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Rationale and Recommendations for Particle Size-Selective Sampling in the Workplace

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Rationale and recommendations for particle size-selective sampling in the workplace

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Because many aerosol hazards depend upon particle size, the American Conference of Governmental Industrial Hygienists established an Air Sampling Procedures Committee to "recommend size-selective aerosol sampling procedures which will permit reliable collection of aerosol fractions which can be expected to be available for deposition in the various major subregions of the human respiratory tract." After reviewing available data on regional deposition of inhaled particles and on the collection efficiencies of sampling instruments, the committee recommends use of three particulate mass fractions for workplace sampling: inspirable particulate mass (IPM), for materials which may be hazardous anywhere in the respiratory tract; thoracic particulate mass (TPM), for materials which may be hazardous anywhere within the lung airways and the gas exchange region; and respirable particulate mass (RPM), for materials which may be hazardous in the gas exchange region of the lung. The mass fractions are defined by simple equations with surrounding tolerance bands to allow practical applications. The role of these fractions in establishing new particle size-selective threshold limit values (PSS-TLVs) depends on assessing information on the toxicology, physicochemistry, and industrial exposure characteristics of chemical agents. **Phalen, R. F.; Hinds, W. C.; John, W.; Lioy, P. J.; Lippmann, M.; McCawley, M. A.; Rabbe, O. G.; Soderholm, S. C.; Stuart, B. O.** Rationale and recommendations for particle-size selective sampling in the workplace. *Appl. Ind. Hyg.* *1*:3-14; 1986.

Introduction

The goal of particle size-selective sampling in the work environment is to provide the most appropriate measure of inhalation hazards by giving recognition to the fact that particle size can greatly influence regional deposition within the respiratory system. The application of information on regional deposition of inhaled particles to industrial hygiene sampling practice has been done only to a limited extent and for few specific materials.

In 1952, the British Medical Research Council (BMRC) adopted a definition of "respirable dust" for pneumoconiosis-producing dusts. It defined respirable dust as that reaching (as opposed to depositing in) the alveolar region and selected the horizontal elutriator as a practical size selector.

In 1961, the U.S. Atomic Energy Commission (AEC), Office of Health and Safety defined "respirable dust".[1] It referred to respirable particulate mass (RPM) as those portions of the inhaled dust which penetrate to the non-ciliated portions of the gas exchange region. This application of the respirable dust concept and concomitant selective sampling was intended only for "insoluble" particles which exhibit prolonged retention in the lung.

The American Conference of Governmental Industrial Hygienists (ACGIH) in 1968 announced in their "Notice of Intended Changes" alternate respirable mass concentration threshold limit values (TLVs) for quartz, cristobalite, and tridymite (three crystalline forms of free silica) to supplement the TLVs based on particle number count concentrations.

The Occupational Safety and Health Act of 1970 led to the adoption of a few permanent standards, none of which address the issue of respirable dust. As a result, the Occupational Safety and Health Administration (OSHA) is enforcing numerous interim standards including 22 maximum acceptable concentrations (MACs) of the American National Standards Institute (ANSI) and approximately 280 of the ACGIH 1968 TLVs including the silica TLVs which specify either dust counts or respirable mass concentrations.

In addressing its responsibility to develop primary ambient air quality standards to protect the public health, the U.S. Environmental Protection Agency (EPA) concluded that the diseases which could be related to the inhalation of ambient aerosols were associated with particles which penetrated through the upper respiratory tract and were available for deposition in the tracheobronchial and/or gas exchange regions. They called this fraction "inhalable" dust. In 1982, the EPA reduced the upper cutpoint of this fraction from 15 μm to 10 μm and changed the designation to "PM_{10}."[2]

Technical Committee 146—Air Quality of the International Standards Organization (ISO) appointed a working group to make recommendations on size definitions for particle sampling and analysis of air contaminants in both occupational and general environmental settings. The working group defined aerosol fractions related to particle deposition within regions of the human respiratory tract. The fraction drawn in by the nose or mouth was called

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"inspirable"; that collected in the head was called "extra-thoracic"; that penetrating through the larynx was called "thoracic" and was further subdivided into "tracheobronchial" and "alveolar."[3]

As seen in the foregoing, the development of particle size-selective occupational threshold limit values has not proceeded in a consistent fashion. The accrual of a reliable data base on size-selective particle deposition in the human respiratory tract in recent years has created the needed information for the development of self-consistent and more standardized particle size-selective threshold limit values (PSS-TLVs). These values should take into account the diseases associated with each inhaled substance and should be based upon the characteristics of the lung, particle size distribution, particle dynamics, and physical and chemical composition of particles emitted by various processes.

What follows is a description of the results of the efforts of the ACGIH Technical Committee on Air Sampling Procedures which recommended size-selective aerosol sampling procedures in work places. A more complete report is available.[4]

In a sequence following the path of inhaled air, the anatomical structures of the respiratory tract include 1) the nose, consisting of the nares, vestibule, and nasal cavity proper (with the conchae or turbinates), 2) the nasopharynx, 3) the lips and oral cavity, 4) the oropharynx, 5) the laryngopharynx, 6) the larynx, 7) the trachea, 8) the bronchi, 9) the bronchioles, 10) the respiratory bronchioles, 11) the alveolar ducts, 12) the alveolar sacs, and 13) the alveoli. These structures are commonly grouped into separate regions for purposes of simplification. Two similar regional models are relevant to a consideration of size-selective aerosol sampling. The two models are those of the Task Group on Lung Dynamics of the International Commission on Radiological Protection,[5] and the Ad Hoc Working Group to Technical Committee 146—Air Quality of the ISO.[3] Table I displays the terminology used here to describe each region for particle size-selective sampling considerations and shows the corresponding regions of the earlier models.

Size-selective sampling criteria for inspirable mass fraction

A complete evaluation of inhalation hazards in a work environment should include consideration of all airborne particles that can enter the respiratory system. The inspirable particulate mass (IPM) fraction of an aerosol is that fraction of the ambient airborne particles which can enter the uppermost respiratory system compartment, the head airways region (HAR). Airborne material which deposits in the head may be absorbed and/or swallowed, although some may be expelled directly from the body by bulk clearing mechanisms, such as sneezing, spitting, or nose blowing. There are at least three general classes of airborne toxic materials for which a valid hazard evaluation must consider all inspirable particles: (1) highly soluble materials which can quickly enter the blood and exhibit their toxicity, e.g., nicotine and soluble salts, (2) materials which can exhibit toxicity after dissolving in the gastrointestinal tract, e.g., toxic metals, and (3) materials which can exhibit toxicity at the deposition site, e.g., acids and nasal carcinogens such as hardwood dusts.

TABLE I
Respiratory tract regions

Region	Anatomic Structures	Task Group Region	Region
1. HAR (Head Airways Region)	Nose Mouth Nasopharynx Oropharynx Laryngopharynx Larynx	Nasopharynx (NP)	Extrathoracic (E)
2. TBR (Tracheobronchial Region)	Trachea Bronchi Bronchioles (to terminal bronchioles)	Tracheobronchial (TB)	Tracheobronchial (B)
3. GER (Gas Exchange Region)	Respiratory bronchioles Alveolar ducts Alveolar sacs Alveoli	Pulmonary (P)	Alveolar (A)

In the past, sampling has often relied on "total dust samplers" whose ability to sample large particles has had an unknown relationship to the ability of the head to inspire material. It is only relatively recently that data on the inspirability (ratio of inspirable to total particulate mass concentration) as a function of particle size have been reported. A major study used a tailor's dummy head on a box (to represent the shoulders) in a wind tunnel and measured the fraction of particles which was caught on a filter behind the nose and mouth.[6] The particles were monodisperse with diameters ranging from 5 to 30 μm. Limited corroborative data has been collected for a 1 m/s wind speed and for particles up to 70 μm in aerodynamic diameter for facing the wind only.[7]

Another study involved polydisperse coal dust passing the nose or mouth of a full-scale model of the human head to obtain the inspirable fraction as a function of size for aerodynamic diameters up to approximately 60 μm.[8] Inspirability has been measured using a larger (3.75 m^2) wind tunnel and a full-size head and torso of a tailor's dummy.[9] The particles were "narrowly graded" allowing measurements up to aerodynamic diameters of about 100 μm. Wind speeds were 1, 2, and 4 m/s. They reported that the presence of the full torso made a significant difference in the air flow patterns and the measured inspirable fraction when facing the wind. The deposition of radiolabeled pollen in the noses of four human subjects has been measured in still air.[10] The pollens were monodisperse with physical diameters of 18, 27.5, and 30.5 μm. Their densities were unknown but were assumed to be 1.0 g/cm^3. Subjects breathed through their noses at a frequency of 15 min^{-1} while at rest.

Based on the limited data provided by these studies, some generalizations can be drawn about the role of several potentially important variables in determining the fraction of airborne particles which is inspired. It is clear from both theoretical considerations and experiments that aerodynamic diameter is an important parameter in determining whether a particle enters the head. For

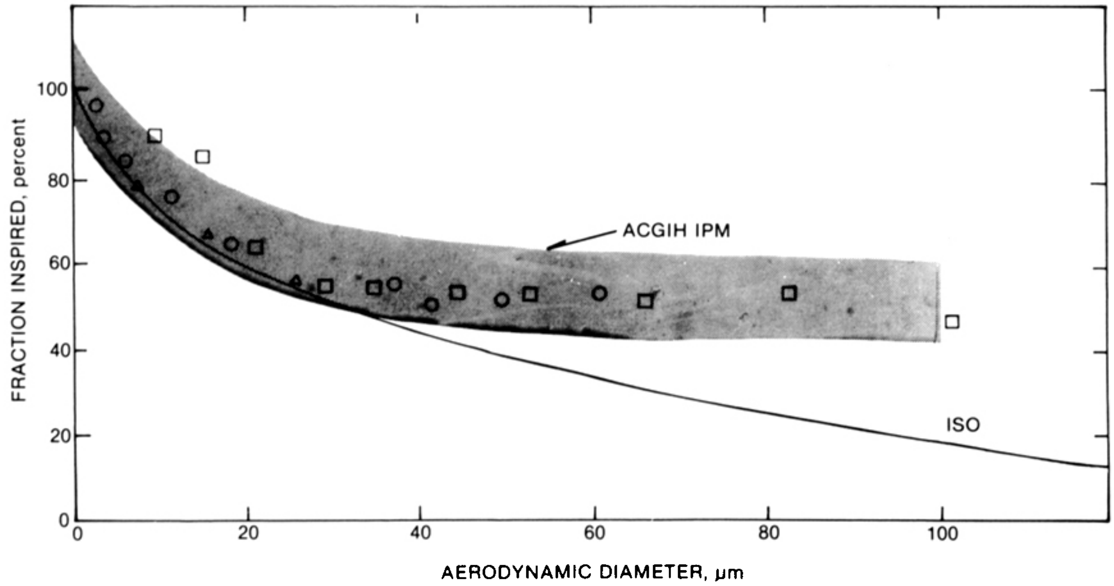

Figure 1—ACGIH recommended IPM size-selective criteria compared to the ISO curve and to recently available data averaged over orientation and wind speed.[6,8,9] Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

orientations to the wind of 90° to 180°, there seems to be little dependence on orientation. The 0° orientation (facing the wind) has complexities which can lead to inspirabilities significantly greater than unity. Inspirability is sensitive to wind speed, especially when facing the wind. Inspirability seems relatively insensitive to minute volume except in the case of facing a wind, a situation in which significant oversampling can occur. There seems to be little difference between nose and mouth breathing. In the case of facing the wind, an effect on inspirability for mouth breathing due to an updraft when the whole torso was included in the tunnel has been noted.[9] Inspirable efficiency for nose breathing using a full torso has not been measured, but the updraft would be expected to have a significant effect, carrying larger particles into the nostrils. Inspirability seems relatively insensitive to the area of the orifice for the same air flow, over reasonable limits. This is in agreement with blunt sampler theory.[9] Also, there seems to be little qualitative difference in inspirability between steady and cyclic flow. The steady flow rate used in the experimental protocols approximated the average flow rate during the inspiratory half of the breathing cycle, so it is approximately twice the minute volume.

For the purposes of recommending sampling criteria for IPM, the orientation-averaged inspirability as a function of aerodynamic particle size are appropriate.[9] These data have several desirable features: (1) a reasonable minute volume of 20 L, similar to that for the reference worker,[11] (2) inclusion of the full torso, (3) true averaging over orientation, since the mannikin was slowly rotated during the experiment, (4) inclusion of one realistic wind speed for the indoor workplace, 1 m/s, and one high wind speed, 4 m/s, (5) inclusion of particle sizes between 3 and 100 µm, (6) enough independently measured points to indicate the scatter of the experimental results, and (7) lack of disagreement with the other available orientation-averaged inspirability data.

For an area sampler which attempts to characterize the work atmosphere as a whole (as distinct from characterizing the work atmosphere experienced by individual workers), present evidence suggests the inspirability curve recommended by Vincent and Armbruster[12] is adequate. Especially for particles having aerodynamic diameters smaller than 30 µm, there would seem to be few if any combinations of orientation, wind, speed, and minute volume for which our best prediction of the actual inspired fraction would differ from the recommended curve by more than 30%. However, for larger particles, deviations from the recommended curve could easily be factors of two or more in special cases.

The following tolerance band has been chosen to conveniently describe the recommended IPM sampling efficiency criteria.

See equation below.

$$E = 50(1 + \exp[-0.06d_a]) \pm 10; \text{ for } 0 < d_a \leq 100\ \mu m$$
$$E = \text{unknown for } d_a > 100\ \mu m$$
where: E = efficiency (%) and d_a = aerodynamic diameter (µm)

Values of this band are shown in Figure 1 along with some of the laboratory data. The recommended uncertainty limits ± 10% in sampling efficiency for all aerodynamic diameters are representative of the scatter in the data and seem realistic as allowable variation among samplers.

Size-selective sampling criteria for thoracic and respirable mass fractions

The thoracic particulate mass (TPM) fraction refers to the portion of the airborne particles that may penetrate the head airways and enter the tracheobronchial airways region (TBR) under the worst-case condition of inhaling through the mouth. The respirable particulate mass (RPM) fraction refers to the existing ACGIH respirable dust sample (but with elaborated criteria) describing that portion of the airborne particles that may penetrate the head and tracheobronchial airways during nasal breathing and thereby expose the gas exchange region (GER) of the lung.

In order to size-selectively sample aerosols for estimating the mass fraction of particles available to the lung (TBR and GER) during inhalation, it is necessary to estimate the fraction of inhaled aerosol that can pass the airways of the head as a function of particle size. Such estimates can be based on either mathematical models of expected deposition with respect to particle size of particles in the nasal-pharyngeal and oral-pharyngeal portions of the head airway region or on laboratory experimental data obtained for human subjects inhaling well-characterized particles under controlled conditions.

Widely used models of regional deposition versus particle size were developed by the International Commission on Radiological Protection Task Group on Lung Dynamics.(5) They calculated the expected deposition of particles in the airways of the lung during breathing, but they did not theoretically determine head airway deposition. Their nasal-pharyngeal (NP) deposition calculations were based upon the empirical log-linear equation of Pattle,(13) which was an empirical fit to experimental data for a nose-breathing man.

Particle deposition has been measured in human volunteers inhaling test aerosols either through mouthpieces or nose masks utilizing monodisperse, insoluble, stable aerosols of different sizes.(14-26)

Clearly, thoracic deposition in the tracheobronchial region and gas exchange region is greater during mouth breathing. This suggests that the thoracic sample should be based upon those particles that penetrate the head airways region during mouth breathing. An estimate of the fraction of particles available to the lung during mouth breathing requires an estimate of the deposition of particles in the head airways region during mouth breathing. The ICRP Task Group provides no predictions of head deposition during mouth breathing, but experimental data are available.(14,19,25,26)

Depending upon the size distribution of the particles in the sample, a portion of the particles in the TPM fraction is deposited in the gas exchange region of the lung, a portion is deposited in the tracheobronchial region of the lung, and a portion is exhaled.

Based upon review of the data and the foregoing considerations, the recommended thoracic particulate mass (TPM) size-selective sampling criterion is a tolerance band consisting of those particles that penetrate a separator whose size collection efficiency is described by a cumulative lognormal function with median(d_{50}) of 10 ± 1 μm aerodynamic diameter and with geometric standard deviation (σ_g) of 1.5 ± 0.1. The recommended tolerance band is shown in Figure 2 as penetration efficiency versus particle aerodynamic diameter. Also shown are selected data from various investigators, but corrected to the reference worker (by adjusting the inertial data to a flow rate of 43.5 L/min) for head penetration of particles inhaled by people via the mouth. The recommended tolerance band is seen to be conservative when compared to data corrected to the Q = 43.5 L/min of the reference worker in that the actual penetration to the lung tends to be less in most cases than the TPM fraction size-selective sample. The TPM criterion, therefore, tends to overestimate the amount of exposure of the lung and correspondingly to provide a reasonable level of protection when used as the basis of TLVs or risk estimates.

For occupational situations where the risk of inhalation exposure is primarily associated with the deposition of insoluble particles in the deep lung, the ACGIH has previously recommended a respirable dust standard. In this context, the word "respirable" has been used to describe that portion of an aerosol that is available to the gas exchange region. Using the ACGIH respirable dust sample as the basis, the recommended respirable particulate mass (RPM) size-selective sampling criterion is a tolerance band consisting of those particles that penetrate a separator whose size collection efficiency is described by a cumulative lognormal function with median (d_{50}) of 3.5 ± 0.3 μm aerodynamic diameter and with geometric standard deviation (σ_g) of 1.5 ± 0.1. This tolerance band is shown in Figure 3 along with the points representing the ACGIH respirable dust definition. The RPM size-selective sampling criteria incorporate and clarify the respirable dust criteria. Although there are no direct measurements of the penetration to the gas exchange region of particles inhaled via the nose, the recommendations of the Task Group on Lung Dynamics(5) for nasal-pharyngeal deposition and for tracheobronchial deposition of particles entering the tra-

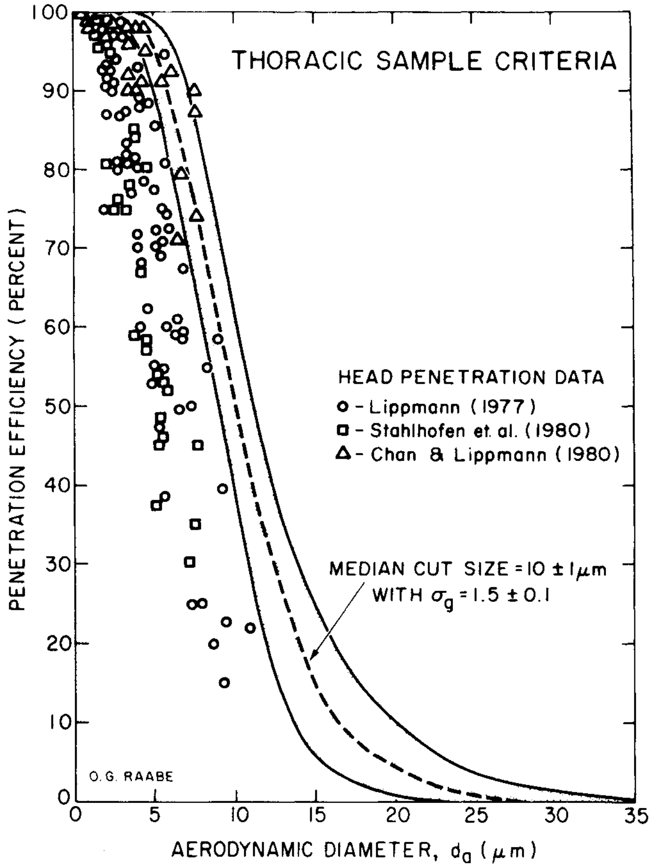

Figure 2—Thoracic particulate mass (TPM) tolerance band given as penetration efficiency to a sample collector. Also shown are selected values for observed human head penetration during inhalation by mouth.(19,25,26) Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

chea are in reasonable agreement with the human data. The sum of the Task Group deposition predictions for the nasal-pharyngeal region and tracheobronchial region were used to calculate an effective penetration curve for nose breathing which is also shown in Figure 3. The respirable particulate mass fraction tolerance band is seen to be conservative in that it somewhat overestimates the fraction of particles available to the deep lung indicated by the Task Group derived penetration curve. Much of the difference is due to adoption of mouth breathing as our reference condition, allowing greater penetration to the thorax.

Since tolerance bands are being recommended for IPM, TPM, and RPM sampling, there may be differences among samples collected with different instruments. The narrowness of the tolerance bands will usually preclude any major differences, however, and the use of bands allows flexibility in instrument design and evaluation. In fact, instruments cannot be designed to meet exact criteria, so that small differences among different types of instruments will occur anyway. The minimum geometric standard deviation for both TPM and RPM tolerance bands is 1.4. It is felt that instruments displaying sharper size separation capabilities would be undesirable for use in sampling RPM and TPM because the objective is to mimic the separation characteristics of human airways, and sharper size cuts would tend to strongly underestimate the actual contribution of the larger particles in the TPM and RPM size ranges.

Sampler efficiencies: inspirable mass fraction

It is desirable that inspirable particulate mass (IPM) sampling eventually replace the present method of total dust sampling using open-face filter holders. So-called total dust samplers such as open-face filter cassettes do not measure total dust and are unsuitable for most monitoring of airborne particles larger than a few micrometers because their sampling efficiency for large particles is sensitive to wind velocity and direction. Implementation of IPM sampling will require the development and testing of suitable sampling instruments.

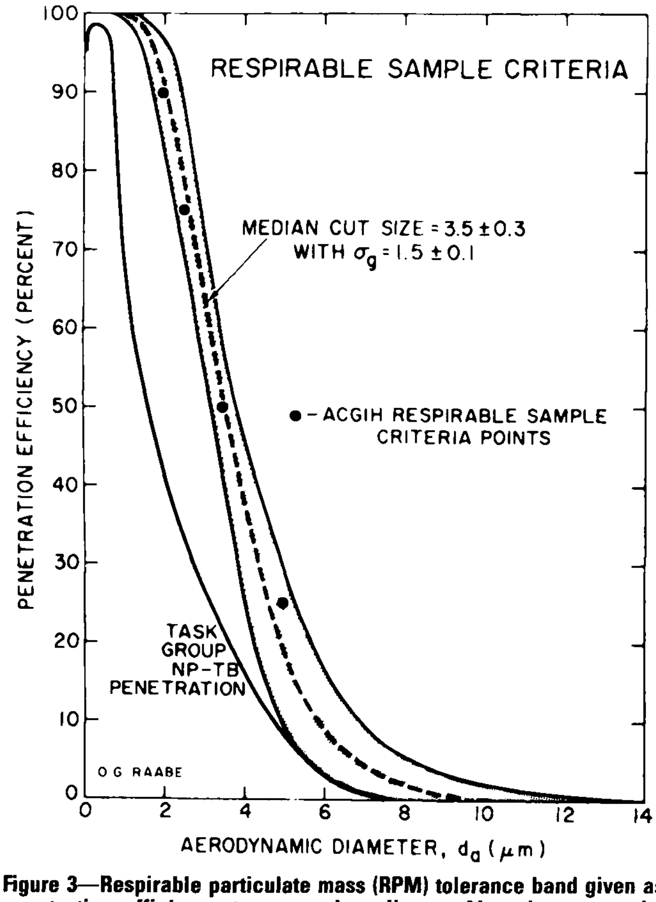

Figure 3—Respirable particulate mass (RPM) tolerance band given as penetration efficiency to a sample collector. Also shown are the assumed penetration values of head and tracheobronchial airways based upon the recommendations of the ICRP Task Group on Lung Dynamics.[5] Reprinted with permission fom the AmericanConference of Governmental Industrial Hygienists.

Sampling in calm air has been evaluated by several investigators.[27-29] These studies deal with the effect of sedimentation and particle inertia on sampling losses. In the work place environment it is rare for the air to be sufficiently calm for this still air analysis to hold. The situation is more complicated for the case of blunt samplers sampling in calm air. Studies of blunt samplers lead to the conclusion that for calm air the particle aerodynamic diameter that results in a 90% sampling efficiency is roughly one-half that predicted for thin-wall tube samplers.[30]

When sampling in moving air for particles whose settling velocities are small compared to the air velocity, accurate samples of large particles can be obtained by using thin-walled probes aligned with the gas streamlines using entering air velocities that match the approaching wind velocity. When these conditions are met, sampling is said to be isokinetic and sampling efficiency is 100% for all particle sizes. Blunt samplers operating in a wind present a complicated situation, and there is no unique probe velocity that permits sampling with 100% efficiency for all particle sizes in a given wind.

Passive samplers, often referred to as "dust fall buckets," are unsatisfactory because particulate mass collected in this way can not be related easily to airborne concentrations.

In the early 1970s, the Federal Republic of Germany established standard sampling criteria for workplace dust measurements. Another European standards group has proposed that samplers have an inlet velocity of 1.1 to 3 m/s and a flow rate of 0.5 to 4 L/min to collect total airborne particulate matter.[30] This corresponds to an inlet diameter range of 2-9 mm. None of these standard method criteria have attempted to match inspirable efficiency curves, nor is there any basis to assume that they correctly sample total airborne particulate matter except in calm conditions.

Investigations of the sampling characteristics of two sampling instruments that were designed to meet the European inlet velocity criteria cited above, the Gravicon VC 25G and the GS 050/3, have been performed.[31] Both have annular (omnidirectional) horizontal inlet slots. The VC 25G sampler

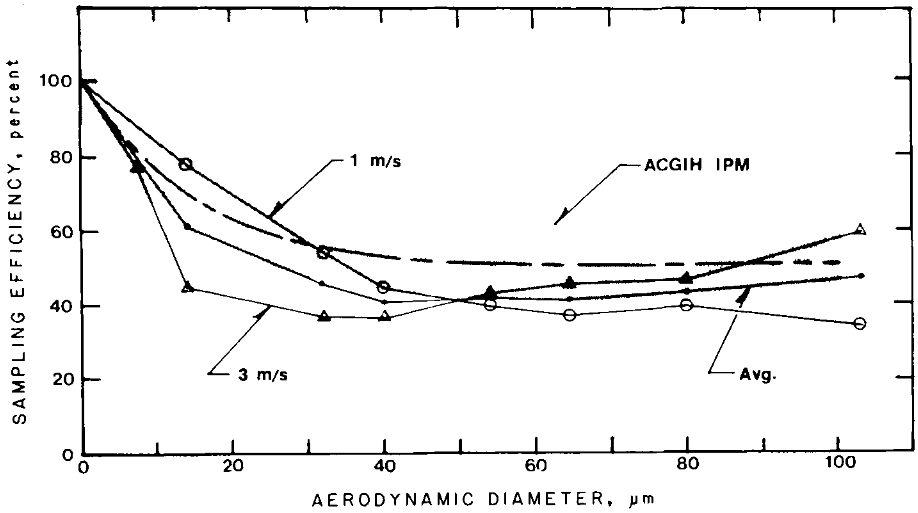

Figure 4—Orientation-averaged sampling performance of the IOM/STD 1 sampler at two wind speeds. Shaded region is the envelope defined by the ACGIH IPM criteria. Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

approximately follows the inspirable mass sampling criteria only for a narrow range of wind velocities somewhere between 2 and 4 m/s (400 and 800 fpm). The sampling efficiency curve averaged for wind velocity for the GS 050/3 is further from the inspirable mass sampling criteria than the VC 25G.

The sampling efficiency of isolated open-face and in-line 37 mm plastic cassettes has been evaluated for various wind velocities and directions relative to the sampler axis.[32] For wind velocities of 0-2 m/s, sampling efficiency is strongly biased in favor of particles larger than a few micrometers in aerodynamic diameter. An opposite bias has also been reported when similar samplers are mounted on a torso.[33] A vertical axis, rotating-arm sampler has been used for total airborne particulate mass sampling.[34] Flow into the inlet at one end of the rotating arms is controlled by a pump to provide isokinetic sampling at the inlet.

A sampler known as the Orb sampler has been used for inspirable mass sampling, but it undersamples particles larger than about 13 μm in diameter.[35]

There are, at present, no samplers that fall within the ACGIH IPM criteria envelope over the range 0 to 100 μm aerodynamic diameter nor are there any devices that will fractionate a total dust stream into IPM and noninspirable particulate mass fractions.

Researchers at the Institute of Occupational Medicine, Edinburgh, UK, have recently developed an area sampler, the IOM/STD1, that comes close to matching the recommended IPM criteria over the range of 0 to 100 μm aerodynamic diameter.[36] The sampling head of their device is a vertical axis cylinder about 5 cm in diameter and 6 cm high. A horizontal axis oval-shaped inlet slot (about 3 mm high x 16 mm wide) is located mid-way up the side of the cylinder. The device samples at 3 L/min through a 37 mm filter mounted in a weighable cassette inside the cylinder. The sampling head is mounted on a larger vertical axis cylinder about 15 cm in diameter and about 18 cm high which houses batteries, pump, and flow control. The sampling head rotates continuously at about 2 rpm. Results of preliminary tests indicate reasonable agreement with the ACGIH IPM criteria (Figure 4).

Sampler efficiencies: thoracic mass fraction

Probably the simplest approach to sampling for thoracic particulate mass (TPM) is to use a sampler whose collection efficiency as a function of particle aerodynamic diameter falls within the acceptance envelope. Such a TPM sampler consists of an inlet, a size-fractionating stage, which is sometimes integral with the inlet, and a particle collector, which is usually a filter.

One of the principal criteria used in the selection of samplers is the flow rate. TPM samplers can be classified into low volume (Q < 20 L/min), medium volume (20 L/min < Q < 150 L/min) and high volume (Q > 150 L/min) samplers. In the low volume category the dichotomous sampler[37] is a virtual impactor having a flow rate of 16.7 L/min. The thoracic particulate mass fraction is selectively passed through the inlet; the virtual impaction stage fur-

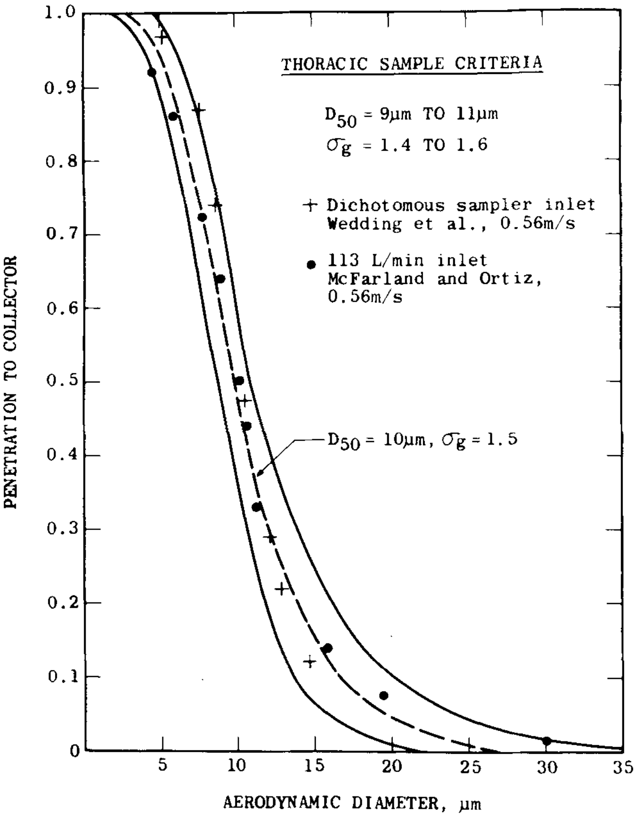

Figure 5—TPM sampling criteria with data for two thoracic particulate mass samplers.[42,53] Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

ther fractionates the aerosol into coarse and fine fractions with a d_{50} of 2.5 μm. Several inlet designs are available. The UMLBL inlet[38,39] is a single stage impactor with a grooved impaction surface and an internal flow pattern designed to suppress particle bounce. Independence of wind direction is assured by cylindrical symmetry about the vertical axis. For thoracic particulate mass sampling alone, the virtual impaction stage of the dichotomous sampler is unnecessary. The fractionating inlet can be coupled directly to a filter to form a sampler which has been called the "Monocut" (Sierra Instruments, Carmel Valley, CA). Such a sampler using the earlier EPA 15 μm cutpoint dichotomous sampler inlet performed well.[40] The newer EPA 10 μm cutpoint inlets should work equally well, affording an alternative to the dichotomous sampler.

Medium volume samplers have been developed. One version employs a sampler geometry which fractionates particles by a combination of impaction and sedimentation.[41] The tortuous air path also suppresses particle bounce. A high volume sampler based on a similar geometry, called the Size-Selective Inlet (SSI), converts a standard hi-vol into a thoracic mass sampler.[42] The SSI can be used only with quartz or glass fiber filters.

A small, portable sampler has been developed with a thoracic cut provided by the inlet, which contains a single stage impactor with an oil-soaked porous plate to suppress particle bounce.[43]

The foregoing samplers are all area samplers. No personal sampler has been designed for the collection of the thoracic particulate mass fraction. The miniature impactor[44] could probably be used to determine the TPM fraction.

The measured sampling efficiencies of two of the samplers discussed above are compared to the TPM sampling criteria in Figure 5. The data points lie within the tolerance band. These particular samplers were chosen for illustrative purposes only; a number of other samplers also satisfy the criteria.

Sampler efficiencies: respirable mass fraction

Most of the requirements for a respirable particulate mass (RPM) fraction sampler are similar to those for the thoracic mass fraction sampler except for characteristics affected by the particle size range. Because the particles to be sampled are smaller, the inlet requirements are less stringent for respirable than for thoracic sampling.

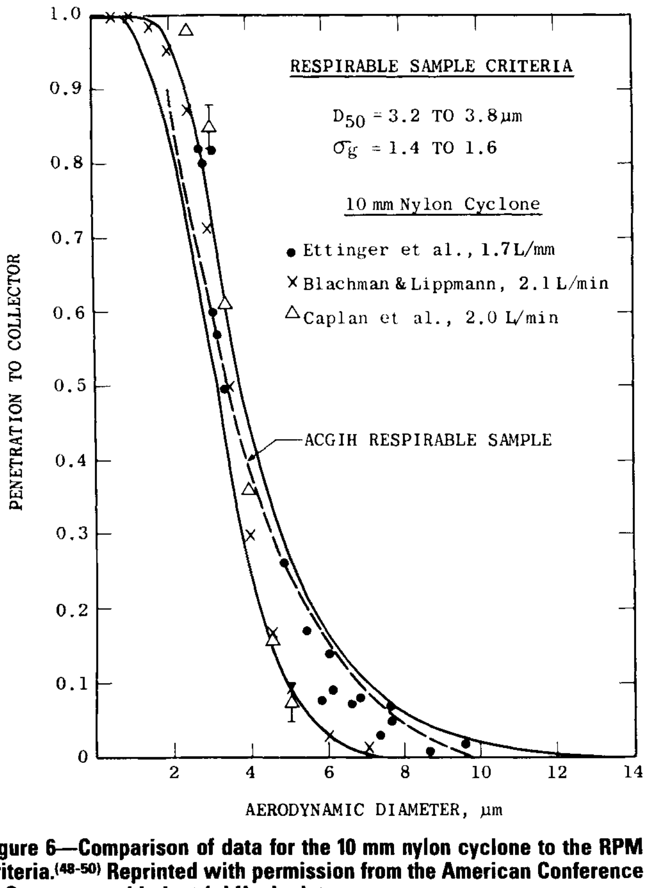

Figure 6—Comparison of data for the 10 mm nylon cyclone to the RPM criteria.[48-50] Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

Cyclones are probably the most commonly used respirable mass samplers. They are available in a wide range of flow rates including a miniature size for personal sampling. The sampling efficiency can be closely matched to that of a respirable curve (Figure 6). Cyclones have important practical advantages including minimal particle bounce and reentrainment, large capacity for loading, and insensitivity to orientation. A disadvantage of the cyclone is the lack of a fundamental theory which can predict performance. However, empirical theories are available to assist the designer.[45-47] Considerable data are available on the performance of the widely-used 10 mm nylon cyclone.[48-50]

Horizontal elutriators have been widely used, particularly by the British. Their main advantage is the predictable performance based on gravitational settling of the particles during passage between horizontal collecting plates. Disadvantages include the restriction to a fixed orientation, the possible reentrainment of particle deposits, and the difficulty of miniaturization.

The collection efficiency of an impactor can be accurately predicted by theory.[51] On the other hand, important details such as wall losses cannot be reliably predicted. Also, impactors suffer from the problems associated with particle bounce and reentrainment. Impactors can be designed over a wide range of flow rates and can be operated in any orientation. A further advantage of the impactor is the possibility of cascading stages to provide size-segregated samples which can be analyzed to produce the particle size distributions of specific chemical species. Particle bounce and reentrainment can be minimized by using virtual impactors. It should be emphasized, however, that the cutoff curves of existing impactors are sharp and hence do not conform to the human respirable curve. Although virtual and other impactors could probably be designed with a respirable cutoff, none are currently available.

Inefficient filters (having large poresizes) have been used as precollectors, allowing respirable particles to penetrate to an after filter. However, the "respirable" cut is only approximate, since the sizing is primarily by intercep-

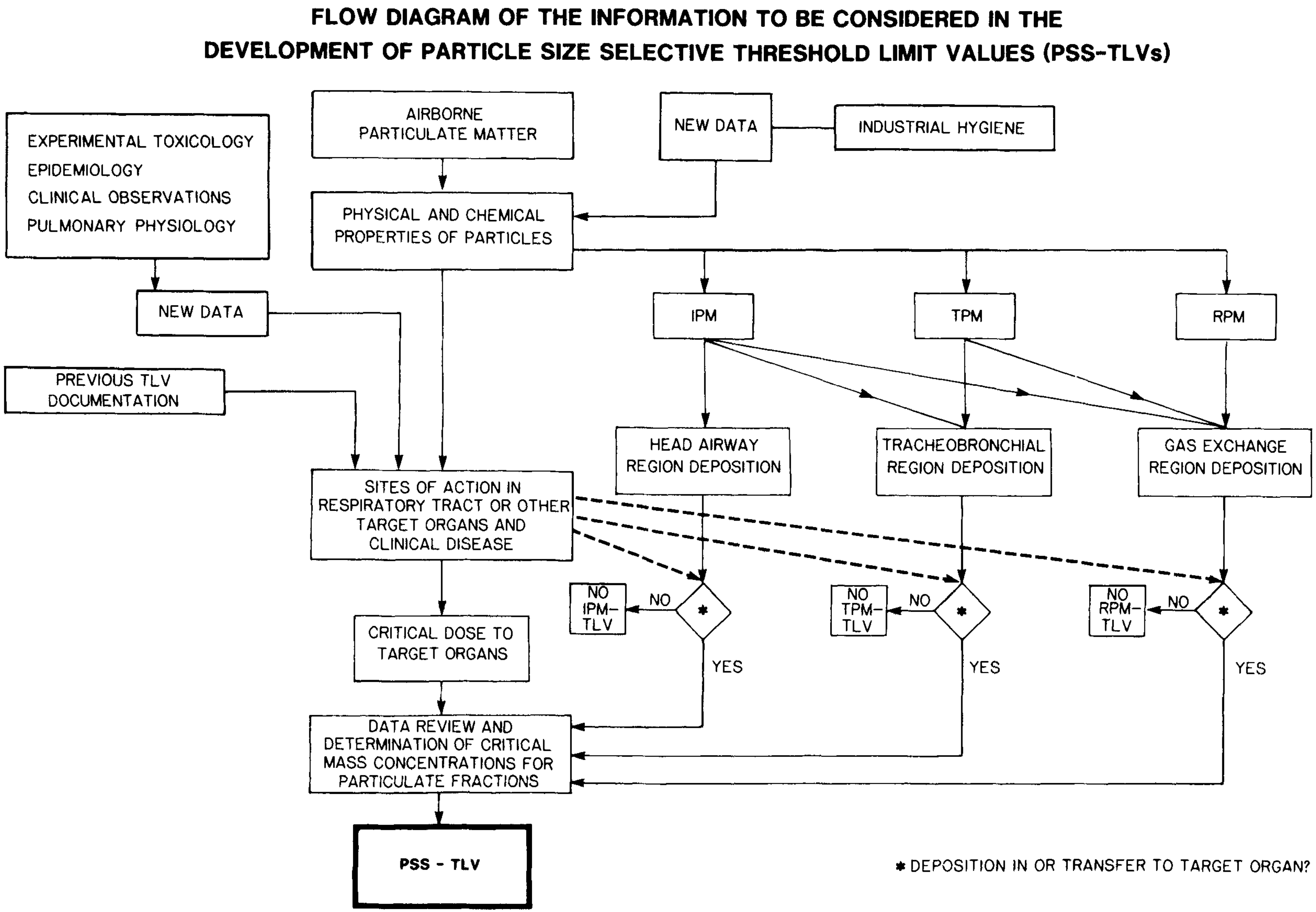

Figure 7—Flow diagram of the informalion to be considered in the development of particle size-selective threshold limit values. Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

tion rather than aerodynamic.[52] The aerodynamic diameter increases with the square root of the particle density; therefore, a serious error will occur in the sampling of high density materials.

Use of size-selection in establishing TLVs

Analyses for specific air contaminants and specific potential diseases associated with different regions of the respiratory tract indicate that size-selective sampling is necessary and critical to a meaningful evaluation of the inhalation hazard to the worker. Different particle size distributions of the same contaminant will cause major changes in deposition in different regions of the respiratory tract, altering not only the relative quantity of material deposited within the region, but also the probability and nature of the associated disease processes. Thus, the adoption of PSS-TLVs is an important and necessary step toward the improvement of standards established for the protection of workers.

As shown in the decision flow diagram in Figure 7, the first step in deriving a Particle Size-Selective Sampling TLV (PSS-TLV) is the identification of the chemical substance that constitutes a potential air pollutant, including examination of all available physicochemical properties related to its airborne and biological behavior. Concomitantly, the literatures of epidemiology, industrial hygiene, and toxicology should be searched to identify diseases that may be associated with the chemical substance affecting specific regions of the respiratory tract or systemic organ systems. New data gathered from these searches, including experimental animal studies, especially on recently developed substances, should be incorporated with existing TLV documentation for insight into possible disease mechanisms.

If no potential diseases related to the chemical substance are found, then the evaluation can be terminated. If a disease potential exists, but the physicochemical nature of the chemical substance is such that no airborne particle phase can be produced, the procedure can revert to the traditional procedure for establishing a TLV.

However, if the physicochemical properties of the chemical substance suggest that it may become airborne as an aerosol, the analysis proceeds. At this stage, the physical and chemical properties of the substance are evaluated under conditions likely to be encountered by workers.

The aerodynamic particle size distribution will determine the mass fraction of the work place aerosol that will enter the head airways, tracheobronchial, or gas exchange regions of the respiratory tract. Particle size-selective sampling is then necessary to estimate the actual quantity of chemical substance that will be presented to the three principal regions of the respiratory tract during the course of each working day. Thus, the mass of the substance presented to each region will be established as the critical value in airborne hazard evaluation. Once the chemical substance is deposited in a particular region or regions of the respiratory tract, the critical factor in selecting the appropriate particle mass fraction (respirable, thoracic, or inspirable) is the extent of dissolution of the substance within each region.

Concurrent examination of the clinical diseases that may affect any systemic organ will identify extrapulmonary sites of action. Subsequently, it will be determined whether the incorporated dose of the substance is a critical dose that is likely to cause acute or chronic injury. Once the particle size and particulate mass fraction are determined and the hazard analyses are completed, a critical mass concentration will be determined for an appropriate size fraction. This review will result in a recommendation for a particle size-selective threshold limit value (PSS-TLV).

If the inhaled chemical material is likely to dissolve only slowly or is essentially insoluble after deposition in any of the three principal regions of the respiratory tract, selection of the appropriate particle size-selective sample should be based on the specific site of action within the respiratory tract that is associated with the most restrictive PSS-TLV as based on comparing each potential disease.

Recommendations

Having considered many aspects of size-selective sampling in evaluating inhalation hazard in the work place, including 1) effects of particle size on deposition site within the respiratory tract, 2) the tendency for many occupational diseases to be associated with material deposited in particular regions of the respiratory tract, 3) the availability of suitable samplers, and 4) the relative inappropriateness of poorly defined "total dust" samples presently collected, it is recommended that

1. The ACGIH Chemical Substance TLV Committee develop particle size-selective TLVs (PSS-TLVs). PSS-TLV is a general term for (a) inspirable particulate mass TLVs (IPM-TLVs) for those materials which are hazardous when deposited anywhere in the respiratory tract, (b)thoracic particulate mass TLVs (TPM-TLVs) for those materials which are hazardous when deposited anywhere within the lung airways and the gas-exchange region, (c) respirable particulate mass TLVs (RPM-TLVs) for those materials which are hazardous when deposited in the gas-exchange region.
2. The size-selective sampling criteria be based upon the following definitions: (a) inspirable particulate mass consists of those particles that are captured according to the following collection efficiency regardless of sampler orientation with respect to wind direction:

$$E = 50(1 + \exp[-0.06d_a]) \pm 10: \quad \text{for } 0 < d_a \leq 100\ \mu m$$

Collection characteristics for $d_a > 100$ μm are presently unknown. E is collection efficiency in percent and d_a is aerodynamic diameter in μm, (b) thoracic particulate mass consists of those particles that penetrate a separator whose size collection efficiency is described by a cumulative lognormal function with a median aerodynamic diameter of 10 μm ± 1.0 μm and with a geometric standard deviation of 1.5 (± 0.1), (c) respirable particulate mass consists of those particles that penetrate a separator whose size collection efficiency is described by a cumulative lognormal function with a median aerodynamic diameter of 3.5 μm ± 0.3 μm and with a geometric standard deviation of 1.5 (± 0.1). This incorporates and clarifies the ACGIH respirable dust standard. The recommended aerosol mass fractions and the respiratory tract regions which they represent are shown in Figure 8.

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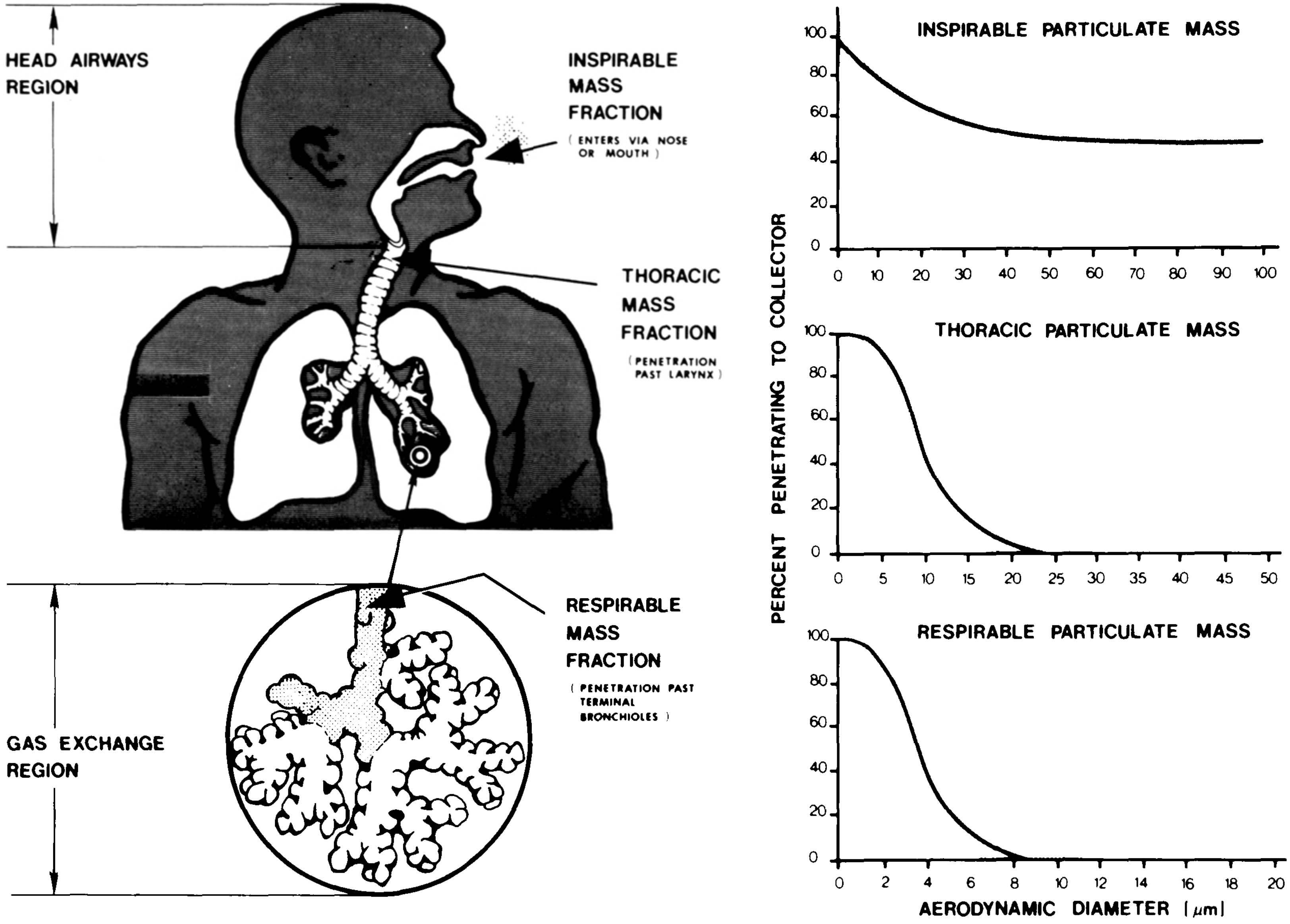

Figure 8—The three aerosol mass fractions recommended for particle size-selective sampling. Reprinted with permission from the American Conference of Governmental Industrial Hygienists.

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Radon was at fault...

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