5 ENVIRONMENTAL MONITORING

5.1 CURRENT SAMPLING CRITERIA

5.1.1 Characteristics of the Currently Approved Sampling Device

The Federal Mine Safety and Health Act of 1977* defines respirable dust as dust measured with a device approved by the Secretary of Labor and the Secretary of Health and Human Services [30 USC 842(e)]. The approved sampler for respirable coal mine dust is the coal mine dust personal sampler unit (CPSU) [30 CFR 74; Jacobson 1971; Jacobson and Lamonica 1969]. The CPSU is generally called the 10-mm nylon cyclone, although the 10-mm nylon cyclone is actually just one component of the CPSU. The CPSU may either be mounted on a worker (with the sampling head positioned in the breathing zone for personal exposure monitoring) or in a fixed location for area sampling [Tomb 1990].

The CPSU consists of a pump unit, a sampling head assembly, and a battery charger if rechargeable batteries are used in the pump unit [30 CFR 74.2]. The sampling head assembly contains two stages. The first stage is a 10-mm nylon cyclone, which has collection characteristics similar to an elutriator. The amount of dust penetration depends on the flow rate [Jacobson and Lamonica 1969]. The second stage is a membrane filter (vinyl, pore size 5 μm) that collects the dust passing through the cyclone. The dust collected on the membrane filter is weighed to a precision (standard deviation) of 81 μg [Parobeck et al. 1981], and the respirable dust concentration in the mine atmosphere is then determined from the mass of dust collected and the volume of air sampled [Tomb 1990].

5.1.2 Current Regulations for Sampler Certification

The specifications for the design and performance of the CPSU are listed in 30 CFR 74. NIOSH is responsible for conducting tests for the certification of the CPSU according to the requirements in 30 CFR 74.4. MSHA is responsible for conducting tests for the intrinsic safety of the pump unit of the CPSU.

Current regulations require that sampling devices be approved in accordance with 30 CFR 74 and calibrated in accordance with MSHA criteria [MSHA 1992a] by a certified person. Approved samplers must be calibrated and operated at the flowrate of 2.0 L of air/min, or at a different flowrate as prescribed by the Secretary of Labor and the Secretary of Health and Human Services [30 CFR 70.204(b)]. To convert a respirable dust concentration measured with an approved

*This Act amended the Federal Coal Mine Health and Safety Act of 1969 (P.L. 91-173).

sampling device to an equivalent concentration measured with an MRE[†] instrument, current regulations require that the concentration measured with the approved sampling device be multiplied by the constant factor prescribed by the Secretary of Labor [30 CFR 70.206].

A constant factor of 1.6 was originally used to convert concentrations measured with the CPSU to the equivalent MRE concentration. The 1.6 factor was based on dust measurements taken by the U.S. Bureau of Mines (BOM) with an earlier version of the CPSU [Jacobson 1970]. Another study had reported a conversion factor of 1.88 [Doyle 1970]. In a subsequent study, it was determined that the collection characteristics of the 10-mm nylon cyclone portion of the CPSU depended on the inherent pulsations of the pump [Lamonica and Treaftis 1971]. Thus, the specifications of the approved CPSU were modified to require pulsation damping of at least 80%, which would result in measured concentrations within 5% of those obtained using a sampling unit with constant flow. A new conversion factor of 1.38 was established for converting CPSU dust concentrations to MRE concentrations [Tomb et al. 1973].

5.1.3 Construction of the Sampling Device

Three studies have reported that charge effects on particles passing through the nylon cyclone can lead to bias in the collection of dust by nonconducting samplers [Briant and Moss 1984; Knight and Kirk 1982; Almich and Carson 1974]. Localized sources of electric field occur in nonconducting samplers, which influence the collection of charged aerosol particles in the air near the sampler. Briant and Moss [1984] reported a 40% reduction in the collection efficiency of a moderately-charged aerosol with a nonconducting, charged sampler. Knight and Kirk [1982] reported a 25% reduction in aerosol collection caused by charge effects of the filter holder of CPSUs. Almich and Carson [1974] reported a 10% variability associated with charge effects. Additional studies have reported charge effects during sampling with nonconductive filter cassettes [Puskar et al. 1991; Demange et al. 1990; Mark 1990; Liu et al. 1985; Turner et al. 1984]. Current specifications for the CPSU state that the cyclone must be constructed of nylon or a material equivalent in performance [30 CFR Part 74.3(b)(1)]. However, other available samplers are constructed of metal and are less sensitive to charge effects than the nylon CPSU (e.g., the Higgins-Dewell cyclone with a 37-mm filter cassette made of conductive material such as graphite-filled plastic) [Higgins and Dewell 1968].

5.2 RECOMMENDED SAMPLING CRITERIA

NIOSH recommends a revision of the current MSHA definition of respirable coal mine dust, which is the mass fraction of dust collected with the CPSU when operated at 2.0 L/min (and multiplied by 1.38 for the MRE equivalent concentration). Instead, NIOSH recommends the recently developed international definition of respirable dust, which represents a compromise between previous definitions of particle-size-selective sampling by the International Standards Organization (ISO), the Comité Européen de Normalisation (CEN), and the American Conference of Governmental Industrial Hygienists (ACGIH) [ACGIH 1984, 1994; CEN 1993; ISO 1993; Soderholm 1989, 1991a,b]. Table 5-1 presents the collection efficiencies for sampling devices that operate in accordance with the international definitions of either respirable, thoracic, or inhalable

[†]Mining Research Establishment of the National Coal Board, London, England.

Table 5-1. Collection efficiencies for particle-size-selective sampling

Respirable dust*		Thoracic dust		Inhalable dust	
Particle aerodynamic diameter (μm)	Respirable particulate mass (%)	Particle aerodynamic diameter (μm)	Thoracic particulate mass (%)	Particle aerodynamic diameter (μm)	Inhalable particulate mass (%)
0	100	0	100	0	100
1	97	2	94	1	97
2	91	4	89	2	94
3	74	6	80.5	5	87
4	50	8	67	10	77
5	30	10	50	20	65
6	17	12	35	30	58
7	9	14	23	40	54.5
8	5	16	15	50	52.5
10	1	18	9.5	100	50
		20	6		
		25	2		

Source: ACGIH [1994].
*The median cut point for a respirable dust sampler (4.0 mm) is in accordance with the international definition [ISO 1993].

dust. The respirable convention (E_R) is the target sampling curve for instruments approximating the respirable fraction. E_R is defined at aerodynamic diameter D by ISO [1993], CEN [1993], and ACGIH [1994] in terms of the cumulative normal function Φ as:

$$E_R = E_I \, \Phi[\ln[D_R / D] / \sigma_R]$$

where the indicated constants are $D_R = 4.25$ μm and $\sigma_R = \ln[1.5]$, and where the *inhalable* convention E_I is defined by:

$$E_I = 0.50\,(1 + \exp[-0.06\,D]),\; D < 100\ \mu m.$$

Two approaches to the approval of samplers may be considered: (1) the testing and approval of a single sampling device (e.g., the CPSU), or (2) the performance-based approval of a variety of sampling devices according to international criteria. Advantages of the single-sampler approach are that it provides consistency in sampling and avoids the potential for intersampler bias in the measurements. A disadvantage of the single-sampler approach is that it creates a disincentive for the development of improved samplers. Advantages of the performance-based sampler approach are that it stimulates the development of improved samplers and facilitates comparison to world exposure and effects data. A disadvantage of the performance-based approach is the extensive and expensive testing that would be required before samplers could be approved.

NIOSH recommends use of the international definition of respirable dust for sampling respirable coal mine dust for the following reasons:

- The particle size distributions reported for respirable dust in U.S. underground coal mines are within the approximate 2- to 10-µm range in which the collection efficiency of the sampler (operated in accordance with the international definition of respirable dust) is reasonably consistent with the fractional deposition of particles in the alveolar region of the human respiratory tract of healthy persons (Figure 5-1).

- The international definition of respirable dust better approximates the fraction of particles deposited in the alveolar region of the human respiratory tract than does the British Medical Research Council (BMRC) definition (see Figure 5-1).

- Respirable coal mine dust concentrations measured according to the current sampling criteria have been compared with those expected to be measured according to the international definition (see Section 5.7).

- Consistency with international standards for respirable dust sampling would be attained. This consistency would facilitate comparisons of the world literature about the health effects of exposure to respirable coal mine dust.

NIOSH recognizes the need to resolve the remaining technical questions associated with the recommended move to samplers that meet the international definition of respirable dust. In the interim, NIOSH recommends the use of the CPSU at a flow rate of 1.7 L/min without MRE conversion (versus 2.0 L/min with MRE conversion currently used by MSHA) for sampling respirable coal mine dust in accordance with the international definition of respirable dust. This NIOSH recommendation should be followed until acceptable criteria are developed for the performance-based approval of alternative samplers that also operate in accordance with the international definition of respirable dust. For example, the Higgins-Dewell sampler [Higgins and Dewell 1968] has been evaluated for performance according to the international definition [Bartley et al. 1994]. An additional advantage of using the flow rate of 1.7 L/min for the CPSU is that it would facilitate the use of a single sample for determining both respirable coal mine dust and respirable crystalline silica (which is currently sampled at 1.7 L/min).

The British MRE factor of 1.38 would not be applied to the values of respirable coal mine dust obtained from sampling according to the international definition. When the REL was derived from data based on the current MSHA sampling method, a conversion factor (Section 5.4) was used to compare the current method with the recommended sampling criteria. Thus, concentrations measured according to the recommended sampling criteria (international definition) do not require the use of a conversion factor.

5.3 BASIS FOR PARTICLE-SIZE-SELECTIVE SAMPLING

5.3.1 Early Definitions of Particle-Size-Selective Sampling

The concept of the CPSU and similar sampling devices (including those operating in accordance with the international particle-size-selective sampling definitions) is based on the following experimental evidence:

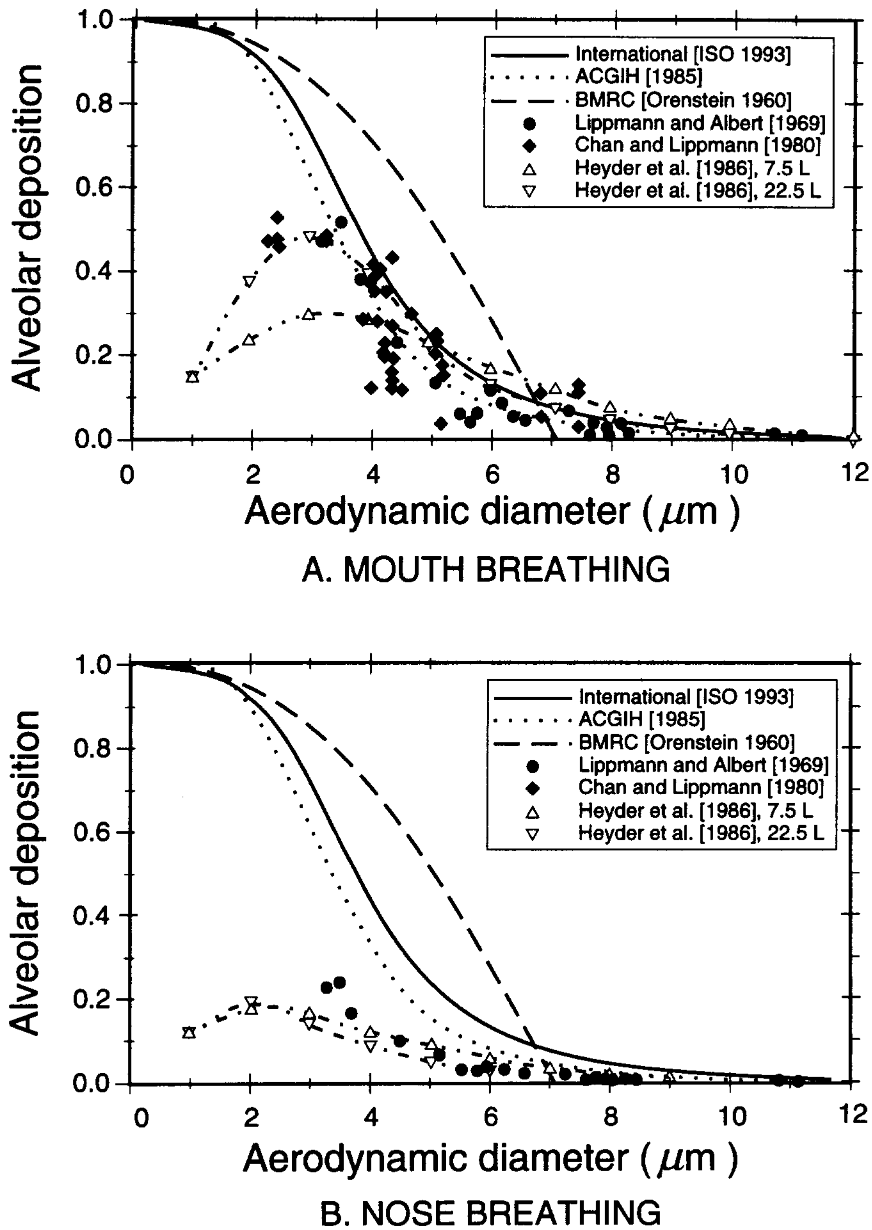

Figure 5–1. Comparison of the particle fraction deposited in the alveolar region of the lungs of healthy subjects [Heyder et al. 1986; Chan and Lippmann 1980; Lippmann and Albert 1969] with the ACGIH [1985], BMRC [Orenstein 1960], and international [ISO 1993] definitions of respirable dust. (Adapted from Soderholm [1989].)

- The deposition of particles in the respiratory tract depends on the size and shape of the particles (i.e., the aerodynamic diameter) [Chan and Lippmann 1980; Lippmann and Albert 1969; Task Group on Lung Dynamics 1966].

- The adverse health effects of inhaled particles depend on where the particles are deposited within the respiratory tract [Lippmann 1985; Nagelschmidt 1965].

As stated by Schlick and Peluso [1970], ". . . the instruments used to evaluate the atmosphere should simulate the respiratory tract in selecting the dust particles." The three major regions of the respiratory tract include the head airways region, the tracheobronchial region (including the trachea and ciliated airways in the lungs), and the alveolar region (including nonciliated airways and alveolar sacs in the lungs) [Soderholm 1989].

Early definitions for sampling respirable dust were developed by the U.S. Atomic Energy Commission (AEC) [Lippmann and Harris 1962] and by the BMRC. The BMRC definitions were adopted by the Johannesburg Pneumoconiosis Conference [Orenstein 1960]. The AEC curve has a sampling efficiency of 50% at a particle diameter of 3.5 µm (unit density, sphere), and the BMRC curve has a 50% sampling efficiency at 5 µm. An objective of particle-size-selective sampling has been to exclude from sampling those particles that are too large to enter the region of the lungs where the particles exert adverse health effects.

5.3.2 Deposition and Clearance of Particles in the Human Respiratory Tract

Data on the deposition of particles in various regions of the human respiratory tract are based on the use of radiotracer techniques [Emmett et al. 1982; Chan and Lippmann 1980; Lippmann and Albert 1969; Albert and Arnett 1955]. Deposition of particles in the small bronchi, bronchioles, and the parenchymal (gas exchange) region of the lung usually occurs by sedimentation for particles as small as 0.5 to 1.0 µm (aerodynamic diameter) [Stuart et al. 1984]. For particles smaller than 0.5 µm, deposition by diffusion occurs in small airways and gas exchange regions. Nonspherical shape of particles such as fibers may alter the deposition pattern. The electrical charges on particles also influence the fraction that is deposited. Freshly generated particles may be highly charged [Mercer 1973], and respiratory tract deposition can increase by 30% after inhalation of highly charged particles [Melandri et al. 1977].

Studies have been conducted on the clearance of particles from the lungs using radioactive particles to noninvasively determine the amount of material retained in the respiratory tract following aerosol exposure [Philipson et al. 1985; Bohning et al. 1982; Stahlhofen et al. 1981; Morrow et al. 1967; Albert and Arnett 1955]. Clearance of particles deposited in the respiratory tract is a continuous process that begins immediately after deposition [Stuart et al. 1984]. For insoluble particles such as coal mine dust, clearance is determined by the mechanical removal of particles by mucociliary transport from the airways. The phases of particle removal include a very rapid phase from extrathoracic airways, a fast phase from ciliated thoracic airways, and a slow phase from nonciliated thoracic airspaces [Stahlhofen et al. 1989; Heyder et al. 1986]. Clearance from ciliated portions of the lungs is called bronchial clearance, and clearance from nonciliated portions is called alveolar clearance [Heyder et al. 1986]. Thus, the partitioning of the lungs into bronchial and alveolar regions is based on the behavior of material deposited in the lungs and not on anatomical or physiological characteristics [Heyder et al. 1986]. The inhaled, insoluble particles that are deposited beyond the ciliated epithelium (i.e., in the respiratory bronchioles, alveolar ducts, and alveoli) can be phagocytized by alveolar macrophages and then cleared to the gastrointestinal tract or gradually dissolved [Phalen 1984; Stuart et al. 1984].

For the quantitation of risk from inhaled particles, the quantity of material deposited in a specified region of the respiratory tract and the amount remaining after physiological clearance from that region must be known [Stuart et al. 1984, 1986]. The amount of retained material may determine the effective dose of a contaminant that can produce acute or chronic pulmonary disease [Phalen et al. 1988]. Factors that affect particle deposition and retention include characteristics of the particles (size, shape, solubility), breathing rates and patterns, health status, and morphology of the respiratory tract [Miller et al. 1988; Phalen et al. 1986; Phalen 1984].

5.3.3 Deposition-Based and Penetration-Based Sampling Criteria

The design of the CPSU and similar sampling devices is based on the concept of the penetration of particles in the lungs (i.e., the ability of a particle to reach but not necessarily be deposited in a region of the lung [Soderholm and McCawley 1990]). Similarly, the international definition of respirable dust is based on the size of particles that enter the alveolar region of the human lungs (i.e., particle penetration, but not necessarily particle deposition or retention) (Figure 5-1). The international definitions of respirable, thoracic, and inhalable dust were influenced, in part, by the status of existing sampler technology and by the need to retain continuity with historical data bases (including respirable coal mine dust data collected according to the BMRC definition). The CEN working group has proposed that samplers purported to meet the international definition of respirable dust should be shown to be effective when sampling particle size distributions that have a median aerodynamic diameter between 1 and 25 μm and a geometric standard deviation between 1.5 and 3.5 [Kenny 1992].

The particle size distributions reported for respirable dust in U.S. underground coal mines are within the approximate 2- to 10-μm range in which the collection efficiency of the sampler (operated in accordance with the international definition of respirable dust) is reasonably consistent with the fractional deposition of particles in the alveolar region of the human respiratory tract (Figure 5-1). Figure 5-1 illustrates the fraction of particles that are deposited in the alveolar region of the human respiratory tract compared with the BMRC, ACGIH, and international definitions of respirable dust. Figure 5-1 also illustrates that although dust samplers conforming to these definitions collect up to 100% of the particles below approximately 2 μm, the alveolar deposition of particles below 2 μm in the human lungs is only about 20%. The deposition-based, size-selective sampling criteria are in better agreement with the deposition of particles in the human respiratory tract [Soderholm and McCawley 1990]. However, this approach would require more complicated size-selective samplers using several substrates. A deposition curve would also need to be determined based on the mean fraction of particles deposited in the respiratory tracts of a given human population. Because of the large variability among individuals in the particle deposition fraction, the deposition curve of the population would not necessarily provide a reasonable approximation of deposition in an individual. Thus, for occupational exposures (including respirable coal mine dust) in which the penetration curves provide a reasonable approximation and are proportional to deposition curves, there is little justification for using the more complicated deposition samplers for routine sampling. However, it is important to determine that the particle size distributions to be sampled lie within the measurable range of the sampler [Liden and Kenny 1991]. This determination should be repeated at periodic intervals because changes in working conditions may alter particle size distributions [Soderholm and McCawley 1990].

The criteria for sampler performance based on particle penetration into the lungs are protective for workers because it is unlikely that penetration-based samplers would underestimate the amount of material that could be deposited [Soderholm and McCawley 1990]. However, the effect of systematically over-estimating the dust deposition is to weaken the exposure-response relationship and potentially to overlook the need to develop appropriate exposure standards [Hewett 1991; Soderholm and McCawley 1990]. Despite this possible limitation, epidemiologic studies have found significant exposure-response relationships based on dust measurements collected with these penetration-based sampling devices (see Chapter 4).

5.4 CONVERSION FACTOR FOR COMPARING CURRENT AND RECOMMENDED SAMPLING CRITERIA

The international definition of respirable dust is shown in Figure 5-2 in terms of sampling efficiency at a given aerodynamic diameter. A quantitative description of the curve is given in CEN [1993]. Figure 5-2 also depicts recently measured sampling efficiencies for the CPSU at 2.0 L/min and at 1.7 L/min and for the Higgins-Dewell sampler at 2.2 L/min [Maynard 1993; Bartley et al. 1994]. These flow rates were chosen to match as closely as possible the international definition of the diameter at which the sampling efficiency equals 50% [Liden and Kenny 1993; Bartley et al. 1994]. This "cut-diameter" has been shown to dominate other cyclone parameters (such as the sampling efficiency sharpness) in characterizing the sampling of dusts distributed over diameters [Bowman et al. 1984] The data presented in Figure 5-2 are consistent with data from earlier studies [Caplan et al. 1973; Blachman and Lippmann 1974; Chan and Lippmann 1977; and Bartley and Breuer 1982].

To calculate a conversion factor for comparing current sampling criteria (Section 5.1) and recommended sampling criteria (Section 5.2), sampling efficiency curves are combined numerically with the aerosol size distributions (mass per unit particle diameter interval) measured in coal mines using data from Mutmansky and Lee [1987]. Liden and Kenny [1991] have documented that computed respirable mass concentrations are equivalent to measured concentrations in assessing distributed aerosol sizes.

Mutmansky and Lee [1987] provide detailed data about the measured concentrations of coal mine dust at various locations within 11 underground coal mine sections using continuous mining machines. The data in Mutmansky and Lee [1987] are consistent with other data on the particle size distributions measured in coal mines [Hinds and Bellin 1988; Bowman et al. 1984]; however, these studies present only a summary of data for each size distribution. The data from Mutmansky and Lee [1987] in Appendix 5 are suitable for accurately estimating the respirable fractions that

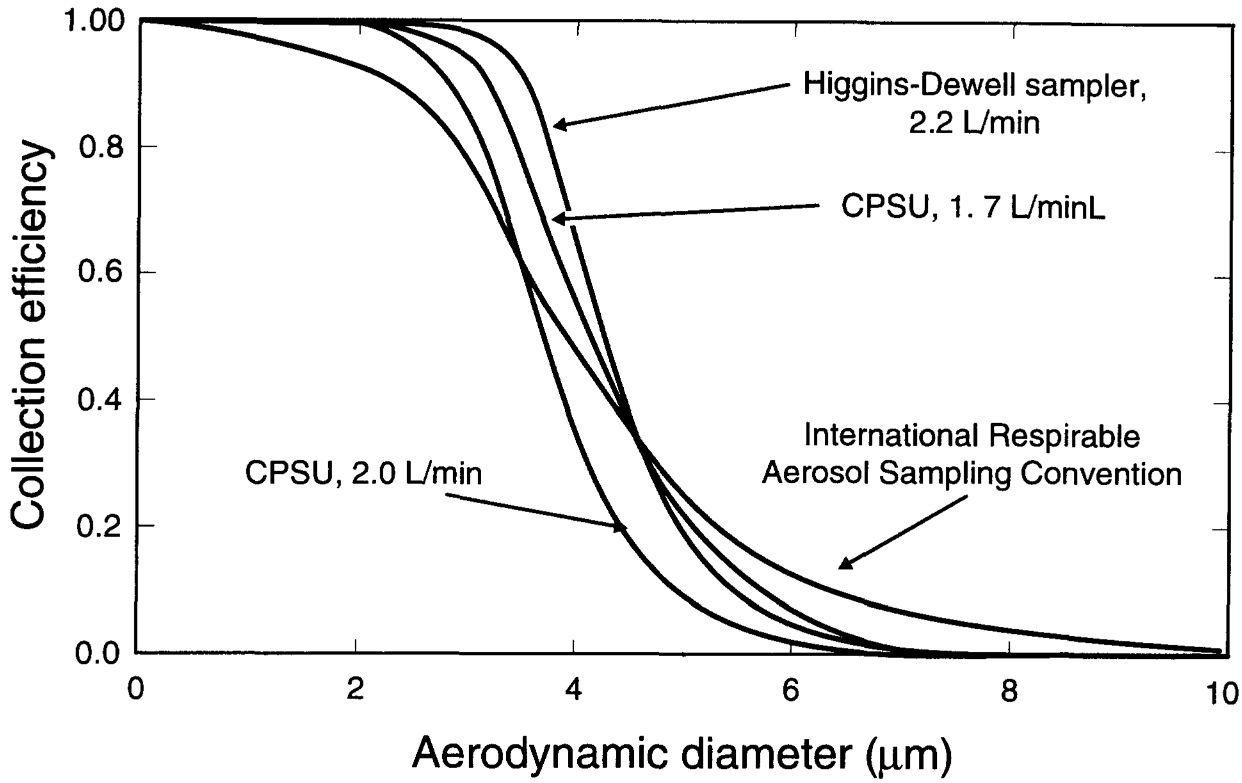

Figure 5-2. Respirable aerosol collection efficiencies.

would be obtained using any of the respirable dust definitions or various sampling systems. Hence, conversion factors can be obtained. The data are presented as cumulative fractions of the dust mass sampled (using the cascade impactor, Sierra Model 298) at diameters smaller than 0.5, 0.9, 2.0, 3.5, 6, 10, 15, and 21 μm. Because the respirable sampling efficiencies are close to zero at diameter D 10 μm, the two fractions of the largest size dust are not needed here. Similarly, the contribution of the 0.5-μm fraction to the total respirable mass is generally less than 10% and is therefore ignored (except insofar as it is a part of the 2.0-μm fraction).

To compute conversion factors, the remaining five cumulative fractions are modelled mathematically. The purpose is twofold: (1) uncertainty in the individual measurements is smoothed out through linear regression, and (2) models are convenient for computation in which a smooth size distribution is needed. Lognormal parameters consisting of mass median diameter (MMD) and geometric standard deviation (GSD) are used. An inverse-lognormal transformation of the data followed by simple linear regression provides two parameters (i.e., section or location). Note that uncertainty in the total dust concentration leaves the cumulative (measured) fractions in error by an unknown constant. Changes from the constant assumed by Mutmansky and Lee [1987] would shift the MMD and GSD in a correlated manner. Insofar as lognormality is a good approximation, however, such shifts are along curves of constant conversion factors and are therefore insignificant (Figures 5-3 and 5-4).

In Figures 5-3 and 5-4, the MMD and GSD for the size distribution of each particular coal mine section or location are shown as solid dots. Figures 5-3 and 5-4 also depict the factors for converting (at any given values of MMD and GSD) from current MSHA sampling criteria (including the 1.38 factor) to the international sampling criteria. The CPSU and the Higgins-Dewell sampler are among those that have been shown to perform within the criteria required for the international definition [Bartley et al. 1994]. Figure 5-3 provides the conversion factor for the CPSU operated at 1.7 L/min, and Figure 5-4 provides the conversion factor for the Higgins-Dewell sampler operated at 2.2 L/min. Both figures indicate the appropriate conversion factor corresponding to any given values of MMD and GSD. But because the size distribution to be sampled is not fixed, the MMD and GSD cannot be specified, and an average conversion factor must be calculated over a range of MMD and GSD values expected in U.S. coal mines.

On the basis of MMD and GSD values from the data of Mutmansky and Lee [1987], the following average conversion factors can be applied to concentrations measured by the current MSHA criteria (Section 5.1) to obtain the equivalent concentration measured according to the international definition of respirable dust (Section 5.2):

CPSU operated at 1.7 L/min: 0.857

SD‡ = 0.029

Higgins-Dewell sampler operated at 2.2 L/min: 0.867

SD = 0.028

The above GSD values indicate the size-distribution-induced component of the variability expected in side-by-side sampling. This component is small relative to the spacial variability estimated in Appendix K.

Thus, with a concentration of 1.00 mg/m^3 measured with the CPSU according to current MSHA sampling criteria (Section 5.1), the corresponding concentration would be 0.86 mg/m3 with the CPSU operated according to the recommended criteria, or 0.87 mg/m^3 with the Higgins-Dewell sampler operated according to the recommended criteria (Section 5.2). A separate preliminary analysis of particle size distributions collected over a 10-year period by different investigators using similar methodology yielded a similar conversion factor of 0.85 for the CPSU operated according to current versus recommended sampling criteria [Hewett 1993]. These conversion factors are considered in the derivation of the REL (see Chapter 7).

‡SD = arithmetic standard deviation.

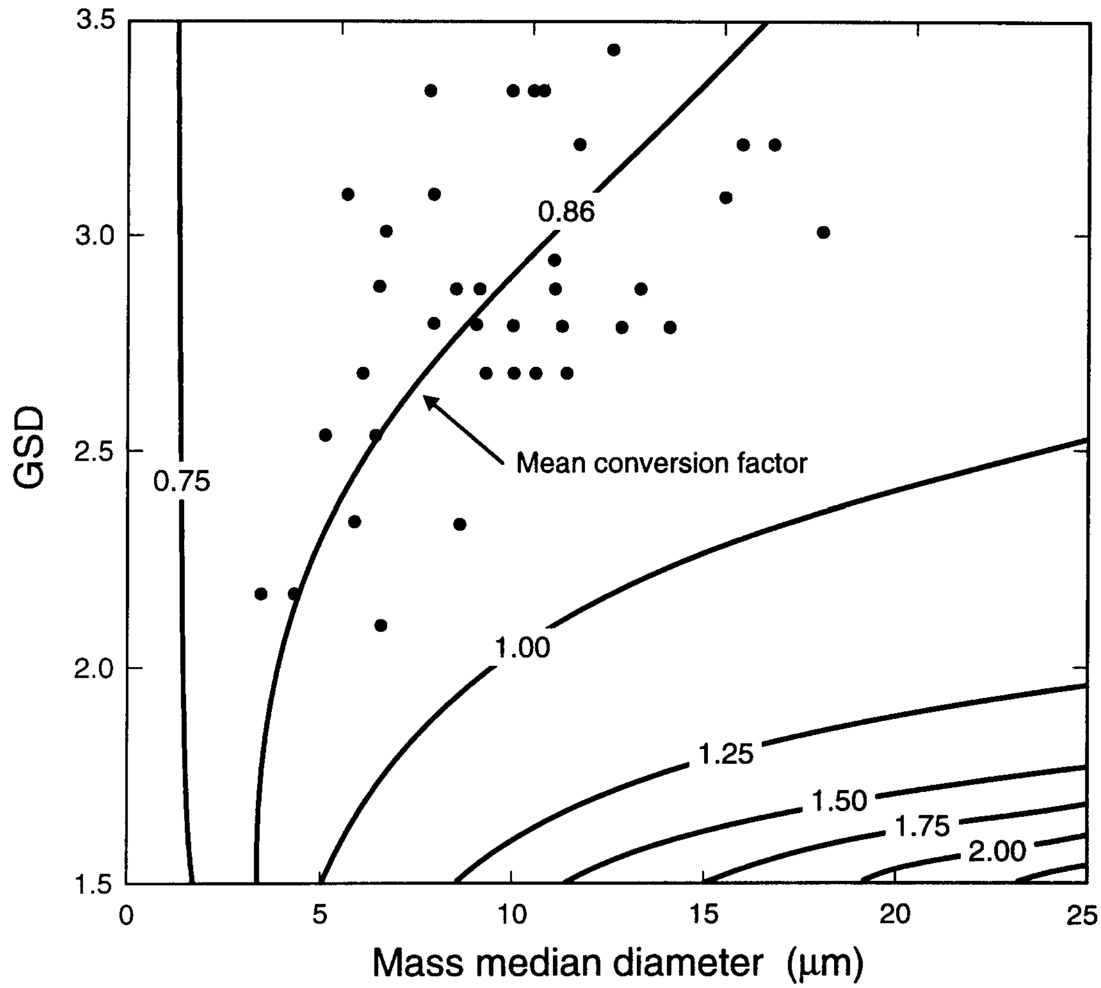

Figure 5–3. Conversion factor: MSHA standard to CPSU at 1.7 L/min.

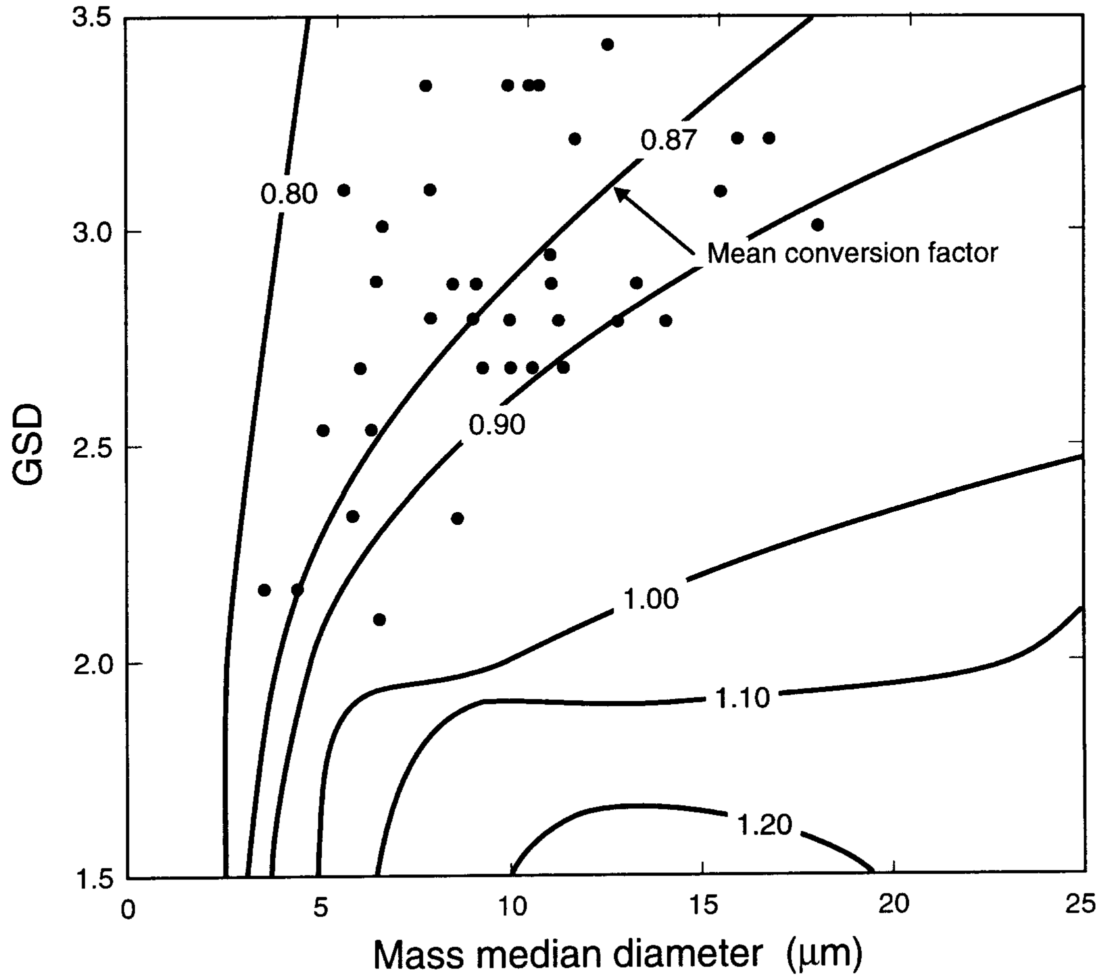

Figure 5–4. Conversion factor: MSHA standard to Higgins-Dewell sampler at 2.2 L/min. Excluded are points from a diesel-operated mine where the size distribution is clearly bimodal over the respirable region. Also, 6 points with GSD >3.5 μm are not plotted (yet fall within the iso-factor curves of the points shown).

5.5 CURRENT SAMPLING PROGRAM

5.5.1 MSHA Inspector Sampling

MSHA inspectors sample at least five occupations in each mechanized mining unit (MMU), including the designated occupation and any roof bolter occupations on the MMU that were not established as designated areas [MSHA 1989a]. MSHA inspectors collect one designated area sample per year at the location specified in the operator's Ventilation System and Methane and Dust Control Plan [30 CFR 75.316]. MSHA inspectors may also collect full-shift respirable dust samples from nondesignated entities (which represent either nondesignated areas or non-designated occupations) if an inspection is requested by a miner or a miner's representative [according to 30 USC 813(g)] or if the inspector suspects that the concentrations of respirable coal mine dust or respirable quartz exceed the PEL. MSHA inspectors collect one personal sample per year from the environment of all underground and surface coal miners who are designated as "Part 90 miners" [MSHA 1989a]. At surface coal mines or surface work areas of underground coal mines, MSHA inspectors collect one sample per year from all designated work positions and at least three other occupations, if available, at these sites. MSHA inspectors also collect full-shift respirable dust samples of the intake air, with placement of the sampling device in the intake airway within 200 ft outby a working face [30 CFR 70.100(b)].

MSHA inspectors determine which entities to sample based on the following: (1) the compliance record of the mine, (2) the adequacy of the dust control parameters, (3) the number of entities being sampled by the operator as designated occupations or areas, Part 90 miners, or designated work positions, (4) the number of entities available for sampling, and (5) changes in mining conditions (since the last inspection) that may affect the concentration of respirable coal mine dust or respirable quartz [MSHA 1989a]. Designated area, nondesignated entity, and intake air samples are area samples, and Part 90 samples are personal samples. Inspections are currently required four times per year in underground coal mines to determine (among other safety and health issues) whether the parameters of the approved dust control plan are being maintained. However, exposure monitoring may be performed during just one of these inspections. Inspections are currently required at least twice per year in surface coal mines [30 USC 813(a)].

5.5.2 Coal Mine Operator Sampling

Current regulations require coal mine operators to take five valid respirable dust samples from designated occupations in each MMU for each bimonthly sampling period; samples are to be collected on consecutive normal production shifts [30 CFR 70.207]. Designated occupations for sampling are listed by mining method [30 CFR 70.207(e)] in Table 5-2. One requirement of designated-occupation sampling is that the sampling device must remain in the location of the occupation being sampled [MSHA 1989a]. Thus, the sampler may be transferred from one miner to another if the first miner moves to another location in the mine. Mine operators are also required to take one valid respirable dust sample from each designated area on a production shift during each bimonthly period [30 CFR 70.208]. The minimum production level required for valid bimonthly operator-collected samples is currently 50% of the average production reported for the last set of five valid samples [30 CFR 70.2(k)]. However, any sample with greater than 2.5 mg/m^3 of respirable coal mine dust is considered a valid sample, regardless of production level [30 CFR Part 70.207(d)].

Table 5-2. MSHA-required operator sampling of designated occupations in underground coal mines*

Mining method of section	Designated occupation for section	Position of sampling devices relative to designated occupation
Conventional	Cutting machine	On miner or on cutting machine within 36 in. inby normal working position
Conventional	Loading machine operator	On miner or on loading machine within 36 in. inby normal working position
Continuous mining (other than auger type)	Continuous mining machine operator	On miner or on continuous mining machine within 36 in. inby normal working position
Continuous mining (auger type)	Jacksetter working nearest working face on return-air side of continuous mining machine	On miner (as described) or at location representing maximum concentration of dust to which person is exposed
Scoop using cutting machine	Cutting machine operator	On miner or on cutting machine within 36 in. inby normal working position
Scoop (shooting off solid)	Coal drill operator	On miner or on coal drill within 36 in. inby normal working position
Longwall	Miner working nearest return-air side of longwall working face	On miner (as described) or along working face on return side within 48 in. of corner
Hand loading with cutting machine	Cutting machine operator	On miner or on cutting machine within 36 in. inby normal working position
Hand loading (shooting off solid)	Hand loader exposed to greatest concentration of dust	On miner or at location representing maximum concentration of dust to which miner is exposed
Anthracite mine	Hand loader exposed to greatest concentration of dust	On miner or at location representing maximum concentration of dust to which miner is exposed

*30 CFR 70.207 (e).

Mine operators are also required to sample surface coal mines or surface work areas of underground coal mines on a bimonthly basis [30 CFR 71.208]. Designated work positions are determined by the MSHA district manager for each work position with an average concentration of respirable dust exceeding 1 mg/m^3 (or less if the applicable standard is less than 1 mg/m^3)

[30 CFR 71.208(e)]. In both underground and surface coal mines, the PEL for respirable coal mine dust is currently reduced if the quartz content exceeds 5% [30 CFR 70.101; 30 CFR 71.101].

Since 1985, samples collected by coal mine operators have been used in addition to MSHA inspector samples to determine the reduced PEL. Under this system, if the sample collected by the MSHA inspector contains more than 5% quartz, the operator has the option of submitting a sample for quartz analysis and subsequent averaging with the inspector quartz sample [Niewiadomski et al. 1990]. If the quartz content of the operator sample differs by more than 2% (e.g., 4% vs. 6% or 10% vs. 12%) from the inspector sample, the operator is given the opportunity to submit another sample. The standard is then based on the average of quartz percentages from one inspector sample and two operator samples (see Table 2-1 for formula). Once an entity (i.e., job, area, or work position) is placed on a reduced standard, it is reevaluated approximately every 6 months by quartz analysis of a valid, operator-collected respirable dust sample of sufficient weight. MSHA uses the low-temperature ashing, infrared method to determine the amount of quartz in respirable dust samples, and individual dust samples weighing 0.5 mg or more can be analyzed for quartz [Niewiadomski et al. 1990].

5.5.3 Ventilation System and Methane and Dust Control Plan

According to 30 CFR 75.316, underground coal mine operators are required to submit a "Ventilation System and Methane and Dust Control Plan," which must be reviewed by the operator and MSHA at least every 6 months. The plan must include information about the mechanical ventilation equipment, the quantity and velocity of air, the operating parameters for required dust control devices, and the locations of designated area sampling (required in accordance with 30 CFR Part 70.208). The minimum production required for approval of the dust control plan is 60% of the average production over the last 30 production shifts [MSHA 1992b].

The Coal Mine Respirable Dust Task Group has evaluated the dust control plan approval process and has made recommendations for improving its effectiveness [MSHA 1992b]. The Task Group noted that primary reliance on environmental controls minimizes the possibility that workers will be exposed to excessive concentrations of respirable coal mine dust. They identified several important factors for improving the effectiveness of dust control plans: (1) sufficient detail and specificity in the dust control plans, (2) proper consideration of production levels, (3) upgrading of plans following abatement of citations, (4) and frequent sampling.

NIOSH makes the following recommendations, which are consistent with those of the Task Group:

- Mine operators should specify dust control parameters for typical production levels.
- Mine operators should evaluate the effectiveness of dust controls at typical production levels.
- Mine operators should perform additional sampling to evaluate dust controls whenever changes in controls or processes (e.g., increased production) might result in worker exposures exceeding the REL.

5.6 SAMPLING RECOMMENDATIONS

5.6.1 Sampling Strategy Issues

The sampling goals determine the approach needed to monitor concentrations of respirable coal mine dust and respirable crystalline silica. These goals may include determining the effectiveness of dust control systems, determining compliance with an exposure limit, and determining individual exposures to investigate exposure-response relationships.

Section 5.5 describes the current MSHA regulations for MSHA inspectors and coal mine operators sampling respirable coal mine dust and respirable crystalline silica at underground and surface worksites. The current sampling program generates more than 100,000 respirable dust samples per year. NIOSH recommends further evaluation of the current sampling program to ensure that exposures are below the REL for each miner during each shift. Numerous types of sampling strategies have been published and could be considered in such an evaluation (see Publications Examined, Sampling Strategies).

The mine operator is responsible for ensuring that the hazards from respirable coal mine dust are minimized or eliminated within each work environment throughout the mine and support facilities. The objective of an effective exposure sampling strategy is to periodically obtain sufficient, valid, and representative exposure estimates so that the work environment is reliably classified as either acceptable or unacceptable.

5.6.1.1 Frequency of Sampling

Exposure sampling should be periodic and should occur frequently enough that a significant and deleterious change in the contaminant generation process or the exposure controls is not permitted to persist. This is particularly true for face areas in underground coal mining where mining conditions can change dramatically within a short span of time.

5.6.1.2 Number of Exposure Measurements

Exposure measurements provide estimates of the magnitude of worker exposures in the recent past. Exposure measurements to determine the efficacy of existing exposure controls are used to predict exposures in the near future. Consequently, a critical attribute of a collection of exposure measurements is their predictive value. Although a single, full-shift sample will accurately measure the average airborne concentration during that shift, a single exposure measurement has little predictive value for demonstrating that a work environment is (and is likely to remain) acceptable. Note, however, that a single exposure measurement above the REL has a high predictive value, since exposures above the REL should occur infrequently (if at all) in a well-controlled work environment. The number of representative full-shift measurements collected should be sufficient to reliably detect work environments where exposure conditions are routinely unacceptable.[§]

[§]Where the work environment is particularly dynamic, it may be desirable to adopt a quality control approach when collecting exposure measurements. For example, one or more measurements could be collected at closely spaced intervals instead of monitoring a number of consecutive work shifts at 2-month intervals, as is the current practice.

5.6.1.3 Validity of Exposure Measurements

A valid exposure estimate measures what it is purported to measure [Leidel and Busch 1994]. Validity refers to possible nonrandom (systematic) sampling errors or biases in exposure measurements that can result in unrepresentative estimates of exposure. Systematic bias cannot be detected with statistical methods based on probability theory and must therefore be considered when designing the sampling strategy. Quality control programs can be useful for identifying systematic measurement errors. For example, proper calibration and periodic checks of the sampling pump flowrate and the condition of the sampling unit and sample cassette are needed for valid exposure measurements.

5.6.1.4 Representative Exposure Measurements

5.6.1.4.1 Sampling design

Each exposure measurement should be representative; that is, when measurements are collected, worker exposures should be comparable with those during unsampled shifts. In principle, a group of exposure measurements is considered representative if the measurements are collected randomly—that is, with no systematic bias in the selection of workers or sampling shifts. Randomly collected samples would include exposure measurements from both above- and below-average production shifts (see section 5.6.1.4.2). A design for statistically representative sampling may be used, for example, when the goal is to determine the distribution of all worker exposures over time to evaluate exposure-response relationships.

However, when the goal of sampling is to determine whether or not worker exposures are being kept below the REL, random sampling is usually not included in the sampling design. Instead, strategies are used that focus sampling efforts on those workers with the highest exposures (i.e., the maximum-risk worker concept discussed by Leidel et al. [1977] and Leidel and Busch [1994]). Such strategies may be more efficient (i.e., use fewer resources) for identifying potential exposures above the REL, but sufficient periodic sampling of all workers or groups of workers should also be performed to ensure that the targeted sampling groups include all workers with the potential for exposures above the REL.

5.6.1.4.2 Level of coal production

The level of coal production significantly affects the amount of airborne respirable coal mine dust [MSHA 1992b]. Thus, for example, a measurement collected from a worker at the coal face during a shift with abnormally low production has little or no predictive value for estimating exposures during unsampled shifts with typical coal production. The mine operator should therefore establish a production-level threshold to ensure that exposure conditions are comparable between sampled and unsampled shifts.

A sample shift with a production level equal to or greater than the production-level threshold is considered typical (i.e., a normal production shift). The definition of a normal production shift should be similar to or more stringent than that used when seeking approval of the dust control plan.** Consistent with standard industrial hygiene practice (which requires exposure measurements to be collected during typical work shifts), NIOSH recommends that for a production shift to be considered a "normal production shift," it must produce at least 80% of the average production over the last 30 production shifts.†† The ventilation rate and the dust suppression devices and techniques used during sampled shifts should also be typical of normal production shifts.

In principle, the distribution of sample shift production levels should be similar to the overall distribution of production levels (truncated at the production level threshold). A significant difference between these distributions should not normally occur. A more stringent threshold should be imposed if it appears that sample shift production levels are routinely lower than those of unsampled shifts. These recommendations may evolve with additional data analyses and future evaluations of the current sampling program.

5.6.1.5 Reliable Classification of Work Environments as Acceptable or Unacceptable

A properly designed exposure sampling strategy will reliably classify a work environment: that is, it will have a high probability of classifying a work environment as acceptable when exposures are well-controlled, or unacceptable when exposures are poorly controlled.

The REL is defined here as the upper limit of exposure to respirable coal mine dust as a TWA concentration for up to 10 hr/day during a 40-hr workweek. Consistent with this definition, NIOSH defines an acceptable work environment as one where single-shift excursions above the REL occur infrequently, if at all. Consequently, NIOSH expects that in a well-controlled, acceptable work environment, the long-term average exposure for each miner will be sufficiently low to preclude the development of adverse health effects or the progression of existing disease.

5.6.1.6 Additional Personal Monitoring

An additional component of an effective sampling program is the need for additional personal exposure monitoring for miners who show early signs of occupational respiratory disease. Such monitoring should be part of an intervention program to prevent further development of disease.

5.6.2 Single, Full-Shift Sampling

The MSHA PEL is based on the standard specified in the Federal Mine Safety and Health Act of 1977 [30 USC 801-962].‡‡ The Act states that "each operator shall continuously maintain the

**The Coal Mine Respirable Dust Task Group [MSHA 1992b] concluded that the current procedure for defining a normal production shift "for sampling purposes" (see Section 5.5.2) is inadequate and makes the current sampling program susceptible to intentionally reduced production during shifts when exposure measurements are being collected.

††The minimum production level currently required for bimonthly operator-collected samples is 50% of the average production reported for the last set of five valid samples [30 CFR 70.2(k)], and the minimum production level required for approval of the dust control plan is 60% of the average production over the last 30 production shifts[MSHA 1992b].

‡‡This Act amended the Federal Coal Mine Health and Safety Act of 1969 (P.L. 91-173).

average concentration of respirable dust in the mine atmosphere during each shift to which each miner in the active workings of such mine is exposed at or below 2.0 milligrams of respirable dust per cubic meter of air" [30 USC 842(b)(2)]. The Act defines "average concentration" as that measured over a single shift:

> [T]he term 'average concentration' means a determination which accurately represents the atmospheric conditions with regard to respirable dust to which each miner in the active workings of a mine is exposed (1) as measured, during the 18 month period following December 30, 1969, over a number of continuous productions shifts to be determined by the Secretary (of Labor) and the Secretary of Health and Human Services, and (2) as measured thereafter, over a single shift only, unless the Secretary (of Labor) and the Secretary of Health and Human Services find, in accordance with the provisions of section 811 of this title, that such single shift measurement will not, after applying valid statistical techniques to such measurement, accurately represent such atmospheric conditions during such shift [30 USC 842(f)].

NIOSH recommends the use of single, full-shift samples to compare worker exposures with the REL. For single, full-shift samples used to determine noncompliance, NIOSH recommends that MSHA make no upward adjustment of the REL to account for measurement uncertainty [NIOSH 1994c]. By enforcing the exposure limit without any upward adjustment, MSHA would provide an equitable sampling program in which (given frequent sampling) the burden of measurement error is shared equally by miners and operators.

Statistical methods that account for measurement uncertainty [e.g., Leidel et al. 1977] may be a useful component of a mine operator's program to keep worker exposures to respirable coal mine dust below the REL during each work shift. Quality control approaches may involve determining long-term average exposures as part of a program for monitoring the effectiveness of engineering controls.

5.6.3 Types of Environmental Monitoring

The three types of environmental monitoring generally used include personal, breathing zone, and area sampling [Leidel et al. 1977]. For personal sampling, the sampling device is attached to the worker and is worn continuously for all work and rest periods during the shift. For breathing zone sampling, the sampling device is placed in the breathing zone of the worker; a second individual may be required to hold the sampling device in this location. For area sampling, the sampler is placed in a fixed location in the workplace.

When the purpose of the environmental monitoring is to determine worker exposures, personal sampling or breathing zone sampling should be used [Leidel et al. 1977]. Area sampling to determine worker exposures should demonstrate that such samples accurately measure worker exposures [Leidel et al. 1977].

5.6.3.1 Personal Sampling

NIOSH recommends personal exposure monitoring, based on an evaluation of the literature

(Section 5.6.3.2). The following summarizes the advantages of personal sampling to estimate worker exposures:

- Personal samples correlate best with exposures judged by biological indicators.
- Personal samples represent variations in worker exposures better than fixed-point area samples.
- Personal samples estimate worker exposures better than area samples, which tend to underestimate worker exposures.
- Personal exposure estimates may be used to evaluate exposure-response and the effectiveness of exposure standards.
- Personal sampling must be used to accurately assess the effectiveness of dust avoidance technologies (e.g., those with remote control operations). Such technologies may be useful for improving worker safety and reducing workplace exposures.

5.6.3.2 Studies Comparing Personal and Area Monitoring

Personal sampling provides the best estimate of worker exposures and the temporal and spatial variability in those exposures [Vincent 1994]. In nearly all the studies where personal and area monitoring were compared with clinical measures of occupation-related adverse health effects, the personal exposure measurements provided the best correlations [Stopford et al. 1978; Linch et al. 1970; Linch and Pfaff 1971]. Also, the personal exposures are frequently higher than the exposures measured by area monitoring [Niven et al. 1992; Cinkotai et al. 1984; Yoshida et al. 1980; Tomb and Ondrey 1976].

In a study of British longwall mines by the Institute of Occupational Medicine, Hadden et al. [1977] compared personal samplers with area samplers placed in the return airway. This sampling location presumably represents the maximum concentration of dust to which longwall miners are exposed. Nevertheless, the average dust concentration of the personal samples taken on a section was 10% higher than that in the area sample. The personal sampler data for the high-risk miners averaged 38% higher than the corresponding area samples. In a companion study for continuous and conventional mining, Garland et al. [1979] concluded that fixed-point gravimetric samples were unreliable for estimating worker exposures over a work shift. The authors also found that the creation of localized dust clouds at the coal face contributes greatly to individual exposure patterns; thus, the use of fixed-point (e.g., area) monitors may underestimate worker exposures at the coal face.

Studies have also reported large spatial variability in workplace dust concentrations. For example, in a study of various workplaces, Vaughan et al. [1990] report that lapel-to-lapel variations on a single worker can be so large that in 5% of the comparisons, a personal sampler on one lapel yielded more than twice the inhalable dust concentration of a sampler on the other lapel (although variability in concentrations of smaller particles such as respirable dust might be less). Variations from lapel to lapel are smaller than personal to area monitoring gradients, as demonstrated by

BOM data that showed large dust concentration gradients in underground coal mines over a 10-year period [Kissel and Jankowski 1993]. Near the continuous miner, gradients were reported to increase up to 1 mg/m^3 per foot in the direction of the coal mine face. Dust gradients are also large in longwall coal mines, as shown by increases in dust concentration by a factor of 10 in the 9-meter distance along the face in the walkway downwind of the shearer. The associated measurement bias can be quite large and variable (17% to 36%) [Kost and Saltsman 1977].

5.6.3.3 Area Sampling

NIOSH recognizes that sampling to assess controls and personal exposures may require separate approaches. Area sampling may be preferable during the development of controls to detect sources of dust or to assess the efficacy of a particular control measure. However, the ultimate acceptance of a new control depends on its ability to reduce personal exposure to respirable coal mine dust and respirable crystalline silica.

The Federal Mine Safety and Health Act of 1977 refers to "the average concentration of respirable dust in the mine atmosphere during each shift to which each miner in the active workings of such mine is exposed" [30 USC 842(b)]. The reference to "atmosphere" could be interpreted as an indication that area sampling is sufficient. However, NIOSH believes that the intent of the Act is to provide for the control of each miner's personal exposure and that personal sampling is therefore preferable. Area sampling should be substituted for personal sampling only where area sampling has been shown to measure an equivalent or higher concentration.

5.7 Analytical Methods

The concentration of respirable coal mine dust in the mine atmosphere is determined gravimetrically [Tomb 1990]. Sampling and analysis for respirable crystalline silica should be performed in accordance with NIOSH Method 7500, 7602, or a demonstrated equivalent [NIOSH 1994b]. Sampling devices that may be used for Method 7500 or 7602 include the CPSU (with a 0.8-µm or 5-µm polyvinyl chloride (PVC) or mixed cellulose ester membrane filter) operated at a flow rate of 1.7 L/min, the Higgins-Dewell sampler operated at 2.2 L/min, or an equivalent sampler [NIOSH 1994b]. The presence of the minerals kaolinite ($Al_2Si_2O_5(OH)_4$) and calcite ($CaCO_3$) in the dust sample may interfere with analysis by Method 7602. This method provides correction procedures to use if either kaolinite or calcite is present. When respirable coal mine dust is to be analyzed in the same sample, mixed cellulose ester membrane filters should not be used because of their high weight variability. A preweighed polyvinyl chloride filter should be used and a final weight should be taken before ashing when Method 7602 is used to analyze crystalline silica in coal mine dust. In Method 7500, the presence of kaolinite and calcite do not interfere with the method if the samples are ashed in a low-temperature asher or if they are suspended in tetrahydrofuran [NIOSH 1994b].

The current analytical method used by MSHA (known as MSHA P-7) [MSHA 1989b] differs from NIOSH Method 7602 in the sample preparation procedures. The uneven deposition of ash that has been observed in the filtration step of MSHA P-7 can adversely affect the quantitation of the quartz [Lorberau 1990]. NIOSH Method 7603 [NIOSH 1994b] is similar to MSHA P-7 both in its use of the same filtration technique and in its specification of a 2.0-L/min flow rate for sample collection. NIOSH Method 7603 and MSHA P-7 are designed specifically to analyze respirable crystalline silica in coal mine dust and thus may reduce some of the interferences that can occur in samples collected in the mining environment. However, NIOSH Method 7602 is the preferred infrared method because it avoids the uneven deposition of ash and has the more appropriate sample collection flow rate of 1.7 L/min (see Appendix J).

In lieu of either NIOSH Method 7603 or MSHA P-7, NIOSH Method 7602 is recommended for the analysis of respirable crystalline silica.