3 m s^{-1}.[31] However, when the approximately 0.05 m s^{-1} worker motion is included, 95% of wind speeds range between 0.1 m s^{-1} and 0.4 m s^{-1}, and this is higher than the recent calm air sampling efficiency measurements at <0.05 m s^{-1}. One such study has shown that the filter-only result from the IOM is a better match to the inhalable convention than the total (filter + wall deposit).[32] However, given that particle aspiration into the human head airways may also be different in this low wind regime, the inhalable convention may also need modification, although it is known that the modification is likely to be strongly dependent on the proportion of nose breathing to mouth breathing, which is a function of workload as well as individual characteristics.[33]

The inhalable convention ends at 100 μm AED without intersecting a zero probability of particle penetration, and in many tests particles larger than about 70 μm AED were not considered due to experimental difficulties. Studies that have been performed above 100 μm AED indicate a diminishing probability of inhalation. Dai *et al.* found a cut-off around 135 μm AED for nasal breathing and moderate exercise in calm air,[34] while Hsu and Swift found a cut-off around 80 μm for nasal breathing and moderate exercise, also in calm air.[35] They found a higher cut-off for oronasal breathing and more strenuous exercise. Kennedy and Hinds still showed a 20% probability of aspiration for mouth breathing at three different workloads and with moving air (wind tunnel) for particles of 120 μm AED, with double that probability for facing the wind.[16] However, they also demonstrated almost zero aspiration of particles greater than 60 μm AED for nose breathing, in line with the work of Breysse and Swift.[36] Large-particle studies of samplers, however, have shown an increasing probability of particle collection by the IOM.[15,20] This phenomenon has been noted in side-by-side field trials of the IOM and CFC in industries where very large particles are common, such as wood-working.[14] Even if the number of very large particles potentially not inhalable but collected is few, they dominate the total mass of the IOM sample and significantly increase the bias between the two measurements.

Other "inhalable" samplers

The performance of some other samplers tested in the European intercomparisons compared reasonably well to the inhalable convention, including the German GSP (www.gsm-neuss.de) and the French CIP-10.[7] In addition, the performance of the Button sampler (www.skcinc.com), developed at the University of Cincinnati, has also been shown to come close to the inhalable convention.[37,38] All three of these samplers have the advantage of higher sample flow-rates leading to enhanced sensitivity of sampling. The GSP sampler uses a 37 mm filter at 3.5 l min^{-1}, which is possible with many personal sampling pumps. The Button sampler operates at 4 l min^{-1}, but the increased pressure drop across a 0.8 μm MCE filter of only 25 mm diameter cannot be guaranteed sustainable by any personal sampling pump for long periods in dusty atmospheres. The CIP-10 operates by a novel principle of pulling air through a rotating head and a foam sampler. The absence of a significant pressure gradient in this sampler allows the unit to operate at 10 l min^{-1} from a small, self-contained battery supply. None of these samplers has received as much field testing against the CFC as has the IOM sampler. However, the Button sampler has been compared to both the IOM and CFC samplers in wood dust studies, and it demonstrated an ability to exclude many of the particles greater than 100 μm that were collected by the IOM (the CFC fell in between these two).[14] Further descriptions and pictures of the CFC, IOM, GSP and Button in use may be found in ref. 39. The CIP-10 can be seen on the manufacturer's web-page (www.arelco.fr), as can the others on their respective manufacturer's pages.

Which convention for beryllium?

At the ACGIH Symposium on Advances in Air Sampling, held in Asilomar, CA in 1987, Raabe presented a tripartite

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protocol for beryllium sampling, which included inhalable sampling for soluble beryllium salts such as beryllium fluoride and sulfate, thoracic sampling for the poorly soluble hydroxide and low-fired oxide, and respirable sampling for the relatively insoluble metal alloys, silicates and high-fired oxide.[40] Since large particles are expectorated and ingested, and only 0.2% of ingested beryllium was absorbed by the body, it was assumed that the inhalable convention would only be important for highly soluble beryllium compounds. However, in an analogous situation, it has been suspected that the adsorption of even a small percentage of sparingly soluble large lead particles expectorated and ingested can outweigh the contribution to body burden of fine particles deposited in the alveolar region with much greater solubility.[40] There is evidence that fine particles of beryllium in any form may be problematic, and it appears that even relatively inert materials can have an effect in the alveolar region.[41] The granulomas associated with Chronic Beryllium Disease which are found in the alveoli may be associated with the deposition of particles containing beryllium on the alveolar walls.[11] Although the draft NIC for beryllium recommends the inhalable convention for the present, the issue of which is the most relevant convention is not completely settled, and the recommendation for a particle size-selective metric could in the future change to the respirable convention (or even something smaller).

Currently, penetration to the alveolar region is measured using a size-selective device known as a (miniature) cyclone in front of a collection filter. Three "respirable" conventions currently exist for particles between approximately 1 μm and 10 μm AED: the 1952 British Medical Research Council (BMRC) or "Johannesburg" convention with a 50% penetration probability (D_{50}) at 5 μm, the "old" (1984) ACGIH convention with a D_{50} at 3.5 μm (which was similar to the 1961 U.S. Atomic Energy Commission standard), and a compromise 1995 International Organization for Standardization (ISO) convention with a D_{50} at 4 μm.[42] The BMRC curve was based on South African studies and was in widespread use in many countries, and is still used in some, but many have recently changed to the ISO convention. The "old" ACGIH convention was only used in the USA, and is now chiefly used only by the U.S. OSHA in their regulatory role, having been abandoned by both the ACGIH and NIOSH in their recommendations. Several cyclones have been developed for use with these conventions, and, by judicious change in flow-rate, these cyclones can be made to perform to different conventions without much change in overall bias. Calibration of the Dorr–Oliver cyclone, which is popular in the USA, in the late 1960s at Los Alamos National Scientific Laboratory[43] indicated it matched the "old" ACGIH convention at a flow-rate of 1.7 l min^{-1}, and so that is flow rate used by OSHA. A more recent calibration by NIOSH indicated a match to the ISO convention at the same flow-rate.[44] It is probable that only one of these calibrations is correct, so that OSHA may be using the ISO convention after all. On the other a hand, a very recent publication suggests a different calibration from that of NIOSH.[45] It is possible the calibrations cluster around two possible solutions, differentiated by a factor still to be determined. One possible solution to this anomaly is differences in manufacturing. Quality assurance issues in cyclone manufacture can be critical to their performance.[46] Dorr–Oliver cyclones are manufactured by two companies in the USA. Slight differences in tolerances, either between or within manufacturers could account for the differences. Additional problems with the Dorr–Oliver cyclone, such as electrostatic and particle build-up issues, and performance dependence on wind speed and orientation have been noted, and the cause of the difference between the two calibrations also may lie in one or another of these environmental factors. Unfortunately, not all cyclones are routinely tested to the same protocols, so that similar issues may exist with other products. A round-robin study to demonstrate the comparability of testing in different laboratories was highly instructive, and needs to be expanded (hopefully even to inhalable samplers).[47] It should be noted that this round-robin used a single cyclone passed around the laboratories and so intra-model variations were excluded. In this context it is worthwhile to note that the U.S. MSHA approach to coal mine dust samplers requires the initial testing of six individual sampling trains and routine testing of off-the-shelf products after initial certification.

Again, some cyclone samplers operate at higher flow-rates than others, leading to differences in sensitivity. One German sampler, the FSP-10 (www.gsm-neuss.de), can be used with a flow rate of 10 l min^{-1} with a personal sampling pump in order to meet the ISO convention. It is able to achieve such high flow rates by using an 8 μm nominal pore diameter filter, which reduces the pressure drop compared to more commonly used filters. An 8 μm MCE filter still exhibits a $>99\%$ collection efficiency for particles of 0.3 μm AED, with a pressure drop of around 1 cm Hg.[5]

Finer fractions than the respirable convention have also been considered in assessing exposure to beryllium. With the so-called "ultra-fine" particulate range, particle number and surface area are potentially more important than mass. However, there is no currently agreed convention for this specific size-range. At this present time, penetration is preferred over deposition for all the ISO conventions, but that might change in future.[42] Deposition fractions become much more important for the fine and "ultra-fine" aerosol fractions, but can be ignored for the purposes of considering the inhalable mass fraction, since the deposition efficiency of very large particles is basically 100%, and these particles carry the majority of the mass. The ultimate selection of a coarse or fine particle metric will depend on the outcome of deliberations over which has the more health-relevant impact. A clear inhalation exposure–response relationship for sensitization to beryllium has not yet been determined. Therefore, other routes of exposure, such as through the skin, may also be important in the development of beryllium sensitization.[48] If CBD is the result of an immunologic response to beryllium, then sensitization might be triggered by a large insult. Assessing the potential for such an insult may require the assessment of all routes of exposure, including penetration of the skin by particles, and inhalation of coarse particles followed by expectoration and ingestion, as well as inhalation of fine particles. The selection of an appropriate exposure metric for inhalation exposure to beryllium requires an improved understanding of factors such as chemical form, surface area and particle size that may affect the bioavailability of beryllium following exposure.[49] Until this is

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achieved, the inhalable convention might represent the most conservative airborne fraction to prevent sensitization, even though the respirable fraction may be the most biologically-relevant fraction to prevent progression to disease.

Summary

An ISO method for collection of metalliferous aerosols using inhalable sampling has been published, although without specifying a particular model of inhalable sampler.[50] A European standard method exists for determining the performance of commercial inhalable samplers against the inhalable convention,[51] and some, but not all, samplers have been tested according to this protocol.[7] It has been noted that the inhalable convention may be in need of modifications to take account of low wind-speeds and very large particles. Without debating in detail the merits of whether the inhalable convention truly is the best metric for airborne beryllium, a variety of inhalable samplers has been described. The most salient points with regard to the assessment of airborne beryllium with these samplers are:

• CFC samples appear to approximate inhalable samples in at least some metals refining industries if a wipe is made of the inside and added to the filter for analysis. *In situ* digestion of the sample would also improve recoveries. An internal capsule would improve recoveries for gravimetric determinations. The sampler is cheap and disposable, but only operates at 2 l min^{-1}.

• IOM requires the analysis of the cassette walls by protocol. The sample is likely to be the most closely related to that which would be provided by an ideal sampler operating to the inhalable convention, provided extremes of conditions and very large particles are avoided. It also operates at 2 l min^{-1}.

• GSP may be close to inhalable using the filter only (although there are certainly deposits that can be measured on the walls, these have not been considered in defining the sample). It operates at 3.5 l min^{-1} with a standard personal pump for long periods of time without faulting the pump.

• Button sampler is close to inhalable using a filter only (there are no walls for deposition), and it has increased sensitivity through its flow rate of 4 l min^{-1}, but long-time operation in dusty atmospheres would require the development of a special heavy-duty pump, or the use of filters with a larger pore size. It can exclude a portion of the very largest particles.

• CIP-10 has an attractive flow rate of 10 l min^{-1} and the unit is relatively small and light-weight, but there has been little testing, and it is not known if the sampling medium (foam) is compatible with beryllium analysis.

All of these samplers should be tested in side-by-side studies at operations where airborne beryllium is present, and a project is in place at NIOSH to do this. Any differences in samplers are more likely to be apparent with the coarsest dusts, and representative scenarios in the beryllium industry might include ore mining and processing, powder handling (beryllium oxide ceramic), and metal cutting and machining (beryllium alloys). Other processes, such as smelting and refining, are probably associated with smaller particles where differences between samplers may be less obvious. Such studies could encompass the low-wind situation, or other extreme conditions.

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