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EXTERNAL REVIEW

# CRITERIA FOR A RECOMMENDED STANDARD

# OCCUPATIONAL EXPOSURE TO RESPIRABLE COAL MINE DUST

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Division of Standards Development and Technology Transfer
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## ABBREVIATIONS

| | |
|---|---|
| ATS | American Thoracic Society |
| BAL | Bronchoalveolar lavage |
| CFR | Code of Federal Regulations |
| CI | Confidence interval |
| CMDPSU | Coal mine dust personal sampler unit |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COPD | Chronic obstructive pulmonary disease |
| CWP | Coal Workers' Pneumoconiosis |
| CWXSP | Coal Workers' X-Ray Surveillance Program |
| DO | Designated occupation |
| DLCO | Diffusing capacity of the lung for carbon monoxide |
| DWP | Designated work position |
| Fed. Reg. | Federal Register |
| $FEV_1$ | Forced expiratory volume in 1 second |
| FVC | Forced vital capacity |
| g/m | Gallons per minute |
| $gh/m^3$ | Gram·hours per cubic meter |
| hr | Hour |
| ILO | International Labour Office |
| LCL (95%) | Lower confidence limit at the 95% level |
| L/min | Liter(s) per minute |
| LLN | Lower limit of normal |
| LOQ | Limit of quantitation |
| LOD | Limit of detection |
| $mg/m^3$ | Milligrams per cubic meter of air |
| $mg\text{-}yr/m^3$ | Milligram·years per cubic meter |
| MMU | Mechanized mining unit |
| MRE | Mining Research Establishment of the National Coal Board, London, England |
| MSHA | Mine Safety and Health Administration |
| NDE | Nondesignated entities (occupations or work areas) |
| NSCWP | National Study of Coal Workers' Pneumoconiosis |
| NIOSH | National Institute for Occupational Safety and Health |
| n | Nanoliter |
| OSHA | Occupational Safety and Health Administration |
| PEL | Permissible exposure limit |
| PFT | Pulmonary function test |
| PMF | Progressive massive fibrosis |
| REL | Recommended exposure limit |

| | |
|---|---|
| SAR | Supplied-air respirator |
| SCBA | Self-contained breathing apparatus |
| SMR | Standardized mortality ratio |
| UCL | Upper confidence limit |
| TLV® | Threshold limit value |
| TWA | Time-weighted average |
| USC | United States Code |

# GLOSSARY

*Active workings*: Any place in a coal mine where miners are normally required to work or travel [30 CFR 70.2 (1991)].

*Chronic obstructive pulmonary disease (COPD)*: Includes chronic bronchitis, impaired lung function, and emphysema; characterized by the irreversible obstruction of lung airways.

*Clearance*: Subsequent to deposition; the translocation, transformation, and removal of deposited particles from the respiratory tract [Lioy et al. 1984].

*Coal face*: The exposed area of a coalbed from which coal is extracted [EIA 1989].

*Coal fines*: Coal with a maximum particle size usually less than one-sixteenth inch and rarely above one-eighth inch [EIA 1989].

*Coal workers' pneumoconiosis*: "A chronic dust disease of the lung arising out of employment in an underground coal mine" [30 USC 902]; diagnosis based on the radiographic classification of the size, shape, profusion, and extent of opacities in the lungs.

*Coal rank*: A classification of coal based on the fixed carbon, volatile matter, and heating value of the coal; indicates the progressive geologic alteration (coalification) from lignite to anthracite [EIA 1989].

*Coal type*: A classification of coal based on physical characteristics or microscopic constituents [EIA 1989].

*Concentration*: The amount of a substance contained per unit volume of air [30 CFR 70.2 (1991)].

*CV*: Coefficient of variation; a measure of relative dispersion; also known as relative standard deviation and defined as the standard deviation/mean [Leidel et al. 1977].

*Deposition*: The collection of inhaled airborne particles by the respiratory tract and the initial regional patterns of these deposited particles [Lioy et al. 1984].

*District manager*: The manager of the Coal Mine Safety and Health District in which the mine is located [30 CFR 70.2 (1991)].

*GM*: Geometric mean; a measure of central tendency for a log-normal distributioin [Leidel et al. 1977].

*GSD*: Geometric standard deviation; a measure of relative dispersion variability) of a lognormal distribution.

*Inspirable dust*: The particulate mass of materials that are hazardous when deposited anywhere in the respiratory tract [ACGIH 1992b].

*LCL*: Lower confidence limit on a measured exposure average.

*UCL*: Upper confidence limit on a measured exposure average.

*Mechanized mining unit (MMU)*: A unit of mining equipment including hand loading equipment used for the production of material [30 CFR 70.2 (1991)].

*MRE instrument*: The gravimetric dust sampler with a four-channel horizontal elutriator developed by the Mining Research Establishment of the National Coal Board, London, England [30 CFR 70.2 (1991)].

*Normal production shift*: A production shift during which the amount of material produced in an MMU is at least 50 percent of the average production reported for the last set of five valid samples; or the amount of material produced by a new MMU before five valid samples are taken [30 CFR 70.2 (1991)].

*Overburden*: Any material, consolidated or unconsolidated, that overlies a coal deposit; overburden ratio refers to the amount of overburden that must be removed to excavate a given quantity of coal [EIA 1989].

*Progressive massive fibrosis*: Aka coal workers' complicated pneumoconiosis; diagnosis based on radiographic determination of the presence of large opacities with a combined area of 1 cm or larger.

*Quartz*: Crystalline silicon dioxide ($SiO_2$) not chemically combined with other substances and having a distinctive physical structure [30 CFR 70.2 (1991)].

*Respirable dust*: The particulate mass of materials that are hazardous when deposited anywhere in the gas-exchange region [ACGIH 1992b].

*Retention*: The temporal distribution of uncleared particles in the respiratory tract [Lioy et al. 1984].

*Thoracic dust*: The particulate mass of materials that are hazardous when deposited anywhere within the lung airways and the gas-exchange region [ACGIH 1992b].

*TWA:* Time-weighted-average employee exposure over an 8-hour work shift as defined in 29 CFR 1910.1000(d)(1).

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# 1 RECOMMENDATIONS FOR A COAL MINE DUST STANDARD

The National Institute for Occupational Safety and Health (NIOSH) recommends that occupational respiratory diseases such as pneumoconioses and chronic obstructive pulmonary diseases (COPDs) be prevented (and in the case of pneumoconioses, halted if they have already developed) among underground and surface coal miners by controlling occupational exposures to respirable coal mine dust and respirable crystalline silica* as detailed in this chapter. NIOSH recommends that the focus of this prevention effort be the control of workplace exposures and the medical surveillance of workers. The information contained in this document demonstrates that coal workers' pneumoconiosis (CWP), silicosis, and COPDs are health threats to underground and surface coal miners.

## SECTION 1.1 DEFINITIONS

### 1.1.1 Miner or Coal Miner

"Miner" or "coal miner" refers to any individual working in a surface or underground coal mine and who (1) is engaged in the extraction and production process, or (2) is regularly exposed to mine hazards, or (3) is employed as a construction, maintenance, or service worker.

### 1.1.2 Coal Mine

"Coal mine" means an area of land and all structures, facilities, machinery,

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*Crystalline silica (or free silica) is defined as silicon dioxide ($SiO_2$). "Crystalline" refers to the orientation of $SiO_2$ molecules in a fixed pattern as opposed to a nonperiodic, random molecular arrangement defined as amorphous. The three most common crystalline forms of free silica encountered in general industry are quartz, tridymite, and cristobalite [NIOSH 1974]. In surface coal mines, the predominant form is quartz.

tools, equipment, shafts, slopes, tunnels, excavations, and other property, real or personal, that (1) is placed on, under, or above the surface of such land by any person, or (2) is used in, or is to be used in, or results from (a) the work of extracting in such an area bituminous coal, lignite, or anthracite from its natural deposits in the earth by any means or method, and (b) the work of preparing the coal so extracted; custom coal preparation facilities are included in this definition [30 USC 802(h)(2)].

### 1.1.3 Radiographic Appearance of Pneumoconioses Classification

The International Labour Office (ILO) publishes and periodically updates recommendations for classifying lung parenchymal and pleural abnormalities consistent with pneumoconiosis on chest radiographs. The *ILO Classification of Radiographs of Pneumoconioses* [ILO 1980] uses a 12-point scale for classifying the profusion or absence of opacities shown on chest radiographs in cases of simple pneumoconioses. The scale, in order of increasing profusion, is as follows: 0/-, 0/0, 0/1, 1/0, 1/1, 1/2, 2/1, 2/2, 2/3, 3/2, 3/3, 3/+. Complicated pneumoconioses, or progressive massive fibrosis (PMF), may be classified as large shadows in three categories, A, B, or C, in order of increasing size, when opacities are equal to or greater than 1 cm in diameter.

### 1.1.4 Mine Operator

Except where indicated, "mine operator" means any owner, lessee, or other person who operates, controls, or supervises a surface or underground coal mine, or any independent contractor performing services or construction at such a mine.

### 1.1.5 Surface Coal Mine

"Surface coal mine" means a surface area of land and all structures, facilities, machinery, tools, equipment, excavations, and other properties (real or personal) that (1) are placed on or above the surface of such land by any person, (2) are used in, or are to be used in, or result from (a) the work of extracting in such an area bituminous coal, lignite, or anthracite from its natural deposits in the earth by any means or method, and (b) the work of preparing the coal so extracted; custom coal preparation facilities are included in this definition [30 CFR 71.2(n)].

### 1.1.6 Surface Work Area of an Underground Coal Mine

"Surface work area of an underground coal mine" means the surface areas of land and all structures, facilities, machinery, tools, equipment, shafts, slopes, excavations, and other property (real or personal) that (1) is placed in, on, or above the surface of such land by any person, or (2) is used in, or is to be used in, or results from (a) the work of extracting bituminous coal, lignite, or anthracite from its natural deposits underground by any means or method, and (b) the work of preparing the coal so extracted; this definition includes custom coal preparation facilities [30 CFR 71.2(p)].

## SECTION 1.2 RECOMMENDED EXPOSURE LIMIT FOR COAL MINE DUST

### 1.2.1 Exposure

To prevent CWP and COPD in coal miners, NIOSH now recommends that the exposure to respirable coal mine dust be limited to 0.9 milligrams per cubic meter of air (0.9 mg/m$^3$) as a time-weighted average (TWA) for up to 10 hr/day during a 40-hr workweek, and as measured according to recommended sampling criteria in Section 5.1. Because some risk of progressive massive fibrosis (PMF) remains even at 0.9 mg/m$^3$, every effort should be made to keep exposures to respirable coal mine dust well below this recommended exposure limit (REL) using state-of-the-art engineering controls and work practices. Occupational exposures to respirable crystalline silica shall not exceed a TWA concentration of 0.05 mg/m$^3$, as determined by a full-shift sample for up to 10 hr/day during a 40-hr workweek [NIOSH 1988d; NIOSH 1974].

In this document, references will be made to the Mine Safety and Health Administration (MSHA) permissible exposure limit (PEL) of 2.0 mg/m$^3$ (or a reduced concentration according to the quartz content) for respirable coal mine dust [30 CFR[†] 70.100 (1991); 30 CFR 71.100 (1991)]. MSHA enforces a reduced PEL for respirable coal mine dust when the percentage of respirable quartz exceeds 5% [70.101 (1991); 30 CFR 71.101 (1991)]. A discussion of the MSHA PEL is included in Chapter 6, and the basis for the NIOSH REL is presented in Chapter 7.

This document evaluates the adequacy of the MSHA PEL for respirable coal mine dust. Recent independent studies from the United States and abroad have shown that the risk of developing CWP after a working lifetime of exposure at the current PEL is greater than earlier estimates indicated. Chapter 4 provides discussions of these epidemiologic studies as well as chronic inhalation studies in animals. The exposure-response studies used as the basis for the recommended standard are discussed in Chapter 7. The NIOSH REL for respirable coal mine dust is based on an evaluation of the world literature on the health effects of exposure, including exposure-response studies of both pneumoconiosis and obstructive airways diseases in U.S. and U.K. coal miners.

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[†] *Code of Federal Regulations.* See CFR in references.

The NIOSH REL will be periodically reviewed and revised as necessary. The following sections shall amend or modify the regulations in 30 CFR 70, 30 CFR 71, 30 CFR 90, and 42 CFR 37. Specific requirements contained in those regulations and not addressed in the NIOSH recommended standard shall be retained.

### 1.2.2 Sampling and Analysis

The concentration shall be determined gravimetrically (see Section 5.1.4). The sampling and analytical method used for respirable crystalline silica shall be NIOSH Methods 7500 and 7602 [NIOSH 1984].

## SECTION 1.3 EXPOSURE MONITORING

### 1.3.1 Type of Sampling

The exposure of miners to respirable coal mine dust and respirable crystalline silica shall be determined by a full-shift, personal air sample collected during an 8- to 10-hr workday.

### 1.3.2 Initial Monitoring Survey

The mine operator shall conduct an initial monitoring survey to determine the exposure of miners to respirable coal mine dust and respirable crystalline silica. A sufficient number of samples shall be collected to characterize each miner's full-shift exposure. Although not all miners must be monitored, a sufficient number of samples must be collected to characterize the exposures of all miners who may be exposed. Chapter 5 provides the recommended sampling strategy for respirable coal mine dust and respirable crystalline silica.

### 1.3.3 Monitoring Exposures at or Below the RELs

If a miner is exposed to respirable coal mine dust or respirable crystalline silica (at concentrations for which the 95% upper confidence limit, or UCL (95%), exceeds the REL for respirable coal mine dust or the REL for respirable crystalline silica), then the miner's exposure shall be monitored by the mine operator at least every 2 weeks. The monitoring frequency may be reduced to once every 6 months when the UCL (95%) of the measured concentration is below the REL for respirable coal mine dust and below the REL for respirable crystalline silica, as determined from at least 2 consecutive samples taken at least 2 weeks apart. Designated occupations (DO) and transferred miners' exposures shall be monitored once every 2 weeks [30 CFR Part 90].

### 1.3.4 Monitoring Exposures Above the RELs

A miner exposed to respirable coal mine dust or respirable crystalline silica at concentrations above the REL shall be notified of the exposure and of the control measures being implemented to reduce exposures.

### 1.3.5 Changes in Operational Conditions

Whenever changes in operational conditions might result in exposure concentrations above the REL, air sampling shall be conducted by the mine operator as if it were an initial monitoring survey (see Section 1.3.2).

### 1.3.6 Intake Air Concentrations

Intake air concentrations of respirable dust shall be maintained at the lowest attainable level; full-shift samples shall be collected within 200 ft outby the working faces of each section in the intake airways by the mine operator at least once every 6 months.

## SECTION 1.4 MEDICAL SURVEILLANCE

### 1.4.1 Medical Examinations

The Coal Workers' X-Ray Surveillance Program (CWXSP) is jointly administered by NIOSH and MSHA. This program requires underground coal mine operators to provide periodic chest radiography to underground coal miners and workers at surface work areas of underground coal mines. The specifications for giving, interpreting, classifying, and submitting the chest radiographs (a.k.a. roentgenograms) required for this program are contained in 42 CFR 37 (1989). See Chapter 6 for a more detailed description of the program. NIOSH recommends that surface coal miners be included in the CWXSP with the same provisions established for underground miners.

In addition to the periodic chest radiography, NIOSH recommends that the medical surveillance program for coal miners be extended to include pulmonary function testing, both at the initial medical examination and at the intervals specified for the chest radiographs. The purpose of the spirometry tests is to detect decrements in lung function resulting from exposure to respirable coal mine dust and to permit timely intervention in the development of COPD.

The medical surveillance program for coal miners shall include the following medical examinations: an examination as soon as possible after beginning employment (within 3 months), an examination every 3 years thereafter if the miner is still engaged in coal mining, and an examination when employment ends if more than 6 months have passed since the last examination. The current medical surveillance program for underground coal miners is described in 42 CFR 37 (1989). The following recommendations expand the existing program by including surface coal miners and by adding pulmonary function tests.

#### *1.4.1.1 Radiographic Examinations*

Chest radiographic examinations shall be conducted according to 42 CFR Part 37 (1989). The chest radiograph (posterior-anterior) shall be no smaller than 14" x 17" and no larger than 16" x 17" to provide evidence of pneumoconiosis in accordance with specifications in 42 CFR 37.41-37.43 (1989). NIOSH recommends that the CWXSP program be extended to include surface coal miners.

#### *1.4.1.2 Spirometry Tests*

Spirometry tests, including forced expiratory volume in 1 sec ($FEV_1$) and forced vital capacity (FVC), shall be conducted according to the guidelines of NIOSH [Fed. Reg. 1980] and the American Thoracic Society (ATS) [ATS 1987]. Technicians should complete a NIOSH-approved course on spirometry. Information about instrumentation, performance, and interpretation of these tests is provided in Chapter 5.

#### *1.4.1.3 Respiratory Questionnaire*

Miners shall complete a valid, standardized respiratory questionnaire regarding respiratory symptoms and smoking history [NIOSH 1990]. The NIOSH recommended questionnaire is included in Appendix A and is comparable with those of the American Thoracic Society (ATS) and the Medical Research Council (MRC) [Samet 1978; Ferris 1978].

#### *1.4.1.4 Occupational History*

Miners shall complete an occupational history listing all jobs held, up to and including present employment. Duties and potential exposures should be noted [ALA 1983; Goldman et al. 1981]. The NIOSH recommended questionnaire is included in Appendix A.

#### 1.4.1.5 *NIOSH-Approved Facilities*

Each mine operator shall make arrangements with a local NIOSH-approved facility or organization to conduct the medical examinations. The local examination facility or organization shall transmit to NIOSH all chest radiographs, pulmonary function test results (including spirograms), completed medical questionnaires, and work histories. NIOSH shall evaluate the technical quality of the chest radiographs and interpret them. In addition, NIOSH shall do the following:

- Evaluate spirometry test results, completed medical questionnaires, and work histories
- Prepare letters to notify miners of the examination results and to recommend any followup examinations
- Permanently store the medical and questionnaire data

#### 1.4.1.6 *Smoking*

The mine operator or physician shall counsel tobacco-smoking miners about the increased risk of developing lung cancer from smoking and the increased risk of developing chronic obstructive pulmonary diseases from the combined exposure to tobacco smoke and respirable coal mine dust. The mine operator or physician shall encourage the miner to participate in a smoking cessation program. The mine operator shall enforce a policy prohibiting smoking at all work areas at the mine site.

### 1.4.2 Abnormalities Found During Medical Examinations

#### *1.4.2.1 Evidence of Pneumoconiosis on Chest Radiographs*

Chest radiographs shall be classified according to the 1980 ILO Classification of Radiographs of Pneumoconioses (or the most current equivalent) by two NIOSH-approved B readers.

Evidence of pneumoconiosis is present when the chest radiograph is classified as ILO category 1/0 or greater. Two interpreters shall be considered in agreement when they meet one of the following criteria:

- They both find complicated pneumoconiosis (category A, B, or C).
- Their findings with regard to simple pneumoconiosis are both in the same major category.
- Their findings are within one minor category (ILO category 12-point scale) of each other. In this case, the higher of the two interpretations shall be reported. The only exception to this criteria is a reading sequence of 0/1, 1/0, or 1/0, 0/1. When such a sequence occurs, it shall not be considered agreement, and additional interpretations shall be required until the readers reach a consensus involving two or more readings in the same major category.

#### *1.4.2.2 Abnormal Pulmonary Function Values*

Results of pulmonary function tests shall be compared with the reference values provided in Appendix E as follows:

- The highest $FEV_1$ and FVC values from each miner's examination shall be used to compare the $FEV_1$, FVC, and $FEV_1$/FVC% with the lower limit of normal (LLN) calculated with the equations published by Knudson et al. [1983] (Appendix E).

- In addition, the miner's annual decline in $FEV_1$ shall be computed by comparison to an individual's previous values; an annual decline of 15% or greater shall be considered significant [ATS 1991].

Any miner who has an $FEV_1$, FVC, or $FEV_1$/FVC% value below the LLN, or who has an annual decline in $FEV_1$ of 15% or greater, shall be referred for a clinical evaluation that includes repeating the spirometry tests as needed.

## SECTION 1.5 TRANSFER OPTION

The following provision [42 CFR 37.7(a) as amended by this criteria document] requires specific action when the chest radiograph of an underground or surface coal miner shows evidence of pneumoconiosis or when the spirometry tests show evidence of chronic obstructive pulmonary disease:

> *§ 37.7 Transfer of affected miner to less dusty area*
>
> *Any miner who, in the judgement of the Secretary [of Health and Human Services] shows evidence of category 1 (1/0, 1/1, 1/2), category 2 (2/1, 2/2, 2/3), or category 3 (3/2, 3/3, 3/+) simple pneumoconioses, or complicated pneumoconioses, based upon the interpretation of one or more of the miner's chest roentgenograms, or who shows evidence of chronic obstructive pulmonary disease, based on confirmed findings of* $FEV_1$*, FVC, or* $FEV_1$*/FVC below the LLN or an accelerated annual decline in* $FEV_1$*, shall be afforded the option of transferring from his or her position to another position in an area of the mine where the concentration of respirable coal mine dust in the mine atmosphere is as low as feasible*

> *below 0.9 mg/m³ and the concentration of respirable crystalline silica is as low as feasible below 0.05 mg/m³. The transfer shall be voluntary and without loss of pay or seniority.*

NIOSH shall notify MSHA if a miner is eligible for transfer, and MSHA shall send a letter notifying the miner of this eligibility. NIOSH recommends that the regulations [30 CFR 90] governing the eligibility and procedures for this transfer option be amended to include all surface coal miners in addition to underground coal miners and workers at surface work areas of underground coal mines. The following provision [30 CFR 90.1 as amended] expands the eligibility criterion:

> *§ 90.1 Scope*
>
> *This Part 90 establishes the option of all underground or surface coal miners who have evidence of the development of pneumoconiosis or chronic obstructive pulmonary disease to work in an area of a mine where the average concentration of respirable dust in the mine atmosphere during each shift is maintained as low as feasible below 0.9 milligrams per cubic meter (mg/m³) of air and the average concentration of respirable crystalline silica is maintained as low as feasible below 0.05 mg/m³. The rule sets forth procedures for miners to exercise this option, and establishes the right of miners to retain their regular rate of pay and receive wage increases.*

## SECTION 1.6 POSTING

All warning signs shall be printed in both English and the predominant language of non-English-reading miners. Miners unable to read the posted signs shall be informed verbally about the hazardous areas of the mine and the instructions printed on the signs.

If respiratory protection is required, the following statement shall be added to this sign in large letters:

**RESPIRATORY PROTECTION REQUIRED IN THIS AREA**

## SECTION 1.7 ENGINEERING CONTROLS AND WORK PRACTICES

The mine operator shall apply engineering controls and work practices to maintain miners' exposures at or below the RELs for respirable coal mine dust and respirable crystalline silica. Chapter 8 and Appendices C and D provide discussions of available engineering controls and work practices.

## SECTION 1.8 RESPIRATORY PROTECTION

### 1.8.1 General Considerations

Respirators shall be used when engineering controls and work practices cannot maintain miners' exposures at or below the RELs for respirable coal mine dust and respirable crystalline silica. Respirators may be used as an interim control measure, but they shall not be used in lieu of feasible engineering controls and work practices. Whenever respirators are used, the mine operator shall institute a respiratory protection program conforming to the recommendations contained in Chapter 8 and the most recent edition of the NIOSH Guide to Industrial Respiratory Protection [1987a] or the NIOSH Guide to Industrial Respiratory Protection [NIOSH 1987b].

### 1.8.2 Respiratory Protection Program

This program shall include at a minimum the following elements:

- A designated individual responsible for the administration of the program

- A written program for respiratory protection that contains standard operating procedures governing the selection and use of respirators

- Initial and annual training of the miners in the proper use and limitations of respirators as required in 30 CFR 48.28 and 48.31 (for certified persons employed at underground coal mines, annual training is required in the use of self-contained, self-rescue devices [30 CFR 75.161])

- Evaluation of working conditions in the mines (including periodic air monitoring of miners' exposures) to identify situations that require respiratory protection

- Routine inspection, cleaning, maintenance, and proper storage of respirators in compliance with the manufacturer's recommendations and the *American National Standard: Practices for Respiratory Protection* (ANSI Z88.2) [ANSI 1969]

- Initial quantitative fit testing of each respirator worn to determine the level of protection provided, and additional daily fit checks to ensure proper assembly, function, and faceseal integrity of the respirator

- Medical evaluation of the miner's physical ability to perform work continuously while breathing through a respirator

- Continual evaluation of program effectiveness through monitoring of miner respirator use patterns, quarterly inspections of the respirator maintenance program, and testing of supervisor and miner awareness of respirator use requirements

### 1.8.3 Respirator Selection

Respirators shall be selected by a qualified person according to the guidelines in Section 8.6.2.2 of this criteria document and the most recent edition of the *NIOSH Respirator Decision Logic* [NIOSH 1987a]. Only NIOSH- and MSHA-approved respirators shall be used.

## SECTION 1.9 INFORMING MINERS OF THE HAZARDS

### 1.9.1 Notification of Hazards

The mine operator shall provide all miners with information about workplace hazards before job assignment and at least annually thereafter.

### 1.9.2 Training

The mine operator shall institute a continuing education program conforming to the requirements in Part B, 30 CFR 48. The purpose of this program is to ensure that all miners have a current knowledge of workplace hazards (e.g., respirable coal mine dust, respirable crystalline silica, and diesel exhaust), effective work practices, engineering controls, and the proper use of respirators and other personal protective equipment. This program shall also include a description of the exposure monitoring and medical surveillance programs and the advantages of participating in them. This information shall be kept on file and shall be readily available to miners for examination and copying. The mine operator shall maintain a written plan of these training programs and a written record of the miners' attendance at such programs (including dates).

Miners shall be instructed about their responsibilities for following proper work practices and sanitation procedures necessary to protect their health and safety.

## SECTION 1.10 SANITATION

### 1.10.1 Smoking

Based on NIOSH recommendations against smoking in the workplace and on safety concerns, particularly for underground coal mines, NIOSH recommends that smoking shall be prohibited in all work areas of underground or surface coal mines and at other work sites where exposure to respirable coal mine dust or respirable crystalline silica occurs.

### 1.10.2 Showering and Changing Facilities

The mine operator shall provide the miners with clean facilities for showering and changing clothes at the end of each workshift. Mine operators shall encourage the miners to use these facilities. The mine operator shall also provide storage facilities such as lockers to permit the miners to store street clothing and personal items.

### 1.10.3 Drinking Water

An adequate supply of potable water shall be provided for drinking purposes at each worksite in accordance with 30 CFR 71.600 through 71.603 (surface coal mines and surface work areas of underground coal mines). Similarly, an adequate supply of potable water shall be provided in underground coal mines (although not included in 30 CFR Part 70: underground coal mines).

### 1.10.4 Facility Specifications

The facilities required in this section shall be built and operated in accordance with specifications in 30 CFR 71.400 through 71.402 (surface coal mines and surface work areas of underground coal mines). (Note: Facilities specifications are not included in 30 CFR 70: Underground Coal Mines).

## SECTION 1.11 RECORDKEEPING

### 1.11.1 Records of Exposure Monitoring

Records of exposure monitoring required in Section 1.3 shall be retained by the mine operator for at least 40 years after termination of employment.

### 1.11.2 Medical Records

Records relating to the provisions of the medical surveillance program in Section 1.4 shall be maintained by NIOSH in accordance with 42 CFR 37.80.

# 2 INTRODUCTION

## 2.1 PURPOSE

This criteria document reviews studies of the health effects of occupational exposure to respirable coal mine dust. Epidemiologic studies from the United States and abroad have shown that underground and surface coal miners and workers in other occupational settings where coal is used are at risk of developing simple CWP, PMF, silicosis, and COPD. Advanced stages of these diseases are associated with respiratory impairment, disability, and premature death. This review also considers concomitant exposures to other agents such as crystalline silica that may exacerbate the health risks of exposure to coal mine dust.

Included in this criteria document are a recommended standard for respirable coal mine dust, a quantitative risk assessment, and an assessment of the technical feasibility of engineering controls. Recommendations regarding medical surveillance and environmental monitoring are also included.

The objective of this criteria document is to develop strategies for preventing occupational respiratory diseases among underground and surface coal miners. These strategies may also apply to workers in other occupations with exposure to respirable coal dust and concomitant exposure to respirable crystalline silica. The prevention strategies developed in this criteria document include the following:

- A recommended exposure limit (REL) for respirable coal mine dust that is based on

  - --an evaluation of the epidemiologic studies of simple CWP, PMF, silicosis, and COPD (assessed by deficits in lung function) among U.S. and British underground coal miners,
  - --quantitative assessment of the exposure-response relationship between working lifetime exposure to respirable coal mine dust and the development of simple CWP, PMF, or reduced lung function, and
  - --a semiquantitative evaluation of the technical feasibility of achieving the REL.

- A revised medical surveillance program that includes
  - --extension of the existing Coal Workers' X-ray Surveillance Program to include surface coal miners, and
  - --pulmonary function tests to detect coal miners at risk of developing COPD, with repeated tests and follow-up examinations for miners whose test results show lower than normal reference values.
- Epidemiologic research to evaluate the effectiveness of the recommended environmental monitoring and medical surveillance and intervention strategies in preventing simple CWP, PMF, silicosis, and COPD.
- A recommended sampling strategy for respirable coal mine dust that is both statistically valid and practical in the coal mine environment.

## 2.2 SCOPE

This document was developed in accordance with Section 20(a)(3) of the

Occupational Safety and Health Act of 1970. In this act, NIOSH is charged with developing criteria for toxic materials and harmful physical agents. These criteria are to describe exposure concentrations at which no worker will suffer impaired health or functional capacities, or diminished life expectancy as a result of work experience. The document responds to Section 2.2(c)(1) of the Act, which authorizes NIOSH to develop and establish recommended occupational safety and health standards. The document also responds to the Federal Mine Safety and Health Act of 1977 [30 USC 801-962 (1986)], which assigns NIOSH the responsibility for recommending improvements in mandatory health standards to prevent and control occupational diseases among miners [30 USC 951 (1986)].

## 2.3 SUMMARY AND PERSPECTIVE

### 2.3.1 Background Information

The history of the arduous working conditions in coal mines and the unfavorable treatment of coal miners and their families has been well documented in the literature [Morgan 1975; Lee 1969]. In the United States, this history has prompted the enactment of occupational safety and health programs and disability compensation programs that are among the most comprehensive in the world [30 USC 801-962 (1986)]. Yet much work remains to improve the conditions in coal mines. Although fatality rates have declined since the 1960s (Figure 2-1), coal mining is still among the most hazardous occupations in the Nation [DHHS 1991; Guidotti 1979]: the number of fatal injuries in coal mines is higher than in all other U.S. mining industries combined [DOL 1988]. U.S. coal miners continue to develop disabling occupational respiratory diseases, but the frequency has been declining since the enactment of the 2.0-mg/m$^3$ standard for respirable coal mine dust in the Federal Coal Mine Health and Safety Act of 1969 [GAO 1990; 30 USC 842 and 845 (1986); Leiderman et al. 1983]. The basis for the 2.0-mg/m$^3$ standard was to

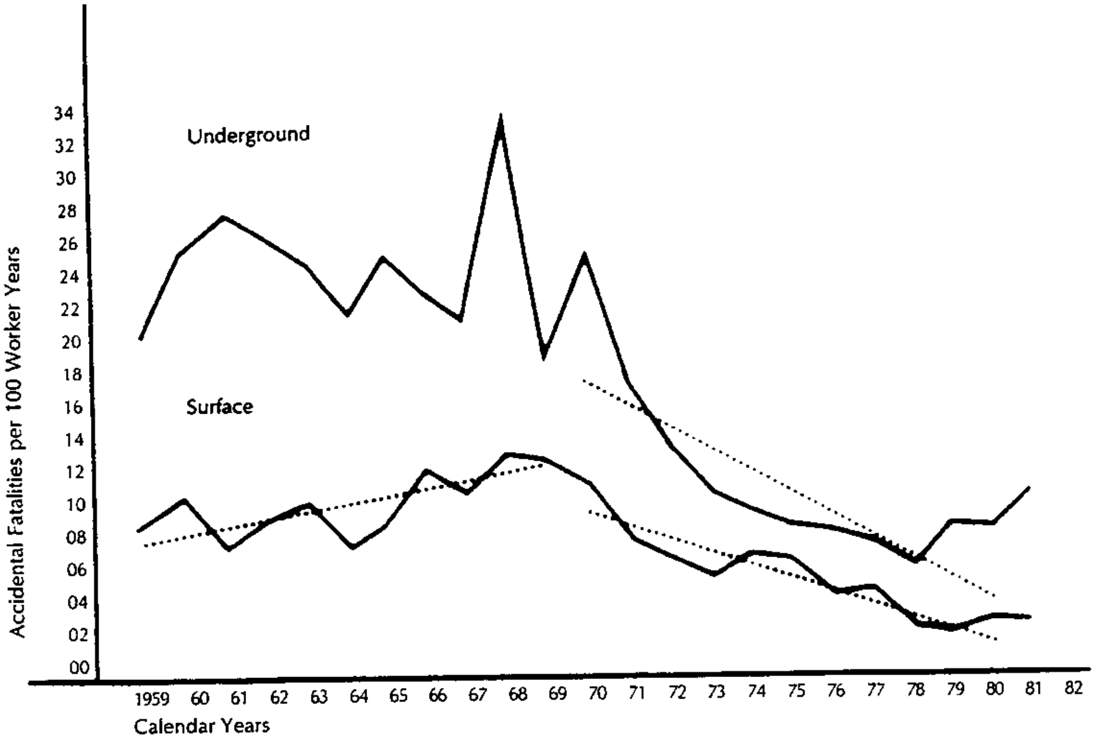

Figure 2-1. Fatality rates in underground and surface bituminous coal mining, United States, 1959-81. (Source: Weeks and Fox [1983].)

prevent PMF, which is associated with disability, reduced lung function, and early death. More than 20 years of data have demonstrated exposure-response relationships between respirable coal mine dust and both simple CWP and PMF, and recent analyses have shown a higher risk of PMF than that estimated when the coal dust standard was enacted. PMF occurs only in individuals with occupational exposure (i.e., no background level exists for PMF in the general population).

In 1991, 847 of the Nation's 2,000 coal companies were cited by the U.S. Department of Labor for tampering with dust samples. These citations raised questions about the accuracy of the exposure measurements and the effectiveness of the dust sampling program in U.S. coal mines [Daykin 1991]. Some data indicate that the prevalence of CWP increased in the late 1980s (Figure 2-2) [Althouse et al. 1992].

### 2.3.2. NIOSH Programs Relating to Coal Mines

NIOSH was established under the Occupational Safety and Health Act of 1970 [29 USC 669 and 671 (1985)], which requires safe and healthful working conditions for every worker. Under the Federal Mine Safety and Health Act of 1977 [30 USC 801 et seq. (1986)], NIOSH has several responsibilities relating to coal miners. These include (1) conducting research and other activities to determine the incidence and prevalence of pneumoconioses and other occupational diseases, (2) identifying the factors important in the development of occupational diseases, and (3) recommending improvements in mandatory health standards to prevent and control occupational diseases among miners [30 USC 951 (1986)]. NIOSH programs that were developed to achieve the objectives of the Federal Mine Safety and Health Act [30 USC 801 et seq. (1986)] include the National Study of Coal Workers' Pneumoconiosis (NSCWP), the CWXSP, and the National Coal Workers' Autopsy Study. NIOSH also has programs for the training and certification of B readers (physicians who

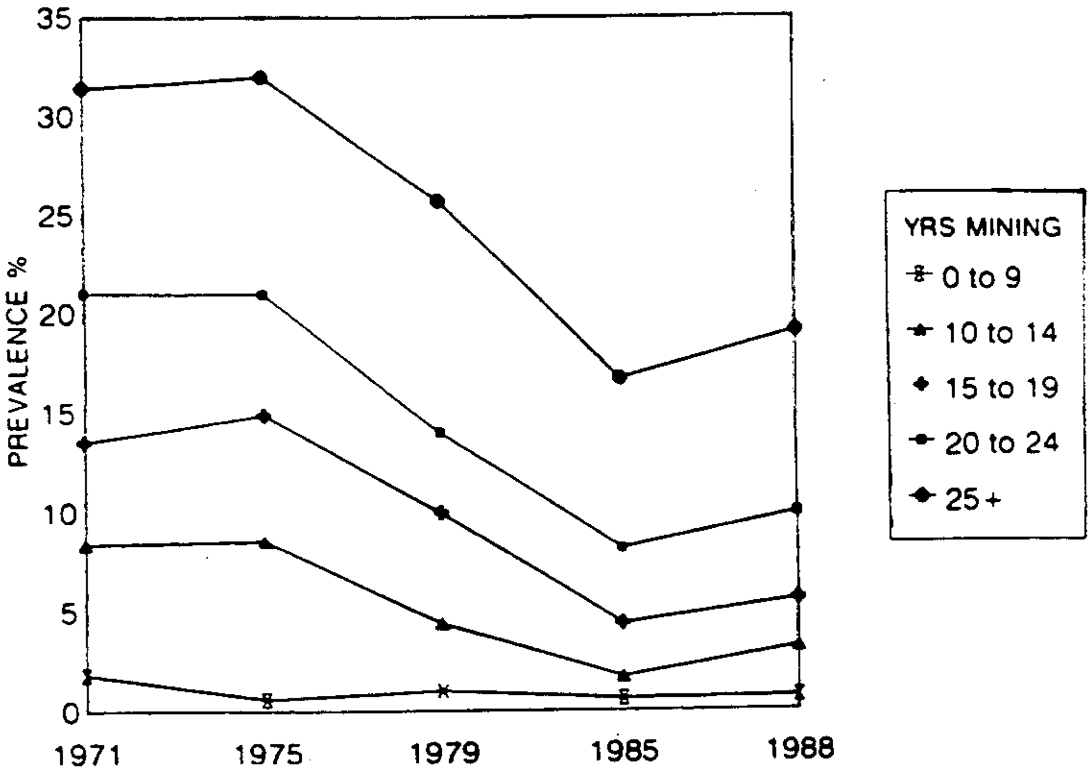

Figure 2-2. Prevalence of CWP category 1 or higher identified in the CWXSP from 1970 to the present by tenure in coal mining. The year represents midyear of the time period. The number of miners examined in each time period is 80,521, 124,441, 63,324, 41,157, and 8,557, respectively. Tabulations are from the Division of Respiratory Disease Studies, NIOSH. (Source: Althouse et al. [1992].)

interpret chest radiographs) and for the certification of coal mine dust sampling units.

### 2.3.3 Studies of Pneumoconiosis

#### *2.3.3.1 Degree of Risk*

Numerous U.S. and foreign studies show that miners exposed to respirable dust in underground coal mines over a working lifetime are at risk of developing simple and complicated CWP [Attfield and Morring 1990b; Maclaren et al. 1989; Hurley et al. 1987; Hurley et al. 1982; Shennan et al. 1981]. Miners who show evidence of the higher radiographic categories of simple CWP are at greater risk of developing PMF. The current U.S. standard [30 USC 801-962 (1986)] is based primarily on estimates from 10-year follow-up studies of British coal miners. These studies indicated the following:

- The risk of PMF increased substantially among coal miners with radiographic evidence of CWP category 2 or greater [Cochrane 1962].

- The risk of CWP category 2 or greater was essentially zero for underground coal miners exposed to respirable coal mine dust at a mean dust concentration of 2 $mg/m^3$ over a 35-year working lifetime [Jacobsen et al. 1971].

More recent estimates are based on 20-year follow-up studies of British coal miners and on studies of U.S. coal miners. These recent estimates of PMF risk are higher than those used as the basis for the current U.S. coal dust standard [Attfield and Morring 1990b; Hurley and Maclaren 1987]. Although U.S. and British studies have shown that the prevalence of simple CWP and PMF has been declining since the 1960s [BCC 1991; Attfield 1989a,b; Attfield and Althouse 1989], there is evidence that CWP category 1 or greater has been increasing since 1985 [Althouse et al. 1992] (Figure 2-2). U.S. and British risk estimates indicate that each year, between 7/1,000 and 65/1,000 miners aged 58 or under will have developed PMF after 40 years of respirable dust exposure at 2 $mg/m^3$ in underground coal mines (bituminous coal with $\leq 5\%$ respirable quartz) [Attfield and Morring 1992b; Hurley and Maclaren 1987].

### *2.3.3.2 The Need to Improve Preventive Measures*

Transferring miners to less dusty jobs is probably not an effective preventive measure if respirable coal mine dust exposures frequently exceed the recommended limit for transferred miners. Appendix B shows that 8-hr air samples for transferred miners have occasionally exceeded both the 1-$mg/m^3$ limit (under 30 CFR 90) and the 2-$mg/m^3$ PEL for respirable coal mine dust. Furthermore, Hurley and Maclaren [1987] estimated that only 1 in 10,000 cases of PMF would be prevented if all eligible miners elected to transfer from jobs with a mean dust concentration of 2 $mg/m^3$ to jobs with a mean dust concentration of $\leq 1$ $mg/m^3$. This study indicates that secondary preventive measures such as transfer are not effective in preventing PMF. Thus, the need is for primary prevention through reducing exposures to respirable coal mine dust.

A study of British coal miners showed that among miners with PMF, 20% had no radiographic evidence of simple CWP at the beginning of the previous approximate 5-year period [Hurley et al. 1987]. Thus, among miners with the rapid development of PMF (which has also been observed in U.S. coal miners [Hodous and Attfield 1990]), simple CWP might not be detected during early radiographic surveys. The currently recommended 3-year interval for radiographic examination [42 CFR 37.3(b) (1989)] is intended to provide early detection of simple CWP.

#### *2.3.3.3 Increasing the Effectiveness of Preventive Measures*

To improve the effectiveness of disease prevention measures, it may be necessary to target certain high-risk groups for medical surveillance and environmental monitoring. Workers at high risk of developing occupational respiratory disease include those in certain job categories, those who use certain mining methods, those who work with high-rank coal, and those who are exposed to respirable crystalline silica. For example, the risk of developing simple CWP or PMF is greater among roof bolters [Attfield 1991a, 1991b] and surface drill crew members [Amandus et al. 1984], probably because of their exposure to high concentrations of respirable crystalline silica [Tomb et al. 1986]. Miners of high-rank coal are at greater risk of developing PMF than miners of low-rank coal [Attfield and Morring 1992; Hurley and Maclaren 1987; Lainhart 1969]. Miners working in longwall mines are potentially exposed to higher concentrations of coal mine dust than those in other types of mines [NIOSH 1988a; Watts and Parker 1987].

### 2.3.4 Studies of COPD

U.S. and foreign studies have shown that coal miners are at increased risk of developing COPD, including chronic bronchitis, emphysema, and impaired lung function--whether or not simple CWP or PMF is present [Soutar and Hurley 1986; Attfield 1985a; Ruckley et al. 1984b; Rogan et al. 1973]. The occurrence of diseases other than pneumoconiosis among coal miners is also illustrated by the cases pending approval for black lung benefits in 1981 (with chest radiographs read by a NIOSH-certified B reader): 10.4% showed evidence of PMF; 54.5% showed simple CWP; and 29.9% showed no evidence of either simple CWP or PMF (5.2% were unreadable) [Leiderman et al. 1983].

Unlike PMF, COPD also occurs among individuals without occupational exposure (i.e., there is a background level of COPD in the general population).

Cigarette smoking is a major contributor to the development of COPD among persons with or without occupational exposure [Fletcher et al. 1976]. The relationship between COPD and exposure to respirable coal mine dust and cigarette smoke is additive (not synergistic) [Attfield and Hodous 1992; Marine et al. 1988]. Transferring miners to less dusty jobs (see Chapter 5) may be effective in preventing COPD when lung function is below normal limits and the decrement is detected early enough for the rate of decline to be reduced [Buist 1988; Fletcher and Peto 1976]. Miners transferred on the basis of abnormal lung function should be counseled about smoking cessation, if applicable.

### 2.3.5 Studies of Surface Coal Miners

Two cross-sectional medical evaluations of surface coal miners [Amandus 1984, 1989] and two NIOSH health hazard evaluations [Banks et al. 1983; Cornwell and Hanke 1983] have been performed at surface coal mines. These studies show that surface coal miners (like underground coal miners) are at risk of developing simple CWP and that miners who previously worked in underground coal mines or who work on drill crews at surface coal mines are at greater risk of developing simple CWP.

# 3 PROPERTIES, PRODUCTION, AND POTENTIAL FOR EXPOSURE

## 3.1 CHEMICAL AND PHYSICAL PROPERTIES OF COAL MINE DUST

### 3.1.1 Composition of Respirable Coal Mine Dust

Coal mine dust is a complex and heterogeneous mixture containing more than 50 different elements and their oxides [Coates 1981; Larsen 1981; Kirby et al. 1954]. The mineral content varies with the particle size of the dust and with the coal seam [Stobbe et al. 1990]. Common minerals associated with coal mine dust include kaolinite, illite, calcite, pyrite, and quartz [Stobbe et al. 1990]. The sulfur content varies from 0.5% (by weight) to more than 10%, with coal from the western United States generally having lower sulfur content [Coates 1981]. Because the concentration of respirable dust in underground coal mines is determined gravimetrically, the proportion from coal is not determined [Tomb 1990]. Airborne respirable dust in underground coal mines has been estimated to be 40% to 95% coal; the remaining portion consists of a variable mixed dust that is generated from fractured rock on the mine roof or floor or that is encountered within the coal seam [Kim 1989; Lee 1986]. The coal component of respirable dust at surface coal mines can be even more variable, depending on the stage of the mining operation.

Few studies exist that have characterized differences in underground coal mine dust and surface coal mine dust. One study compared the size distribution of respirable quartz at surface and underground coal mines and found that the distributions in particle sizes less than 4.2 µm are similar. Surface mines contained more particles in the size range of 4.2 to 9.6 µm (2.7% versus 6.4%); yet, both surface and underground miners had less than 0.25% of respirable quartz larger than 9.6 µm [Huggins et al. 1985].

Coal is categorized by rank, which is roughly associated with the relative geologic age of the coal and the degree to which the coalification process has progressed [Larsen 1981]. The geologic process of coalification begins with organic materials (e.g., celluloses, lignins, and other plant compounds, which are deoxygenated and then dehydrogenated) and ends with anthracite coal [Larsen 1981]. Tables 3-1 and 3-2 list the classification of coals by rank. Note that the lower-rank coals are classified on the basis of heat content, whereas the higher rank coals have a narrower range of heat content (generally above 14,000 Btu) and are therefore classified by their percentage of fixed carbon. The agglomerating character of bituminous coals is a critical characteristic for some coal consumers and is therefore used to distinguish between certain adjacent coal groups.

Coal rank is defined by the percentage of fixed carbon (the proportion of carbon that remains when coal is heated and the volatile material is removed), by the percentage of volatile material, and by the heat content of coal [Mutmansky and Lee 1984]. High-rank coal includes anthracite and semi-anthracite ("hard coal," with 91% to 95% carbon); intermediate-rank coal includes high-, medium-, and low-volatile bituminous and subbituminous ("soft coal," with 76% to 90% carbon); and low-rank coal includes lignite (with 65% to 75% or less carbon) [Parkes 1982]. The rank of coal tends to increase from the western to the eastern United States, with anthracite occurring primarily in eastern Pennsylvania [Schlick and Fannick 1971]. Most of the coal currently mined in the United States is bituminous [Given 1984]. Table 3-3 lists the coal rank by State.

As the coal rank increases, the percentage of fixed carbon increases, and the percentages of oxygen (including the functional oxygen groups $-OCH_3$, $-COOH$, $-OH$, and $-C=O$), hydrogen, and volatile material decrease [Jones 1986; Coates 1981; Larsen 1981]. Also, as the coal rank increases, the percentage of the noncoal components (such as minerals) decreases [Stobbe et al. 1986; Davis

**Table 3-1.—Classification of coals by rank: coals classified by percentage of fixed carbon**

| Coal rank and group | % fixed carbon[1] ≥ | % fixed carbon[1] < | Agglomerating character |
|---|---|---|---|
| Anthracitic: | | | |
| Meta-anthracite | 98 | --- | Nonagglomerating |
| Anthracite | 92 | 98 | Nonagglomerating |
| Semianthracite[2] | 86 | 92 | Nonagglomerating |
| Bituminous | | | |
| Low-volatile bituminous | 78 | 86 | Commonly agglomerating[4] |
| Medium-volatile bituminous | 69[5] | 78 | Commonly agglomerating[4] |
| High-volatile A bituminous | --- | 69[5] | Commonly agglomerating[4] |

Source: Adapted from American Society for Testing and Materials 1988, Standard Classification of Coal by Rank, ASTM Designation D 388-84.

[1] Percentages are based on dry mineral-matter-free coal. Volatile matter (not shown) is the complement of fixed carbon; that is, the sum of the percentages of fixed carbon and volatile matter is 100%. As fixed carbon percentage decreases, volatile matter percentage therefore increases by the same amount.

[2] If agglomerating, classify in low-volatile group of the bituminous class.

[4] There may be nonagglomerating varieties in the bituminous class—most notably in the high-volatile C bituminous group.

[5] Coals having 69% or more fixed carbon are classified according to fixed carbon, regardless of Btu value. Coals with less than 69% fixed carbon but with 14,000 or more Btu/lb, are classified as high-volatile A bituminous.

**Table 3-2.—Classification of coals by rank: coals classified by heat content**

| Coal rank and group | Heat content (Btu/lb)[1] ≥ | Heat content (Btu/lb)[1] < | Agglomerating character |
|---|---|---|---|
| Bituminous | | | |
| High-volatile B bituminous | 13,000 | 14,000 | Commonly agglomerating[2] |
| High-volatile C bituminous | 11,500 | 13,000 | Commonly agglomerating[2] |
| High-volatile C bituminous | 10,500 | 11,500 | Agglomerating |
| Subbituminous | | | |
| Subbituminous A | 10,500 | 11,500 | Nonagglomerating |
| Subbituminous B | 9,500 | 10,500 | Nonagglomerating |
| Subbituminous C | 8,300 | 9,500 | Nonagglomerating |
| Lignitic | | | |
| Lignite A | 6,300 | 8,300 | Nonagglomerating |
| Lignite B | --- | 6,300 | Nonagglomerating |

Source: Adapted from American Society for Testing and Materials 1988, Standard Classification of Coal by Rank, ASTM Designation D 388-84.

[1] Calorific values in Btu/lb, on a moist mineral-matter-free basis.

[2] There may be nonagglomerating varieties in the bituminous class—most notably in the high-volatile C bituminous group.

**Table 3-3.—Coal classification: source and analyses of U.S. coal[*]**

| Classification by rank | State/ county | Bed | Type of sample[1] | Proximate percent | | | | Ultimate percent | | | | | Calorific value (Btu/lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Moisture | Volatile matter | Fixed carbon | Ash | Sulfur | Hydrogen | Carbon | Nitrogen | Oxygen | |
| *Meta-anthracite | Rhode Island<br>Newport | Middle | 1 | 13.2 | 2.6 | 65.3 | 18.9 | 0.3 | 1.9 | 64.2 | 0.2 | 14.5 | 9,310 |
| | | | 2 | --- | 2.9 | 75.3 | 21.8 | 0.3 | 0.5 | 74.1 | 0.2 | 3.1 | 10,740 |
| | | | 3 | --- | 3.8 | 96.2 | --- | 0.4 | 0.6 | 94.7 | 0.3 | 4.0 | 13,720 |
| Anthracite | Pennsylvania<br>Lackawana | Clark | 1 | 4.3 | 5.1 | 81.0 | 9.6 | 0.8 | 2.9 | 79.7 | 0.9 | 6.1 | 12,880 |
| | | | 2 | --- | 5.3 | 84.6 | 10.1 | 0.8 | 2.5 | 83.3 | 0.9 | 2.4 | 13,470 |
| | | | 3 | --- | 5.9 | 94.1 | --- | 0.9 | 2.8 | 92.5 | 1.0 | 2.8 | 14,980 |
| Semianthracite | Arkansas<br>Johnson | Lower Hartshorne | 1 | 2.6 | 10.6 | 79.3 | 7.5 | 1.7 | 3.8 | 81.4 | 1.6 | 4.0 | 13,880 |
| | | | 2 | --- | 10.8 | 81.5 | 7.7 | 1.8 | 3.6 | 83.6 | 1.6 | 1.7 | 14,240 |
| | | | 3 | --- | 11.7 | 88.3 | --- | 1.9 | 3.9 | 90.6 | 1.8 | 1.8 | 15,430 |
| Low-volatile bituminous coal | West Virginia<br>Wyoming | Pocahontas No. 3 | 1 | 2.9 | 17.7 | 74.0 | 5.4 | 0.8 | 4.6 | 83.2 | 1.3 | 4.7 | 14,400 |
| | | | 2 | --- | 18.2 | 76.3 | 5.5 | 0.8 | 4.4 | 85.7 | 1.3 | 2.3 | 14,830 |
| | | | 3 | --- | 19.3 | 80.7 | --- | 0.8 | 4.6 | 90.7 | 1.4 | 2.5 | 15,690 |
| Medium-volatile bituminous coal | Pennsylvania<br>Clearfield | Upper Kittanning | 1 | 2.1 | 24.4 | 67.4 | 6.1 | 1.0 | 5.0 | 81.6 | 1.4 | 4.9 | 14,310 |
| | | | 2 | --- | 24.9 | 68.8 | 6.3 | 1.1 | 4.8 | 83.3 | 1.5 | 3.0 | 14,610 |
| | | | 3 | --- | 26.5 | 73.5 | --- | 1.1 | 5.2 | 88.9 | 1.6 | 3.2 | 15,590 |
| High-volatile A bituminous coal | West Virginia<br>Marion | Pittsburgh | 1 | 2.3 | 36.5 | 56.0 | 5.2 | 0.8 | 5.5 | 78.4 | 1.6 | 8.5 | 14,040 |
| | | | 2 | --- | 37.4 | 57.2 | 5.4 | 0.8 | 5.4 | 80.2 | 1.6 | 6.6 | 14,370 |
| | | | 3 | --- | 39.5 | 60.5 | --- | 0.8 | 5.7 | 84.8 | 1.7 | 7.0 | 15,180 |
| High-volatile B bituminous coal | Kentucky<br>(Western field)<br>Muhlenburg | No. 9 | 1 | 8.5 | 36.4 | 44.3 | 10.8 | 2.8 | 5.4 | 65.1 | 1.3 | 14.6 | 11,680 |
| | | | 2 | --- | 39.8 | 48.5 | 11.7 | 3.0 | 4.9 | 71.2 | 1.5 | 7.7 | 12,760 |
| | | | 3 | --- | 45.0 | 55.0 | --- | 3.4 | 5.5 | 80.6 | 1.7 | 8.8 | 14,460 |
| High-volatile C bituminous coal | Illinois<br>Sangamon | No. 5 | 1 | 14.4 | 35.4 | 40.6 | 9.6 | 3.8 | 5.8 | 59.7 | 1.0 | 20.1 | 10,810 |
| | | | 2 | --- | 41.4 | 47.4 | 11.2 | 4.4 | 4.9 | 69.8 | 1.2 | 8.5 | 12,630 |
| | | | 3 | --- | 46.6 | 53.4 | --- | 5.0 | 5.6 | 78.6 | 1.3 | 9.5 | 14,230 |
| Subbituminous A coal | Wyoming<br>Sweetwater | No. 3 | 1 | 16.9 | 34.8 | 44.7 | 3.6 | 1.4 | 6.0 | 60.4 | 1.2 | 27.4 | 10,650 |
| | | | 2 | --- | 41.8 | 53.8 | 4.4 | 1.7 | 4.9 | 72.7 | 1.5 | 14.8 | 12,810 |
| | | | 3 | --- | 43.7 | 56.3 | --- | 1.8 | 5.2 | 76.0 | 1.5 | 15.5 | 13,390 |
| Subbituminous B coal | Wyoming<br>Shedian | Monarch | 1 | 22.2 | 33.2 | 40.3 | 4.3 | 0.5 | 6.9 | 53.9 | 1.0 | 33.4 | 9,610 |
| | | | 2 | --- | 42.7 | 51.7 | 5.6 | 0.6 | 5.6 | 69.3 | 1.2 | 17.7 | 12,350 |
| | | | 3 | --- | 45.2 | 54.8 | --- | 0.6 | 6.0 | 73.4 | 1.3 | 18.7 | 13,080 |

(Continued)

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See footnotes at end of table.

**Table 3-3 (Continued).–Coal classification: source and analyses of U.S. coal**[*]

| Classification by rank | State/ county | Bed | Type of sample[†] | Proximate percent |  |  |  | Ultimate percent |  |  |  |  | Calorific value (Btu/lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Moisture | Volatile matter | Fixed carbon | Ash | Sulfur | Hydrogen | Carbon | Nitrogen | Oxygen |  |
| Subbituminous C coal | Colorado<br>El Paso | Fox Hill | 1 | 25.1 | 30.4 | 37.7 | 6.8 | 0.3 | 6.2 | 50.5 | 0.7 | 35.5 | 8,560 |
|  |  |  | 2 | --- | 40.6 | 50.3 | 9.1 | 0.4 | 4.6 | 67.4 | 1.0 | 17.5 | 11,430 |
|  |  |  | 3 | --- | 44.6 | 55.4 | --- | 0.5 | 5.0 | 74.1 | 1.1 | 19.3 | 12,560 |
| Lignite | North Dakota<br>McLean | Unnamed | 1 | 36.8 | 27.8 | 29.5 | 5.9 | 0.9 | 6.9 | 40.6 | 0.6 | 45.1 | 7,000 |
|  |  |  | 2 | --- | 43.9 | 46.7 | 9.4 | 1.4 | 4.5 | 64.3 | 1.0 | 19.4 | 11,080 |
|  |  |  | 3 | --- | 48.4 | 51.6 | --- | 1.6 | 5.0 | 70.9 | 1.1 | 21.4 | 12,230 |

Source: U.S. Department of the Interior, Bureau of Mines; EIA [1991].

[*] Note: Source and analysis of coal was selected to represent the various ranks of the specifications for classification of coals by rank adopted by the American Society for Testing and Materials.

[†] 1 = Sample as received; 2 = Moisture-free; 3 = Moisture- and ash-free.

et al. 1977; Walton et al. 1975]. However, the percentage of crystalline freesilica (i.e., silicon dioxide that is not chemically combined with other minerals) may increase. The surfaces of the silica particles may be occluded (coated) by other minerals, such as aluminosilicate (clay) [Grayson 1990; Robock and Bauer 1990; Wallace et al. 1990]. Further, dust of high-rank coal may contain a greater concentration of respirable crystalline silica because the anthracite seams are dominated by quartzitic rock in the roof and floor [Mutmansky and Lee 1984]. Dust of high-rank coal also contains a greater concentration of oxygen radicals when the coal is freshly crushed [Dalal et al. 1989; Vallyathan et al. 1988] and a greater concentration of respirable particles that have large surface areas relative to other particles in the same aerodynamic size range (i.e., plate-shaped particles) [Addison and Dodgson 1990; Reisner 1971]. These differences in the characteristics of high-rank and low-rank coal with respect to the particle composition and shape may partially explain the differences in the prevalence of simple CWP and PMF among miners exposed to coal of different ranks (see Chapter 4).

### 3.1.2 Particle Size Distributions of Coal Mine Dust

The objective of particle size-selective sampling is to exclude from sampling those particles that are too large to enter the region of the lungs where particles exert an adverse health effect. Sampling the respirable fraction of coal mine dust was initiated in the 1960s for the purpose of determining exposure to the fraction of dust that enters the alveolar region of the lungs and initiates the development of pneumoconiosis. Since that time, both U.S. and British studies have shown that coal miners are also at risk of developing chronic obstructive pulmonary diseases. The proportion of thoracic dust to which underground coal miners are exposed may be 5 to 7 times that of respirable dust. Figures 3-1 and 3-2 illustrate the mass frequency distribution of particle sizes in underground coal mines.

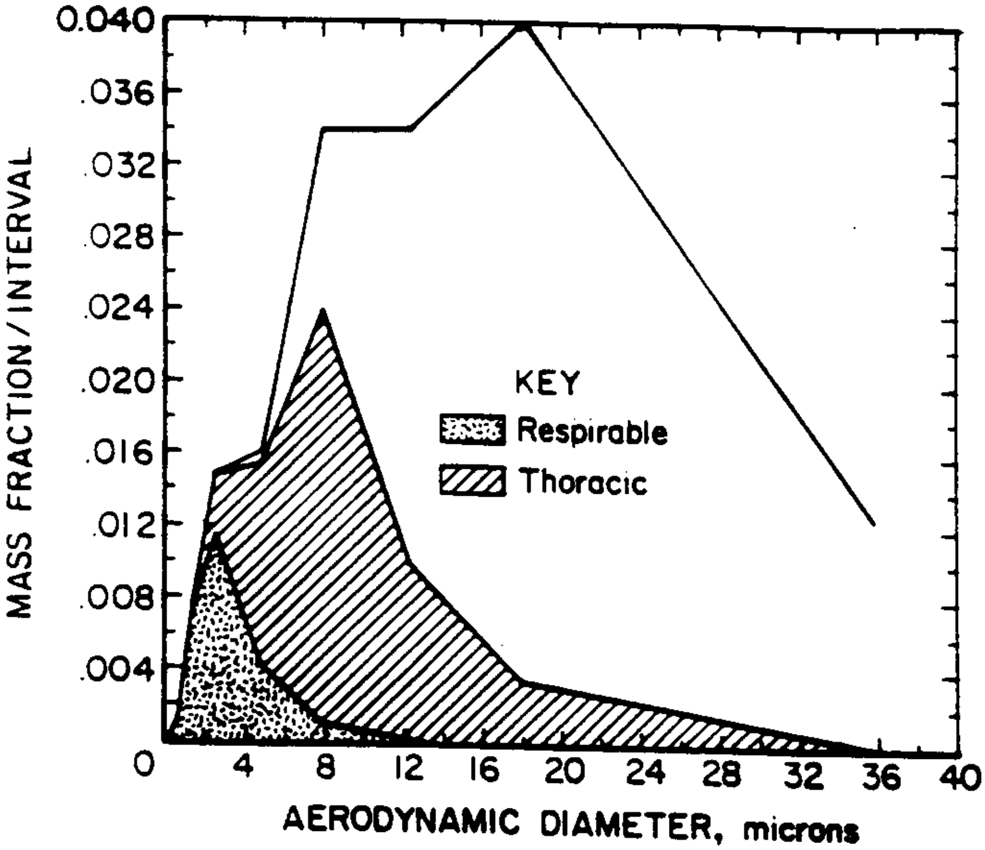

Figure 3-1. Average mass frequency distribution of shearer-generated dust showing the thoracic and respirable mass fractions. (Source: Potts et al. [1990].)

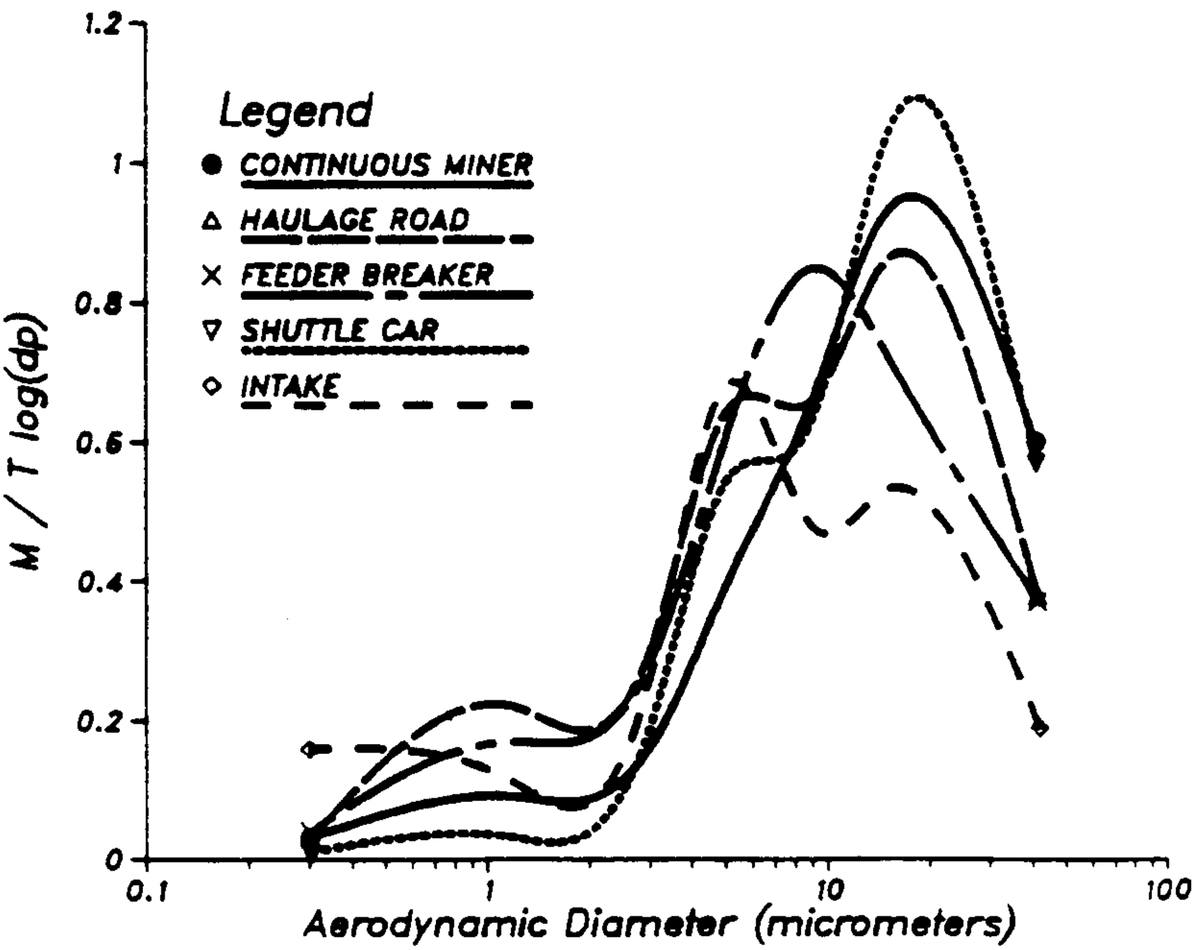

Figure 3-2. Relative mass frequency distribution. A spline procedure was used to show the trend in the histogram data. (Source: Burkhart et al. [1987].)

Although it may be assumed that the respirable dust data would be inadequate for the detection of an association with obstructive lung disease, both U.S. and British studies have demonstrated exposure-response relationships between respirable coal mine dust and decrements in $FEV_1$. These studies have shown that coal miners are at risk of developing not only pneumoconiosis, but also decrements in pulmonary function apart from the effects of cigarette smoking.

## 3.2 COAL PRODUCTION AND MINING METHODS

As mechanization was introduced into the mines, the total number of U.S. coal miners decreased from over 400,000 in 1950 to nearly 130,000 in 1990, and coal production increased fivefold (Table 3-4) [EIA 1991; Morgan 1975]. In 1990, U.S. coal production totaled 1,029 million short tons (1 short ton = 2,000 lb), an increase of about 8% over 1988 production; 40% of the total production was from underground mines [David and Pantos 1991; Mellish et al. 1990; DOE 1989; NCA 1989]. Figure 3-3 shows U.S. coal production from both surface and underground coal mines. Figure 3-4 illustrates U.S. coal production by rank. Table 3-4 lists coal mine production and miners employed from 1900 through 1990. Note that although production has increased, the number of miners employed has decreased, even in recent years.

Whether coal is mined by underground or surface methods depends on the depth of the coalbed from the surface and the character of the terrain. Underground methods are usually used to mine coalbeds deeper than about 200 feet, and surface methods to mine coalbeds of shallower depth [EIA 1989].

**Table 3-4.—Miners exployed and U.S. production trends of bituminous coal and lignite in surface and underground mines, 1900-1990[1]**

| Year | Production (thousand short tons) | | | Miners employed[2,3] | Average tons per miner per day[4] |
|---|---|---|---|---|---|
| | Underground | Surface | Total | | |
| 1900 | 212,316 | NA[5] | NA | 304,375 | 2.98 |
| 1901 | 225,828 | NA | NA | 340,235 | 2.94 |
| 1902 | 260,217 | NA | NA | 370,056 | 3.06 |
| 1903 | 282,749 | NA | NA | 415,777 | 3.02 |
| 1904 | 278,660 | NA | NA | 437,832 | 3.15 |
| 1905 | 315,063 | NA | NA | 460,629 | 3.24 |
| 1906 | 342,875 | NA | NA | 478,425 | 3.36 |
| 1907 | 394,759 | NA | NA | 516,258 | 3.29 |
| 1908 | 332,574 | NA | NA | 516,264 | 3.34 |
| 1909 | 379,744 | NA | NA | 543,152 | 3.34 |
| 1910 | 417,111 | NA | NA | 555,533 | 3.46 |
| 1911 | 405,907 | NA | NA | 549,775 | 3.50 |
| 1912 | 450,105 | NA | NA | 548,632 | 3.68 |
| 1913 | 478,435 | NA | NA | 571,882 | 3.61 |
| 1914 | 421,436 | 1,268 | 422,704 | 583,506 | 3.71 |
| 1915 | 439,792 | 2,832 | 442,624 | 557,456 | 3.91 |
| 1916 | 498,500 | 4,020 | 502,520 | 561,102 | 3.90 |
| 1917 | 546,273 | 5,518 | 551,791 | 603,143 | 3.77 |
| 1918 | 571,275 | 8,111 | 579,386 | 615,305 | 3.78 |
| 1919 | 460,270 | 5,590 | 465,860 | 621,998 | 3.84 |
| 1920 | 559,807 | 8,860 | 568,667 | 639,547 | 4.00 |
| 1921 | 410,865 | 5,057 | 415,922 | 663,754 | 4.20 |
| 1922 | 412,059 | 10,209 | 422,268 | 687,958 | 4.28 |
| 1923 | 552,625 | 11,940 | 564,565 | 704,793 | 4.47 |
| 1924 | 470,080 | 13,607 | 483,687 | 619,604 | 4.56 |
| 1925 | 503,182 | 16,871 | 520,053 | 588,493 | 4.52 |
| 1926 | 556,444 | 16,923 | 573,367 | 593,647 | 4.50 |
| 1927 | 499,385 | 18,378 | 517,763 | 593,918 | 4.55 |
| 1928 | 480,956 | 19,789 | 500,745 | 522,150 | 4.73 |
| 1929 | 514,721 | 20,268 | 534,989 | 502,993 | 4.85 |
| 1930 | 447,684 | 19,842 | 467,526 | 493,202 | 5.06 |
| 1931 | 363,157 | 18,932 | 382,089 | 450,213 | 5.30 |
| 1932 | 290,069 | 19,641 | 309,710 | 406,380 | 5.22 |
| 1933 | 315,360 | 18,270 | 333,630 | 418,703 | 4.78 |
| 1934 | 338,578 | 20,790 | 359,368 | 458,011 | 4.40 |
| 1935 | 348,726 | 23,647 | 372,373 | 462,403 | 4.50 |
| 1936 | 410,962 | 28,126 | 439,088 | 477,204 | 4.62 |
| 1937 | 413,780 | 31,751 | 445,531 | 491,864 | 4.69 |
| 1938 | 318,138 | 30,407 | 348,545 | 441,333 | 4.89 |
| 1939 | 357,133 | 37,722 | 394,855 | 421,788 | 5.25 |

(Continued)

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See footnotes at end of table.

**Table 3-4 (Continued).—Miners exployed and U.S. production trends of bituminous coal and lignite in surface and underground mines, 1900-1990[a]**

| Year | Production (thousand short tons) Underground | Surface | Total | Miners employed[b] | Average tons per miner per day[c] |
|---|---|---|---|---|---|
| 1940 | 417,604 | 43,167 | 460,771 | 439,075 | 5.19 |
| 1941 | 459,078 | 55,071 | 514,149 | 456,981 | 5.20 |
| 1942 | 515,490 | 67,203 | 582,693 | 461,991 | 5.12 |
| 1943 | 510,492 | 79,685 | 590,177 | 416,007 | 5.38 |
| 1944 | 518,678 | 100,896 | 619,576 | 393,347 | 5.67 |
| 1945 | 467,630 | 109,987 | 577,617 | 383,100 | 5.78 |
| 1946 | 420,958 | 112,962 | 533,922 | 396,434 | 6.30 |
| 1947 | 491,229 | 139,395 | 630,624 | 419,182 | 6.42 |
| 1948 | 460,012 | 139,506 | 599,518 | 441,631 | 6.26 |
| 1949 | 331,823 | 106,045 | 437,868 | 433,698 | 6.43 |
| 1950 | 392,844 | 123,467 | 516,311 | 415,582 | 6.77 |
| 1951 | 415,842 | 117,823 | 533,665 | 372,897 | 7.04 |
| 1952 | 356,425 | 110,416 | 466,841 | 335,217 | 7.47 |
| 1953 | 349,551 | 107,739 | 457,290 | 293,106 | 8.17 |
| 1954 | 289,112 | 102,594 | 391,706 | 227,397 | 9.47 |
| 1955 | 343,465 | 121,168 | 464,633 | 225,093 | 9.84 |
| 1956 | 365,774 | 135,100 | 500,874 | 228,163 | 10.28 |
| 1957 | 360,649 | 132,055 | 492,704 | 228,635 | 10.59 |
| 1958 | 286,884 | 123,562 | 410,446 | 197,402 | 11.33 |
| 1959 | 283,434 | 128,594 | 412,028 | 179,636 | 12.22 |
| 1960 | 284,888 | 130,624 | 415,512 | 169,400 | 12.83 |
| 1961 | 272,766 | 130,211 | 402,977 | 150,474 | 13.87 |
| 1962 | 281,266 | 140,883 | 422,149 | 143,822 | 14.72 |
| 1963 | 302,256 | 156,672 | 458,928 | 141,646 | 15.83 |
| 1964 | 321,808 | 165,190 | 486,998 | 128,698 | 16.84 |
| 1965 | 332,661 | 179,427 | 512,088 | 133,732 | 17.52 |
| 1966 | 338,524 | 195,357 | 533,881 | 131,752 | 18.52 |
| 1967 | 349,133 | 203,494 | 552,626 | 131,523 | 19.17 |
| 1968 | 344,142 | 201,103 | 545,245 | 127,894 | 19.37 |
| 1969 | 347,132 | 213,373 | 560,505 | 124,532 | 19.90 |
| 1970 | 338,788 | 264,144 | 602,930 | 140,140 | 18.84 |
| 1971 | 275,888 | 276,304 | 552,192 | 145,664 | 18.02 |
| 1972 | 304,103 | 291,284 | 595,386 | 149,265 | 17.74 |
| 1973 | 299,353 | 292,384 | 591,738 | 148,121 | 17.58 |
| 1974 | 277,309 | 326,098 | 603,406 | 166,701 | 17.58 |
| 1975 | 292,826 | 355,612 | 648,438 | 189,880 | 14.74 |
| 1976 | 294,880 | 383,805 | 678,685 | 202,280 | 14.46 |
| 1977 | 265,950 | 425,394 | 691,344 | 221,428 | 14.84 |
| 1978 | 242,177 | 422,950 | 665,127 | 242,295 | 14.68 |
| 1979 | 320,321 | 455,978 | 776,299 | 224,203 | 15.33 |

(Continued)

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See footnotes at end of table.

**Table 3-4 (Continued).–Miners exployed and U.S. production trends of bituminous coal and lignite in surface and underground mines, 1900-1990[a]**

| Year | Production (thousand short tons) | | | Miners employed[b] | Average tons per miner per day[b] |
|---|---|---|---|---|---|
| | Underground | Surface | Total | | |
| 1980 | 336,925 | 486,719 | 823,644 | 224,938 | 16.32 |
| 1981 | 315,875 | 502,477 | 818,352 | 226,250 | 18.08 |
| 1982 | 338,572 | 494,951 | 833,523 | 214,400 | 18.13 |
| 1983 | 299,892 | 478,111 | 778,003 | 173,543 | 21.19 |
| 1984 | 351,474 | 540,285 | 891,759 | 175,746 | 22.26 |
| 1985 | 350,073 | 528,856 | 878,930 | 167,009 | 23.13 |
| 1986 | 359,800 | 526,223 | 886,023 | 152,668 | 25.69 |
| 1987 | 372,238 | 542,963 | 915,202 | 141,065 | 28.19 |
| 1988 | 381,546 | 565,164 | 946,710 | 133,913 | 30.57 |
| 1989 | 393,322 | 584,058 | 977,381 | 130,103 | 32.05 |
| 1990 | 424,119 | 601,449 | 1,025,570 | 129,619 | 33.25 |

Source: EIA [1991].

[a] Note: Subbituminous coal is included with bituminous coal. Totals may not equal sum of components because of independent rounding.

Sources: 1900-1976: U.S. Department of Interior, Bureau of Mines, *Minerals Yearbooks*; 1977-1978: Energy Information Administration, *Bituminous Coal & Lignite Production and Mine Operations*; 1979-1990: *Coal Production*, various issues.

[b] After 1978, excludes miners employed at mines that produced less than 10,000 tons.

[c] NA = Not available; relatively small amounts included with underground.

[d] Note: The number of "miners employed" listed here is lower than that listed in MSHA [1991], perhaps because of exclusion here of mines producing less than 10,000 tons.

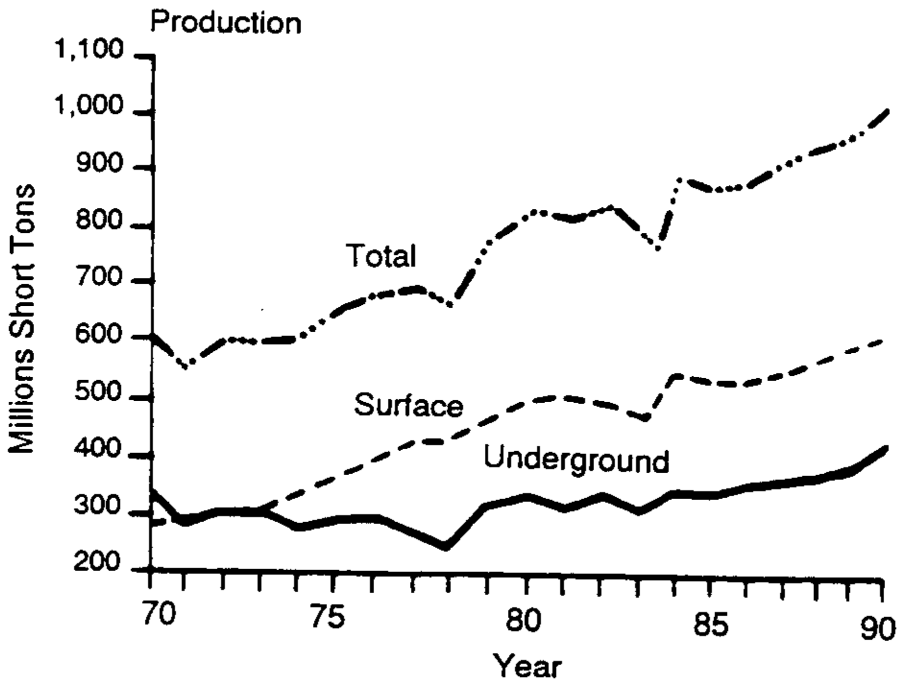


Figure 3-3. U.S. coal production in surface and underground mines, 1970-90. (Source: Energy Information Administration, Annual Energy Review 1990 [May 1991].)

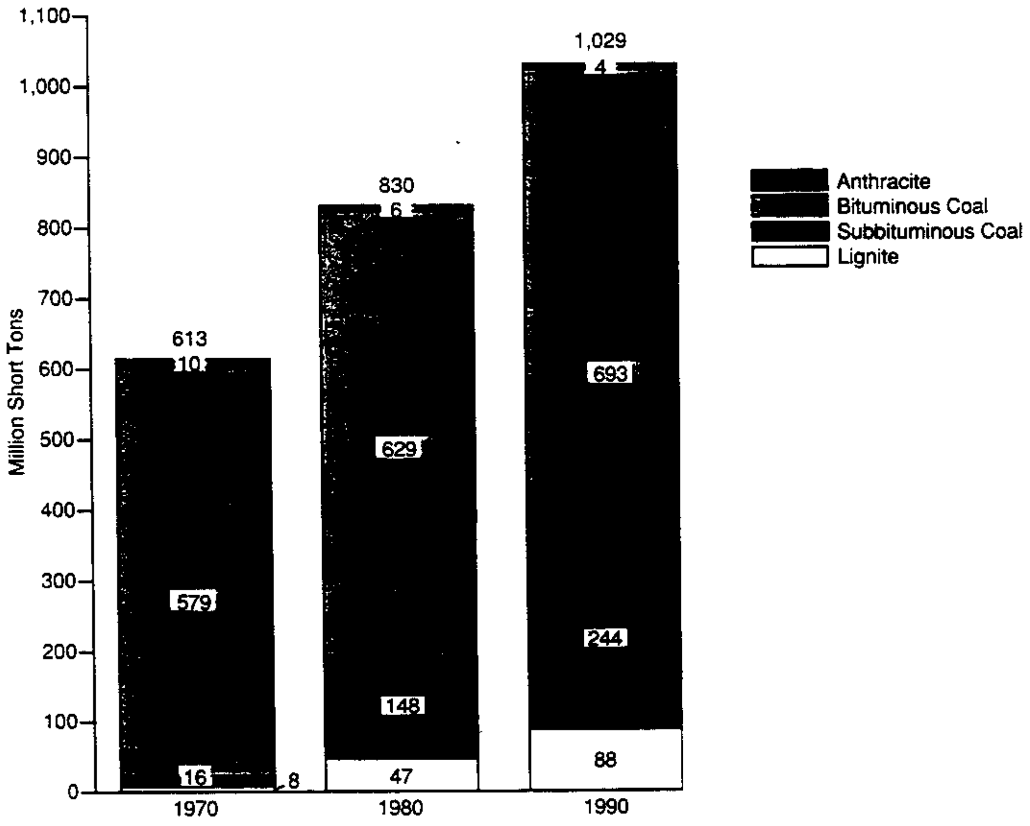


Figure 3-4. U.S. coal production by rank, 1970-90 (in millions of short tons). Bituminous coal is the major rank of coal mined in the United States, but lower-rank coals are becoming more important while anthracite is declining. (Source: EIA [1991].)

### 3.2.1 Underground Coal Mining Methods

#### *3.2.1.1 Room-and-Pillar Mining*

The most common underground coal mining method is the "room-and-pillar mining system," in which the mine roof is supported primarily by coal pillars that are left at regular intervals [EIA 1989]. The rooms are the areas where the coal is mined. Either a "conventional" or a "continuous" mining method is used to extract the coal in the room-and-pillar method. Conventional mining consists of a series of operations in which the coal face is cut so that it breaks easily when blasted (with either explosives or high-pressure air); the broken coal is then loaded onto conveyers or into shuttle cars for removal to the surface. In continuous mining the coal is extracted and removed from the coal face in one operation, using a continuous mining machine. "Room-and-pillar retreat mining" occurs after coal has been extracted from the "rooms" in a mine section; additional coal is extracted by mining the supportive pillars [EIA 1989].

#### *3.2.1.2 Longwall Mining*

Another common underground coal mining method is the "longwall mining system," in which long sections of coal (up to about 1,000 ft) are removed without leaving pillars of coal for support. Instead, a movable, powered, roof support system is used to support the roof in the working area. When the roof supports are moved, the area caves in and is called the gob area. After subsidence occurs, the gob area supports the overlying strata. Longwall mining is used where the coalbed is thick and generally flat, and where surface subsidence is acceptable [EIA 1989]. Recovery of approximately 80 percent of the coal is possible with the longwall mining system [Jankowski et al. 1990]. In 1988, mines using longwall methods accounted for about 35% of the coal produced in underground coal mines [Lewis 1990].

### *3.2.1.3 Additional Coal Mining Methods*

A "shortwall mining system" is a room-and-pillar mining system in which the working face is wider than usual (up to 150 ft), but smaller than in longwall mining [EIA 1989].

A "drift mine" is driven horizontally into coal that is exposed or accessible in a hillside. A "punch mine" is a small drift mine used to recover coal from strip-mine highwalls or from small coal deposits. A "shaft mine" is driven vertically into the coal deposit, and a "slope mine" is driven at an angle to reach the coal deposit [EIA 1989].

"Hydraulic mines" use high-pressure water jets to break coal from a steeply inclined, thick coalbed. The coal is transported to the surface by a system of flumes or a pipeline. Hydraulic mines are used in western Canada but have not yet been used in the United States [EIA 1989].

### *3.2.1.4 Roof Supports*

The principal method of supporting the mine roof is through "roof bolting," in which bolts are installed in the mine roof to strengthen it by pulling together rock strata or fastening weak strata to strong strata. The bolts are 2 to 10 ft long and have an expansion shell or resin grouting [EIA 1989].

### *3.2.1.5 Control of Gases and Airborne Dust*

The principal method of controlling noxious gases and airborne respirable dust concentrations in coal mines is through "mine ventilation," in which fans supply fresh air and remove gases and dust from the mine. To reduce the possibility of a coal dust explosion, "rock dust" is sprayed in underground coal mines. Rock dust is a very fine noncombustible material, usually pulverized limestone [EIA 1989]. Table 3-5 provides a description of mining equipment used in underground coal mines.

### 3.2.2 Surface Coal Mining Methods

Strip mining, the most common type of surface coal mining, produced 99% of the coal from U.S. surface coal mines in 1987 (Table 3-6). Strip mining is a large-scale, earth-moving process during which the overburden, or material overlying a bed of coal, is excavated and the underlying coal is removed. The working area of the strip mine is known as the "pit." Overburden material excavated from the strip being mined typically is side-cast into the strip pit previously mined. The process is repeated over and over until some limit is reached (e.g., a geologic limit; a property-line limit; or some economic-equipment limit) [Stefanko 1983].

The average thickness of the overburden to be removed at surface coal mines typically ranges between 30 and 60 ft. The nature of the overburden at surface coal mines is variable, but generally is some combination of sandstone, shale, limestone, and loose soils. The unexcavated face of exposed overburden or coal in a strip pit is referred to as the "highwall." Highwalls up to 180 ft in height have been mined [Stefanko 1983].

#### *3.2.2.1 Specific Surface Coal Mining Operations*

The process of extracting coal from a surface coal strip mine and delivering it to consumers typically involves the following operations: (1) drilling; (2) blasting; (3) overburden excavation (stripping); (4) coal loading; (5) coal haulage; (6) reclamation; (7) coal preparation; and (8) transportation to the consumer [Stefanko 1983].

**Table 3-5.—Glossary of underground coal mining equipment**

| Equipment name | Description |
|---|---|
| Coal cutting | Used in conventional mining to undercut, topcut, or machine shear the coal face so that coal can be fractured easily when blasted; can cut 9-13 ft into coal face |
| Continuous auger | Used in mining coalbeds less than 3 ft thick; auger machine cutting depth is about 5 ft; usually uses a continous conveyer belt to haul coal to surface |
| Continuous mining | Used during "continuous mining" to cut or rip coal machine from the coal face and load it into shuttle cars or conveyors; eliminates use of blasting and performs functions of other machines (e.g., drills, cutting machines, and loaders); has turning "drum" with sharp bits; extracts 16-22 ft of coal before roof bolting is required; extracts coal at 8-15 tons/min |
| Conveyer systems | Carries coal; "mainline conveyer" is permanently installed and carries coal to surface; "section conveyer" connects working face to mainline conveyer |
| Face drill | Used in conventional mining to drill shotholes in coalbed for explosive charges |
| Loading machine | Used in conventional mining to scoop broken coal from working area and load into "shuttle car" |
| Longwall mining machine | Shears coal from a long straight coal face (up to about 600 ft) by working back and forth across the face under a movable, hydraulic jack roof support system; broken coal transported by conveyor; extracts coal at 1,000 tons per shift |
| Mine locomotive | Operates on tracks; used to haul mine cars containing coal and other material, or to move personnel in "mantrip" cars; some can haul 20 tons at 10 mph; electric or battery-powered |
| Ram car/scoop car | Rubber-tired haulage vehicle; unloaded via movable steel plate at rear of haulage bed |
| Roof-bolting machine (roof bolter) | Used to drill holes and place bolts to support the mine roof; can be installed on a continuous machine |
| Scoop | Rubber-tired haulage vehicle used in thin coalbeds |
| Shortwall mining machine | Usually a continuous mining machine used with a powered, self-advancing roof support system; shears coal from a short coal face (up to 150 ft long); broken coal hauled by shuttle cars to conveyer belt |
| Shuttle car | A rubber-tired haulage vehicle that hauls coal to mine cars or conveyers for delivery to surface; unloaded by built-in conveyer |

Source: EIA [1989].

**Table 3-6.—Coal production (short tons) in the United States by work location and type of coal in 1987 (operator data)[*]**

| Work location | Type of coal | | All coal |
|---|---|---|---|
| | Anthracite | Bituminous[†] | |
| Underground mines | 567,887 | 364,026,658 | 364,594,545 |
| Surface mines | | | |
| Strip mines | 1,831,286 | 526,571,449 | 528,402,735 |
| Auger mines | -- | 3,316,768 | 3,316,768 |
| Culm bank | 879,312 | 682,590 | 1,561,902 |
| Dredge | 4,789 | 190,323 | 195,112 |
| Total (surface) | 2,715,387 | 530,761,130 | 533,476,517 |
| Total (underground and surface) | 3,283,274 | 894,787,788 | 898,071,062 |

[*] Adapted from MSHA [1988].
[†] Includes subbituminous and lignite.

### 3.2.2.1.1 Drilling

Topsoil is first removed and stored for reclamation of the area to be mined. In most cases, a series of holes are drilled in the overburden material where explosives can be placed for blasting. Drilling and blasting the overburden layer creates fragments that are easier to excavate, resulting in fewer problems with the operation and maintenance of excavating equipment, and thus a more rapid and economical stripping process [Stefanko 1983].

If the overburden is 50 ft or greater in thickness, vertical holes for blasting are drilled in the highwall. The advantage of drilling vertical holes rather than placing explosives in a horizontal hole above the coal seam is that thicker and harder layers of overburden may be fractured without damaging the underlying coal seam. In some mines vertical holes for blasting are also routinely drilled when the overburden is less than 50 ft thick. When the overburden is less than 50 ft thick and consists of soft shale materials, an auger-type drill may be used to place long horizontal holes for blasting about 1 to 2 ft above the coal seam. This horizontal hole approach allows a large area of overburden to be blasted with a small number of holes [Stefanko 1983].

A typical drill bit for vertical drilling has three rollers (i.e., tricone) equipped with bearings that permit the rollers to rotate independently when the drill stem is rotated with applied thrust. Various teeth configurations are available, ranging from long pointed teeth for softer rock to buttons of hard alloyed materials for very hard cutting. Diesel or electric power is used to rotate the drill stem [Stefanko 1983].

The spacing of the vertical holes in the highwall depends on factors such as the strength of the overburden material to be blasted and the type of explosive that will be used. A larger hole allows a greater amount of explosives, and permits a greater spacing between holes. Thus, 15-in diameter holes might be placed about 35 ft apart, while 7-in diameter holes might be spaced about 15 ft apart [Stefanko 1983].

A stream of compressed air (referred to as "bail air") typically is injected into the drill stem and forced out through orifices in the drill bit. This cools the drill bit's cutting points and bearings. Also, this keeps the hole being drilled free of cuttings. The injected air "bails" the drill cuttings up and out of the drill hole. As the bail air exits the drill hole, a dust cloud is formed that may contain relatively large amounts of crystalline silica. The amount of dust from the drill hole and the amount of respirable crystalline silica in the dust cloud may fluctuate considerably, depending on factors such as geology, drilling methods, weather conditions, and water content [BOM 1986]. These factors must be considered in selecting a dust collection method for the drilling machinery.

### 3.2.2.1.2 Blasting

The next step in the work process is to place explosives in the holes that have been drilled in the overburden. Ammonium nitrate (94%) with fuel oil (6%), generically referred to as ANFO, is the most commonly used explosive in surface coal mining. It is detonated by using special cast primers that in turn are ignited by blasting caps. A detonating fuse typically is used with a high explosive core of pentaerythritol tetranitrate (PETN). Millisecond-delay elements permit delays between detonation of individual holes to improve fragmentation [Stefanko 1983].

### 3.2.2.1.3 Overburden excavation (stripping)

The blast causes some of the overburden to fall into the pit. However, most of the overburden is retained in the highwall area as fragmented material. Several different types of equipment may be used to remove the fragmented overburden material. Descriptions of the types of equipment used are provided in Table 3-7. When there are small amounts of overburden, bulldozers, scrapers, and front-end loaders may be used. When there are large amounts of overburden, power shovels may be operated in the pit, or draglines may be operated from on top of the overburden beside the pit. In addition, bucket-wheel excavators are used at a few surface coal mines in the United States [Stefanko 1983].

The overburden removed in gaining access to the coal is called the "spoil." The excavated overburden from the pit and the highwall typically are discharged (spoiled) at the side of the pit opposite the highwall. The process builds up mounds of loose material that are collectively called the spoil bank [Stefanko 1983].

**Table 3-7.—Glossary of surface coal mining equipment**

| Equipment name | Description |
|---|---|
| Auger | A large-diameter (16- to 48-in) screw drill that cuts, transports, and loads overburden or coal onto vehicles or conveyors |
| Bucket wheel | A boom-mounted, rotating, vertical wheel with buckets on its periphery, which loads an internal conveyor network that discharges away from the digging area |
| Bulldozer | A tractor with a vertically curved steel blade mounted on the front end. The blade is held at a fixed distance by arms secured on a pivot or shaft near the horizontal center of the tractor. |
| Dragline | Excavating equipment that can cast a cable-hung bucket a considerable distance. It can collect material by pulling the bucket towards itself on the ground with a second cable, elevate the bucket, and dump the material in a pile. |
| Front-end loader | A tractor-loader with a digging bucket mounted and operated on the front end |
| Power shovel | An excavating and loading machine with a digging bucket at the end of an arm suspended from a boom that extends crane-like from the part of the machine that houses the power plant |
| Ripper | A steel accessory (tooth-shaped) that is mounted or towed by a bulldozer, and is used in place of blasting for loosening compacted materials |
| Scraper | A steel tractor that can dig, haul, and grade, and has a cutting edge, a carrying bowl, a movable front wall, and a dumping or ejecting mechanism |

Sources: EIA [1989]; Skelly and Loy [1979]

#### 3.2.2.1.4 Coal loading

Following overburden removal, the exposed coal seam is excavated and loaded onto trucks by power shovels or by front-end loaders, either rubber-tired or track-mounted. In some mines, coal excavation may include drilling and blasting so the coal can be excavated with relative ease, or using a ripper to loosen it [Stefanko 1983].

#### 3.2.2.1.5 Coal haulage

In the United States, large, off-highway, diesel or electric trucks typically are used in surface coal mines to transport coal from the pit to the coal preparation plant or a railroad-loading siding. Eastern and midwestern strip mines tend to employ rear-dump units (35- to 85-ton capacity) because this type of truck maneuvers well in compact pit operations, has good traction capabilities, and can cope with the steep ramps and sharp haul road turns. Western strip mines tend to use drop-bottom tractor trailer units (100- to 200-ton capacity) because the pits are larger, the haul distances are longer, the ramps have gentler grades, and traction is not a problem [Stefanko 1983].

#### 3.2.2.1.6 Reclamation

The Surface Mining Control and Reclamation Act of 1977 [30 USC 1201 et seq.] and State laws require reclamation of a surface mine work area after coal has been extracted. This enables the land to be used in the future for some other purpose, it minimizes wind and water erosion, and it is more aesthetically acceptable. The reclamation process includes putting the overburden back in the same stratigraphic layer in which it originally existed; providing drainage; replacing topsoil; recontouring; and reestablishing permanent vegetation [Stefanko 1983].

### 3.2.2.1.7 Coal preparation

Most of the coal produced in the United States undergoes some degree of processing or preparation before it is used. The amount of preparation depends on the specifications of the customer. About two-thirds of the coal shipped to electric power plants from eastern mines is cleaned, whereas most of the coal shipped to electric utilities from western mines is only crushed and screened to facilitate handling and to remove any extraneous material [EIA 1989].

Cleaning upgrades the quality and heating value of coal by removing or reducing the amount of pyrite, rock, clay, or other ash-producing material, in addition to any materials mixed with the coal during mining, such as wire and wood. Coal cleaning is based on the principle that coal is lighter than rock and other impurities mixed or embedded in it. The impurities are separated by various mechanical devices using pulsating water current, rapidly spinning water, and liquids of different densities (dense media). Finely sized coal is cleaned by froth flotation. In this process, the coal adheres to air bubbles in a reagent and floats to the top of the washing device, while the refuse sinks to the bottom [EIA 1989].

Exposure to respirable dust at preparation plants may occur during loading, unloading, and moving coal; when processing equipment is cleaned; when heavy media (e.g., magnetite) are added to liquid slurry to achieve a desired specific gravity in a cyclone; and when refuse is transported [Llewellyn 1981].

### 3.2.2.1.8 Transportation to consumers

Coal may be delivered to consumers via several different modes of transportation. These include railroads, barges, ships, trucks, conveyors, and slurry pipelines. Railroads deliver nearly 70% of the coal distributed to domestic customers and export terminals. More than half of railroad coal shipments are made by unit trains. A unit train is dedicated to coal transportation, and carries coal from a specified loading facility straight to a specified customer without stopping [DOE 1989].

## 3.3 NUMBER OF MINERS POTENTIALLY EXPOSED IN U.S. COAL MINES

In 1990, an average of 146,505 miners were employed in U.S. underground and surface coal mines including 2,285 workers at anthracite coal mines and 144,220 workers at bituminous coal mines [MSHA 1991]. The average number of hours worked per miner in 1990 was 1,964. In 1986, 151,737 people were part of the coal mining workforce, with 69,863 underground coal miners; 8,757 surface workers at underground mines; 52,291 surface coal miners; 12,952 plant or mill workers; and 7,753 office workers [Butani and Bartholomew 1988].

### 3.3.1 Exposure to Respirable Coal Mine Dust

A comparison of respirable coal mine dust exposures for certain jobs in underground coal mines in 1969 and 1991 is provided in Table 3-8. From 1981 through 1984, the arithmetic mean concentration of airborne respirable dust in underground coal mines ranged from 1.01 to 1.12 mg/m$^3$ (arithmetic standard derivation, 1.40 to 1.97 mg/m$^3$) for more than 16,000 samples per year collected by Mine Safety and Health Administration (MSHA) inspectors [Watts and Parker 1987]. In 1984, mines using longwall methods had the greatest percentage of samples exceeding the MSHA PEL for respirable coal mine dust of 2.0 mg/m$^3$ (MRE). Of the respirable coal mine dust samples taken in longwall coal mines, the percentage of samples that exceeded the MSHA PEL was 43.7% (66/151) in the mines using plows to extract the coal and 25.2% (243/963) in mines using shearers. By comparison, mines using continuous mining methods had the greatest number (versus percentage) of samples exceeding the MSHA PEL

**Table 3-8.–A comparison of respirable coal mine dust concentrations for underground coal mine occupations in 1969 and 1991[*]**

| Occupation | 1969[†] (mg/m$^3$) | 1991[‡] (m/m$^3$) |
|---|---|---|
| Cutting machine helper | 8.4 | 0.8 |
| Continuous miner operator | 7.7 | 1.5 |
| Loading machine operator | 7.1 | 1.3 |
| Cutting machine operator | 6.9 | 1.9 |
| Coal drill operator | 6.7 | 1.3 |
| Continuous miner helper | 6.5 | 1.3 |
| Loading machine helper | 6.0 | 1.4 |
| Shot firer | 5.9 | ---[§] |
| Timberman | 4.7 | --- |
| Roof bolter operator | 4.6 | 1.2 |
| Beltman | 3.7 | 0.9 |
| Section foreman | 3.2 | 0.8 |
| Scoop car operator | --- | 0.9 |
| Supply man | 3.0 | 1.0 |
| Shuttle car operator | 2.7 | 0.9 |
| Boomboy | 2.4 | --- |
| Mechanic | 2.1 | 0.6 |
| Longwall operator (tail) | --- | 1.7 |
| Longwall operator (head) | --- | 1.5 |
| Longwall jack setter | --- | 1.4 |

Source: MSHA [1992].

[*] Note: Number of samples not provided; values presumed to be arithmetic means.
[†] Wheeler [1970].
[‡] Respirable dust spot inspection program.
[§] The studies did not include these occupations.

(1,193 out of 10,946 samples, or 10.9%). Because compliance with the MSHA PEL is determined by an arithmetic average of five samples collected when production is at least 50 percent of normal [30 CFR 70 (1988)], the occurrence of individual samples that exceed the MSHA PEL is not an indication that a mine is out of compliance. In addition, although the 2.0 mg/m$^3$ standard was determined for a 40-hr/week, 50-week/year exposure, the current work schedules may be 9 to 10 hr/day, 45 to 50 hr/week.

Table 3-9 lists the respirable coal mine dust exposures by job categories from samples taken in underground and surface coal mines in 1984. The table

**Table 3-9.—Respirable coal mine dust samples taken by MSHA inspectors in underground and surface coal mines, 1984, by job category**

| Job category | Number of samples | Respirable coal dust concentration (mg/m³) | | Percent >2 mg/m³ |
|---|---|---|---|---|
| | | AM[1] | ASD[2] | |
| Underground: | | | | |
| Auger jack setter (return side) | 116 | 2.44 | 4.17 | 36.2 |
| Longwall shear or plow operator (tailgate side) | 387 | 2.03 | 1.45 | 34.6 |
| Longwall jack setter | 499 | 1.80 | 1.30 | 28.7 |
| Auger jack setter, intake | 279 | 1.69 | 5.47 | 16.8 |
| Continuous miner operator | 2,579 | 1.31 | 2.31 | 14.2 |
| Headgate operator | 136 | 1.30 | 1.24 | 18.4 |
| Cutting machine operator | 516 | 1.23 | 3.05 | 12.2 |
| Utility man | 30 | 1.17 | 4.20 | 9.1 |
| Continuous miner helper | 1,405 | 1.15 | 1.31 | 13.7 |
| Loading machine operator | 283 | 1.15 | 1.30 | 12.4 |
| Roof bolter | 3,451 | 1.09 | 1.24 | 11.9 |
| Mobile bridge operator | 136 | 1.03 | 1.45 | 11.0 |
| Roof bolter helper | 629 | 1.02 | 0.97 | 12.1 |
| Shotfirer | 174 | 1.00 | 1.28 | 10.3 |
| Coal drill operator | 483 | 0.97 | 3.02 | 6.2 |
| Shuttle car operator | 757 | 0.86 | 1.22 | 4.9 |
| Section foreman | 277 | 0.83 | 0.99 | 5.4 |
| Shuttle car operator (standard side) | 2,123 | 0.80 | 2.00 | 5.6 |
| Scoop car operator | 938 | 0.78 | 0.99 | 5.6 |
| Motorman | 148 | 0.74 | 0.96 | 6.1 |
| Mechanic | 181 | 0.66 | 0.81 | 2.8 |
| Hand loader | 117 | 0.47 | 0.50 | 4.3 |
| Surface: | | | | |
| Fine coal plant operator | 197 | 1.51 | 1.19 | 32.0 |
| Highwall drill operator | 817 | 1.29 | 2.05 | 17.1 |
| Cleanup man | 169 | 1.04 | 1.67 | 10.0 |
| Scalper-screen operator | 108 | .88 | .80 | 9.3 |
| Cleaning plant operator | 216 | .88 | 1.50 | 6.5 |
| Laborer | 525 | .97 | 3.16 | 7.4 |
| Refuse truck driver | 634 | .59 | .61 | 3.3 |
| Tipple operator | 375 | .64 | .86 | 6.4 |
| Mechanic | 339 | .63 | 2.19 | 2.9 |
| Bulldozer operator | 1,651 | .48 | .98 | 2.0 |
| Scraper operator | 221 | .43 | .69 | 3.2 |
| Highlift operator | 1,565 | .34 | .43 | 1.3 |
| Oiler-greaser | 189 | .32 | .35 | 0.5 |
| Coal truck driver | 179 | .29 | .24 | 0 |
| Coal shovel operator | 107 | .26 | .28 | 0 |
| Crane-dragline operator | 232 | .43 | 3.15 | 0.9 |

Source: Watts and Parker [1987].

[1] AM = arithmetic mean concentration.

[2] ASD = arithmetic standard deviation.

includes the mean concentration of respirable dust and the percentage of samples that exceeded the 2.0 mg/m$^3$ MSHA PEL. Tailgate operators using shears at longwall mines were exposed to a mean concentration of respirable coal mine dust that exceeded the 2.0 mg/m$^3$ MSHA PEL to an increasing extent from 1983 through 1987 (2.1, 2.3, 2.6, 3.7, and 4.1 mg/m$^3$, respectively) [NIOSH 1988a].

Figure 3-5 shows the respirable coal mine dust concentrations by occupation, which were measured in U.S. coal mines during 1968-1969 and 1973 surveys. This figure indicates compliance with the 2.0 mg/m$^3$ standard for all job categories in 1973. A possible reason for the discrepancy between these earlier data and the more recent data (discussed above) is the increase in coal production, particularly in longwall mines, without sufficient development or utilization of dust control technology.

NIOSH receives from MSHA respirable coal mine dust data collected by its inspectors and by coal mine operators; these data have been summarized for use in epidemiologic studies [Dieffenbach 1985-1990]. From 1984 through 1989, more than 15,000 samples per year were collected by inspectors and more than 70,000 samples per year were collected by operators [Dieffenbach 1990]. Table 3-10 compares the concentrations of respirable coal mine dust in 1989 by mining method.

### 3.3.2 Exposure to Respirable Crystalline Silica

MSHA has reported that 33 percent of the roof bolters in underground coal mines have been exposed to respirable crystalline silica concentrations that exceed the MSHA PEL of 0.1 mg/m$^3$ (TWA) [30 CFR 70 (1988); Tomb et al. 1986]. The percentage would be even greater for coal miners exposed to concentrations of respirable crystalline silica that exceed the NIOSH recommended exposure limit (REL) of 0.05 mg/m$^3$. Figure 3-6 shows the percentage of samples for surface coal mine occupations that exceeded the MSHA PEL of 0.1 mg/m$^3$ or the

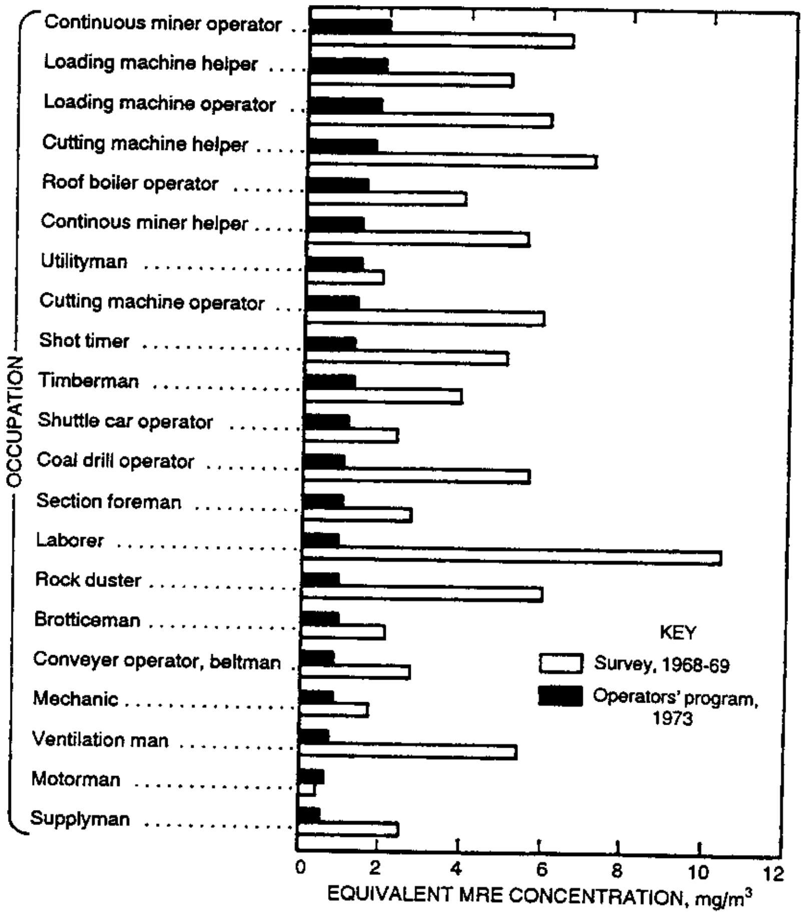


Figure 3-5. Comparison of the average dust exposures relative to specific occupations in 29 selected mines. (Source: Parobeck [1975].)

**Table 3-10.—Comparison of mean respirable coal mine dust concentration by mining method, using 1989 inspector- and operator-collected samples**

| Mining method | Number of samples | Respirable coal mine dust concentration ($mg/m^3$) | | | |
|---|---|---|---|---|---|
| | | Mean concentration | Standard deviation | Minimum concentration | Maximum concentration |
| MSHA inspector-collected samples: | | | | | |
| Longwall/shear | 252 | 1.7 | 0.9 | 0.1 | 5.8 |
| Longwall/plow | 30 | 2.2 | 1.1 | 0.1 | 6.1 |
| Continuous/ripper | 1,980 | 1.3 | 2.1 | 0.1 | 59.3 |
| Continuous/bore | 1 | 1.1 | --- | 1.1 | 1.1 |
| Continuous/auger | 63 | 1.1 | 1.2 | 0.1 | 5.3 |
| Continuous/shortwall | 2 | 1.0 | 0.7 | 0.5 | 1.5 |
| Conventional with cutting machine | 178 | 1.0 | 1.1 | 0.1 | 7.7 |
| Scoop with cutting machine | 133 | 1.2 | 1.8 | 0.1 | 14.8 |
| Scoop/shoot off solids | 48 | 0.6 | 0.7 | 0.1 | 3.7 |
| Conventional/shoot off solid-loading machine | 2 | 0.6 | 0.7 | 0.1 | 1.1 |
| Hand load/cutting machine | 1 | 0.2 | --- | 0.2 | 0.2 |
| Hand load/shoot off solid | 27 | 0.6 | 0.9 | 0.1 | 4.4 |
| Hand load/anthracite | 45 | 0.3 | 0.2 | 0.1 | 0.7 |
| Other mining methods | 9,825 | 1.0 | 1.5 | 0.1 | 75.7 |
| Total: All mining methods | 12,587 | 1.0 | 1.6 | 0.1 | 75.7 |
| Operator-collected samples: | | | | | |
| Longwall/shear | 2,615 | 1.6 | 1.3 | 0.1 | 27.8 |
| Longwall/plow | 133 | 1.3 | 1.1 | 0.1 | 8.1 |
| Continuous/ripper | 43,647 | 0.9 | 1.1 | 0.0 | 41.1 |
| Continuous/bore | 6 | 0.3 | 0.3 | 0.1 | 0.7 |
| Continuous/auger | 1,359 | 0.7 | 0.8 | 0.1 | 7.7 |
| Continuous/shortwall | 15 | 1.1 | 1.2 | 0.1 | 3.7 |
| Conventional with cutting machine | 3,597 | 0.7 | 0.9 | 0.1 | 8.4 |
| Scoop with cutting machine | 3,135 | 0.6 | 0.8 | 0.1 | 13.2 |
| Scoop/shoot off solids | 1,162 | 0.5 | 0.6 | 0.1 | 6.4 |
| Conventional/shoot off solid-loading machine | 126 | 0.5 | 0.6 | 0.1 | 5.0 |
| Hand load/cutting machine | 25 | 0.2 | 0.2 | 0.1 | 0.7 |
| Hand load/shoot off solid | 565 | 0.4 | 0.6 | 0.1 | 7.9 |
| Hand load/anthracite | 1,504 | 0.2 | 0.2 | 0.1 | 6.4 |
| Total: All mining methods | 57,889 | 0.9 | 1.0 | 0.0 | 41.1 |

Source: Dieffenbach [1990].

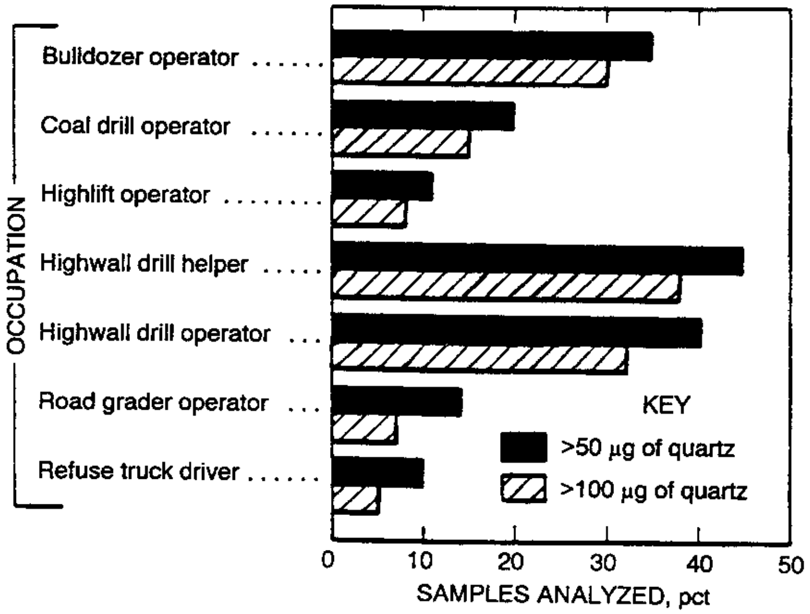


Figure 3-6. Surface coal mine dust samples, by occupation, that had full-shift quartz contents that exceeded 50 and 100 micrograms per cubic meter. (Source: Tomb et al. [1986].)

NIOSH REL of 0.05 mg/m$^3$ for respirable crystalline silica. The underground coal mine occupations with samples exceeding 5 percent quartz are listed in Figure 3-7. Note that 2 mg/m$^3$ of respirable coal mine dust with 5% quartz would correspond to a quartz concentration of 0.1 mg/m$^3$. Finally, Figure 3-8 lists the percentages of quartz by surface or underground location, and Table 3-11 lists the percentages of quartz by surface coal mine occupation. These data illustrate the importance of monitoring the concentrations of respirable crystalline silica to which miners are exposed. Sampling criteria for respirable crystalline silica as a component of respirable coal mine dust is discussed in Chapter 5.

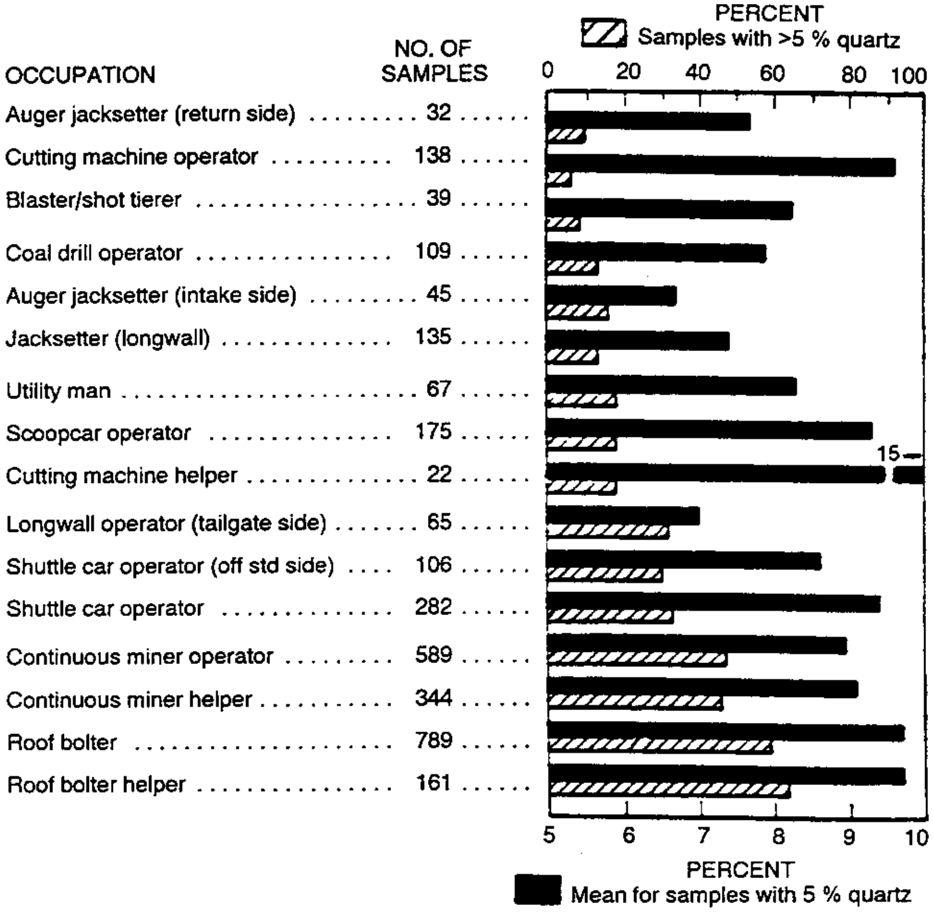


Figure 3-7. Underground coal mine samples, by occupation, with mean percent quartz greater than five percent. (Source: Tomb et al. [1986].)

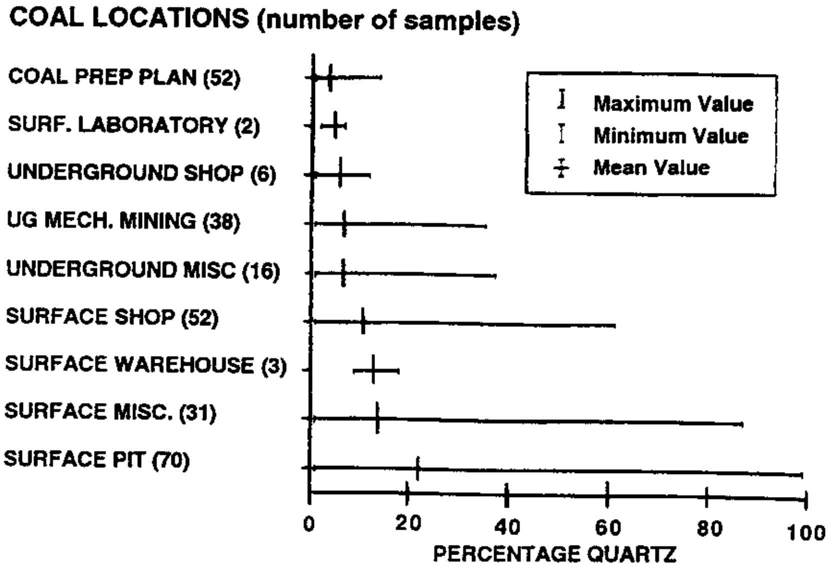


Figure 3-8. Bulk dust percentage quartz range according to coal mine

**Table 3-11.—Bulk dust average percentage quartz for coal mine occupations (based on ≥5 samples analyzed)**

| Coal occupation titles | Percentage quartz (mean) | Number of samples analyzed |
|---|---|---|
| Laborer (surface) | 19 | 15 |
| Supply man (surface) | 16 | 6 |
| Bulldozer (surface) | 15 | 7 |
| Mechanic (surface) | 14 | 60 |
| Oiler (surface) | 11 | 12 |
| Electrician (surface) | 11 | 32 |
| Roof bolter (underground) | 11 | 7 |
| Scoop operator (surface) | 11 | 7 |
| Welder (surface) | 6 | 17 |
| Mechanic underground (non-face) | 5 | 7 |

Source: Greskevitch et al. [1992].

# 4 EFFECTS OF EXPOSURE

## 4.1 EFFECTS ON HUMANS

This section describes diseases and disorders associated with exposure to respirable coal mine dust, epidemiologic studies of pneumoconioses in underground and surface coal miners, radiographic opacities among nonminers, and nonpneumoconiotic diseases among coal miners. The emphasis in this section is on studies that (1) have been performed since the passage of the Federal Coal Mine Health and Safety Act of 1969 [30 USC 801 et seq. 1988], (2) include investigation of exposure-response relationships for occupation-related diseases among coal miners, and (3) utilize standardized methods of exposure monitoring and disease classification. Several excellent reviews that include early health studies in coal miners have been published [Cotes and Steel 1987; Merchant et al. 1986; Morgan and Lapp 1976; Morgan and Seaton 1975]. Section 7.1.5 contains further discussions of epidemiologic studies correlating respirable coal mine dust with disease.

### 4.1.1 Description of Occupational Respiratory Diseases

### 4.1.1.1 Pneumonconiosis

### 4.1.1.1.1 Historical perspective

The term "pneumonokoniosis" was introduced in 1866 [Meiklejohn 1951]. In 1874, this was shortened to "pneumoconiosis." Literally, the word means "dusty lung." There is no universal agreement on the definition [Parkes 1982]. The ILO [1983] defined pneumoconiosis as "the accumulation of dust in the lungs and the tissue reaction to its presence." Some authorities include inert dusts deposited in the lungs, even if the dust deposition has not been linked with "tissue reaction" [Parkes 1982]. Thus, "any dust-ridden state of the lungs or disease process resulting from it may legitimately be called 'pneumoconiosis'" [Parkes 1982]. Different types of pneumoconioses are sometimes classified by referring to the specific type of dust deposited in the lung. "Pneumoconiosis due to silica dust" and "pneumoconiosis due to carbonaceous dust" would be two examples. This terminology tends not to be used because it is cumbersome. The term "silicosis" was introduced in 1870 to describe "pneumoconiosis due to silica" [NIOSH 1974].

The term "black lung" refers to coal workers' pneumoconiosis, which was originally defined in the Federal Coal Mine Health and Safety Act of 1969 as "a chronic dust disease of the lung arising out of employment in an underground coal mine" [30 USC 902]. The definition of pneumoconiosis was amended in the Black Lung Benefits Reform Act of 1977 to the following: ". . . a chronic dust disease of the lung and its sequelae, including respiratory and pulmonary impairments, arising out of coal mine employment" [30 USC 901 (a) and 902 (b) (1986)]. The medical definition of CWP is "a parenchymal lung disease produced by the deposition of coal dust and the host response to the retained dust" [Weeks and Wagner 1986; Wyngaarden and Smith 1982].

#### 4.1.1.1.2 CWP

Simple CWP is diagnosed in living miners in terms of the radiographic classification of the size, shape, profusion, and extent of opacities in the lungs. The radiographic appearance of simple CWP per se is not necessarily associated with impaired lung function [Parkes 1982; Morgan et al. 1974] or increased mortality [Cochrane et al. 1979; Jacobsen 1976]. However, miners with simple CWP are at increased risk of developing complicated CWP or progressive massive fibrosis (PMF) [McClintock et al. 1971; Cochrane et al. 1962]. Simple CWP is detected by chest radiography. Each radiograph is classified according to the profusion (concentration) of small opacities (less than 10 mm in diameter) in different zones of the lungs (extent) according to the International Labor Office (ILO) classification [ILO 1980]. Simple CWP is classified as major category 1, 2, or 3; the absence of CWP is coded as category 0. Category 0 is described as "small opacities absent or less profuse than the lower limit of category 1" [ILO 1980]. Within the 12-point profusion scale, each major category may be followed by a subcategory to indicate whether an adjacent main category was seriously considered when classifying within one of the four major categories (e.g., 1/2 was judged as category 1, but category 2 was seriously considered; 2/1 was judged as category 2, but category 1 was seriously considered). The shape of the small opacities is recorded as rounded (p, q, r) or irregular (s, t, u), with corresponding diameters or widths of up to about 1.5 mm (p or s), 1.5 mm to 3 mm (q or t), or 3 mm to 10 mm (r or u). In addition to the characteristics of simple CWP, pleural abnormalities (including pleural thickening of the chest wall or diaphragm, obliteration of the costophrenic angle, and pleural calcification) are also recorded according to the ILO classification [ILO 1980]. Table 4-1 summarizes the ILO classification of radiographs.

Individuals who interpret chest radiographs for pneumoconioses must be either an A reader or a B reader. A person can become an A reader by attending a NIOSH approved course on interpretation of chest radiographs for pneumoconioses. Certification as a B reader requires passing an examination that tests proficiency in interpretation of chest radiographs for pneumoconioses [Wagner et al. 1992; Morgan 1979]. For this reason, B readers are considered to have more expertise than A readers in interpretation of chest radiographs. The variability between readers in the interpretation of radiographic appearances of pneumoconioses has been examined in several studies [Rom 1989; Ducatman et al. 1988; Felson et al. 1973; Fay and Ashford 1960; Fletcher and Oldham 1949]. At a workshop held in 1990, the issues training, certification, and quality assurance were discussed [Attfield and Wagner 1992].

**Table 4-1.—International classification of radiographs of pneumoconioses [ILO 1980]: summary of detailed classification**

| Features | Codes | Definitions |
|---|---|---|
| Technical quality | 1 | Good |
| | 2 | Acceptable, with no technical defect likely to impair classification of the radiograph for pneumoconiosis |
| | 3 | Poor, with some technical defect but still acceptable for classification purposes |
| | 4 | Unacceptable |
| Parenchymal abnormalities | | |
| Small opacities | | The category of profusion is based on assessment of the concentration of opacities by comparison with the standard radiographs |
| Profusion | 0/– 0/0 0/1<br>1/0 1/1 1/2<br>2/1 2/2 2/3<br>3/2 3/3 3/+ | Category 0 - small opacities absent or less profuse than the lower limit of category 1<br>Categories 1, 2 and 3 - represent increasing profusion of small opacities as defined by the corresponding standard radiographs |
| Extent | RU RM RL<br>LU LM LL | The zones in which the opacities are seen are recorded<br>The right (R) and left (L) thorax are both divided into three zones—upper (U), middle (M) and lower (L)<br>The category of profusion is determined by considering the profusion as a whole over the affected zones of the lung and by comparing this with the standard radiographs |
| Shape and size | | |
| Rounded | p/p q/q r/r | The letters p, q, and r denote the presence of small rounded opacities. Three sizes are defined by the appearances on standard radiographs<br>p = diameter up to about 1.5 mm<br>q = diameter exceeding about 1.5 mm and up to about 3 mm<br>r = diameter exceeding about 3 mm and up to about 10 mm |
| Irregular | s/s t/t u/u | The letters s, t, and u denote the presence of small irregular opacities. Three sizes are defined by the appearances on standard radiographs<br>s = width up to about 1.5 mm<br>t = width exceeding about 1.5 mm and up to about 3 mm<br>u = width exceeding 3 mm and up to about 10 mm |
| Mixed | p/s p/t p/u p/q p/r<br>q/s q/t q/u q/p q/r<br>r/s r/t r/u r/p r/q<br>s/p s/q s/r s/t s/u<br>t/p t/q t/r t/s t/u<br>u/p u/q u/r u/s u/t | For mixed shapes (or sizes) of small opacities the predominant shape and size is recorded first; the presence of a significant number of another shape and size is recorded after the oblique stroke |
| Large opacities | A B C | The categories are defined in terms of the dimensions of the opacities<br>Category A - an opacity having a greatest diameter exceeding about 10 mm and up to and including 50 mm, or several opacities each greater than about 10 mm, the sum of whose greatest diameters does not exceed about 50 mm<br>Category B - one or more opacities larger or more numerous than those in category A whose combined area does not exceed the equivalent of the right upper zone<br>Category C - one or more opacities whose combined area exceeds the equivalent of the right upper zone |

**Table 4-1 (Continued).—International classification of radiographs of pneumoconioses [ILO 1980]: summary of detailed classification**

| Features | Codes | Definitions |
|---|---|---|
| Symbols | | It is to be taken that the definition of each of the symbols is preceded by an appropriate word or phrase such as "suspect," "changes suggestive of," or "opacities suggestive of," etc. |
| | ax | - coalescence of small pneumoconiotic opacities |
| | bu | - bulla(e) |
| | ca | - cancer of lung or pleura |
| | cn | - calcification in small pneumoconiotic opacities |
| | co | - abnormality of cardiac size or shape |
| | cp | - cor pulmonale |
| | cv | - cavity |
| | di | - marked distortion of the intrathoracic organs |
| | ef | - effusion |
| | em | - definite emphysema |
| | es | - eggshell calcification of hilar or mediastinal lymph nodes |
| | fr | - fractured rib(s) |
| | hi | - enlargement of hilar or mediastinal lymph nodes |
| | ho | - honeycomb lung |
| | id | - ill-defined diaphragm |
| | ih | - ill-defined heart outline |
| | kl | - septal (Kerley) lines |
| | od | - other significant abnormality |
| | pi | - pleural thickening in the interlobar fissure or mediastinum |
| | px | - pneumothorax |
| | rp | - rheumatoid pneumoconiosis |
| | tb | - tuberculosis |
| Comments | | |
| Presence | Y N | Comments should be recorded pertaining to the classification of the radiograph, particularly if some other cause is thought to be responsible for a shadow which could be thought by others to have been due to pneumoconiosis; also to identify radiographs for which the technical quality may have affected the reading materially |

The primary lesion of CWP is the coal macule [Cotes and Steel 1987]. Macules consist of a mass of dust particles, collagen, fibrin, and particle-laden alveolar macrophages [Kleinerman 1979]. The proportions of dust, cellular material, and collagen vary depending on the rank of coal dust inhaled [Cotes and Steel 1987]. In the region around the macules, the airspaces are enlarged, which constitutes focal emphysema [Merchant et al. 1986]. The lesions are usually symmetrically distributed in both lungs, with a greater concentration in the upper lobes [Merchant et al. 1986].

Complicated CWP, or progressive massive fibrosis (PMF), is classified radiographically as category A, B, or C, as determined by the presence of large opacities with a combined area of 1 cm or larger. PMF develops more frequently in miners already affected by simple CWP; yet PMF also develops in miners with no previous radiographic evidence of simple CWP [Hodous and Attfield 1990; Hurley et al. 1987]. PMF may continue to progress even in the absence of further dust exposure [Parkes 1982; Atuhaire et al. 1985]. The lesions of PMF are usually asymmetrically located in the lungs and are usually situated in either of the upper lobes or in the apical segment of the lower lobes [Merchant et al. 1986]. The blood vessels and airways transversing the lesions are destroyed [Merchant et al. 1986]. Advanced PMF is associated with (1) breathlessness at rest or with exercise; (2) chronic bronchitis and recurrent chest illness; (3) right ventricular hypertrophy; and (4) episodes of right heart failure [Cotes and Steel 1987]. PMF is associated with increased mortality [Atuhaire et al. 1985; Miller and Jacobsen 1985].

An early investigation of lung function among coal miners with PMF by Gilson et al. [1949] found reduced ventilatory capacity and vital capacity, increased residual volume, uneven distribution of lung ventilation, and impaired gas transfer or diffusing capacity; total lung capacity was also reduced. Subsequent investigators have confirmed that PMF is associated with moderate to severe airways obstruction, decreased oxygen diffusing capacity, and both obstructive and restrictive alterations of lung function [Morgan and Lapp 1976; Lapp and Morgan 1975; Lapp and Seaton 1971].

#### ***4.1.1.1.3 Silicosis***

Silicosis may develop when inhaled respirable crystalline silica is deposited on the alveolar walls. The rate at which silicosis develops can vary. The following are approximate guidelines. In "chronic silicosis," the duration of exposure until silicosis is first diagnosed is usually more than 20 years. In "accelerated silicosis," the duration of exposure is usually between 5 and 15 years. In "acute silicosis" (silicotic alveolar proteinosis), the duration of exposure is usually shorter than 5 years. A worse prognosis is associated with more rapid development of silicosis.

In chronic silicosis, the characteristic microscopic feature is a nodule which can be divided into three zones [Silicosis and Silicate Disease Committee 1988]. The central zone is composed of whorls of dense, hyalinized fibrous tissue; the midzone is made up of concentrically arranged collagen fibers, often exhibiting a feature known as onion skinning; and the peripheral zone consists of more randomly oriented collagen fibers, mixed with dust-laden macrophages and lymphoid cells. If typical silicotic nodules are examined by polarized light, the center of the nodule often is found to contain weakly birefringent granules of crystalline material which is silica, whereas the peripheral zone of the nodule exhibits sharply birefringent particles of variable configuration [Silicosis and Silicate Disease Committee 1988]. These prove to be silicates of a variety of types, but not crystalline silica.

In accelerated silicosis, the lung nodules seen are at earlier stages of development than in a chronic silicotic nodule [Silicosis and Silicate Disease Committee 1988]. Otherwise, the lung nodules in accelerated silicosis have no specific distinguishing morphologic feature.

Acute silicosis (silicotic alveolar proteinosis) is characterized by filling of the lung alveoli by lipoproteinaceous material [Silicosis and Silicate Disease Committee 1988]. This condition typically is associated with a history of exposure to relatively large quantities of fine particles of almost pure silica (e.g., as may occur in sandblasting or drilling). Microscopically, the material in the alveolar air spaces consists of an amorphous finely granular eosinophilic substance that stains by the periodic acid-Schiff reaction, but is resistant to diastase digestion and nonreactive to traditional mucin stains [Silicosis and Silicate Disease Committee 1988]. The material in the alveolar air spaces contains considerable lipid, predominantly phospholipid, much of which is identical to pulmonary surfactant.

#### *4.1.1.1.4 Mixed-Dust Pneumoconiosis*

In coal mining, particularly surface coal mining, the typical worker has exposure to a mixture of dusts over a working lifetime, rather than exposure to silica alone or to carbonaceous dust alone. The term "mixed-dust lesion" has been used to describe pulmonary lesions where crystalline silica is deposited in combination with less fibrogenic dusts such as iron oxides, kaolin, mica, and coal. Typically, the mixed-dust lesion has a stellate "medusa head" configuration. This lesion has a central zone of collagen that is often hyalinized, surrounded by linearly and radially arranged collagen and reticulin fiber strands mixed with dust-containing macrophages [Silicosis and Silicate Disease Committee 1988].

The knowledge that mixed-dust lesions may occur in coal miners is important in the context of screening for adverse respiratory health effects. With the exception of "acute silicosis" (which has a distinctive radiologic presentation similar to pulmonary edema and other diseases that fill air space with fluids and cells), a definitive determination cannot be made from the chest radiograph alone as to whether changes consistent with "pneumoconiosis" have resulted from carbonaceous dust or silica dust. That is, in the absence of lung tissue examination or knowledge of the exposure history, a chest radiograph showing pneumoconiosis in a coal miner may represent CWP, silicosis, or mixed-dust pneumoconiosis [Cotes and Steel 1987]. A comparison of the radiographic and pathologic features of pneumoconioses due to exposure to coal silica, or mixed dust is presented in Table 4-2.

**Table 4-2.—Comparison of features of simple pneumoconiosis due to silica, mixed dust and coal**

| | Silica | Mixed dust fibrosis | Coal |
|---|---|---|---|
| Description | Nodule | Medusa head[*] | Macule[*] |
| Dust content | Low | Intermediate | High |
| Proportion of silica | High | Intermediate | Low |
| Fibrous tissue | Concentric | Stellate | Very little |
| Emphysema | None | Irregular (if present) | Focal |
| Calcification | Yes | No | No |
| Relation to exposure | Yes | Yes | Yes |
| CXR small opacities | q-r | p-q and s | p-q |
| Age affects CXR reading | Yes | Yes | No |
| Incr. prevalence of TB | Yes | (Yes) | No |
| Usually affects lung function[†] | Yes | Yes | No |
| Progression after exposure ceased | Yes | Yes | No |

Source: Cotes and Steel [1987].

[*] The stellate secondary nodule of coalworkers' pneumoconiosis resembles that of mixed dust fibrosis but the fibrosis is often less conspicuous than the emphysema; the circumscribed secondary nodule (infective nodule) resembles the coal macule but is often larger and contains collagen.

[†] After allowing for years of exposure and smoking.

### *4.1.1.2 Nonpneumoconiotic Occupational Respiratory Diseases and Conditions*

#### 4.1.1.2.1 Chronic obstructive pulmonary disease

The term chronic obstructive pulmonary disease (COPD) includes chronic bronchitis, impaired lung function, and emphysema, but excludes pneumoconiosis, asthma, and neoplasms [Soutar 1987a]. COPD is characterized by the irreversible obstruction of airways due to either bronchitis or emphysema [Fletcher and Peto 1977; Fletcher et al. 1976]. Cigarette smoking is a major cause of COPD, but air pollution and occupational exposure to dust, particularly among smokers, also contribute to COPD [Samet 1992; Fletcher et al. 1976].

The American College of Chest Physicians has defined COPD as "diseases of uncertain etiology characterized by persistent slowing of airflow during forced expiration" [ATS 1975]. Samet [1992] has cautioned that "excessive decline of ventilatory function should not be considered equivalent to chronic obstructive lung disease, but as indicating the presence of the disease process that leads to chronic obstructive lung disease."

Discussions of the meanings of the terms chronic bronchitis and emphysema continue despite international conferences focused on standardization of terms and diagnosis [ATS 1987, 1975; Ciba 1959]. In 1961, it was proposed that the term "chronic non-specific lung disease" (CNSLD) should be used instead of the terms asthma, chronic bronchitis, and emphysema [Orie et al. 1961]. The basis for this proposal (later called the Dutch Hypothesis [Fletcher et al. 1969]) was the hypothesis that endogenous (or host) and exogenous (or environmental) factors influence disease development. Individuals with a predisposition to developing allergy and bronchial hyperreactivity were considered to be more susceptible to developing CNSLD. Sluiter et al. [1991] continue to urge usage of a nonspecific term such as CNSLD, provided that "defining criteria" are also used to characterize each patient. Figure 4.1 depicts the Dutch Hypothesis.

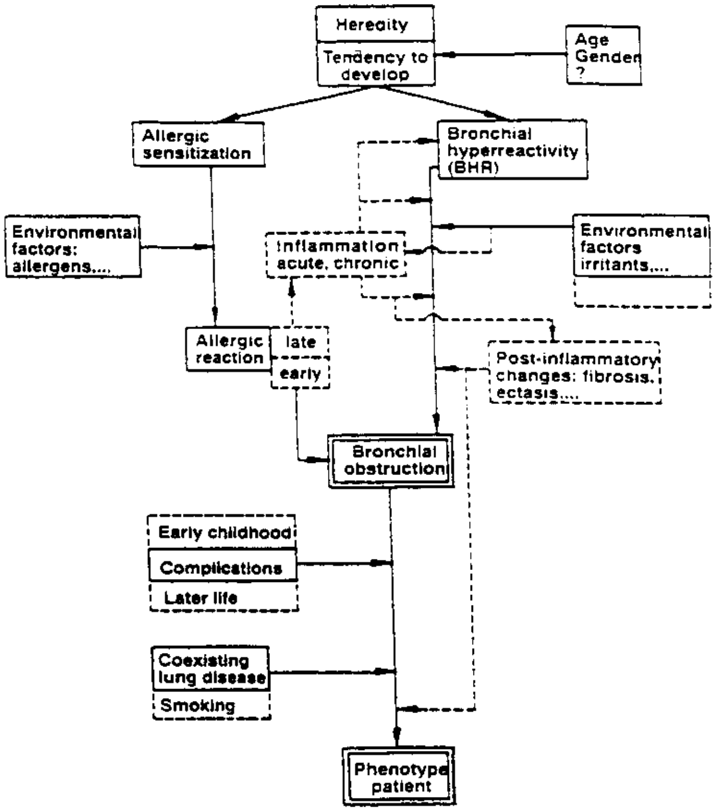


Figure 4.1. Schematic presentation of the Dutch Hypothesis 1990. The dotted lines indicate the increase in knowledge and insight in the period between 1961 and 1990. (Source: Sluiter et al. [1991].)

#### 4.1.1.2.2 Chronic bronchitis

Chronic bronchitis has been defined as "the presence of chronic or recurrent cough which occurs without localized bronchopulmonary disease, is productive of phlegm or sputum, and is present for at least three months of two sequential years" [Kilburn 1986]. Impairment of lung function, however, is probably the most important component of chronic bronchitis, since it can lead to breathlessness, disability, and premature death [Soutar 1987b].

The pathologic definition of chronic bronchitis includes hypertrophy and hyperplasia of bronchial mucous glands and the lack of cartilaginous support of the airways [Kilburn 1986]. Chronic bronchitis caused by or aggravated by occupational exposure to dust has been referred to as occupational bronchitis or industrial bronchitis [Morgan and Lapp 1976].

#### 4.1.1.2.3 Emphysema

Emphysema has been defined as "a condition of the lung characterized by abnormal, permanent enlargement of the air spaces distal to the terminal bronchiole, accompanied by destruction of their walls" [ATS 1962]. There are several types of emphysema, with different clinical manifestations [Thurlbeck 1976]. Emphysema is anatomically diagnosed if lung tissue is available; also, pulmonary function tests indicating increased lung volumes (total lung capacity and increased vital capacity) suggest the presence of emphysema [Kilburn 1986].

#### 4.1.1.2.4 Abnormalities in pulmonary function tests

Pulmonary function tests (PFTs) are used to assess dysfunction, including obstructive and restrictive disease processes; however, the commonly used spirometric tests (forced expiratory volume in 1 second [$FEV_1$] and forced vital capacity [FVC]) may not be useful for identifying specific diseases [Buist and Vollmer 1988]. Age, height, and cigarette smoking are important nonoccupational factors that affect lung function [Buist and Vollmer 1988; Hankinson 1986]. Abnormalities in PFTs that have been associated with exposure to coal mine dust include changes in ventilatory capacity, lung volumes, lung mechanics, diffusing capacity, gas exchange, and hemodynamics [Morgan and Lapp 1976]. Decrements in $FEV_1$ and FVC have been shown to be related to coal mine dust exposure in cross-sectional epidemiologic studies [Attfield and Hodous 1992; Seixas et al. 1992; Marine et al. 1988; Rogan et al. 1973], including clinically significant decrements in ex-miners with chronic bronchitis [Hurley and Soutar 1986; Soutar and Hurley 1986]. Decrements in $FEV_1$ have been associated with reduced survival rates, both in coal miners and in the general population [Silver and Hattis 1991; Olofson 1987]. Longitudinal studies have demonstrated an association between cumulative exposure and decline in $FEV_1$ [Attfield 1985; Love and Miller 1982].

### 4.1.2 Epidemiologic Studies

#### *4.1.2.1 Studies of Pneumoconiosis and Silicosis*

##### 4.1.2.1.1 U.S. underground coal miners

###### *4.1.2.1.1.1 Studies of CWP and PMF during the 1960s*

U.S. studies from the 1960s have reported prevalences ranging from 4% to 46% for CWP category 1 or greater among underground coal miners. The higher prevalences are associated with exposure to dust of higher rank coal, with increasing worker age, and with number of years worked underground [Morgan et al. 1973; Tokuhata et al. 1970; Lainhart 1969; Higgins et al. 1968; Morgan 1968; Enterline 1967; McBride et al. 1966; Hyatt et al. 1964; McBride et al. 1963; Lieben et al. 1961]. For coal miners with 40 or more years of work underground, among bituminous coal miners, the prevalence of simple CWP was 18% and the prevalence of PMF was 14% [McBride et al. 1963], while among anthracite coal miners, the prevalence of simple CWP was 29% and the prevalence of PMF was 51% [McBride et al. 1966]. Job categories associated with the highest prevalences of simple CWP and PMF (combined) were face workers (cutting machine operators, 22%; loading machine operators, 18%) and transportation workers (motormen and brakemen, 14%) among 1,616 Appalachian bituminous coal miners with an average age of 46 years and an average of 21 years work experience underground [Lainhart 1969]. Before 1970, the average concentration of respirable dust for most job categories in underground coal mines exceeded 2 mg/m$^3$, while the average concentration for some jobs at the working face (where the coal is extracted) exceeded 6 mg/m$^3$ (Table 3-8) [GAO 1990; Jacobson 1971; Doyle 1970a]. Table 4-3 summarizes prevalence rates of simple CWP and PMF for U.S. studies from 1961 through 1970.

#### *4.1.2.1.1.2 Studies of CWP and PMF, 1969-88*

The NSCWP and the CWXSP, which both began about 1970, have shown general downward trends in the prevalence rates of CWP and PMF among U.S. underground coal miners over a period of 16 to 19 years (Table 4-4; Figure 4-2). The NSCWP and the CWXSP are ongoing studies that are conducted in rounds, or cross-sectional intervals, of about 5 years each. The NSCWP is a research and medical evaluation study, as provided in the Federal Coal Mine Health and Safety Act of 1969. The CWXSP was also established in the 1969 Act and was designed for the early detection of CWP and the transfer of those miners with radiographic evidence of CWP to jobs with respirable dust exposure of 1 mg/m$^3$ or less [Althouse et al. 1986; Attfield et al. 1984a,b]. The NSCWP currently has on file about 30,000 chest X-rays, while the CWXSP has about 250,000.

**Table 4.3—Prevalence rates of CWP (Category 1 or greater) for some U.S. studies undertaken between 1961 and 1970, in order of coal rank**

| Study (by coal rank) | Prevalence of CWP (Category 1 or greater) | PMF | Mean age (yr) | Mean tenure (yr) | | Comments (see below) |
|---|---|---|---|---|---|---|
| | | | | Mine | UG | |
| High rank | | | | | | |
| A. Eastern Pennsylvania[a] | 22 | 9.6 | 55 | 26 | --- | 1 |
| B. Eastern Pennsylvania[b] | 34 | --- | 45 | --- | 22 | 1,2 |
| Medium-high rank | | | | | | |
| C. Central Pennsylvania[c] | 25 | 8.3 | 47 | 27 | --- | 1 |
| D. Southern West Virginia[d] | 46 | 7.2 | 52 | --- | 25 | 1,3 |
| E. Southern West Virginia[e] | 14 | 5.4 | 44 | --- | --- | 4 |
| Medium rank | | | | | | |
| F. Appalachia[f] | 10 | 3.0 | 47 | --- | 22 | 5 |
| G. Eastern West Virginia[e] | 6 | 1.1 | 43 | --- | --- | 4 |
| H. Northern West Virginia[g] | 7 | 0.9 | 48 | --- | 19 | 1,3 |
| I. Western Pennsylvania[h] | 9 | 3.7 | 47 | 26 | --- | 1 |
| Medium-low rank | | | | | | |
| J. Illinois/Indiana[f] | 6 | 1.5 | 48 | --- | 20 | 5 |
| K. Utah[f] | 4 | 0.7 | 51 | --- | 20 | 5 |

Source: Attfield and Castellan 1992

Notes: PMF = progressive massive fibrosis; Mine = all work in coal mining; UG = work underground.

1. The 1959 ILO classification was used.
2. Exact figure for average age is not given; figure given here has been estimated from age distribution data.
3. Group contains both current and ex-miners and could not be subdivided [ILO 1959].
4. Radiographic classification is nort stated but is probably the ILO 1959 scheme, given that the study was undertaken from 1963 to 1964.
5. The classification used is not stated explicitly. The reading sheet shown in the report looks very similar to that of the ILO 1968 classification [ILO 1968], but Morgan [1968] states that the ILO 1959 classification system was used.

[a] McBride et al. [1966].
[b] Tokuhata et al. [1970].
[c] Lieken et al. [1961].
[d] Hyatt et al. [1964].
[e] Enterline [1967].
[f] Higgins et al. [1968].
[g] McBride et al. [1963].
[h] Lainhart [1969].

**Table 4-4.—Adjusted summary prevalence estimates for small combined opacities by round of the Coal Workers' X-ray Surveillance Program, separately by first and second readers, and by data from a large concurrent epidemiological study**

| | Reader | Adjusted summary prevalences, %<br>Round 1 (1970-73) | Round 2 (1973-78) | Round 3 (1978-81) | Round 4 (1981-86) |
|---|---|---|---|---|---|
| CWP Category 1 or greater | | | | | |
| All participants (CWXSP)[a] | First | 22.4 | 7.1 | 6.0 | 5.5 |
| | Second | 13.8 | 5.9 | 5.7 | 3.0 |
| Tenure >4 years (CWXSP)[b] | First | 35.0 | 20.3 | 11.4 | 7.8 |
| | Second | 22.1 | 18.2 | 9.2 | 4.0 |
| Common tenure distribution (CWXSP)[c] | First | 19.5 | 11.7 | 8.7 | 7.2 |
| | Second | 10.7 | 9.9 | 7.3 | 3.6 |
| Epidemiologic data (NSCWP) Common tenure distribution[c] | | 6.6 | 5.1 | 3.6 | 2.3 |
| CWP Category 2 or greater | | | | | |
| All participants (CWXSP)[a] | First | 6.5 | 1.8 | 1.1 | 0.8 |
| | Second | 4.5 | 1.2 | 0.6 | 0.3 |
| Tenure >4 years (CWXSP)[b] | First | 10.8 | 5.7 | 2.2 | 1.2 |
| | Second | 7.5 | 3.8 | 1.3 | 0.5 |
| Common tenure distribution (CWXSP)[c] | First | 4.0 | 2.0 | 1.2 | 1.0 |
| | Second | 2.4 | 1.2 | 0.7 | 0.4 |
| Epidemiologic data (NSCWP) Common tenure distribution[c] | | 1.5 | 1.2 | 0.5 | 0.3 |

Source: Adapted from Attfield and Althouse [1992].

Abbreviations: CWXSP: Coal Workers' X-ray Surveillance Program; NSCWP: National Study of Coal Workers' Pneumoconiosis.

[a] All participants = summary rates based on all mandatory and voluntary X-rays.

[b] Tenure >4 years = summary rates based on all miners with more than 4 years tenure in mining.

[c] Common tenure distribution = summary rates standardized to date in right-most column of Table 2 of Attfield and Althouse [1992].

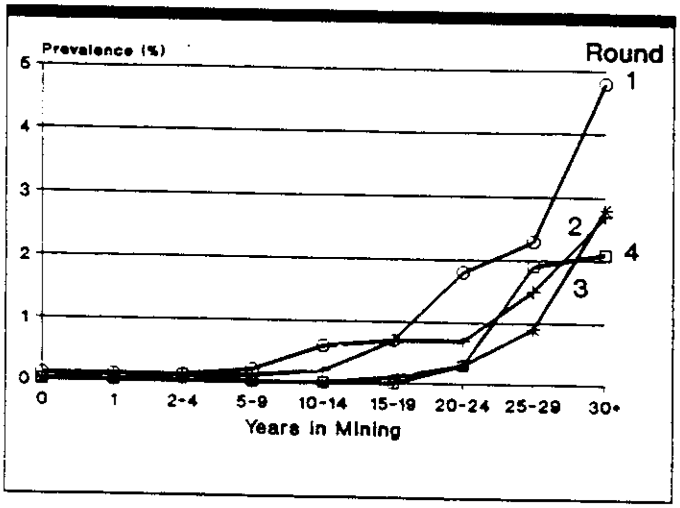


Figure 4-2. Tenure-specific prevalences of large opacities by round of the Coal Workers' X-ray Surveillance Program, based on the first readings only. (Source: Attfield and Althouse [1992].)

Thirty-one mines were originally selected for inclusion in the NSCWP from the different mining regions across the continental U.S.; however, many of those mines are no longer in production. Round 4 of the NSCWP included just two of the original 31 mines; however, Round 4 also included a follow-up study of miners in previous rounds for comparison of the disease frequencies among working miners and ex-miners.

Because both the NSCWP and the CWXSP consist of successive cross-sectional studies (rounds), interpretation of temporal trends between the rounds of either the NSCWP or the CWXSP is affected by differences in X-ray standards, X-ray readers, groups of miners studied, and tenure distributions that occurred in the successive rounds. Valid interpretation of data from either the NSCWP or the CWXSP is difficult for Rounds with poor participation rates. Participation rates for the NSCWP were 90%, 75%, 52%, and 70% for Rounds 1, 2, 3, and 4, respectively, and participation rates for the CWXSP were 50%, 44%, 32%, and 30% for Rounds 1, 2, 3, and 4, respectively. Recent modifications in the CWXSP have been focused on improving education of miners about the program and on increasing participation.

Analyses of Round 4 of the NSCWP (1985-1988) included the determination of both the incidence and the prevalence of simple CWP and PMF among 3,182 underground miners and ex-miners who had been previously examined in Round 1 of the NSCWP (1970-1975) [Attfield 1992a]. The prevalence of simple CWP category 1/0 or greater for the whole cohort was 6.8%, while the prevalence of simple CWP category 1/0 or greater for miners with 15 to 19 or 20 to 24 years underground experience were 3.4% or 11.7%, respectively. Prevalences were about twofold higher both among miners of high rank coal and among ex-miners who had left work for health reasons.

Investigation of the incidence of simple CWP over approximately 15 years of followup (between Rounds 1 and 4 of the NSCWP) indicated that about 70% of the simple CWP found at Round 4 had developed after 1970. The average concentration of respirable coal mine dust between Rounds 1 and 4 for all mining occupations was about 1 mg/m$^3$. The group of miners who developed simple CWP between Rounds 1 and 4 included both miners with mining experience before 1970 and miners who started working during or after 1970.

Using exposure data collected by the Bureau of Mines (BOM) during 1968 and 1969 and health effects data collected during Round 1 of the NSCWP (1969 to 1971), Attfield and Morring [1992a] estimated the respirable coal mine dust concentrations associated with specific job categories and mines. Statistical analysis of the data was performed using logistic regression analysis, which demonstrated a relationship between increasing dust exposure and prevalence of simple CWP and PMF (Table 4-5 lists the regression coefficients). It was estimated that by age 58, after 40 years of exposure to 2 mg/m$^3$ of respirable coal mine dust, 1.5% to 11.5% of bituminous coal miners will develop CWP category 2 or greater, and 1.3% to 6.5% will develop PMF (Table 4-6; Figure 4-3. Among anthracite coal miners, an estimated 14.2% will develop CWP category 2 or greater, and 8.9% will develop PMF [Attfield and Morring 1992b].

#### *4.1.2.1.1.3 Other studies of pneumoconiosis and silicosis*

In a separate analysis of data from the NSCWP and the CWXSP collected between 1969 and 1988, Hodous and Attfield [1990] reported that of the 69 incident cases of PMF, 57% (40 cases) occurred among miners with CWP category 0 (14%, 10 cases) or category 1 (43%, 30 cases) at the start of the 5-year study interval during which PMF developed. This development of PMF from initial CWP category 0 or 1 is in agreement with recent British data [Hurley et al. 1987] and suggests that working coal miners with CWP below category 2 are also at risk of developing PMF. Thus, although the risk of PMF increases with

**Table 4-5.—Coefficients from logistic analysis of X-ray status against dust exposure by coal rank group**[a,b]

| Term | Category 1 or greater | | | Category 2 or greater | | | PMF (all categories) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coeff. | SE | p | Coeff. | SE | p | Coeff. | SE | p |
| Intercept | -5.03 | 0.23 | 0.0001 | -6.59 | 0.38 | 0.0001 | -9.52 | 0.64 | 0.0001 |
| Age (yr) | 0.0339 | 0.0054 | 0.0001 | 0.0399 | 0.0086 | 0.0001 | 0.0885 | 0.0128 | 0.0001 |
| Dust exposure (g hr/m$^3$) | | | | | | | | | |
| Anthracite | 0.0164 | 0.0009 | 0.0001 | 0.0178 | 0.0011 | 0.0001 | 0.0148 | 0.0013 | 0.0001 |
| Med/low volatile bitum. | 0.0153 | 0.0008 | 0.0001 | 0.0161 | 0.0011 | 0.0001 | 0.0123 | 0.0013 | 0.0001 |
| High vol. bitum. "A" | 0.0078 | 0.0007 | 0.0001 | 0.0079 | 0.0010 | 0.0001 | 0.0043 | 0.0014 | 0.0013 |
| High vol. bitum. (MW) | 0.0053 | 0.0010 | 0.0001 | 0.0053 | 0.0015 | 0.0005 | 0.0016 | 0.0022 | 0.4786 |
| High vol. bitum. (West) | 0.0031 | 0.0011 | 0.0061 | 0.0005 | 0.0023 | 0.8171 | 0.0003 | 0.0027 | 0.9190 |
| Model log-likelihood | | -2594.1 | | | -1314.1 | | | -714.9 | |
| $\chi^2$ for all exposure terms (5 degrees of freedom) | | 700.4 | | | 513.6 | | | 251.4 | |
| Number of miners | | 9023 | | | 9023 | | | 9023 | |

[a] Note: See the Breakdown by Coal Type section for definitions of coal rank groups.
[b] Source: Attfield and Morring 1992.

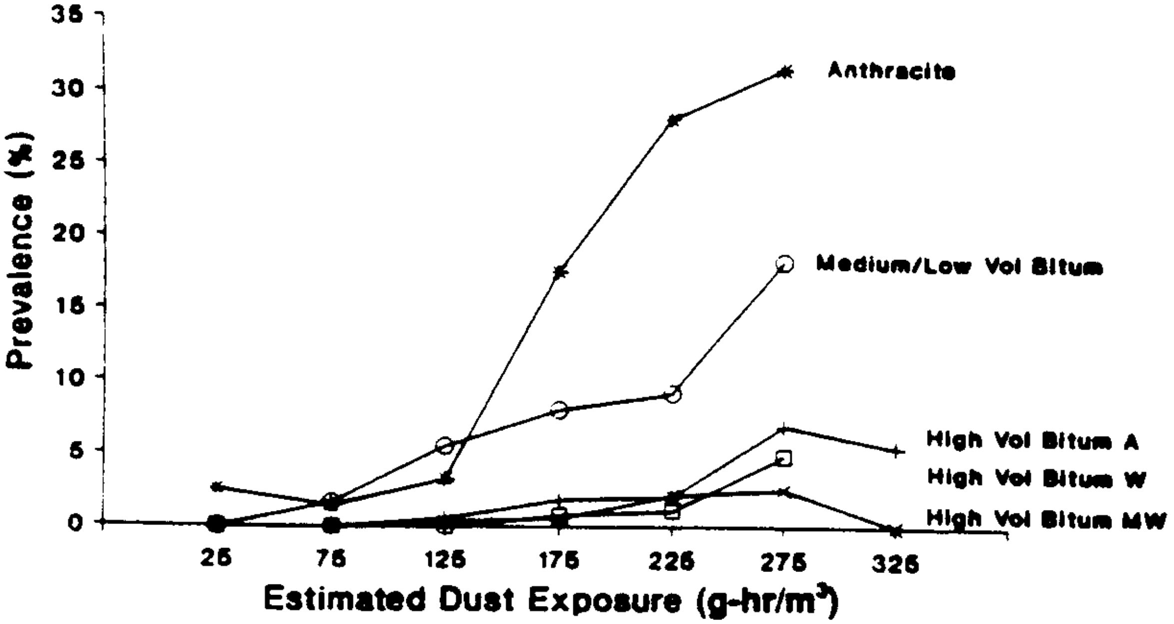


Figure 4-3. Exposure-response by coal rank group using prevalence of PMF and estimated dust exposure. (Source: Attfield and Morring [1992b].)

Table 4-6.—U.S. and British predictions, by coal rank, of the prevalence of CWP and PMF among underground coal miners at age 58 after a 40-year work exposure to a mean concentration of 2 mg/m$^3$ of respirable coal dust (with ≤5% quartz).[*]

| | Prevalence of CWP or PMF (%) | | |
|---|---|---|---|
| Coal rank | CWP category 1 or greater | CWP category 2 or greater | PMF |
| Anthracite[*]: | | | |
| U.S. prediction | 31.7 | 14.2 | 8.9 |
| British prediction | -- | -- | -- |
| Med/Low-volatile bituminous[†]: (89% carbon) | | | |
| U.S. prediction | 28.2 | 11.5 | 6.5 |
| British prediction | 12.1 | 3.2 | 1.8 |
| High-volatile bituminous "A"[‡]: (83% carbon) | | | |
| U.S. prediction | 12.1 | 4.0 | 2.2 |
| British prediction | 8.3 | 1.8 | 0.7 |
| High-volatile bituminous (Midwest)[§] | | | |
| U.S. prediction | 8.9 | 2.8 | 1.5 |
| British prediction | -- | -- | -- |
| High-volatile bituminous (West)[**] | | | |
| U.S. prediction | 6.7 | 1.5 | 1.3 |
| British prediction | -- | -- | -- |

Source: U.S. data: Attfield and Morring [1992b].
British data: Hurley and Maclaren [1987].

[*] Central Pennsylvania coalfields.

[†] Southeastern West Virginia coalfields.

[‡] Western Appalachia coalfields.

[§] Illinois, Indiana, Western Kentucky coalfields.

[**] Colorado and Utah coalfields.

increasing category of simple CWP [McClintock et al. 1971; Cochrane 1962], these findings suggest prevention of simple CWP is not sufficient to prevent PMF in all miners. Silica exposure may be a factor in this rapid progression to PMF because r-type small opacities, which were predominant on 65% of the radiographs showing PMF, are suggestive of silicosis [Ruckley et al. 1984].

In a study conducted under the National Coal Workers' Autopsy Study (NCWAS) [initiated under 30 USC 843 (d) (1970)], Green et al. [1989] reported that among the 3,365 underground coal miners autopsied (10% of all coal miners who died during the period from 1971-1980), the prevalence of silicosis was 12.5% among underground coal face workers and 6.4% among surface workers at underground coal mines. The NCWAS is a voluntary program, and the cases are submitted by next-of-kin to determine eligibility for black lung benefits.

#### *4.1.2.1.2 Studies of U.K. Coal Miners*

The factors that are important in the development of PMF among British coal miners have been reported in numerous British studies to include the following: (1) cumulative dust exposure [Hurley et al. 1987; Hurley et al. 1984; Hurley et al. 1982], (2) age of the miner and residence time of dust in the lungs [Maclaren et al. 1989; Shennan et al. 1981; McLintock et al. 1971], and (3) initial category of CWP (i.e., at the start of a study interval) [Hurley and Jacobsen 1986; Cochrane 1962]. The increased risk of PMF among miners with initial CWP category 2 or 3 is threefold to fourfold higher than among miners with initial CWP category 1 (Figure 4-4) [Hurley and Jacobsen 1986; Cochrane 1962].

The 5-year incidences of PMF among working British coal miners (during the period from 1952-1977) were reported to be 0.2%, 4.4%, 12.5%, and 13.9% for miners with CWP category 0, 1, 2, or 3, respectively, at the start of a 5-year interval [Hurley et al. 1987]. The incidence of PMF of 4.4% among miners with initial CWP category 1 is 3-4 times higher than previous estimates [Maclaren and Soutar 1985; Shennan et al. 1981; McLintock et al. 1971]. At the start of the 5-year study intervals, the largest proportion of miners (47,087 of 52,264 5-year man-intervals at risk) were classified with CWP category 0 (i.e., no radiographic evidence of CWP or PMF). Thus, although the incidence of PMF is reported to increase with increasing category of CWP, the 0.2% incidence of PMF among miners with CWP category 0 constitutes 20% of the total cases of PMF in the study (94 of 462 cases) [Hurley et al. 1987].

In a study commissioned by NIOSH, Hurley and Maclaren [1987] used logistic regression analyses of British data to estimate the probability of radiographic change over 5-year intervals for various combinations of age, respirable coal mine dust exposure, carbon content (representing different coal ranks), and CWP category at the start of the study interval. The five-year exposure intervals occurred during the calendar period of 1953 through 1977, with a range of cumulative coal mine dust exposure from 12 gh/m$^3$ to >519 gh/m$^3$ [Hurley and Maclaren 1987; Hurley et al. 1984]. Based on the results from this analysis, the risk of developing PMF by age 58, after 40 years of exposure to 2 mg/m$^3$ of respirable coal mine dust, was predicted to range from 0.71% for miners exposed to bituminous coal dust with 83% carbon to 1.85% for miners exposed to bituminous coal dust with 89% carbon (Table 4-6). The statistical model used to derive the estimates assumes zero risk only at zero exposure.

Among ex-miners the incidence of PMF was reported to be 2.5-fold higher than among working miners of similar age groups (45-64) [Maclaren and Soutar 1985]; however, when the cumulative exposure to respirable coal mine dust was included in the analysis, the relationship for CWP category 2 or greater was not distinguishable for miners and ex-miners [Hurley and Maclaren 1988; Maclaren and Soutar 1985; Soutar et al. 1986]. Of the 1,902 ex-miners studied by Maclaren and Soutar [1985], 9% developed PMF after leaving mining, and of the 172 miners with PMF, 32% had no evidence of simple CWP (category 0) when they left mining [Maclaren and Soutar 1985]. In other British studies, rapid radiographical progression of CWP (i.e., an increase of two or more CWP categories over an approximately 5-year period) was reported among miners who had been exposed to respirable coal mine dust with relatively high respirable quartz content (11-20%) [Robertson et al. 1987; Hurley et al. 1982; Seaton et al. 1981]. Jacobson and Maclaren [1982] found that the quartz-related rapid progression of simple CWP was associated with a higher attack rate of PMF.

In a pathologic study of 430 British coal miners, Douglas et al. [1986] found that the mean weight of dust in the lungs increased with increasing size of pneumoconiotic lesions, regardless of the rank of coal that was mined. The authors also determined that the miners with PMF had not been exposed to higher amounts of dust but had accumulated more dust in their lungs per unit of exposure than had the miners without PMF, indicating differences in deposition or clearance in the lungs of miners who developed PMF.

#### *4.1.2.1.3 Irregular opacities on chest radiographs*

Although most studies have used rounded opacities as a measure of simple CWP [Attfield and Morring 1990b; Hurley et al. 1982; Jacobsen et al. 1971], the CWXSP uses combined opacities to determine a miner's right to transfer to a low dust job and the ILO [1980] guidelines require the classification of profusion of all small opacities, regardless of shape or size. Dick et al. [1984] found that the ILO 1980 version gave comparable results on the relationship between the profusion of small opacities and the coal mine dust exposure to those of the ILO 1971 version [Jacobson et al. 1971]. The profusion of irregularly-shaped opacities were related to coal mine dust exposure [Dick et al. 1984]; however, the gradient and level of profusion were lower than for rounded opacities [Collins et al. 1988]. The presence of irregularly shaped (but not rounded) small opacities on coal miners' chest radiographs has been shown to be correlated with decrements in $FEV_1$ and FVC, after controlling for the effect of coal mine dust exposure [Collins et al. 1988]. The presence of irregular opacities on chest X-rays has also been associated with emphysema and interstitial fibrosis [Cockcroft and Andersson 1987; Cockcroft et al. 1982, 1981].

#### *4.1.2.1.4 Radiographic opacities among nonminers*

In a study of a group of U.S. workers other than coal miners, Castellan et al.

[1985] determined the false positive or background level of radiographic findings that are compatible with simple CWP. Among "blue collar" workers with fewer than 5 years of experience in jobs with possible respiratory hazards, 0.21% (3/1,422) showed radiographic evidence of category 1/0 or 1/1. The study population consisted of 50.6% males, 49.4% females, 52.5% whites, and 44.2% blacks. The mean age was 33.8 years (range 16 to 70 years); however, the mean age of persons with radiographic opacities was 47.5 years. Pack-years of smoking ranged from 0 to 90; mean pack-years for persons with small irregular opacities of category 0/1 or greater was 35.9, compared to 7.5 for persons with negative radiographs.

In a study of 200 hospitalized patients, Epstein et al. [1984] reported that 11% (22/200) of patients with no known dust exposure or relevant pulmonary disorder had small opacities of profusion greater or equal to category 1/0 by ILO standards. The study population consisted of 64.5% males and 35.5% females, with a mean age of 44.2 years (range 15 to 84). The mean age of patients with radiographic opacities was 54.7 years, or 14.2 years greater than patients with negative radiographs.

Both the Castellan et al. [1985] and the Epstein et al. [1984] studies suggested an effect of age on the presence of radiographic opacities. The Castellan et al. [1985] study may be bias toward low values by inclusion of only a working population, while the Epstein et al. [1984] study bias toward high values by inclusion of only a hospitalized population.

#### *4.1.2.1.5 Studies of Mortality Among U.S. and U.K. Coal Miners*

Studies from both the United States and the United Kingdom have found that mortality from occupational respiratory diseases (PMF, chronic bronchitis, or emphysema), from cancers of the digestive system, and from accidents are all

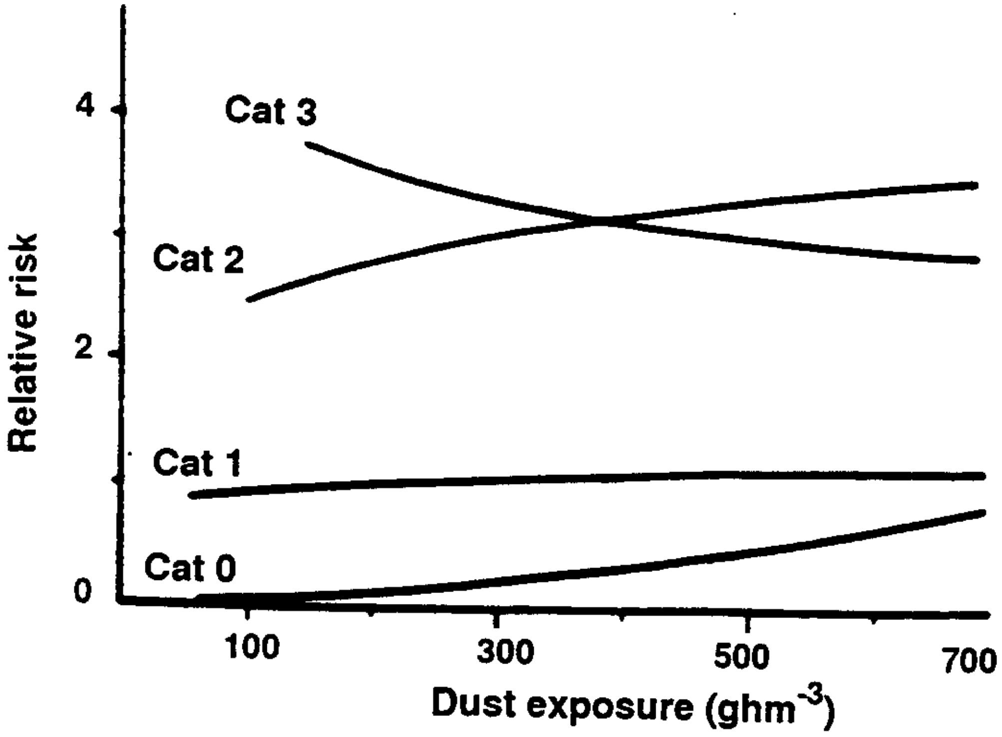


Figure 4-4. Relative risks of PMF incidence over a 5-year interval at various levels of cumulative exposure to respirable coal mine dust and by radiographic category of CWP at the start of the interval (relative to a miner with CWP category 1 and cumulative exposure to 200 gram·hours/m$^3$). (Source: Hurley et al. [1987].)

higher among coal miners than expected in the general population [Attfield 1985; Cochrane et al. 1979; Ortmeyer et al. 1974]. However, mortality from all causes and mortality resulting from lung cancer, heart disease, and coronary artery disease among working coal miners is generally lower than among men from the same regions [Foxman et al. 1986; Miller and Jacobsen 1985; Costello et al. 1974, 1975], which indicates a "healthy worker" effect [Steenland 1992; Weinkam et al. 1992; Fox and Collier 1976].

Several studies of mortality among U.S. coal miners have been published [Attfield 1985; Amandus 1983; Rockette 1977; Costello et al. 1974; Ortmeyer et al. 1974; Enterline 1972]. These studies determined standardized mortality ratios (SMRs) but did not include exposure information. Attfield [1985] and Ortmeyer et al. [1974] included surrogate indices of coal mine dust exposure by comparing SMRs for miners with more than or less than 30 years of experience. Amandus et al. [1983] used years of underground mining experience as a surrogate for dust exposure in a regression model; however, it was not statistically significant and was removed from the final model. Silver and Hattis [1991] used data on respirable coal mine dust exposures and decrements in $FEV_1$ [Attfield and Morring 1990b] to estimate the excess risk of mortality for U.S. coal miners; their method used a coefficient that related mortality to decline in $FEV_1$ [Olofson et al. 1987].

Attfield [1985] found that the subgroup with radiographic evidence of simple CWP had SMRs for nonmalignant respiratory diseases of 216.7 ($P<0.01$) for current smokers and 205.3 ($P<0.05$) for ex-smokers [Attfield 1985]. For the subgroup without radiographic evidence of CWP, the SMR for nonmalignant respiratory diseases was significant only for current smokers (SMR=167.8; $P<0.05$) [Attfield 1985]. In the study of Appalachian bituminous coal miners, Amandus [1983] reported an SMR of 304.9 ($P<0.05$) for nonmalignant respiratory diseases among miners and ex-miners who were current smokers, whereas the SMR for nonmalignant respiratory diseases among nonsmokers was 67.1 (not statistically significant). The SMR for lung cancer in either study was not elevated or statistically significant (i.e., 80.9 in Attfield [1985] and 86.0 in Amandus [1983].

#### **4.1.2.1.6 Surface coal miners**

##### ***4.1.2.1.6.1 Health hazard evaluations among drillers at surface coal mines***

In 1980, NIOSH performed a health hazard evaluation (HHE) of a surface coal mine that had been in operation in West Virginia since 1972 [Banks et al. 1983]. This HHE was initiated because in 1979 a driller who had worked at this mine for five years was hospitalized and diagnosed as having silico-proteinosis, a type of silicosis. Of the other nine miners evaluated in the HHE, two cases of category 1 pneumoconiosis were identified; both involved surface coal miners who had worked as drillers—one for 4 years and the other for 6 years.

In 1982, at the request of MSHA, NIOSH conducted an HHE [Cornwell and Hanke 1983] at three surface coal mines to evaluate the respiratory status of surface coal miners who were drillers and driller helpers. The study group of drillers included active miners who were current or former drillers and/or driller helpers. The comparison group consisted of workers who had never worked as drillers or driller helpers. The study found one case of category 2 simple pneumoconiosis in the driller group and one case of category 1 simple pneumoconiosis in the nondriller group. The mean length of employment on drill crews for the driller group was 3.8 years, a period that may not have been sufficient to detect exposure-related disease.

### *4.1.2.1.6.2 Medical evaluations of miners at bituminous surface coal mines, 1972-73*

During 1972 and 1973, NIOSH studied U.S. surface coal miners at seven bituminous mines and one anthracite mine [Fairman et al. 1977]. A total of 1,438 miners were examined; participation rate was 95.5%. Table 4-3 shows the prevalence of pneumoconioses among bituminous surface coal miners. Miners who had previously worked in underground coal mines or who had worked on drill crews at surface coal mines had higher prevalences of pneumoconioses than miners who had never worked underground and had never worked on drill crews (Table 4-7).

Table 4-7.-Prevalence of pneumoconioses among bituminous surface coal miners

| Subgroup | Number of workers | Prevalence of pneumoconioses | | | |
|---|---|---|---|---|---|
| | | Category 1 | | Category 2 or higher | |
| | | % | Number | % | Number |
| "Blue collar" workers with no previous occupational dust exposure [Castellan et al. 1985] | 1,422 | 0.2 | 3 | 0.0 | 0 |
| Surface coal miners: | | | | | |
| Never worked under-ground or on drill crew; ≤10 years on surface coal mine jobs | 516 | 0.8 | 4 | 0.0 | 0 |
| Never worked under-ground or on drill crew; >10 years on surface coal mine jobs | 486 | 3.5 | 17 | 0.4 | 2 |
| Drill crew members for 1-10 years; never worked in an underground coal mine | 82 | 3.8 | 3 | 0 | 0 |
| Drill crew member for >10 years; never worked in underground coal mine | 49 | 14.3 | 6 | 2.3 | 1 |
| Worked 1 year or more in an underground coal mine | 215 | 12.1 | 26 | 2.3 | 5 |
| Total | 1,348* | 4.2 | 56 | 0.6 | 8 |

Source: Amandus et al. [1984]; 1972-73 NIOSH survey of eight surface coal mines.
*Two or more readers determined that of the original 1,438 X-rays, 90 were unreadable.

#### *4.1.2.1.6.3 Medical evaluations of miners at anthracite surface coal mines, 1984-85*

In 1984 and 1985, NIOSH offered medical examinations to 1,348 miners employed at 31 surface coal mines in the anthracite coal region of northeastern Pennsylvania [Amandus et al. 1989]; participation was 80% (1,073/1,348). Miners were grouped according to previous employment in other jobs involving exposure to dust, including jobs in underground coal mining, noncoal mining, construction, welding, sandblasting, manufacturing, steel mills, foundries, and shipbuilding. Table 4-8 shows the prevalence of pneumoconioses among anthracite surface coal miners. The results indicate a higher risk of developing pneumoconioses among miners who have worked on drill crews of anthracite surface coal mines. The results also suggest that surface coal miners at anthracite coal mines are at greater risk of developing pneumoconioses than miners at bituminous surface coal mines. These findings are consistent with studies of underground coal miners, which have shown higher prevalences of pneumoconioses among anthracite coal miners than among bituminous coal miners (see Section 4.1.2.1). The results of the Amandus et al. [1989] study are consistent with those of the Amandus [1984] study. Both studies found an excess prevalence (relative to "background" [Castellan et al. 1985]) of pneumoconioses among surface coal miners who have never worked in underground coal mines or on surface coal mine drill crews. Both studies also found that surface coal miners who have never worked in underground coal mines but have worked on surface drill crews are at risk of developing radiographic category 2 or higher pneumoconioses.

### *4.1.2.2 Studies of Obstructive Airways Diseases Among Coal Miners*

#### 4.1.2.2.1 Lung function and radiographic evidence of disease

An early study of U.S. coal miners found evidence of airflow obstruction

**Table 4-8.—Prevalence of pneumoconioses among anthracite surface coal miners**

| Anthracite surface miner subgroup | Number of workers | Prevalence of pneumoconioses | | | |
|---|---|---|---|---|---|
| | | Category 1 | | Category 2 or Higher | |
| | | % | Number | % | Number |
| Previous dust exposure | 537 | 7.1 | 38 | 1.1 | 6 |
| No previous dust exposure | 516 | 3.5 | 18 | 1.0 | 5 |
| No previous dust exposure; never worked on surface coal mine drill crew | 448 | 2.7 | 12 | 0 | 0 |
| No previous dust exposure; 1-9 years on surface coal mine drill crew | 46 | 4.3 | 2 | 2.2 | 1 |
| No previous dust exposure; >10 years on surface coal mine drill crew | 122 | 18.2 | 4 | 3.3 | 4 |

Source: Amandus et al. [1989]; 1984-85 NIOSH medical evaluation of miners at 31 mines in northeastern Pennsylvania.

(i.e., reduced $FEV_1$ with normal FVC), among older ex-miners to a greater extent than could be accounted for by age alone [Henschel 1969]. Neither reductions in $FEV_1$ nor symptoms of chronic bronchitis have been found to correlate with radiographic evidence of simple CWP [Rasmussen 1968; Pemberton 1956]. However, associations between diffusing capacity and arterial oxygen tension at rest and the presence of p or q opacities on the chest radiograph have been observed [Cotes et al. 1970; Lyons et al. 1967]. In addition, simple CWP was associated with increased residual volume (RV), which is consistent with pinhead opacities observed on the chest X-rays and with emphysema determined at autopsy [Morgan et al. 1974; Morgan 1971; Ryder et al. 1970].

#### 4.1.2.2.2 Decreased lung function and bronchitis

In an early study of U.S. coal miners, Hyatt et al. [1964] reported an association between increase in respiratory symptoms (including cough, phlegm wheeze, and dyspnea) and decrements in several measures of lung function including $FEV_1$ and FVC. Both years worked underground and cigarette smoking contributed independently to the increase in respiratory symptoms and the decrement in lung function [Hyatt et al. 1964]. Several subsequent cross-sectional studies from the U.S. and U.K have found a relationship between exposure to respirable coal mine dust (or surrogates of exposure) and decrements in lung function [Attfield and Hodous 1992; Gauld et al. 1988, 1985; Soutar and Hurley 1986; Hankinson et al. 1977; Rogan et al. 1973] and symptoms of bronchitis [Rom et al. 1981; Kibelstis et al. 1973], even after controlling for the effects of smoking (Figure 4-5). In a study of British coal miners, Rae et al. [1971] found a statistically significant association between increasing exposure to dust and increasing prevalence of bronchitis (based on symptoms of cough and phlegm); a twofold greater prevalence of bronchitis was found among smokers than nonsmokers.

#### *4.1.2.2.3 Dust-Related Loss of Lung Function*

The average loss of lung function (measured by loss of $FEV_1$) from exposure to respirable coal mine dust has been estimated in U.S. and British cross-sectional studies to be 0.6 to 0.76 ml per $gh/m^3$ [Attfield and Hodous 1992; Soutar and Hurley 1986; Rogan et al. 1973]. The reanalysis by Marine et al. [1988] of the early British data reported by Rogan et al. [1973] revealed that the 0.6 ml effect per unit of dust exposure was underestimated by about 36% for nonsmokers and by 56% for cigarette smokers. Table 4-9 lists the estimated loss of $FEV_1$ expected from coal mine dust exposure. In a longitudinal study of new coal miners (those who began working in mining since 1970), the average dust exposure-related loss was 13.8 ml per $gh/m^3$ during the first 3 to 4 years of mining (at Round 2 of the NSCWP), with no additional exposure-related loss over the next approximately 13 years (between Rounds 2 and 4 of the NSCWP); thus, the average exposure-related loss was 3.39 ml per

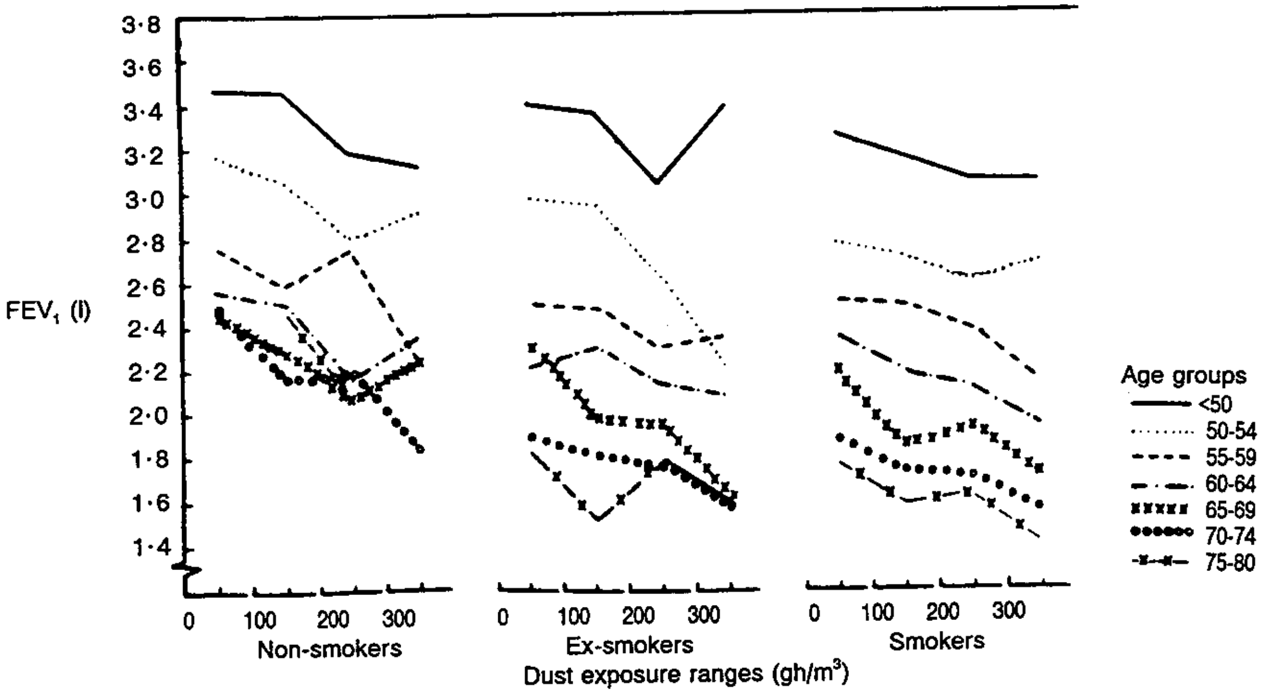


Figure 4-5. Mean observed $FEV_1$ by dust exposure ranges for miners and ex-miners. Groups consisting of one man, without men in adjacent dust exposure groups, have been omitted. (Source: Soutar [1987].)

**Table 4-9.—Estimates of reduced lung function (forced expiratory volume in one second, $FEV_1$) associated with exposure to respirable coal mine dust**

| **Reference** | **Loss of $FEV_1$ per exposure unit (ml per $gh/m^3$)** | **Total loss of $FEV_1$: (ml per 180 $gh/m^3$)** |
|---|---|---|
| Attfield and Hodous [1992][1] | 0.69 | 124 |
| Seixas et al. [1991][2] | 3.39 | 610 |
| Soutar and Hurley [1986][3] | 0.76 | 137 |
| Marine et al. [1988][4] | 0.94 (smokers)<br>1.02 (nonsmokers) | 169<br>184 |

[1] U.S. miners working before 1970; average of 18 years underground.
[2] U.S. miners new to mining since 1970; average of 13 years underground.
[3] British miners working during 1950s, 22 years of follow-up.
[4] British miners working during 1950s, 10 years of follow-up.

Note: Cumulative exposure of 180 $gh/m^3$ corresponds to 45 years (2,000 hr/yr) at a mean concentration of 2 $mg/m^3$ of respirable coal mine dust.

$gh/m^3$ over the 15- to 17-year period [Seixas et al. 1992, 1991a,b]. In another U.S. study, an average loss of 67 ml $FEV_1$ per year for the first two years of mining was observed, with an average loss of 14.4 ml $FEV_1$ per year for the next 5 years; however, dust exposure estimates were not provided [Hodous and Hankinson 1990].

The results of these studies suggest a nonlinear relationship between the loss of $FEV_1$ and increasing cumulative dust exposure (at constant mean concentration), with the greatest rate of loss of $FEV_1$ (reversible or irreversible) occurring during the first few years of mining. A possible mechanism for thisresponse may be based on the first-order kinetics of dust buildup in the lungs (at lung burdens or tissue doses that do not overload clearance mechanisms), such that the lung burden (or tissue dose) increases at a faster rate in the first few years of exposure than in subsequent years. Evidence for such a mechanism has been reported in analyses that included statistical modeling of the data from studies of chronic inhalation of respirable dust in animals [Smith 1990, 1985; Mermelstein and Kilpper 1990].

Two longitudinal studies of lung function have found a relationship between exposure to coal mine dust and decline in lung function. In a study of 1,677 British coal miners, Love and Miller [1982] found that the loss of $FEV_1$ in 11 years increased with increasing previous cumulative dust exposure (i.e., exposure occurring before the period of study). Miners with the average previous cumulative exposure of 117 gram·hour per cubic meter (gh/$m^3$) had a loss of 42 ml of $FEV_1$ in 11 years, with an additional loss of $FEV_1$ of 122 ml among smokers. In a study of 1,470 U.S. coal miners, Attfield [1985a] found that the dust-related loss of $FEV_1$ was 36 to 84 ml over 11 years, with the additional loss of $FEV_1$ of 100 ml among smokers. Criticisms of both studies are that the best-fitting statistical models accounted for only a small proportion of the variation in the loss of $FEV_1$ (7% in Love and Miller [1982] and 12% in Attfield [1985a]) and that the participation of miners in both the initial and the followup surveys was low (27% in Love and Miller [1982] and 15% in Attfield [1985a]). The low participation raises questions about the possibility of selection bias from the loss of miners, particularly those with increased susceptibility to the effects of smoking and/or dust exposure.

#### 4.1.2.2.4 Emphysema

In a study of 1,712 working U.S. coal miners, Hankinson et al. [1977] found that among nonsmokers with dust-induced bronchitis, the maximal expiratory flow was decreased, without an increase in total lung capacity. The authors concluded that dust-induced or "industrial" bronchitis leads to large airway obstruction but not to emphysema. However, in a quantified pathology study of 886 Australian coal miners, Leigh et al. [1983, 1982] determined that emphysema is related to coal dust exposure (using years of coal face work as a surrogate for exposure). The authors reported that smoking was not correlated with either emphysema or chronic bronchitis determined at autopsy, possibly because of selection bias of the cases that were submitted for autopsy (presumably for the purpose of determining qualification for work-related compensation and less likely to have a history of heavy smoking).

In a pathologic study of 450 British coal miners, Ruckley et al. [1984] found a direct relationship between exposure to respirable coal mine dust during life and the presence of centriacinor emphysema at autopsy, among miners with pathologically-determined fibrotic lesions. The prevalence of any emphysema among miners studied was 47% emphysema in those with no fibrotic lesions, 65% emphysema in those with simple CWP, and 83% in those with PMF. Both panacinar and centriacinar emphysema occurred more frequently in smokers than in nonsmokers, but the relationship with dust exposures was only apparent among those with centriacinar emphysema. The amount of dust in the lungs was also associated significantly with the presence of centriacinar emphysema ($P<0.05$), regardless of the composition of the retained dust. Ryder et al. [1973, 1971] and Cockcroft et al. [1984, 1982] showed a significant increase in emphysema among deceased coal miners with pneumoconiosis compared to nonmining control populations. However, the miners had experienced parallel decrements in $FEV_1$ and FVC (as opposed to a greater decrement in $FEV_1$, which is the pattern observed with emphysema). Moreover, the miners concerned included some with PMF so that it was not clearly established that the miners' lower average lung function was attributable to emphysema, as distinct from PMF.

#### 4.1.2.2.5 Clinical significance of dust-related loss of lung function

The question of whether exposure to coal mine dust can cause reduction in lung function severe enough to be of clinical significance has been debated in the literature [Barnhart 1987; Soutar 1987b; Morgan 1986; SSA 1986; Seaton 1983; Morgan 1980]. A clinically significant loss of lung function has been defined as the lower limit of normal $FEV_1$, or 80-85% of predicted $FEV_1$, while <65% of predicted $FEV_1$ is considered to be a severe effect [Marine et al. 1988; Boehlecke 1986; Miller and Scacci 1981]. Gold and Boushey [1988] suggest a four-level assessment of pulmonary impairment (Table 4-10). Other investigators have recommended the use of the lower 95% confidence limit to delineate normal and abnormal lung function values [Hankinson 1986; Knudson

**Table 4-10.–Severity of pulmonary impairment (% of predicted normal)**

| Impairment Assessment | VC | $FEV_1$ | $FEV_1/FVC$ | $FEF_{25-75\%}$ | TLC | $DL_{co}$ |
|---|---|---|---|---|---|---|
| Normal | >80 | >80 | >70 | >65 | >80 | >80 |
| Mild | 66-80 | 66-80 | 60-70 | 50-65 | 66-80 | 61-80 |
| Moderate | 50-65 | 50-65 | 45-59 | 35-49 | 50-65 | 40-60 |
| Severe | <50 | <50 | <45 | <35 | <50 | <40 |

Source: Gold and Boushey 1988.

1983; ATS 1982; Crapo and Morris 1981].

Evidence that the effects of exposure to coal mine dust on pulmonary function can be clinically significant was found in two studies of 4,059 British coal miners followed for 22 years [Hurley and Soutar 1986; Soutar and Hurley 1986]. An "excess effect" of exposure to coal mine dust was observed in a subgroup of 199 men who had left the coal industry before normal retirement age, taken other jobs, and reported symptoms of chronic bronchitis at the 22-year follow-up survey. The average loss of $FEV_1$ among the 199 miners was 600 ml, and the average cumulative exposure to respirable coal mine dust was 300 gh/$m^3$. The 35 ex-smokers in the subgroup had the greatest loss in $FEV_1$, an average of 942 ml.

Among the individuals who experienced the most severe effect on lung function following exposure to respirable coal mine dust, the loss of $FEV_1$ was 2 ml per gh/$m^3$ for 4.9% of the cohort and 3.14 ml per gh/$m^3$ for 0.86% of the cohort [Hurley and Soutar 1986; Soutar and Hurley 1986]. However, the average cumulative exposure reported for that subgroup exceeds the cumulative exposure of 140-180 gh/$m^3$ that a miner would experience from exposure to a mean concentration of 2 mg/$m^3$ of respirable coal mine dust for a working lifetime (1,740-2,000 hr/yr for 40 to 45 years). In a study of 3,380 British coal miners, Marine et al. [1988] estimated that nonsmoking coal miners with a cumulative respirable dust exposure of 174 gh/$m^3$ have an excess risk of 1.8 percent of developing severe respiratory dysfunction (measured as <65% of predicted $FEV_1$), while the excess risk among smokers was estimated to be 3.5%. Silver et al. [1991] estimated similar excess risks for U.S. miners (Table 4-11). Chapter 5 provides further discussion on reference values for pulmonary function tests.

#### 4.1.2.2.6 Factors that affect lung function

Occupational exposure to respirable dust has been shown to be associated with decrements in lung function among coal miners [Attfield and Hodous 1992; Soutar and Hurley 1986; Attfield 1985; Love and Miller 1982], grain dust handlers [Kauffmann et al. 1982], hard rock miners [Manfreda et al. 1984], gold miners [Cowie and Mabena 1991; Irwig and Rocks 1978], and other workers exposed to organic and inorganic particles [Kilburn 1980, 1984]. Nonoccupational factors that affect lung function include age, race, gender, height, weight, physical activity, and altitude. The nonlinear relationship between lung function and weight was first reported by Hutchinson [1846]; yet recent studies have generally omitted weight in prediction equations for lung function [Schoenberg et al. 1978]. The effect of weight on measures of lung function is to first increase lung function (muscularity effect) and then to decrease lung function (obesity effect).

The role of dust exposure compared to the role of smoking in the development of COPD among coal miners has been the subject of much debate [Attfield and Hodous 1992; Morgan 1986; Cochrane 1983; Morgan 1983; Seaton 1983; Elisburg 1980; Morgan 1980]. While Morgan [1986, 1978] has stated that the effect of cigarette smoking on the loss of $FEV_1$ is several-fold higher than that of coal mine dust exposure, Attfield and Hodous [1992] have found the effects of cigarette smoking and exposure to coal mine dust are similar and additive. Similarly, Marine et al. [1988] found the effects of cigarette smoking and coal mine dust exposure to be additive. In a study of British coal miners, the effect of smoking was a substantial reduction in the ratio of $FEV_1/FVC$

**Table 4-11.—Estimated prevalence of reduced lung function associated with exposure to respirable coal mine dust**

| Reference | Prevalence of reduced $FEV_1$ (%) | |
|---|---|---|
| | Smokers | Nonsmokers |
| Marine et al. [1988][*]: | | |
| $FEV_1$ <80% of expected | 27.2 | 15.5 |
| Background (no dust exposure) | 17.1 | 9.7 |
| Excess (exposure-related) | 10.1 | 5.6 |
| $FEV_1$ <65% of expected | 8.5 | 5.0 |
| Background (no dust exposure) | 5.0 | 3.2 |
| Excess (exposure-related) | 3.5 | 1.8 |
| Silver et al. [1991][†]: | | |
| $FEV_1$ <80% of expected | --- | 18.4 |
| Background (no dust exposure | --- | 11.3 |
| Excess (exposure-related) | --- | 7.1 |
| $FEV_1$ <65% of expected | --- | 3.9 |
| Background (no dust exposure) | --- | 1.7 |
| Excess (exposure-related) | --- | 2.2 |

[*] British miners; average age of 47 years; 27-32 years of work underground at a mean concentration of 3.1-3.7 $mg/m^3$ of respirable coal mine dust.

[†] Estimates for U.S. miners at age 65; 45 years of work underground (2,000 hours/year); cumulative exposure 180 $gh/m^3$. Based on data of U.S. miners working before 1970; average of 18 years underground; estimated mean concentration of 3.1 $mg/m^3$ of respirable coal mine dust. Expected $FEV_1$ based on average height of 1.755 meters.

(i.e., $FEV_1$ was reduced more than FVC), whereas the coal mine dust exposure did not reduce $FEV_1/FVC$ (i.e., FVC was reduced at least as much as $FEV_1$) [Soutar 1987b; Soutar and Hurley 1986].

There is some evidence that certain physical characteristics of coal mine dust may affect lung function. Morgan et al. [1974] reported greater decrements of $FEV_1$ and FVC and greater residual volume (RV) among miners exposed to higher-rank coal (an effect observed in smokers, ex-smokers, and never smokers) (Figures 4-6 and 4-7). However, because the study did not control for dust exposure, the results could reflect differences in the extent of dust exposure. Attfield and Hodous [1992] found that miners exposed to higher-rank eastern coal had greater decrements in lung function than those exposed to lower-rank western coal.

Potts et al. [1990] have suggested that the larger-sized thoracic dust, which

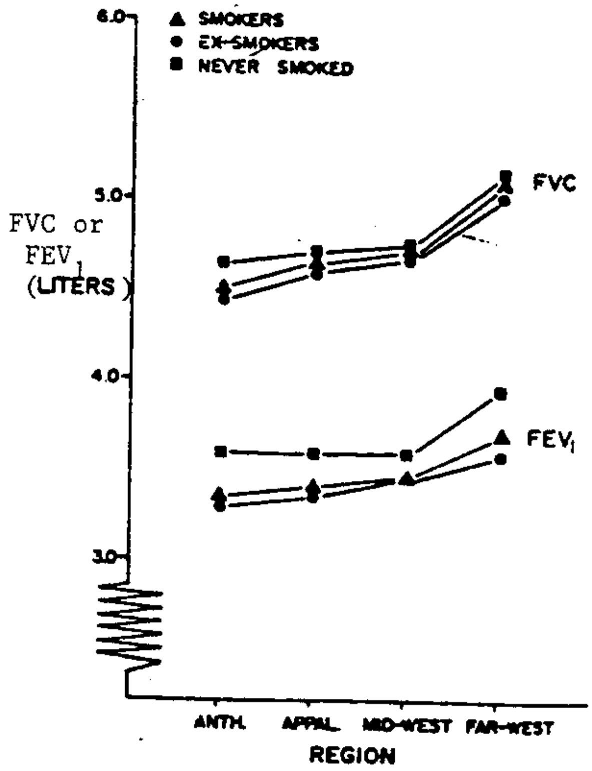


Figure 4-6. Relationship of FVC and $FEV_1$ to geographic region and smoking status. (Source: Morgan et al. [1974].)

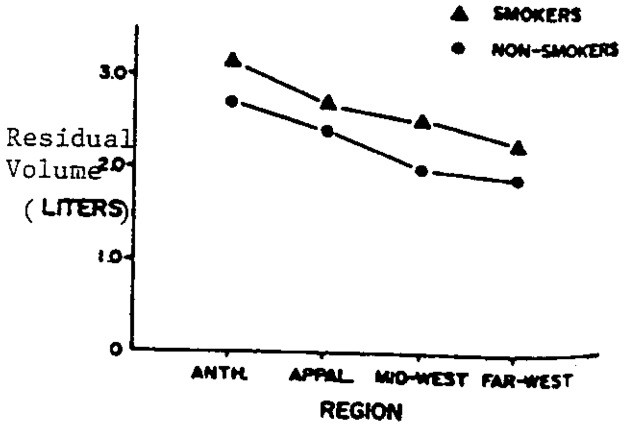


Figure 4-7. Relationship of RV to smoking status and georgraphic region. (Source: Morgan et al. [1974].)

deposits primarily in the bronchial airways (see Glossary), may be important in the development of bronchitis and loss of lung function. Thoracic dust concentrations are variable in different locations of underground coal mines, and thoracic dust concentrations may be fivefold to sevenfold higher than respirable dust levels [Potts et al. 1990; Burkhart et al. 1987].

Two British studies investigated the correlation between "total" or "inspirable" dust and respiratory disease [Cowie et al. 1981; Mark et al. 1981]. Both studies found that estimates of the concentration of the coarse fractions of dust provide no better correlations with disease than do concentrations of the respirable fraction.

#### 4.1.2.3 Studies of Gastric Cancer

The higher prevalence of gastric cancer that has been reported among coal miners may be influenced by factors in addition to coal mine dust exposure, including diet, cigarette smoking, and chewing tobacco [Wu 1990; Ames and Gamble 1983; Whong et al. 1983; Ames 1982]. Meyer et al. [1980] suggested that when respirable coal mine dust is inhaled it reaches the stomach through normal pulmonary clearance mechanisms. Miller and Jacobsen [1985] found an association between cancers of the digestive organs and coal mine dust exposure, but the effect was not observed independently from the condition of pneumoconiosis. The occurrence of gastric cancer among coal miners is not used as part of the basis for the recommended standard in this criteria document because epidemiologic exposure-response studies have not found a significant relationship between exposure to respirable coal mine dust and gastric cancer.

## 4.2 ANIMAL AND HUMAN STUDIES OF LUNG OVERLOADING AND CLEARANCE

Although there has been extensive epidemiologic study of coal miners, including determination of exposure-response relationships, animal studies have provided additional useful information on the toxicity of particular components in the respirable coal mine dust (e.g., silica or diesel exhaust) and on the deposition and clearance of particles in the respiratory tract. Thus, this section focuses on studies of the overloading of lung clearance mechanisms in animals (also known as the overload hypothesis) and on studies of the etiologic factors of fibrogenesis in both humans and animals. The animal studies of the overloading of lung clearance mechanisms are relevant because these studies have provided information on dose-response relationships, including determination of pulmonary responses at low doses in animals.

### 4.2.1 Overloading of Lung Clearance Mechanisms

The overload phenomenon has been observed in studies of several animal species exposed to various insoluble, respirable particles, including diesel exhaust [Strom et al. 1988; Wolff et al. 1987], carbon black [Strom et al. 1989], and test toner (used in photographic processes) [Bellmann et al. 1991; Muhle et al. 1989], mineral dusts [Vincent et al. 1985], and amosite fibers [Bolton et al. 1983]. The overloading of lung clearance is not a unique phenomenon; it is consistent with overloading in other biological systems [Witschi 1990], such as saturation of metabolic pathways or receptor sites. The exposure, dose, and response relationships for inhaled respirable particles have been investigated through the development of physiologically-based toxicokinetic models to describe the retention and clearance kinetics in the alveolar region of the lungs of rats [Stober et al. 1990; Yu et al. 1988].

The clearance of particles from the alveolar or pulmonary region of the lungs is regarded as a first-order process [Mermelstein and Kilpper 1990; Morrow 1988; Vincent et al. 1985]. At initial dust exposure, no clearance occurs, and the lung burden rises. As clearance increases, the lung burden begins to level off to a constant, steady-state value, and clearance equals deposition (Figure 4-8). However, when deposition exceeds clearance, first-order clearance is no longer maintained, and the lung burden may increase linearly [Morrow 1988]. This "overloading" of pulmonary clearance causes the activation of alveolar macrophages and the release of reactive oxygen species and cellular factors that stimulate pathogenic events [Driscoll et al. 1990].

Activated alveolar macrophages may release tumor necrosis factor (associated with infiltration of inflammatory cells) and increased levels of fibronectin (associated with fibrogenesis) [Driscoll et al. 1990; Borm et al. 1986; Vilcek et al. 1986]. Activated alveolar macrophages may also release inflammatory and immune products such as superoxide anion ($O_2^-$), hydrogen peroxide, and hydroxyl radical [Wallaert et al. 1990; Nathan 1987; Fels and Cohn 1986]. Other factors such as gamma interferon may influence the susceptibility of alveolar macrophages to being activated [Driscoll et al. 1990].

Additional pathologic responses to the overloading of lung clearance mechanisms include the following: accumulation of dust-laden macrophages, increased lung weight, persistent inflammation, increased epithelial permeability, elevated infiltration of neutrophils, septal thickening, lipoproteinosis, increased transfer of material to lymph nodes, disproportionate retention of test material (i.e., increase in the ratio of the retained mass to the aerosol concentration), decreased or obliterated alveolar clearance, changes in pulmonary mechanics, impaired pulmonary function, and the onset of fibrosis after a critical dose (time-integrated concentration) and a sufficient time interval have occurred [Morrow et al. 1991; Muhle et al. 1991; Bowden 1987; Campbell and Senior 1981].

Relatively innocuous dusts can stimulate chronic inflammation and fibrosis when pulmonary dust burdens are high enough to overload the normal particle clearance mechanisms [Morrow 1988; Oberdorster 1988]. In a chronic inhalation

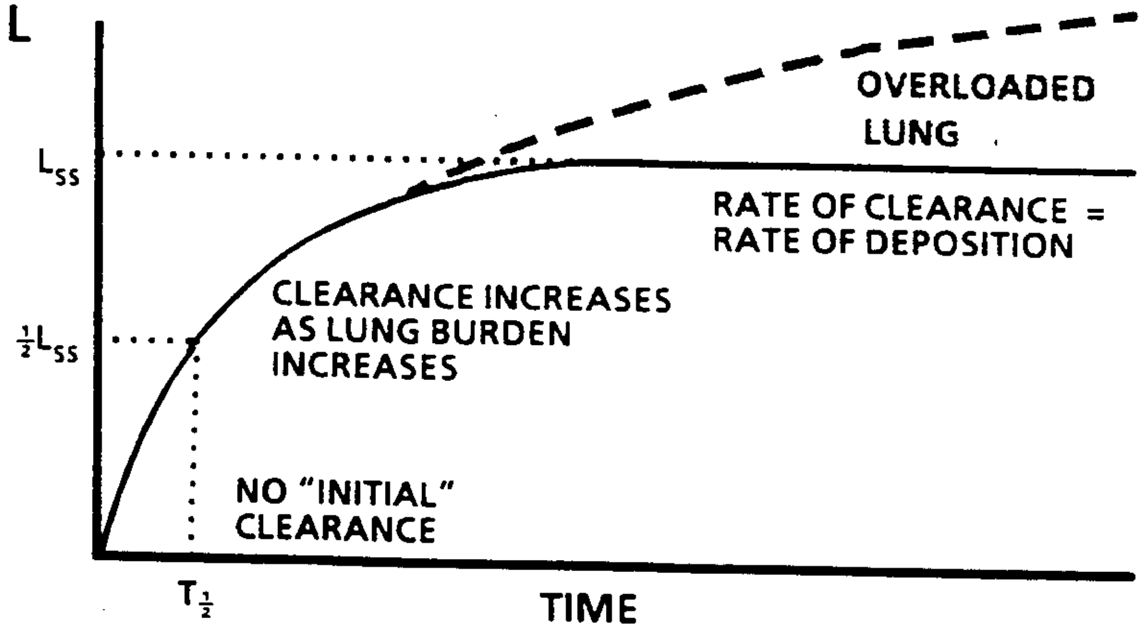


Figure 4-8. Overloading of alveolar clearance when the steady-state lung burden ($L_{ss}$) is exceeded. (Source: Mermelstein and Kilpper [1990].)

study in rats of respirable test toner (a dust with low solubility and low acute toxicity that is used in photographic processes), retardation of particle clearance progressively increased with lung burdens of toner above about 1.0 mg per gram of lung [Muhle et al. 1991; Mermelstein and Kilpper 1990]. A mild to moderate degree of lung fibrosis was observed in all of the rats exposed to 5.6 mg/m$^3$ respirable dust (16 mg/m$^3$ total dust) and a very slight degree of fibrosis was seen in 25% of the rats exposed to 1.4 mg/m$^3$ respirable dust (4 mg/m$^3$ total dust) (Table 4-11). Signs of lung overloading persisted 15 months after cessation of exposure.

#### *4.2.1.2 Relevance of Animal Studies of Impaired Alveolar Clearance to Humans Exposed to Respirable Coal Mine Dust*

The finding in animal studies of the persistance of lung overloading after cessation of exposure [Muhle et al. 1991] may be relevant to epidemiologic studies of coal miners, in which a residence-time effect of dust in the lungs on the incidence of PMF has been observed [Maclaren et al. 1989]. In addition, the incidence of PMF among miners and ex-miners has been found to be similar [Hurley and Maclaren 1988].

Evaluation of animal studies on the overload hypothesis is also pertinent because miners may accumulate lung burdens of more than 10 mg of dust per gram of lung over a working lifetime under the current MHSA permissible exposure limit of 2 mg/m$^3$ for respirable coal mine dust [Pritchard 1989]. Table 4-11 shows that from about 5 to 15 mg/g of dust was retained in the lungs of British coal miners who had been exposed to cumulative exposures comparable to those U.S. miners would experience over 40-45 years at about 2 mg/m$^3$ of respirable coal mine dust. These levels of retained dust are in the range in which mild to moderate fibrosis occurred in most animals in the chronic inhalation study (Tables 4-12 and 4-13). A dose-related response was observed in the animal study [Muhle et al. 1991], and coal miners experienced fibrosis

**Table 4-12.—Cumulative exposure, retained dust levels, and disease in British coal miners**

| Coal rank (% carbon) | Number of men | Cumulative exposure ($gh/m^3$)[*] | Retained dust in lungs (mg/g lung) | Pathology group[†] |
|---|---|---|---|---|
| 91.4-94.0 | 31 | 136.9 | 5.4 | M |
| 88.8-90.6 | 26 | 192.1 | 5.8 | M |
| 81.1-85.5 | 26 | 140.6 | 7.0 | M |
| 81.1-85.5 | 43 | 194.6 | 11.3 | F |
| 81.1-85.5 | 41 | 184.8 | 15.0 | PMF |

[*] In U.S. coal miners, estimates of cumulative exposure to respirable coal mine dust range from 122 to 180 gram*hour per cubic meter, $gh/m^3$ (i.e., 35 years of exposure at 2 $mg/m^3$ and 1,740 hours/years equals 122 $gh/m^3$; or, 45 years of exposure at 2 $mg/m^3$ and 2,000 hours/year equals 180 $gh/m^3$).

[†] M: Focal dust deposits (macules) with minimal evidence of fibrosis (rarely had radiographic evidence of CWP).

F: "M" + one or more fibrotic dust lesions between 1 mm and 9 mm diameter.

PMF: Fibrotic dust lesions 10 mm or more in diameter.

Based on data from Douglas et al. [1986].

**Table 4-13.—Findings of chronic inhalation study of test toner in F-344 rats for 24 months (6 hr/day, 5 days/week)**

| Mean concentration ($mg/m^3$) | Retained dust in lungs (mg/g lung) | Pulmonary response at end of study (26.5 months) |
|---|---|---|
| 0.35 | 0.21 | No evidence of overloading |
| 1.43 | 1.80 | Symptoms of overloading:<br>Slight decrease in clearance/increase in retention; slight chronic inflammation<br>Limited, very slight fibrosis in 25% of animals |
| 5.63 | 15.0 | Extensive symptoms of overloading:<br>Decrease in clearance/increase in retention; chronic inflammation; chronic inflammation; decrease in pulmonary function; increase in lung weight<br>Slight to moderate fibrosis in all animals |

Source: Mermelstein and Kilpper [1990].

at comparable amounts of retained dust in the lungs (Table 4-10).

Such comparisons of the lung dust burdens that caused overloading of alveolar clearance in animal studies to the lung burdens found in coal miners suggest that overloading may occur in the lungs of coal miners exposed under the current limit of 2 mg/m$^3$ for exposure to respirable coal mine dust. However, these comparisons do not consider the duration of exposure or the role of dust composition (particularly the silica concentration) in determining the degree of fibrosis. For example, cumulative exposures involving high concentrations and short durations would be considered equivalent to cumulative exposures involving low concentrations and long durations.

#### 4.2.1.3 Composition of Respirable Dust and Fibrotic Lung Diseases

The composition as well as the amount of dust retained in the lungs influence the development of fibrotic lung diseases such as pneumoconiosis and silicosis. Noncoal minerals (especially silica) have been shown to be preferentially retained in the lungs and to be associated with more severe lesions [Davis et al. 1977]. Among coal miners who had equal amounts of retained silica per 100 g of dry tissue, those who had been exposed to coal mine dust with 4% to 5% crystalline (free) silica had less severe silicosis than mixed-metal miners and tunnel and quarry workers who had been exposed to 20% to 25% crystalline (free) silica [Dobreva et al. 1977]. Possible explanations for the differing severity of silicosis with equal amounts of retained silica include (1) the mitigating effects of other components in the coal mine dust (including the coating of silica particles) to reduce the toxicity of the silica particles to the alveolar macrophages, or (2) a greater rate of deposition (i.e., higher doses in shorter periods) in the workers exposed to crystalline (free) silica.

#### 4.2.1.4 Biological Factors in Individual Susceptibility to Fibrosis

Two objectives in the determination of susceptibility are (1) determining what factors protect against disease and (2) what factors are associated with vulnerability; and these factors may not be the converse of each other [Liddell and Miller 1983]. The process of lung fibrosis is a multi-faceted, cascading process involving various inflammatory cells (e.g., polymorphonuclear leukocytes) and distinct mediators [Lehnert 1990; Bowden 1987]. Cellular factors that are released from overloaded and activated alveolar macrophages include arachidonic acid metabolites [Demers et al. 1988], superoxide anion ($O_2^-$) [Wallaert et al. 1990], fibronectin, and tumor necrosis factor (TNF) [Driscoll et al. 1990].

The functions of TNF, which has been the subject of much research, include: (1) direct activation of polymorphonuclear leukocytes (PMN) cells, which stimulates adhesion of PMNs to endothelial cell surfaces; (2) indirect activation of fibroblast growth; and (3) induction of mononuclear phagocytes to produce and release cytokine interleukin-1 (IL-1), which has been suggested to cause fibroblast proliferation and increase in lung collagen, and reactive oxygen species which cause lung tissue damage [Borm et al. 1988]. Individuals with greater TNF release in response to coal mine dust may be more susceptible to fibrogenesis, and such differences in the release of TNF could be acquired or genetically controlled [Borm et al. 1988; Schraufnagel et al. 1987].

Bronchoalveolar lavage in humans has been used recently to recover alveolar macrophages (AM) to study the differences in factors released from AM of dust-exposed miners and unexposed controls. In a study of AM in coal miners without clinically detectable pneumoconiosis (but with a history of working underground for a mean of 17 years), a statistically significant increase in AM with surface ruffling was observed [Lapp et al. 1991]. Significant increases in AM with surface ruffling was also observed in AM from coal miners with pneumoconiosis [Takemura et al. 1989] and in rats chronically exposed to coal dust [Castranova et al. 1985]. Increased surface ruffling may be an indicator that AM are activated [Lapp et al. 1991]. Coal miners with pneumoconiosis [Takemura et al. 1989], but not those without pneumoconiosis [Lapp et al. 1991], also had significantly larger numbers of lysosomes and significantly higher frequencies of multinucleated AM than did comparison workers [Takemura et al. 1989].

Chronic smokers may have impaired clearance of particles deposited in the lungs and persistent inflammatory responses [Mauderly et al. 1990; Oberdorster 1988]. The slowing of particle clearance from the alveolar region of the lung would promote sequestration of larger lung burdens of inhaled materials than would accumulate in similarly exposed nonsmokers. Inflammatory and epithelial changes in smokers are centered primarily in conducting airways, rather than the alveolar lung. Rats chronically exposed to cigarette smoke had impairments of alveolar clearance of tracer particles of a magnitude similar to clearance impairments reported for human smokers [Bohning et al. 1982]. However, epidemiologic studies of coal miners have found that the development of CWP was correlated with dust exposure and was not modified by smoking history [Jacobsen et al. 1977; Muir et al. 1977].

Lung dust burdens may not be simply a reflection of dust exposure, but patterns of deposition or clearance may differ between miners who develop pneumoconiosis and those who do not. Pathologic studies have shown that miners with progressive massive fibrosis (PMF, or complicated coal workers' pneumoconiosis) had accumulated both more dust in their lungs and more dust per unit of dust exposure than had miners without PMF [Douglas et al. 1986]. Factors that may cause differences in accumulation include differences in breathing rate or in lung morphology.

# 5 RECOGNITION OF THE HAZARD

## 5.1 ENVIRONMENTAL MONITORING

### 5.1.1 Characteristics of the Approved Sampling Device

The Federal Coal Mine Safety and Health Act of 1969, amended in 1977, defines respirable dust as that ". . . measured with a device approved by the Secretary (of Labor) and the Secretary of Health and Human Services" [30 USC 842(e) (1986)]. The approved sampler for respirable coal mine dust is the Coal Mine Dust Personal Sampler Unit (CMDPSU) [30 CFR Part 74 (1988)], originally described by Jacobson [Jacobson 1970; Jacobson and Lamonica 1969]. The CMDPSU often called the "10-mm nylon cyclone" sampler, may be mounted either (1) on a worker, with the sampling head mounted at the breathing zone for personal exposure monitoring, or (2) in a fixed location for area sampling [Tomb 1990].

The CMDPSU 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 (1988)]. 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 is dependent on the flow rate [Jacobson and Lamonica 1969]. The second stage is a membrane filter (vinyl, pore size 5 μm), which collects the dust that passes through the cyclone. The dust collected on the membrane filter is weighed to a precision of 7.1 μg [Parobeck et al. 1981]; 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].

The specifications for the design and performance of the CMDPSU are contained in 30 CFR Part 74 [1988]. NIOSH is responsible for conducting tests for the certification of the CMDPSU according to the requirements in 30 CFR 74.4. MSHA is responsible for conducting tests for the safety of the pump unit of the

CMDPSU.

A constant factor of 1.6 was originally specified in 30 CFR Part 70 for the conversion of concentrations measured with the CMDPSU to the equivalent British MRE concentration [Fed. Reg. 1970]. The 1.6 factor was based on dust measurements taken by the Bureau of Mines with an earlier version of the CMDPSU [Jacobson 1970]. Another study had reported a conversion factor of 1.88 [Doyle 1970]. A later study determined that the collection characteristics of the 10-mm nylon cyclone portion of the CMDPSU were dependent on the inherent pulsations of the pump [Lamonica and Treaftis 1972]. Thus, the specifications of the approved CMDPSU 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 for converting between dust concentrations determined by the CMDPSU and the equivalent MRE concentration was established [Tomb et al. 1973].

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 due to charge effects of the filter holder of 10-mm nylon cyclone samplers. 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 et al. 1990; Liu et al. 1985; Turner et al. 1984].

Current regulations for the specifications of the CMDPSU state, "The cyclone

. . . shall be constructed of nylon or a material equivalent in performance" [30 CFR Part 74.3(b)(1) (1988)]. However, other samplers are available that are constructed of metal and less sensitive to charge effects (e.g., HD cyclone, with a 37-mm filter cassette made of conductive material such as graphite-filled plastic) [Higgins and Dewell 1967].

### 5.1.2 Definition of Respirable Dust

NIOSH recommends a shift from the current MSHA definition of respirable coal mine dust (i.e., CMDPSU operated at 2.0 L/min; multiplication by 1.38 for MRE equivalent concentration) to the recently developed international definition of respirable dust. The international definition 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 1992b, 1984; CEN 1992; ISO 1983, 1991; Soderholm 1989, 1991a]. The following defines the respirable particulate mass fraction according to the ISO, the CEN, and the ACGIH [ACGIH 1991b].

The respirable particulate mass consists of ". . . materials that are hazardous when deposited in the gas-exchange region" [ACGIH 1991b].

Respirable particulate mass and SR(d) consists of particles captured according to the following collection efficiency, SR(d):

$$\mathrm{SR}(d) = \mathrm{SI}(d)\ [1 - F(x)]$$

where: $\mathrm{SI}(d) = 50\%\ (1+e^{-0.06d})$, the collection efficiency of an ideal sampler of the inhalable fraction with particle aerodynamic diameter d in µm

F(x) = the cumulative probability function of a standardized normal variable, x=ln (dΓ)/ln({), with Γ = 4.25 µm, and { = 1.5

This definition is in accordance with the ISO/CEN proposed definition [CEN 1992] (Table 5-1).

The basis for the particle-size selective sampling definitions is the following: (1) the deposition of particles in the respiratory tract depends on the size and shape of the particles (i.e., aerodynamic diameter) (Figure 5-1) [Chan and Lippman 1980; Lippman and Albert 1969; ICRP 1966], and (2) the adverse health effects of inhaled particles depend on the location within the respiratory tract where the particles are deposited [Lippmann 1985]. The three major regions of the respiratory tract include the head airways region, the tracheobronchial region (includes trachea and ciliated airways in the lungs), and the alveolar region (includes nonciliated airways and alveolar sacs in the lungs) [Soderholm 1988].

#### *5.1.2.1 Basis for Particle-Size Selective Sampling*

The basis for the concept of the CMDPSU and similar devices arose from experimental evidence on the effect of particle size on regional deposition in the lungs [Task Group on Lung Dynamics 1965] and from results of an autopsy study that showed the mass of respirable dust in the lungs of miners is associated with the severity of pneumoconiosis [Nagelschmidt 1965]. Schlick and Peluso [1970] concluded that ". . . the instruments used to evaluate the atmosphere should simulate the respiratory tract in selecting the dust particles."

Early definitions for sampling respirable dust were developed by the U.S. Atomic Energy Commission (AEC) [Lippman and Harris 1962] and by the British Mine Research Council (BMRC); the BMRC definitions were adopted by the Johannesburg Pneumoconiosis Conference [Orenstein 1960]. The AEC curve has a sampling

**Table 5-1.—Collection efficiencies for particle-size selective sampling as defined by the American Conference of Governmental Industrial Hygienists**

| Respirable | | Thoracic | | Inhalable | |
|---|---|---|---|---|---|
| Particle aerodynamic diameter (µm) | Respirable particulate mass (RPM) (%) | Particle aerodynamic diameter (µm) | Thoracic particulate mass (TPM) (%) | Particle aerodynamic diameter (µm) | Inhalable particulate mass (IPM) (%) |
| 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 [1991].

*The median cut point for a respirable dust sampler of 4.0 µm is in accordance with the International Standards Organization/European Standardization Committee (ISO/CEN) proposed definition [CEN 1990].

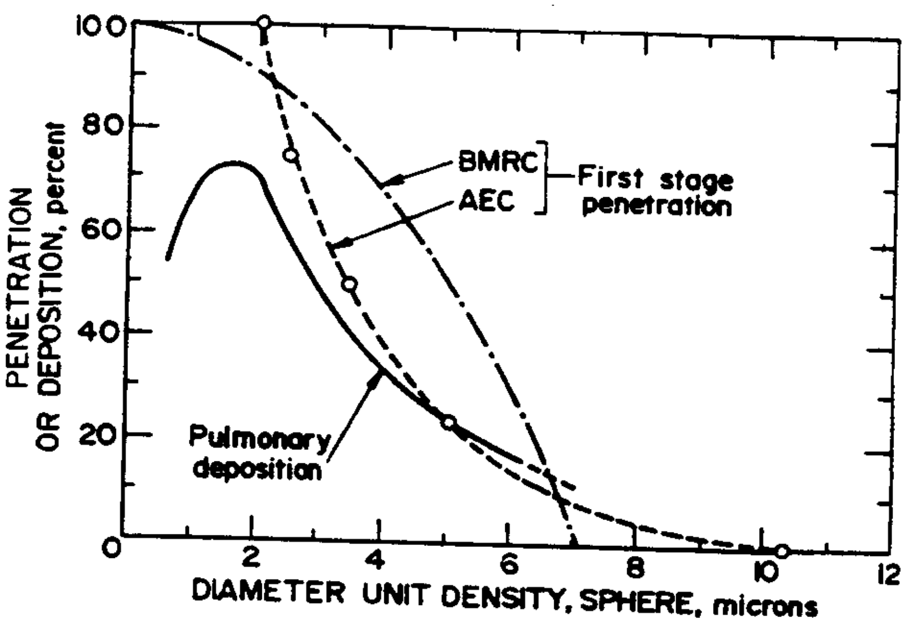


Figure 5-1. Comparison of recommended respirable size criteria with pulmonary deposition curve. (Source: Jacobson [1970].)

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 (Figure 5-1).

The objective of particle size-selective sampling defined by ISO/CEN/ACGIH is to exclude from sampling those particles that are too large to enter the region of the lungs where the particles exert the adverse health effect. Thus, the ISO/CEN/ACGIH particle size-selective definitions are based on the penetration of particles in the lungs. Particle penetration has been defined as ". . . the ability of a particle to reach but not necessarily deposit in a region of the lung" [Soderholm and McCawley 1990]. Particle deposition has been defined as ". . . the mean probability of an inspired particle being deposited in the respiratory tract . . . on airway surfaces" [Heyder et al. 1986]. Data on the deposition of particles in the various regions of the human respiratory tract are based on the use of radiotracer techniques [Albert and Lippmann 1966; Albert and Arnett 1955]. The clearance of particles from the lungs has been studied using the technique of magnetopneumography, which utilizes the radioactive particles to noninvasively determine the amount of material retained in the respiratory tract following aerosol exposure [Philipson et al. 1985; Buhning et al. 1982; Stahlhofen et al. 1981; Morrow et al. 1967; Albert and Arnett 1955].

#### *5.1.2.2 Deposition and Clearance of Particles in the Respiratory Tract*

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 less than 0.5 µm, deposition by diffusion occurs in small airways and gas exchange regions. The nonspherical shape of particles such as fibers, greatly alters deposition patterns such that much longer particles are able to reach the alveoli compared to the aerodynamic diameters of spherical particles reaching the alveoli [Stuart et al. 1984]. Clearance is difficult for such fibers.

The electrical charges on particles also influence the fraction that deposits. 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].

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 removal include a very rapid phase of particle removal from extrathoracic airways, a fast phase of particle removal from ciliated thoracic airways, and a slow phase of particle removal from nonciliated thoracic airspaces [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, then cleared to the gastrointestinal tract or gradually dissolved [Stuart et al. 1984].

For the quantitation of risk from inhaled particles, ". . . the quantity of material that is deposited in a specified region of the respiratory tract, and the amount that remains after physiological clearance from that region, must be known" [Stuart et al. 1984]. The amount of retained material determines the effective dose of a contaminant that can produce acute or chronic pulmonary disease, and the amount of material that is retained depends on the clearance of that material from the lungs.

#### *5.1.2.3 Biologic Plausibility of Particle Size-Selective Sampling Criteria*

Several studies have measured the deposition and retention of particles in the human respiratory tract [Stahlhofen et al. 1989; Miller et al. 1988; Heyder et al. 1986; Emmett et al. 1982; Chan and Lippmann 1980; Lippmann and Albert 1969; Task Group on Lung Dynamics 1966; Orenstein 1960]. 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 [Phalen et al. 1988]. The ISO/CEN/ACGIH definition for 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 5-2). The ISO/CEN/ACGIH 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 ISO/CEN working group has proposed that samplers claiming to meet the ISO/CEN/ACGIH definition of respirable dust should be shown to be effective when sampling particle size distributions having a median aerodynamic diameter between 1 and 25 µm and a geometric standard deviation between 1.5 and 3.5 [CEN 1993; Kenny 1992].

The particle size distributions of respirable coal mine dust reported for U.S. underground coal mines are within the range (approximately 2-10 µm) for which the ISO/CEN/ACGIH definition of respirable dust agrees reasonably well with the data on the deposition efficiency of particles in the human lungs (Figure 5-2, mouth breathers). Figure 5-2 illustrates the deposition efficiency of particles in the human respiratory tract compared to the BMRC, ACGIH, and ISO/CEN/ACGIH definitions of respirable dust.

Figure 5-3 illustrates the poor correlation between the ISO/CEN/ACGIH definition of thoracic dust and the deposition efficiency of particles in the

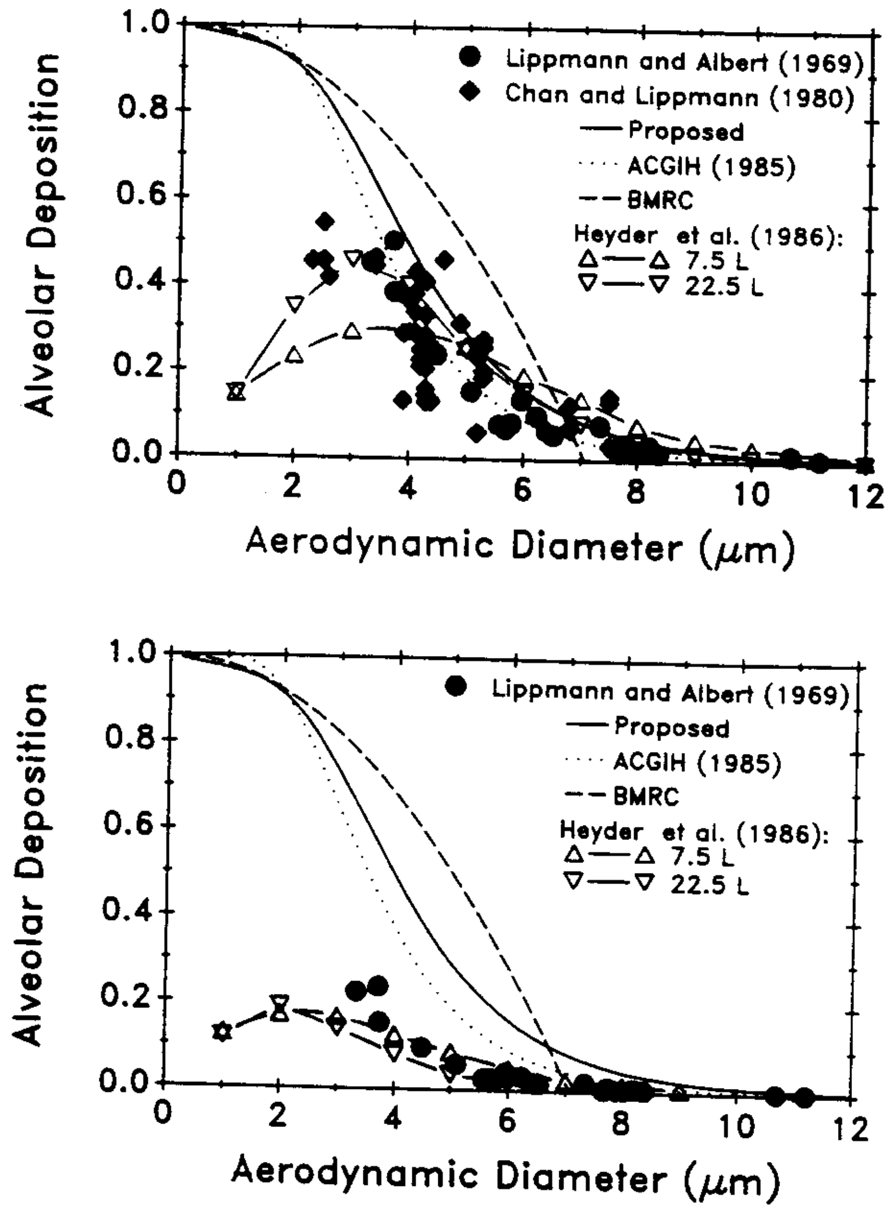


Figure 5-2. Comparison between (1) the existing definitions [ACGIH 1985; Orenstein 1960] and the proposed ISO/CEN/ACGIH definition [ACGIH 1991] of the respirable particulate, and (2) the fraction of particles that is expected to deposit in the alveolar region of the lungs [Heyder et al. 1986; Chan and Lippmann 1980; Lippmann and Albert 1969].

Notes: In (b), the data of Lippmann and Albert [1969] for subjects breathing through a mouthpiece were multiplied by a factor based on the Miller et al. [1988] relations [Equations (7) and (8) of Soderholm 1989] for deposition in the head to estimate alveolar deposition during nasal breathing. In (a) and (b), all data values were multiplied by the fraction of particles of that aerodynamic diameter which is inspirable [Equation (1) of Soderholm 1989] to transform them from a fraction of inspired particles into a fraction of ambient particles. (Source: Soderholm [1989].)

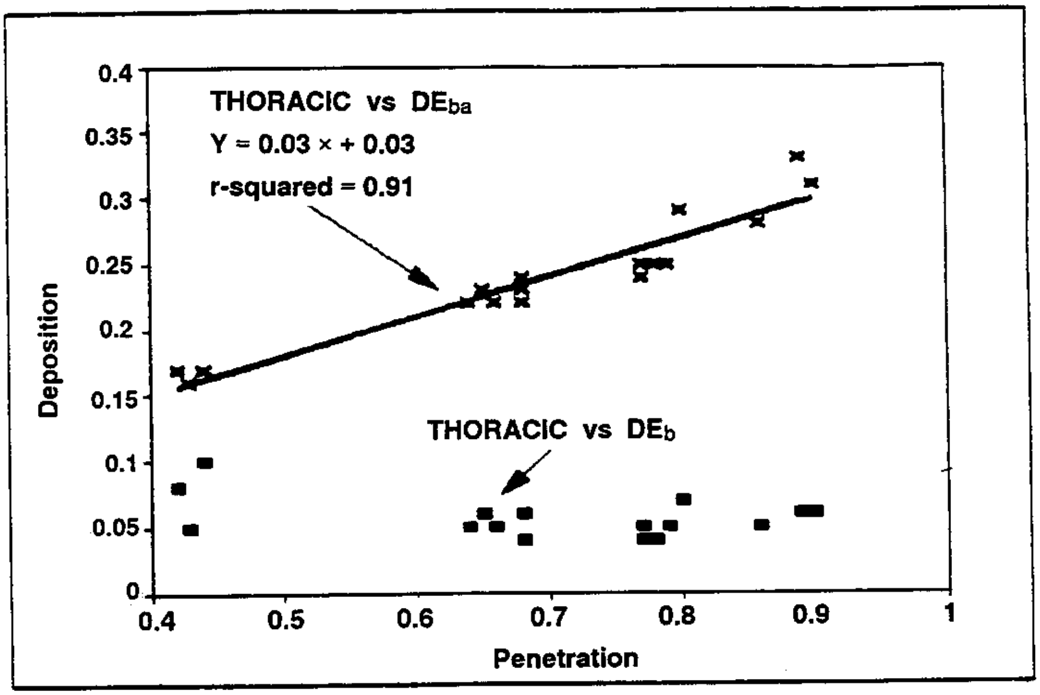


Figure 5-3. Comparison of tracheobronchial deposition ($DE_b$ and total lung deposition ($DE_{ba}$) with the thoracic particulate criteria estimate of exposure for Chinese metal/non-metal mines and U.S. coal mines. (Source: McCawley et al. [1992].)

tracheobronchial region of human lungs [McCawley et al. 1992]. The reason for the high correlation between thoracic and total lung deposition is probably the preponderance of particles larger than about 2 µm aerodynamic diameter in the size distributions determined for the study mines. However, the primary point of Figure 5-3 is that for the particle size fraction that deposits in the tracheobronchial region of the lungs (and may contribute to the development of obstructive lung diseases) the ISO/CEN/ACGIH definition of thoracic dust correlates very poorly (see "Thoracic versus $DE_b$"). ISO and CEN, but not ACGIH, offer a definition of "tracheobronchial dust, which is the difference between thoracic and respirable dust and would be expected to correlate more closely with tracheobronchial deposition. Figure 5-2 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%. Thus, sampler criteria based on particle penetration into the lungs is protective of workers because it is unlikely that penetration-based samplers would underestimate the amount of material capable of depositing [Soderholm and McCawley 1990]. However, the effect of systematically overestimating the dust deposition is to weaken the exposure-response relationship and to potentially overlook the need to develop appropriate exposure standards [Hewett 1991; Soderholm and McCawley 1990].

#### *5.1.2.4 Development of Particle Size-Selective Samplers*

The development of particle size-selective criteria for dust sampling is influenced by knowledge of the factors that affect the deposition and retention of dust in the human lungs and by the available sampler technology. The definitions of inhalable, thoracic, and respirable dust were based on the ability of particles to reach, but not necessarily deposit and remain, in specific regions of the respiratory tract [Soderholm and McCawley 1990]. Although the deposition-based size-selective sampling criteria suggested by McCawley [Soderholm and McCawley 1990] are in better agreement with the deposition in the human respiratory tract, the deposition/retention approach would require more complicated size-selective samplers using several substrates. However, the particle size distributions in the coal mines can vary greatly, and exposure-response relationships would be more likely to be detected if data from deposition-based particle-size selective sampling were obtained [Hewett 1991].

Although size-selective sampling criteria have been developed from penetration curves, size-selective sampling criteria could be developed from curves of the deposition efficiency of particles in the human lungs [Soderholm and McCawley 1990]. The deposition approach would better reflect the biologic plausibility of particle interaction in the human lungs; however, a deposition curve would need to be determined, based on the mean deposition efficiency of the population. Because of the large variability in deposition efficiencies among individuals, the mean deposition curve 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. It is important to determine that the size distributions to be sampled lie within the range of applicability of the sampler; and to perform this determination again at periodic intervals because changes in working conditions may alter particle size distributions.

#### *5.1.2.5 Definition of Respirable Dust for Sampling in Coal Mines*

NIOSH recognizes the importance of particle size-selective sampling, which has as its objective the approximation of the amount of inhaled material that is (1) deposited and retained in specific regions of the human respiratory tract (i.e., dose) and (2) associated with occupational respiratory disease. Determination of dose facilitates the quantitation of health risks so that control measures can be recommended to reduce those exposures.

NIOSH further recognizes the importance of collecting data on the particle size distribution, particle characteristics, and worker exposure conditions in order to determine the most feasible sampling criteria. The determination of whether the particle size distributions to be sampled lie within the measurable range of the sampler is also important for optimizing sampler performance [Liden and Kenny 1991].

The objective of sampler design and performance criteria should be to estimate as closely as possible (given technical and practicable constraints) the deposition and retention of particles in the human respiratory tract. Additional factors that should be considered in determining the most feasible sampling criteria include consideration of the variability among individuals in the deposition and retention of particles and in breathing rates and patterns.

For sampling respirable coal mine dust, NIOSH recommends the ISO/CEN/ACGIH definition of respirable dust for the following reasons:

- The particle size distributions reported for respirable dust in U.S. underground coal mines are within the range (approximately 2 to 10 µm) in which the ISO/CEN/ACGIH definition of respirable dust is reasonably consistent with current knowledge of the deposition efficiency of particles in the human respiratory tract.

- The ISO/CEN/ACGIH definition of respirable dust better approximates the deposition efficiency of particles in the human respiratory tract than does the BMRC definition.

- A comparison of respirable coal mine dust concentrations measured according to the current sampling criteria with those measured according to the ISO/CEN/ACGIH definition has been performed (see Section 5.1.7).

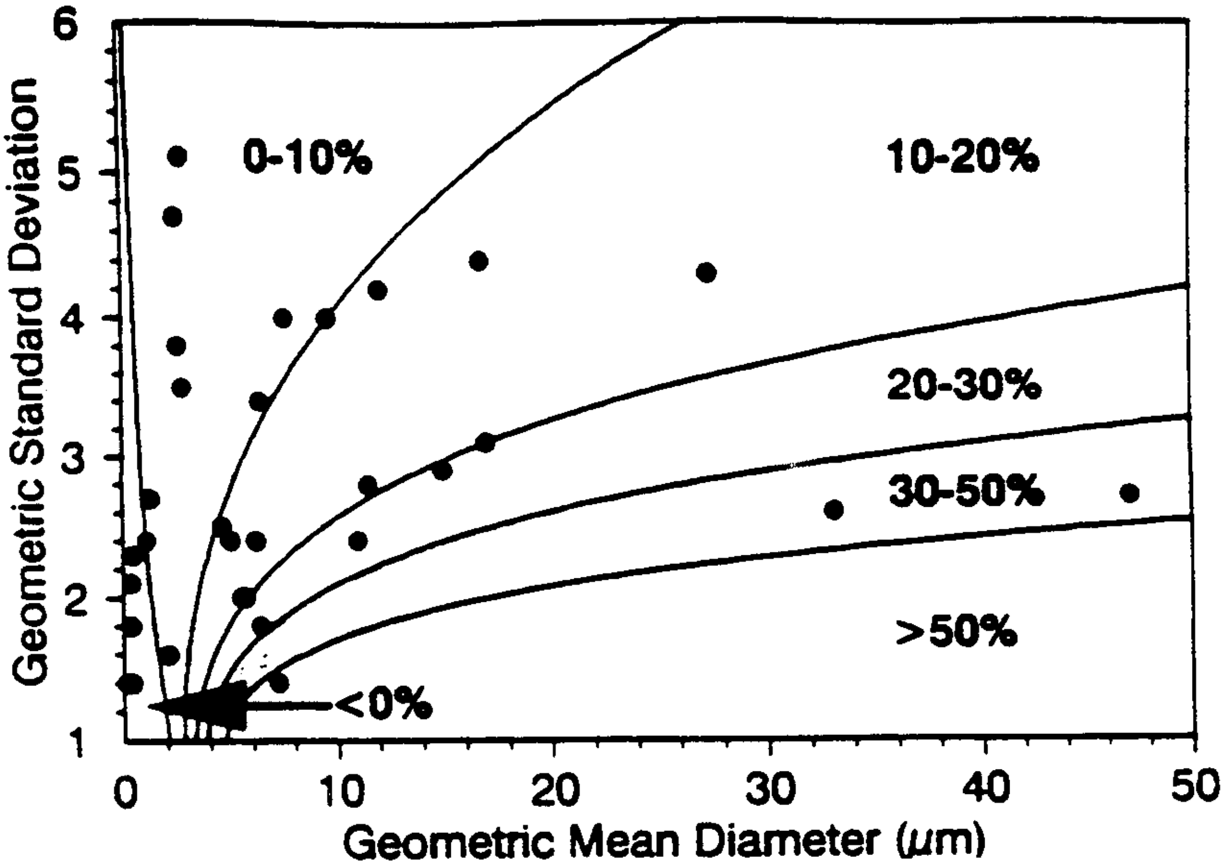


Figure 5-4. The percentage of increase in the measured concentration of respirable dust using the proposed definition [Soderholm 1989] over that which would be measured using the current definition [ACGIH 1990]; the percentage increase lies within the range indicated for assumed lognormal size distributions whose parameters fall within the areas outlined. Circles indicate the parameters of 31 size distributions that have been measured in workplaces [Hinds 1988]. (Source: Soderholm [1991].)

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

### 5.1.3 Sampler Performance Criteria

Two approaches to the approval of samplers may be considered: (1) the testing and approval of a single sampling device (e.g., the CMDPSU), or (2) the performance-based approval of a variety of sampling devices according to ISO/CEN/ACGIH criteria. Advantages of the single-sampler approach is it provides consistency in sampling and avoids the potential for intersampler bias in the measurements. An advantage of the performance-based sampler approach is it stimulates the development of improved samplers [Soderholm and McCawley 1990]. A disadvantage of the single-sampler approach is the disincentive for the development of improved samplers, while a disadvantage of the performance-based approach is the extensive and expensive testing that would be required before samplers could be approved.

#### *5.1.3.1 Current Regulations for Sampler Approval and Calibration*

Current regulations include the following: sampling devices shall be approved in accordance with 30 CFR 74 [1991] and calibrated in accordance with MSHA Informational Report No. 1121, "Standard Calibration and Maintenance Procedures for Wet Test Meters and Coal Mine Respirable Dust Samplers" by a certified person. Approved samplers shall be calibrated and operated ". . . at the flowrate of 2.0 liters of air per minute, 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) (1986)]. Current regulations also include: "To convert a concentration of respirable dust as measured with an approved sampling device to an equivalent concentration of respirable dust as measured with an MRE instrument, the concentration of respirable dust measured with the approved sampling device shall be multiplied by the constant factor prescribed by the Secretary (of Labor) . . . and the product shall be the equivalent concentration as measured with an MRE instrument" [30 CFR 70.206 (1991)].

#### 5.1.3.2 NIOSH Recommendations for Sampler Specifications

NIOSH recommends the use of the CMDPSU at a flow rate of 1.7 L/min without MRE conversion (vs. 2.0 L/min with MRE conversion currently used by MSHA) for sampling respirable coal mine dust in accordance with the ISO/CEN/ACGIH definition of respirable dust, until such time as acceptable criteria are developed for the performance-based approval of alternative samplers also in accordance with the ISO/CEN/ACGIH definition of respirable dust. For example, the HD sampler [Higgins and Dewel 1967] has been evaluated for performance according to the ISO/CEN/ACGIH definition [Bartley et al. 1993]. The flow rate of 1.7 Lpm for the CMDPSU would facilitate the use of a single sample for determination of both respirable coal mine dust and respirable crystalline silica, which is currently sampled at 1.7 Lpm. Because the number of quartz samples currently collected is inadequate for the accurate estimates of exposures [Villnave et al. 1991] and because certain jobs in both underground and surface coal mines are associated with exposures that frequently exceed both the MSHA PEL and the NIOSH REL for respirable crystalline silica [Tomb 1986], NIOSH recommends that the number of samples analyzed for respirable crystalline silica should be increased to one sample per biweekly sampling period for roof bolters, drillers, and other "high risk" occupations for exposure to respirable crystalline silica.

In addition, the British Mine Research Equivalent (MRE) factor of 1.38 will no longer be applied to the values of respirable coal mine dust obtained according to the ISO/CEN/ACGIH definition. Although the current U.S. standard of 2 mg/m$^3$ (MRE) respirable coal mine dust was based entirely on British data, the NIOSH REL for respirable coal mine dust was based primarily on exposure-response studies of U.S. coal miners (see Chapter 7). Thus, the REL for respirable coal mine dust does not require a conversion factor to be applied to the measured dust concentrations. A correction factor was derived for comparison between the current and recommended methods (Section 5.1.7) for use in deriving the REL. Therefore, concentrations measured according to the recommended sampling criteria (i.e., ISO/CEN/ACGIH) do not require a conversion factor.

#### *5.1.3.3 Operation of Approved Sampler*

Current regulations include the following: The approved sampling device (see Section 5.1.1) ". . . shall be worn or carried directly to and from the mechanized mining unit or designated area to be sampled and shall be operated portal to portal" [30 CFR 70.201(b) (1991)]. Sampling devices are to be operated for the " . . . entire shift or for 8 hours, whichever is less" [30 CFR 70.201(b)]. The respirable dust sampling shall be done by a certified person, who has passed the MSHA examination on the sampling of respirable coal mine dust [30 CFR 70.202-203 (1991)].

NIOSH recommends that samplers shall be operated for up to a 10-hour workshift (40-hr workweek). NIOSH recommends that samples collected shall be personal samples. A method for estimating an exposure limit "reduction factor" for extended workshifts is described in Brief and Scala [1975].

### 5.1.4 Variability in Sampling and Analytical Methods

#### *5.1.4.1 MSHA Gravimetric Method for Respirable Coal Mine Dust*

The current procedure for measuring the concentration of respirable coal mine dust is as follows. Each filter is preweighed by the filter manufacturer to ±0.1. Following sampling with the Coal Mine Dust Personal Sample Unit (CMDPSU) at 2.0 L/min, the filter with coal mine dust is sent to MSHA for weighing. The current MSHA procedure for weighing respirable dust samples uses a Mettler Model AE163 analytical balance in conjunction with an automatic weighing system with a precision of ±0.02 mg [Tomb 1990]. Each balance is calibrated twice per day.

Quality control for the automatic weighing system includes the systematic weighing of one in eight filters on a second Mettler AE163 balance. Tolerance is set at ±0.1 mg between the two weighings of the same sample. Weights are truncated at the 0.1 mg level (e.g., 3.457 mg is truncated to 3.4 mg) [Bowman et al. 1985]. The difference of the two truncated weights is then recorded as the weight of coal dust deposited. The respirable concentration (mg/m$^3$) is computed by multiplying by a correction equal to 1.38 and dividing by the volume of air sampled (2.0 L/min x sampling time [min]).

#### *5.1.4.2 Weighing Imprecision*

The weighing inaccuracy corresponding to the MSHA weighing procedure has been estimated and is documented in Parobeck et al. [1981] and Bowman et al. [1985]. Including both the above truncation on the weights prior to subtraction and analytical errors (for example, due to balance inaccuracy or to filter mass instability), the estimated standard deviation σ weigh in the measured deposited mass has been reported as:

$$\sigma \text{ weigh} = 0.081 \text{ mg.}$$

The coefficient of variation (CV), or relative standard deviation, in the respirable dust concentrations estimates due to a weighing error ($CV_{weigh}$) can be estimated, as illustrated in the following examples:

Example 1: The following conditions represent sampling at the current PEL for respirable coal mine dust (using the CMDPSU): sampling time, 8 hours; sampler flow rate, 2.0 L/min; respirable dust concentration, 2.0 mg/m$^3$. $CV_{weigh}$ is given by the following equation:

$CV_{weigh}$

$= [(0.081 \text{ mg} \times 1.38)/(2.0 \times 10^{-3} \text{ m}^3/\text{min} \times 8 \text{ hr} \times 60 \text{ min/hr})]/2 \text{ mg/m}^3$

$= 5.8\%.$

Example 2: The conditions corresponding to sampling at the REL (again using the CMDPSU): sampling time, 8 hours; sampler flow rate, 1.7 L/min; respirable dust concentration, 0.9 mg/m$^3$. Note that a correction factor (e.g., 1.38) is not recommended for the REL. The $CV_{weigh}$ is given by the following:

$CV_{weigh}$

$= [(0.081 \text{ mg})/(1.7 \times 10^{-3} \text{ m}^3/\text{min} \times 8 \text{ hr} \times 60 \text{ min/hr})]/0.9 \text{ mg/m}^3$

$= 11.0\%.$

Example 3: Similarly using the HD cyclone, the following conditions correspond to sampling at the REL: sampling time, 8 hrs; sampler flow rate, 2.2 L/min; respirable dust concentration, 0.9 mg/m$^3$. Then, $CV_{weigh}$ is given by the following:

$CV_{weigh}$

$= [(0.081 \text{ mg})/(2.3 \times 10^{-3} \text{ m}^3/\text{min} \times 8 \text{ hr} \times 60 \text{ min/hr})]/0.9 \text{ mg/m}^3$

$= 8.5\%$

Note that the value $CV_{weigh}$ for sampling at the REL, using either the CMDPSU or the HD cyclone, is larger than $CV_{weigh}$ for sampling at the current PEL and sampling criteria. The NIOSH accuracy criteria for determining the acceptability of sampling and analytical methods is the following: 95% of a method's concentration estimates should be within 25% of the true concentration [NIOSH 1984]. Translated to the method inaccuracy CV, this means that CV must be less than 12.8% (even if the method has no systematic error) [Gunderson and Anderson 1980].

### 5.1.4.3 *Feasibility of Reducing Weighing Impression*

For respirable dust samplers, RSD is comprised not only of $CV_{weigh}$, but also 5% from the sampling pump uncertainty [30 CFR Part 74 (1988)] and 5% from intersampler variability [Bartley et al. 1993]. With $CV_{weigh}$ as large as 11.0% or 8.2%, the weighing errors dominate the method inaccuracy. Thus, the total CV can be significantly reduced by lowering $CV_{weigh}$.

$CV_{weigh}$ itself is comprised of two parts:

$$(CV_{weigh})^2 = (CV_{trunc})^2 + (CV_{analy})^2,$$

where $CV_{trunc}$ refers to the truncation procedure and $CV_{analy}$ to the variability in the analysis itself. Truncation errors are analyzed as follows: Define the function $x_{trunc}(x)$ of a random variable x by dropping the decimal part of x. The error $\Delta = x_{trunc}(x) - x$ looks like a saw-tooth, falling from 0 to -1 between each integer. The mean or expected error $E(\Delta)$ is thus -1/2 (i.e., truncation is negatively biased). Similarly, $E(\Delta^2) = 1/3$, which means the variance $\sigma^2$ is

$$\sigma^2 = E(\Delta^2) - E(\Delta)^2 = 1/12.$$

The bias cancels the <u>difference</u> between two such independent truncated numbers, but the variance is doubled. Thus, the standard deviation in the difference $\sigma_{diff}$ is

$$\sigma_{diff} = 1/\mathrm{Sqrt}[6].$$

With dust mass equal to the difference of two weights truncated at the 0.1 mg level, the standard deviation $\sigma_{trunc}$ is 0.1 mg/Sqrt[6] or about 0.41 x 0.1 mg.

Thus, the two truncations lead to the following:

$CV_{trunc} = 0.41 \times 0.1$ mg/mass,

where mass is the sampled mass. For example, after 8 hours of sampling 0.9 mg/$m^3$ at 1.7 L/min,

mass = 0.734,

and therefore,

$CV_{trunc} = 5.6\%$.

At $CV_{weigh} = 11.0\%$, this corresponds to

$CV_{analy} = 9.5\%$.

Thus, to reduce $CV_{weigh}$, NIOSH recommends: (1) Reduce $CV_{analy}$ by improving quality control of the weighing procedure itself. The weighing imprecision may have been reduced when MSHA instituted an automatic weighing system following the publication by Parobeck et al. [1981]; (2) Essentially eliminate $CV_{trunc}$ by using scientific rounding (at no greater than the 0.01 mg level) instead of the current MSHA method of truncating measured weights at the 0.1 mg level. The result of these recommendations would be to reduce $CV_{analy}$ by half and to essentially eliminate $CV_{trunc}$, thereby reducing $CV_{weigh}$ to about 5%.

#### *5.1.4.4 Coefficient of Variation for Sampling and Gravimetric Determination of Respirable Coal Mine Dust (Unbiased Method)*

The coefficient of variation (CV) for sampling and measurement of respirable coal mine dust is estimated to include error components for weighing ($CV_{weigh}$), sampler pump fluctuations ($CV_{pump}$), and intersampler variability ($CV_{samp}$) [Bowman et al. 1985]. The weighing error refers to the standard deviation in the deposited coal dust mass, which is estimated as the difference in filter weights before and after exposure. The weighing error therefore incorporates the errors in each of the two weighings [Parobeck et al. 1981]. MSHA cites the values of 0.07 for $CV_{weigh}$, 0.05 for $CV_{pump}$, and 0.05 for $CV_{samp}$ [MSHA 1992].

The $CV_{weigh}$ of 0.07 corresponds to the weighing error of the mass deposited on the filter when the single, 8-hour measured concentration is 2.0 mg/m$^3$. Thus, to determine $CV_{weigh}$ for sampling at another PEL, the value for $CV_{weigh}$ should be multiplied by a factor of (2 mg/m$^3$ / PEL). $CV_{weigh}$ depends on the PEL because of a fixed imprecision in the filter weighings [Caplan et al. 1977]. The values of 0.05 for $CV_{pump}$ and 0.05 for $CV_{samp}$ are consistent with the values cited in MSHA regulations [30 CFR Part 74 (1988)]. However, the $CV_{samp}$ of 0.05 [30 CFR Part 74 (1988)] is larger than the 0.0166 recently recommended by an international sampling committee as feasible for personal pump air flow imprecisions (i.e., 3 standard deviations are to be at most equal to 5%) [CEN 1991].

The total CV can be computed from its components as follows:

$$CV = (CV_{weigh}^2 + CV_{pump}^2 + CV_{samp}^2)^{1/2},$$

where $CV_{weigh} = 0.07(2 \text{ mg/m}^3/\text{PEL})$, $CV_{pump} = 0.05$, and $CV_{samp} = 0.05$. Then,

for PEL = 0.9 mg/m$^3$, CV = 0.1709.

The total CV is reduced if weighing error and pump error are reduced (see Section 5.1.4.3):

where $CV_{weigh} = 0.05(2 \text{ mg/m}^3/\text{PEL})$, $CV_{pump} = 0.0166$, and $CV_{samp} = 0.05$. Then,

for PEL = 0.9 mg/m$^3$, CV = 0.1229.

CV is used as the coefficient of variation for noncompliance determinations based on single, 8-hr samples. It should be noted that CV = 0.1709 exceeds the value of 0.128 determined by NIOSH as the maximum CV for approval of a sampling and analytical method [Gunderson and Anderson 1980]. However, reductions in the weighing error and pump error are feasible and can reduce the CV for sampling and measurement of concentrations below 2.0 mg/m$^3$ (see Section 5.1.4.3). Further, to ensure that sampler performance in the field is comparable to these specified criteria, a quality control program should be used for the routine measurement of sampler performance.

#### 5.1.4.5 *Determination of Variability in Sampling Respirable Coal Mine Dust: Adjustment for Biased Methods*

The statistical evaluation of workplace exposures as measured by unbiased sampling methods is described by Leidel et al. [1977] (see Section 5.1.5.4). However, when the sampling method includes bias, adjustment for that bias is made by adding the estimated value of that bias to the quantity 1.645*CV (in Section 5.1.5.7). Such bias adjustment is required when using performance-based sampling criteria. Performance-based sampling criteria enable the certification of any sampler meeting specified criteria to be used for sampling in accordance with the ISO/CEN/ACGIH definition of respirable dust. This bias associated with performance-based sampling results from the differences in the collection characteristics of an ideal laboratory sampler relative to those of a prospective sampler. Generalization of the Leidel et al. [1977] approach to include biased sampling methods is provided in Appendix G.

### 5.1.5 Sampling Strategy for Respirable Coal Mine Dust

The Federal Coal Mine Health and Safety Act of 1969, amended 1977, mandates the following: "Each operator of a coal mine shall take the collection of accurate samples of the amount of respirable dust in the mine atmosphere to which each miner in the active working of such mine is exposed" [30 USC 842(a) (1986)]. The regulations regarding dust sampling have been prescribed for both underground coal mines [30 CFR 70.201-70.220] and for surface coal mines or surface work areas of underground coal mines [30 CFR 71.201-71.220]. Requirements for personal sampling for miners with pneumoconiosis at underground or surface coal mines are provided in 30 CFR Part 90. Sampling by MSHA inspectors is described in an MSHA handbook [MSHA 1989].

The NIOSH recommended sampling strategy includes the following components:

- Accurate estimates of the TWA concentration of respirable coal mine dust and respirable crystalline silica to which each worker is exposed over an 8- to 10-hr shift

- Distinction between compliance sampling by coal mine operators and noncompliance sampling by MSHA inspectors

- Biweekly sampling by coal mine operators for frequent feedback on the effectiveness of dust control methods

- A high level of confidence in the measured concentrations with respect to the REL

- Random, unannounced sampling by MSHA inspectors for noncompliance determination based on single, full-shift samples

- Emphasis on sampling miners in "high risk" jobs

- Analysis of all samples for both respirable crystalline silica and respirable coal mine dust

The objectives of sampling for compliance or noncompliance are fundamentally different. In compliance sampling, the mine operator needs information on the dust concentrations in order to evaluate the effectiveness of dust controls. If results of compliance sampling indicate that dust concentrations are not below the standard, then this information can be used to make necessary adjustments to controls. In contrast, noncompliance sampling is performed to provide a valid statistical and legal basis to enforce the standard; a high degree of certainty that the standard has been violated is required, and the results have legal and economic implications. For these reasons, the NIOSH recommended strategy distinguishes between the responsibilities for sampling by mine operators and MSHA inspectors (i.e., operators are responsible for demonstrating the effectiveness of dust controls in maintaining exposures below the REL and inspectors are responsible for collecting samples for noncompliance determinations).

A statistical sampling strategy can estimate and account for random error, but systematic error (e.g., as a result of incorrect sampling procedures) cannot be dealt with in a statistical strategy. Systematic error is a technical issue that must be addressed separately. In 1991, the Secretary of Labor directed MSHA to conduct a review of the program to control respirable coal mine dust and to develop recommendations for improving the program. In response, MSHA established an interagency task group, the Coal Mine Respirable Dust Task Group. The Task Group developed numerous recommendations for MSHA to consider, including the following that pertaining to collection of respirable dust samples: (1) redefinition of the "normal production shift" from the current definition of 50% of normal to a level that will result in more representative determination of exposures; (2) development of uniform procedures for the approval of dust control plans, including minimum acceptable dust control parameters (e.g., ventilation, water) by mining method; (3) determination of noncompliance on the basis of single samples; (4) quality control measures to ensure the integrity of the respirable dust sampling program, including use of tamper-resistant sampler cassettes; and (5) training for miners on proper sampling procedures.

The NIOSH recommended sampling strategy focuses on control of exposures through frequent sampling of "high risk" workers and evaluation of dust control plan parameters. The strategy incorporates practical aspects of controlling exposures in the mining environment. Like the existing MSHA sampling strategy, the NIOSH recommended strategy does not allow for the estimation of mean exposures for individuals or groups over time. Unlike the existing MSHA sampling strategy, the NIOSH approach includes consideration of sampling and analytical errors in the measurement of respirable dust concentrations. Neither approach includes consideration of the environmental variability of exposure measurements, which is generally much larger than the sampling and analytical error [Nicas et al. 1991]. Thus, research is needed to develop a sampling strategy that will provide determination of the distribution of exposures of all miners over time. Such data are needed for the study of exposure-response relationships and for future risk assessment and standard setting activities.

#### *5.1.5.1 MSHA Inspector Sampling*

MSHA inspectors sample at least five occupations in each mechanized mining unit (MMU), including the designated occupation (DO) and any roof bolter occupations on the MMU that were not established as designated areas (DA). MSHA inspectors may collect one DA sample per year (e.g., if the coal mine operator was required according to 30 CFR 70.208(c) to sample that DA in the last 6 months). MSHA inspectors may collect full-shift respirable dust samples from nondesignated entities (NDE), which represent either nondesignated areas or nondesignated occupations, if an inspection is requested by a miner or a miner's representative [according to 30 CFR 813(g) (1986)] or if the inspector suspects the concentrations of respirable coal mine dust or respirable quartz may 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. At surface coal mines or surface work areas of underground coal mines, MSHA inspectors collect one sample per year from all designated work positions (DWP) 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.

NIOSH recommends that MSHA use samples collected by inspectors exclusively for noncompliance determinations and eliminate noncompliance determinations from samples collected by coal mine operators. NIOSH recommends that MSHA inspections be conducted at random and unannounced to the coal mine operators through a schedule of random spot inspections approximately 6 times per mine per year. Inspections are currently required 4 times per year in underground coal mines to determine, among other safety and health issues, if the parameters of the approved dust control plan are being maintained; inspections are currently required at least 2 times per year in surface coal mines [under 30 CFR 813(a) (1986)]. NIOSH recommends that noncompliance be determined on the basis of single 8-hr TWA concentrations, including a statistical comparison of the probability that the single sample exceeds the REL (see Section 5.1.5.4.1).

MSHA inspectors make a determination of which entities to sample based on the following: the compliance record of the mine; the adequacy of the dust control parameters; the number of entities being sampled by the operator as DOs, DAs, Part 90 miners, or DWPs; the number of entities available for sampling; and changes in mining conditions since the last inspection that may affect the concentration of respirable coal mine dust or respirable quartz.

DO, DA, NDE, and intake samples are area samples (i.e., the sampling device remains in the environment, rather than with the individual miner). Part 90 samples are personal samples (i.e., the sampling device must remain in the environment of the individual miner).

#### *5.1.5.2 Coal Mine Operator Sampling*

Current regulations require coal mine operators to take five valid respirable dust samples from designated occupations (DOs) in each mechanized mining unit (MMU) for each bimonthly sampling period; samples are to be collected on consecutive normal production shifts [30 CFR 70.207 (1991)]. Designated occupations for sampling are listed by mining method [30 CFR 70.207(e) (1991)] in Table 5-2.

**Table 5-2.—Designated occupations for sampling required by MSHA regulations [30 CFR 70.206(e) (1991)]***

| Mining method of section | Designated occupation (DO) for section | Position of sampling device relative to DO |
|---|---|---|
| Conventional | Cutting machine operator | On miner, or on cutting (shooting off machine within 36-in. inby solid) normal working position |
| Conventional | Loading machine operator | On miner, or on loading machine within 36-in. inby normal working position |
| Continuous mining | Continuous mining machine | On miner, or on continuous (other than operator) mining machine within 36-in. (auger type) in by 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 |

*NIOSH recommends that "dust" refer to respirable coal mine dust or respirable crystalline silica.

NIOSH recommends that coal mine operators submit single, full-shift samples (for up to a 10-hr work day) to MSHA on either a biweekly or a biannual basis, depending on exposure levels and any changes in processes or production. The purpose of this strategy is to provide the mine operator with frequent feedback on dust concentrations and effectiveness of the approved dust controls. Two weeks is about the minimum time mine operators could receive sample results from MSHA.

Operators shall sample at times when production is representative of normal production levels. Currently, the minimum production level for a valid bimonthly operator sample is 50%, and the minimum production level for MSHA approval of the dust control plan is 60% of the average production over the last 30 production shifts [MSHA 1992]. However, approval of a plan for controlling respirable dust at 60% of average production may not provide adequate control of exposures at actual production levels. Therefore, NIOSH recommends that MSHA establish a definition of normal production (for both approval of the dust control plan and routine sampling) which more closely approximates actual production levels. Further, the recommended biweekly sampling by operators will provide frequent feedback on the effectiveness of controls at actual production levels.

Although NIOSH recommends that noncompliance determinations shall not be based on samples submitted by operators, MSHA may use these data for analyses of dust concentrations or to target MSHA sampling or inspection efforts. Whenever a sample exceeds the PEL, MSHA shall inform mine operators to inspect and adjust controls as necessary to reduce the respirable dust concentrations. Although mine operators could not be cited on the results of the operator-submitted samples, citations could be issued for not following the required sampling procedures or adhering to the approved dust control plan.

### *Section 5.1.5.2.1 Ventilation system and methane and dust control plan*

According to 30 CFR Part 75.316, underground coal mine operators are required to submit a "ventilation system and methane and dust control plan" (hereafter referred to as DCP). The DCP must be reviewed by the operator and MSHA at least every 6 months [30 CFR 75.316]. The DCP must include information on the mechanical ventilation equipment, the quantity and velocity of air, and the locations of "designated area" sampling (required in accordance with 30 CFR Part 70.208). A minimum of 60% of the average production over the last 30 production shifts is acceptable for approval of the plan [MSHA 1992]. Because a DCP approved at 60% of average production may not adequately control respirable dust when actual production exceeds that level, NIOSH recommends that MSHA establish a definition of normal production for approval of the dust control plan which more closely approximates actual production levels. The recommended biweekly sampling by operators will provide frequent feedback on the effectiveness of the DCP at actual production levels.

Currently, there is no requirement for recordkeeping of production levels for each mechanized mining unit (MMU), and MSHA determines production level from information "obtained informally" from the mine operator [MSHA 1992]. NIOSH recommends that coal mine operator shall be required to provide records to MSHA on the production levels for each MMU for the purpose of determining average production level and certification of the ventilation system and methane and dust control plan (DCP).

Sampling to evaluate the effectiveness of the DCP is currently performed by MSHA inspectors. However, MSHA inspectors may not sample immediately to evaluate a DCP submitted by an operator, and may approve the plan temporarily until MSHA inspectors can samples [MSHA 1992]. Thus, a plan may be implemented "temporarily" which does not maintain respirable dust concentrations below the exposure limit. In 1991, MSHA sampled only 58% of the 2,099 MMUs in operation for at least 181 days during fiscal year 1991 [MSHA 1992]. NIOSH recommendations require the mine operator to submit samples and production information to MSHA for use in the certification of the DCP. MSHA may verify this information with inspector sampling.

#### *5.1.5.2.2 Continuous monitoring of dust control plan*

The continuous monitoring of dust control parameters is the preferable method for determining the effectiveness of the DCP. MSHA states, "The technology currently exists for the monitoring of such parameters as water pressure and flow rate, but has yet to be integrated into a system that can be implemented in underground mining" [MSHA 1992]. MSHA reports that continuous monitoring of parameters such as water pressure and flow rate are technically feasible, but a system has not yet been developed for implementing continuous monitoring in underground mines [MSHA 1992]. An important research need is the evaluation and testing of a continuous monitoring system for use in underground mines.

Currently, MSHA does not require mine operators to monitor the DCP on a regular basis [MSHA 1992]. During regular safety and health inspections, MSHA inspectors examine the operation of the DCP by visual observation and measurement of control parameters such as pressure of water sprays, quantity and velocity of air currents [MSHA 1992]. However, because of the changing conditions from day to day in underground mines, the DCP should be evaluated regularly to determine if it is effective in controlling respirable dust concentrations.

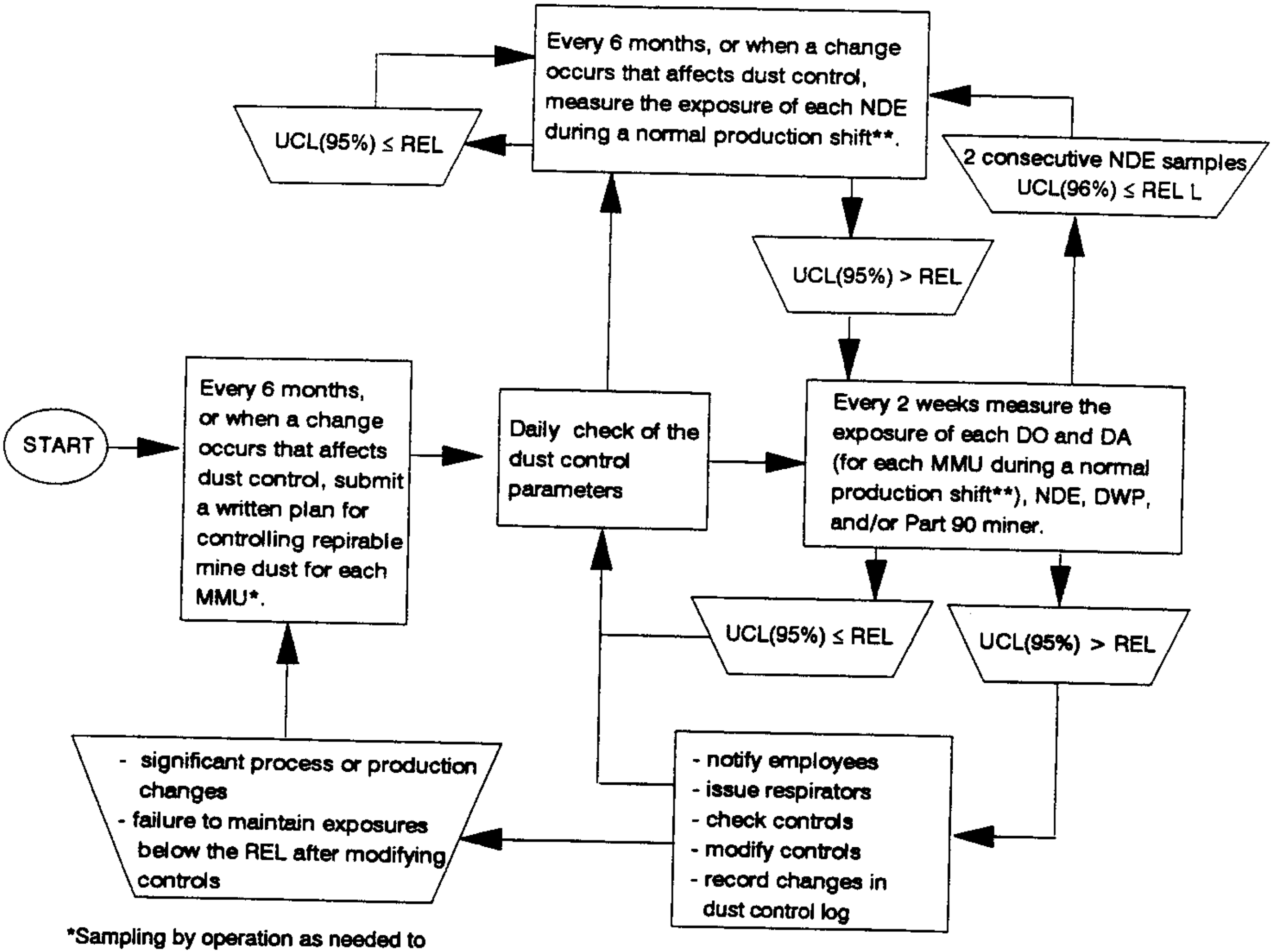
In the absence of continuous monitors, a daily check of the DCP parameters may represent the best means of ensuring that the daily DCP parameters match the production level. There should be a daily check of those parameters determined by MSHA to be essential for the control of respirable dust levels. For example, these parameters may include ventilation rates, number of working water sprays, water pressure, presence and location of auxiliary ventilation, etc. The status of these parameters are daily recorded by a responsible party into a dust control plan logbook for each MMU.

The DCP log will be reviewed by the MSHA inspector when conducting the 6 month review of a DCP. Citations can be issued during unannounced visits by the MSHA inspector if the dust control parameters measured or checked by the inspector do not match those entered into the log on the day of the inspection.

#### *5.1.5.2.3 Coal mine operator sampling procedures*

Figure 5.5 illustrates the coal mine operator sampling strategy. This strategy is described below:

1. Every 6 months, the coal mine operator shall submit to MSHA a written plan for controlling respirable dust for each mechanized mining unit (MMU). The mine operator shall conduct an initial monitoring survey to determine miners' exposures to respirable coal mine dust and respirable crystalline silica. A sufficient number of samples shall be collected to characterize each miner's exposure. Though not all miners have to be monitored, sufficient samples must be collected to characterize the exposures of all miners who may be potentially exposed. An initial determination shall be made by MSHA of which occupations or areas will be classified as a



*Sampling by operation as needed to verify effectiveness of dust control plan

**Based on reasonable estimate of normal production

**ABBREVIATIONS**

| | |
|---|---|
| REL: | recommended exposure limit |
| UCL(95%): | 95% upper confidence limit |
| DA: | designated area |
| DO: | designated occupation |
| DWP: | designated work position |
| NOE: | nondesignated entity (either nondesignated occupation or nondesignated area) |
| Part 90: | transfered miners [30 CFR Part 90] |

Figure 5-5. Coal mine operator sampling strategy.

designated occupation (DO), designated area (DA), designated work position (DWP), or nondesignated entity (NDE, including either nondesignated occupations or nondesignated areas). MSHA shall specify representative NDEs for sampling by the coal mine operator every 6 months.

2. The mine operator shall conduct daily checks of the dust control plan and record values of parameters (e.g., ventilation rates, water pressure, etc.) in the logbook.

3. Every 6 months, the mine operator shall measure the exposure for each NDE specified by MSHA. If the 95% upper confidence limit, or UCL(95%), of the measured concentration exceeds the REL, then that occupation shall be sampled every 2 weeks. When the UCL(95%) is below the REL for two consecutive biweekly samples, the 6 month sampling schedule can be resumed.

4. Every 2 weeks, the mine operator shall measure the exposure of each DO and DA (for each mechanized mining unit), DWP, and/or Part 90 miner. If the UCL(95%) of the measured concentration exceeds the REL, the employer shall do the following: notify employees, issue respirators, check controls, modify controls, record changes in the dust control plan logbook.

5. If the biweekly samples submitted to MSHA frequently exceed the REL, then MSHA may do the following: (1) conduct an unannounced inspection of the MMU, during which the inspector measures exposures for five occupations and checks the parameters of the DCP; citations could be issued either for failing to comply with the minimum requirements of the DCP and/or for exposures exceeding the REL; or (2) require that the dust control plan be re-approved, with increased emphasis on implementing effective dust controls at representative production levels.

6. Whenever there are changes in operational conditions that may result in exposure concentrations above the REL, air sampling shall be conducted as if it were an initial monitoring survey.

7. Coal mine operators shall take samples of the concentrations of respirable dust in the intake air at least once every 6 months, as determined from full-shift samples collected within 200 ft outby the working faces of each section in the intake airways. Concentrations of respirable dust in intake air shall be maintained at the lowest attainable level.

#### *5.1.5.3 Respirable Coal Mine Dust Sampling in Surface Coal Mines or Surface Work Areas of Underground Coal Mines*

According to current regulations, the mine operators are required to sample each designated work position (DWP) on a bimonthly basis [45 Fed. Reg. 80, 746 (1980)]. DWPs are determined by the MSHA District Manager based on previous samples. As in underground coal mines, the PEL for respirable coal mine dust is currently reduced if the quartz content exceeds 5% (see Section 6.1). Since 1985, samples collected by coal mine operators have been used, in addition to MSHA inspector samples, in the determination of 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 MSHA inspector's quartz data (Figure 3-3) [Niewiadomski et al. 1988]. If the quartz content of the operator sample varies by more than 2% from the inspector data, 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.

NIOSH recommends the following with regard to sampling and analysis of respirable crystalline silica at underground and surface coal mines:

- Exposures to respirable crystalline silica shall be determined according to the same sampling procedures as respirable coal mine dust;
- All respirable coal mine dust samples with sufficient weight gain shall be analyzed for respirable crystalline silica; and
- The concentration of respirable crystalline silica shall not exceed the REL of 0.050 mg/m$^3$ [NIOSH 1978].

#### 5.1.5.4 *Statistical Basis for Single, Full-Shift Sampling*

A statistical test for a compliance officer's determination of noncompliance is based on the calculation of the one-sided, lower 95% confidence interval (95% LCL, $\alpha = 0.05$) [Leidel et al. 1977]. The LCL gives the lower bound on the true exposure average and places the burden of proof of noncompliance on the government. However, an employer would use the upper 95% confidence interval to ensure that employees' exposures do not exceed the standard. For either the compliance officer's test or the employer's test to compare a single, full-shift concentration to a standard for that same full-shift period, the variability associated with the sampling and analytical methods is included in the calculations. This sampling and analytical variability is expressed as the coefficient of variation (CV) (see Section 5.1.4.4).

The MSHA permissible exposure limit (PEL) is based on the standard specified in the Coal Mine Health and Safety Act of 1969 (amended 1977). The Act states ". . . each operator shall continuously maintain the average concentration of respirable dust in the mine atmosphere during each shift to which each mine 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) (1986)]. "Average concentration" is further defined in the following [30 USC 842(f) (1986)]:

> ". . . the 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."

A statistically valid technique can be applied to a single, full-shift measurement to determine (with a high degree of certainty) if the average concentration exceeds the exposure limit (which is defined for the same full-shift time period) [Leidel et al. 1977]. The single, full-shift sample does not accurately represent the long-term average concentrations of respirable coal mine dust. However, the Coal Mine Health and Safety Act of 1969 (amended 1977) clearly defines the "average concentration" as that measured "over a single shift only."

#### *5.1.5.4.1 Determination of noncompliance by MSHA inspectors from single, full-shift samples*

For noncompliance determinations by MSHA inspectors, NIOSH recommends the use of the Leidel et al. [1977] statistical procedure for the comparison of measured concentrations to the permissible exposure limits (PEL). The Leidel et al. procedure is as follows:

(1) Compute the ratio X/STD, where X equals the measured concentration, and STD equals the applicable standard, such as the PEL;

(2) If $X/STD \leq 1$, then noncompliance determination is not applicable;

(3) If $X/STD > 1$, then compute the 95% one-sided lower confidence limit as follows:

$$LCL(95\%) = X/STD - (1.645)(CV),$$

where 1.645 is the z-value for the 95% one-sided confidence limit ($\alpha = 0.05$) for the normal (Gaussian) distribution and the CV is the coefficient of variation of the sampling and analytical method (see Section 5.1.4.4).

(4) If $X/STD > 1$ and $LCL(95\%) \leq 1$, then classify exposure as "possible overexposure"; if $LCL(95\%) > 1$, then classify exposure as "noncompliance."

Table 5-3 lists the measured concentrations of respirable coal mine dust determined from single 8-hr samples and the corresponding noncompliance determinations based on the 95% lower confidence limit (one-sided confidence intervals, $\alpha = 0.05$).

A "possible overexposure" situation occurs when the average concentration measured is above the exposure limit and the lower confidence limit is below the exposure limit (i.e., the hypothesis that the concentration measured is less than or equal to the exposure limit could not be rejected at the 95% confidence level). The "possible overexposure" situation is not inconsistent with compliance, and no citation would be issued. However, the coal mine operator should examine the dust controls to determine if they are operating effectively.

Table 5-4 and Figure 5-6 describe "compliance," "noncompliance," and "possible overexposure" concentrations relative to an exposure limit.

Table 5-3.—Compliance officer's test of single, full-shift concentrations relative to the recommended exposure limits (RELs) for respirable coal mine dust and respirable crystalline silica*

| Sampling Method | CV† | REL (mg/m$^3$) | X (mg/m$^3$) | Noncompliance Determination |
|---|---|---|---|---|
| Respirable coal mine dust: unbiased method | 0.1709 | 0.9 | ≤0.9 | NA |
| | | | 0.91-1.15 | Possible overexposure |
| | | | ≥1.16 | Noncompliance |
| | 0.1229 | 0.9 | ≤0.9 | NA |
| | | | 1.01-1.08 | Possible overexposure |
| | | | ≥1.09 | Noncompliance |
| Respirable coal mine dust: adjustment for bias | 0.1229 | 0.9 | ≤0.9 | NA |
| | | | 1.01-1.12 | Possible overexposure |
| | | | ≥1.13 | Noncompliance |
| Respirable crystalline silica: unbiased method | 0.30 | 0.05 | ≤0.05 | NA |
| | | | 0.051-0.074 | Possible overexposure |
| | | | ≥0.075 | Noncompliance |
| Respirable crystalline silica: adjustment for bias | 0.30 | 0.05 | ≤0.05 | NA |
| | | | 0.051-0.075 | Possible overexposure |
| | | | ≥0.078 | Noncompliance |

* Measured with the Coal Mine Dust Personal Sampler Unit (CMDPSU); see Section 5.1.4.5 and Appendix G for discussion of unbiased and biased methods and noncompliance concentration using HD sampler

† See Section 5.1.4.4 for computation of CV for respirable coal mine dust; CV for respirable crystalline silica from Shulman et al. [1992]

Abbreviations: CV = coefficient of variation; X = measured concentration

Note: Computed according to Leidel et al. [1977]; all values scientifically rounded.

Table 5-4.—Classification of concentrations based on single, full-shift samples relative to an exposure limit

| Classification | Criteria* | Comments |
|---|---|---|
| Noncompliance | 95% confidence that measured concentration is above the PEL | LCL(95%) ≤PEL |
| Possible Overexposure | Measured concentration cannot be classified as compliance (employer's test) or noncompliance (compliance officer's test) | |
| Compliance | 95% confidence that measured concentration is below the PEL | UCL(95%) ≥PEL |

* X = measured concentration
PEL = permissible exposure limit
LCL(95%) = lower 95% confidence limit, one-side ($\alpha$ = 0.05)
UCL(95%) = upper 95% confidence limit, one-sided ($\alpha$ = 0.05)

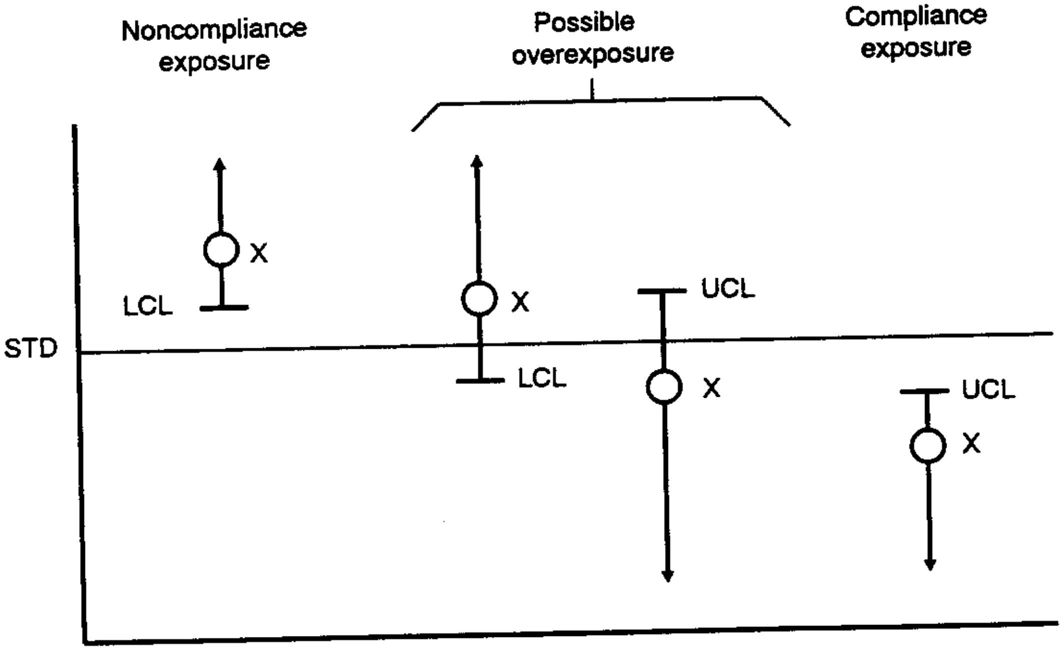


Figure 5-6. Classification of exposures relative to an exposure limit. (Source: Leidel et al. [1977].) Abbreviations: STD = standard, such as recommended exposure limit (REL), or permissible exposure limit (PEL); LCL = lower confidence limit; UCL = upper confidence limit; X = measured concentration.

Table 5-5.—Measured concentrations of respirable coal mine dust or respirable crystalline silica as the 95% upper confidence limit of exposure relative to the REL[*]

| Sampling method | CV[†] | REL | X |
|---|---|---|---|
| Respirable coal mine dust: unbiased method | 0.1709 | 0.9 | $\leq 0.65$ |
|  | 0.1229 | 0.9 | $\leq 0.72$ |
| Respirable coal mine dust: adjustment for bias | 0.1229 | 0.9 | $\leq 0.68$ |
| Respirable crystalline silica: unbiased method | 0.30 | 0.05 | $\leq 0.025$ |
| Respirable crystalline silica: adjustment for bias | 0.30 | 0.05 | $\leq 0.023$ |

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[*] Measured with the Coal Mine Dust Personal Sampler Unit (CMDPSU); see Section 5.1.4.5 and Appendix {G} for discussion of unbiased and biased methods.

[†] See Section 5.1.4.4 for computation of CV.

Abbreviations: CV = coefficient of variation; X = measured concentration, corresponding to compliance as calculated from the UCL(95%) in equation 2.

Notes: Computed according to Leidel et al. [1977]; all values scientifically rounded.

### ***Section 5.1.5.4.2 Sampling by coal mine operators based on single, full-shift samples***

A statistical test for an employer's determination of compliance is based on the calculation of the one-sided, upper 95% confidence interval [UCL (95%), $\alpha = 0.05$] [Leidel et al. 1977]. The UCL (95%) gives the upper bound on the true exposure average. A single, full-shift concentration is compared to the standard for that same full-shift period, the variability associated with the sampling and analytical methods is included in the calculations. This sampling and analytical variability is expressed as the coefficient of variation (CV) (see Section 5.1.4.4).

The Leidel et al. [1977] procedure for the employer's test for compliance with a standard is as follows:

(1) Compute the ratio X/STD, where X equals the measured concentration, and STD equals the applicable standard, such as the PEL;

(2) Compute UCL(95%) as follows:
$UCL(95\%) = X/STD + (1.645)(CV)$,

where 1.645 is the z-value for the 95% one-sided confidence limit ($\alpha = 0.05$) and the CV is the coefficient of variation of the sampling and analytical method (see Section 5.1.4.4).

(3) If $UCL(95\%) \leq 1$, then classify exposure as "compliance."
If $UCL(95\%) > 1$, then classify as "possible overexposure" (see Table 5-4 and Figure 5-6)

Table 5-5 lists the measured concentrations of respirable coal mine dust from single, 8-hr samples which correspond to compliance with the REL (based on the one-sided 95% upper confidence limit, $\alpha = 0.05$).

#### 5.1.5.5 Long-term mean exposures

In a review of exposure assessment strategies, Rappaport [1991] states that the strategy for compliance sampling often leads to biased estimates of exposure because such strategies are neither representative nor random, but target high exposure situations. Rappaport urges ". . . the hygienist should reject the notion that he/she has to choose between sampling for compliance and sampling to evaluate health effects and should seek, instead, a single strategy that satisfies both needs" [Rappaport 1991b]. To this end, Rappaport [1991b] recommends the mean-exposure strategy, which is based on the determination of the mean exposure, which is the parameter of the exposure distribution that best determines the risk of adverse health effects from long-term exposure.

This approach was suggested many years ago for determining the long-term effects of coal mine dust exposure [Long 1953; Roach 1953; Wright 1953; Oldham and Roach 1952]. More recently, Rappaport [1985] described a method for determining whether or not the mean of the lognormal distribution of exposures is acceptable in terms of the PEL. The method uses the statistical procedure of hypothesis testing to determine whether or not the mean exposure is in compliance with the PEL at a given alpha level of significance. Rappaport [1991b] states that the mean-exposure approach is "conducive to rigorous analysis; monitoring is encouraged; there should be a clear correlation between the mean exposure and the chronic hazard for most (if not all) toxicants; and the statistical structure provides sufficient power for routine use."

The advantages of the mean-exposure sampling strategy are: (1) it is a sampling strategy that is compatible with both compliance and epidemiologic research purposes, and (2) as a compliance strategy, it relates compliance to health risk. However, this approach has not been tested to determine the feasibility of implementation in the coal mine environment.

Further, if the PEL were defined as a long-term mean concentration, then several factors would need to be considered: (1) a sufficient number of samples would need to be randomly collected; (2) the environmental variability over time (geometric standard deviation of the mean of the lognormal distribution) would need to be used in the computation of the lower 95% confidence interval (one-sided); and (3) a statistical procedure for comparison of the geometric mean to the PEL (which is based on the arithmetic mean) would need to be followed. Although determination of a long-term mean concentration is more consistent with the approach used to derive the REL (i.e., long-term mean exposure), a long-term mean approach may not be effective for controlling exposures in the highly variable mining environment if an upper limit on exposures were not included. Because some risk of both pneumoconiosis and obstructive airways diseases remains at the REL for respirable coal mine dust (and all values above zero exposure), setting the REL as an upper limit of exposure will ensure that the long-term mean exposure will be below the REL. Thus, the recommended sampling strategy will help minimize the risk of occupation-related diseases in coal miners.

### 5.1.6 Analytical Methods

Respirable coal mine dust is a heterogeneous mixture of compounds (see Chapter 3); therefore, the concentration of respirable coal mine dust in the mine atmosphere should be determined gravimetrically, which is the approach currently used by MSHA [Tomb 1990]. Sampling and analysis for respirable crystalline silica should be performed in accordance with NIOSH Method 7500 or 7602 [NIOSH 1984]. The sampling device used for both Methods 7500 and 7602 is the 10-mm cyclone (with a 0.8-µm or 5-µm PVC or MCE membrane) operated at a flow rate of 1.7 Lpm. 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. Correction procedures are provided in Method 7602 for use if either kaolinite or calcite is present. When respirable coal mine dust is to be analyzed in the same sample, MCE membrane filters should not be used because of their high weight variability. A preweight PVC filter should be used and a final weight taken prior to ashing when Method 7602 is used for the analysis of 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 are suspended in tetrahydrofuran [NIOSH 1984].

The current analytical method used by MSHA, known as MSHA P-7 [MSHA 1989], differs from the NIOSH Method 7602 in the sample preparation procedures. The uneven deposition of ash has been observed in the filtration step of the MSHA P-7 method, which can adversely affect the quantitation of the quartz [Lorberau 1990]. The NIOSH Method 7603 [NIOSH 1984] is similar to the MSHA P-7 method both in utilization of the same filtration technique and in specification of a 2.0 Lpm flow rate for sample collection. NIOSH Method 7603 and MSHA P-7 are designed specifically for the analysis of respirable crystalline silica contained 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 (IR) method because the uneven deposition of ash is avoided and because the more appropriate sample-collection flow rate of 1.7 Lpm (see Section 5.1.3.2) is used. In lieu of either NIOSH Method 7603 or the MSHA P-7 method, NIOSH Method 7602 is recommended for the analysis of respirable crystalline silica.

NIOSH recommends personal samples as the preferable sampling method; however, an area sampling method may be appropriate if the position of the certified coal mine dust personal sampler unit (CMDPSU) interferes with the miner's safety or mobility and if the area sample represents the maximum concentration of coal mine dust to which the miner may be exposed. MSHA evaluated the feasibility of area sampling in underground coal mining and concluded that area samples, which were generally lower than the personal samples, are acceptable when samplers are located near the worker with the highest dust exposure [Tomb and Ondrey 1976]. Personal sampling does not require separate measurements for each miner exposed as long as adequate sampling is done to allow each miner's exposure to be determined by similarity of function <u>and</u> proximity to a sampled miner [Corn and Esmen 1979].

### 5.1.7 Correction Factor for Current and Recommended Sampling Criteria

The ISO/CEN/ACGIH definition is shown in Figure 5-7 in terms of sampling efficiency at a given aerodynamic diameter. A quantitative description of the curve is given in CEN [1992]. The figure also depicts recently measured sampling efficiencies [Bartley et al. 1993] for the 10-mm nylon cyclone at 2.0 L/min and at 1.7 L/min and for the metallic BGI cyclone at 2.3 L/min. The latter flow rates were chosen [Liden and Kenny 1993; Bartley et al. 1993] to best match the international definition as to the diameter at which the sampling efficiency equals 50%. This "cut-diameter" has been shown [Bowman et al. 1984] to dominate other cyclone parameters (such as the

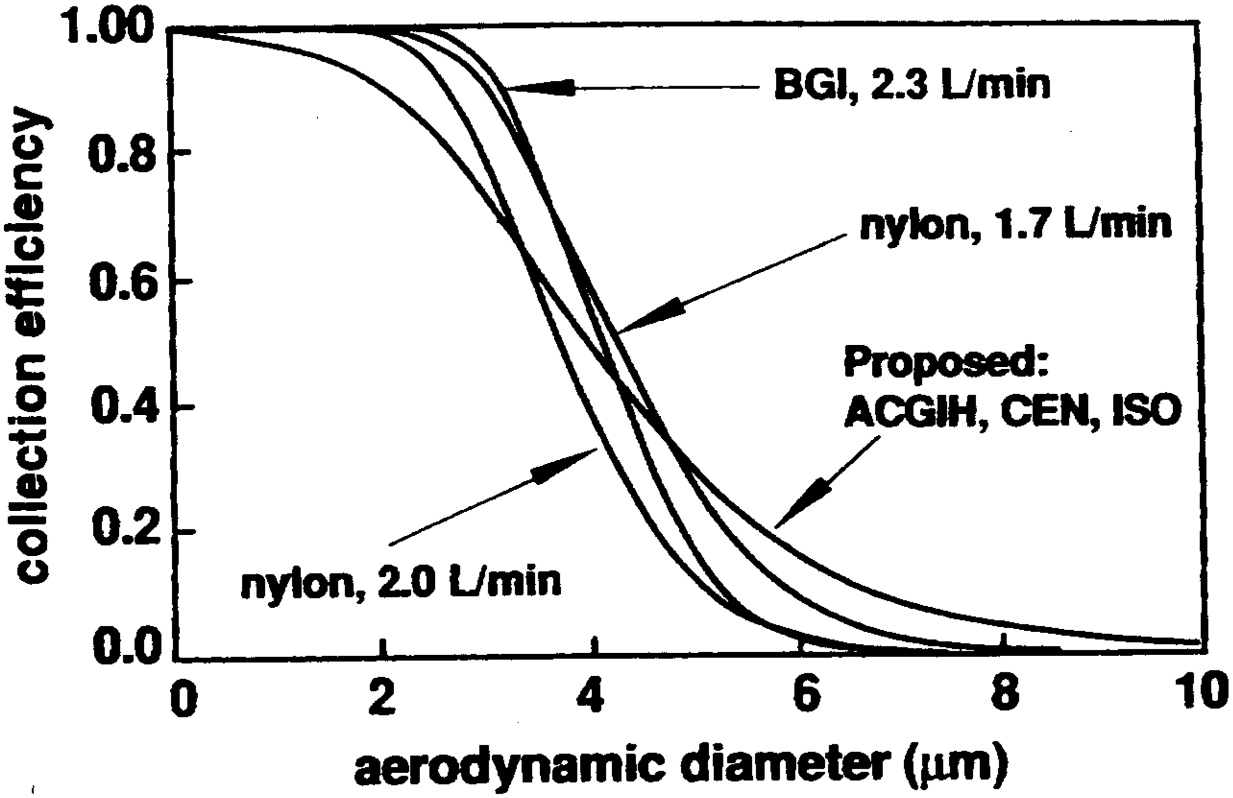


Figure 5-7. Respirable aerosol collection efficiencies. (Source: Bartley et al. [1993].)

sampling efficiency sharpness) in characterizing the sampling of dusts distributed over diameters. The curves are consistent with earlier data presented in Caplan et al. 1973; Blachman and Lippmann 1974; Chan and Lippmann 1977; and Bartley and Breuer 1984.

To calculate a "correction factor" between the current sampling method, sampling efficiency curves are combined numerically with those aerosol size distributions (mass per unit particle diameter interval) that are expected in coal mines. Verification of the equivalence between computed respirable mass concentrations and measured concentrations in assessing distributed aerosol sizes has been documented in Liden and Kenny 1992. Data exist in the literature describing the needed size distributions as measured in coal mines [Hinds and Bellin 1988; Bowman et al. 1984]; however, only a summary of data for each size distribution is presented.

Mutmansky and Lee [1987] provide detailed data taken at various locations within 11 underground coal mine sections that used continuous miners; these data are consistent with other data found in the literature. Cascade impactor (Sierra Model 298) measurements were presented characterizing the airborne dust found. Data given in Appendix 5 of Mutmansky and Lee [1987] are suitable for the accurate estimation of the respirable fractions that would be obtained using any of the respirable dust definitions or various sampling systems. Hence, correction factors can be obtained. The data are presented as cumulative fractions of the dust mass sampled 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 0.5-µm fraction's contribution 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).

For computing correction 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.

The parameters of the lognormal distribution needed to compute the correction factors are the mass median diameter (MMD) and geometric standard deviation (GSD). An inverse-lognormal transformation of the data followed by simple linear regression is performed, which provides two parameters (i.e., section or location). It should be noted 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 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 correction factor and are therefore insignificant.

In Figures 5-8 and 5-9, the MMD and GSD represent a particular coal mine section or location are shown as solid dots. Figures 5-8 and 5-9 also depict the correction factors for converting, at any given value (MMD, GSD), from current MSHA sampling criteria (including the 1.38 factor) to the ISO/CEN/ACGIH sampling criteria. The CMDPSU and the HD sampler are among those that have been shown to perform within the criteria required for the ISO/CEN/ACGIH definition [Bartley et al. 1993]. Figure 5-8 provides the correction factor for the 10-mm nylon cyclone operated at 1.7 L/min. Figure 5-9 provides the correction factor for the BGI sampler operated at 2.3 L/min. Figures 5-8 and 5-9 indicate that the appropriate correction factor corresponding to any given values of MMD and GSD. However, because the size distribution to be sampled is not fixed, the MMD and GSD cannot be specified and an average correction factor must be calculated over a range of values of MMD and GSD expected in U.S. coal mines.

Based on MMD and GSD values in Mutmansky and Lee [1987], the following average correction factors can be applied to concentrations measured by the current MSHA method to obtain the equivalent concentration according to the ISO/CEN/ACGIH definition of respirable dust:

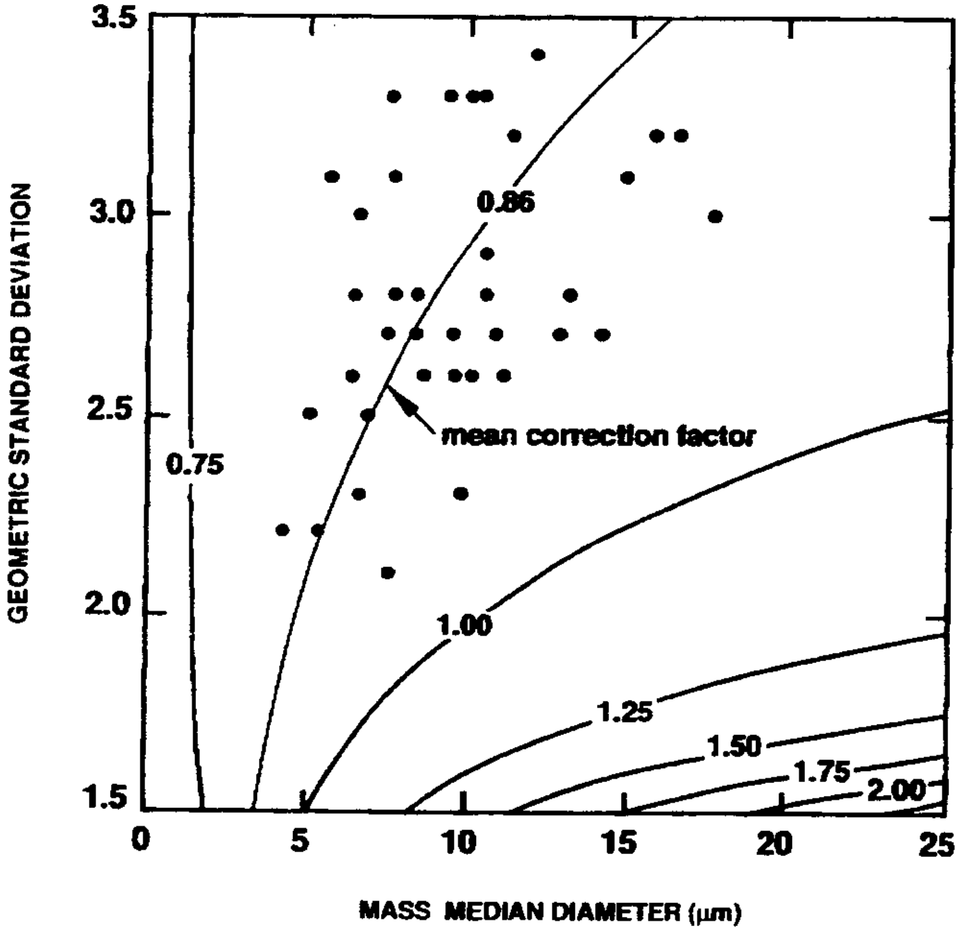


Figure 5-8. Correction factor: MSHA standard to nylon cyclone at 1.7 L/min. (Source: Bartley et al. [1993].)

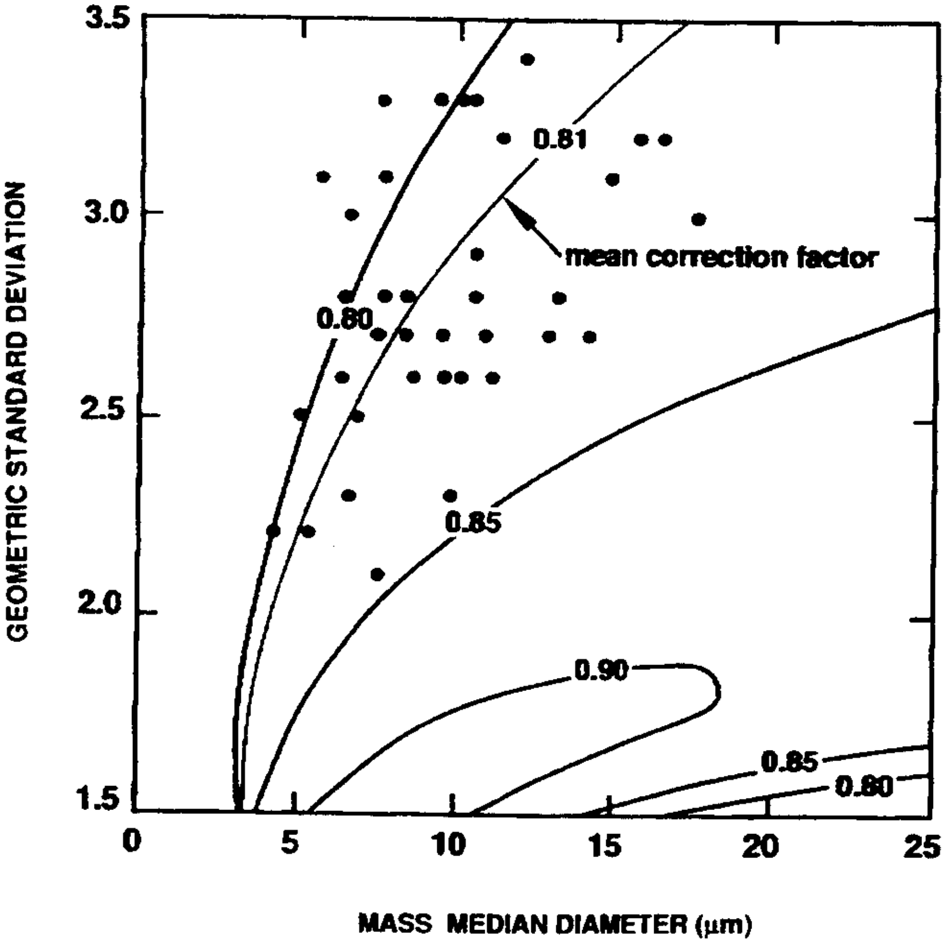


Figure 5-9. Correction factor: MSHA standard to HD cyclone at 2.2 L/min. Excluded are points from a diesel-operated mine where the size distribution is clearly bimodal over the respirable region. Also, 6 points with GSD >3.5 µm are not plotted (yet fall within the iso-factor curves of the points shown). (Source: Bartley et al. [1993].)

CMDPSU operated at 1.7 L/min: 0.857
(standard deviation = 0.029)

HD operated at 2.3 L/min: 0.811
(standard deviation = 0.015)

The above standard deviation values indicate the size-distribution-induced variability expected in side-by-side sampling.

Thus, if the concentration measured with the CMDPSU according to current MSHA sampling criteria were 1.00 mg/m$^3$, then the corresponding concentration would be 0.86 mg/m$^3$ with the CMDPSU operated according to the recommended criteria or 0.81 mg/m$^3$ with the BGI cyclone operated according to the recommended criteria. A separate preliminary analysis of particle size distributions collected over a 10-yr period by different investigators using similar methodology yielded a similar correction factor of 0.85 for the CMDPSU operated at current vs. recommended sampling criteria [Hewett et al 1993]. These correction factors are considered in the derivation of the REL (see Chapter 7).

## 5.2 MEDICAL SURVEILLANCE

### 5.2.1 Objectives of Medical Surveillance and Screening

Primary prevention of work-related disease through environmental control of exposures should be the primary emphasis of an environmental and medical monitoring program; however, environmental monitoring is not sufficient to prevent workers from developing occupational diseases. A secondary prevention program of medical surveillance is important for identifying miners who, for reasons of individual susceptibility or increased exposure to respirable coal mine dust or respirable crystalline silica, show early signs of adverse health effects that have been associated with coal mine dust exposure. The World Health Organization (WHO) has stated that ". . . medical intervention in the form of preplacement and periodic health examinations is essential in the early detection and management of occupational diseases" [WHO 1986]. Further, the early detection of health impairment is defined as "the detection of disturbances of homeostatic and compensatory mechanisms while biochemical, morphological, and functional changes are still reversible" [WHO 1973]. Thus, a medical surveillance program should be designed for the detection of early indicators of progression along the etiologic continuum from occupational exposure to work-related disease [Figure 5-10].

Medical surveillance can be defined as "the systematic collection, analysis, and dissemination of disease data on groups of workers or populations

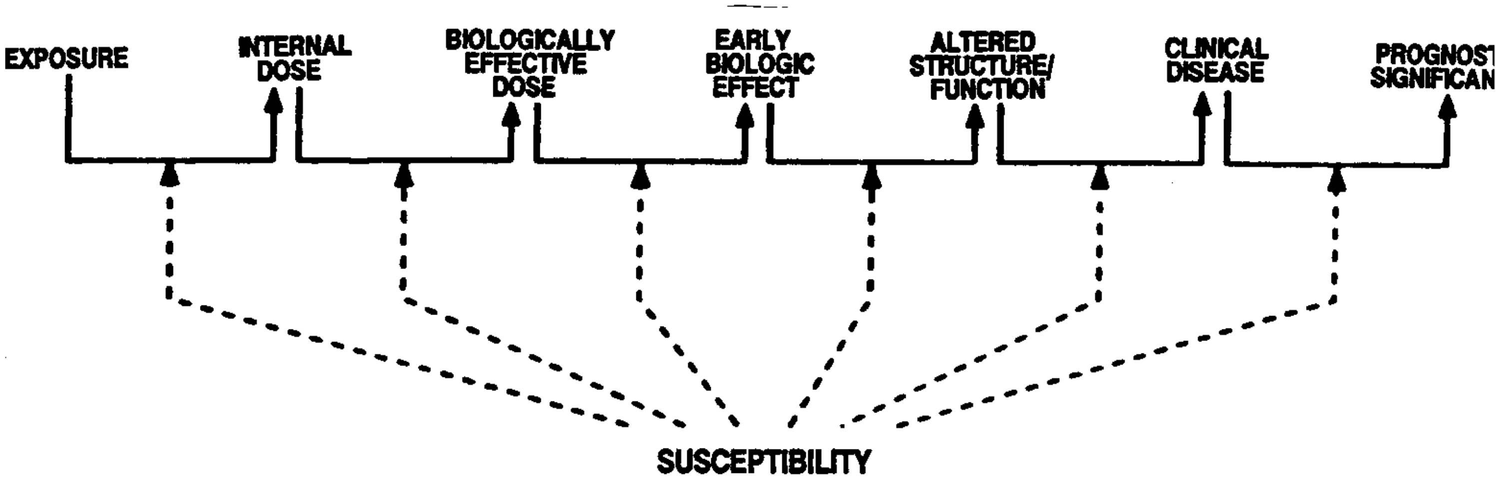


Figure 5-10. Biologic marker components in sequential progression between exposure and disease. (Source: Schulte [1991].)

[Block 1988]. Medical surveillance is useful for evaluating the effectiveness of disease prevention activities, including primary prevention through control of exposures.

Medical screening may be defined as "the application of an examination, historical question, or laboratory test to apparently healthy persons with the goal of detecting absorption of intoxicants or early pathology before the worker would normally seek clinical care for symptomatic disease [Halperin et al. 1986]. Criteria for effective screening programs for occupational diseases include the following: (1) screening must be selective; (2) identification of the disease in its latent stage (before symptoms appear) must lead to treatment that impedes the progression of the disease; (3) adequate follow-up is critical and further diagnostic tests and effective management of the disease must be available, accessible, and acceptable; (4) the screening test must have good reliability and validity (as evaluated by the sensitivity and specificity); and (5) the benefits of the screening program should outweigh the costs [Levy and Halperin 1988]. Sensitivity is defined as "the proportion of truly diseased persons in the screened population who are identified as diseased by the screening test" [Last 1988]. Specificity is defined as "the proportion of truly nondiseased persons who are so identified by the screening test [Last 1988].

Medical screening tests are used to detect organ dysfunction or disease in an individual before he or she would normally seek medical care (i.e., preclinical stage) and while intervention is still beneficial. Medical screening tests may indicate either the presence of a disease or a higher probability of the presence of disease, which indicates the need for further evaluation and diagnostic tests.

### 5.2.2 Recommended Medical Surveillance Program for Coal Miners

The procedures for chest radiographic examinations are specified in 42 CFR 37. The operators of underground coal mines are required to provide chest radiographs for all miners included in the CWXSP. The miners included in this program are required to receive a chest radiograph when they begin work at an underground coal mine and again 3 years after the initial examination. If a miner is still engaged in underground coal mining and if the second radiograph shows evidence of category 1 or higher pneumoconiosis according to the ILO classification [ILO 1980], then a third chest radiograph is required 2 years following the second one. In addition to mandatory chest radiographs, mine operators are required to offer voluntary chest radiographs every 5 years to underground coal miners. These mandatory and voluntary chest radiographs, together with the transfer option, constitute the CWXSP. All chest radiographs that are taken as part of the CWXSP are submitted to and become the property of NIOSH. These chest radiographs are interpreted by qualified readers, and radiographic findings are reported to MSHA by NIOSH and to the miners by MSHA.

Modifications to the existing medical surveillance program have been provided in the Federal Coal Mine Health and Safety Act of 1969 and the Amendments Act of 1977 as follows: (1) the stipulation that chest roentgenograms ". . . shall be supplemented by such other tests as the Secretary of Health and Human Services deems necessary" [30 USC 843(a) (1986)]; and (2) the redefinition of pneumoconiosis in the 1977 Amendments Act as ". . . a chronic dust disease of the lung and its sequelae, including respiratory and pulmonary impairments, arising out of coal mine employment."

#### 5.2.2.1 *Overview of Recommended Medical Surveillance Procedures*

This section summarizes the basic components of the recommended medical surveillance program for coal miners.

##### 5.2.2.1.1 **Examinations, tests, and questionnaires**

The following examinations, tests, and questionnaires should be given to individual miners:

- Preplacement and periodic chest roentgenographic examination conducted according to 42 CFR 37 [1989], including a quality control program

- Preplacement and periodic spirometry tests, consisting of forced expiratory volume in one second ($FEV_1$) and forced vital capacity (FVC), conducted according to guidelines of NIOSH [Fed. Reg. 1980] and the American Thoracic Society (ATS) [ATS 1987] and including a quality control program

- A standardized respiratory questionnaire of respiratory symptoms and smoking history [Ferris 1978 (ATS)] (See Appendix A)

- An occupational history questionnaire of jobs up to and including present employment, including notation of duties and potential exposures [ALA 1983; Goldman et al. 1981] (See Appendix F)

Further medical examinations and tests are recommended for individual miners with respiratory symptoms, lung function below the lower limit of normal reference values (see Appendix E), or annual decline in lung function of $\geq$15%. Counseling about smoking cessation or job transfer may also be recommended by the physician.

#### 5.2.2.1.2 Recommended components of a medical surveillance program

The recommended components of a medical surveillance program for coal miners are as follows:

- A plan for the approval of medical facilities where examinations and tests are to be conducted and for the training and certification of physicians and technicians working in such facilities (provisions for "giving, interpreting, classifying, and submitting chest roentgenograms" have been previously described [42 CFR 37 (1988)])

- An education program to explain to coal miners the reasons for establishing the medical monitoring program and the value of participation

- A program designed to evaluate the effectiveness of the new medical monitoring and intervention strategies (as sufficient data become available) including establishing registries to improve follow-up of miners and ex-miners

- A system to integrate medical monitoring and environmental surveillance programs so that "hot spots" of occupation-related disease can be investigated in conjunction with environmental monitoring of exposure conditions

#### *5.2.2.2 Actions Based on Results of Medical Surveillance Procedures*

The following procedures are recommended upon completion of the medical screening tests among coal miners:

(1) Test confirmation, including repeating spirometry tests and evaluation of the results relative to quality control parameters for the group (e.g., survey bias, instrument error, test interpretation, etc.)

(2) Notification of the worker, including whether or not test results are within the normal range, with a contact person for further information

(3) Diagnostic evaluation, with further medical tests as needed

(4) Evaluation and control of exposures following identification of regions, mines, or job categories associated with high disease incidence, including notification of MSHA and mine operators to perform assessments of exposures to respirable coal mine dust and respirable crystalline silica and evaluations of dust control

measures

(5) Removal of the worker from exposure, either temporarily while further tests are performed, or permanently, with the medical basis of such a recommendation provided to the worker (retention of wages and benefits should be guaranteed)

(6) Counseling for cessation of cigarette smoking, if the need is indicated by smoking history and results of medical tests.

### 5.2.3 Evaluation of the Work-Relatedness of Obstructive Airways Diseases Among Coal Miners

A decision-making strategy to determine whether or not a disease resulted from (or was aggravated by) the conditions of employment was suggested by Kusnetz and Hutchinson [1979]. The important issues in such a decision-making strategy include the following: (1) evidence of disease; (2) epidemiologic evidence that the disease resulted from the occupational exposure; (3) evidence of exposure including degree or duration sufficient to result in the disease; (4) other relevant factors such as possible nonoccupational exposure as a causative factor or special circumstances of the individual or the work environment; and (5) overall evidence that the disease resulted from, or was aggravated by, conditions at work.

The following is a review of these issues, as they relate to the exposure-related obstructive airways diseases in coal miners. Several independent epidemiologic studies have demonstrated an exposure-response relationship between exposure to respirable coal mine dust and decrements in lung function, both among smokers and lifelong nonsmokers, and whether or not pneumoconiosis is present [Attfield and Hodous 1992; Seixas et al. 1992; Soutar et al. 1988; Soutar and Hurley 1986]. The assumption of a Gaussian or normal distribution of responses to exposure allows for a proportion of miners who will have either a less severe or a more severe response than the mean response of the group. Further, there is a "background" level of occurrence of COPD among persons without occupational exposure to respirable coal mine dust or other causative agents; for example, cigarette smokers are also at increased risk of developing COPD.

Although epidemiologic studies have established that coal miners as a group are at risk of exposure-related decrements in lung function (which may for some individuals be sufficient for clinically significant impairment [Hurley and Soutar 1986; Marine et al. 1988]), the relative contribution of coal mine dust exposure to a measured decrement of lung function in an individual cannot be determined. Yet, medical surveillance and intervention strategies must provide a basis for decisions about the work-relatedness of COPD *in individuals* in order to assure that the occurrence of COPD will be prevented to a level that is no greater in coal miners than is found in similar, but unexposed, populations.

Additional criteria for determining the causality of disease due to occupational or environmental exposure in an epidemiologic setting have been described by the following: consistency, strength, coherence, biologic plausibility of the findings, and the determination of a dose-response relationship [Hill 1965]. Regarding these causality criteria and the occurrence of chronic airflow limitation in coal miners (due to COPD), Becklake [1985] concludes that these criteria ". . . have all been fulfilled for coal mining. . . " and that ". . . the evidence suggests beyond reasonable doubt a causal relationship to chronic airflow limitation. . . ." For the individual, it is ". . . unlikely that medical evidence could ever provide conclusive 'proof' of the work relatedness of chronic airflow limitation in a particular case, using 'proof' in the scientific sense"; however, ". . . a reasonable statement of probability . . . " can be provided.

### 5.2.4 Chest Radiographs

#### *5.2.4.1 Definition of Pneumoconiosis*

The Federal Mine Safety and Health Amendments Act of 1977 defines the term "pneumoconiosis" to mean ". . . a chronic dust disease of the lung and its sequelae, including respiratory and pulmonary impairments, arising out of coal mine employment" [30 USC 902(b) (1986)]. This definition differs from the previous definition in the Federal Coal Mine Health and Safety Act of 1969 (i.e., ". . . a chronic dust disease of the lung arising out of employment in a coal mine") by the specific mention of "sequelae" and "respiratory and pulmonary impairments."

Prevention of pneumoconiosis was the reason that periodic chest X-rays were specified in the medical examinations that were mandated [30 USC 843 (1986)]. The CWXSP, currently administered by NIOSH, Division for Respiratory Disease Studies, was started in 1969, to carry out the medical examinations specified in the Act. See Chapter 4 for further information on the CWXSP.

#### *5.2.4.2 Periodic Chest X-Ray*

The provisions for periodic chest X-rays were described in the Federal Coal Mine Health and Safety Act of 1969 and reaffirmed in the 1977 Amendments Act: "Each worker who begins work in a coal mine for the first time shall be given, as soon as possible after commencement of his employment, and again three years later if he is still engaged in coal mining, a chest roentgenogram" [30 USC 842(a) (1986)]. Further, all chest roentgenograms are to be given ". . . in accordance with specifications prescribed by the Secretary of Health and Human Services and shall be supplemented by such other tests as the Secretary of Health and Human Services deems necessary" [30 USC 842(a) (1986)]. The medical examinations and tests are to be offered at no charge to the miner; the operator of the mine is to pay for the costs of the tests and examinations and ". . . whatever other costs are necessary to enable the miner to take such examinations or tests" [30 USC 843(c) (1986)].

An important objective of providing chest radiographs as part of a longitudinal medical monitoring program is the identification of miners with the rapid progression of CWP (i.e., an increase of two or more CWP categories). The rapid progression of CWP has been reported among miners exposed to respirable coal mine dust with relatively high (11% to 20%) respirable quartz content [Robertson et al. 1987; Hurley et al. 1982; Jacobsen and Maclaren 1982; Seaton et al. 1981].

In order to determine if radiographic changes have occurred, it is necessary for miners to receive periodic medical surveillance. Although the preemployment medical examination is required for all new miners, the subsequent periodic medical examinations are voluntary. Participation rates in the first four rounds of the CWXSP have been low and declining (i.e., 50%, 44%, 32%, and 30%). Thus, extra effort is needed to increase participation in periodic medical examinations of all miners, especially those in jobs that have been associated with increased risk of developing silicosis or mixed dust pneumoconiosis (e.g., drill crew members in surface mines, roof bolters in underground mines) [Amandus et al. 1989; Attfield 1991a,b]. Given the consistently poor participation in the CWXSP, it would be prudent to determine the reasons for the poor participation [Main 1985], to improve the program, and perhaps to make the periodic medical examinations mandatory, as are pre-employment examinations. Recently, the CWXSP has been modified to provide improved communication with miners on the importance of participation in the program, and the initial response has been favorable.

### 5.2.5 Pulmonary Function Tests

#### *5.2.5.1 Spirometry Tests in a Medical Monitoring Program for Coal Miners*

Inclusion of lung function testing in a medical monitoring program for coal miners is justified on the basis of findings from numerous epidemiologic studies of coal miners from several countries, which have demonstrated an exposure-response relationship for respirable coal mine dust that is independent of the occurrence of simple CWP. The following important findings have been reported by several investigators [Attfield and Hodous 1992; Attfield and Hodous 1990; Marine et al. 1988; Soutar et al. 1988; Soutar and Hurley 1986; Attfield 1985; Love and Miller 1982; Rogan et al. 1973; Rae et al. 1971]: (1) similar exposure-related losses in lung function are observed in both nonsmokers and current smokers; (2) smokers are likely to suffer an additional smoking-related loss of lung function; (3) the average 40-year loss of $FEV_1$ with exposure to 2 $mg/m^3$ of respirable coal mine dust is about 100 ml; however, (4) this average loss in lung function may mask a more severe decline in a sensitive subgroup of miners, just as a subgroup of smokers in the general population with emphysema or bronchitis experiences a greater decline.

A study of British coal miners found that ex-miners with chronic bronchitis had experienced severe effects of dust exposure, as defined by an average exposure-related decrement in lung function of 600 ml [Soutar and Hurley 1986]. In another British study, Soutar et al. [1989] estimated a 10% risk of a similar decrement (592 ml loss) in $FEV_1$ following a cumulative exposure to respirable coal mine dust comparable to 40 years at 2 $mg/m^3$. Although studies of U.S. coal miners have not identified a sensitive subgroup [Attfield and Hodous 1990b; Silver, Hattis, and Attfield 1991], studies thus far have not included examiners. Becklake [1985] stated that "small group differences" in lung function may be attributed either to "small numbers of individuals with considerable disability or to "the more disabled" miners being excluded either from cross-sectional studies of working miners only or from longitudinal studies with followup of working miners only.

Seixas et al. [1991] studied the exposure-related decrements in lung function among new miners (i.e., starting after 1970). The loss of $FEV_1$ per exposure unit was about fivefold higher than the previous studies, which had not been restricted to new miners [Attfield and Hodous 1992; Rogan et al. 1971]. Hodous and Hankinson [1990] also observed the rapid decline in the lung function of new coal miners. These studies suggest the possibility that the lungs may adjust to the dust exposure over time, resulting in lower subsequent decline, or that miners who suffer more severe decline are self-selecting out of coal mining.

### 5.2.5.2 Development of COPD

Burrows and Earle [1969] report that the development of COPD occurs over 20 to 40 years and that the disease outcome can be predicted from two measures of $FEV_1$: $FEV_1$ following inhalation of a bronchodilator, and the rate of decline of $FEV_1$. Most people who will develop disabling COPD become symptomatic during their forties and early fifties, with disability occurring in their late fifties and early sixties [Petty 1988]. Similarly, Lapp and Seaton [1971] reported that in miners and ex-miners, COPD occurred primarily after the age of 50.

Studies from the United States and abroad provide the epidemiologic evidence that exposure to respirable coal mine dust is associated with decrements in lung function, which occurs even without radiographic evidence of CWP. Thus, inclusion of pulmonary function tests in the medical surveillance program for coal miners would provide a means for detecting nonpneumoconiotic occupational respiratory diseases associated with exposure to coal mine dust.

### 5.2.5.3 Pulmonary Function Tests for Medical Screening

Pulmonary function tests (PFTs) are useful for the early detection of pulmonary diseases (including emphysema and pulmonary fibrosis) for the periodic examination of pulmonary function in workers in occupations with known pulmonary hazards, and for the epidemiologic study of populations to gain knowledge about the etiology of pulmonary disease [Gold and Boushey 1988]. PFTs "permit . . . a precise and reproducible assessment of the functional state of the respiratory system and allow quantification of the severity of disease, thereby enabling assessment of natural history and of the response to therapy" [Gold and Boushey 1988].

The utility of PFTs for screening workers is that PFTs ". . . offer the best hope for the early detection of chronic obstructive lung disease in cigarette smokers, and for objective documentation of the severity of occupational lung disease" [Gold and Boushey 1988]. However, Gold and Boushey [1988] also warn that the limitations of PFTs must be realized (i.e., PFTs are tests of function, whereas most respiratory diseases are defined in other terms, including structure [emphysema] or symptoms [chronic bronchitis]). Results of PFTs provide inferential evidence, not proof, of disease [Gold and Boushey 1988]. Thus, PFTs are useful for screening workers to identify those who may need further medical evaluation [Hankinson 1986].

"Spirometry is the single most important test in evaluating a miner's lung function" [Attfield and Wagner 1992]. The most widely accepted spirometry tests for screening workers are the $FEV_1$ and FVC [Hankinson 1986]. During the $FEV_1$ or FVC maneuver, expiratory flow from the lungs is caused by the force of lung elastic recoil and pleural pressure [Gold and Boushey 1988]. A spirogram illustrating derivation of $FEV_1$ and FVC is shown in Figure 5-11. The patterns associated with restrictive and obstructive ventilatory defects are listed in Table 5-6. The World Health Organization (WHO) recommends that lung function tests of $FEV_1$ and vital capacity (VC) be included as part of the preplacement health examination and as part of the periodic examinations held every 3 years [WHO 1986].

The ratio of $FEV_1/FVC$ has been recommended as a better estimate of obstructive lung disease than $FEV_1$ alone because both obstructive and restrictive impairment can cause a decrease in $FEV_1$ [Morgan and Lapp 1988]. However, $FEV_1$ has less variability in the normal range of values than does $FEV_1/FVC$ [Hankinson 1986, 1990]. In addition, an exposure-response relationship between coal mine dust exposure and reduced $FEV_1$ has been reported in several epidemiologic studies of coal miners [Seixas et al. 1992; Attfield and Hodous 1992; Soutar and Hurley 1986]. Abnormally low $FEV_1$ has been associated with reduced life expectancy in studies of both coal miners [Amandus 1983; Ortmeyer et al. 1973, 1974] and other populations [Foxman et al. 1986; Peto et al. 1983; Higgins et al. 1981; Fletcher and Peto 1977; Higgins and Keller 1970, 1973].

**Table 5-6.—Characteristics and causes of restrictive and ventilatory defects**

| Defect | Characteristics | Supplemental characteristics | Common causes |
|---|---|---|---|
| Restrictive ventilatory defect | Decreased VC<br>Relatively normal expiratory flow rate<br>Relatively normal MVV | Decreased TLC<br>Decreased lung compliance<br>Chronic alveolar hyperventilation<br>Increased (A-a)$PO_2$<br>Abnormal distribution of inspired gas<br>Decreased $DL_{co}$ | Interstitial lung disease<br>Intestitial pneumonitis<br>Fibrosis<br>Pneumoconiosis<br>Granulomatosis<br>Edema<br>Space-occupying lesions<br>Tumor<br>Cysts<br>Pleural diseases<br>Pneumothorax<br>Hemothorax<br>Pleural effusion, emphysema<br>Fibrothorax<br>Chest-wall diseases<br>Injury<br>Kyphoscoliosis<br>Spondylitis<br>Neuromuscular disease<br>Extrathoracic conditions<br>Obesity<br>Peritonitis<br>Ascites<br>Pregnancy |
| Obstructive ventilatory defect | Normal or decreased VC<br>Decreased maximum expiratory airflow<br>Decreased MVV | Increased RV<br>Increased airway resistance<br>Abnormal distribution of inspired gas<br>Significant response to bronchodilator<br>Decreased $DL_{co}$<br>Decreased lung elastic recoil | Upper airway<br>Pharyngeal and laryngeal tumors, edema, infections<br>Foreign bodies<br>Tumors, collapse, and stenosis of trachea<br>Central and peripheral airway<br>Bronchitis<br>Bronchiectasis<br>Bronchiolitis<br>Bronchial asthma<br>Parenchymal disease<br>Emphysema |

Source: Gold and Boushey [1988].

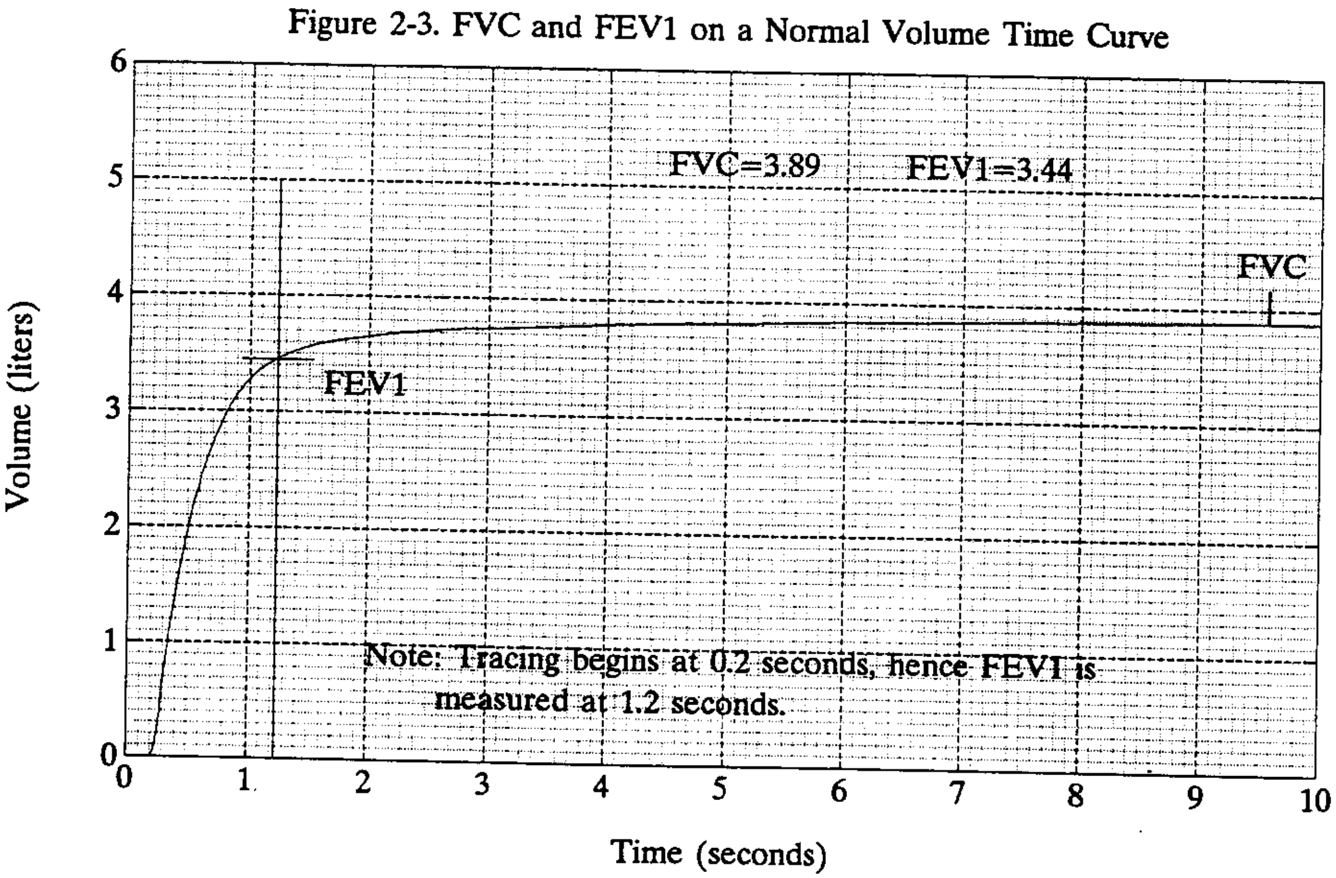


Figure 5-11. FVC and $FEV_1$ on a normal volume time curve.

Figure 5-12 shows the relationship between decline in $FEV_1$ and disability or death by age and smoking status.

#### 5.2.5.3.1 Lung function and silicosis

An indication of the potential usefulness of PFTs in the early warning of adverse health effects from silica exposure was found in a study of granite shed workers [Theriault 1974]. The exposure-related effects on ventilatory capacity occurred 13.5 years before the appearance of radiographic opacities. This finding may pertain to roof bolters in underground mines and to surface coal mine drillers, jobs that are associated with exposure to respirable crystalline silica at concentrations that exceed both the MSHA PEL and the NIOSH REL [Tomb et al. 1986]. However, unlike studies of coal miners, FVC was correlated with radiographic category in granite workers [Theriault 1974].

#### 5.2.5.3.2 Transfer option

Miners who are identified with lung function below the lower limit of normal reference values (See Appendix E) and who have received further confirmatory medical examination and testing, may be advised by their physicians to transfer to a job in an area of the mine with lower dust concentrations or to leave mining entirely. Miners who elect to transfer to jobs within the mine on the basis of dust-related functional impairment of the lungs should be entitled to the same provisions as miners who elect to transfer on the basis of radiographic evidence of simple CWP. Because the respiratory symptom of dyspnea (breathlessness) tends to correlate with respiratory impairment [Attfield and Wagner 1992], including decrements in $FEV_1$ and FVC [Lapp and Seaton 1991], miners with decrements in lung function may be more likely to perceive the need to participate in a job transfer program to areas with lower dust concentrations. Miners with radiographic changes are not as likely to have respiratory symptoms and thus, may not perceive the importance of transferring to a low dust area.

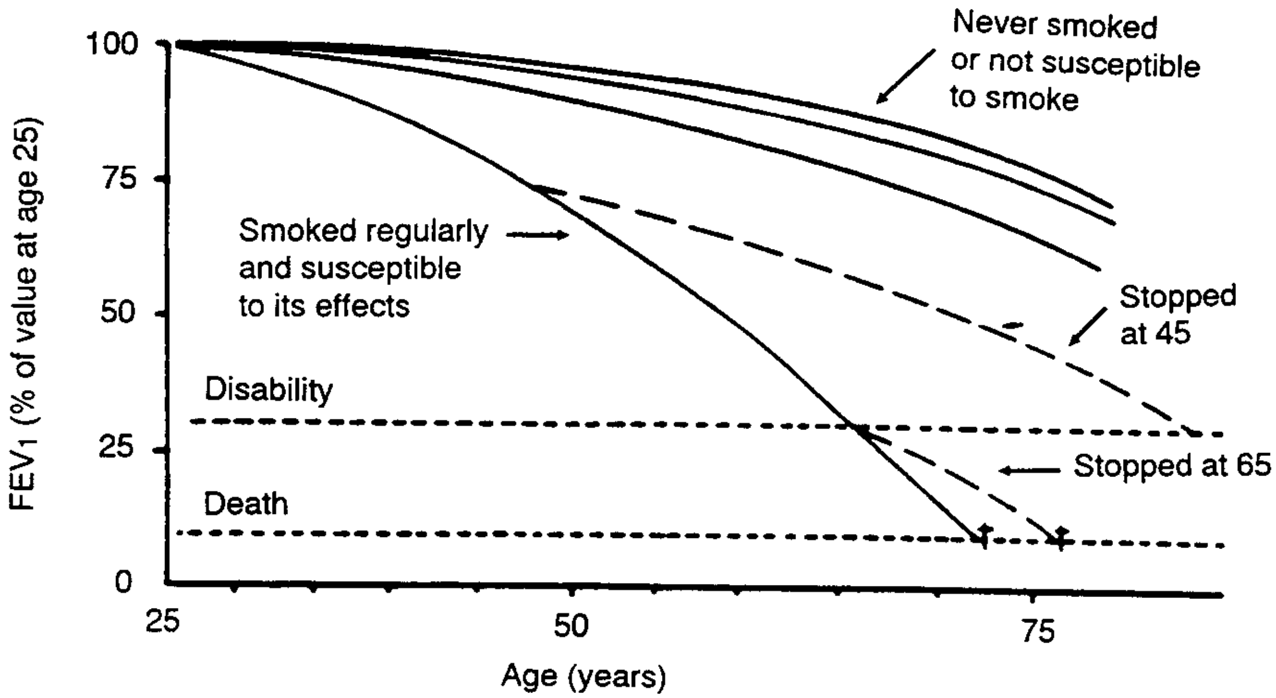


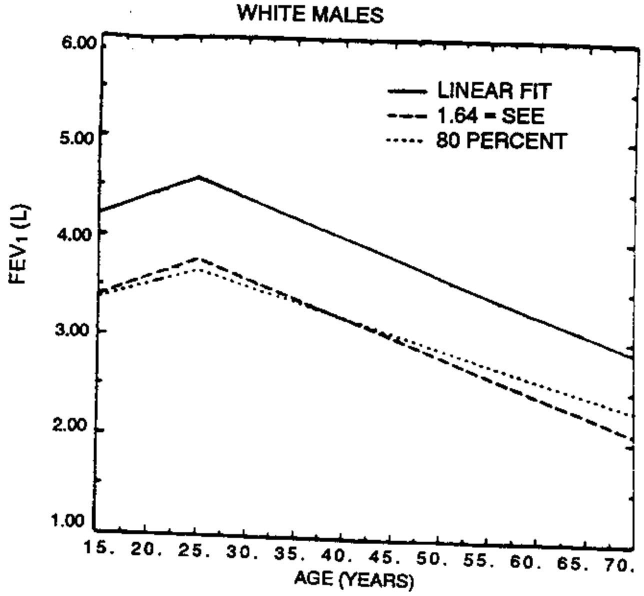
Figure 5-12. Risks for various men if they smoke: differences between these lines illustrate effects that smoking and smoking cessation can have on $FEV_1$ of a man who is liable to develop chronic obstructive lung disease if he smokes. † = death, the underlying cause of which is irreversible chronic obstructive lung diseases, whether the immediate cause of death is respiratory failure, pneumonia, cor pulmonale, or aggravation of other heart disease by respiratory insufficiency. Although this shows rate of loss of $FEV_1$ for one particular susceptible smoker, other susceptible smokers will have different rates of loss, thus reaching 'disability' at different ages. (Source: Peto et al. [1976] (in Buist and Vollmer [1988]).)

#### *5.2.5.4 Cross-Sectional Reference Values for Spirometry Tests*

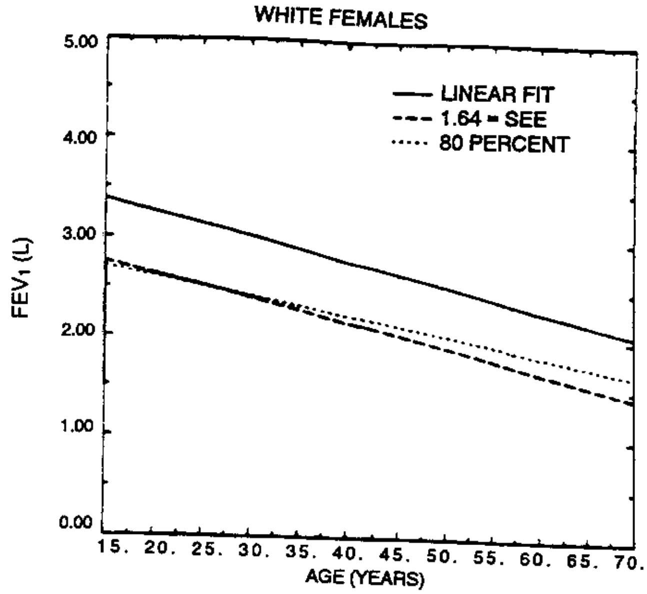
Numerous studies of predicted normal values for spirometry tests have been published [Ferris 1965; Kory et al. 1961, 1963; Cotes 1966; Dickman et al. 1969; Morris et al. 1971, 1973, 1982; Cherniak and Raber 1972; Higgins and Keller 1973; Peterson et al. 1975; Knudson et al. 1966, 1976, 1983; ATS 1979, 1982; Crapo et al. 1981; Miller and Scacci 1981; Peterson and Hankinson 1985; Peterson and Hodous 1988]. The studies of Morris et al. [1971, 1973, 1982] and Knudson et al. [1976, 1983] were ". . . based on rigid criteria for normals and produced equations which give the most satisfactory predicted values for FVC, $FEV_1$, and $FEF_{25-75\%}$" [Miller and Scacci 1981].

The equations of predicted normal values by Morris et al. [1971], Knudson et al. [1976, 1983], and Crapo et al. [1981] were evaluated by NIOSH [Hankinson 1990] for their usefulness in predicting normal values for the population of U.S. coal miners. The population in the study consisted of nonsmoking male miners who were new to mining in Round 3 (1977-1981) or Round 4 (1982-1987) of the National Study of Coal Workers' Pneumoconiosis (NSCWP). The values for $FEV_1$, FVC, and $FEV_1$/FVC of the miners in the study were used to derive the lower value of the 95% confidence interval, or lower limit of normal (LLN), to provide a comparison with the LLN derived from the predicted normal values being evaluated [Morris et al. 1971; Knudson et al. 1976, 1983; Crapo et al. 1981].

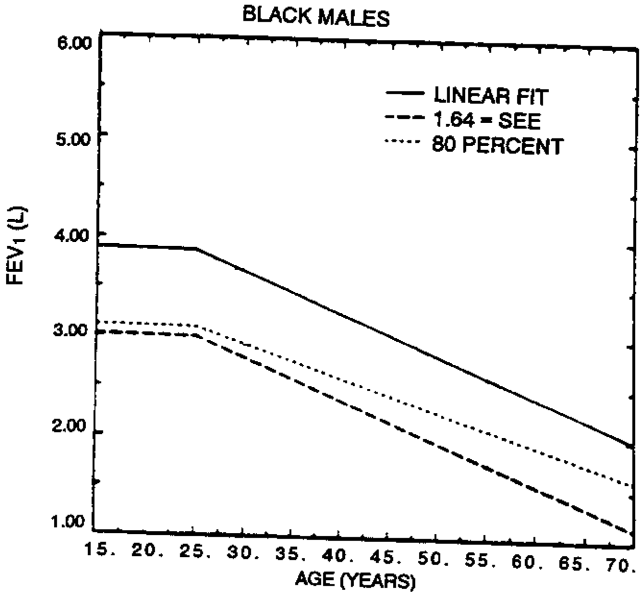
The equations of Knudson [1983] were selected as the best predictors of normal lung function determined cross-sectionally in the coal miner population. Figure 5-13 compares predicted normal values of $FEV_1$ derived from the percent predicted method [Miller and Scacci 1981] and the lower 95% confidence limit method [Hankinson 1986; Knudson 1983]. Hankinson [1986] determined that the $FEV_1$ or FVC predictions were similar whether derived from either the three best spirometry curves, all five spirometry curves, or the single best curve compared to the maximum value.



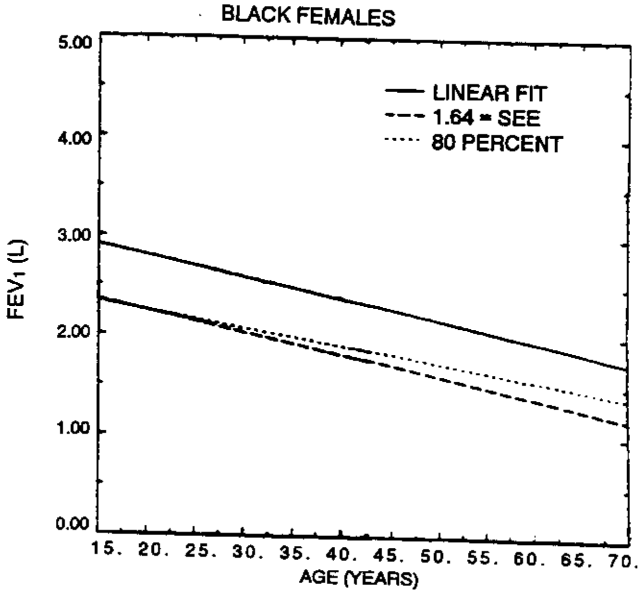
Observed forced expiratory volume in 1 second ($FEV_1$) (liters) v age (years) for white males using two linear curve model: solid line is linear least square fit: dashed lines are the lower limits of normal using residual method (1.645 SE of the estimate [*SEE]) and percent predicted methods (80% of



Observed forced expiratory volume in 1 second ($FEV_1$) (liters) v age (years) for white females: solid line is linear least square fit; dashed lines are the lower limits of normal using residual method (1.645 SE of the estimate [*SEE]) and percent predicted methods (80% predicted).



Observed forced expiratory volume in 1 second ($FEV_1$) (liters) v age (years) for black males using two linear curve model: solid line is linear least square fit: dashed lines are the lower limits of normal using residual method (1.645 SE of the estimate [*SEE]) and percent predicted methods (80% of predicted).



Observed forced expiratory volume in 1 second ($FEV_1$) (liters) v age (years) for black females: solid line is linear least square fit; dashed lines are the lower limits of normal using residual method (1.645 SE of the estimate [*SEE]) and percent predicted methods (80% predicted).

Figure 5-13. Comparison of predicted normal values for $FEV_1$ based on the percent predicted method [Miller and Scacci 1981] and the lower 95% confidence limit method [Hankinson 1991, 1986; Knudson 1983]. (Source: Hankinson [1986].)

Table 5-7 lists the recently proposed NIOSH criteria for interpreting spirometry (values determined cross-sectionally). The previous NIOSH criteria for spirometry interpretation was based on the approach of the Intermountain Thoracic Society (ITS) in 1975, which used percent predicted method to delineate normal and abnormal values [Kanner and Morris 1975]. The proposed NIOSH criteria use the lower 95% confidence interval, or lower limit of normal (LLN), to delineate normal and abnormal values [Hankinson 1991]; however, the percent-predicted approach is still used to determine the severity of obstructive or restrictive disease (see Table 5-8). A computerized scheme for interpretation of spirometry tracings has been developed [Hankinson 1991].

#### 5.2.5.4.1 Spirometry tests: number of blows and selection of value

Recommendations regarding the number of blows into the spirometer have ranged from three to five blows [Quanjer 1983; Ferris 1978; ATS 1969; MRC 1965; Hutchinson 1846]. Three blows has been shown to be sufficient, however, because mean $FEV_1$ and FVC values are comparable (as is variability) when obtained from three blows or from five blows [Nathan et al. 1979]. Recommendations for the selection of values have included either the mean of the last three blows [ATS 1969] or the best FVC and $FEV_1$, whether or not these values are obtained from the same spirometry curve [Quanjer 1983 (European Community); Ferris 1973 (ATS)]. Although the issue of whether the mean or the maximum $FEV_1$ and FVC values provides the best estimate of the true value has been debated [Oldham and Cole 1983; Ullah et al. 1983; Sorenson et al. 1980; Ferris et al. 1978; Fletcher et al. 1976], Samet [1992] concludes that the choice of either a mean or a maximum value has little effect on either estimates of lung function or on the variability.

**Table 5-7.—Proposed NIOSH criteria for interpreting spirometry**

| Interpretation of presence and severity of obstructive or restrictive airways disease | Criteria for determining the interpretation of disease: Obstructive disease ($FEV_1$/FVC%) | Criteria for determining the interpretation of disease: Restrictive disease (FVC predicted) |
|---|---|---|
| Normal | >LLN* | >LLN |
| Mild | >60 | >65 |
| Moderate | ≥45 to 60 | ≥51 to 65 |
| Severe | ≤45 | ≤51 |

*Lower limit of normal. Severity is graded only if values are below the LLN. To calculate the LLN, multiply the predicted value [Knudson et al. 1983] by the appropriate value from the table. For example, for a 30-year-old male 170 cm tall, the LLN for the $FEV_1$/FVC% would be (0.869 x 83.5, or 72.6%). For blacks and orientals, the LLN for $FEV_1$ and FVC is multiplied by an additional factor of 0.85 to account for the 15% lower predicted lung volumes at any given height [Lanese et al. 1978; Schoenberg et al. 1978; Seltzer et al. 1974].

**Table 5-8.—Percentage predicted normal method for determining the severity of obstructive or restrictive airways disease**

| Age range | FVC (%) | $FEV_1$/FVC% (%) |
|---|---|---|
| Males: | | |
| 6 to 12 | 74.9 | 85.0 |
| 12 to 25 | 79.8 | 85.0 |
| 25 to 40 | 81.1 | 86.9 |
| 40 to 99 | 73.4 | 86.9 |
| Females: | | |
| 6 to 11 | 73.0 | 80.5 |
| 11 to 20 | 74.9 | 80.5 |
| 20 to 40 | 76.9 | 85.9 |
| 40 to 99 | 71.8 | 85.9 |

Source: Hankinson [1991].

### 5.2.5.4.2 Spirometry tests: ATS acceptability and reproducibility criteria

The ATS criteria for acceptability of a spirometry curve is based on the technician's observation that the individual performed the test with a smooth, continuous exhalation, with apparent maximal effort, with a satisfactory start, and without coughing, glottis closure, early termination, a leak, or an obstructed mouthpiece [ATS 1987]. The ATS criteria of reproducibility include a minimum of three acceptable curves that do not vary by more than 100 ml or 5%, whichever is greater [ATS 1987].

However, two separate studies--a study of 7,790 U.S. coal miners [Kellie et al. 1987] and a study of 542 Vermont granite workers [Eisen et al. 1984, 1983]--have shown that adherence to the ATS reproducibility criteria resulted in biased estimates of $FEV_1$. Eisen [1987] reported that individuals with persistent test failure had a twofold higher annual average rate of $FEV_1$ decline than did those without persistent test failure. Kellie et al. [1987] found that coal miners who failed the reproducibility criteria had lower mean $FEV_1$ and had significantly more respiratory symptoms (i.e., cough, phlegm, wheeze, and dyspnea) than did miners with reproducible tests.

Thus, the exclusion of individuals from an epidemiologic study on the basis of ATS reproducibility criteria could result in estimates of lung function that are biased upward because individuals with lower function would be systematically excluded [Eisen 1987]. In longitudinal studies, the bias would be toward lesser rates of decline [Samet 1989]. Kellie et al. [1987] also concluded that increased spirometry variability is associated with poorer health. Height is another factor that is associated with ability to meet ATS reproducibility criteria (i.e., shorter individuals have more difficulty satisfying ATS reproducibility criteria than do taller subjects) [Hankinson and Bang 1991].

The implication of these epidemiologic findings for interpretation of spirometry tests in individuals is that the maximum value should be used, and that use of the reproducibility criteria may invalidate the spirometry tests of individuals with functional impairment. Hankinson [1986] and the ATS [1984] recommend that the largest FVC and $FEV_1$ should be reported regardless of the spirometry curve(s) on which they occur. Miller and Scacci [1981] have suggested criteria that can be used to determine if an individual has used full effort. Because those individuals who fail to meet ATS reproducibility criteria are more likely to have decrements in $FEV_1$ and greater rates of decline in $FEV_1$ [Eisen 1987; Kellie et al. 1987], further lung function testing for those individuals is necessary to determine the cause of the variability. A prudent strategy would be to repeat the spirometry tests within a few weeks for individuals who do not meet the ATS reproducibility requirements and to refer them for further medical tests if the repeated spirometry values continue to be highly variable or if reproducible, abnormally low values are obtained.

#### *5.2.5.5 Longitudinal Changes in Lung Function*

An important objective of performing periodic PFTs for individual miners is to identify those with a rapid rate of decline in lung function. The issue of participation in the periodic medical surveys, discussed with regard to periodic chest X-rays in Section 5.2.4.2, is equally important for identifying miners with excessive annual decline in $FEV_1$ or FVC. Excessive annual decline has been described as being within the range of approximately 78 to 106 ml/year [Buist et al. 1988; Burrows 1986; Pern et al. 1984; Clement 1982; Glindmeyer et al. 1982]. Pern et al. [1984] observed, in a study of British coal miners, that "rapid decliners" had a mean rate of decline of 106 ml/year (smokers) or 78 ml/year (nonsmokers). Buist and Vollmer [1988] reported that ". . . to develop clinically significant airflow obstruction, the average rate of decline of $FEV_1$ over adult life probably needs to be greater than 90 ml/year . . . ."

Yet, longitudinal changes in lung function are difficult to detect and to interpret because of the relatively small expected annual decline in $FEV_1$ or FVC (25 to 30 ml/yr), the instrumentation variability (±3%), and the within subject variability (3% or 150 ml) [Hankinson 1992; Buist and Vollmer 1988; Burrows 1986]. A statistical factor that influences the probability of detecting a significant longitudinal decline is that the standard error of the estimate (SEE) decreases with increased interval between examinations [Berry 1974; Burrows et al. 1986]. Clement et al. [1982] concludes that ". . . at least 6 to 8 years of followup are required to appreciate with precision the rates of decline in $FEV_1$." The age of onset of decline in $FEV_1$ in the general population is about 36 years [Burrows 1986]. Glidmeyer et al. [1982] and Burrows et al. [1986] observed less decline in $FEV_1$ in longitudinal studies than in cross-sectional studies. Vollmer et al. [1988] concluded that inadequate statistical modeling, changing smoking patterns, and selection bias tend to make longitudinally measured rates appear less than those in cross-sectional studies.

Because of the various factors that affect lung function, a normal reference values should be established for each population being tested [Woolcock 1969]. Normal reference values depend on age, race, gender, height, and weight. The relationship between lung function and weight was first shown to be nonlinear by Hutchinson [1846]; yet recent studies have generally omitted weight in prediction equations for lung function [Schoenberg et al. 1978]. The effect of weight on measures of lung function is to first increase lung function (muscularity effect) and then to decrease lung function (obesity effect). Schoenberg et al. [1978] reported that simple linear regression on age and height are inaccurate and tend to over-predict lung function for young adults. Thus, when young adults start working at age 18 to 20, a PFT with reference values based on simple linear regression on age and height may indicate abnormal lung function. Then, because the subsequent rate of decline may parallel that observed in adults, it may be concluded that the initial PFT was below normal and that no further decline was occurring. However, as shown in Figure 5-14, the initial PFT was normal, and the subsequent decline was considerably greater than that attributed to aging alone.

Methods for determining longitudinal decline in lung function were evaluated by Hankinson and Wagner [1993]. These methods include (1) calculation of the lower 95% confidence limit (one-sided, $\alpha = 0.05$) for the annual change in $FEV_1$ and the use of a formula for the standard error of the estimate (SEE) [Burrows et al. 1986]; and (2) use of the criterion of greater than 15% annual loss of $FEV_1$ in an individual [ATS 1991], with adjustment for age-associated decline. These two methods were found to give essentially equivalent results. The ATS criterion of greater than 15% annual decline was found to be slightly more sensitive for individuals with smaller $FEV_1$. The authors recommended establishing a baseline value of $FEV_1$ for each worker from several initial spirometry tests, with annual examinations to follow. Hankinson and Wagner [1993] also compared the usefulness of cross-sectional versus longitudinal evaluations of $FEV_1$. They concluded that about 50% of a worker population may benefit from the longitudinal (in addition to cross-sectional) evaluation of spirometry test results.

#### *5.2.5.6 Additional Medical Tests of Pulmonary Function*

Additional tests of lung function may be indicated for further evaluation of miners with abnormal PFTs or with respiratory symptoms. Such tests may be too difficult or too expensive to administer in routine screening, or they may have large variability within a normal population [Hankinson 1986]. Tests of lung function include--in addition to spirometry (e.g., $FEV_1$, FVC)--tests of lung volumes (e.g., total lung capacity, TLC; functional residual capacity, FRC; residual volume, RV); air flow resistance (e.g., airways resistance, $R_{aw}$); elastic resistance (e.g., static compliance, $C_{st}$); interaction of elastic and flow resistance (e.g., maximum voluntary ventilation, MVV); ventilation and perfusion, or tests of arterial blood gases and gas exchange (e.g., arterial blood oxygen tension [$PaO_2$]; alveolar-arterial oxygen tension, $P[A\text{-}a]O_2$); gas

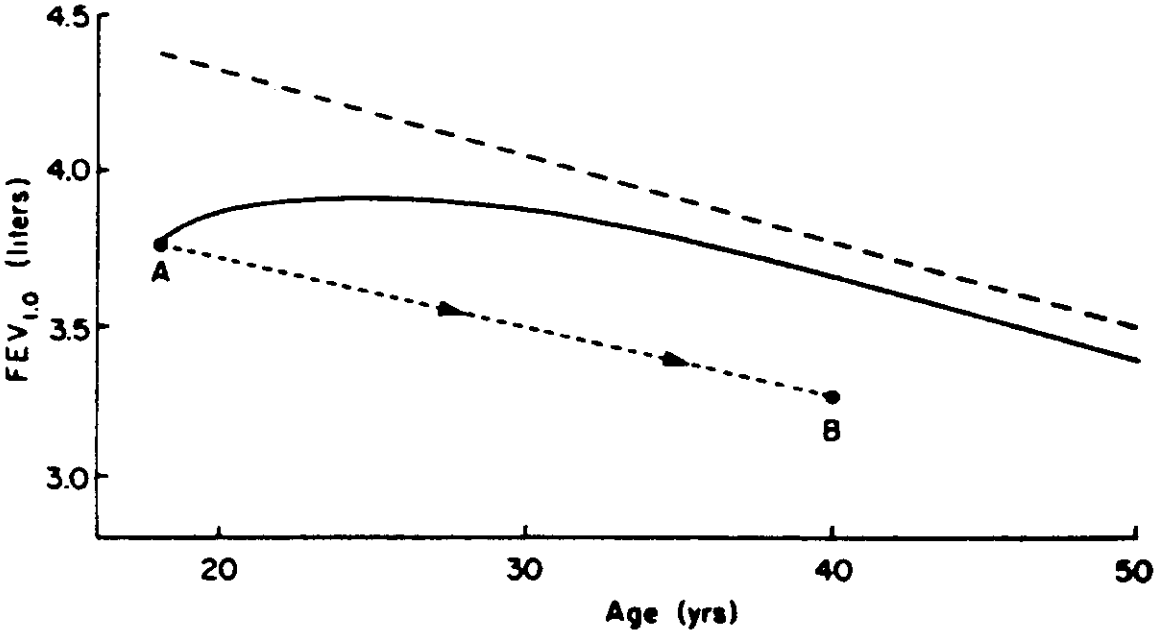


Figure 5-14. $FEV_{1.0}$ by age in white males. Solid line: predicted values (table 2 B2) [Schoenberg et al. 1978] for a man whose height is 175 cm and weight is 60 kg at age 18, 65 kg at age 20, 70 kg at age 25, and 75 kg from age 30 on. Dashed line: predicted values according to Kory et al. [1961]. Dashed line with arrow AB: postulated course of lung function decrement during employment with risk of airway obstruction, for example in a cotton textile worker, $FEV_{1.0}$ decreases from 3.78 liters (100% of predicted) at age 18 to 3.26 liters (89% of predicted) at age 40. Using Kory's equation, the initial value at A is judged abnormal and the subsequent decrement appears similar to that expected from the increase in age (line AB is approximately parallel to the dashed line). In fact, the decrement expected from aging alone is only 0.12 liters (according to the solid line); the actual decrement of 0.522 liters is markedly in excess of this. (Source: Schoenberg et al. [1978].)

transfer (e.g., diffusing capacity for carbon monoxide, DLCO); blood gas status (e.g., hypoxia); acid-base status (e.g., pH); exercise (e.g., maximal oxygen intake, $VO_2$) [Miller and Scacci 1988; Hankinson 1986].

Two basic types of spirometers are available for determination of $FEV_1$, FVC, or $FEV_1$/FVC: the flow spirometer and the volume spirometer. The flow spirometer measures the rate at which air is exhaled and must integrate flow to determine volume. The volume spirometer collects exhaled air and directly measures volume. The advantages and disadvantages of each type of spirometer have been described [Hankinson 1993]. A significant advantage of the volume spirometer is its simplicity and direct measurement of volume, while a significant disadvantage of the flow spirometer is that a small error in estimating zero flow can affect the resulting volume, particularly for measurement of FVC.

A decrease in peak expiratory flow (PEF) and maximum flow at 50% of vital capacity ($Vmax_{50}$) have been reported to be associated with dust-induced bronchitis [Hankinson et al. 1977]. Bates [1973] reported that changes in residual volume (RV) were also associated with bronchitis. In a study of U.S. coal miners, Morgan et al. [1974] reported that increased RV was associated with simple CWP.

Both recommended methods for performing DLCO [Ferris 1978] and prediction equations for normal values [Crapo and Morris 1981] are available. Changes in the membrane diffusing capacity or in the capillary volume due to structural lung damage can influence the diffusing capacity of the lung [Miller and Scacci 1981]. The single-breath method of measuring the diffusing capacity of carbon monoxide (DLCO) is the most widely used and best standardized method of measuring diffusing capacity [Gold and Boushey 1988; Hankinson 1986].

Because DLCO can be abnormal in numerous respiratory disorders, the test lacks specificity for work-related respiratory diseases. Also, cigarette smoking has been associated with reduced DLCO (due to elevated carboxyhemoglobin) and should be considered in the diagnosis [Hankinson 1986]. DLCO is indicated when other tests, such as spirometry, do not show sufficient lung impairment to explain a patient's respiratory symptoms or when occupational exposure is associated with restrictive lung disease (e.g., respirable coal mine dust) [Hankinson 1986; Miller and Scacci 1981].

### *5.2.5.7 Medical Intervention Strategies*

#### 5.2.5.7.1 Transferring miners with simple CWP to low dust jobs

In a study commissioned by NIOSH, Hurley and Maclaren [1987] used British data to estimate the risk of PMF among coal miners who reduce their exposure to coal mine dust to 1 mg/m$^3$ once radiographic evidence of CWP category 1/0 or greater is found (i.e, comparable to participation in the U.S. transfer program) [30 USC 843(a)(b) (1986)]. The authors estimated that if 100% of the eligible miners elected to transfer, then just 1 in 10,000 cases of PMF would be prevented (7.1/1,000 without transfer versus 7.0/1,000 with transfer). Maclaren and Soutar [1985] found in a study of British miners, that of those miners who developed PMF after leaving mining, 32% had no evidence of CWP (category 0) when they left mining.

The indication that the transfer of miners with simple CWP does not substantially reduce the risk of developing PMF is consistent with the theories that cumulative exposure (with dust deposition exceeding clearance) and residence time of dust in the lungs are important determinants in the development of PMF [Maclaren et al. 1989; Hurley et al. 1987]. Sufficient cumulative respirable coal mine dust exposure and disease development may have already occurred such that lowering exposure would not be effective in preventing progression to PMF. Thus, primary prevention, rather than secondary intervention, is the most effective means of reducing the incidence of PMF and, logically, other occupational respiratory diseases as well. The effectiveness of reducing exposures among coal miners with early development of airways obstruction (before such changes become irreversible) remains to be determined.

Insufficient study has been done on the effectiveness of the transfer program to make specific conclusions. However, if a miner develops an exposure-related respiratory disease despite dust control, then the only reasonable alternative is to offer the miner the opportunity to continue working in an area with a lower dust concentration. A problem with the transfer program, however, is that the dust concentrations to which transferred miners are exposed may not be much lower than for those who did not transfer (see Tables in Appendix B). Although most occupations had mean concentrations below the 1 mg/m$^3$ PEL for exposure of transferred miners to respirable coal mine dust, for some occupations (e.g., roof bolters) the mean concentrations even exceeded the 2 mg/m$^3$ PEL for respirable coal mine dust in 1989 (Appendix B). An additional factor to consider in evaluating the effectiveness of the transfer program is the poor rate of participation, with only 23% (2,119/9,138) of coal miners who have been eligible to transfer since the beginning of the program electing to participate [Wagner and Spieler 1990].

## 5.3 THE BLACK LUNG PROGRAM

The Black Lung Program, initially established in 1969 as part of the Federal Coal Mine Health and Safety Act, is intended to provide compensation for coal miners who are partially or totally disabled from their normal coal mine employment. Standards for determining coal miners' total disability or death due to pneumoconiosis are based on criteria for length of employment, radiographic evidence of pneumoconiosis, and/or values for pulmonary function tests or arterial blood-gas tests that are below predicted normal values [29 CFR Part 718].

The initial program established in 1969 was administered by the Social Security Administration (SSA) and used public funds to compensate disabled coal miners. It was intended that the second phase of the program would be administered by the Department of Labor (DOL) and structured according to general principles of workers' compensation. However, the number of claims filed under the initial program far exceeded estimates and the Black Lung Benefits Act of 1972 was enacted to provide simplified interim eligibility criteria for claims filed with the SSA and to delay the transfer of responsibility to DOL for processing and paying claims until 1973. The SSA continues to administer funds for claims filed before July 1, 1973.

In 1978, the Black Lung Benefits Reform Act of 1977 was enacted, which again mandated the use of interim criteria based on the presumption of eligibility to resolve old, unapproved claims. In addition, the Black Lung Benefits Revenue Act of 1977 was enacted, which created the Black Lung Disability Trust Fund, to be financed by an excise tax on coal that is mined and sold in the United States.

In 1981, the Black Lung Benefits Revenue Act of 1981 and the Black Lung Benefits Amendments of 1981 were enacted. The amendments tightened the eligibility standards, eliminated certain presumptions, and temporarily increased the excise tax on coal to reduce the debt of the Trust Fund to the U.S. Treasury, which was more than $1.5 billion in 1981 and $2.8 billion in 1985. In 1985 and 1987, budget-related laws were passed, but further changes were made in the eligibility criteria or adjudication procedures. By the end of 1991, the Trust Fund's cumulative debt to the U.S. Treasury was $3.3 billion. Tables 5-9 through 5-12 provide information on the number of beneficiaries and the costs of the Black Lung Program.

**Table 5-9.—Summary of claims activity, U.S. Department of Labor Black Lung Program, Fiscal Year 1991 and cumulative, July 1, 1973 to December 31, 1991**

| | Cumulative decisions—all levels* (July 1, 1973 to December 31, 1991) | | | |
|---|---|---|---|---|
| **Claim category** | **Approved** | **Denied** | **Total number of decisions** | **Approval rate (%)** |
| Section 435 claims filed, 7/1/73 to 2/28/78 | 56,080 | 63,725 | 119,805 | 46.8 |
| Section 727 claims filed, 3/1/78 to 3/31/80 | 20,494 | 41,044 | 61,538 | 33.3 |
| Section 718 (PRE) claims filed, 1/1/82 to present | 4,125 | 28,529 | 32,654 | 12.6 |
| Section 718 (POST) claims filed, 1/1/82 to present | 5,890 | 77,804 | 83,694 | 7.0 |
| Part B denials denied claims inherited from SSA | 21,867 | 45,917 | 67,784 | 32.3 |
| SSA Approvals claims approved by SSA under the 1977 amendments | 15,931 | 710 | 16,641 | 95.7 |
| Subtotal | 124,387 | 257,729 | 382,116 | 32.6 |
| Medical only | 116,738 | 1,656 | 118,394 | 98.6 |
| Grand total | 241,125 | 259,385 | 500,510 | 48.2 |

Source: DOL [1992].

*Refers to the most recent decision (any level-DCMWC, ALJ, BRB, etc.).

Abbreviations: DCMWC = Division of Coal Mine Workers' Compensation, ALJ = Administrative Law Judge, BRB = Benefits Review Board.

Table 5-10.—Department of Labor Black Lung Benefits Program obligations for FY 1982-91

| Year | Program obligations (in billions) |
|---|---|
| 1982 | $1.79 |
| 1983 | 2.15 |
| 1984 | 2.50 |
| 1985 | 2.83 |
| 1986 | 2.88 |
| 1987 | 2.95 |
| 1988 | 2.99 |
| 1989 | 3.05 |
| 1990 | 3.05 |
| 1991 | 3.26 |

Source: DOL [1992].

## Table 5-11.—Black Lung claims by class of beneficiary, 1983-91

| Class of beneficiary | Number of beneficiaries,* by year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 |
| Primary beneficiaries: | | | | | | | | | |
| Minors | $64,181 | $62,785 | $60,906 | $59,004 | $56,688 | $54,339 | $51,588 | $45,587 | $45,842 |
| Widows | 35,178 | 36,495 | 37,827 | 39,049 | 40,702 | 41,901 | 42,923 | 43,500 | 43,842 |
| Others | 813 | 854 | 887 | 1,119 | 997 | 1,054 | 1,110 | 1,153 | 1,186 |
| Total primary beneficiaries | 100,172 | 100,134 | 99,620 | 99,172 | 98,387 | 97,294 | 95,621 | 93,240 | 90,870 |
| Dependents of primary beneficiaries: | | | | | | | | | |
| Dependents of minors | 63,040 | 60,275 | 58,113 | 54,747 | 52,237 | 49,343 | 46,053 | 42,846 | 39,800 |
| Dependents of widows | 2,398 | 2,298 | 2,306 | 2,207 | 2,199 | 2,079 | 2,002 | 1,902 | 1,825 |
| Dependents of others | 433 | 409 | 398 | 424 | 466 | 440 | 511 | 503 | 506 |
| Total dependents | 65,871 | 62,982 | 60,817 | 57,378 | 54,902 | 51,862 | 48,566 | 45,251 | 42,131 |
| Total of all beneficiaries | 166,043 | 163,116 | 160,437 | 156,550 | 153,289 | 149,156 | 144,187 | 138,491 | 133,001 |

Source: DOL [1992].

*Active claims,including those paid by an RMO, cases paid by the Trust Fund, cases in interim pay status, cases being offset as a result of concurrent Federal or State benefits, and cases temporarily suspended.

### Table 5-12.—Monthly Black Lung benefit rates, 1973-91

| Period | Benefit rates by type of beneficiary | | | |
|---|---|---|---|---|
| | Claimant | Claimant and 1 dependent | Claimant and 2 dependents | Claimant and 3 or more dependents |
| 7/1/73 to 9/30/73 | $169.80 | $254.70 | $297.10 | $339.50 |
| 10/1/73 to 9/30/74 | 177.60 | 226.40 | 610.80 | 355.20 |
| 10/1/74 to 9/30/75 | 187.40 | 281.10 | 328.00 | 374.80 |
| 10/1/75 to 9/30/76 | 196.80 | 295.20 | 344.40 | 393.50 |
| 10/1/76 to 9/30/77 | 205.40 | 308.10 | 359.50 | 410.80 |
| 10/1/77 to 9/30/78 | 219.90 | 329.80 | 384.80 | 439.70 |
| 10/1/78 to 9/30/79 | 232.00 | 348.00 | 405.90 | 463.90 |
| 10/1/79 to 9/30/80 | 254.00 | 381.00 | 444.50 | 508.00 |
| 10/1/80 to 9/30/81 | 279.80 | 419.60 | 489.60 | 559.50 |
| 10/1/81 to 9/30/82 | 293.20 | 439.80 | 513.10 | 586.40 |
| 10/1/82 to 12/31/83 | 304.90 | 457.30 | 533.60 | 609.80 |
| 1/1/84 to 12/31/84[*] | 317.10 | 475.60 | 554.90 | 634.20 |
| 1/1/85 to 12/31/86 | 328.20 | 492.30 | 574.30 | 656.40 |
| 1/1/87 to 12/31/87 | 338.00 | 507.00 | 591.50 | 676.00 |
| 1/1/88 to 12/31/88 | 344.80 | 517.20 | 603.40 | 689.60 |
| 1/1/89 to 12/31/89 | 358.90 | 538.30 | 628.10 | 717.80 |
| 1/1/90 to 12/31/90 | 371.80 | 557.70 | 650.60 | 743.60 |
| 1/1/91 to 12/31/91 | 387.10 | 580.60 | 677.40 | 774.10 |

Source: DOL [1992].

[*] These benefit rates include the additional 0.5% increase that was granted retroactive to January 1, 1984. The rates in effect before the retroactive payments (1/1/84 through 6/30/84) were $315.60 for a claimant only, $473.30 for a claimant and 1 dependent, $552.20 for a claimant and 2 dependents, and, $631.10 for a claimant and 3 or more dependents.

# 6 OTHER STANDARDS AND RECOMMENDATIONS

## 6.1 MSHA STANDARD FOR RESPIRABLE COAL MINE DUST

The current Federal standard of 2 mg/m$^3$ for "respirable dust in the mine atmosphere" was established by the Federal Coal Mine Health and Safety Act of 1969, which was amended by the Federal Mine Safety and Health Act of 1977 [30 USC 801-962 (1986)]. However, an interim standard of 3 mg/m$^3$ was in effect from 1969 to 1972 [30 USC 842 (b) (1986)], when the current standard became effective. The Mine Safety and Health Administration (MSHA), of the U.S. Department of Labor was established under the Federal Mine Safety and Health Act of 1977. This agency is responsible for enforcing the provisions of the Act [30 USC 801 et seq. (1986)], including the establishment of safety and health regulations [30 CFR 70 (1988)]. Two Federal agencies preceded MSHA: the Mine Enforcement and Safety Administration (MESA), U.S. Department of the Interior, from 1972 to 1977, and the U.S. Bureau of Mines Inspection Division before 1972.

MSHA has adopted a PEL of 2 mg/m$^3$ for respirable coal dust, which is measured gravimetrically as an 8-hour TWA of the respirable coal mine dust. Exposure limits for respirable quartz also apply; thus, if the respirable quartz content exceeds 5%, a formula (10 divided by the percentage of respirable quartz) is used to determine the reduced PEL for respirable coal dust [30 CFR 70 (1988)]. When the respirable coal dust concentration is 2 mg/m$^3$ and the quartz content is 5%, the MSHA PEL of 0.1 mg/m$^3$ for respirable crystalline quartz is reached [54 Fed. Reg.[*] 2504, 2509, and 2521 (1989)].

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[*] Federal Register. See Fed. Reg. in references.

OSHA has adopted a PEL of 2 $mg/m^3$ for the respirable dust fraction containing less than 5 percent quartz and 0.1 $mg/m^3$ for the respirable quartz fraction of coal dust containing more than 5 percent quartz. Both OSHA PELs are 8-hour TWAs.

Coal mine operators are required to take bimonthly samples of airborne respirable dust in the active workings of a coal mine with a device approved by the Secretaries of the U.S. Department of Labor and the Department of Health and Human Services [30 CFR 70 and 74 (1988)]. A conversion factor of 1.38 is applied to the results of the gravimetric analysis of airborne samples. The conversion factor adjusts for differences in sampling devices used in the United States (a 10-mm nylon cyclone) and the United Kingdom (a horizontal elutriator developed by the British Mining Research Establishment [MRE]. The "respirable" particulate size fraction (which approximates dust penetration in the nonciliated or gas-exchange region of the human lungs [Soderholm and McCawley 1990; ACGIH 1990; Brown et al. 1950]), is defined by the British Medical Research Council criterion for particle-size selective dust samplers as: "100% efficiency at 1 micron or below, 50% at 5 microns, and zero efficiency for particles of 7 microns and upwards" [ATC 1970; Orenstein 1960].

The health basis for the current Federal standard for respirable coal mine dust [30 USC 801-962 (1986)] was derived primarily from British data [Jacobsen et al. 1971; McLintock et al. 1971; Cochrane 1962]. U.S. studies of the prevalence of CWP and PMF before 1969 used the surrogate of years worked underground to estimate the exposure to coal mine dust (see Chapter 4.1). However, the British studies had investigated the relationship between PMF and the increasing category of simple CWP [Cochrane 1962] as well as the relationship between the concentration of respirable coal mine dust and the risk of developing simple CWP [Jacobson et al. 1971 and PMF [McLintock et al. 1971]. Cochrane [1962] reported that the incidence of PMF among 1,429 Welsh miners and ex-miners had increased during an 8-year study interval--from nearly zero at CWP categories 0 and 1 to about 15% at category 2 and 30% at category 3 (Figure 6-1). McLintock et al. [1971] also found a relationship between increasing categories of simple CWP and the development of PMF among 105,490 British coal miners. Thus, the strategy for preventing PMF was directed at preventing CWP category 2. Jacobson et al. [1971] predicted that the probability of progression to category 2/1 or greater was essentially zero for miners exposed to a mean coal dust concentration of 2 mg/m$^3$ over a 35-year working lifetime (Figure 6-2).

### 6.2 ACGIH TLV

The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) for respirable coal mine dust is 2 mg/m$^3$ as a TWA.

### 6.3 WHO Exposure Limit

The World Health Organization (WHO) [WHO 1986] has recommended a "tentative health-based exposure limit" for respirable coal mine dust (with <6% respirable quartz) ranging from 0.5 to 4.0 mg/m$^3$. WHO recommended that this limit should be based on (1) the risk factors (i.e., coal rank or carbon content, proportion of respirable quartz and other minerals, and particle size distribution of the coal dust) for CWP category 1 that is determined at each mine, and (2) the assumption that the risk of PMF over a working lifetime (56,000 hr) would not exceed 2/1,000. A shortcoming of the WHO approach is that the risk of disease must be determined separately for each individual mine or group of mines, and the exposure limit would vary from mine to mine. The computation of risk would be influenced by job category within a mine, by study participation and sampling biases, and by whether health effects or dust composition data are used.

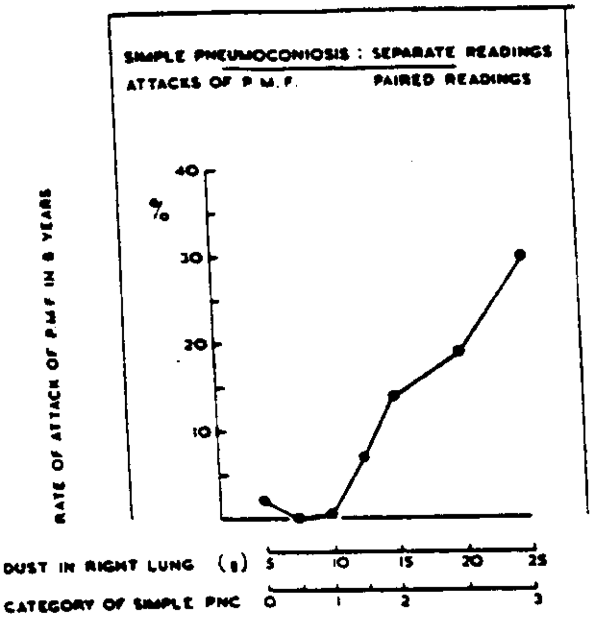

Figure 6-1. Attack rate of PMF among miners and ex-miners aged 25-64 in 8 years by category of CWP. (Source: Cochrane [1962].)

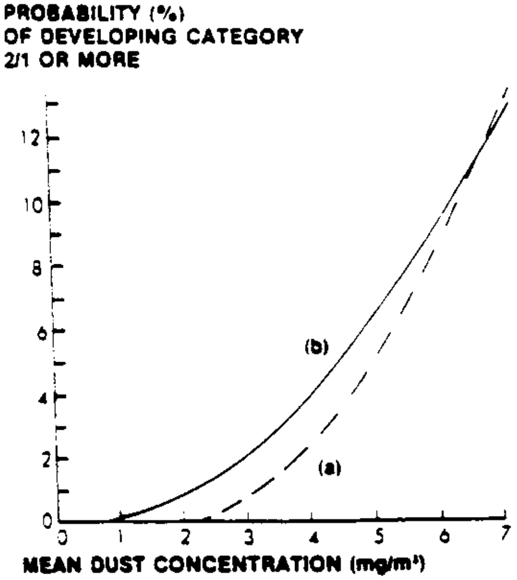

Figure 6-2. Probability of developing CWP category 2/1 or greater after 35 years of exposure to various concentrations of respirable coal mine dust.*
*Data from Jacobsen et al. [1971] (dotted line) and Hurley et al. [1982] (solid line) are based on 10 and 20 years of pneumoconiosis field research, respectively. (Source: Merchant et al. [1986].)

## 6.4 Limits in Other Countries

The German coal mine dust standard is based on long-term personal exposure measurements, with consideration given to both the concentration and the duration of exposure for each miner. When a miner's cumulative exposure approaches the standard, the miner is assigned to a work area with a lower dust concentration [Breuer and Reisner 1988]. This approach is based on epidemiologic studies that show how cumulative dust exposure and dust residence time in the lungs affect the occurrence of simple CWP and PMF [Maclaren et al. 1989; Hurley et al. 1987; Reisner 1984; Hurley et al. 1984; Hurley et al. 1982]. In this strategy, workers are assigned to jobs based on cumulative exposure, apparently without regard to the individual variations in response to exposure (which could be detected in medical screening tests). Although it is important to limit the cumulative exposures of miners, such an approach may reduce the incentive to control the mean concentration of dust in the mines.

Occupational exposure limits for respirable coal mine dust and respirable crystalline silica in various countries are listed in Table 6-1. Exposure limits cannot be directly compared from country to country, because of differences in measurement strategies. Prinz and Stolz [1990] describe differences in the sampling locations within the mines relative to the miners, as well as differences in the number of samples and the frequency of sampling in various countries. These differences make it difficult to compare the exposure-related risks of miners in different countries. An exception is the comparison of exposure-related risks for U.S. and British miners. The exposure measurements for British coal miners were collected in the Pneumoconiosis Field Research program, which is separate from the program for compliance sampling. Measurements in the United States can be compared with those in the United Kingdom by applying the MRE conversion factor. However, U.S. and British measurements cannot be considered absolutely comparable because unmeasured factors probably contribute to differences.

Table 6-1. Occupational exposure limits for respirable coal mine dust and respirable crystalline silica in various countries[•]

| Country | Recommended value (gravimetric) | Comment |
|---|---|---|
| Australia | 5 $\text{mg/m}^3$ | Coal dust with ≤ 5% respirable free silica (RFS) |
| | $\frac{25\ \text{mg/m}^3}{\%\ \text{RFS} + 5}$ | Silica-containing dust |
| Belgium | $\frac{10\ \text{mg/m}^3}{\%\ \text{respirable quartz} + 2}$ | |
| Brazil | $\frac{8\ \text{mg/m}^3}{\%\ \text{respirable quartz} + 2}$ | |
| Canada, Alberta[•] | 5 $\text{mg/m}^3$ | Coal mine dust (average concentration |
| Finland | 2.0 $\text{mg/m}^3$ | Coal dust |
| | 0.2 $\text{mg/m}^3$ | Quartz-fine dust (< 5 µm) |
| Federal Republic of Germany | 4.0 $\text{mg/m}^3$ | Quartz-containing dust |
| | 0.15 $\text{mg/m}^3$ | Coal-mine dust with > 5% quartz |
| Italy | 3.33 $\text{mg/m}^3$ | Coal dust with < 1% quartz |
| | $\frac{10\ \text{mg/m}^3}{q + 3}$ where q = % of quartz (mass) | Coal dust with > 1% quartz |
| Netherlands | 0.075 $\text{mg/m}^3$ | Silica: cristobalite, tridymite |
| Poland | 0.05 $\text{mg/m}^3$ | Silica: cristobalite, tridymite |
| UK['] | 3.8 $\text{mg/m}^3$ | Coal mine dust (average concentration at the coal face) |
| USA (MSHA) | 2.0 $\text{mg/m}^3$ | Coal dust with < 5% silica |
| | $\frac{10\ \text{mg/m}^3}{\%\ SiO_2}$ | Coal dust with > 5% silica |
| Yugoslavia | 4 $\text{mg/m}^3$ | Fine dust with < 2% free crystalline silica (fcs) |
| | $\frac{0.07 \times 100\ \text{mg/m}^3}{\%\ \text{fcs}}$ | Fine dust with 72% fcs |
| | 0.07 $\text{mg/m}^3$ | Pure quartz fine dust |

Source: WHO 1986, 1980 (except as otherwise noted)

[•] Source: Kaegi and Baynton 1981 (proposed occupational exposure limit)

['] Source: Jacobsen 1984 (based on maximum allowable concentration of 7 $\text{mg/m}^3$ in the return airway during the working shift).

# 7 ASSESSMENT OF HEALTH EFFECTS

## 7.1 BASIS FOR THE RECOMMENDED STANDARD

As part of a comprehensive environmental and medical monitoring program to protect the health of the nation's coal miners, NIOSH recommends an exposure limit (REL) for respirable coal mine dust of 0.9 $mg/m^3$, as an 8-hr TWA for up to a 10-hr workday and a 40-hr workweek. Because some risk of PMF remains even at 0.9 $mg/m^3$, NIOSH recommends that every effort should be made to reduce exposures to respirable coal mine dust below the REL using state-of-the-art engineering controls and work practices. Compliance with the REL shall be determined by full-shift sampling with a device operated in accordance with criteria of the proposed international (ISO/CEN/ACGIH) definition of respirable dust, as developed by the International Standards Organization (ISO), the Comité Européen de Normalisation (CEN), and the American Conference of Governmental Industrial Hygienists (ACGIH) [ACGIH 1991; CEN 1991b; ISO 1991; Soderholm 1991a].

### 7.1.1 Approved Sampling Device

The sampling device currently approved for respirable dust in coal mines is the coal mine dust personal sampler unit (CMDPSU) [30 CFR Part 74 (1991)]. For sampling in accordance with the ISO/CEN/ACGIH definition of respirable dust, the CMDPSU shall be operated at a flow rate of 1.7 L/min (see Section 5.1.3.2). Another sampler currently available in the U.S., the Higgins-Dervell (HD) sampler, has been shown to perform in accordance with the ISO/CEN/ACGIH definition when operated at a flow rate of 2.2 L/min [Bartley et al. 1993].

### 7.1.2 Primary Basis for the REL

Studies from both the U.S. and the U.K. have shown that coal miners are at risk of developing both pneumoconiosis and obstructive airways diseases from exposure to respirable coal mine dust for a working lifetime at the current U.S. standard of 2 mg/m$^3$. PMF is associated with impaired lung function, disability, and early death. Quantitative exposure-response studies of PMF among U.S. and U.K. coal miners have been performed [Attfield and Morring 1992a,b; Hurley and Maclaren 1987]. These studies suggest that miners exposed for a working lifetime at the current U.S. standard are at a substantial risk of developing PMF.

The prevention of PMF was a primary basis of the current U.S. standard of 2 mg/m$^3$ for respirable coal mine dust, which was enacted in 1969 [30 CFR 801 et seq. (1986)]. Since that time, numerous studies have demonstrated that miners are also at risk of developing chronic obstructive pulmonary diseases, a disease that can occur as well in persons without occupational dust exposure. Exposure-response studies of U.K. miners [Soutar et al. 1989; Marine et al. 1988; Hurley and Soutar 1986; Rogan et al. 1973] and U.S. miners [Attfield and Hodous 1992; Seixas et al. 1992] indicate that miners may develop severe exposure-related decrements in lung function, even without evidence of pneumoconiosis.

The Federal Coal Mine Health and Safety Act of 1969, amended in 1977, states the following:

> Among other things, it is the purpose of this subchapter to provide, to the greatest extent possible, that the working conditions in each underground coal mine are sufficiently free of respirable dust concentrations in the mine atmosphere to permit each miner the opportunity to work underground during the period of his entire adult

> working life without incurring any disability from pneumoconiosis or any other occupation-related disease during or at the end of such period [30 CFR 841(b) (1986)].

The best available scientific data indicate the mean concentration of respirable coal mine dust should be less than 1 mg/m$^3$ to assure that each miner will not incur any disability from pneumoconiosis or any other occupation-related disease; however, quantitation of the risk of exposure at mean concentrations below 1 mg/m$^3$ cannot be determined with reasonable certainty from the existing data and methodologies. U.S. and U.K. exposure-response studies indicate that the risk of PMF is greater than zero at 1.0 mg/m$^3$ (Table 7.1) [Attfield and Morring 1992b; Hurley and Maclaren 1987]. However, these studies do not provide risk estimates below 1 mg/m$^3$.

The concentration of 1.0 mg/m$^3$ is based on current sampling methods. Section 5.1.7 describes the correction factor for comparison of measured concentrations obtained from current and recommended sampling strategies. The concentration of 0.9 mg/m$^3$ based on the recommended sampling strategy is equivalent to the concentration of 1.0 mg/m$^3$ based on current sampling methods.

Because some risk of PMF remains at the REL of 0.9 mg/m$^3$, NIOSH recommends that every effort shall be made to reduce exposures to coal mine dust below the REL using state-of-the-art engineering controls and work practices.

### 7.1.3 REL for Respirable Crystalline Silica

The NIOSH REL for respirable crystalline silica is 0.05 mg/m$^3$ [NIOSH 1974]. NIOSH recommends that the concentration of both respirable coal mine dust and respirable crystalline silica be determined from all dust samples, as specified in Section 5.1.5. NIOSH further recommends that MSHA collect samples to determine noncompliance with the RELs for both respirable coal mine dust and respirable crystalline silica and that control efforts be focused on maintaining exposures below both RELs. NIOSH recommends eliminating the current MSHA practice of using the percentage of quartz in respirable coal mine dust to determine its PEL.

### 7.1.4 Medical surveillance

The REL of 0.9 mg/m$^3$ does not assure a zero risk of coal miners developing simple or complicated pneumoconiosis or obstructive airways diseases. Therefore, a medical surveillance program that includes initial and periodic chest X-rays and spirometry tests is important for the early detection and prevention of disability from pneumoconiosis or exposure-related obstructive airways diseases. Both underground and surface coal miners should be encouraged to increase their participation in the medical surveillance programs.

### 7.1.5 Studies Evaluated for the REL

An abundance of data exist for the determination of an REL for respirable coal mine dust. The REL is based on the following:

- Exposure-response studies of U.S. coal miners, including exposure-response studies for simple CWP, PMF, and decrements in lung function of miners who began working either before or after the 1969 Coal Mine Health and Safety Act (from 1,158 to 9,078 miners were included in the studies, with cumulative exposure estimates up to 1970, personal exposure measurements from 1970 to 1979, and exposure estimates derived from work histories after 1979)

- Exposure-response studies from the British Pneumoconiosis Field Research Program, which incorporates measurements of health effects in more than 50,000 miners and estimates for up to 30 years of individual working lifetime exposures to respirable coal mine dust

- Quantitative assessments of the risk of developing simple CWP or PMF over a working lifetime at the current MSHA PEL (separate analyses from U.S. and British data)

- Comparison of the exposure-response studies of U.S. and British coal miners with (1) pathologic studies of British coal miners (with data on both exposures and lung dust burdens), and (2) animal studies of the chronic inhalation of respirable dusts (including evaluation of the level of lung dust burden required for overloading of lung clearance mechanisms, activation of alveolar macrophages, and development of fibrosis)

The weight-of-evidence and the consistency of the estimated health effects from the numerous independent studies in both humans and animals provide a firm basis for making a health-based recommendation for an acceptable level of exposure to respirable coal mine dust. Table 7-1 summarizes the findings from the exposure-response studies that were used as part of the basis for the REL.

Since the enactment of the Federal Coal Mine Health and Safety Act of 1969 (amended in 1977), NIOSH has had an integral role in gathering and analyzing data that are needed to evaluate the adequacy of the current standard. Within NIOSH, the Division of Respiratory Disease Studies (DRDS) has had the responsibility for administering three programs that were mandated in that Act: the National Study of Coal Workers' Pneumoconiosis (NSCWP), the National Coal Workers' Autopsy Program (NCWAP), and the Coal Workers' X-Ray Surveillance Program (CWXSP). The NSCWP is the research program with the medical and work history information that was used for the exposure-response studies. These exposure-response studies of U.S. coal miners are a primary basis for the determination of the REL.

In addition, several exposure-response studies of British coal miners [Maclaren et al. 1989; Marine et al. 1988; Soutar et al. 1988; Hurley and Maclaren 1987; Hurley et al. 1987] and German coal miners [Breuer and Reisner 1988; Reisner 1985; Reisner 1971] were evaluated. The British Pneumoconiosis Field Research (PFR) program was used for exposure-response studies of respirable coal mine dust exposure and pneumoconiosis (both simple CWP and PMF) and COPD. In Germany, information has been gathered since 1954 on personal exposure measurements and medical data for individual coal miners, and exposure-response studies have been published [Reisner 1988, 1971]. The findings from the German studies are consistent with those of the U.S. and U.K. However, because of the use of different methodologies (see Chapter 6), it was not possible to compare the German studies with U.S. exposure-response studies or to use them in the quantitative determination of the REL.

Most studies of U.S. miners have used "years worked" as a surrogate for dust exposure [Attfield 1985a; Attfield et al. 1984a, 1984b]. In addition, some recent studies of U.S. coal miners have examined the exposure-response relationship for cumulative respirable coal mine dust [Attfield and Morring 1992a, 1992b] and decrements in lung function [Attfield and Hodous 1992; Seixas et al. 1991]. A preliminary analysis has also been performed on the prevalence of radiographic changes in U.S. miners who participated in Round 4 (1985-1988), including miners who were new to mining in 1970 [Attfield 1992a].

The validity of using respirable coal mine dust data gathered for compliance purposes for exposure-response studies can be questioned, particularly in light of the recent allegations of wide-spread tampering with the collection of dust samples by mine operators. However, exposure-response studies of U.S.

Table 7-1.–Published studies of the estimated prevalence or the excess risk of severe adverse health effects[a] in miners with cumulative exposures to respirable coal mine dust similar to those expected at the current MSHA PEL for a working lifetime[b]

| Reference | Country | Adverse health effect | Estimated prevalence (per 1,000) | Excess risk (per 1,000) | Mean cumulative exposure (gh/m$^3$) | Age (years) | Comments |
|---|---|---|---|---|---|---|---|
| Attfield and Morring 1992 | United States | PMF | 22-89 | NA | 139 | 58 | Range based on coal rank |
| Hurley and Maclaren 1988 | United Kingdom | PMF | 47.6 | NA | 200 | 50 | Attack rate in 11-year period irrespective of simple CWP |
| Hurley and Maclaren 1987 | United Kingdom | PMF | 7-18 | NA | 139 | 58 | Range based on coal rank |
| Silver et al. 1991 | United States | <65% FEV$_1$ | NA | 22 | 180 | 65 | Nonsmokers |
| Marine et al. 1988 | United Kingdom | <65% FEV$_1$ | NA | 18<br>35 | 174 | 47 | Nonsmokers<br>Smokers<br>(exposure-attributable effect) |

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[a] A severe adverse health effect is defined as being associated with disability and reduced life expectancy--for example, PMF [Attfield 1985; Miller and Jacobsen 1985; Cochrane 1979; Ortmeyer et al. 1974] and FEV$_1$ of <65% of the expected value [Marine et al. 1988; Higgins and Keller 1970].

[b] Cumulative exposure of 180 gh/m$^3$ is equivalent to a mean concentration of 2.0 mg/m$^3$ for 45 years at 2,000 hr/year; however, dose rates may be greater than expected under the current 2.0 mg/m$^3$ U.S. standard.

miners working before 1970 have also been performed; these studies used exposure data that were collected by the Bureau of Mines before the enactment of the coal mine dust standard [Attfield and Morring 1992a].

#### 7.1.5.1 Estimated Risk of Developing Pneumoconiosis

Both U.S. and British studies indicate that the risk of developing PMF is greater than the estimates of risk that were used as a basis for the current U.S. coal mine dust standard. U.S. and British mean estimates indicate that each year between 7/1,000 (0.7%) and 89/1,000 (8.9%) miners who were exposed for 40 years at the current MSHA PEL of 2 $mg/m^3$ respirable dust in underground coal mines (with $\leq$5% respirable quartz) will develop PMF by the age of 58. The range of estimates is partly due to the higher risks predicted for exposure to higher-rank coal, the differences in exposure conditions, the characteristics of the coal mining population studied, and the statistical models used by British and U.S. investigators. Coal miners at higher risk of developing PMF may be those exposed to mean concentrations of respirable coal mine dust above 2 $mg/m^3$ [Attfield and Morring 1992b] (e.g., longwall miners), those exposed to dust with greater than 5% respirable quartz [Robertson et al. 1987; Hurley et al. 1982; Seaton et al. 1981] (e.g., roof bolters), and those with increased individual susceptibility [Borm et al. 1992]. Similarly, the risk of developing PMF may be lower for miners who are exposed to dust concentrations below 2 $mg/m^3$, who work fewer than 40 years in coal mining, or who work with coal of lower rank.

Separate analyses of the risk of simple CWP and PMF among U.S. underground coal miners were performed on data from both U.S. and British coal miners. Table 7-2 illustrates that the risk estimates from the two separate analyses are reasonably consistent. These studies indicate that from 4 to 55 cases of PMF per 1,000 miners will be prevented each year by reducing exposure to a mean concentration of 1 $mg/m^3$ (mean estimates based on the difference in the

Table 7-2.–Predicted prevalences of PMF by coal rank among coal miners in the United States or the United Kingdom at age 58 after a 40-year working lifetime

| | United States: employed pre-1970* | | United States: employed pre-1970 to 1988+ | | United Kingdom§ |
|---|---|---|---|---|---|
| Coal rank | Prevalence (cases per 1,000) | (95% confidence intervals)* | Prevalence (cases per 1,000) | (95% confidence intervals) | Prevalence (cases per 1,000) |
| Mean concentration = 2 mg/m³ | | | | | |
| Anthracite coal | 89 | (69-113) | -- | -- | -- |
| Medium/low volatile Bituminous "A" coal (average carbon=89%) | 65 | (49-85) | 51 | -- | 18 |
| High volatile Bituminous "A" coal (average carbon=83%) | 22 | (17-29) | 14 | (7-27) | 7 |
| Mean concentration = 1 mg/m³ | | | | | |
| Anthracite coal | 34 | (24-48) | -- | -- | -- |
| Medium/low volatile Bituminous "A" coal (average carbon=89%) | 29 | (20-41) | 16 | -- | 7 |
| High volatile Bituminous "A" coal (average carbon=83%) | 17 | (12-24) | 9 | (4-19) | 3 |

*Confidence intervals supplied by Attfield [1993].
+Source: Attfield 1992a.
§Confidence intervals not available in Hurley and Maclaren [1987].
Source: Adapted from Attfield and Morring [1992] and Hurley and Maclaren [1987].

predicted prevalence of PMF at 2 mg/m$^3$ or 1 mg/m$^3$). The statistical (logistic regression) models used to analyze the exposure-response relationship do not account for a threshold effect (i.e., the estimated response at low exposures may be higher than would be predicted by a threshold model). Although there is no known background level of PMF in unexposed populations, the logistic models include a nonzero risk of PMF at zero exposure, which may result from extrapolation to zero exposure in a study population without a truly unexposed group.

### 7.1.5.2 Estimated Risk of Developing Nonpneumoconiotic Diseases

In addition to the risk of pneumoconiosis, coal miners have an increased risk of developing COPD, which is often detected from decrements in measures of lung function, especially FEV$_1$. Decrements in lung function associated with coal mine dust exposure have been shown, for some miners, to be severe enough to be disabling, whether or not pneumoconiosis is also present [Hurley and Soutar 1986; Soutar and Hurley 1986]. A severe or disabling decrement in lung function has been defined as an FEV$_1$ of <65% of expected values, while an impairment in lung function has been defined as <80% of expected values [Marine et al. 1988; Boehlecke 1986; Miller and Scacci 1981].

In a study of British coal miners, Marine et al. [1988] found the following excess prevalences (i.e., above background prevalence in the absence of dust exposure) of a severe decrement in FEV$_1$ (i.e., FEV$_1$ <65% of expected) for miners with a cumulative exposure to 174 gh/m$^3$ (approximately equal to the cumulative exposure of miners working at 2 mg/m$^3$ for 40 years): 1.8% (18/1,000) among those who never smoked; 3.5% (35/1,000) among current smokers. For impaired lung function (FEV$_1$ <80% of expected), the excess prevalence for miners with cumulative dust exposure of 174 gh/m$^3$ was 5.6% (56/1,000) among those who never smoked and 10.1% (101/1,000) among smokers. Silver et al. [1991] estimated similar prevalences among U.S. miners--2.2%

excess prevalence of $FEV_1$ <65% and 7.1% excess prevalence of $FEV_1$ <80% expected among those who never smoked (smokers not studied). The results are provided in Table 4-7 (Chapter 4).

The exposure-response relationship between respirable coal mine dust and reduced lung function in U.S. miners was studied by Attfield and Hodous [1992]. Table 7-3 provides estimates of the percentage of U.S. miners who will have impaired lung function ($FEV_1$ <80% of expected values) or a severe decrement in lung function ($FEV_1$ < 65% of expected values) at the age of 58 after a 40-year working lifetime exposure to a mean concentration of either 2 mg/$m^3$ or 1 mg/$m^3$. Among nonsmokers, an estimated 3.5% will have an exposure-related deficit in $FEV_1$ of <80%, an estimated 0.8% will have an $FEV_1$ of <65%. Among smokers, an estimated 6.4% will develop an exposure-related loss of <80% $FEV_1$ while an estimated 3.8% will develop <65% $FEV_1$. For either nonsmokers or smokers, these percentages are reduced by more than half if exposure for a working lifetime is reduced to a mean concentration of 1 mg/$m^3$. However, the exposure-related risk of a severe lung function decrement ($FEV_1$ <65%) among nonsmokers is still 0.3% (3/1,000) at the mean concentration of 1 mg/$m^3$.

### 7.1.5.3 Hypothesis of Overloading Lung Clearance Mechanisms

The overload hypothesis was developed from findings of chronic inhalation studies in animals. The overloading of lung clearance mechanisms may also be relevant to the etiology of fibrotic lung diseases in coal miners (see Section 4.2). No published studies were found that investigated directly the question of overloading lung clearance mechanisms in humans. However, pathologic studies of coal miners [Douglas et al. 1986; Ruckley et al. 1984] indicate that coal miners who had cumulative exposures near the current exposure limit (137 to 195 gh/$m^3$) had retained dust burdens of 5.4 to 15.0 mg dust/g tissue. These were 5- to 30-fold higher than the levels found in

Table 7-3. Percentage of U.S. miners (at age 58) predicted to have reduced lung function (measured by forced expiratory volume in one second, $FEV_1$) associated with exposure to respirable coal mine dust for a 40-year working lifetime.

| Mean concentration | Level of reduced $FEV_1$ | Percentage of miners with reduced $FEV_1$ | |
|---|---|---|---|
| | | Smokers | Nonsmokers |
| 2 mg/$m^3$ | $FEV_1$ <80% of expected | 37.0 | 14.1 |
| | Background (no dust exposure) | 30.6 | 10.6 |
| | Excess (exposure-related) | 6.4 | 3.5 |
| | $FEV_1$ <65% of expected | 15.4 | 2.3 |
| | Background (no dust exposure) | 11.6 | 1.5 |
| | Excess (exposure-related) | 3.8 | 0.8 |
| 1 mg/$m^3$ | $FEV_1$ <80% of expected | 33.7 | 12.3 |
| | Background (no dust exposure) | 30.6 | 10.6 |
| | Excess (exposure-related) | 3.1 | 1.7 |
| | $FEV_1$ <65% of expected | 13.4 | 1.8 |
| | Background (no dust exposure) | 11.6 | 1.5 |
| | Excess (exposure-related) | 1.8 | 0.3 |

Source: Attfield and Hodous [1992].

chronic inhalation studies of rodents that caused overloading of lung clearance mechanisms and the development of fibrosis (0.5 to 1.0 mg dust/g tissue) [Morrow et al. 1991; Muhle et al. 1991; Mermelstein and Kilpper 1990; Muhle et al. 1990; Morrow 1988].

Mermelstein and Kilpper [1990] estimated that after 2 years of exposure to a mean respirable dust concentration of 1.5 $mg/m^3$, the human lung burden will exceed the concentration at which overload of lung clearance mechanisms may occur. Their estimates also indicate that at a mean concentration of 0.35 $mg/m^3$ for 7 years, the lung burden does not exceed the "overload transition zone," suggesting that fibrogenesis would not occur.

An important aspect of the overload hypothesis is that the overloading of the lung clearance mechanisms is independent of the composition of the respirable dust if the dust is relatively inert and not cytotoxic. Exposure to cytotoxic dusts (e.g., silica) lowers the lung burden that is necessary to cause overloading and fibrogenesis. Although the estimates by Mermelstein and Kilpper [1990], were based on studies of respirable "test toner" (used in photographic processes), they may be applicable to respirable coal mine dust because of similar particle characteristics and size distribution (mass median aerodynamic diameter of 4.0 µm; geometric standard deviation of 1.5) [Muhle et al. 1991]. Although not proven in humans, the overload hypothesis provides both a biologically plausible mechanism for fibrogenesis and risk predictions that agree with epidemiologic studies.

#### 7.1.5.4 Consideration of the Coal Rank Effect in Determination of the REL for Respirable Coal Mine Dust

Several epidemiologic studies have shown that the prevalence of simple CWP and PMF increases with increasing coal rank [Lainhart 1969; McBride et al. 1966; McBride et al. 1963]. Recent exposure-response studies have estimated that the probability of developing PMF over a working lifetime is higher for exposures to respirable coal mine dust of higher rank [Attfield et al. 1992b; Hurley and Maclaren 1987]. However, studies in animals exposed to respirable coal dust of different rank have not found differences in the effects of exposure to high or low rank coal [Morrow and Yuile 1982; Moorman et al. 1975]. Further, studies to date have not found a coal rank effect on the exposure-response relationship between respirable coal mine dust and the development of chronic obstructive pulmonary diseases.

Biochemical studies have shown that coal dust with freshly fractured surfaces contain a higher concentration of oxygen radicals [Dalal et al. 1989] and that surface characteristics of silica particles influences toxicity observed in cellular systems [Wallace et al. 1990]. Pathologic studies have shown a dose-related increase in the severity of PMF with higher concentrations of organic radicals in the lung tissue [Jafari et al. 1988; Vallyathan et al. 1988]. However, these studies did not determine the lung dust burdens relative to radical concentration. It has been shown that increasing lung dust burden is associated with increasing severity of disease [Douglas et al. 1986; Ruckley et al. 1984]. Douglas et al. [1986] found that the mean weight of dust in the lungs increased with increasing size of pneumoconiotic lesions regardless of the rank of coal to which miners were exposed.

Thus, the coal rank effect (including the role of the concentration and radical reactivity of respirable crystalline silica as a component in the respirable coal mine dust) needs to be further elucidated. Then it may be possible to determine whether a coal rank-dependent REL for respirable coal mine dust or for respirable crystalline silica might contribute to reducing the incidence of pneumoconiosis, silicosis, and obstructive airways diseases.

## 7.2 APPLICABILITY OF THE REL FOR RESPIRABLE COAL MINE DUST TO WORKERS OTHER THAN UNDERGROUND COAL MINERS

### 7.2.1 Surface coal miners

Studies of U.S. surface coal miners have shown that they, like underground miners, are at risk of developing CWP and silicosis, particularly among workers on drill crews (see Tables 4-7 and 4-8) [Amandus et al. 1989; Amandus et al. 1984; Fairman et al. 1977]. Further, Amandus et al. [1989] found that decrements in lung function (measured by $FEV_1$, FVC, peak flow) are significantly related to years worked as drill operators or drill helpers at surface mines. Based on the evaluation of existing data, NIOSH recommends inclusion of surface miners in the same program for environmental and medical monitoring recommended in this document for underground coal miners, including the existing Coal Workers' X-Ray Surveillance Program (see Chapter 1). The RELs for respirable crystalline silica and respirable coal mine dust should also apply to surface coal miners.

### 7.2.2 Workers With Exposure to Coal Dust in Occupations Other Than Mining

Extensive environmental sampling data and health effects data exist for underground coal miners (Chapter 4), and several studies are available concerning surface coal miners [Amandus et al. 1989; Amandus et al. 1984; Fairman et al. 1977; NIOSH 1974] and workers exposed to silica [MMWR 1990; Suratt et al. 1977; NIOSH 1972]. However, few studies have been done of workers who are exposed to respirable coal dust in occupations other than coal mining. A Bureau of Mines survey of 21 coal preparation and mineral processing plants (there are about 500 in the United States) found that one-third had high dust levels in localized areas of the plant (up to 11 $mg/m^3$), although worker occupancy in those areas was often temporary [Divers and Cecala 1990].

Several NIOSH health hazard evaluations concluded that potential health hazards from coal dust and quartz may exist for workers at coal-powered electrical generating plants [Lewis 1983; Zey and Donohue 1983; Hartle 1981]. In a combined environmental study and medical evaluation of workers exposed to coal dust and to boiler gases (including sulfur dioxide), respiratory symptoms of cough, phlegm, and wheezing were two-fold higher than expected, four cases of pneumoconiosis were found, and no decrements in lung function were observed [Zey and Donohue 1983]. A study of surface miners and coal cleaning plant workers in the anthracite coal mining region of the United States found that pulmonary function (measured by $FEV_1$, FVC, and peak flow) was not related to years worked in coal cleaning plants in anthracite coal mining regions [Amandus et al. 1989]. Although the exposure and health effects data is limited for workers other than miners who are exposed to respirable coal dust, the available evidence indicates a potential for exposures sufficient to cause pneumoconiosis. It is reasonable to assume that the etiology of pneumoconiosis would be similar, given comparable exposures, for miners exposed to coal mine dust or to coal dust. Thus, the REL for respirable coal mine dust should also apply to workers exposed to coal dust in occupations other than mining.

## 7.3 TECHNICAL FEASIBILITY OF ACHIEVING THE REL FOR RESPIRABLE COAL MINE DUST AND RESPIRABLE CRYSTALLINE SILICA IN UNDERGROUND AND SURFACE COAL MINES

The Federal Mine Safety and Health Amendments Act of 1977 requires NIOSH to develop and revise recommended occupational safety and health standards for miners [30 USC 811]. Specifically, the Secretary of Health, Education, and Welfare (now the Secretary of Health and Human Services) is required to consider, "in addition to the attainment of the highest degree of health protection for the miner . . . the latest available scientific data in the field, the technical feasibility of the standards, and experience gained under this and other health statutes" [30 USC 8116 (A)].

NIOSH considers a 0.9-mg/m$^3$ REL for coal mine dust (based on recommended sampling strategy in Chapter 5) to be technically feasible for most coal mines if effective control methods are used and rigorously maintained at reasonable levels of production according to a preapproved dust control plan. Tables 7-4 through 7-7 show the percentage of samples below various concentrations of respirable coal mine dust for both underground and surface occupations. These tables indicate that the average concentration of respirable coal mine dust is below the current MSHA PEL of 2.0 mg/m$^3$ (MRE) for most occupations, and in general, about one-third to one-half of all samples were below 1.0 mg/m$^3$. Underground coal mine occupations for which it may be technically difficult to achieve the REL include longwall shear or plow operators, jack setters (longwall or auger, return side), and tailgate operators. Thus, control of respirable coal mine dust for these high-dust occupations should be a priority.

Tables 7-8 through 7-10 illustrate that for most strip mine occupations, the average concentration of respirable crystalline silica exceeds the NIOSH REL of 0.05 mg/m$^3$. Thus, control of respirable crystalline silica should be a priority for surface coal mining operations.

Bureau of Mines (BOM) data indicate that the dust concentrations in underground coal mines for the period 1981-84 had a range of arithmetic means from 1.01 to 1.12, and a range of geometric means from 0.59 to 0.69 mg/m$^3$ [BOM 1987]. Respirable dust data obtained from the operator sampling program for longwall mines during the period of October 1, 1989, to September 30, 1990, indicate that some operators maintained dust concentrations at or below 1.0 mg/m$^3$ on more than 50% of the total number of individual samples submitted for compliance determination for the entire period [MSHA 1990]. Some examples are mine 36-00970 entity 0150, mine 36-00840 entity 0740, mine 36-00906 entity 0800, 46-01968 entity 0560, mine 01-01322 entity 0110. In reviewing operator data it must be remembered that the present limit is 2.0 mg/m$^3$, and operators are under no strictures to maintain dust below that limit.

Because the mine environment and mining methods vary, the combination of effective dust control techniques will vary across mines and mining sections. The parameters of the dust control methods (e.g., ventilation or water) should be specified in the dust control plan for the effective control of respirable dust at reasonable "normal" production levels (i.e., 90% of the average level for the previous 6 months). Appendix C lists available control techniques by mining method.

### 7.3.1 Sources of Dust and Dust Control Methods Currently Used in Underground Coal Mines

A primary source of dust generation in underground mines is the shearer or plow that is cutting the coal face [Jankowski et al. 1991b; Mundell et al. 1984]. Double drum shearers disperse more dust than single drum shearers because the drum on the shearer cannot rotate in the same direction as the airflow [Mundell et al. 1984]. Respirable dust exposure of a coal face worker (e.g., shearer operator) is influenced by his work position (e.g., relative to the cutting drum) and the direction of airflow [McClelland and Jankowski 1991; Mundell et al. 1984]. Another major source of dust exposure for the shearer operator is the dust generated by roof supports in longwall operations, with geologic conditions being the most important factor (roof strength was inversely related to the amount of dust generated) [Organiscak et al. 1990; Organiscak et al. 1985].

The methods to control miners' exposures to respirable dust include (1) engineering controls, (2) administrative controls, and (3) personal protective equipment. Engineering controls for respirable coal mine dust include dilution and removal of the dust by the intake air stream, containment of the

Table 7-4.–Samples of respirable coal mine dust collected by MSHA inspectors for underground occupations, 1987-91

| MSHA code | Occupation | Number of samples | Concentration of coal mine dust (mg/m³) Arithmetic mean | Standard deviation | Percentage of samples ≤0.5 mg/m³ | ≤1.0 mg/m³ | ≤1.5 mg/m³ | ≤2.0 mg/m³ | >2.0 mg/m³ |
|---|---|---|---|---|---|---|---|---|---|
| 044 | Shear operator, plow operator (longwall) | 1,252 | 2.58 | 1.83 | 1 | 10 | 24 | 45 | 55 |
| 041 | Jack setter (longwall) | 2,398 | 2.36 | 3.10 | 2 | 14 | 30 | 53 | 47 |
| 052 | Tailgate operator | 136 | 2.77 | 3.09 | 15 | 29 | 36 | 53 | 47 |
| 055 | Jack setter (auger-return side) | 156 | 2.62 | 3.91 | 26 | 47 | 57 | 65 | 35 |
| 048 | Roof bolter mounted | 373 | 1.79 | 1.25 | 4 | 28 | 46 | 67 | 33 |
| 032 | Brattice man | 60 | 1.66 | 1.33 | 12 | 37 | 58 | 70 | 30 |
| 036 | Continuous miner operator | 10,533 | 1.78 | 2.48 | 14 | 41 | 56 | 72 | 28 |
| 038 | Cutting machine operator | 1,661 | 1.82 | 3.07 | 22 | 49 | 60 | 72 | 28 |
| 035 | Continuous miner helper | 5,461 | 1.71 | 3.03 | 14 | 42 | 57 | 74 | 26 |
| 010 | Timberman; propman; jack setter | 161 | 1.94 | 3.50 | 26 | 50 | 62 | 76 | 24 |
| 043 | Loading machine operator | 803 | 1.54 | 2.22 | 20 | 51 | 65 | 77 | 23 |
| 070 | Auger operator | 240 | 1.59 | 2.74 | 31 | 58 | 69 | 77 | 23 |
| 047 | Roof bolter helper | 1,245 | 1.43 | 1.59 | 21 | 51 | 65 | 78 | 22 |
| 037 | Cutting machine helper | 175 | 1.62 | 3.67 | 22 | 55 | 68 | 79 | 21 |
| 007 | Blaster; shotfirer; shooter | 288 | 1.32 | 1.61 | 32 | 56 | 67 | 80 | 20 |
| 046 | Roof bolter | 7,898 | 1.40 | 2.27 | 22 | 53 | 68 | 81 | 19 |
| 053 | Utility man | 1,163 | 1.23 | 1.17 | 23 | 53 | 70 | 83 | 17 |
| 072 | Mobile bridge operator | 1,342 | 1.22 | 1.52 | 27 | 60 | 73 | 84 | 16 |
| 040 | Headgate operator | 839 | 1.19 | 0.96 | 14 | 54 | 71 | 86 | 14 |
| 050 | Shuttle car operator (on side) | 9,371 | 1.15 | 1.61 | 24 | 59 | 73 | 87 | 13 |

Table 7-5.–Samples of respirable coal mine dust collected by mine operators for underground occupations, 1987-91.

| MSHA code | Occupation | Number of samples | Concentration of coal mine dust (mg/m$^3$) |  | Percentage of samples |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Arithmetic mean | Standard deviation | ≤0.5 mg/m$^3$ | ≤1.0 mg/m$^3$ | ≤1.5 mg/m$^3$ | ≤2.0 mg/m$^3$ | >2.0 mg/m$^3$ |
| 044 | Shear Operator; plow operator (longwall) | 12,043 | 2.40 | 1.74 | 4 | 18 | 30 | 50 | 50 |
| 052 | Tailgate operator | 807 | 2.50 | 2.15 | 12 | 27 | 36 | 50 | 50 |
| 041 | Jack setter (longwall) | 1,664 | 2.34 | 1.76 | 4 | 21 | 36 | 53 | 47 |
| 010 | Timberman; propman, jack setter | 10 | 1.71 | 1.16 | 10 | 40 | 50 | 60 | 40 |
| 048 | Roof bolter mounted | 53 | 2.50 | 2.49 | 4 | 23 | 38 | 64 | 36 |
| 040 | Headgate operator | 47 | 1.16 | 0.92 | 9 | 28 | 45 | 68 | 32 |
| 035 | Continuous miner helper | 422 | 1.62 | 1.38 | 15 | 44 | 57 | 72 | 28 |
| 050 | Shuttle car operator (on side) | 405 | 1.72 | 1.57 | 12 | 41 | 55 | 72 | 28 |
| 043 | Loading machine operator | 1,044 | 1.35 | 1.50 | 26 | 58 | 70 | 78 | 22 |
| 047 | Roof bolter helper | 39 | 1.30 | 1.15 | 28 | 51 | 69 | 79 | 21 |
| 036 | Continuous miner operator | 217,092 | 1.37 | 1.5 | 25 | 54 | 67 | 80 | 20 |
| 053 | Utility man | 36 | 1.12 | 0.86 | 28 | 53 | 64 | 83 | 17 |
| 007 | Blaster; shotfirer; shooter | 31 | 0.81 | 1.10 | 55 | 77 | 84 | 84 | 16 |
| 046 | Roof bolter | 2,816 | 1.17 | 1.42 | 28 | 61 | 74 | 86 | 14 |
| 072 | Mobile bridge operator | 114 | 1.20 | 1.58 | 25 | 57 | 76 | 87 | 13 |
| 038 | Cutting machine operator | 35,507 | 0.98 | 1.25 | 36 | 68 | 80 | 89 | 11 |
| 070 | Auger operator | 2,728 | 1.01 | 1.21 | 34 | 67 | 79 | 89 | 11 |
| 055 | Jack setter (auger-return side) | 2,899 | 1.04 | 0.98 | 27 | 60 | 77 | 90 | 10 |

Table 7-6.–Samples of respirable coal mine dust collected by MSHA inspectors from workers for surface occupations, 1987-91

| MSHA code | Occupation | Number of samples | Concentration of coal mine dust (mg/m³) |  | Percentage of samples |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Arithmetic mean | Standard deviation | ≤0.5 mg/m³ | ≤1.0 mg/m³ | ≤1.5 mg/m³ | ≤2.0 mg/m³ | >2.0 mg/m³ |
| 380 | Fine coal plant operator | 592 | 1.58 | 1.62 | 12 | 40 | 57 | 75 | 25 |
| 388 | Scalper-screen operator | 334 | 1.70 | 3.32 | 28 | 57 | 66 | 75 | 25 |
| 384 | Driller; highwall operator | 2,839 | 1.84 | 4.27 | 30 | 60 | 69 | 77 | 23 |
| 347 | Froth cell operator | 95 | 1.63 | 2.02 | 8 | 36 | 55 | 78 | 22 |
| 334 | Coal drill operator | 57 | 1.67 | 2.48 | 26 | 60 | 74 | 79 | 21 |
| 319 | Welder; blacksmith (shop) | 253 | 1.89 | 3.9 | 45 | 64 | 71 | 81 | 19 |
| 313 | Cleanup man | 500 | 1.21 | 1.59 | 31 | 57 | 71 | 83 | 17 |
| 316 | Laborer; blacksmith | 1,515 | 1.04 | 1.80 | 45 | 69 | 79 | 87 | 13 |
| 379 | Dryer operator | 156 | 1.56 | 7.44 | 33 | 65 | 78 | 90 | 10 |
| 356 | Rock driller | 70 | 0.86 | 0.95 | 37 | 77 | 84 | 90 | 10 |
| 392 | Tipple operator | 1,463 | 0.88 | 2.03 | 49 | 77 | 85 | 91 | 9 |
| 374 | Cleaning plant operator | 915 | 1.07 | 3.17 | 35 | 69 | 81 | 91 | 9 |
| 383 | Driller; highwall helper | 140 | 0.93 | 1.82 | 49 | 76 | 86 | 91 | 9 |
| 314 | Coal sampler | 325 | 0.88 | 1.21 | 39 | 76 | 83 | 92 | 8 |
| 341 | Beltman; conveyor man | 222 | 0.78 | 1.11 | 51 | 77 | 86 | 92 | 8 |
| 386 | Refuse truck driver | 3,118 | 0.78 | 1.14 | 39 | 77 | 88 | 94 | 6 |
| 357 | Washer operator | 214 | 0.85 | 0.77 | 34 | 69 | 81 | 94 | 6 |
| 302 | Electrician | 465 | 0.66 | 0.67 | 48 | 80 | 91 | 95 | 5 |
| 307 | Blaster; shotfirer; shooter | 219 | 0.71 | 0.82 | 45 | 80 | 89 | 95 | 5 |
| 368 | Bulldozer operator | 6,280 | 0.67 | 1.80 | 51 | 84 | 91 | 96 | 4 |

Table 7-7.–Samples of respirable coal mine dust collected by mine operators for surface occupations, 1987-91

| MSHA code | Occupation | Number of samples | Concentration of coal mine dust ($mg/m^3$) Arithmetic Mean | Standard deviation | Percentage of samples ≤0.5 $mg/m^3$ | ≤1.0 $mg/m^3$ | ≤1.5 $mg/m^3$ | ≤2.0 $mg/m^3$ | >2.0 $mg/m^3$ |
|---|---|---|---|---|---|---|---|---|---|
| 347 | Froth cell operator | 269 | 1.63 | 1.11 | 5 | 29 | 51 | 70 | 30 |
| 388 | Scalper-screen operator | 793 | 1.48 | 1.47 | 23 | 46 | 60 | 76 | 24 |
| 380 | Fine coal plant operator | 1,785 | 1.34 | 1.08 | 18 | 47 | 61 | 80 | 20 |
| 379 | Dryer operator | 244 | 1.16 | 0.99 | 30 | 58 | 66 | 82 | 18 |
| 356 | Rock driller | 121 | 1.10 | 1.49 | 44 | 68 | 77 | 83 | 17 |
| 316 | Laborer; blacksmith | 2,641 | 1.17 | 1.18 | 30 | 58 | 69 | 84 | 16 |
| 319 | Welder; blacksmith (shop) | 105 | 1.28 | 2.14 | 46 | 70 | 75 | 84 | 16 |
| 384 | Driller; highwall operator | 6,073 | 1.17 | 2.51 | 2 | 68 | 78 | 86 | 14 |
| 357 | Washer operator | 348 | 1.16 | 0.92 | 25 | 53 | 69 | 86 | 14 |
| 313 | Cleanup man | 1,292 | 1.09 | 1.99 | 31 | 65 | 75 | 87 | 13 |
| 392 | Tipple operator | 1,574 | 1.01 | 1.23 | 37 | 67 | 78 | 88 | 12 |
| 374 | Cleaning plant operator | 1,340 | 1.08 | 0.82 | 24 | 58 | 72 | 89 | 11 |
| 302 | Electrician | 413 | 0.94 | 1.17 | 42 | 70 | 80 | 91 | 9 |
| 383 | Driller; highwall helper | 516 | 0.80 | 1.24 | 50 | 81 | 86 | 92 | 8 |
| 334 | Coal drill operator | 241 | 0.77 | 1.14 | 52 | 81 | 88 | 93 | 7 |
| 386 | Refuse truck driver | 2,009 | 0.75 | 1.65 | 50 | 80 | 89 | 94 | 6 |
| 314 | Coal sampler | 414 | 0.82 | 0.88 | 35 | 75 | 87 | 94 | 6 |
| 368 | Bulldozer operator | 4,230 | 0.65 | 0.85 | 53 | 82 | 91 | 95 | 5 |
| 307 | Blaster; shotfirer; shooter | 170 | 0.74 | 0.88 | 36 | 80 | 91 | 96 | 4 |
| 341 | Beltman; conveyor man | 185 | 0.64 | 2.04 | 62 | 90 | 96 | 98 | 2 |

Table 7-8.--Average concentrations of respirable crystalline silica at surface worksites by job category for samples collected from 1982 through 1991[*]

| | Coal-mine-operator-collected samples | | | | | MSHA-inspector-collected samples | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number of samples | Percent >0.072 mg/m³ | Percent >0.050 mg/m³ | Arithmetic mean | Standard deviation | Number of samples | Percent >0.072 mg/m³ | Percent >0.050 mg/m³ | Arithmetic mean | Standard deviation |
| **Strip mine** | | | | | | | | | | |
| Shotfirer | 11 | 45 | 73 | 0.07 | 0.03 | 43 | 51 | 65 | 0.10 | 0.11 |
| Pan scraper opr.[†] | 13 | 8 | 31 | 0.06 | 0.11 | 131 | 47 | 60 | 0.11 | 0.17 |
| Coal driller | 5 | 0 | 0 | 0.03 | 0.02 | 31 | 45 | 45 | 0.15 | 0.34 |
| Rock driller | 3 | 67 | 100 | 0.21 | 0.22 | 32 | 69 | 78 | 0.27 | 0.28 |
| Coal shovel opr. | 0 | -- | -- | -- | -- | 16 | 6 | 25 | 0.05 | 0.09 |
| Bulldozer opr. | 144 | 40 | 55 | 0.10 | 0.13 | 1271 | 49 | 59 | 0.15 | 0.22 |
| Road grader opr. | 3 | 67 | 100 | 0.07 | 0.01 | 24 | 17 | 25 | 0.04 | 0.04 |
| Coal truck driver | 12 | 33 | 58 | 0.06 | 0.04 | 90 | 24 | 30 | 0.07 | 0.17 |
| Drag line opr. | 0 | -- | -- | -- | -- | 19 | 5 | 11 | 0.02 | 0.05 |
| High lift opr. | 26 | 38 | 50 | 0.07 | 0.07 | 718 | 14 | 24 | 0.04 | 0.06 |
| Highwall driller hlp.[†] | 12 | 75 | 83 | 0.43 | 0.33 | 77 | 77 | 84 | 0.37 | 0.83 |
| Highwall driller | 243 | 54 | 74 | 0.18 | 0.28 | 1233 | 74 | 82 | 0.30 | 0.47 |
| Refuse truck driver | 94 | 18 | 29 | 0.05 | 0.10 | 713 | 31 | 43 | 0.06 | 0.07 |
| Strip shovel opr. | 1 | -- | -- | 0.01 | -- | 10 | 50 | 70 | 0.10 | 0.13 |
| Auger opr. | 1 | 0 | 0 | 0.02 | -- | 24 | 21 | 29 | 0.05 | 0.06 |
| Auger hlp. | 0 | -- | -- | -- | -- | 30 | 3 | 3 | 0.02 | 0.03 |
| Boom opr. | 0 | -- | -- | -- | -- | 12 | 8 | 8 | 0.02 | 0.03 |
| **Preparation facility** | | | | | | | | | | |
| Coal sampler | 1 | -- | -- | 0.01 | -- | 90 | 8 | 11 | 0.03 | 0.07 |
| Crusher attendant | 2 | 0 | 0 | 0.02 | 0.02 | 51 | 10 | 20 | 0.05 | 0.15 |
| Car dropper | 0 | -- | -- | -- | -- | 40 | 0 | 5 | 0.01 | 0.01 |
| Cleaning plant opr. | 0 | -- | -- | -- | -- | 330 | 2 | 3 | 0.01 | 0.02 |
| Dryer opr. | 0 | -- | -- | -- | -- | 67 | 1 | 1 | 0.01 | 0.02 |
| Fine coal plant opr. | 9 | 0 | 0 | 0.00 | 0.01 | 358 | 2 | 4 | 0.01 | 0.03 |
| Scalper/screen opr. | 5 | 0 | 0 | 0.01 | 0.01 | 206 | 6 | 11 | 0.02 | 0.03 |
| Tipple opr. | 0 | -- | -- | -- | -- | 393 | 1 | 3 | 0.01 | 0.02 |
| Washer opr. | 2 | 0 | 0 | 0.03 | 0.02 | 56 | 2 | 5 | 0.01 | 0.03 |
| Froth cell opr. | 0 | -- | -- | -- | -- | 40 | 0 | 3 | 0.01 | 0.01 |
| Diester table opr. | 0 | -- | -- | -- | -- | 20 | 0 | 0 | 0.01 | 0.01 |

(continued)

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See footnotes at end of table.

Table 7-8 (Continued).--Average concentrations of respirable crystalline silica at surface worksites by job category for samples collected from 1982 through 1991*

| | Coal-mine-operator-collected samples | | | | | MSHA-inspector-collected samples | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number of samples | Percent >0.072 $mg/m^3$ | Percent >0.050 $mg/m^3$ | Arithmetic mean | Standard deviation | Number of samples | Percent >0.072 $mg/m^3$ | Percent >0.050 $mg/m^3$ | Arithmetic mean | Standard deviation |
| Shop/maintenance | | | | | | | | | | |
| Electrician | 1 | -- | -- | 0.00 | -- | 74 | 1 | 1 | 0.01 | 0.01 |
| Mechanic | 3 | 0 | 0 | 0.02 | 0.02 | 321 | 2 | 4 | 0.01 | 0.04 |
| Laborer | 13 | 8 | 8 | 0.03 | 0.06 | 553 | 4 | 8 | 0.02 | 0.06 |
| Greaser/oiler | 7 | 29 | 43 | 0.06 | 0.08 | 100 | 3 | 8 | 0.01 | 0.02 |
| Welder | 0 | -- | -- | -- | -- | 69 | 1 | 1 | 0.00 | 0.01 |
| Welder/nonshop | 0 | -- | -- | -- | -- | 33 | 0 | 0 | 0.00 | 0.00 |
| Miscellaneous | | | | | | | | | | |
| Conveyor opr. | 0 | -- | -- | -- | -- | 16 | 13 | 13 | 0.04 | 0.08 |
| Clean-up | 10 | 30 | 30 | 0.05 | 0.05 | 240 | 4 | 5 | 0.01 | 0.02 |
| Beltman | 0 | -- | -- | -- | -- | 30 | 0 | 0 | 0.01 | 0.01 |
| Backhoe opr. | 3 | 33 | 67 | 0.07 | 0.04 | 11 | 9 | 18 | 0.02 | 0.03 |
| Utility man | 2 | 0 | 0 | 0.01 | 0.01 | 47 | 6 | 11 | 0.03 | 0.10 |
| Vacuum filter opr. | 0 | -- | -- | -- | -- | 11 | 0 | 9 | 0.01 | 0.02 |

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*Includes occupations with 10 or more samples; 0.072 $mg/m^3$ is equivalent to the MSHA PEL of 0.100 $mg/m^3$ for respirable quartz, without MRE conversion; 0.050 $mg/m^3$ equals the NIOSH REL for respirable crystalline silica.

†Abbreviations: Opr.=operator; hlp.=helper

Table 7-9.--Occupations with the highest concentrations of respirable crystalline silica at surface worksites from 1982 through 1991*

| | Coal-mine-operator-collected samples | | | | | MSHA-inspector-collected samples | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Occupation | N | Mean concentration (mg/m³) | Standard deviation | Percent >0.072 mg/m³ | Percent >0.050 mg/m³ | Occupation | N | Mean concentration (mg/m³) | Standard deviation | Percent >0.072 mg/m³ | Percent >0.050 mg/m³ |
| Highwall driller | 243 | 0.18 | 0.28 | 54 | 74 | Highwall driller hlp. | 77 | 0.37 | 0.83 | 77 | 84 |
| Bulldozer opr.† | 144 | 0.10 | 0.12 | 40 | 50 | Highwall driller | 1233 | 0.30 | 0.47 | 74 | 82 |
| Highlift opr. | 26 | 0.07 | 0.07 | 38 | 50 | Rock driller | 32 | 0.27 | 0.28 | 69 | 78 |
| Refuse truck driver | 94 | 0.05 | 0.10 | 18 | 29 | Shotfirer | 43 | 0.10 | 0.11 | 51 | 65 |
| | | | | | | Pan scraper opr. | 131 | 0.11 | 0.17 | 47 | 60 |
| | | | | | | Bulldozer opr. | 1271 | 0.15 | 0.22 | 49 | 59 |
| | | | | | | Coal driller | 31 | 0.15 | 0.34 | 45 | 45 |
| | | | | | | Refuse truck driver | 713 | 0.06 | 0.07 | 31 | 43 |
| | | | | | | Coal truck driver | 90 | 0.07 | 0.17 | 24 | 30 |
| | | | | | | Crusher attendant | 51 | 0.05 | 0.15 | 10 | 20 |

*Only occupations with >20 samples were included; 0.072 mg/m³ corresponds to the MSHA PEL for respirable crystalline silica of 0.100 mg/m³ without MRE conversion; 0.050 mg/m³ equals the NIOSH REL for respirable crystalline silica.

†Abbreviations: Opr.=operator; hlp.=helper

Table 7-10.--Average concentrations of respirable crystalline silica at surface worksites by year, from 1982 through 1991*

| | Operator samples | | | | | Inspector samples | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | Number of samples | Arithmetic average | Standard deviation | Percent >0.072 mg/m³ | Percent >0.050 mg/m³ | Number of samples | Arithmetic average | Standard deviation | Percent >0.072 mg/m³ | Percent >0.050 mg/m³ |
| 1982 | none | none | none | none | none | 530 | 1.14 | 0.40 | 36 | 42 |
| 1983 | none | none | none | none | none | 1,110 | 0.11 | 0.30 | 32 | 37 |
| 1984 | none | none | none | none | none | 1,002 | 0.11 | 0.27 | 33 | 39 |
| 1985 | none | none | none | none | none | 766 | 0.09 | 0.21 | 29 | 35 |
| 1986 | 70 | 0.15 | 0.20 | 47 | 61 | 885 | 0.08 | 0.17 | 24 | 31 |
| 1987 | 130 | 0.10 | 0.18 | 33 | 49 | 717 | 0.06 | 0.26 | 24 | 31 |
| 1988 | 123 | 0.13 | 0.26 | 40 | 54 | 958 | 0.09 | 0.27 | 26 | 35 |
| 1989 | 121 | 0.13 | 0.18 | 42 | 62 | 84 | 0.09 | 0.26 | 26 | 32 |
| 1990 | 128 | 0.09 | 0.14 | 37 | 49 | 681 | 0.08 | 0.18 | 28 | 34 |
| 1991 | 58 | 0.14 | 0.32 | 40 | 52 | 379 | 0.08 | 0.26 | 20 | 26 |
| 1982-91 | 630 | 0.12 | 0.21 | 39 | 54 | 7712 | 0.10 | 0.25 | 28 | 35 |

*0.072 mg/m³ corresponds to the MSHA PEL for respirable crystalline silica of 0.100 mg/m³ without MRE conversion; 0.050 mg/m³ equals the NIOSH REL for respirable crystalline silica.

dust away from the miners by localized air streams and water sprays, water infusion in the coal seam to reduce the formation of respirable dust, and improved cutting machine parameters [Organiscak et al. 1981; Green 1987; Mundell et al. 1984; McClelland 1987, 1988]. The Bureau of Mines has conducted some studies into remote location of the shearer operator or continuous miner operator.

Administrative methods to control workers' exposures to respirable dust include (1) remote location of the shearer operator and (2) modified cutting sequence, or cutting in one direction in longwall sections. The disadvantages of remote shearer operation include difficulty in maintaining desired cutting height; the disadvantages of modified cutting sequence include the loss of production.

Personal protective equipment consists of approved respirators and a respiratory protection program. The use of respirators in the active workings is currently restricted by 30 CFR 70.300.

The effectiveness of various engineering controls depends on basic mining variables: mining technique, specific type of mechanized mining unit, coal seam, and ventilation parameters. The BOM has published numerous papers about effective dust control technologies for various mining systems.

When the air velocity at the coal face exceeds about 500 feet per minute (fpm) and the dust has low moisture content (<2% to 3% water, by weight), entrainment of dust in the air can occur; however, by wetting the coal (5% to 8% water, by weight), face velocity of 900 fpm is possible without entrainment [Mundell et al. 1984; Breuer 1972]. Water is applied through sprays mounted on cutting drums, cowls, the shearer, and roof supports along the coal face [Mundell et al. 1984]. A water-powered scrubber for continuous mining machines was found to be equally effective in reducing respirable coal mine dust and respirable quartz, with a collection efficiency of 72% for all respirable dust (using a double filter panel) [Jayaraman et al. 1990]. Water infusion in retreating longwalls was shown in one U.S. study to reduce dust concentrations by 47% to 64% [McClelland et al. 1987; Cervik et al. 1985]. Another source of dust entrainment is face airflow in the opposite direction of coal transport, which has been a common practice in longwall mines [Mundell et al. 1984]. Regarding cutting machine parameters, the depth of cut and bit sharpness are the most important for affecting the generation of respirable dust [Mundell et al. 1984].

### 7.3.2 Engineering and Administrative Controls Used to Maintain Respirable Dust Concentrations Below the 2.0 mg/m$^3$ PEL in Underground Coal Mines

A study of continuous miner controls conducted by the BOM indicates that, with optimum water sprays and local air flow to control the dust cloud, operator exposures can be maintained well below 1.0 mg/m$^3$ [Colinet et al. 1991]. Maintaining respirable dust concentrations below the MSHA PEL of 2.0 mg/m$^3$ has generally been difficult in mines using longwall methods [Tomb et al. 1990; Dieffenbach 1988; Watts and Parker 1987]. However, compliance has been successfully maintained in mines with effective dust control systems [Webster et al. 1990]. In a study of six high tonnage longwall mines by the U.S. Bureau of Mines (BOM), the production average was 4,600 tons/shift, yet effective dust control measures were used to keep the mines in compliance with the MSHA PEL of 2.0 mg/m$^3$ respirable coal mine dust [Jankowski et al. 1991a]. The major sources of respirable dust were found to be the shearer during the tail-to-head cut pass (40% to 59% of total respirable dust), and the stageloader/crusher (17% to 28% of total dust generated on the longwall face). Dust control measures included the following: (1) reduction of dust generated by the shearer by using high drum water flow rates, deep cutting, shearer-clearer-type external water spray systems [Jankowski et al. 1986], and radio-remote control; (2) reduction of dust generated during coal transport by adjusting high shearer water flow rates and using an enclosed stageloader with scrubber; and (3) reduction of exposure to dust generated during support advance by using electrohydraulic control systems (administrative control). In another BOM study, Jankowski et al. [1991b] tested an improved design of the shearer drum (the major source of respirable dust generated in longwall mining), which used a high-pressure, inward-facing, drum spray. The 800 psi, 30° inward-facing system was the best for reducing dust concentrations along the longwall face (up to 68% reduction in dust generated).

Although the concentration of respirable dust in a coal mine is directly related to the level of active coal production, several reports have shown that improvements in mining equipment resulted in both reducing respirable coal mine dust concentrations and increasing production. Howe [1987] reported that the use of new mining equipment, the 12 CM 7 with remote and scrubber, resulted in a reduction of respirable coal mine dust concentrations from 1.5-1.8 mg/m$^3$ to 0.5-0.8 mg/m$^3$ at the coal face. In addition, production increased by 32%. Rice [1987] reported on an electronic longwall mining system that included electronic sensing devices, remote control shearers, and shields with microprocessors. This system improved roof control and reduced respirable dust exposure by 31% at the coal face by shunting dust away from workers.

A recent development for controlling the generation of respirable dust is the concept of the constant depth linear cutting (CDLC) drum, mounted on a continuous mining machine, which reduced by 95% the amount of respirable dust generated by the shearer in laboratory tests (the shearer contributes 1/3 to 2/3 of the total respirable dust generated underground) [Roepke and Strebig 1989; Olson and Roepke 1984]. The CDLC also improves the size of the coal produced (by 50% reduction in the <1/4-inch-mesh product), and reduces horsepower, torque, and thrust by 40% to 70% without loss of production as compared to conventional rotary drums. The U.S. government holds four patents on the CLDC, and a prototype may be developed for testing in underground coal mines.

For controlling respirable dust in mines using longwall methods, Jankowski et al. [1986] discuss three basic dust control techniques: (1) a water spray system (e.g., the shearer-clearer system, which keeps shearer-generated dust near the face and away from the shearer operator); (2) a drum spray system (which helps prevent dust from becoming airborne); and (3) a cutting sequence that allows shearer operators to work on the intake-air side of the lead cutting drum. Effective maintenance of machinery and adherence to an approved respirable dust control plan are needed to minimize exposures to respirable dust concentrations. Maintaining production levels on high-tonnage longwall faces will require additional dust control technology and rigorous maintenance of dust control programs, reduction of production volumes, or modification of the present regulations on respirator usage. A trend in technology may be toward automated coal faces operated from a remote location, so that miners are not at the coal face during production [Fisher 1991; Rice 1987; Jankowski and Robert 1984].

### 7.4 Other Factors Considered in Determination of the REL for Respirable Coal Mine Dust

Determination of an REL for respirable coal mine dust is based on an evaluation of the latest available scientific data on the health effects of exposure over a working lifetime and on the technical feasibility of achieving the REL. The Occupational Safety and Health (OSH) Act of 1970 requires safe and healthful working conditions for every working person; the Act further requires that NIOSH preserve human resources by providing medical and other criteria that will ensure, insofar as practicable, that no worker will suffer diminished health, functional capacity, or life expectancy as a result of work experience [29 USC 669 and 671 (1986)]. The Federal Coal Mine Safety and Health (FCMSH) Act of 1977 (which amended the Federal Coal Mine Health and Safety Act of 1969) provides ". . . to the greatest extent possible, that the working conditions in each underground coal mine are sufficiently free of respirable dust concentrations in the mine atmosphere to permit each miner the opportunity to work underground during the period of his entire adult working life without incurring any disability from pneumoconiosis or any other occupation-related disease during or at the end of such period" [30 USC 841 (1986)]. Thus, the intent of the mandates for NIOSH is to include consideration of all the work-related diseases among coal miners in the determination of the REL.

Regarding dust-related lung function decrements, the wording of the 1970 OSH Act implies that an REL should protect workers from any work-related decrement in lung function that results in "diminished health, functional capacity, or life expectancy," whereas the FCMSH Act implies that the REL should protect workers from any exposure-related lung function decrement that results in "disability." Definitions for these terms were not provided in the acts, and "disability" has been defined by several criteria [AMA 1984; ATS 1982; Cotes 1983; Miller and Scacci 1981; DOL 1980; Epler et al. 1980; WHO 1980; SSA 1986; Gaensler and Wright 1966]. According to the American Medical Association (AMA) and American Thoracic Society (ATS) criteria, impairment is purely a medical determination (i.e., "a functional abnormality that persists after appropriate therapy and with no reasonable prospect of improvement" [ATS 1982]). However, disability is an administrative definition that includes nonmedical considerations (i.e., "capacity to meet personal, social, or occupational demands" [AMA 1984]) as well as the medical determination. Thus, impairment can exist without disability [Hansen and Wasserman 1988; Richman 1982; Richman 1980].

The NIOSH mandate of protecting "any worker" implies that the standard should apply to individuals with the greatest sensitivity to the exposure, and not just to individuals with an average response. Studies of all adverse health effects caused by or aggravated by exposure to respirable mine dust were considered in the determination of the REL for respirable coal mine dust. However, the relative severity of the effects and the quality of the data were also considered in determining the REL.

Evaluation of the economic feasibility, including consideration of the cost of upgrading or retrofitting mining equipment or of reduced production levels, are beyond the purview of NIOSH. Because consideration of economic factors is excluded from the NIOSH mandate [29 USC 669 and 671 (1985)], such factors do not influence the recommendation of an REL. However, those who perform an economic evaluation should not ignore the cost-effectiveness of eliminating occupational respiratory disease, including lower costs associated with black lung disability (such as benefits paid to miners and dependents, and fees for litigation and administration). They should also be aware of the cost-effectiveness of maintaining a healthier, more experienced workforce that would use less sick leave for exposure-related health problems.

# 8 METHODS FOR PROTECTING COAL MINERS

Methods for protecting miners from exposure to respirable coal mine dust and respirable crystalline silica include primary and secondary prevention measures. Primary prevention measures, which should be given first priority, include engineering and administrative controls to reduce dust exposures, safe and healthful work practices through training and informing workers of hazards, and temporary use of respiratory protection equipment during the failure of dust control equipment. Secondary prevention measures include medical screening tests (e.g., chest radiographs), transfer rights for miners with CWP, and smoking cessation.*

## 8.1 INFORMING WORKERS OF HAZARDS

Employers should establish a training program for all coal miners and other workers exposed to respirable coal mine dust and respirable crystalline silica. Training should be also provided whenever a new job is assigned, and workers should be informed about the health and safety hazards of the worksite. Training should include information about measures workers can take to protect themselves from exposure to respirable dust (e.g., the use of appropriate work practices, emergency procedures, and personal protective equipment, including the emergency use of respiratory protective equipment).

## 8.2 WORK PRACTICES

### 8.2.1 Worker Isolation

If feasible, workers should be isolated from work areas where the concentration of respirable coal mine dust or respirable crystalline silica a

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*Proposed secondary prevention measures include pulmonary function tests and transfer rights for miners with functional impairment of lungs.

positive pressure so that air flows out of rather than into the room. exceeds the RELs. This can be done by using automated equipment operated from closed control booth or room. The control room should be maintained at a However, when workers must perform process checks, adjustments, maintenance, or other related operations in work areas where respirable dust concentrations exceed the RELs, then personal protective clothing and equipment, including respiratory protective equipment, may be necessary.

### 8.2.2 Sanitation and Hygiene

Tobacco products should not be smoked, chewed, or carried uncovered in work areas. Workers should be provided with and advised to use facilities for showering and changing clothes at the end of each workshift. Tools and protective clothing and equipment should be cleaned as needed to maintain sanitary conditions. The work area should be kept free of flammable debris. Flammable work materials (rags, solvents, etc.) should be stored in approved safety cans.

## 8.3 POSTING

All warning signs should be printed in both English and the predominant language of workers who do not read English. Workers who cannot read posted signs should be identified so that they may receive information about hazardous areas and be informed of the instructions printed on the signs.

## 8.4 EMERGENCIES

The employer shall formulate a set of written procedures covering fire, explosion, asphyxiation, and any other foreseeable emergency that may arise during coal mining or in other occupations where workers are exposed to respirable coal dust. All potentially affected workers should receive training in evacuation procedures to be used in the event of fire or explosion. Selected workers should be given specific training in first aid, cardiopulmonary resuscitation, and fire control. Procedures should include prearranged plans for transportation of injured workers and provisions for emergency medical care. At least two trained persons in every work area should have received extensive emergency training. Necessary emergency equipment, including appropriate respirators and other personal protective equipment, should be stored in readily accessible locations.

## 8.5 ENGINEERING CONTROLS

Engineering controls should be the principal method for minimizing exposure to respirable coal mine dust and respirable crystalline silica in the workplace. Engineering control measures include diluting the dust generated (by adequate ventilation at the coal face), controlling the respirable dust generated and entrained (e.g., with improved shearer drum design), and suppressing the dust generated (e.g., by water application).

### 8.5.1 Dust Control

To be effective, the dust control system in a mine should be evaluated as soon as possible after any change in production, process, or control that might increase the concentrations of respirable coal mine dust or respirable crystalline silica.

Jobs that require rock drilling (e.g., roof bolters) can generate dust containing respirable free silica. Wet drills (including use of surface-active agents) or drills with attached dust collectors are advisable [Olishifski 1971]. Dry drilling without dust controls should be prohibited. Appendix C contains further information about reducing respirable dust concentrations during overburden drilling in surface coal mining operations.

### 8.5.2 Ventilation

Any scheme for exhausting air from a work area must also provide a positive means of bringing in at least an equal volume of air from the outside, conditioning it, and evenly distributing it throughout the exhausted area. The ventilation system should be designed and operated to prevent the accumulation or recirculation of airborne contaminants in the workplace.

Principles for the design and operation of ventilation systems are presented in Industrial Ventilation--A Manual of Recommended Practice [ACGIH 1992]; American National Standard: Fundamentals Governing the Design and Operation of Local Exhaust Systems, Z9.2 (1971) [ANSI 1979]; and Recommended Industrial Ventilation Guidelines, published by NIOSH [Hagopian and Bastress 1976].

#### *8.5.2.1 Ventilation in Underground Coal Mines*

Underground coal mines are required to be mechanically ventilated [30 CFR 75.300 et seq.]. The purpose of mechanical ventilation is to provide wholesome air to the underground miners and to carry off toxic and explosive gases and dusts. The primary purposes of ventilation are dilution of respirable coal dust, removal of explosive concentrations of coal dust and methane from the working faces, and removal of methane from mined-out areas. In addition to supplying fresh air and exhausting noxious and explosive gases and dusts, mine ventilation systems must furnish paths of escape in the event of an underground fire. Ventilation and escape considerations relating to fire safety are extremely complex.

The portions of the mine used as part of the ventilation system are sometimes referred to as "air courses." Air courses are often described as follows:

- Intake air courses, which bring in fresh air to the working face
- Return air courses, which exhaust air from the working face
- Neutral air courses, which have no perceptible air flow.

The number of entries available for ventilation vary with the mining method used and the geological characteristics of the rock strata mined.

Exhaust fans are commonly used to ventilate underground coal mines today. Positive-pressure fans are used infrequently--usually where the mine is closed to the surface and there is leakage to the surface through the air intakes. The volume of air flow through an underground mine is a function of the fan capacity and the "resistance" of the mine ventilation configuration.

Because of the multiple functions imposed on underground coal mine ventilation systems and the wide variations in underground mining methods, no general statements can be made about the availability of intake air to dilute respirable dust at the working face. Current ventilation techniques are largely dictated by regulations relating to available types of air courses, escapeway requirements, and methane regulation. The ventilation plan for each underground coal mine is approved by MSHA on a case-by-case basis.

#### *8.5.2.2 Proposed Standards for Mine Ventilation*

NIOSH presented testimony to MSHA regarding proposed safety standards for underground coal mine ventilation [NIOSH 1988a, 1988b, 1990] and expressed concern about the proposed "relaxation of the ventilation standard" [NIOSH 1988a]. NIOSH representatives noted that the proposed relaxation of the 60-foot-per-minute (fpm) minimum mean entry air velocities [30 CFR 75.301-4a] might result in increased concentrations of respirable dust. They also noted that the proposed relaxation of the present 250-fpm limit might result in an increased rate of propagation if a fire occurred. NIOSH expressed further concern about the proposed relaxation of the standard by allowing the use of belt conveyers as intake air courses for the working face at the mine, a practice that is prohibited in the existing regulation [30 CFR 75.326]. Belt conveyers are the sites of frequent fires, and belt haulageways are a significant source of respirable dusts [NIOSH 1988a].

## 8.6 PERSONAL PROTECTIVE EQUIPMENT

### 8.6.1 Protective Clothing and Equipment

Workers should wear work uniforms, coveralls, or similar full-body coverings that are laundered each day. Employers should collect work clothing at the end of each workshift and provide for its laundering. Employers should also provide lockers or other closed areas to store street clothes separately. Laundry personnel should be informed about the potential hazards of handling contaminated clothing and instructed about measures to minimize their health risk.

Employers should ensure that protective clothing is inspected and maintained to preserve its effectiveness. Clothing should be kept reasonably free of oil or grease.

Workers and persons responsible for worker health and safety should be informed that protective clothing may interfere with the body's heat dissipation, especially during hot weather (e.g., in surface coal mines) or in hot work situations (e.g., confined spaces). Additional monitoring is required to prevent heat-related illness when protective clothing is worn under these conditions.

### 8.6.2 Respiratory Protection

#### *8.6.2.1 The Need for Respirator Protection*

The need for respiratory protection in U.S. coal mines has changed considerably since 1969. the use of sophisticated extraction machines have greatly increased coal production and the quantity of dust generated. New chemicals have also been introduced for use in dust control systems, and viable biological matter has been discovered in the mining environment. Other potentially hazardous exposures include coal tar pitch volatiles from creosote-treated timbers and polyurethane resins used in some roof support systems.

Engineering controls should be the primary method used to control exposure to airborne contaminants. Respiratory protection is the least preferred method of controlling worker exposures and should not be used routinely to prevent or minimize exposures. Respirators should be used by workers only in the following circumstances:

- During the development, installation, or testing of required engineering controls

- When engineering controls are not feasible to control exposure to airborne contaminants during short-term operations such as maintenance and repair

- During emergencies

### *8.6.2.2 Selection of Respirators*

Several factors in the mine environment affect the selection of respirators. Safety factors are a particular concern, and impairment of vision must be avoided. For example, the presence of water spray to suppress dust results in dirty water droplets that can quickly obscure full-facepiece respirators. Silt can also collect around respirator face-seals and irritate the skin. The particulate filter medium can become saturated and change its filtration and breathing resistance characteristics.

The NIOSH Respirator Decision Logic [NIOSH 1987a] should always be followed to select the correct respirator. The issues to be evaluated are as follows:

- Other available means of reducing exposure, such as increased or redirected ventilation and improved dust and vapor control systems
- The nature of the task to be performed (location, physical demands, industrial processes involved, and frequency and duration of respirator use)
- The space restrictions within the work location
- The physical nature of the air contaminant, including odor threshold, eye irritation, and other warning properties
- The interaction of contaminants with the filter medium
- The concentrations of respirable coal mine dust, respirable crystalline silica, and other toxic contaminants in the miner's breathing zone.

- Toxicologic data, RELs, and PELs
- The required use of eye and face protection devices
- The level of respiratory protection needed by the miner
- The worker's fitness to wear a respirator as determined by his or her health, potential hypersensitivity to a substance, type of respirator, fit testing, training, and conditions of respirator use (this issue is particularly important with the use of self-contained breathing apparatus)
- The performance characteristics, capabilities, and limitations of different types of respirators

#### *8.6.2.3 Respiratory Protection Program*

When respirators are used, employers should institute a complete respiratory protection program that includes worker training at regular intervals in the use and limitations of respirators, routine air monitoring, and the inspection, cleaning, maintenance, and proper storage of respirators. Any respiratory protection program must, at a minimum, meet the requirements of 29 CFR 1910.134. Respirators should be used according to the manufacturer's instructions.

Each respirator user should be fit-tested and, if possible, should receive a quantitative, on-the-job evaluation of his or her respiratory protection factor assumed for that class of respirator. The wearer's physical ability to wear a respirator should be periodically evaluated by a physician. The miners should be informed annually about the hazard of dust exposure and they should be trained in the use and care of the respirators. In addition, the program should be constantly reviewed, and if necessary, corrective action should be taken to maintain program effectiveness. For additional information about the use of respiratory protection, refer to the NIOSH Guide to the NIOSH Guide to Industrial Respiratory Protection [NIOSH 1987b] or the NIOSH Respirator Decision Logic [NIOSH 1987a].

Table 8.1 lists the recommended minimum respiratory protection for respirable coal mine dust and respirable crystalline silica. The current edition of the NIOSH Respirator Decision Logic [NIOSH 1987a] should be consulted if a certain condition requires a specific type of respirator other than those listed in Table 8.1.

### 8.6.3 Transfer Option

Any miner who ". . . based upon such readings or other medical examinations, shows evidence of the development of pneumoconiosis shall be afforded the option of transferring from his position to another position in any area of the mine . . . where the concentration of respirable dust in the mine atmosphere is not more than 1.0 milligrams [sic] of dust per cubic meter of air, or . . . where the concentration of respirable dust is the lowest attainable below 2.0 milligrams per cubic meter of air [30 USC 843 (c)(2) (1986)]." Any miner who is transferred shall receive pay that is ". . . not less than the regular rate of pay received by him immediately prior to his transfer" [30 USC 843(c)(3) (1986)].

Table 8-1.—NIOSH recommended respiratory protection for workers exposed to respirable coal mine dust and respirable crystalline silica[1]

| Airborne concentration[2] (mg/m³) |  |  |
|---|---|---|
| Respirable coal mine dust | Respirable crystalline silica | Minimum respiratory protection[3] |
| <0.90 | <0.05 | No respirator required |
| ≤4.5 | ≤0.25 | Single-use or quarter-mask[4] respirator |
| ≤9 | ≤0.5 | Any air-purifying, half-mask respirator (including disposable respirators[5],[6]) equipped with any type of particulate filter other than a single-use filter, or |
|  |  | Any air-purifying, full-facepiece respirator equipped with any type of particulate filter[7] or |
|  |  | Any supplied-air respirator equipped with a half mask and operated in a demand (negative-pressure) mode |
| ≤22.5 | ≤1.25 | Any powered, air-purifying respirator equipped with a hood or helmet and any type of particulate filter, or |
|  |  | Any supplied-air respirator equipped with a hood or helmet and operated in a continuous-flow mode |
| ≤45 | ≤2.5 | Any air-purifying, full-facepiece respirator equipped with a high-efficiency filter, or |
|  |  | Any powered, air-purifying respirator equipped with a tight-fitting facepiece and a high-efficiency filter, or |
|  |  | Any supplied-air respirator equipped with a full facepiece and operated in a demand (negative-pressure) mode, or |
|  |  | Any supplied-air respirator equipped with a tight-fitting facepiece and operated in a continuous-flow mode, or |
|  |  | Any self-contained respirator equipped with a full facepiece and operated in a demand (negative-pressure) mode |
| ≤900 | ≤50 | Any supplied-air respirator equipped with a half mask and operated in a pressure-demand or other positive-pressure mode |
| ≤1,800 | ≤100 | Any supplied-air respirator equipped with a full facepiece and operated in a pressure-demand or other positive-pressure mode |
| ≤9,000 | ≤500 | Any self-contained respirator equipped with a full facepiece and operated in a pressure-demand or other positive-pressure mode, or |
|  |  | Any supplied-air respirator equipped with a full facepiece and operated in a pressure-demand or other positive-pressure mode in combination with an auxiliary self-contained breathing apparatus operated in a pressure-demand or other positive-pressure mode |

[1] Only NIOSH/MSHA-approved respiratory equipment should be used.

[2] The concentration of respirable coal mine dust or silica that is highest during any given condition determines the minimum respiratory protection to be supplied to and worn by the miner.

[3] The type of appropriate respiratory protection for each exposure concentration was determined from quantitative fit testing conducted by Los Alamos National Laboratories (LANL) on a panel of human volunteers, and workplace protection factor data or laboratory data more recently reported than the LANL data.

[4] An orinasal respirator that covers the nose and mouth and that generally consists of a quarter-facepiece.

[5] A respirator that is discarded after the end of its recommended period of use, after excessive resistance or physical damage, or when odor breakthrough or other warning indicators render the respirator unsuitable for further use.

[6] A protection factor of 10 can be assigned to disposable particulate respirators if they have been properly fitted using a quantitative fit test.

[7] The afforded level of protection was based on consideration of the efficiency of dust, fume, and mist filters.

No scientific basis has been published concerning the selection of a 1.0 mg/m$^3$ PEL for transferred miners' respirable coal mine dust, nor are there any data to indicate that reducing exposures to that concentration has been effective. Based on the health effects studies of underground coal miners, NIOSH recommends that miners with radiographic evidence of CWP or impaired lung function (on the basis of spirometry and other tests) be offered the option to transfer to work areas with a concentration of respirable coal mine dust that is the lowest feasible concentration below the RELs for respirable coal mine dust and respirable crystalline silica. Transferred miners should also be afforded increased medical and environmental monitoring [42 CFR 37; 30 CFR 90].

The first priority should be the primary prevention of occupational respiratory diseases among coal miners through adherence to the recommended exposure limit. However, a secondary program of medical monitoring is necessary to identify miners who develop occupational respiratory diseases either because of excessive exposures or because of increased individual susceptibility to disease. When a miner is identified with a respiratory disease that is attributable to respirable coal mine dust exposure or that would be aggravated by further exposure to respirable coal mine dust, the most prudent intervention would be to reduce further dust exposure. However, the effectiveness of reducing further dust exposure is equivocal for preventing disease progression in miners with radiographic evidence of CWP [Hurley and Maclaren 1987] and has not been evaluated for COPD.

Unless unequivocal evidence to the contrary is provided, miners with radiographic evidence of pneumoconiosis should be transferred to areas with the lowest concentrations of respirable coal mine dust and respirable crystalline silica attainable below the applicable exposure limits. Miners should be given the option to transfer if their chest radiographs show evidence of pneumoconiosis (ILO category 1 or higher), and each eligible miner should make an informed decision about whether or not to exercise this transfer right. Chapter 5 recommends modifications to the existing CWXSP.

### 8.6.4 Smoking Cessation

Because of the overwhelming evidence of the adverse health consequences of smoking, the number of workers affected, and the additive effects of smoking and dust exposures on the development of occupational respiratory diseases (e.g., chronic bronchitis, emphysema, and lung cancer), NIOSH and the Association of Schools of Public Health (ASPH) cosponsored a "Proposed National Strategy for the Prevention of Occupational Lung Diseases." This proposal recommended the elimination of smoking in the workplace as an important strategy for prevention of occupational lung diseases [ASPH 1986]. The recommendation was further supported by NIOSH's conclusion that nonsmokers exposed to environmental tobacco smoke* in the workplace had an increased risk of lung cancer [NIOSH 1991].

NIOSH recommends the following regarding smoking in the workplace:

- Workers should be prohibited from smoking at workplaces
- Information on health promotion and the harmful effects of smoking should be disseminated
- Smoking-cessation classes should be offered to workers at no cost to the participant

The recommendation to prohibit smoking in the workplace is not applicable to underground coal miners because smoking is a potential fire hazard and,

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*Tobacco smoke in the ambient atmosphere composed of sidestream smoke and exhaled mainstream smoke [NIOSH 1991].

therefore, already prohibited in underground coal mines. However, the smoking cessation program is recommended for miners who smoke and have medical evidence of respiratory disease. Workers' acceptance of the importance of smoking cessation will undoubtedly be heightened if they observe that exposures to dust and other agents with adverse respiratory effects are being controlled effectively in the workplace.

## 8.7 EXPOSURE MONITORING

Routine environmental monitoring is an important part of an occupational health program designed to protect workers from the adverse effects of exposure to respirable coal mine dust and respirable crystalline silica. Routine environmental monitoring provides a means of assessing the effectiveness of engineering controls and work practices. The environmental monitoring, both the initial and periodic surveys, should be conducted by competent industrial hygiene and engineering personnel.

A sampling strategy should be used to provide a statistically valid estimate of each worker's exposure. The NIOSH publication Occupational Exposure Sampling Strategy Manual contains information about the number and frequency of samples required to estimate workers' exposures (see also Chapter 5 of this document). The concentration of respirable coal mine dust and respirable crystalline silica should be determined as a time-weighted average (TWA) by collecting samples over an 8-hr or 10-hr shift, for up to a 40-hr workweek. For extended workshifts, Brief and Scala [1975] present a method for estimating an exposure limit reduction factor.

When the mine environment contains concentrations that exceed the REL for respirable coal mine dust or respirable crystalline silica, workers must wear respirators for protection until adequate engineering controls or work practices are instituted. Exposure monitoring should be conducted whenever changes in production, process, controls, work practices, or weather affect exposure conditions.

## 8.8 MEDICAL MONITORING

### 8.8.1 Medical Examinations

Medical examinations are conducted before job placement and periodically thereafter. The preplacement medical examination allows the physician to assess the applicant's functional capacity and to inform him or her of the physical demands and risks of the job. The preplacement medical examination should include an occupational history questionnaire to determine any previous occupational exposures. The preplacement examination also provides the baseline medical data needed to determine if any adverse health effects have occurred after beginning the job. In any preplacement or periodic medical examination, a determination should be made of factors that may interact to produce adverse effects on the worker's health (including the exacerbation of pre-existing health problems and nonoccupational exposures such as cigarette smoking or other use of tobacco products).

#### *8.8.1.1 Preplacement Medical Examination*

The preplacement medical examination should consist of a medical history questionnaire and a clinical examination. The medical history questionnaire should contain an occupational history, including the number of years worked in each job. Special attention should be given to any history of occupational exposure to hazardous chemical and physical agents [Guidotti et al. 1983].

The clinical examination should determine the fitness of the worker to perform the intended job assignment. Appropriate pulmonary and musculoskeletal evaluations should be done for workers whose jobs may require extremes of physical exertion or stamina (e.g., heavy lifting), especially those who must wear personal respiratory protection. The standard 12-lead electrocardiogram is not recommended because it is of little practical value in monitoring for asymptomatic cardiovascular disease. Physicians' interviews of workers provide more valuable diagnostic information. These interviews elicit reports of the occurrence of angina, breathlessness, and other symptoms of chest illnesses and their relationship to work.

Special attention should also be given to workers who wear eyeglasses for visual acuity. These workers must be able to wear simultaneously their eyeglasses and any equipment needed for respiratory and eye protection, and maintain their concurrent use during work activities.

#### *8.8.1.2 Periodic Medical Examination*

Periodic medical examinations should be conducted at 3-year intervals or more frequently, depending on age, health status at the time of a prior examination, and reported signs or symptoms associated with exposure to respirable coal mine dust and respirable crystalline silica. The periodic medical examinations should focus on the early identification of work-related adverse health effects, preferably before such effects become irreversible.

The physician should note the occurrence of any occupationally related disease or other work-related adverse health effect.

The physician's interview with the worker is an essential part of a periodic medical examination. The interview gives the physician the opportunity to learn of (1) changes in the work setting (e.g., confined spaces), and (2) potentially hazardous workplace exposures that are in the vicinity of the worker but are not related to the worker's job activities. During the periodic medical examination, the physician should re-examine organ systems at risk to note changes from the previous examination.

Workers exposed to respirable coal mine dust or respirable crystalline silica are at risk of suffering adverse health effects. Medical monitoring as described below should be made available to all workers. The employer should provide the following information to the physician responsible for the medical monitoring program:

- Identification and extent of exposure to physical and chemical agents that may be encountered by the worker
- Any available workplace sampling results that characterize exposures for job categories previously and currently held by the worker
- A description of any protective devices or equipment the worker is required to use
- The frequency and nature of any reported illness or injury of a worker

The objectives of the medical monitoring program are to augment the primary preventive measures, which include industrial hygiene monitoring of the workplace, the implementation of engineering controls, and the use of proper work practices and personal protective equipment. Medical monitoring data may also be used for epidemiologic analysis, preferably in conjunction with exposure data from the environmental monitoring.

## 8.9 RECORDKEEPING

Medical records must be maintained for workers as specified in Section 1.11 of this document. They must be kept for at least 40 years after termination of employment. Copies of environmental exposure records for each worker must be included with the medical records. These must be made available to the past or present workers or to anyone having the specific written consent of a worker, as specified in 42 CFR 37.80.

### 8.10 PROTECTION OF CONTRACT MINERS

Some provisions of the standard recommended in this criteria document may be difficult to apply to a special category of miners known as contract miners. Coal miners who are contracted to work on specific jobs at various mines for relatively short periods of time may not gain the full benefits of exposure monitoring, medical surveillance, hazard training, and transfer programs normally available to other mine employees. NIOSH recognizes the need to include these contract miners in a recommended standard and will continue to explore options that will address their occupational health and safety needs.

# 9 RESEARCH NEEDS

Additional research or data analysis is needed for improvements in dust control methods, medical screening and intervention, respirable dust samplers or sampling strategies, characterization of respirable dust, and evaluation of exposure, dose, and response relationships for future recommended standards. The following is a list of such research needs:

Engineering control methods

- Develop improved methods of controlling exposures to both respirable coal mine dust and respirable crystalline silica in underground and surface coal mines.

Sampler development

- Develop sampling devices to accurately and precisely measure the relevant distribution of particles deposited and retained in the lungs.

- Develop continuous monitors for sampling respirable coal mine dust.

Sampling strategy

- Develop a sampling strategy for use in epidemiologic research, in conjunction with or apart from the compliance sampling strategy.

- Evaluate the validity and feasibility of an exposure limit based on the long-term average (vs. 8-hour TWA) concentration in conjunction with a feasible sampling strategy.

Medical screening and intervention

- Determine the factors affecting the incidence of PMF among miners without radiographic evidence of simple CWP for the purpose of effective early intervention.

- Evaluate the effectiveness of the existing transfer program (which enables miners with CWP category 1/0 or greater to transfer to jobs in areas of the mine with mean concentrations of respirable coal mine dust of $\leq 1$ mg/m$^3$) in preventing the progression of simple CWP.

- Identify early markers of disease to identify miners with increased susceptibility to the effects of exposure to respirable coal mine dust and respirable crystalline silica.

Evaluation of pulmonary function

- Evaluate lung function decrements among surface coal miners.

- Evaluate the reversibility of lung function decrements among coal miners after removal from or reduction in exposures to respirable coal mine dust.

- Determine the normal reference values for longitudinal changes in coal miners' lung function by age, height, weight, gender, and race.

- Determine the prevalence of miners who have normal spirometry values and normal chest radiographs, but who have abnormalities in gas exchange to ascertain the need for additional lung function tests (such as diffusing capacity [DLCO] or transcutaneous measurements of arterial oxygen pressure) in addition to the recommendation for spirometry tests ($FEV_1$ and FVC).

### Exposure, dose, and response relationships

- Determine the effect of dose rate (i.e., intensity of exposure) on the development of both pneumoconiotic and nonpneumoconiotic respiratory diseases among coal miners.
- Assess the influence of dust composition and characteristics (e.g., quartz concentration, thoracic sized particles) on the development of both pneumoconiotic and nonpneumoconiotic diseases among coal miners.
- Evaluate the role of overloading lung clearance mechanisms on the development of occupational respiratory diseases among coal miners.
- Analyze the relationship between exposure to thoracic coal mine dust and chronic obstructive pulmonary disease (COPD).

### Characteristics of dust

- Compare the composition of airborne respirable dust in underground coal mines with that of surface mines and other work sites where exposure to coal dust occurs.
- Determine particle size distributions and particle characterization at surface coal mines compared with those of underground coal mines.

## APPENDIX A

## NIOSH RECOMMENDED RESPIRATORY QUESTIONNAIRE

### RESPIRATORY DISEASES

### COUGH

Q1. Do you usually cough first thing in the morning (on getting up) in the winter?
(Count a cough with first smoke or on first going out-of-doors. Exclude clearing throat or a single cough.)
_____ 1. YES
_____ 2. NO

Q2. Do you usually cough during the day (or at night) in the winter?
(Ignore an occasional cough.)
_____ 1. YES
_____ 2. NO

IF NO TO BOTH QUESTIONS Q1 AND Q2, SKIP TO QUESTION Q5:

Q3. Do you cough like this on most days (or nights) for as much as three months each year?
_____ 1. YES
_____ 2. NO

Q4. How many years have you coughed like this?
_____ YEARS

### PHLEGM

Q5. Do you usually bring up any phlegm from your chest first thing in the morning (on getting up) in the winter?
(Count phlegm with first smoke or on first going out of doors. Exclude phlegm from the nose. Count swallowed phlegm.)
_____ 1. YES
_____ 2. NO

Q6. Do you usually bring up any phlegm from your chest during the day (or at night) in the winter?
(Accept twice or more.)
_____ 1. YES
_____ 2. NO

IF NO TO BOTH QUESTIONS Q5 AND Q6 SKIP TO QUESTION Q9:

Q7. Do you bring up phlegm like this on most days (or nights) for as much as three months each year?
_____ 1. YES
_____ 2. NO

Q8. How many years have you brought up phlegm like this?
_____ YEARS

PERIODS OF INCREASED COUGH AND PHLEGM

Q9. In the past three years have you had a period of (increased) cough and phlegm lasting for three weeks or more?
_____ 1. YES
_____ 2. NO
If YES, have you had more than one such period?
_____ 1. YES
_____ 2. NO

Q10. During the past 12 months, has your cough and phlegm (or periods of increased cough and phlegm) required more frequent doctor, emergency room, or hospital visits?
_____ 1. YES
_____ 2. NO

BREATHLESSNESS

Q11. Are you disabled from walking by any disease other than heart or lung disease?
_____ 1. YES
_____ 2. NO

* IF YES, SKIP TO QUESTION Q17

Q12. Are you troubled by shortness of breath when hurrying on level ground or walking up a slight hill?
_____ 1. YES
_____ 2. NO

* IF NO, SKIP TO QUESTION Q17

Q13. Do you get short of breath walking with other people of your own age on level ground?
_____ 1. YES
_____ 2. NO

Q14. Do you have to stop for breath when walking at your own pace on level ground?
_____ 1. YES
_____ 2. NO

Q15. Do you ever have to stop for breath after walking about 100 yards (or after a few minutes) on level ground?
_____ 1. YES
_____ 2. NO

Q16. When did your shortness of breath start?
MONTH _____ / YEAR _____

WHEEZING

Q17. Does your chest EVER sound wheezing or whistling:
_____ 1. YES
_____ 2. NO

IF NO, SKIP TO QUESTION Q21
IF YES:

Q18. Does this happen when you have a cold?
_____ 1. YES
_____ 2. NO

Q19. Does this happen occasionally apart from colds?
_____ 1. YES
_____ 2. NO

Q20. Does this happen most days or nights?
_____ 1. YES
_____ 2. NO

Q21. Have you EVER had attacks of shortness of breath with wheezing?
_____ 1. YES
_____ 2. NO
IF YES, is/was your breathing absolutely normal between attacks?
_____ 1. YES
_____ 2. NO

Q22. When did you first notice wheezy or whistling breathing?
MONTH _____ / YEAR _____

Q23. How often are you having wheezing at this time?
_____ times per day
_____ times per week
_____ times per month
_____ times per year

Q24. How often were you having wheezing 12 months ago?
_____ times per day
_____ times per week
_____ times per month
_____ times per year

Q25. Do you wheeze or have tightness in the chest after exercising?
_____ 1. YES
_____ 2. NO
If YES, when did this first occur?
MONTH _____ / YEAR _____

CHEST ILLNESSES

Q26. If you get a cold, does it USUALLY go to your chest (usually means more than half the time)?
______ 1. YES
______ 2. NO

Q27. During the past 3 years, have you had any chest illness that has kept you from your usual activities for as much as a week (e.g., kept you off work, indoors at home, or in bed)?
______ 1. YES
______ 2. NO

* IF NO, SKIP TO QUESTION Q31

Q28. Did you bring up more phlegm than usual in any of these illnesses?
______ 1. YES
______ 2. NO

Q29. How many illnesses like this have you had in the past 12 months?
______ ILLNESSES

Q30. Is the number of illnesses like this:
______ 1. Greater than the year before?
______ 2. About the same as the year before?
______ 3. Less than the year before?

CHRONIC LUNG OR HEART PROBLEMS

Q31. Do you have any CHRONIC or REPEATING lung or heart problems?
______ 1. YES
______ 2. NO
* IF NO, SKIP TO QUESTION Q38
IF YES, specify the problem ________________________________________

Q32. Do you have any of the following symptoms with your lung or heart problems?
YES NO
__ __ 1. Breathing troubles
__ __ 2. Coughing
__ __ 3. Bringing up phlegm
__ __ 4. Chest pain
__ __ 5. Chest tightness
__ __ 6. Irregular heart beat/arrhythmia
__ __ 7. Some other symptom (specify ______________________________)
__ __ 8. No symptoms
If YES to MORE than one of these symptoms, which ONE symptom is the MOST disturbing to you when you have an attack?
____________________________________________

In the past 12 months, have symptoms from chronic heart or lung problems:

Q33. Interfered more frequently with your usual activities?
______ 1. YES
______ 2. NO

Q34. Required increased or stronger breathing medication or medication for your heart or lungs?
_____ 1. YES
_____ 2. NO

Q35. Required more frequent physician or emergency room visits?
_____ 1. YES
_____ 2. NO

Q36. Required more frequent hospitalizations?
_____ 1. YES
_____ 2. NO

ASTHMA

Q37. Required hospitalizations of longer duration?
_____ 1. YES
_____ 2. NO

Q38. Have you EVER had asthma?
_____ 1. YES
_____ 2. NO

* IF NO, SKIP TO QUESTION Q47

Q39. Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO

Q40. Did you have asthma attacks when you were a child (18 years or younger)?
_____ 1. YES
_____ 2. NO

Q41. Do you still have asthma attacks?
_____ 1. YES
_____ 2. NO

* IF NO, SKIP TO QUESTION Q47

Q42. Do you have any of the following symptoms when you have an attack?

| YES | NO | |
|---|---|---|
| __ | __ | 1. Wheezing or whistling breathing |
| __ | __ | 2. Shortness of breath |
| __ | __ | 3. Cough |
| __ | __ | 4. Chest tightness |
| __ | __ | 5. Some other symptom specify_______________) |

If YES to MORE than one of these symptoms, which ONE symptom is the MOST disturbing to you when you have an attack?
_____________________________________________

Q43. When did the asthma attacks that you are now having (as an adult) seem to start?
MONTH _____ / YEAR _____

Q44. How often are you having attacks at this time?
FILL IN THE MOST APPROPRIATE SELECTION:
_____ times per day
_____ times per week
_____ times per month
_____ times per year

Q45. How often were you having attacks 12 months ago?
FILL IN THE MOST APPROPRIATE SELECTION:
_____ times per day
_____ times per week
_____ times per month
_____ times per year

Q46. In the past 12 months, have you had to change to a stronger medication, take increased medication for asthma attacks, see your doctor more often for your asthma, or visit the emergency room more often for asthma attacks?
_____ 1. YES
_____ 2. NO

OTHER CHEST CONDITIONS

Q47. Have you ever had any of the following conditions?
YES NO
__ __ 1.Attacks of bronchitis
If YES:
a.Were they confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b.When were they first diagnosed?
MONTH _____ / YEAR _____

__ __ 2. Pneumonia (include bronchopneumonia)
If YES:
a.Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b. When was it first diagnosed?
MONTH _____ / YEAR _____

__ __ 3. Hay fever
If YES:
a. Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b. When was it first diagnosed?
MONTH _____ / YEAR _____

__ __ 4. Tuberculosis or any other chronic lung infection
If YES:
a. Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b. When was it first diagnosed?
MONTH _____ / YEAR _____

c. Do you still have it?
_____ 1. YES
_____ 2. NO

__ __ 5. Pneumoconiosis or dust disease (e.g., silicosis, coal worker's pneumoconiosis, asbestosis, etc.)
If YES:
a. Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b. When was it first diagnosed?
MONTH _____ / YEAR _____
c. Do you still have it?
_____ 1. YES
_____ 2. NO

Have you ever had any of the following conditions?
YES NO
__ __ 6. Chronic bronchitis
If YES:
a. Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b. When was it first diagnosed?
MONTH _____ / YEAR _____
c. Do you still have it?
_____ 1. YES
_____ 2. NO

__ __ 7. Emphysema
If YES:
a. Was it confirmed by a doctor?
_____ 1. YES
_____ 2. NO
b. When was it first diagnosed?
MONTH _____ / YEAR _____
c. Do you still have it?
_____ 1. YES
_____ 2. NO

CHEST X-RAYS

Q48. Have you ever had a chest x-ray?
_____ 1. YES
_____ 2. NO

* IF NO, SKIP TO THE NEXT SECTION

Q49. Have you ever been told that your chest x-ray was abnormal?
_____ 1. YES
_____ 2. NO

* IF NO, SKIP TO QUESTION Q52

Q50. Have you ever been told that your chest x-ray showed changes that might be related to exposures at work?

_____ 1. YES
_____ 2. NO

Q51. What were you told?

________________________________________
________________________________________
________________________________________

Q52. What year was your most recent chest x-ray?

_____

Q53. Please provide the name and address or the physician, clinic, hospital, etc. where your most recent chest x-ray was taken:

________________________________________
________________________________________
________________________________________

# APPENDIX B

## 1989 RESPIRABLE COAL MINE DUST CONCENTRATIONS ASSOCIATED WITH TRANSFERRED MINERS, LISTED BY OCCUPATION

Table B-1.--MSHA inspector-collected samples

| Occupation | Mine area | M | Concentration (mg/m$^3$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mean | Std | Min | Max | Range |
| Belt/conveyor man (001) | Underground face | 2 | 0.6 | 0.1 | 0.5 | 0.7 | 0.2 |
| Mechanic (004) | Underground face | 3 | 0.3 | 0.2 | 0.1 | 0.5 | 0.4 |
| Laborer (016) | Underground face | 3 | 1.1 | 1.4 | 0.2 | 2.8 | 2.6 |
| Roof bolter-mounted intake (019) | Underground face | 1 | 3.8 | | 3.8 | 3.8 | 0.0 |
| Roof bolter-single head (046) | Underground face | 4 | 1.8 | 0.2 | 1.5 | 2.0 | 0.5 |
| Section foreman (049) | Underground face | 6 | 0.9 | 0.8 | 0.1 | 2.4 | 2.3 |
| Belt/conveyor man (101) | Underground nonface | 4 | 0.7 | 0.3 | 0.5 | 1.2 | 0.7 |
| Electrician (102) | Underground nonface | 5 | 0.7 | 0.5 | 0.2 | 1.5 | 1.3 |
| Mechanic (104) | Underground nonface | 5 | 0.3 | 0.3 | 0.1 | 0.7 | 0.6 |
| Mason (108) | Underground nonface | 1 | 1.5 | | 1.5 | 1.5 | 0.0 |
| Supply man (109) | Underground nonface | 13 | 0.9 | 0.8 | 0.2 | 3.4 | 3.2 |
| Laborer (116) | Underground nonface | 32 | 0.6 | 0.4 | 0.1 | 2.1 | 2.0 |
| Coal dump operation (122) | Underground nonface | 1 | 0.5 | | 0.5 | 0.5 | 0.0 |
| Dispatcher (265) | Transportation underground | 1 | 0.1 | | 0.1 | 0.1 | 0.0 |
| Motorman (269) | Transportation underground | 5 | 0.3 | 0.2 | 0.1 | 0.5 | 0.4 |
| Mechanic (304) | Surface | 4 | 0.5 | 0.5 | 0.1 | 1.1 | 1.0 |
| Supply man (309) | Surface | 2 | 0.3 | 0.1 | 0.2 | 0.4 | 0.2 |
| Laborer (316) | Surface | 5 | 0.2 | 0.1 | 0.1 | 0.4 | 0.3 |
| Utility man (328) | Surface | 3 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 |
| Dispatcher (365) | Surface | 1 | 0.1 | | 0.1 | 0.1 | 0.0 |
| Bulldozer operator (368) | Surface | 2 | 0.5 | 0.6 | 0.1 | 1.0 | 0.9 |
| Motorman (369) | Surface | 1 | 0.3 | | 0.3 | 0.3 | 0.0 |
| Car dropper (373) | Surface | 1 | 0.4 | | 0.4 | 0.4 | 0.0 |
| Cleaning plant operator (374) | Surface | 1 | 0.5 | | 0.5 | 0.5 | 0.0 |
| Fine coal plant (380) | Surface | 1 | 0.6 | | 0.6 | 0.6 | 0.0 |
| Highlift operator (382) | Surface | 2 | 0.3 | 0.0 | 0.3 | 0.3 | 0.0 |
| Lampman (385) | Surface | 4 | 0.2 | 0.2 | 0.1 | 0.4 | 0.3 |
| Tipple operator (392) | Surface | 1 | 0.4 | | 0.4 | 0.4 | 0.0 |
| Water truck operator (395) | Surface | 1 | 0.3 | | 0.3 | 0.3 | 0.0 |
| Dust Sampler (414) | Administration | 1 | 0.2 | | 0.2 | 0.2 | 0.0 |
| Assistant mine foreman (430) | Administration | 1 | 0.2 | | 0.2 | 0.2 | 0.0 |
| ALL | | 123 | 0.6 | 0.6 | 0.1 | 3.8 | 3.7 |

Table B-2.--Coal mine operator-collected samples

| Occupation | Mine area | Concentration (mg/m³) | | | | | |
|---|---|---|---|---|---|---|---|
| | | M | Mean | Std | Min | Max | Range |
| Mechanic (004) | Underground face | 8 | 0.4 | 0.2 | 0.2 | 0.8 | 0.6 |
| Roof bolter-twin head intake (012) | Underground face | 4 | 1.3 | 0.6 | 0.4 | 1.7 | 1.3 |
| Laborer (016) | Underground face | 27 | 0.7 | 1.0 | 0.1 | 4.8 | 4.7 |
| Roof bolter-mounted intake (019) | Underground face | 12 | 5.1 | 7.8 | 0.1 | 24.0 | 23.9 |
| Continuous miner helper (035) | Underground face | 10 | 1.2 | 0.9 | 0.1 | 3.0 | 2.9 |
| Roof bolter-single head (046) | Underground face | 6 | 0.8 | 0.3 | 0.5 | 1.2 | 0.7 |
| Section foreman (049) | Underground face | 21 | 0.9 | 0.6 | 0.2 | 2.5 | 2.3 |
| Shuttle car opr-on side (050) | Underground face | 6 | 0.4 | 0.3 | 0.1 | 0.8 | 0.7 |
| Utility man (053) | Underground face | 6 | 0.3 | 0.4 | 0.1 | 1.1 | 1.0 |
| Belt/conveyor man (101) | Underground nonface | 31 | 0.9 | 0.7 | 0.1 | 3.0 | 2.9 |
| Electrician (102) | Underground nonface | 21 | 0.5 | 0.6 | 0.1 | 2.7 | 2.6 |
| Mechanic (104) | Underground nonface | 56 | 0.4 | 0.3 | 0.1 | 1.0 | 1.7 |
| Mason (108) | Underground nonface | 35 | 1.2 | 2.2 | 0.1 | 12.5 | 12.4 |
| Supply man (109) | Underground nonface | 12 | 0.3 | 0.3 | 0.1 | 1.0 | 0.9 |
| Timberman (110) | Underground nonface | 27 | 0.5 | 0.5 | 0.1 | 2.0 | 1.9 |
| Laborer (116) | Underground nonface | 177 | 0.8 | 0.7 | 0.1 | 4.1 | 4.0 |
| Coal dump operator (122) | Underground nonface | 9 | 1.0 | 0.3 | 0.5 | 1.5 | 1.0 |
| Belt cleaner (154) | Underground nonface | 21 | 0.7 | 0.7 | 0.1 | 2.4 | 2.3 |
| Pumper (157) | Underground nonface | 5 | 0.3 | 0.2 | 0.1 | 0.5 | 0.4 |
| Trackman (216) | Transportation underground | 10 | 0.4 | 0.3 | 0.1 | 1.1 | 1.0 |
| Motorman (269) | Transportation underground | 23 | 0.4 | 0.3 | 0.1 | 1.1 | 1.0 |
| Mechanic (304) | Surface | 24 | 0.6 | 0.3 | 0.1 | 1.2 | 1.1 |
| Supply man (309) | Surface | 11 | 0.1 | 0.1 | 0.1 | 0.4 | 0.3 |
| Cleanup man (313) | Surface | 18 | 0.2 | 0.1 | 0.1 | 0.5 | 0.4 |
| Coal sampler (314) | Surface | 5 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 |
| Laborer (316) | Surface | 30 | 0.2 | 0.2 | 0.1 | 1.0 | 0.9 |
| Utility Man (328) | Surface | 17 | 0.2 | 0.3 | 0.1 | 1.1 | 1.0 |
| Belt/conveyor man (341) | Surface | 31 | 1.1 | 3.5 | 0.1 | 15.6 | 15.5 |
| Car trimmer (343) | Surface | 11 | 0.3 | 0.2 | 0.1 | 0.6 | 0.5 |
| Dispatcher (365) | Surface | 17 | 0.2 | 0.2 | 0.1 | 0.5 | 0.4 |
| Bulldozer operator (368) | Surface | 5 | 0.3 | 0.3 | 0.1 | 0.8 | 0.7 |
| Car dropper (373) | Surface | 17 | 0.2 | 0.1 | 0.1 | 0.7 | 0.6 |
| Cleaning plant operator (374) | Surface | 45 | 0.6 | 0.4 | 0.1 | 1.8 | 1.7 |
| Dryer operator (379) | Surface | 4 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 |
| Fine coal plant opr (380) | Surface | 10 | 0.5 | 0.2 | 0.2 | 1.0 | 0.8 |
| Highlift operator (382) | Surface | 5 | 0.2 | 0.1 | 0.1 | 0.3 | 0.2 |
| Lampman (385) | Surface | 41 | 0.2 | 0.5 | 0.1 | 3.3 | 3.2 |
| Repump truck driver (386) | Surface | 5 | 0.3 | 0.1 | 0.1 | 0.4 | 0.3 |
| Tipple operator (392) | Surface | 1 | 0.4 | | 0.4 | 0.4 | 0.0 |
| Carpenter (394) | Surface | 3 | 0.1 | 0.0 | 0.1 | 0.1 | 0.0 |
| Groundman (398) | Surface | 6 | 0.2 | 0.2 | 0.1 | 0.7 | 0.6 |
| Dust sampler (414) | Administration | 6 | 0.1 | 0.0 | 0.1 | 0.2 | 0.1 |
| Assistant mine foreman (430) | Administration | 6 | 0.2 | 0.1 | 0.1 | 0.4 | 0.3 |
| Fireboss/preshift examiner (462) | Administration | 1 | 0.1 | | 0.1 | 0.1 | 0.0 |
| ALL | | 846 | 0.6 | 1.4 | 0.1 | 24.0 | 23.9 |

# Appendix C

## Optional Dust Control Techniques for Coal Mining Environments

**"One solution to control of respirable dust exposures is competent, careful application of known technology in dust collection and bulk materials handling."**

**K.J. Kaplan-1988**

## CONVENTIONAL MINING

Hollow-steel, drilling-auger-based, dry dust collection systems for face drills[1]

Hollow-steel, drilling-auger-based, water suppression systems for face drills[1]

Water-filled dummies for stemming shotholes to reduce dust in coal breaking[16]

External cutter bar sprays machine-mounted at the front and rear of the cutter bar on cutting machines[15]

External sprays mounted on loading machines near the gathering arms on the pan and directed at the conveyor[15]

Cardox$^{R}$ (liquified carbon dioxide), Airdox$^{R}$ (compressed air), or Hydrox$^{R}$ (sodium nitrate and ammonium chloride reaction) chemical and hydraulic coal burster systems for high pressure breakage of face coals[18]

Low porosity line brattice with tight top and bottom seals for single-split and double-split ventilation systems[15]

Double-split ventilation systems to keep extraction and roof bolting activities in separate fresh air currents[15]

Improved stopping-construction techniques using mortar supplemented with steel or fiberglass fibers brushed on as sealant coatings[15]

Machine-mounted water spray systems to (1) wet coal surfaces to immobilize dust and prevent it from becoming airborne, and (2) generate water droplets to collide with and engulf airborne dust particles accelerating settlement from the airstream[15]

Upgraded water supply systems incorporating increased pump capacity for additional flow and pressure with increased line sizes to decrease pressure losses[2,6,15]

"Non-clogging" filtration system that uses hydrocyclone, flushable Y-strainer, and micropolishing filter devices to improve water quality and reduce maintenance downtime[2,6,15]

Haulroads that have been wet, with calcium chloride applied to maintain moisture content and minimize airborne dust in intake airstreams[15]

Belt scrapers, installed on the return side of the belt near the drive, for cleaning the load bearing side of the belt[2,14,15]

## AUGER-TYPE CONTINUOUS MINING

Double-split ventilation systems to keep extraction and roof bolting activities in separate fresh air currents[15]

Combination line brattice plus auxiliary fan face ventilation systems for improved continuous face ventilation[15]

Improved stopping-construction techniques using mortar supplemented with steel or fiberglass fibers brushed on as sealant coatings[15]

Machine-mounted external water spray systems to (1) wet coal surfaces to immobilize dust and prevent it from becoming airborne, and (2) generate water droplets to collide with and engulf airborne dust particles accelerating settlement from the airstream[15]

Wet-auger water spray systems supplying nozzles on the auger shaft and at cutting bits for dust suppression[15]

Upgraded water supply systems incorporating increased pump capacity for additional flow and pressure with increased line sizes to decrease pressure losses[2,6,15]

"Non-clogging" filtration system that uses hydrocyclone, flushable Y-strainer, and micropolishing filter devices to improve water quality and reduce maintenance downtime[2,6,15]

Nonionic surfactant additives and wetting agents for improved performance of water-spray, dust-suppression systems[1,15]

Machine-mounted high pressure water powered scrubber for reducing dusts on blowing ventilation systems[1,18]

Haulroads that have been wet with water, with calcium chloride applied to maintain moisture content and minimize airborne dust in intake airstreams[15]

Belt scrapers, installed on the return side of the belt near the drive, for cleaning the load-bearing side of the belt[2,14,15]

## CONTINUOUS MINER-TYPE MINING

Double-split ventilation systems to keep extraction and roof bolting activities in separate fresh air currents[15]

Combination line brattice plus auxiliary fan face ventilation systems for improved continuous face ventilation[15]

Blowing diffuser fans mounted on the continuous miner opposite the exhaust tubing or brattice to sweep dust into the exhaust ventilation system[15]

Improved stopping-construction techniques using mortar supplemented with steel or fiberglass fibers brushed on as sealant coatings[15]

Large bits (conical and others) used on drum-type continuous miners and operation at reduced speed to break the coal out in larger chunks and reduce dust generation[16]

Machine-mounted water spray systems that use additional sprays or improved mounting positions to (1) wet coal surfaces to immobilize dust and prevent it from becoming airborne, and (2) generate water droplets to collide with and engulf airborne dust particles accelerating settlement from the airstream[15]

Continuous miner-mounted conveyor throat venturi sprays to prevent dispersion of dust clouds into the operator's station[15]

Machine-mounted, high pressure, water powered scrubber for dust collection [1,15]

Nonionic surfactant additives and wetting agents for improved performance of water spray dust suppression systems[1,2,15]

Continuous miner-mounted venturi scrubber and ducting systems for dust capture and removal[3]

Upgraded water supply systems incorporating increased pump capacity for additional flow and pressure with increased line sizes to decrease pressure losses[2,6,15]

"Non-clogging" filtration system that uses hydrocyclone, flushable Y-strainer, and micropolishing filter devices to improve water quality and reduce maintenance downtime[2,6,15]

Remote control operation systems for continuous miners to keep operators out of the zone of dust production[16]

Half-curtain face ventilation techniques to redirect dusts[1]

High-pressure shrouded water sprays mounted on continuous miner cutting head[4]

Campbell flooded bed scrubber systems installed on the continuous miner[1,17]

Twin flooded fibrous-bed scrubber and water droplet eliminator systems[5,15]

Auxiliary ventilation tubing on the exhaust of face ventilation fans to reroute dust from the continuous miner past downstream roof bolter working places directly into return entries[1]

Roof-bolter flooded bed scrubber and fan modules that receive a split of dusty air from the continuous miner, extracts the respirable dust, and delivers it to the roof bolters as a split of fresh air[1]

Wet drilling with or without water-jet-assisted cutting in roof bolting operations[22]

Belt scrapers, installed on the return side of the belt near the drive, for cleaning the load bearing side of the belt[2,14,15,19]

Machine-mounted, high pressure, water powered scrubber[1]

Venturi scrubbers and ceramic flow-through filters for particulate emission control on diesel powered equipment[20]

Haulroads that have been wet, with calcium chloride applied to maintain moisture content and minimize airborne dust in intake airstreams[15]

Short-hole water infusion from horizontal holes drilled into the working face to a depth equal to the daily advance of the face to increase the moisture content of the coal[15]

Long-hole water infusion holes drilled parallel into the coal seam in advance of the face and before extraction to increase the moisture content of the coal[2,11,12,13,15]

## LONGWALL MINING

Increased ventilation air quantity and face velocities for increased dust dilution[2]

Longwall shearer remote controls for operators[2]

Computer-controlled systems for automated advancement of roof support systems from a direction downwind of the shearer or plow[2,7]

Water sprays directed over shield and chock roof support canopies to suppress dust generated during support movement[6,7]

Large bits (conical and others) used on drum-type shearer and operation at reduced drum rotational speed to break the coal out in larger chunks and reduce dust generation[16]

Deep-cut shearer cutting drums with lower drum rotational speeds[2]
Shearer-Clearer external water spray system using high pressure air-moving water sprays to confine shearer-generated dust near the face and away from operators[2,6,10]

Splitter-arm, passive belting barriers[2,6,9,10]

Machine cooling water relocated into panline sprays or a crescent spray ring wrapped around shearer ranging arms[2,10]

Alternate design mining sequence taking the primary face cut downwind with operators positioned upwind ahead of the lead cutting drum[2,6,7]

Special fabricated shearer cutting drums incorporating cavity filling, water-through-the-bit, and pick face flushing sprays[2]

Upgraded water supply systems incorporating increased pump capacity for additional flow and pressure with increased line sizes to decrease pressure losses[2,6]

Installation of a "non-clogging" filtration system utilizing hydrocyclone, flushable Y-strainer, and microfilter devices to improve water quality and reduce maintenance downtime[2,6]

Ventilation curtains (wing curtain, gob curtain, and stage loader curtain) used in the headgate area to minimize air leakage into the gob and reduce the shearer operator's dust exposure when cutting out at the headgate[2,6,14]

Stageloader and crusher enclosed with steel plates or strips of conveyor belting to isolate conveyed material from the airstream and reduce dust entrainment[2,6,14]

Spraybars containing multiple full-cone water sprays mounted in the stageloader/crusher and at the stageloader-belt conveyor transfer point to provide uniform coverage of the coal stream [2,6,14]

A water-powered scrubber and brattice partition to reduce tailgate worker's dust exposure[2,8]

Belt scrapers, installed on the return side of the belt near the drive, for cleaning the load-bearing side of the belt[2,14,15]

High-pressure, water-jet-assisted cutting for shearers[1]

Nonionic surfactant additives and wetting agents for enhanced performance of water spray dust suppression systems[1,2]

Water infusion holes drilled into the coal seam before extraction to increase the moisture content of the coal[2,11,12,13]

## UNDERGROUND AREAS OUTBY MINING SECTIONS

Water sprinkled on empty coal cars, the tops of loaded cars, and coal on conveyor belts to reduce or eliminate dust blown into ventilating airstreams[16]

A water-powered scrubber at belt conveyor transfer points to capture and eliminate dusts suspended in the airstream[2,8]

Filter cartridge-based compact dry dust collectors for dust control at transfer points and airlock stations[19]

## SURFACE OPEN PIT MINING

Steel collar vacuum dust collection systems drilled with cyclones and baghouses for drill units[1]

Water-based or oil-based wet drilling techniques to eliminate dusts generated during shothole drilling and reduce dusts during subsequent rock and coal breakage[16,18]

Environmentally-controlled airtight cab enclosures for highwall rotary blasthole drill units and bulldozers[1,17]

Trucks equipped with water sprays optionally using wetting agents for roadway and haulroad dust control[16]

Wood-based adhesive polymer foam for roadway dust and materials handling[1]

Building conveyors with elevated discharge chutes around a steel tube with discharge windows at appropriate intervals, or the use of telescopic chutes to materially cut blowage of dusts[16]

## PREPARATION PLANTS

Nonionic surfactant additives for water-spray dust suppression systems at conveyor transfer points, crushers, and vibrating screens[1]

Overhead air supplied island (OASIS) for operators and maintenance personnel at stationary locations[1,17]

Airtight enclosures around transfer chutes with and without local exhaust systems to control suspended dusts[16]

Airtight housings and hoods with vacuum fans and dust collectors or electrostatic precipitators to clean up dusts at rotary breakers, raw coal screens, and crushers[16,21,23]

A water-powered scrubber at belt conveyor transfer points to capture and eliminate dusts suspended in the airstream[2,8,21]

Prepared coal confined in storage bins or silos to prevent dust dispersal[16]

Building conveyors with elevated discharge chutes around a steel tube with discharge windows at appropriate intervals, or the use of telescopic chutes to materially cut blowage of dusts[16]

Sprayed storage piles of fine prepared coal that will stand for appreciable times with fuel oil to reduce dust blowage[16]

## OTHER DUST EXPOSURE CONTROL OPTIONS

Within the hierarchy of dust control technologies, all available engineering controls should be implemented first. During implementation periods, or after exhausting engineering technologies, two additional dust exposure mediation techniques may be instituted:

1. Use of administrative controls (i.e., rotating workers from high dust-making operations to low dust-making operations to expose the mine personnel to lower average daily dust concentrations)[19].

2. Use of respirators capable of removing respirable size particulates, which are commercially available from a number of suppliers and may be provided to miners with proper training in their use and maintenance[19,21]

## REFERENCES

1. ____. International Symposium on Respirable Dust in the Mineral Industries-Final Technical Program, Pennsylvania State University, October, 1986.

2. Shirey GA, Colinet JF, and JA Kost, Dust Control Handbook for Longwall Mining Operations, Mining Research Contract J0348000 Final Report, Bureau of Mines, Pittsburgh, PA, May 1985.

3. Jayaraman NI, Dust Control for a Borer-Type Continuous Miner Using a Venturi Scrubber on a Transfer Car, Report of Investigation 8408, Bureau of Mines, Pittsburgh, PA, 1979.

4. Jayaraman NI, Kissell FN, Cross W, Janosik J, and J Odoski, High-Pressure Shrouded Water Sprays for Dust Control, Report of Investigation 8536, Bureau of Mines, Pittsburgh, PA, 1981.

5. Divers EF, LaScola JC, and GJ Hundman, New Twin Scrubber Installation for Continuous Mining Machines, Bureau of Mines-Technical Progress Report 112, Pittsburgh, PA, February 1981.

6. Jankowski RA and JA Organiscak, Dust Sources and Controls on the Six U.S. Longwall Faces Having the Most Difficulty Complying With Dust Standards, Information Circular 8957, Bureau of Mines, Pittsburgh, PA, 1981.

7. Organiscak JA, Listak JM, and RA Jankowski, Factors Affecting Respirable Dust Generation From Longwall Roof Supports, Information Circular 9019, Bureau of Mines, Pittsburgh, PA, 1985.

8. Organiscak JA, Volkwein JC, and RA Jankowski, Reducing Longwall Tailgate Workers' Dust Exposure Utilizing Water-Powered Scrubbers, Report Of Investigations 8780, Bureau of Mines, Pittsburgh, PA, 1983.

9. Jankowski RA and CA Babbitt, Using Barriers to Reduce Dust Exposure of Longwall Face Workers, Report of Investigations 9037, Bureau of Mines, Pittsburgh, PA, 1986.

10. Jayaraman NI, Jankowski RA and FN Kissell, Improved Shearer-Clearer System for Double-Drum Shearers on Longwall Faces, Report of Investigations 8963, Bureau of Mines, Pittsburgh, PA, 1985.

11. Cervik J, Sainato A and E Baker, Water Infusion-An Effective and Economical Longwall Dust Control, Report of Investigations 8838, Bureau of Mines, Pittsburgh, PA, 1983.

12. Taylor CD and RJ Evans, Water-Jet-Assisted Cutting, Proceedings: Bureau of Mines Open Industry Meeting, Pittsburgh, PA, June 21, 1984, Information Circular 9045, Bureau of Mines, Pittsburgh, PA, 1985.

13. Taylor CD, Kovscek PD and ED Thimons, Dust Control on Longwall Shearers Using Water-Jet-Assisted Cutting, Information Circular 9077, Bureau of Mines, Pittsburgh, PA, 1986.

14. Organiscak, JA, Jankowski RA and JS Kelly, Dust Controls To Improve Quality of Longwall Intake Air, Information Circular 9114, Bureau of Mines, Pittsburgh, PA, 1986.

15. Kost JA, Yingling JC and BJ Mondics, Guidebook for Dust Control in Underground Mining, Final Report USBM Contract J0199046, Bureau of Mines, Pittsburgh, PA, 1981.

16. Cummins AB and IA Given, Eds., SME Mining Engineering Handbook, Society of Mining Engineers of the American Institute of Mining, Mineral, and Petroleum Engineers, New York, NY, 1973.

17. Frantz, RL and RJ Ramani, Eds., Respirable Dust in the Mineral Industries: Health Effects, Characterization and Control, The Pennsylvania State University, University Park, PA, 1988.

18. Bourgoyne AT, Millheim KK, Chenevert ME, and FS Young, Applied Drilling Engineering, Society of Petroleum Engineers, Richardson, TX, 1986.

19. Barrett J, Sutherland W, Jacobsen M, Tinney G, and P Turcic, Eds., Proceedings of the Symposium on Control of Respirable Coal Mine Dust, Mine Safety and Health Administration, Beckley, WV, 1983.

20. Wheeler RW, Ed., International Conference on the Health of Miners, Annals of the American Conference of Governmental and Industrial Hygienists, Cincinnati, OH, 1986.

21. Divers EF and AB Cecala, Dust Control in Coal Preparation and Mineral Processing Plants, Information Circular 9248, Bureau of Mines, Pittsburgh, PA, 1990.

22. Adam RFJ, Planning a Dust Free Coal Mine, Proceedings of the VIIth International Pneumoconiosis Conference, Part II. NIOSH, U.S. Department of Health and Human Services, DHHS (NIOSH) Publication No. 90-108, Pittsburgh, PA, 1990.

23. Divers EF and RA Jankowski, Respirable Dust Control in Coal Preparation, Mining Engineering, Vol. 40, No. 12, 1988.

# APPENDIX D

## METHODS FOR CONTROLLING RESPIRABLE COAL MINE DUST FROM OVERBURDEN DRILLING AT SURFACE COAL MINES

This appendix focuses on methods of reducing excess respirable dust exposures during overburden drilling, the activity that places surface coal miners at greatest risk of exposure to respirable crystalline silica. However, the protection of surface coal miners in other job activities from potential health hazards should not be overlooked.

## D.1 ENGINEERING CONTROLS

Engineering controls for overburden drilling include: dry dust collection systems, wet dust suppression systems, and enclosed cabs [Bureau of Mines 1986; Volkwein et al. 1979]. Proper maintenance of the dust suppression system is critically important for drills using dry dust suppression methods. Failure to rigorously maintain these systems will result in inadequate dust control. Acute silicosis has been reported in miners operating equipment relying on dry dust suppression (NIOSH Alert on Silicosis).

### D.1.1 Dry Dust Collection Systems

Dry dust collection systems typically include the following components:

#### D.1.1.1 Drill Platform Shroud

A drill platform shroud is essentially a "skirt" made of a flexible material (usually rubber) that hangs from the underside of the drill platform and surrounds the drill hole. The shroud enclosure, which is maintained under negative pressure, contains the dust that comes out of the drill hole. When the system is equipped with an adjustable shroud, the shroud height (the distance between the ground and the bottom of the shroud) should be kept as low as possible. A Bureau of Mines [1986] study found that while results differ with different drills, in general, the control efficiency decreases as the shroud height increases. The same study reported that, in the two drills tested, control efficiencies varied from 99 to 41 percent over the 0- to 27-inch height range and that the collection system performed most efficiently when the shroud height was no greater than 9 inches. In practice, however, maintaining a consistent height around the shroud because of uneven ground surfaces is not always possible.

### D.1.1.2 Drill Stem Seal

The point at which the drill stem passes through the drill platform can be a source of dust emission. To control this dust source, a flexible "collar" that acts like a seal is placed around the drill stem at the platform level. The integrity of the seal must be maintained to prevent dust leakage.

### D.1.1.3 Dust Collector

The dust from the shroud enclosure is transported through a duct to a collection chamber containing paper or fabric filters. An exhaust fan, located on the clean side of the filters, maintains a negative pressure inside the duct and the shroud enclosure, and draws the dust-laden air through the filters at rates greater than 4 to 6 times the bailing airflow and varying from 600 to 6,000 cubic feet per minute depending on the size of the system. The filtered air is exhausted to the atmosphere while the dust is trapped on the filters. The filters are periodically cleaned with a reverse pulse of compressed air, which sends the collected dust into a hopper for discharge onto the ground away from the drill crew.

Test data have shown that dry dust collection systems are capable of achieving greater than 95 percent control efficiency [Bureau of Mines 1986], but this control efficiency may not always be reproducible in practice. Table C-1 summarizes the advantages and disadvantages of a dry dust collection system. Figure C-1 is an illustration of a dry dust collection system.

### D.1.2 Wet Dust Suppression Systems

In wet dust suppression systems, water is pumped from a storage tank into a line injecting the bail air into the interior of the drill stem. The water droplets in the bail air coat and aggregate the dust as they are carried upward through the drill hole. Thus, the dust is suppressed by the weight of the moisture as the air bails out the cuttings from the hole. Because the water is expended in the process, the storage tank may have to be refilled one or more times per day. Normally, the water has to be transported to the drilling site.

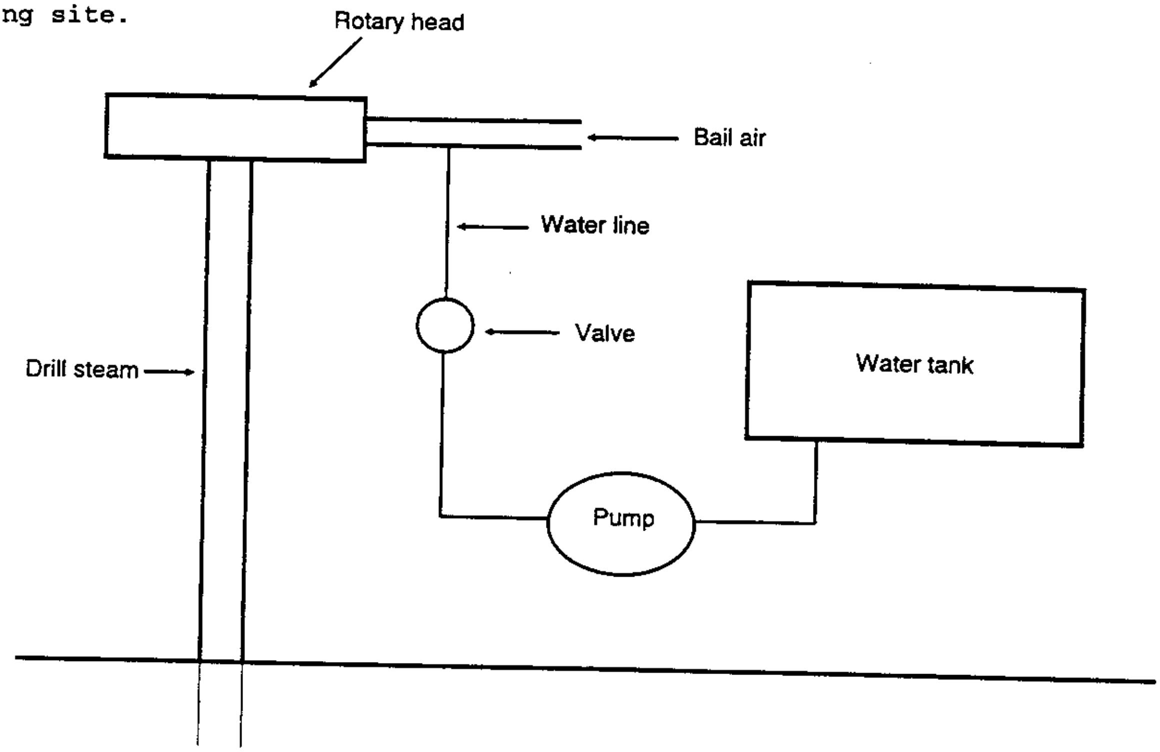

Figure D-1. Wet dust collection system. (Source: Bureau of Mines [1986].)

Table D-1.--Advantages and disadvantages of dry dust collection systems*

| Advantages | Disadvantages |
|---|---|
| Operates at any outside temperature | Expensive to install |
| Does not require any expendable material (water) | Expensive to maintain |
| Functions well when properly maintained and operated | Requires conscious effort by driller to ensure efficiency |
| | May not be suitable where ground water or coal-bed fires are present |

*Adapted from Bureau of Mines [1986]

The effectiveness of the control also depends on the experience and skill of the driller who controls the flow rate manually with a control valve. The driller often must adjust the flow rate based on his visual estimation of the moisture content of the cuttings. Excessive water in the bail air would make the cuttings too heavy to be bailed up the drill hole. Also, cuttings with excessive moisture would plug up the air orifices of the drill bit. The flow-efficiency relationship may have to be determined more than once in a particular mine because it is affected by different drills, different bit sizes or different types of geologic strata. A flowmeter should be installed at the control valve to aid this determination [Bureau of Mines 1986].

In one study [Bureau of Mines 1986], for example, control efficiencies for a selected drill varied from 9% at a water flow rate of 0.2 gallons per minute (gpm) to 96% at 1.2 gpm, and the greatest increase in control efficiency was in the range of 0.4 to 0.6 gpm. These numbers are valid only for the conditions under which the tests were conducted.

Bit life can be shortened by 50% or more because of the degradation effects of excessive moisture on the bit [Bureau of Mines 1988]. When outdoor temperatures drop below the freezing point, the system must be heated to alleviate operational problems. Antifreeze compounds may be added to the water to prevent freezing, but this method could be extremely expensive when large volumes of water are used.

The control efficiency of wet dust suppression is similar to that of dry dust collection [Bureau of Mines 1986]. Table D-2 summarizes the advantages and disadvantages of a wet dust suppression system. Figure D-2 is an illustration of a wet dust suppression system.

### D.1.3 Enclosed Cab

Drills come in different sizes. Depending on the size, the drills may or may not be equipped with cabs, and the cabs may be partially or totally enclosed. When a totally enclosed cab is available, an effective way to protect the driller working inside the cab is to pressurize it (positive pressure relative to the outside) with outside air drawn through an air filter capable of removing respirable dust. A NIOSH health hazard evaluation [Cornwell and Hanke 1983] reported that the use of a pressurized cab alone (without dry dust collection or wet dust suppression) could afford a 70% reduction in the concentration of respirable dust inside the cab as compared to that outside. Subsequent information [Cornwell 1990] revealed that the air filter used for the cab was graded as 99.9% efficient in removing fine test dust as defined by the Society of Automotive Engineers [SAE 1987]. Thus, the control efficiency may be highly dependent on the grade of the air filter.

Air conditioning should be installed in the cab to eliminate the necessity of opening the cab door or windows in hot weather. When the cab door or windows are open, even the best dust filtration system will not be effective. The air conditioning unit needs to be rugged in construction. Ordinary automotive air-conditioning units are not able to withstand the severe conditions found in the mining environment [Volkwein et al. 1979]. Ideally, the air conditioning system should be incorporated into the engine intake system to reduce the number of maintenance items and to insure proper maintenance of both systems [Volkwein et al. 1979].

Table D-2.--Advantages and disadvantages of wet dust suppression systems*

| Advantages | Disadvantages |
|---|---|
| Inexpensive to install | Systems must be heated in cold temperatures or anti-freezing additive must be used |
| Inexpensive to maintain | Proper operation requires some expertise on behalf of drill operator |
| Functions well when properly operated | Requires use of expendable material (water) |
| Not affected by groundwater or bed fires | May cause decreased bit life and drilling efficiency |

*Adapted from Bureau of Mines [1986]

## D.1.4 Improved Control Technology

### D.1.4.1 Dust Agglomerator

In a dry dust collection system, the discharge of dust from the dust collector accounts for 40% of the respirable dust emitted [Bureau of Mines 1989]. The discharged dust can be dispersed by the wind, from impact on the ground, or by equipment driven over dust piles. The dispersed dust poses a potential health hazard not only to the drill crew but also to other miners working in the vicinity. An agglomerator tested by the Bureau of Mines [1989] offers a solution to these problems. The discharged dust is fed directly into a device that uses gentle water sprays and a spinning motion to coalesce the dust particles into nonrespirable pellets.

### D.1.4.2 Water Separation

The moist environment around the drill bit in wet dust suppression has been noted to reduce drill bit life by 50% or more [Bureau of Mines 1988]. Water separation is a method used to prevent water from reaching the drill bit, thereby prolonging the bit life. In this method, the bail air is guided through one or more sharp turns as it travels down the interior of the drill stem. Because it has a higher inertia than that of air, the water cannot negotiate the turns and thus is separated from the bail air. The dried bail air continues to travel through the drill stem and out of the air orifices of the bit. Under positive pressure, the water is forced out through weep holes into the annular space around the drill stem. Consequently, the drill cuttings are wetted as they are carried upward through this annulus by the bail air below. The Bureau of Mines [1988] reported that no significant difference in the dust control efficiency was noted between water drilling with and without water separation and that data from one mine showed greater than a 400% increase in average bit life--9,000 feet per bit with water separation versus 1,938 feet per bit without.

## D.2 WORK PRACTICES

The selection of a suitable drilling site affects the control efficiency of a dry dust collection system. A drilling site with a flat surface should be selected because this would allow uniform shroud height around the drill. Sometimes the ground surface can be leveled with appropriate equipment.

Where applicable, and coupled with proper maintenance (e.g., replacing worn parts when required), periodic and pre-operational inspections should be made on engineering controls. The following is a checklist of inspection items associated with the different control systems:

- Dry Dust Collection System
    - Check the integrity of seals and shroud material.
    - Check fan belts for proper tension and for wear and tear.
    - Check fan blades for wear and tear.
    - Check the integrity of dust collector filters.
    - Check exhaust ductworks for leakage.
- Wet Dust Suppression System
    - Check the control valve and the flow meter for proper operation.
    - Check pipe connections for leakage.
- Pressurized Cab
    - Check the integrity of seals around the door and windows.
    - Check air filters for dust accumulations.
    - Check fan belts for proper tension and for wear and tear.

When the drill is operating with a totally enclosed cab, the drill crew should stay inside the cab with the door and windows closed as much as practicable. When work must be done outside the cab, the drill crew should try to position themselves upwind from dust emissions. The drill crew will drag dust with them into the cab as they enter and exit during the drilling operation.

Therefore, good housekeeping is necessary to maintain a relatively dust-free environment inside the cab. Vacuuming is effective but may not be practical at the work site. Whenever possible, wet wiping is preferred over dry sweeping. If dry sweeping is used, care should be exercised to prevent dispersing the settled dust. Cleaning with compressed air should be avoided.

Where a dry dust collection system is used, the shroud must be raised periodically to let the cuttings spill out of the enclosure. The drill crew should be careful to raise the shroud only enough to clear the cuttings but at the same time to keep the shroud height low enough to maintain the dust capture efficiency of the system.

## D.3 ENGINEERING CONTROLS AND WORK PRACTICES FOR OTHER OCCUPATIONS

For other surface coal miners who are potentially exposed to respirable crystalline silica and respirable coal mine dust, general industrial hygiene control methods should be applied where they are feasible and appropriate to particular operational conditions. Judicial application of engineering controls (e.g., local exhaust ventilation, enclosures) and/or work practices (e.g., equipment maintenance, housekeeping) is needed in jobs such as bulldozer operators, shotfirers, pan scraper operators, truck drivers, and crusher attendants (Table 3.7.5).

## D.4 DUST CONTROL ON UNPAVED ROADS

The application of dust suppressants to unpaved roads in surface mines is generally considered useful in reducing dust emissions and improving driver safety by increasing visibility [Rosbury and Zimmer 1983]. The benefits of reduced dust emissions from treated roads could extend to miners working in the vicinity, and especially to truck drivers, in the form of reduced exposures to respirable crystalline silica and respirable coal mine dust.

Table D-3 lists the various types of dust suppressants.

Table D-3.--Dust suppressants for controlling particulate emissions from unpaved roads*

| Category | Description | Examples |
|---|---|---|
| Salts | Hygroscopic compounds that extract calcium chloride, magnesium moisture from the atmosphere and chloride, hydrated lime, dampen the road surface | Sodium silicates |
| Surfactants | Substances capable of reducing the surface tension of the transport liquid, thereby allowing available moisture to wet more dirt particles per unit volume | Soaps, detergents |
| Adhesives | Compounds that are mixed with calcium lignon sulfonate, native soils to form a new surface | Sodium lignon sulfonate, ammonium lignon sulfonate, Portland cement |
| Bitumens | Compounds derived from coal or asphalt, oils petroleum and mixed with native soils to form a new surface | |
| Films | Polymers that form discrete layers vinyls, fabrics or membranes | |

*Adapted from Rosbury and Zimmer [1983]

# APPENDIX E

## INTERPRETATION OF PULMONARY FUNCTION TESTS:

## SPIROMETRY

The largest forced vital capacity (FVC), largest forced expiratory volume in one second ($FEV_1$), and the ratio of the largest $FEV_1$ to the largest FVC ($FEV_1$/FVC%) from each workers's pulmonary function examination should each be compared with the lower limit of normal (LLN or 95th percentiles) cutoff for the respective parameter using the reference equations developed by Knudson et al. [1983] (Tables E-1, E-2, and E-3 for males and Tables E-4, E-5*, and E-6 for females). When previous test results for a worker are available, in addition to comparing the current results with predicted values, a physician should determine if any significant change in $FEV_1$ has occurred.

Regarding interpretation of longitudinal changes in lung function, the American Thoracic Society has recommended that a change in $FEV_1$ of $\geq$15% from year to year should be considered significant [ATS 1991]. Thus, any worker whose $FEV_1$ is below the LLN or who has a suspected excessive annual decline in $FEV_1$ ($\geq$15% from year to year) should be referred for a clinical evaluation, which may include a repeat pulmonary function evaluation.

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*An exception to the Knudson et al. [1983] predicted values is made for females less than 40 years old. The 95% confidence limit for the less than 40 years age group is located at approximately 77% of the mean $FEV_1$ for this age group. The 95th percentile for this age group is 70.3%, while that for females older than 40 years is 77.9%. If the value 70.3% is used, then a female's LLN for the $FEV_1$ will increase between the ages of 39 and 40. The females in most other studies, and even the males in this same study, usually exhibit a decrease in the 95th percentile for the older age groups. Therefore, the same 95th percentile (77.9%) is used for all females older than 20 years.

Table F-1.--Lower limit of normal (LLN) for FVC for males

| Ht | Age | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (cm)* | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 | 65 |
| 157 | 2.89 | 3.01 | 3.13 | 3.25 | 3.02 | 2.97 | 2.92 | 2.87 | 2.82 | 2.77 | 2.73 | 2.68 | 2.38 | 2.33 | 2.29 | 2.25 | 2.20 | 2.16 | 2.12 | 2.07 | 2.03 | 1.98 | 1.94 | 1.90 | 1.85 |
| 158 | 2.94 | 3.06 | 3.18 | 3.29 | 3.08 | 3.04 | 2.99 | 2.94 | 2.89 | 2.84 | 2.79 | 2.75 | 2.44 | 2.40 | 2.35 | 2.31 | 2.27 | 2.22 | 2.18 | 2.13 | 2.09 | 2.05 | 2.00 | 1.96 | 1.92 |
| 159 | 2.99 | 3.11 | 3.22 | 3.34 | 3.15 | 3.10 | 3.06 | 3.01 | 2.96 | 2.91 | 2.86 | 2.81 | 2.50 | 2.46 | 2.41 | 2.37 | 2.33 | 2.28 | 2.24 | 2.20 | 2.15 | 2.11 | 2.06 | 2.02 | 1.98 |
| 160 | 3.04 | 3.15 | 3.27 | 3.39 | 3.22 | 3.17 | 3.12 | 3.08 | 3.03 | 2.98 | 2.93 | 2.88 | 2.56 | 2.52 | 2.48 | 2.43 | 2.39 | 2.35 | 2.30 | 2.26 | 2.21 | 2.17 | 2.13 | 2.08 | 2.04 |
| 161 | 3.08 | 3.20 | 3.32 | 3.44 | 3.29 | 3.24 | 3.19 | 3.14 | 3.10 | 3.05 | 3.00 | 2.95 | 2.63 | 2.58 | 2.54 | 2.50 | 2.45 | 2.41 | 2.36 | 2.32 | 2.28 | 2.23 | 2.19 | 2.15 | 2.10 |
| 162 | 3.13 | 3.25 | 3.37 | 3.48 | 3.36 | 3.31 | 3.26 | 3.21 | 3.16 | 3.12 | 3.07 | 3.02 | 2.69 | 2.64 | 2.60 | 2.56 | 2.51 | 2.47 | 2.43 | 2.38 | 2.34 | 2.29 | 2.25 | 2.21 | 2.16 |
| 163 | 3.18 | 3.29 | 3.41 | 3.53 | 3.43 | 3.38 | 3.33 | 3.28 | 3.23 | 3.18 | 3.14 | 3.09 | 2.75 | 2.71 | 2.66 | 2.62 | 2.58 | 2.53 | 2.49 | 2.44 | 2.40 | 2.36 | 2.31 | 2.27 | 2.23 |
| 164 | 3.22 | 3.34 | 3.46 | 3.58 | 3.49 | 3.45 | 3.40 | 3.35 | 3.30 | 3.25 | 3.20 | 3.16 | 2.81 | 2.77 | 2.72 | 2.68 | 2.64 | 2.59 | 2.55 | 2.51 | 2.46 | 2.42 | 2.37 | 2.33 | 2.29 |
| 165 | 3.27 | 3.39 | 3.51 | 3.62 | 3.56 | 3.51 | 3.47 | 3.42 | 3.37 | 3.32 | 3.27 | 3.22 | 2.87 | 2.83 | 2.79 | 2.74 | 2.70 | 2.66 | 2.61 | 2.57 | 2.52 | 2.48 | 2.44 | 2.39 | 2.35 |
| 166 | 3.32 | 3.44 | 3.55 | 3.67 | 3.63 | 3.58 | 3.53 | 3.49 | 3.44 | 3.39 | 3.34 | 3.29 | 2.94 | 2.89 | 2.85 | 2.80 | 2.76 | 2.72 | 2.67 | 2.63 | 2.59 | 2.54 | 2.50 | 2.45 | 2.41 |
| 167 | 3.36 | 3.48 | 3.60 | 3.72 | 3.70 | 3.65 | 3.60 | 3.55 | 3.51 | 3.46 | 3.41 | 3.36 | 3.00 | 2.95 | 2.91 | 2.87 | 2.82 | 2.78 | 2.74 | 2.69 | 2.65 | 2.60 | 2.56 | 2.52 | 2.47 |
| 168 | 3.41 | 3.53 | 3.65 | 3.77 | 3.77 | 3.72 | 3.67 | 3.62 | 3.57 | 3.53 | 3.48 | 3.43 | 3.06 | 3.02 | 2.97 | 2.93 | 2.88 | 2.84 | 2.80 | 2.75 | 2.71 | 2.67 | 2.62 | 2.58 | 2.53 |
| 169 | 3.46 | 3.58 | 3.69 | 3.81 | 3.84 | 3.79 | 3.74 | 3.69 | 3.64 | 3.59 | 3.55 | 3.50 | 3.12 | 3.08 | 3.03 | 2.99 | 2.95 | 2.90 | 2.86 | 2.82 | 2.77 | 2.73 | 2.68 | 2.64 | 2.60 |
| 170 | 3.51 | 3.62 | 3.74 | 3.86 | 3.90 | 3.86 | 3.81 | 3.76 | 3.71 | 3.66 | 3.61 | 3.57 | 3.18 | 3.14 | 3.10 | 3.05 | 3.01 | 2.97 | 2.92 | 2.88 | 2.83 | 2.79 | 2.75 | 2.70 | 2.66 |
| 171 | 3.55 | 3.67 | 3.79 | 3.91 | 3.97 | 3.93 | 3.88 | 3.83 | 3.78 | 3.73 | 3.68 | 3.64 | 3.25 | 3.20 | 3.16 | 3.11 | 3.07 | 3.03 | 2.98 | 2.94 | 2.90 | 2.85 | 2.81 | 2.76 | 2.72 |
| 172 | 3.60 | 3.72 | 3.84 | 3.95 | 4.04 | 3.99 | 3.95 | 3.90 | 3.85 | 3.80 | 3.75 | 3.70 | 3.31 | 3.26 | 3.22 | 3.18 | 3.13 | 3.09 | 3.05 | 3.00 | 2.96 | 2.91 | 2.87 | 2.83 | 2.78 |
| 173 | 3.65 | 3.77 | 3.88 | 4.00 | 4.11 | 4.06 | 4.01 | 3.97 | 3.92 | 3.87 | 3.82 | 3.77 | 3.37 | 3.33 | 3.28 | 3.24 | 3.19 | 3.15 | 3.11 | 3.06 | 3.02 | 2.98 | 2.93 | 2.89 | 2.84 |
| 174 | 3.69 | 3.81 | 3.93 | 4.05 | 4.18 | 4.13 | 4.08 | 4.03 | 3.99 | 3.94 | 3.89 | 3.84 | 3.43 | 3.39 | 3.34 | 3.30 | 3.26 | 3.21 | 3.17 | 3.13 | 3.08 | 3.04 | 2.99 | 2.95 | 2.91 |
| 175 | 3.74 | 3.86 | 3.98 | 4.10 | 4.25 | 4.20 | 4.15 | 4.10 | 4.05 | 4.01 | 3.96 | 3.91 | 3.49 | 3.45 | 3.41 | 3.36 | 3.32 | 3.27 | 3.23 | 3.19 | 3.14 | 3.10 | 3.06 | 3.01 | 2.97 |
| 176 | 3.79 | 3.91 | 4.02 | 4.14 | 4.32 | 4.27 | 4.22 | 4.17 | 4.12 | 4.07 | 4.03 | 3.98 | 3.56 | 3.51 | 3.47 | 3.42 | 3.38 | 3.34 | 3.29 | 3.25 | 3.21 | 3.16 | 3.12 | 3.07 | 3.03 |
| 177 | 3.84 | 3.95 | 4.07 | 4.19 | 4.38 | 4.34 | 4.29 | 4.24 | 4.19 | 4.14 | 4.09 | 4.05 | 3.62 | 3.57 | 3.53 | 3.49 | 3.44 | 3.40 | 3.35 | 3.31 | 3.27 | 3.22 | 3.18 | 3.14 | 3.09 |
| 178 | 3.88 | 4.00 | 4.12 | 4.24 | 4.45 | 4.40 | 4.36 | 4.31 | 4.26 | 4.21 | 4.16 | 4.11 | 3.68 | 3.64 | 3.59 | 3.55 | 3.50 | 3.46 | 3.42 | 3.37 | 3.33 | 3.29 | 3.24 | 3.20 | 3.15 |
| 179 | 3.93 | 4.05 | 4.17 | 4.28 | 4.52 | 4.47 | 4.42 | 4.38 | 4.33 | 4.28 | 4.23 | 4.18 | 3.74 | 3.70 | 3.65 | 3.61 | 3.57 | 3.52 | 3.48 | 3.44 | 3.39 | 3.35 | 3.30 | 3.26 | 3.22 |
| 180 | 3.98 | 4.09 | 4.21 | 4.33 | 4.59 | 4.54 | 4.49 | 4.44 | 4.40 | 4.35 | 4.30 | 4.25 | 3.80 | 3.76 | 3.72 | 3.67 | 3.63 | 3.58 | 3.54 | 3.50 | 3.45 | 3.41 | 3.37 | 3.32 | 3.28 |
| 181 | 4.02 | 4.14 | 4.26 | 4.38 | 4.66 | 4.61 | 4.56 | 4.51 | 4.46 | 4.42 | 4.37 | 4.32 | 3.87 | 3.82 | 3.78 | 3.73 | 3.69 | 3.65 | 3.60 | 3.56 | 3.52 | 3.47 | 3.43 | 3.38 | 3.34 |
| 182 | 4.07 | 4.19 | 4.31 | 4.42 | 4.73 | 4.68 | 4.63 | 4.58 | 4.53 | 4.48 | 4.44 | 4.39 | 3.93 | 3.88 | 3.84 | 3.80 | 3.75 | 3.71 | 3.66 | 3.62 | 3.58 | 3.53 | 3.49 | 3.45 | 3.40 |
| 183 | 4.12 | 4.24 | 4.35 | 4.47 | 4.79 | 4.75 | 4.70 | 4.65 | 4.60 | 4.55 | 4.50 | 4.46 | 3.99 | 3.95 | 3.90 | 3.86 | 3.81 | 3.77 | 3.73 | 3.68 | 3.64 | 3.60 | 3.55 | 3.51 | 3.46 |
| 184 | 4.17 | 4.28 | 4.40 | 4.52 | 4.86 | 4.81 | 4.77 | 4.72 | 4.67 | 4.62 | 4.57 | 4.52 | 4.05 | 4.01 | 3.96 | 3.92 | 3.88 | 3.83 | 3.79 | 3.74 | 3.70 | 3.66 | 3.61 | 3.57 | 3.53 |
| 185 | 4.21 | 4.33 | 4.45 | 4.57 | 4.93 | 4.88 | 4.84 | 4.79 | 4.74 | 4.69 | 4.64 | 4.59 | 4.11 | 4.07 | 4.03 | 3.98 | 3.94 | 3.89 | 3.85 | 3.81 | 3.76 | 3.72 | 3.68 | 3.63 | 3.59 |
| 186 | 4.26 | 4.38 | 4.50 | 4.61 | 5.00 | 4.95 | 4.90 | 4.86 | 4.81 | 4.76 | 4.71 | 4.66 | 4.17 | 4.13 | 4.09 | 4.04 | 4.00 | 3.96 | 3.91 | 3.87 | 3.83 | 3.78 | 3.74 | 3.69 | 3.65 |
| 187 | 4.31 | 4.42 | 4.54 | 4.66 | 5.07 | 5.02 | 4.97 | 4.92 | 4.88 | 4.83 | 4.78 | 4.73 | 4.24 | 4.19 | 4.15 | 4.11 | 4.06 | 4.02 | 3.97 | 3.93 | 3.89 | 3.84 | 3.80 | 3.76 | 3.71 |
| 188 | 4.35 | 4.47 | 4.59 | 4.71 | 5.14 | 5.09 | 5.04 | 4.99 | 4.94 | 4.90 | 4.85 | 4.80 | 4.30 | 4.26 | 4.21 | 4.17 | 4.12 | 4.08 | 4.04 | 3.99 | 3.95 | 3.91 | 3.86 | 3.82 | 3.77 |
| 189 | 4.40 | 4.52 | 4.64 | 4.75 | 5.21 | 5.16 | 5.11 | 5.06 | 5.01 | 4.96 | 4.92 | 4.87 | 4.36 | 4.32 | 4.27 | 4.23 | 4.19 | 4.14 | 4.10 | 4.05 | 4.01 | 3.97 | 3.92 | 3.88 | 3.84 |
| 190 | 4.45 | 4.57 | 4.68 | 4.80 | 5.27 | 5.23 | 5.18 | 5.13 | 5.08 | 5.03 | 4.98 | 4.94 | 4.42 | 4.38 | 4.34 | 4.29 | 4.25 | 4.20 | 4.16 | 4.12 | 4.07 | 4.03 | 3.99 | 3.94 | 3.90 |
| 191 | 4.49 | 4.61 | 4.73 | 4.85 | 5.34 | 5.29 | 5.25 | 5.20 | 5.15 | 5.10 | 5.05 | 5.00 | 4.48 | 4.44 | 4.40 | 4.35 | 4.31 | 4.27 | 4.22 | 4.18 | 4.13 | 4.09 | 4.05 | 4.00 | 3.96 |
| 192 | 4.54 | 4.66 | 4.78 | 4.90 | 5.41 | 5.36 | 5.31 | 5.27 | 5.22 | 5.17 | 5.12 | 5.07 | 4.55 | 4.50 | 4.46 | 4.42 | 4.37 | 4.33 | 4.28 | 4.24 | 4.20 | 4.15 | 4.11 | 4.07 | 4.02 |
| 193 | 4.59 | 4.71 | 4.82 | 4.94 | 5.48 | 5.43 | 5.38 | 5.33 | 5.29 | 5.24 | 5.19 | 5.14 | 4.61 | 4.56 | 4.52 | 4.48 | 4.43 | 4.39 | 4.35 | 4.30 | 4.26 | 4.21 | 4.17 | 4.13 | 4.08 |

*Abbreviations: Ht=height; cm=centimeters

Table E-2.--Lower limit of normal (LLN) for $FEV_1$ for males

| Ht | Age | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (cm) | *17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 | 65 |
| 157 | 2.52 | 2.62 | 2.73 | 2.83 | 2.52 | 2.48 | 2.43 | 2.38 | 2.34 | 2.29 | 2.25 | 2.20 | 2.10 | 2.06 | 2.01 | 1.97 | 1.92 | 1.88 | 1.83 | 1.79 | 1.74 | 1.70 | 1.65 | 1.61 | 1.56 |
| 158 | 2.56 | 2.67 | 2.77 | 2.87 | 2.58 | 2.53 | 2.48 | 2.44 | 2.39 | 2.34 | 2.30 | 2.25 | 2.15 | 2.11 | 2.06 | 2.02 | 1.97 | 1.93 | 1.88 | 1.84 | 1.79 | 1.75 | 1.70 | 1.66 | 1.61 |
| 159 | 2.61 | 2.71 | 2.81 | 2.92 | 2.63 | 2.58 | 2.54 | 2.49 | 2.44 | 2.40 | 2.35 | 2.30 | 2.20 | 2.16 | 2.11 | 2.07 | 2.02 | 1.98 | 1.93 | 1.89 | 1.84 | 1.80 | 1.75 | 1.71 | 1.66 |
| 160 | 2.65 | 2.75 | 2.85 | 2.96 | 2.68 | 2.63 | 2.59 | 2.54 | 2.50 | 2.45 | 2.40 | 2.36 | 2.26 | 2.21 | 2.17 | 2.12 | 2.08 | 2.03 | 1.98 | 1.94 | 1.89 | 1.85 | 1.80 | 1.76 | 1.71 |
| 161 | 2.69 | 2.79 | 2.90 | 3.00 | 2.73 | 2.69 | 2.64 | 2.59 | 2.55 | 2.50 | 2.46 | 2.41 | 2.31 | 2.26 | 2.22 | 2.17 | 2.13 | 2.08 | 2.04 | 1.99 | 1.95 | 1.90 | 1.86 | 1.81 | 1.77 |
| 162 | 2.73 | 2.84 | 2.94 | 3.04 | 2.79 | 2.74 | 2.69 | 2.65 | 2.60 | 2.55 | 2.51 | 2.46 | 2.36 | 2.31 | 2.27 | 2.22 | 2.18 | 2.13 | 2.09 | 2.04 | 2.00 | 1.95 | 1.91 | 1.86 | 1.82 |
| 163 | 2.77 | 2.88 | 2.98 | 3.08 | 2.84 | 2.79 | 2.75 | 2.70 | 2.65 | 2.61 | 2.56 | 2.52 | 2.41 | 2.36 | 2.32 | 2.27 | 2.23 | 2.18 | 2.14 | 2.09 | 2.05 | 2.00 | 1.96 | 1.91 | 1.87 |
| 164 | 2.82 | 2.92 | 3.02 | 3.13 | 2.89 | 2.84 | 2.80 | 2.75 | 2.71 | 2.66 | 2.61 | 2.57 | 2.46 | 2.42 | 2.37 | 2.33 | 2.28 | 2.24 | 2.19 | 2.15 | 2.10 | 2.06 | 2.01 | 1.96 | 1.92 |
| 165 | 2.86 | 2.96 | 3.07 | 3.17 | 2.94 | 2.90 | 2.85 | 2.81 | 2.76 | 2.71 | 2.67 | 2.62 | 2.51 | 2.47 | 2.42 | 2.38 | 2.33 | 2.29 | 2.24 | 2.20 | 2.15 | 2.11 | 2.06 | 2.02 | 1.97 |
| 166 | 2.90 | 3.00 | 3.11 | 3.21 | 3.00 | 2.95 | 2.90 | 2.86 | 2.81 | 2.77 | 2.72 | 2.67 | 2.56 | 2.52 | 2.47 | 2.43 | 2.38 | 2.34 | 2.29 | 2.25 | 2.20 | 2.16 | 2.11 | 2.07 | 2.02 |
| 167 | 2.94 | 3.05 | 3.15 | 3.25 | 3.05 | 3.00 | 2.96 | 2.91 | 2.86 | 2.82 | 2.77 | 2.73 | 2.61 | 2.57 | 2.52 | 2.48 | 2.43 | 2.39 | 2.34 | 2.30 | 2.25 | 2.21 | 2.16 | 2.12 | 2.07 |
| 168 | 2.99 | 3.09 | 3.19 | 3.29 | 3.10 | 3.06 | 3.01 | 2.96 | 2.92 | 2.87 | 2.82 | 2.78 | 2.67 | 2.62 | 2.58 | 2.53 | 2.49 | 2.44 | 2.40 | 2.35 | 2.31 | 2.26 | 2.22 | 2.17 | 2.13 |
| 169 | 3.03 | 3.13 | 3.23 | 3.34 | 3.15 | 3.11 | 3.06 | 3.02 | 2.97 | 2.92 | 2.88 | 2.83 | 2.72 | 2.67 | 2.63 | 2.58 | 2.54 | 2.49 | 2.45 | 2.40 | 2.36 | 2.31 | 2.27 | 2.22 | 2.18 |
| 170 | 3.07 | 3.17 | 3.28 | 3.38 | 3.21 | 3.16 | 3.11 | 3.07 | 3.02 | 2.98 | 2.93 | 2.88 | 2.77 | 2.72 | 2.68 | 2.63 | 2.59 | 2.54 | 2.50 | 2.45 | 2.41 | 2.36 | 2.32 | 2.27 | 2.23 |
| 171 | 3.11 | 3.21 | 3.32 | 3.42 | 3.26 | 3.21 | 3.17 | 3.12 | 3.07 | 3.03 | 2.98 | 2.94 | 2.82 | 2.78 | 2.73 | 2.68 | 2.64 | 2.59 | 2.55 | 2.50 | 2.46 | 2.41 | 2.37 | 2.32 | 2.28 |
| 172 | 3.15 | 3.26 | 3.36 | 3.46 | 3.31 | 3.27 | 3.22 | 3.17 | 3.13 | 3.08 | 3.03 | 2.99 | 2.87 | 2.83 | 2.78 | 2.74 | 2.69 | 2.65 | 2.60 | 2.56 | 2.51 | 2.47 | 2.42 | 2.38 | 2.33 |
| 173 | 3.20 | 3.30 | 3.40 | 3.51 | 3.36 | 3.32 | 3.27 | 3.23 | 3.18 | 3.13 | 3.09 | 3.04 | 2.92 | 2.88 | 2.83 | 2.79 | 2.74 | 2.70 | 2.65 | 2.61 | 2.56 | 2.52 | 2.47 | 2.43 | 2.38 |
| 174 | 3.24 | 3.34 | 3.44 | 3.55 | 3.42 | 3.37 | 3.32 | 3.28 | 3.23 | 3.19 | 3.14 | 3.09 | 2.97 | 2.93 | 2.88 | 2.84 | 2.79 | 2.75 | 2.70 | 2.66 | 2.61 | 2.57 | 2.52 | 2.48 | 2.43 |
| 175 | 3.28 | 3.38 | 3.49 | 3.59 | 3.47 | 3.42 | 3.38 | 3.33 | 3.28 | 3.24 | 3.19 | 3.15 | 3.03 | 2.98 | 2.94 | 2.89 | 2.85 | 2.80 | 2.76 | 2.71 | 2.66 | 2.62 | 2.57 | 2.53 | 2.48 |
| 176 | 3.32 | 3.43 | 3.53 | 3.63 | 3.52 | 3.48 | 3.43 | 3.38 | 3.34 | 3.29 | 3.25 | 3.20 | 3.08 | 3.03 | 2.99 | 2.94 | 2.90 | 2.85 | 2.81 | 2.76 | 2.72 | 2.67 | 2.63 | 2.58 | 2.54 |
| 177 | 3.36 | 3.47 | 3.57 | 3.67 | 3.57 | 3.53 | 3.48 | 3.44 | 3.39 | 3.34 | 3.30 | 3.25 | 3.13 | 3.08 | 3.04 | 2.99 | 2.95 | 2.90 | 2.86 | 2.81 | 2.77 | 2.72 | 2.68 | 2.63 | 2.59 |
| 178 | 3.41 | 3.51 | 3.61 | 3.72 | 3.63 | 3.58 | 3.54 | 3.49 | 3.44 | 3.40 | 3.35 | 3.30 | 3.18 | 3.13 | 3.09 | 3.04 | 3.00 | 2.95 | 2.91 | 2.86 | 2.82 | 2.77 | 2.73 | 2.68 | 2.64 |
| 179 | 3.45 | 3.55 | 3.66 | 3.76 | 3.68 | 3.63 | 3.59 | 3.54 | 3.50 | 3.45 | 3.40 | 3.36 | 3.23 | 3.19 | 3.14 | 3.10 | 3.05 | 3.01 | 2.96 | 2.92 | 2.87 | 2.83 | 2.78 | 2.73 | 2.69 |
| 180 | 3.49 | 3.59 | 3.70 | 3.80 | 3.73 | 3.69 | 3.64 | 3.59 | 3.55 | 3.50 | 3.46 | 3.41 | 3.28 | 3.24 | 3.19 | 3.15 | 3.10 | 3.06 | 3.01 | 2.97 | 2.92 | 2.88 | 2.83 | 2.79 | 2.74 |
| 181 | 3.53 | 3.64 | 3.74 | 3.84 | 3.79 | 3.74 | 3.69 | 3.65 | 3.60 | 3.55 | 3.51 | 3.46 | 3.33 | 3.29 | 3.24 | 3.20 | 3.15 | 3.11 | 3.06 | 3.02 | 2.97 | 2.93 | 2.88 | 2.84 | 2.79 |
| 182 | 3.58 | 3.68 | 3.78 | 3.88 | 3.84 | 3.79 | 3.75 | 3.70 | 3.65 | 3.61 | 3.56 | 3.51 | 3.38 | 3.34 | 3.29 | 3.25 | 3.20 | 3.16 | 3.11 | 3.07 | 3.02 | 2.98 | 2.93 | 2.89 | 2.84 |
| 183 | 3.62 | 3.72 | 3.82 | 3.93 | 3.89 | 3.84 | 3.80 | 3.75 | 3.71 | 3.66 | 3.61 | 3.57 | 3.44 | 3.39 | 3.35 | 3.30 | 3.26 | 3.21 | 3.17 | 3.12 | 3.08 | 3.03 | 2.99 | 2.94 | 2.90 |
| 184 | 3.66 | 3.76 | 3.87 | 3.97 | 3.94 | 3.90 | 3.85 | 3.80 | 3.76 | 3.71 | 3.67 | 3.62 | 3.49 | 3.44 | 3.40 | 3.35 | 3.31 | 3.26 | 3.22 | 3.17 | 3.13 | 3.08 | 3.04 | 2.99 | 2.95 |
| 185 | 3.70 | 3.80 | 3.91 | 4.01 | 4.00 | 3.95 | 3.90 | 3.86 | 3.81 | 3.76 | 3.72 | 3.67 | 3.54 | 3.49 | 3.45 | 3.40 | 3.36 | 3.31 | 3.27 | 3.22 | 3.18 | 3.13 | 3.09 | 3.04 | 3.00 |
| 186 | 3.74 | 3.85 | 3.95 | 4.05 | 4.05 | 4.00 | 3.96 | 3.91 | 3.86 | 3.82 | 3.77 | 3.72 | 3.59 | 3.55 | 3.50 | 3.46 | 3.41 | 3.36 | 3.32 | 3.27 | 3.23 | 3.18 | 3.14 | 3.09 | 3.05 |
| 187 | 3.79 | 3.89 | 3.99 | 4.10 | 4.10 | 4.05 | 4.01 | 3.96 | 3.92 | 3.87 | 3.82 | 3.78 | 3.64 | 3.60 | 3.55 | 3.51 | 3.46 | 3.42 | 3.37 | 3.33 | 3.28 | 3.24 | 3.19 | 3.15 | 3.10 |
| 188 | 3.83 | 3.93 | 4.03 | 4.14 | 4.15 | 4.11 | 4.06 | 4.01 | 3.97 | 3.92 | 3.88 | 3.83 | 3.69 | 3.65 | 3.60 | 3.56 | 3.51 | 3.47 | 3.42 | 3.38 | 3.33 | 3.29 | 3.24 | 3.20 | 3.15 |
| 189 | 3.87 | 3.97 | 4.08 | 4.18 | 4.21 | 4.16 | 4.11 | 4.07 | 4.02 | 3.98 | 3.93 | 3.88 | 3.74 | 3.70 | 3.65 | 3.61 | 3.56 | 3.52 | 3.47 | 3.43 | 3.38 | 3.34 | 3.29 | 3.25 | 3.20 |
| 190 | 3.91 | 4.02 | 4.12 | 4.22 | 4.26 | 4.21 | 4.17 | 4.12 | 4.07 | 4.03 | 3.98 | 3.94 | 3.80 | 3.75 | 3.71 | 3.66 | 3.62 | 3.57 | 3.53 | 3.48 | 3.43 | 3.39 | 3.34 | 3.30 | 3.25 |
| 191 | 3.95 | 4.06 | 4.16 | 4.26 | 4.31 | 4.27 | 4.22 | 4.17 | 4.13 | 4.08 | 4.03 | 3.99 | 3.85 | 3.80 | 3.76 | 3.71 | 3.67 | 3.62 | 3.58 | 3.53 | 3.49 | 3.44 | 3.40 | 3.35 | 3.31 |
| 192 | 4.00 | 4.10 | 4.20 | 4.31 | 4.36 | 4.32 | 4.27 | 4.23 | 4.18 | 4.13 | 4.09 | 4.04 | 3.90 | 3.85 | 3.81 | 3.76 | 3.72 | 3.67 | 3.63 | 3.58 | 3.54 | 3.49 | 3.45 | 3.40 | 3.36 |
| 193 | 4.04 | 4.14 | 4.25 | 4.35 | 4.42 | 4.37 | 4.32 | 4.28 | 4.23 | 4.19 | 4.14 | 4.09 | 3.95 | 3.90 | 3.86 | 3.81 | 3.77 | 3.72 | 3.68 | 3.63 | 3.59 | 3.54 | 3.50 | 3.45 | 3.41 |

* Abbreviations: Ht=height; cm=centimeters

Table E-3.--Lower limit of normal (LLN) for $FEV_1/FVC\%$ for males

| Ht | Age | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (cm)* | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 | 65 |
| 157 | 74.5 | 74.5 | 74.5 | 74.5 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 158 | 74.4 | 74.4 | 74.4 | 74.4 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 159 | 74.3 | 74.3 | 74.3 | 74.3 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 160 | 74.3 | 74.3 | 74.3 | 74.3 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 161 | 74.2 | 74.2 | 74.2 | 74.2 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 162 | 74.1 | 74.1 | 74.1 | 74.1 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 163 | 74.1 | 74.1 | 74.1 | 74.1 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 164 | 74.0 | 74.0 | 74.0 | 74.0 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 165 | 73.9 | 73.9 | 73.9 | 73.9 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 166 | 73.9 | 73.9 | 73.9 | 73.9 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 167 | 73.8 | 73.8 | 73.8 | 73.8 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 168 | 73.7 | 73.7 | 73.7 | 73.7 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 169 | 73.6 | 73.6 | 73.6 | 73.6 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 170 | 73.6 | 73.6 | 73.6 | 73.6 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 171 | 73.5 | 73.5 | 73.5 | 73.5 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 172 | 73.4 | 73.4 | 73.4 | 73.4 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 173 | 73.4 | 73.4 | 73.4 | 73.4 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 174 | 73.3 | 73.3 | 73.3 | 73.3 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 175 | 73.2 | 73.2 | 73.2 | 73.2 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 176 | 73.2 | 73.2 | 73.2 | 73.2 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 177 | 73.1 | 73.1 | 73.1 | 73.1 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 178 | 73.0 | 73.0 | 73.0 | 73.0 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 179 | 73.0 | 73.0 | 73.0 | 73.0 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 180 | 72.9 | 72.9 | 72.9 | 72.9 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 181 | 72.8 | 72.8 | 72.8 | 72.8 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 182 | 72.7 | 72.7 | 72.7 | 72.7 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 183 | 72.7 | 72.7 | 72.7 | 72.7 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 184 | 72.6 | 72.6 | 72.6 | 72.6 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 185 | 72.5 | 72.5 | 72.5 | 72.5 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 186 | 72.5 | 72.5 | 72.5 | 72.5 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 187 | 72.4 | 72.4 | 72.4 | 72.4 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 188 | 72.3 | 72.3 | 72.3 | 72.3 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 189 | 72.3 | 72.3 | 72.3 | 72.3 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 190 | 72.2 | 72.2 | 72.2 | 72.2 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 191 | 72.1 | 72.1 | 72.1 | 72.1 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 192 | 72.1 | 72.1 | 72.1 | 72.1 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |
| 193 | 72.0 | 72.0 | 72.0 | 72.0 | 73.0 | 72.8 | 72.6 | 72.5 | 72.3 | 72.1 | 71.9 | 71.7 | 71.5 | 71.4 | 71.2 | 71.0 | 70.8 | 70.6 | 70.4 | 70.3 | 70.1 | 69.9 | 69.7 | 69.5 | 69.3 |

* Abbreviations: Ht=height; cm=centimeters

Table E-4.--Lower limit of normal for FCV for females

| Ht (cm)* | Age | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 | 65 |
| 148 | 2.17 | 2.27 | 2.32 | 2.29 | 2.27 | 2.24 | 2.21 | 2.19 | 2.16 | 2.14 | 2.11 | 2.08 | 2.01 | 1.99 | 1.96 | 1.94 | 1.91 | 1.89 | 1.86 | 1.84 | 1.81 | 1.78 | 1.76 | 1.73 | 1.71 |
| 149 | 2.20 | 2.30 | 2.35 | 2.33 | 2.30 | 2.27 | 2.25 | 2.22 | 2.20 | 2.17 | 2.14 | 2.12 | 2.05 | 2.02 | 2.00 | 1.97 | 1.94 | 1.92 | 1.89 | 1.87 | 1.84 | 1.82 | 1.79 | 1.77 | 1.74 |
| 150 | 2.23 | 2.33 | 2.39 | 2.36 | 2.33 | 2.31 | 2.28 | 2.26 | 2.23 | 2.20 | 2.18 | 2.15 | 2.08 | 2.05 | 2.03 | 2.00 | 1.98 | 1.95 | 1.93 | 1.90 | 1.88 | 1.85 | 1.83 | 1.80 | 1.77 |
| 151 | 2.26 | 2.36 | 2.42 | 2.40 | 2.37 | 2.34 | 2.32 | 2.29 | 2.27 | 2.24 | 2.21 | 2.19 | 2.11 | 2.09 | 2.06 | 2.04 | 2.01 | 1.99 | 1.96 | 1.94 | 1.91 | 1.88 | 1.86 | 1.83 | 1.81 |
| 152 | 2.29 | 2.40 | 2.46 | 2.43 | 2.40 | 2.38 | 2.35 | 2.33 | 2.30 | 2.27 | 2.25 | 2.22 | 2.15 | 2.12 | 2.10 | 2.07 | 2.04 | 2.02 | 1.99 | 1.97 | 1.94 | 1.92 | 1.89 | 1.87 | 1.84 |
| 153 | 2.32 | 2.43 | 2.49 | 2.46 | 2.44 | 2.41 | 2.39 | 2.36 | 2.33 | 2.31 | 2.28 | 2.26 | 2.18 | 2.15 | 2.13 | 2.10 | 2.08 | 2.05 | 2.03 | 2.00 | 1.98 | 1.95 | 1.93 | 1.90 | 1.88 |
| 154 | 2.35 | 2.46 | 2.52 | 2.50 | 2.47 | 2.45 | 2.42 | 2.39 | 2.37 | 2.34 | 2.32 | 2.29 | 2.21 | 2.19 | 2.16 | 2.14 | 2.11 | 2.09 | 2.06 | 2.04 | 2.01 | 1.98 | 1.96 | 1.93 | 1.91 |
| 155 | 2.38 | 2.49 | 2.56 | 2.53 | 2.51 | 2.48 | 2.45 | 2.43 | 2.40 | 2.38 | 2.35 | 2.32 | 2.25 | 2.22 | 2.20 | 2.17 | 2.15 | 2.12 | 2.09 | 2.07 | 2.04 | 2.02 | 1.99 | 1.97 | 1.94 |
| 156 | 2.41 | 2.52 | 2.59 | 2.57 | 2.54 | 2.51 | 2.49 | 2.46 | 2.44 | 2.41 | 2.38 | 2.36 | 2.28 | 2.25 | 2.23 | 2.20 | 2.18 | 2.15 | 2.13 | 2.10 | 2.08 | 2.05 | 2.03 | 2.00 | 1.98 |
| 157 | 2.45 | 2.55 | 2.63 | 2.60 | 2.57 | 2.55 | 2.52 | 2.50 | 2.47 | 2.44 | 2.42 | 2.39 | 2.31 | 2.29 | 2.26 | 2.24 | 2.21 | 2.19 | 2.16 | 2.14 | 2.11 | 2.08 | 2.06 | 2.03 | 2.01 |
| 158 | 2.48 | 2.58 | 2.66 | 2.63 | 2.61 | 2.58 | 2.56 | 2.53 | 2.50 | 2.48 | 2.45 | 2.43 | 2.35 | 2.32 | 2.30 | 2.27 | 2.25 | 2.22 | 2.19 | 2.17 | 2.14 | 2.12 | 2.09 | 2.07 | 2.04 |
| 159 | 2.51 | 2.61 | 2.69 | 2.67 | 2.64 | 2.62 | 2.59 | 2.56 | 2.54 | 2.51 | 2.49 | 2.46 | 2.38 | 2.35 | 2.33 | 2.30 | 2.28 | 2.25 | 2.23 | 2.20 | 2.18 | 2.15 | 2.13 | 2.10 | 2.08 |
| 160 | 2.54 | 2.64 | 2.73 | 2.70 | 2.68 | 2.65 | 2.62 | 2.60 | 2.57 | 2.55 | 2.52 | 2.49 | 2.41 | 2.39 | 2.36 | 2.34 | 2.31 | 2.29 | 2.26 | 2.24 | 2.21 | 2.18 | 2.16 | 2.13 | 2.11 |
| 161 | 2.57 | 2.68 | 2.76 | 2.74 | 2.71 | 2.68 | 2.66 | 2.63 | 2.61 | 2.58 | 2.55 | 2.53 | 2.45 | 2.42 | 2.40 | 2.37 | 2.35 | 2.32 | 2.29 | 2.27 | 2.24 | 2.22 | 2.19 | 2.17 | 2.14 |
| 162 | 2.60 | 2.71 | 2.80 | 2.77 | 2.74 | 2.72 | 2.69 | 2.67 | 2.64 | 2.61 | 2.59 | 2.56 | 2.48 | 2.46 | 2.43 | 2.40 | 2.38 | 2.35 | 2.33 | 2.30 | 2.28 | 2.25 | 2.23 | 2.20 | 2.18 |
| 163 | 2.63 | 2.74 | 2.83 | 2.80 | 2.78 | 2.75 | 2.73 | 2.70 | 2.67 | 2.65 | 2.62 | 2.60 | 2.51 | 2.49 | 2.46 | 2.44 | 2.41 | 2.39 | 2.36 | 2.34 | 2.31 | 2.29 | 2.26 | 2.23 | 2.21 |
| 164 | 2.66 | 2.77 | 2.86 | 2.84 | 2.81 | 2.79 | 2.76 | 2.73 | 2.71 | 2.68 | 2.66 | 2.63 | 2.55 | 2.52 | 2.50 | 2.47 | 2.45 | 2.42 | 2.39 | 2.37 | 2.34 | 2.32 | 2.29 | 2.27 | 2.24 |
| 165 | 2.70 | 2.80 | 2.90 | 2.87 | 2.85 | 2.82 | 2.80 | 2.77 | 2.74 | 2.72 | 2.69 | 2.67 | 2.58 | 2.56 | 2.53 | 2.50 | 2.48 | 2.45 | 2.43 | 2.40 | 2.38 | 2.35 | 2.33 | 2.30 | 2.28 |
| 166 | 2.73 | 2.83 | 2.93 | 2.91 | 2.88 | 2.86 | 2.83 | 2.80 | 2.78 | 2.75 | 2.73 | 2.70 | 2.61 | 2.59 | 2.56 | 2.54 | 2.51 | 2.49 | 2.46 | 2.44 | 2.41 | 2.39 | 2.36 | 2.33 | 2.31 |
| 167 | 2.76 | 2.86 | 2.97 | 2.94 | 2.92 | 2.89 | 2.86 | 2.84 | 2.81 | 2.79 | 2.76 | 2.73 | 2.65 | 2.62 | 2.60 | 2.57 | 2.55 | 2.52 | 2.49 | 2.47 | 2.44 | 2.42 | 2.39 | 2.37 | 2.34 |
| 168 | 2.79 | 2.89 | 3.00 | 2.98 | 2.95 | 2.92 | 2.90 | 2.87 | 2.85 | 2.82 | 2.79 | 2.77 | 2.68 | 2.66 | 2.63 | 2.60 | 2.58 | 2.55 | 2.53 | 2.50 | 2.48 | 2.45 | 2.43 | 2.40 | 2.38 |
| 169 | 2.82 | 2.92 | 3.04 | 3.01 | 2.98 | 2.96 | 2.93 | 2.91 | 2.88 | 2.85 | 2.83 | 2.80 | 2.71 | 2.69 | 2.66 | 2.64 | 2.61 | 2.59 | 2.56 | 2.54 | 2.51 | 2.49 | 2.46 | 2.43 | 2.41 |
| 170 | 2.85 | 2.96 | 3.07 | 3.04 | 3.02 | 2.99 | 2.97 | 2.94 | 2.91 | 2.89 | 2.86 | 2.84 | 2.75 | 2.72 | 2.70 | 2.67 | 2.65 | 2.62 | 2.60 | 2.57 | 2.54 | 2.52 | 2.49 | 2.47 | 2.44 |
| 171 | 2.88 | 2.99 | 3.10 | 3.08 | 3.05 | 3.03 | 3.00 | 2.97 | 2.95 | 2.92 | 2.90 | 2.87 | 2.78 | 2.76 | 2.73 | 2.70 | 2.68 | 2.65 | 2.63 | 2.60 | 2.58 | 2.55 | 2.53 | 2.50 | 2.48 |
| 172 | 2.91 | 3.02 | 3.14 | 3.11 | 3.09 | 3.06 | 3.03 | 3.01 | 2.98 | 2.96 | 2.93 | 2.90 | 2.81 | 2.79 | 2.76 | 2.74 | 2.71 | 2.69 | 2.66 | 2.64 | 2.61 | 2.59 | 2.56 | 2.53 | 2.51 |
| 173 | 2.94 | 3.05 | 3.17 | 3.15 | 3.12 | 3.09 | 3.07 | 3.04 | 3.02 | 2.99 | 2.96 | 2.94 | 2.85 | 2.82 | 2.80 | 2.77 | 2.75 | 2.72 | 2.70 | 2.67 | 2.64 | 2.62 | 2.59 | 2.57 | 2.54 |
| 174 | 2.98 | 3.08 | 3.21 | 3.18 | 3.15 | 3.13 | 3.10 | 3.08 | 3.05 | 3.02 | 3.00 | 2.97 | 2.88 | 2.86 | 2.83 | 2.80 | 2.78 | 2.75 | 2.73 | 2.70 | 2.68 | 2.65 | 2.63 | 2.60 | 2.58 |
| 175 | 3.01 | 3.11 | 3.24 | 3.21 | 3.19 | 3.16 | 3.14 | 3.11 | 3.08 | 3.06 | 3.03 | 3.01 | 2.91 | 2.89 | 2.86 | 2.84 | 2.81 | 2.79 | 2.76 | 2.74 | 2.71 | 2.69 | 2.66 | 2.63 | 2.61 |
| 176 | 3.04 | 3.14 | 3.27 | 3.25 | 3.22 | 3.20 | 3.17 | 3.14 | 3.12 | 3.09 | 3.07 | 3.04 | 2.95 | 2.92 | 2.90 | 2.87 | 2.85 | 2.82 | 2.80 | 2.77 | 2.74 | 2.72 | 2.69 | 2.67 | 2.64 |
| 177 | 3.07 | 3.17 | 3.31 | 3.28 | 3.26 | 3.23 | 3.20 | 3.18 | 3.15 | 3.13 | 3.10 | 3.07 | 2.98 | 2.96 | 2.93 | 2.91 | 2.88 | 2.85 | 2.83 | 2.80 | 2.78 | 2.75 | 2.73 | 2.70 | 2.68 |
| 178 | 3.10 | 3.21 | 3.34 | 3.32 | 3.29 | 3.26 | 3.24 | 3.21 | 3.19 | 3.16 | 3.13 | 3.11 | 3.01 | 2.99 | 2.96 | 2.94 | 2.91 | 2.89 | 2.86 | 2.84 | 2.81 | 2.79 | 2.76 | 2.74 | 2.71 |
| 179 | 3.13 | 3.24 | 3.38 | 3.35 | 3.33 | 3.30 | 3.27 | 3.25 | 3.22 | 3.20 | 3.17 | 3.14 | 3.05 | 3.02 | 3.00 | 2.97 | 2.95 | 2.92 | 2.90 | 2.87 | 2.84 | 2.82 | 2.79 | 2.77 | 2.74 |
| 180 | 3.16 | 3.27 | 3.41 | 3.39 | 3.36 | 3.33 | 3.31 | 3.28 | 3.26 | 3.23 | 3.20 | 3.18 | 3.08 | 3.06 | 3.03 | 3.01 | 2.98 | 2.95 | 2.93 | 2.90 | 2.88 | 2.85 | 2.83 | 2.80 | 2.78 |
| 181 | 3.19 | 3.30 | 3.45 | 3.42 | 3.39 | 3.37 | 3.34 | 3.32 | 3.29 | 3.26 | 3.24 | 3.21 | 3.11 | 3.09 | 3.06 | 3.04 | 3.01 | 2.99 | 2.96 | 2.94 | 2.91 | 2.89 | 2.86 | 2.84 | 2.81 |
| 182 | 3.23 | 3.33 | 3.48 | 3.45 | 3.43 | 3.40 | 3.38 | 3.35 | 3.32 | 3.30 | 3.27 | 3.25 | 3.15 | 3.12 | 3.10 | 3.07 | 3.05 | 3.02 | 3.00 | 2.97 | 2.94 | 2.92 | 2.89 | 2.87 | 2.84 |
| 183 | 3.26 | 3.36 | 3.51 | 3.49 | 3.46 | 3.44 | 3.41 | 3.38 | 3.36 | 3.33 | 3.31 | 3.28 | 3.18 | 3.16 | 3.13 | 3.11 | 3.08 | 3.05 | 3.03 | 3.00 | 2.98 | 2.95 | 2.93 | 2.90 | 2.88 |
| 184 | 3.29 | 3.39 | 3.55 | 3.52 | 3.50 | 3.47 | 3.44 | 3.42 | 3.39 | 3.37 | 3.34 | 3.31 | 3.22 | 3.19 | 3.16 | 3.14 | 3.11 | 3.09 | 3.06 | 3.04 | 3.01 | 2.99 | 2.96 | 2.94 | 2.91 |

*Abbreviations: Ht=height; cm=centimeters

Table E-5.--Lower limit of normal for $FEV_1$ for females

| Ht (cm)* | Age |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 | 65 |
| 148 | 2.13 | 2.25 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.95 | 1.92 | 1.89 | 1.86 | 1.83 | 1.80 | 1.77 | 1.74 | 1.71 | 1.68 | 1.65 | 1.62 | 1.59 | 1.56 | 1.53 | 1.50 | 1.47 | 1.44 |
| 149 | 2.16 | 2.27 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.91 | 1.88 | 1.85 | 1.82 | 1.79 | 1.76 | 1.73 | 1.70 | 1.68 | 1.65 | 1.62 | 1.59 | 1.56 | 1.53 | 1.50 | 1.47 |
| 150 | 2.19 | 2.30 | 2.15 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.91 | 1.88 | 1.85 | 1.82 | 1.79 | 1.76 | 1.73 | 1.70 | 1.67 | 1.64 | 1.61 | 1.58 | 1.55 | 1.52 | 1.49 |
| 151 | 2.22 | 2.33 | 2.17 | 2.14 | 2.11 | 2.08 | 2.05 | 2.02 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.85 | 1.82 | 1.79 | 1.76 | 1.73 | 1.70 | 1.67 | 1.64 | 1.61 | 1.58 | 1.55 | 1.52 |
| 152 | 2.25 | 2.36 | 2.20 | 2.17 | 2.14 | 2.11 | 2.08 | 2.05 | 2.02 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.84 | 1.81 | 1.78 | 1.75 | 1.72 | 1.69 | 1.66 | 1.63 | 1.60 | 1.58 | 1.55 |
| 153 | 2.28 | 2.39 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.05 | 2.02 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.84 | 1.81 | 1.78 | 1.75 | 1.72 | 1.69 | 1.66 | 1.63 | 1.60 | 1.57 |
| 154 | 2.30 | 2.42 | 2.25 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.01 | 1.98 | 1.95 | 1.92 | 1.89 | 1.86 | 1.83 | 1.80 | 1.77 | 1.75 | 1.72 | 1.69 | 1.66 | 1.63 | 1.60 |
| 155 | 2.33 | 2.45 | 2.27 | 2.24 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.01 | 1.98 | 1.95 | 1.92 | 1.89 | 1.86 | 1.83 | 1.80 | 1.77 | 1.74 | 1.71 | 1.68 | 1.65 | 1.62 |
| 156 | 2.36 | 2.48 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.15 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.92 | 1.89 | 1.86 | 1.83 | 1.80 | 1.77 | 1.74 | 1.71 | 1.68 | 1.65 |
| 157 | 2.39 | 2.50 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.15 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.91 | 1.88 | 1.85 | 1.82 | 1.79 | 1.76 | 1.73 | 1.70 | 1.67 |
| 158 | 2.42 | 2.53 | 2.35 | 2.32 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.91 | 1.88 | 1.85 | 1.82 | 1.79 | 1.76 | 1.73 | 1.70 |
| 159 | 2.45 | 2.56 | 2.38 | 2.35 | 2.32 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.11 | 2.08 | 2.05 | 2.02 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.84 | 1.82 | 1.79 | 1.76 | 1.73 |
| 160 | 2.48 | 2.59 | 2.40 | 2.37 | 2.34 | 2.31 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.11 | 2.08 | 2.05 | 2.02 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.84 | 1.81 | 1.78 | 1.75 |
| 161 | 2.51 | 2.62 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.25 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.02 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.84 | 1.81 | 1.78 |
| 162 | 2.53 | 2.65 | 2.46 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.25 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.01 | 1.98 | 1.95 | 1.92 | 1.89 | 1.86 | 1.83 | 1.80 |
| 163 | 2.56 | 2.68 | 2.48 | 2.45 | 2.42 | 2.39 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.01 | 1.98 | 1.95 | 1.92 | 1.89 | 1.86 | 1.83 |
| 164 | 2.59 | 2.70 | 2.51 | 2.48 | 2.45 | 2.42 | 2.39 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.15 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.92 | 1.89 | 1.86 |
| 165 | 2.62 | 2.73 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.15 | 2.12 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.91 | 1.88 |
| 166 | 2.65 | 2.76 | 2.56 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 | 2.32 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.11 | 2.09 | 2.06 | 2.03 | 2.00 | 1.97 | 1.94 | 1.91 |
| 167 | 2.68 | 2.79 | 2.58 | 2.56 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 | 2.32 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.11 | 2.08 | 2.05 | 2.02 | 1.99 | 1.96 | 1.93 |
| 168 | 2.71 | 2.82 | 2.61 | 2.58 | 2.55 | 2.52 | 2.49 | 2.46 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.11 | 2.08 | 2.05 | 2.02 | 1.99 | 1.96 |
| 169 | 2.73 | 2.85 | 2.64 | 2.61 | 2.58 | 2.55 | 2.52 | 2.49 | 2.46 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.25 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.01 | 1.99 |
| 170 | 2.76 | 2.88 | 2.66 | 2.63 | 2.60 | 2.57 | 2.54 | 2.51 | 2.48 | 2.46 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.25 | 2.22 | 2.19 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 | 2.01 |
| 171 | 2.79 | 2.91 | 2.69 | 2.66 | 2.63 | 2.60 | 2.57 | 2.54 | 2.51 | 2.48 | 2.45 | 2.42 | 2.39 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.16 | 2.13 | 2.10 | 2.07 | 2.04 |
| 172 | 2.82 | 2.93 | 2.71 | 2.68 | 2.65 | 2.63 | 2.60 | 2.57 | 2.54 | 2.51 | 2.48 | 2.45 | 2.42 | 2.39 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.15 | 2.12 | 2.09 | 2.06 |
| 173 | 2.85 | 2.96 | 2.74 | 2.71 | 2.68 | 2.65 | 2.62 | 2.59 | 2.56 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 | 2.21 | 2.18 | 2.15 | 2.12 | 2.09 |
| 174 | 2.88 | 2.99 | 2.77 | 2.74 | 2.71 | 2.68 | 2.65 | 2.62 | 2.59 | 2.56 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 | 2.32 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 | 2.11 |
| 175 | 2.91 | 3.02 | 2.79 | 2.76 | 2.73 | 2.70 | 2.67 | 2.64 | 2.61 | 2.58 | 2.55 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 | 2.32 | 2.29 | 2.26 | 2.23 | 2.20 | 2.17 | 2.14 |
| 176 | 2.94 | 3.05 | 2.82 | 2.79 | 2.76 | 2.73 | 2.70 | 2.67 | 2.64 | 2.61 | 2.58 | 2.55 | 2.52 | 2.49 | 2.46 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.26 | 2.23 | 2.20 | 2.17 |
| 177 | 2.96 | 3.08 | 2.84 | 2.81 | 2.78 | 2.75 | 2.72 | 2.70 | 2.67 | 2.64 | 2.61 | 2.58 | 2.55 | 2.52 | 2.49 | 2.46 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.25 | 2.22 | 2.19 |
| 178 | 2.99 | 3.11 | 2.87 | 2.84 | 2.81 | 2.78 | 2.75 | 2.72 | 2.69 | 2.66 | 2.63 | 2.60 | 2.57 | 2.54 | 2.51 | 2.48 | 2.45 | 2.43 | 2.40 | 2.37 | 2.34 | 2.31 | 2.28 | 2.25 | 2.22 |
| 179 | 3.02 | 3.14 | 2.90 | 2.87 | 2.84 | 2.81 | 2.78 | 2.75 | 2.72 | 2.69 | 2.66 | 2.63 | 2.60 | 2.57 | 2.54 | 2.51 | 2.48 | 2.45 | 2.42 | 2.39 | 2.36 | 2.33 | 2.30 | 2.27 | 2.24 |
| 180 | 3.05 | 3.16 | 2.92 | 2.89 | 2.86 | 2.83 | 2.80 | 2.77 | 2.74 | 2.71 | 2.68 | 2.65 | 2.62 | 2.60 | 2.57 | 2.54 | 2.51 | 2.48 | 2.45 | 2.42 | 2.39 | 2.36 | 2.33 | 2.30 | 2.27 |
| 181 | 3.08 | 3.19 | 2.95 | 2.92 | 2.89 | 2.86 | 2.83 | 2.80 | 2.77 | 2.74 | 2.71 | 2.68 | 2.65 | 2.62 | 2.59 | 2.56 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 | 2.33 | 2.30 |
| 182 | 3.11 | 3.22 | 2.97 | 2.94 | 2.91 | 2.88 | 2.85 | 2.82 | 2.80 | 2.77 | 2.74 | 2.71 | 2.68 | 2.65 | 2.62 | 2.59 | 2.56 | 2.53 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 | 2.32 |
| 183 | 3.14 | 3.25 | 3.00 | 2.97 | 2.94 | 2.91 | 2.88 | 2.85 | 2.82 | 2.79 | 2.76 | 2.73 | 2.70 | 2.67 | 2.64 | 2.61 | 2.58 | 2.55 | 2.52 | 2.50 | 2.47 | 2.44 | 2.41 | 2.38 | 2.35 |
| 184 | 3.17 | 3.28 | 3.02 | 2.99 | 2.97 | 2.94 | 2.91 | 2.88 | 2.85 | 2.82 | 2.79 | 2.76 | 2.73 | 2.70 | 2.67 | 2.64 | 2.61 | 2.58 | 2.55 | 2.52 | 2.49 | 2.46 | 2.43 | 2.40 | 2.37 |

*Abbreviations: Ht=height; cm=centimeters

Table E-6.--Lower limit of normal for $FEV_1/FVC\%$ for females

|  | Age |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ht (cm)* | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | 51 | 53 | 55 | 57 | 59 | 61 | 63 | 65 |
| 148 | 74.8 | 75.9 | 77.5 | 77.2 | 76.9 | 76.5 | 76.2 | 75.9 | 75.6 | 75.2 | 74.9 | 74.6 | 74.2 | 73.9 | 73.6 | 73.3 | 72.9 | 72.6 | 72.3 | 72.0 | 71.6 | 71.3 | 71.0 | 70.7 | 70.3 |
| 149 | 74.7 | 75.8 | 77.3 | 77.0 | 76.7 | 76.4 | 76.0 | 75.7 | 75.4 | 75.1 | 74.7 | 74.4 | 74.1 | 73.8 | 73.4 | 73.1 | 72.8 | 72.5 | 72.1 | 71.8 | 71.5 | 71.2 | 70.8 | 70.5 | 70.2 |
| 150 | 74.5 | 75.6 | 77.2 | 76.9 | 76.5 | 76.2 | 75.9 | 75.6 | 75.2 | 74.9 | 74.6 | 74.3 | 73.9 | 73.6 | 73.3 | 73.0 | 72.6 | 72.3 | 72.0 | 71.7 | 71.3 | 71.0 | 70.7 | 70.3 | 70.0 |
| 151 | 74.4 | 75.5 | 77.0 | 76.7 | 76.4 | 76.1 | 75.7 | 75.4 | 75.1 | 74.7 | 74.4 | 74.1 | 73.8 | 73.4 | 73.1 | 72.8 | 72.5 | 72.1 | 71.8 | 71.5 | 71.2 | 70.8 | 70.5 | 70.2 | 69.9 |
| 152 | 74.2 | 75.3 | 76.9 | 76.5 | 76.2 | 75.9 | 75.6 | 75.2 | 74.9 | 74.6 | 74.3 | 73.9 | 73.6 | 73.3 | 73.0 | 72.6 | 72.3 | 72.0 | 71.7 | 71.3 | 71.0 | 70.7 | 70.4 | 70.0 | 69.7 |
| 153 | 74.1 | 75.1 | 76.7 | 76.4 | 76.1 | 75.7 | 75.4 | 75.1 | 74.8 | 74.4 | 74.1 | 73.8 | 73.5 | 73.1 | 72.8 | 72.5 | 72.2 | 71.8 | 71.5 | 71.2 | 70.8 | 70.5 | 70.2 | 69.9 | 69.5 |
| 154 | 73.9 | 75.0 | 76.6 | 76.2 | 75.9 | 75.6 | 75.2 | 74.9 | 74.6 | 74.3 | 73.9 | 73.6 | 73.3 | 73.0 | 72.6 | 72.3 | 72.0 | 71.7 | 71.3 | 71.0 | 70.7 | 70.4 | 70.0 | 69.7 | 69.4 |
| 155 | 73.8 | 74.8 | 76.4 | 76.1 | 75.7 | 75.4 | 75.1 | 74.8 | 74.4 | 74.1 | 73.8 | 73.5 | 73.1 | 72.8 | 72.5 | 72.2 | 71.8 | 71.5 | 71.2 | 70.9 | 70.5 | 70.2 | 69.9 | 69.6 | 69.2 |
| 156 | 73.6 | 74.7 | 76.2 | 75.9 | 75.6 | 75.3 | 74.9 | 74.6 | 74.3 | 74.0 | 73.6 | 73.3 | 73.0 | 72.7 | 72.3 | 72.0 | 71.7 | 71.3 | 71.0 | 70.7 | 70.4 | 70.0 | 69.7 | 69.4 | 69.1 |
| 157 | 73.5 | 74.5 | 76.1 | 75.7 | 75.4 | 75.1 | 74.8 | 74.4 | 74.1 | 73.8 | 73.5 | 73.1 | 72.8 | 72.5 | 72.2 | 71.8 | 71.5 | 71.2 | 70.9 | 70.5 | 70.2 | 69.9 | 69.6 | 69.2 | 68.9 |
| 158 | 73.3 | 74.4 | 75.9 | 75.6 | 75.3 | 74.9 | 74.6 | 74.3 | 74.0 | 73.6 | 73.3 | 73.0 | 72.7 | 72.3 | 72.0 | 71.7 | 71.4 | 71.0 | 70.7 | 70.4 | 70.1 | 69.7 | 69.4 | 69.1 | 68.7 |
| 159 | 73.2 | 74.2 | 75.8 | 75.4 | 75.1 | 74.8 | 74.5 | 74.1 | 73.8 | 73.5 | 73.2 | 72.8 | 72.5 | 72.2 | 71.8 | 71.5 | 71.2 | 70.9 | 70.5 | 70.2 | 69.9 | 69.6 | 69.2 | 68.9 | 68.6 |
| 160 | 73.0 | 74.1 | 75.6 | 75.3 | 74.9 | 74.6 | 74.3 | 74.0 | 73.6 | 73.3 | 73.0 | 72.7 | 72.3 | 72.0 | 71.7 | 71.4 | 71.0 | 70.7 | 70.4 | 70.1 | 69.7 | 69.4 | 69.1 | 68.8 | 68.4 |
| 161 | 72.8 | 73.9 | 75.4 | 75.1 | 74.8 | 74.5 | 74.1 | 73.8 | 73.5 | 73.2 | 72.8 | 72.5 | 72.2 | 71.9 | 71.5 | 71.2 | 70.9 | 70.6 | 70.2 | 69.9 | 69.6 | 69.2 | 68.9 | 68.6 | 68.3 |
| 162 | 72.7 | 73.8 | 75.3 | 75.0 | 74.6 | 74.3 | 74.0 | 73.7 | 73.3 | 73.0 | 72.7 | 72.3 | 72.0 | 71.7 | 71.4 | 71.0 | 70.7 | 70.4 | 70.1 | 69.7 | 69.4 | 69.1 | 68.8 | 68.4 | 68.1 |
| 163 | 72.5 | 73.6 | 75.1 | 74.8 | 74.5 | 74.1 | 73.8 | 73.5 | 73.2 | 72.8 | 72.5 | 72.2 | 71.9 | 71.5 | 71.2 | 70.9 | 70.6 | 70.2 | 69.9 | 69.6 | 69.3 | 68.9 | 68.6 | 68.3 | 68.0 |
| 164 | 72.4 | 73.5 | 75.0 | 74.6 | 74.3 | 74.0 | 73.7 | 73.3 | 73.0 | 72.7 | 72.4 | 72.0 | 71.7 | 71.4 | 71.1 | 70.7 | 70.4 | 70.1 | 69.7 | 69.4 | 69.1 | 68.8 | 68.4 | 68.1 | 67.8 |
| 165 | 72.2 | 73.3 | 74.8 | 74.5 | 74.2 | 73.8 | 73.5 | 73.2 | 72.8 | 72.5 | 72.2 | 71.9 | 71.5 | 71.2 | 70.9 | 70.6 | 70.2 | 69.9 | 69.6 | 69.3 | 68.9 | 68.6 | 68.3 | 68.0 | 67.6 |
| 166 | 72.1 | 73.1 | 74.6 | 74.3 | 74.0 | 73.7 | 73.3 | 73.0 | 72.7 | 72.4 | 72.0 | 71.7 | 71.4 | 71.1 | 70.7 | 70.4 | 70.1 | 69.8 | 69.4 | 69.1 | 68.8 | 68.5 | 68.1 | 67.8 | 67.5 |
| 167 | 71.9 | 73.0 | 74.5 | 74.2 | 73.8 | 73.5 | 73.2 | 72.9 | 72.5 | 72.2 | 71.9 | 71.6 | 71.2 | 70.9 | 70.6 | 70.2 | 69.9 | 69.6 | 69.3 | 68.9 | 68.6 | 68.3 | 68.0 | 67.6 | 67.3 |
| 168 | 71.8 | 72.8 | 74.3 | 74.0 | 73.7 | 73.3 | 73.0 | 72.7 | 72.4 | 72.0 | 71.7 | 71.4 | 71.1 | 70.7 | 70.4 | 70.1 | 69.8 | 69.4 | 69.1 | 68.8 | 68.5 | 68.1 | 67.8 | 67.5 | 67.2 |
| 169 | 71.6 | 72.7 | 74.2 | 73.8 | 73.5 | 73.2 | 72.9 | 72.5 | 72.2 | 71.9 | 71.6 | 71.2 | 70.9 | 70.6 | 70.3 | 69.9 | 69.6 | 69.3 | 69.0 | 68.6 | 68.3 | 68.0 | 67.7 | 67.3 | 67.0 |
| 170 | 71.5 | 72.5 | 74.0 | 73.7 | 73.4 | 73.0 | 72.7 | 72.4 | 72.1 | 71.7 | 71.4 | 71.1 | 70.7 | 70.4 | 70.1 | 69.8 | 69.4 | 69.1 | 68.8 | 68.5 | 68.1 | 67.8 | 67.5 | 67.2 | 66.8 |
| 171 | 71.3 | 72.4 | 73.8 | 73.5 | 73.2 | 72.9 | 72.5 | 72.2 | 71.9 | 71.6 | 71.2 | 70.9 | 70.6 | 70.3 | 69.9 | 69.6 | 69.3 | 69.0 | 68.6 | 68.3 | 68.0 | 67.7 | 67.3 | 67.0 | 66.7 |
| 172 | 71.2 | 72.2 | 73.7 | 73.4 | 73.0 | 72.7 | 72.4 | 72.1 | 71.7 | 71.4 | 71.1 | 70.8 | 70.4 | 70.1 | 69.8 | 69.5 | 69.1 | 68.8 | 68.5 | 68.2 | 67.8 | 67.5 | 67.2 | 66.8 | 66.5 |
| 173 | 71.0 | 72.1 | 73.5 | 73.2 | 72.9 | 72.6 | 72.2 | 71.9 | 71.6 | 71.2 | 70.9 | 70.6 | 70.3 | 69.9 | 69.6 | 69.3 | 69.0 | 68.6 | 68.3 | 68.0 | 67.7 | 67.3 | 67.0 | 66.7 | 66.4 |
| 174 | 70.8 | 71.9 | 73.4 | 73.0 | 72.7 | 72.4 | 72.1 | 71.7 | 71.4 | 71.1 | 70.8 | 70.4 | 70.1 | 69.8 | 69.5 | 69.1 | 68.8 | 68.5 | 68.2 | 67.8 | 67.5 | 67.2 | 66.9 | 66.5 | 66.2 |
| 175 | 70.7 | 71.8 | 73.2 | 72.9 | 72.6 | 72.2 | 71.9 | 71.6 | 71.3 | 70.9 | 70.6 | 70.3 | 70.0 | 69.6 | 69.3 | 69.0 | 68.7 | 68.3 | 68.0 | 67.7 | 67.3 | 67.0 | 66.7 | 66.4 | 66.0 |
| 176 | 70.5 | 71.6 | 73.1 | 72.7 | 72.4 | 72.1 | 71.7 | 71.4 | 71.1 | 70.8 | 70.4 | 70.1 | 69.8 | 69.5 | 69.1 | 68.8 | 68.5 | 68.2 | 67.8 | 67.5 | 67.2 | 66.9 | 66.5 | 66.2 | 65.9 |
| 177 | 70.4 | 71.5 | 72.9 | 72.6 | 72.2 | 71.9 | 71.6 | 71.3 | 70.9 | 70.6 | 70.3 | 70.0 | 69.6 | 69.3 | 69.0 | 68.7 | 68.3 | 68.0 | 67.7 | 67.4 | 67.0 | 66.7 | 66.4 | 66.1 | 65.7 |
| 178 | 70.2 | 71.3 | 72.7 | 72.4 | 72.1 | 71.8 | 71.4 | 71.1 | 70.8 | 70.5 | 70.1 | 69.8 | 69.5 | 69.2 | 68.8 | 68.5 | 68.2 | 67.8 | 67.5 | 67.2 | 66.9 | 66.5 | 66.2 | 65.9 | 65.6 |
| 179 | 70.1 | 71.2 | 72.6 | 72.2 | 71.9 | 71.6 | 71.3 | 70.9 | 70.6 | 70.3 | 70.0 | 69.6 | 69.3 | 69.0 | 68.7 | 68.3 | 68.0 | 67.7 | 67.4 | 67.0 | 66.7 | 66.4 | 66.1 | 65.7 | 65.4 |
| 180 | 69.9 | 71.0 | 72.4 | 72.1 | 71.8 | 71.4 | 71.1 | 70.8 | 70.5 | 70.1 | 69.8 | 69.5 | 69.2 | 68.8 | 68.5 | 68.2 | 67.9 | 67.5 | 67.2 | 66.9 | 66.6 | 66.2 | 65.9 | 65.6 | 65.2 |
| 181 | 69.8 | 70.8 | 72.3 | 71.9 | 71.6 | 71.3 | 71.0 | 70.6 | 70.3 | 70.0 | 69.7 | 69.3 | 69.0 | 68.7 | 68.3 | 68.0 | 67.7 | 67.4 | 67.0 | 66.7 | 66.4 | 66.1 | 65.7 | 65.4 | 65.1 |
| 182 | 69.6 | 70.7 | 72.1 | 71.8 | 71.4 | 71.1 | 70.8 | 70.5 | 70.1 | 69.8 | 69.5 | 69.2 | 68.8 | 68.5 | 68.2 | 67.9 | 67.5 | 67.2 | 66.9 | 66.6 | 66.2 | 65.9 | 65.6 | 65.3 | 64.9 |
| 183 | 69.5 | 70.5 | 71.9 | 71.6 | 71.3 | 71.0 | 70.6 | 70.3 | 70.0 | 69.7 | 69.3 | 69.0 | 68.7 | 68.4 | 68.0 | 67.7 | 67.4 | 67.1 | 66.7 | 66.4 | 66.1 | 65.7 | 65.4 | 65.1 | 64.8 |
| 184 | 69.3 | 70.4 | 71.8 | 71.5 | 71.1 | 70.8 | 70.5 | 70.2 | 69.8 | 69.5 | 69.2 | 68.8 | 68.5 | 68.2 | 67.9 | 67.5 | 67.2 | 66.9 | 66.6 | 66.2 | 65.9 | 65.6 | 65.3 | 64.9 | 64.6 |

* Abbreviations: Ht=height; cm=centimeters

POLICY REPRESENTATIVE REVIEW

## APPENDIX F. NIOSH Occupational History Questionnaire Used in the Coal Workers' X-ray Surveillance Program

OMB NO 68-R 1322

DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
CENTERS FOR DISEASE CONTROL
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
MINER IDENTIFICATION DOCUMENT

**FOR ALOSH USE ONLY**

RETURN TO

RECEIVING CENTER
APPALACHIAN LABORATORY FOR
OCCUPATIONAL SAFETY AND HEALTH
BOX 4258
MORGANTOWN, WEST VIRGINIA 26505

ASSURANCE OF CONFIDENTIALITY

The U.S. Public Health Service hereby gives assurance that your identity and your relationship to any information obtained by reason of your participation in The Periodic Medical Examination Program will be kept confidential in accordance with Public Health Services (42 CFR Part 1).

Your social security number is required by Public Health Service REGULATIONS (42 CFR Part 37). It will be used for identification purposes only and n ot be released except as required by law, without your written consent.

*PLEASE PRINT OR TYPE ALL RESPONSES*

**X-RAY FACILITY NAME:**

**NIOSH FACILITY CERTIFICATION NO.:**

**DATE OF X-RAY EXAMINATION:**

**TYPE OF X-RAY (Please check one)**
Preemployment ☐ Mandatory (newly hired miners) ☐ Voluntary (every 3 1/2 - 4 1/2 years) ☐

**MINER'S NAME (Please Print)**
Last First MI

SOCIAL SECURITY NUMBER
☐☐☐ - ☐☐ - ☐☐☐☐

**MAILING ADDRESS** STREET: CITY: COUNTY: STATE: ZIP CODE:

SEX
M / F

TELEPHONE #

AGE

Date of Birth (M-D-Y)

RACE ETHNIC CODE (Please check one)
1 ☐ American Indian or Alaskan Native
2 ☐ Asian or Pacific Islander
3 ☐ Black, not Hispanic origin
4 ☐ Hispanic
5 ☐ White, not Hispanic origin

**EMPLOYER'S NAME:**

**EMPLOYER'S ADDRESS:** STREET/PO BOX: CITY: STATE: ZIP CODE:

**MINE NAME:**

**MSHA MINE IDENTIFICATION NO.:**

**EMPLOYER IS (Please check one)**
☐ Mine Operator ☐ Construction Contractor

**MSHA CONTRACTOR ID NO.:**

### OCCUPATIONAL HISTORY

**UNDERGROUND COAL MINE**

**Do you now or have you ever worked at an UNDERGROUND coal mine? Yes _____ No _____**

**If yes list title for any job you have held for more than one(1) year in an UNDERGROUND coal mine.**
**(Site: S = Surface LF = Longwall Face CMF = Continuous Mine Face CvMF = Conventional Mine Face UNF = Underground Non Face O = Other)**
*Please use correct job titles as assigned by Mine Safety and Health Administration.*
*Job title list available at X-ray facility*

| JOB TITLE | JOB SITE | | | | | | APPROXIMATE YEARS | |
|---|---|---|---|---|---|---|---|---|
| | S | LF | CMF | CvMF | UNF | O | FROM 19 __ | TO 19 __ |
| *EXAMPLE:*<br>*Continuous Miner Operator* | | | *X* | | | | *1971* | *1975* |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

## SURFACE COAL MINE

Do you now or have you ever worked at a SURFACE COAL MINE? Yes _____ No _____

If yes list title for any job you have held for more than one(1) year in a SURFACE coal mine.

| JOB TITLE | APPROXIMATE YEARS (DATES) | |
|---|---|---|
| | FROM 19 __ | TO 19 __ |
| | | |
| | | |
| | | |
| | | |

## OTHER

Have you ever worked in any mine other than coal? (gold,salt,silver,other metals, non metals, etc.) Yes _____ No ____ If yes,

| TYPE OF MINE | APPROXIMATE YEARS (DATES) | |
|---|---|---|
| | FROM 19 __ | TO 19 __ |
| | | |
| | | |
| | | |
| | | |

Have you ever worked with asbestos? Yes ______ No ________

If yes, what was your job? ______________________________

______________________ Dates: From _____________ To _______________
MO/YR MO/YR

Have you ever worked for more than one (1) year in any other dusty job not listed above?

| JOB | YES | NO | YRS | JOB | YES | NO | YRS |
|---|---|---|---|---|---|---|---|
| **Cotton, flax or hemp** | | | | **Quarry** | | | |
| **Diesel / Diesel Exhaust** | | | | **Sandblasting** | | | |
| **Drilling** | | | | **Tunnelling** | | | |
| **Foundry** | | | | **Other (specify)** | | | |
| **Pottery** | | | | | | | |

**CONSENT** I wish to participate in the periodic Medical Examination Program conducted under section 203 of the Federal Mine Safety and Health Act of 1977 (30 U.S.C. 843). I authorize the Public Health Service to furnish any significant medical findings revealed by the X-ray and other medical tests under the program to my personal physician:

| | | | |
|---|---|---|---|
| Personal Physician's Name | | | Physician's Telephone Number |
| Street Address | City | State | Zip |

I understand that I will be advised of any findings concerning coal workers pneumoconiosis (black lung disease) directly.

| | |
|---|---|
| Date Signed | Miner's Signature |

# APPENDIX G

## Noncompliance Determinations Based on Single, Full-Shift Samples and Using Sampling Criteria in Accordance with the ISO/CEN/ACGIH Definition of Respirable Dust

The statistical evaluation of workplace exposures as measured by unbiased sampling methods is described by Leidel et al. [1977]. This approach is to demonstrate (with 95% confidence) that a concentration exceeds the permissible exposure level (PEL), given the coefficient of variation (CV) associated with the sampling and analytical methods.

However, when the sampling method includes bias, an estimate of that bias must be added to the quantity 1.645*CV (see section 5.1.4.4). Such bias must be considered when using performance-based criteria, an approach which enables the certification of any sampler meeting the specified criteria. Performance-based sampling in accordance with the ISO/CEN/ACGIH definition of respirable dust requires determination of the bias attributable to the differences in the collection characteristics of an ideal laboratory sampler relative to those of a prospective sampler.

Generalization of the Leidel et al. [1977] approach to include biased methods is as follows: Suppose that in sampling a concentration $C_{true}$, a method provides concentration estimates C with standard deviation $\sigma$ about mean $\mu$. With approximately normal distributions, 95% of the measurements C obey:

$$C < \mu + 1.645 \cdot \sigma.$$

This can be expressed in terms of the uncorrectable bias and true relative standard deviation RSD (or, coefficient of variation, CV), which is defined as follows:

$$\text{bias} = (\mu - C_{true})/C_{true}$$

$$\text{RSD} = \sigma/C_{true}.$$

Although $\mu$ and $\sigma$ are unknown, the fractional quantities bias and RSD can be measured in the laboratory. Then in the notation of Leidel et al. [1977] the above inequality can be expressed as:

$$C_{true} > \text{LCL}(95\%),$$

where the 95% lower confidence limit LCL(95%) is defined as

$$\text{LCL}(95\%) = C/[1 + {}_{95\%}A_{+}],$$

and the "upper accuracy" ${}_{95\%}A_{+}$ is defined as:

$${}_{95\%}A_{+} = \text{bias} + 1.645 \cdot \text{RSD}.$$

The net result of citing only when the lower confidence limit LCL(95%) exceeds the PEL is that citations will be (incorrectly) issued only 5% of the time in the worst-case situation in which the true (unknown) concentration is slightly below the PEL.

### specific examples

In the case of sampling coal mine dust, the quantities bias and RSD depend on both the sampler characteristics as well as the dust size distribution to be sampled. Dependence on the environment (through the size distributions), in fact, precludes correction of the bias through calibration. Sampler characteristics can be obtained through sampler evaluation as presented by

Bartley et al. [1993]. The set of coal mine distributions published by Mutmansky and Lee [1987] is taken as representative of the range of sizes to be expected, as described in more detail in Section 5.1.7.

Then for each size distribution to be encountered, the imprecision, i.e., the relative standard deviation (RSD), and bias relative to the international definition (also described in Section 5.1.2) of respirable dust may be estimated. From these values, the upper 95%-confidence limit ${}_{[95\%,95\%]}A_{+}$ of the upper accuracy ${}_{95\%}A_{+}$, accounting for uncertainty in the sampler evaluation experiments themselves can be determined. The second 95% within the brackets, refers to upper 95% confidence limits based on the evaluation tests.

Assume that the weighing imprecision is improved as recommended in Section 5.1.4.3. Further, assume that the random pumped airflow imprecision is controlled to less than 1.66% [CEN 1991]. The inter-sampler, and therefore the total, variation and bias are then computed based on the sampler evaluation and size distribution.

Estimates of the upper accuracy are as follows. For the Higgins-Dewell (HD) sampler [Higgins and Dewell 1967], the limit on the upper accuracy, averaged over the expected size distributions, is given by:

$${}_{[95\%,95\%]}A_{+} = 23\% \text{ (HD cyclone at 2.2 L/min).}$$

For the traditional 10 mm nylon cyclone,

$${}_{[95\%,95\%]}A_{+} = 24\% \text{ (nylon cyclone at 1.7 L/min).}$$

As an example of the use of these figures, MSHA would issue a citation when $C/[1 + {}_{[95\%,95\%]}A_{+}] > \text{PEL}$. Therefore, if the PEL is selected to equal 0.9 mg/m$^3$, MSHA inspectors would cite if a concentration C obeys the inequality

$$C > \mathrm{PEL} \cdot [1 + {}_{[95\%,95\%]}A_{+}]$$

$$= 0.9\ \mathrm{mg/m^3} \cdot [1 + 0.23] \quad \text{[HD sampler]}$$

$$= 1.11\ \mathrm{mg/m^3}\ \text{[HD Sampler]}.$$

Similarly, using the 10 nylon cyclone, citations would be issued when

$$C > 1.12\ \mathrm{mg/m^3}\ \text{[nylon cyclone]}.$$

Accuracy Criterion

The use of a variety of samplers, such as the HD as well as the nylon cyclone, requires the establishment of rigorous sampler evaluation tests and criteria for interpreting the test results. The basic idea behind the tests is to characterize samplers sufficiently that performance during actual use can be predicted and controlled. Specifically, regarding respirable aerosol sampling, this means that performance is adequate over those size distributions which are expected to be encountered during coal mine dust sampling. Sampling larger particles would require further accuracy control under expected wind conditions.

Two approaches to accuracy criteria are presented here. Consideration of single-sided confidence limit estimates of a sampling method's accuracy leads to accuracy criteria closely related to the citation limits discussed above. Two-sided asymmetric limits given by the traditional NIOSH accuracy criterion are also described [NIOSH 1984]. The two criteria are very close in the case of methods with significant bias as in sampling respirable coal mine dust.

single-sided limits

Tests which provided the upper accuracy presented above serve the purpose of sampler characterization. The upper accuracy $_{95\%}A_+$, in fact, itself provides a means of partially expressing the adequacy of a sampling method: A sampling method would be rejected if $_{95\%}A_+$ is too large for practicality, for example, 25%.

Remember, however, that $_{95\%}A_+$ was devised so as to protect the coal mine operator from being inappropriately cited. The operator is protected, but not the coal miner. As an extreme example, the operator would never be inappropriately cited if the sampler always gave zero readings.

In order to be useful from the miner's point of view as well as the operator's, a sampler must also be capable of demonstrating that the concentration is *below* a given value at specified confidence (e.g., 95%). This is accomplished in exact analogy to the lower confidence limit LCL(95%) described above. An upper confidence limit UCL(95%) is specified so that the true concentration $C_{true}$ is less than UCL(95%) in 95% of the sampler uses:

$$C_{true} < \mathrm{UCL}(95\%).$$

The 95% upper confidence limit UCL(95%) is defined in terms of a "lower accuracy" $_{95\%}A_-$ as

$$\mathrm{UCL}(95\%) \equiv C/[1 + {}_{95\%}A_-],$$

and $_{95\%}A_-$ is defined as:

$$_{95\%}A_- \equiv -\mathrm{bias} + 1.645 \cdot \mathrm{RSD}.$$

The accuracy criterion would then be expressed as a double requirement:

$$_{[95\%,95\%]}A_{\pm}(\text{bias, RSD}) < 25\%.$$

Note that the accuracy criterion is symmetric about bias = 0; i.e., the criterion depends only on |bias| (and RSD). Again, the second 95% refers to confidence in the estimates of bias and RSD.

example

Values $_{[95\%,95\%]}A_{+}$ are given above for the HD and nylon cyclones. $_{[95\%,95\%]}A_{-}$ may be computed similarly:

$$_{[95\%,95\%]}A_{-} = 10\% \text{ (HD at 2.2 L/min)}$$

$$_{[95\%,95\%]}A_{-} = 11\% \text{ (nylon at 1.7 L/min)}.$$

Therefore, the above accuracy criterion would be satisfied for either of these samplers.

alternative criterion: two-sided confidence limits

An alternative accuracy criteria is in widespread use within NIOSH for evaluating the adequacy of sampling and analytical methods [NIOSH 1984]. Specifically, 95% of all samples collected must fall within accuracy $_{95\%}A = 25\%$ of a true or standard value $C_{true}$, accounting for both bias and imprecision within the sampling method. This results in a slightly more restrictive criterion than the above single-sided criteria when the bias is small. Inaccuracy in the evaluation experimentation itself must also be accounted for. An additional criterion requires that the mean bias must be less than

10%. This added criterion partially evens out the variation with bias of the significance of the two-sided criterion to compliance decisions.

The functional form ${}_{95\%}A$(bias, RSD) of the accuracy for 95% of sample uses is determined numerically in terms of estimates, bias and RSD. Specifically, ${}_{95\%}A$ is found as the solution of

$$\Phi[(\text{bias} + {}_{95\%}A)/\text{RSD}] + \Phi[(\text{bias} - {}_{95\%}A)/\text{RSD}] = 0.95$$

where $\Phi$ is the cumulative normal function. The upper 95% confidence limit ${}_{[95\%,95\%]}A$(bias, RSD) is then determined based on the measured uncertainty in bias and RSD. The accuracy criterion rejects samplers unless:

$${}_{[95\%,95\%]}A(\text{bias, RSD}) < 25\%.$$

<u>example</u>

Values of the upper 95% confidence on the accuracy ${}_{[95\%,95\%]}A$ computed for the HD and nylon cyclones are as follows:

$${}_{[95\%,95\%]}A = 26\% \text{ (HD at 2.2 L/min)}$$

$${}_{[95\%,95\%]}A = 27\% \text{ (nylon at 1.7 L/min)}.$$

Furthermore, mean values of the bias are less than 10%. Therefore, the two-sided accuracy criterion would be satisfied for either of these samplers.

Despite its widespread use, the traditional two-sided accuracy criterion has several disadvantages over the single-sided criterion. The functional form of ${}_{95\%}A$(bias, RSD) is more complicated than the simple linear expressions given above for $_{95\%}A_{\pm}$. Furthermore, the meaning of $_{95\%}A$(bias, RSD) is not as clear as $_{95\%}A_{\pm}$, since the latter were developed specifically with the application in mind. At bias ≈ 0, $_{95\%}A$ provides two-sided confidence intervals, whereas noncompliance determinations require one-sided confidence intervals. With significant bias, however, the two accuracy constraints are nearly identical, because the two-sided intervals become highly asymmetric about mean measurements. Mathematically, $_{95\%}A$(bias, RSD) is approximately equal to the larger of the two functions $_{95\%}A_{\pm}$(bias, RSD) at |bias| >> RSD. This can be seen in Figure G-1, where the functions A (bias, RSD) and $A_{+}$ (bias, RSD) are plotted as contour diagrams at bias >0 (since both criteria depend only on |bias|).

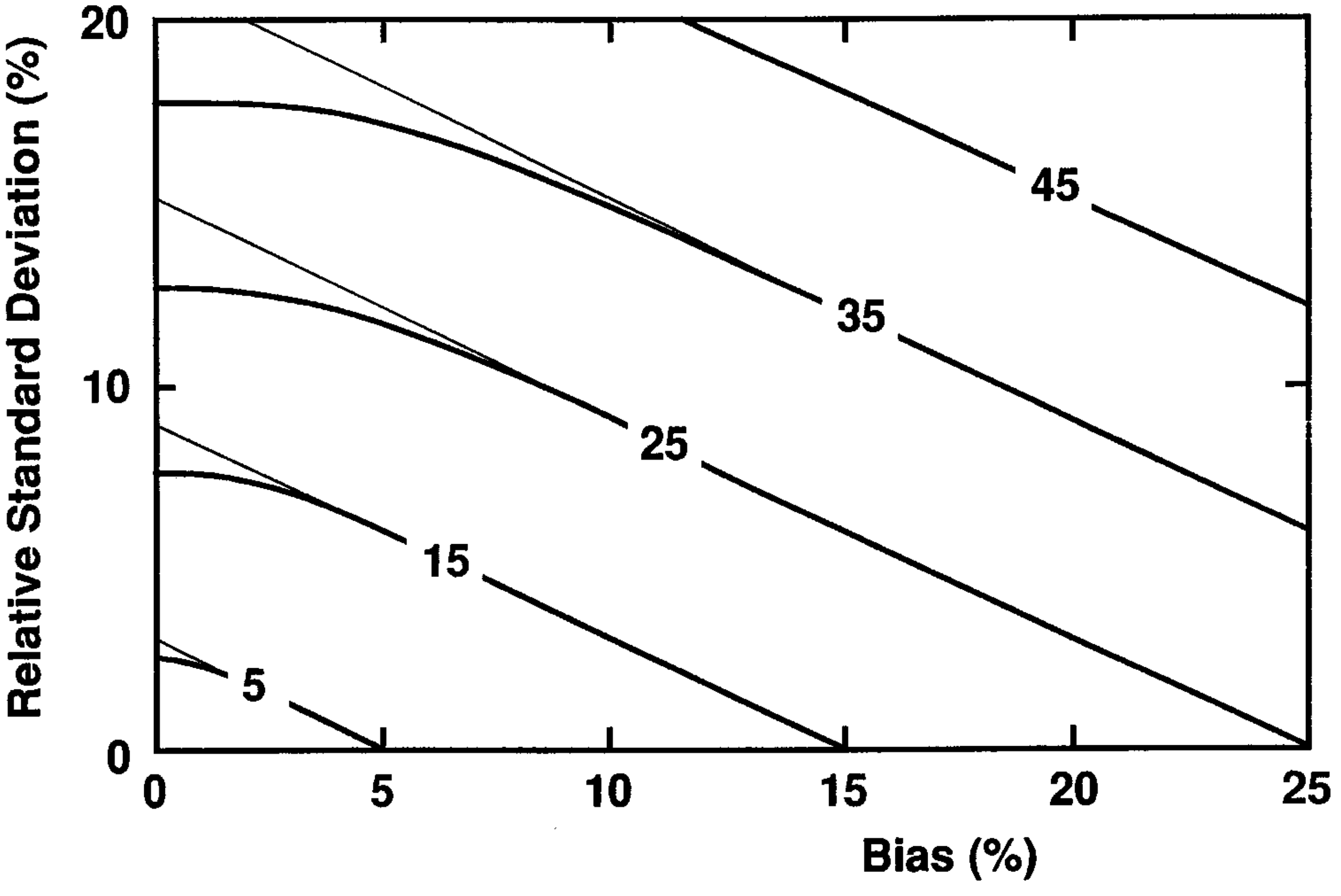

FIGURE G–1. ACCURACY CONTOURS: 95% confidence
fine lines represent single-sided accuracy
thicker curves: two-sided accuracy

# REFERENCES

ACCP/ATS [1975]. Pulmonary terms and symbols. A report of the ACCP-ATS Joint Committee on pulmonary nomenclature. Chest *67*:583-593.

ACGIH [1984]. Particle size-selective sampling in the workplace: report of the ACGIH Technical Committee on air sampling procedures. Ann Am Conf Gov Ind Hyg *11*:23-100.

ACGIH [1991]. Notice of intended change: Appendix D—particle size-selective sampling criteria for airborne particulate matter. Appl Occup Environ Hyg *6*:817-818.

ACGIH [1992a]. Industrial ventilation—a manual of recommended practice. 22nd ed. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

ACGIH [1992b]. 1992-1993 Threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Addisón J, Dodgson J [1990]. The influence of shape, size, and composition of individual dust particles on the harmfulness of coal mine dusts: development of methods of analysis. In: Proceedings of the VIIth International Pneumoconioses Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Adelman R, Saul RL, Ames BL [1988]. Oxidative damage to DNA: relation to species metabolic rate and life span. Proc Natl Acad Sci *85*:2706-2708.

Albert RE, Arnett LC [1955]. Clearance of radioactive dust from the human lung. Arch Ind Health *12*:99-106.

Almich BP, Carson GA [1974]. Some effects of charging on 10-mm nylon cyclone performance. Am Ind Hyg Assoc J *35*:603-612.

Althouse RB, Attfield M, Kellie MD [1986]. Use of data from x-ray screening program for coal workers to evaluate effectiveness of 2 mg/m$^3$ coal dust standard. J Occup Med *28*(8):741-745.

Althouse RB, Castellan RM, Wagner GR [1992]. Pneumoconioses in the United States: highlights of surveillance data from NIOSH and other federal sources. Occup Med 7(2):197-208.

Amandus HE, Lapp HL, Jacobson G, Reger RB [1976]. Significance of irregular small opacities in radiographs of coal miners in the U.S.A. Br J Ind Med *33*:13-17.

Amandus HE [1983]. The appalachian coal miner mortality study: a 14-year follow-up. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, NTIS No. PB83-235556.

Amandus HE, Hanke W, Kullman G, Reger RB [1984]. A re-evaluation of radiological evidence from a study of U.S. strip coal miners. Arch Environ Health *39*(5):346-351.

Amandus HE, Piacitelli G [1987]. Dust exposures at U.S. surface coal mines in 1982-1983. Arch Environ Health *42*:374-381.

Amandus HE, Petersen MR, Richards TB [1989]. Health status of anthracite surface coal miners. Arch Environ Health *44*(2):75-81.

American Thoracic Society [1991]. Lung function testing: selection of reference values and interpretative strategies. Am Rev Respir Dis *144*(5):1202-1218.

Ames RG [1982]. Gastric cancer in coal miners: some hypotheses for investigation. J Soc Occup Med *32*:73-81.

Ames RG, Gamble JF [1983]. Lung cancer, stomach cancer, and smoking status among coal miners. Scand J Work Environ Health *9*:443-448.

Ames RG, Hall DS [1985]. The effects of cigarette smoking cessation on 5-year pulmonary function changes in U.S. underground coal miners. Occup Med *35*(4):111-113.

ANSI [1969]. American national standard: practices for respiratory protection. New York, NY: American National Standards Institute, ANSI Z88.2-1969.

APHA [1991]. A public health approach to preventing occupational diseases and injuries. In: Weeks JL, Levy BS, Wagner GR, eds. Preventing Occupational Diseases and Injury. Washington, DC: American Public Health Association.

Armstrong BG, Oakes D [1982]. Effects of approximation in exposure assessments on estimates of exposure-response relationships. Scand J Work Environ Health *8*(suppl 1):20-23.

Ary IS [1989]. Keynote address, VPI conference. In: Sutherland WH, Forshey DR, Karmis M, eds. Proceedings of the Twentieth Annual Institute on Coal Mining Health, Safety and Research, Milestones in Health, Safety and Research. Blacksburg, Virginia, August 29-31, p. 25.

ASPH [1986]. A proposed national strategy for the prevention of occupational lung diseases. In: Proposed national strategies for the prevention of leading work-related diseases and injuries. Part 1. Washington, DC: The Association of Schools of Public Health, under a cooperative agreement with the National Institute for Occupational Safety and Health.

ATC [1970]. Guide for respirable mass sampling. Am Ind Hyg Assoc J 133-137.

ATS [1962]. Chronic bronchitis, asthma, and pulmonary emphysema. American Thoracic Society, a statement by the committee on diagnostic standards for nontuberculous respiratory diseases. Am Rev Respir Dis *85*:762-768.

ATS [1979]. ATS statement—snowbird workshop on standardization of spirometry. Am Rev Respir Dis *119*:831-838.

ATS [1982]. Evaluation of impairment/disability secondary to respiratory disease. Am Rev Respir Dis *126*:945-951.

ATS [1985]. Guidelines as to what constitutes an adverse respiratory health effect with special reference to epidemiologic studies of air pollution. Am Rev Respir Dis *131*:666-668.

ATS [1987a]. Standardization of spirometry—1987 update. Am Rev Respir Dis *136*:1285-1298.

ATS [1987b]. Standards for the diagnoisis and care of patients with chronic obstructive pulmonary disease (COPD) and asthma. Official statement of the American Thoracic Society, adopted by the ATS board of directors. Am Rev Respir Dis *136*:225-244.

Attfield MD, Reger R, Glenn R [1984a]. The incidence and progression of pneumoconiosis over nine years in U.S. coal miners: I. principle findings. Am J Ind Med *6*:407-415.

Attfield MD, Reger R, Glenn R [1984b]. The incidence and progression of pneumoconiosis over nine years in U.S. coal miners: II. relationship with dust exposure and other potential causative factors. Am J Ind Med *6*:417-425.

Attfield MD [1985a]. Longitudinal decline in $FEV_1$ in United States coalminers. Thorax *40*:132-137.

Attfield MD [1985b]. The mortality analysis of data from the first round of the national coal study. Chapter 7. In: The national coal study and related research—final report from round three of the study. NTIS No. PB-85-221-026.

Attfield MD, Hodous TK [1989]. Distribution of values of forced expiratory volume in one second ($FEV_1$) in smoking and nonsmoking coal miners. Paper presented at the American Thoracic Society Conference, Cincinnati, Ohio, 1989.

Attfield MD, Vallyathan V, Green FHY [1991]. Radiographic appearances of small opacities and their correlation with pathology grading of macules, nodules, and dust burden in lungs. Paper presented at the Seventh International Symposium on Inhaled Particles, Edinburgh, Scotland, September 16-20, 1991.

Attfield MD [1992a]. British data on coal miners' pneumoconiosis and relevance to U.S. conditions. Am J Public Health *82*(7):978-983.

Attfield MD [1992b]. Prevalence and incidence of coalworkers' pneumoconiosis in U.S. underground miners. Paper presented at the 9th International Symposium on Epidemiology in Occupational Health, Cincinnati, OH, September 23-25, 1992.

Attfield MD [1992c]. Some observations on the variation in height coefficients in prediction equations for forced vital capacity. J Clin Epidemiol *45*(9):951-957.

Attfield MD, Althouse RB [1992]. Surveillance data on U.S. coal miners' pneumoconiosis, 1970 to 1986. Am J Public Health *82*(7):971-977.

Attfield MD, Castellan RB [1992]. Epidemiologic data on U.S. coal miners' pneumoconiosis, 1960 to 1988. Am J Public Health 82(7):964-970.

Attfield MD, Hodous TK [1992]. Pulmonary function of U.S. coal miners related to dust exposure estimates. Am Rev Respir Dis *145*:605-609.

Attfield MD, Morring K [1992]. The derivation of estimated dust exposures for U.S. coal miners working before 1970. Am Ind Hyg Assoc J *53*(4):248-255.

Attfield MD, Wagner G [1992]. A report on a workshop on the National Institute for Occupational Safety and Health B reader certification program. J Occup Med *34*(9):875-878.

Atuhaire LK, Campbell MJ, Cochrane AL, Jones M, Moore F [1985]. Mortality of men in the Rhondda Fach 1950-80. Br J Ind Med *42*:741-745.

Ayer HE [1969]. The proposed ACGIH mass limits for quartz: review and evaluation. Am Ind Hyg Assoc J *30*:117-124.

Banks DE, Bauer MA, Castellan RM, Lapp NL [1983]. Silicosis in surface coal mine drillers. Thorax *38*:275-278.

Barnhart S [1987]. Evaluation of impairment and disability in occupational lung disease. Occupational Medicine: State of the Art Review *2*(2):227-241.

Bartlett GL, Pedersen AB [1988]. Effects of coal dusts and alveolar macrophages on growth of lung fibroblasts. In: Frantz RL, Ramani RV, eds.

Bartley DL, Breuer GM [1982]. Analysis and optimization of the performance of the 10 mm cyclone. Am Ind Hyg Assoc J *43*:520-528.

Bartley DL, Doemeny LJ [1986]. Critique of 1985 ACGIH report on particle-size-selective sampling in the workplace. Am Ind Hyg Assoc J *47*(8):443-447.

Bartley DL, Fischbach TJ [1991]. Alternative approaches for analyzing sampling and analytical methods. Paper presented at the ACGIH Sampler Performance Conference, October 31, 1991.

Bartley DL, Chen CC, Song R, Fischbach TJ [in press]. Respirable aerosol sampler performance testing. Am Ind Hyg Assoc J.

Bates DV, Pham QT, Chau N, Pivoteau C, Dechoux J, Sadoul P [1985]. A longitudinal study of pulmonary function in coal miners in Lorraine, France. Am J Ind Med *8*:21-32.

BCC [1991]. British Coal Corporation, Medical Service, Annual Report 1989-90. Doncaster, England: Traffort Print Ltd.

Becklake MR [1985]. Chronic airflow limitation: its relationship to work in dusty occupations. Chest *88*(4):608-617.

Becklake MR [1988]. Pneumoconioses. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 1556-1592.

Bellmann B, Muhle H, Creutzenberg O, Dasenbrock C, Kilpper R, MacKenzie JC, et al. [1991]. Lung clearance and retention of toner, utilizing a tracer technique, during chronic inhalation exposure in rats. Fundam Appl Toxicol *17*:300-313.

Blachman MW, Lippmann M [1974]. Performance characteristics of the multicyclone aerosol sampler. Am Ind Hyg Assoc J *35*:311-316.

Blanc PD, Gamsu G [1988]. The effect of cigarette smoking on the detection of small radiographic opacities in inorganic dust diseases. J Thorac Imaging *3*(4):51-56.

Block DL [1988]. Occupational health and safety programs in the workplace. 2nd ed. In: Levy BS, Wegman DH, eds. Occupational health: recognizing and preventing work-related disease. Boston, MS: Little, Brown, and Co., pp. 75-86.

BMRC [1961]. Recommendations of the MRE panels relating to selective sampling. Inhaled particles and vapours. Oxford, England: Pergamon Press.

Boden LI, Gold M [1984]. The accuracy of self-reported regulatory data: the case of coal mine dust. Am J Ind Med *6*:427-440.

Boehlecke B [1986]. Laboratory assessment of respiratory impairment for disability evaluation. In: Merchant JA, ed. Occupational respiratory diseases. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 86-102.

Bohning DE, Atkins HL, Cohn SH [1982]. Long-term particle clearance in man: normal and impaired. Ann Occup Hyg *26*(1-4):259-271.

Bolton RE, Vincent HJ, Jones AD, Addison J, Beckett ST [1983]. An overload hypothesis for pulmonary clearance of UICC amosite fibers inhaled by rats. Br J Ind Med *40*:264-272.

Borm PJA, Palmen N, Engelen JJM, Buurman WA [1988]. Spontaneous and stimulated release of tumor necrosis factor-alpha (TNF) from blood monocytes of miners with coal workers' pneumoconiosis. Am Rev Respir Dis *138*:1589-1594.

Bowden DH [1987]. Macrophages, dust, and pulmonary disease. Exp Lung Res *12*:89-107.

Breslin AJ, Ong L, Glauberman H, George AC, LeClare P [1967]. The accuracy of dust exposure estimates obtained from occupational air sampling. AIHA J *28*:56-61.

Breuer H, Reisner MTR [1988]. Criteria for long-term dust standards on the basis of personal dust exposure records. Ann Occup Hyg *32*(Suppl 1):523-527.

Briant JK, OR Moss [1984]. The influence of electrostatic charges on the performance of 10-mm nylon cyclones. Am Ind Hyg Assoc J *45*:440-445.

Bridbord K, Costello J, Gamble J, Groce D, Hutchison M, Jones W, Merchant J, et.al [1979]. Occupational safety and health implications of increased coal utilization. Environ Health Perspect *33*:285-302.

Brief RS, Scala RA [1975]. Occupational exposure limits for novel work schedules. Am Ind Hyg Assoc J *36*:467-469.

Brown JH, Cook KM, Ney FG, Hatch T [1950]. Influence of particle size upon the retention of particulate matter in the human being. Am J Public Health *40*:450-458.

Buist AS [1988]. Smoking and other risk factors. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 1001-1029.

Buist AS, Vollmer WM [1988]. The use of lung function tests in identifying factors that affect lung growth and aging. Stat Med 7:11-18.

Bureau of Mines [1986]. Investigation of quartz dust sources and control mechanisms on surface coal mine operations, volume 1, results, analysis, and conclusions. Washington, DC: U.S. Department of the Interior, NTIS No. PB-86-215-852.

Bureau of Mines [1987]. Respirable dust levels in coal, metal and nonmetal mines. Washington, DC: U.S. Department of the Interior, Information Circular 9125.

Bureau of Mines [1988]. Impact of drill stem water separation on dust control for surface coal mines. Washington, DC: U.S. Department of the Interior, Technology News No. 308.

Bureau of Mines [1989]. Dust agglomerator for surface coal mine drills. Washington, DC: U.S. Department of the Interior, Technology News No. 338.

Burkhart JE, McCawley MA, Wheeler RW [1987]. Particle size distributions in underground coal mines. Am Ind Hyg Assoc J *48*(2):122-126.

Burrows B [1986]. Pulmonary function testing. In: Merchant JA, ed. Occupational respiratory diseases. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 86-102.

Burrows B, Lebowitz MD, Camilli AE, Knudson RJ [1986]. Longitudinal changes in forced expiratory volume in one second in adults. Am Rev Respir Dis *133*:974-980.

Butani SJ, Bartholomew AM [1988]. Characterization of the 1986 coal mining workforce. Washington, DC: U.S. Department of Interior, Bureau of Mines Information Circular No. 9192.

Campbell EJ, Senior RM [1981]. Cell injury and repair. Clin Chest Med *2*(3):357-375.

Caplan KJ, Doemeny LJ, Sorenson SD [1973]. Evaluation of coal mine dust personal sampler performance. NIOSH contract no. PH CPE-R-70-0036.

Caplan KJ, Doemeny LJ, Sorenson SD [1977]. Performance characteristics of the 10 mm respirable mass sampler: Part II—coal dust studies. Am Ind Hyg Assoc J *38*:162-173.

Castellan RM, Sanderson WT, Petersen MR [1985]. Prevalence of radiographic appearance of pneumoconiosis in an unexposed blue collar population. Am Rev Respir Dis *131*:684-686.

Castranova V, Bowman L, Reasor MJ, Lewis T, Tucker J, Miles PR [1985]. The response of rat alveolar macrophages to chronic inhalation of coal dust and/or diesel exhaust. Environ Res *36*:405-419.

CEN [1992a]. Size fraction definitions for the measurement of airborne particles in the workplace. Brussels, Belguim.

CEN [1992b]. Workplace atmospheres. Assessment of the performance of instruments for measurement of airborne particles. Brussels, Belguim: CEN/TC137/WG3/N117-118.

CEN [1993]. Workplace atmospheres. Assessment of performance of instruments for measurement of airborne particles. Brussels, Belguim: CEN/TC137/WG2/N125.

Cervik J, Sainato A, Baker E [1985]. Longwall dust control by water infusion. Mining Engineering *37*(2):149-153.

30 CFR 70 [1988]. Code of federal regulations. Washington, DC: U.S. Government Printing, Office of the Federal Register.

30 CFR 74 [1988]. Code of federal regulations. Washington, DC: U.S. Government Printing, Office of the Federal Register.

42 CFR 37 [1989]. Code of federal regulations. Washington, DC: U.S. Government Printing, Office of the Federal Register.

20 CFR 718 [1992]. Code of federal regulations. Washington, DC: U.S. Government Printing, Office of the Federal Register.

Chan TL, Lippmann M [1977]. Particle efficiencies of air sampling cyclone: an empirical theory. Environ Sci Tech *11*:377.

Chan TL, Lippmann M [1980]. Experimental measurements and empirical modelling of the regional deposition of inhaled particles in humans. Am Ind Hyg Assoc J *41*:399-409.

Checkoway H, Savitz DA, Heyer NJ [1991]. Assessing the effects of nondifferential misclassification of exposures in occupational studies. Appl Occup Environ Hyg *6*(6):528-533.

Chernack RM, Raber MB [1972]. Normal standards for ventilatory function using an automated wedge spirometer. Am Rev Respir Dis *106*:38-44.

Ciba [1959]. Terminology, definition, and classification of chronic pulmonary emphysema and related conditions. A report of conclusions of a Ciba Guest Symposium. Thorax *14*:286-299.

Clarke SW, Pavia D [1988]. Deposition and clearance. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 313-331.

Clement J, Van de Woestijnekp [1982]. Rapid decreasing forced expiratory volume in one second or vital capacity and development of chronic airflow obstruction. Am Rev Respir Dis *125*:553-558.

Coates DR [1981]. Energy and fossil fuels. Chapter 6. In: Environmental geology. New York, NY: John Wiley and Sons, Inc., pp. 140-156.

Cochrane AL [1962]. The attack rate of progressive massive fibrosis. Br J Ind Med *19*:52-64.

Cochrane AL [1973]. Relation between radiographic categories of coalworkers' pneumoconiosis and expectation of life. Br J Ind Med 2:532-534.

Cochrane AL [1976]. An epidemiologist's view of the relationship between simple pneumoconiosis and morbidity and mortality. Proc R Soc Med *69*(1):12-14.

Cochrane AL, Haley TJL, Moore F, Hole D [1979]. The mortality of men in the Rhondda Fach, 1950-1970. Br J Ind Med *36*:15-22.

Cochrane AL, Moore F [1980]. A 20-year follow-up of men aged 55-64 including coal miners and foundry workers in Staveley, Derbyshire. Br J Ind Med *37*:226-229.

Cochrane AL, Moore F, Moncrieff CB [1982]. Are coalminers, with low "risk factors" for ischaemic heart disease at greater risk of developing progressive massive fibrosis? Br J Ind Med *39*:265-268.

Cochrane AL [1983]. Coal and the lung. Thorax *38*:877-878.

Cockcroft AE, Wagner JC, Seal RME, Lyons JP, Campbell MJ [1981]. Irregular opacities in coalworkers pneumoconiosis—correlation with pulmonary function and pathology. Ann Occup Hyg *26*:767-787.

Cockcroft A, Berry G, Cotes JE, Lyons JP [1982]. Shape of small opacities and lung function in coalworkers. Thorax *37*:765-769.

Cockcroft A, Lyons JP, Andersson NK, Saunders MJA [1983]. Prevalence and relation to underground exposure of radiological irregular opacities in South Wales and workers with pneumoconiosis. Br J Ind Med *40*:169-172.

Cockcroft A, Seal RME, Wagner JC, et al. [1984]. Post mortem study of emphysema in coalworkers and non-coalworkers. Lancet *2*:600-603.

Cockcroft A, Andersson N [1987]. Radiological irregular opacities and coalwork exposure: a case-referent study. Br J Ind Med *44*:484-487.

Coffin DL, Palekar LD [1986]. Tumorigenesis and cytotoxicity of silica. In: Goldsmith DF, Winn DM, Shy CM, eds. Silica, silicosis, and cancer.

Coggbon D, Barker DJP, Cole RB [1990]. Stomach cancer and work in dusty industries. Br J Ind Med *47*:298-301.

Cohrssen JJ, Covello VT [1989]. Risk assessment. In: Risk analysis: a guide to principles and methods for analyzing health and environmental risks. Springfield, VA: U.S. Department of Commerce, The National Technical Information Service. NTIS No. PB-137-772.

Collins HPR, Dick JA, Bennett JG, Pern PO, Richards MA, Thomas DJ, Washington JS, Jacobsen M [1988]. Irregularly shaped small shadows on chest radiographs, dust exposure, and lung function in coalworkers' pneumoconiosis. Br J Ind Med *45*:43-55.

Collins HPR, Soutar CA [1988]. Reproducibility of a radiographic classification of progressive massive fibrosis. Ann Occup Hyg *32*(1):567-573.

Corn M [1990]. Reflections on progress with mine dust control and dust control technology. In: Proceedings of the VIIth International Pneumoconioses Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Corn M [1992]. Historical perspective on approaches to estimation of inhalation risk by air sampling. Am J Ind Med *21*:113-123.

Corn M, Esmen NA [1979]. Workplace exposure zones for classification of employee exposures to physical and chemical agents. Am Ind Hyg Assoc J *40*:47-57.

Corn M, Breysse P, Hall T, Chen G, Risby T, Swift DI [1985]. A critique of MSHA procedures for determination of permissible respirable coal mine dust containing free silica. Am Ind Hyg Assoc J *46*(1):4-8.

Cornwell R, Hanke W [1983]. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 82-112/113/114.

Costello J, Ortmeyer CE, Morgan WKC [1974]. Mortality of lung cancer in U.S. coal miners. *64*(3):222-224.

Costello J, Ortmeyer CE, Morgan WKC [1975]. Mortality from heart disease in coal miners. Chest *67*:417-421.

Cotes JE, Rossiter CE, Higgins ITT, Gilson JC [1966]. Average normal values for the forced expiratory volume in white caucasian males. Br Med J *1*:1016-1019.

Cowie H, Lloyd MH, Soutar CA [1985]. Study of lung function data by principal components analysis. Thorax *40*:438-443.

Cowie RL, Mabena SK [1991]. Silicosis, chronic airflow limitation, and chronic bronchitis in South African gold miners. Am Rev Respir Dis *143*:80-84.

Crapo RO, Morris AH, Gardner RM [1981]. Reference spirometric values for spirometry values using techniques and equipment that meets ATS recommendations. Am Rev Respir Dis *123*:859-864.

Dalal NS, Suryan MM, Jafari B, Shi X, Vallyathan V, Green FHY [1988]. Electron spin resonance detection of reactive free radicals in fresh coal dust and quartz dust and its implications to pneumoconiosis and silicosis. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: health effects, characterization and control, pp. 24-29.

Dalal NS, Suryan MM, Vallyathan V, Green FHY, Jajari B, Wheeler R [1989a]. Detection of reactive free radicals in fresh coal mine dust and their implications for pulmonary injury. Ann Occup Hyg *33*(1):79-84.

Dalal NS, Xianglin S, Vallyathan V [1989b]. Potential role of silicon-oxygen radicals in acute lung injury. In: Mossman BT, Begin RO, eds. Effects of mineral dusts on cells. Berlin, Germany: Springer-Verlag. NATO ASI Series, Vol. H30, pp. 265-272.

Dalal NS, Vallyathan V, Leelarasamee N, Castranova V, Van Dyke K [1990]. Chemiluminescence and biologic reactivity of freshly fractured silica. In: Proceedings of the VIIth International Pneumoconioses Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Dalal NS, Petersen M, Green FHY, Vallyathan V [1991]. Presence of stable coal radicals in autopsied coal miners' lungs and its possible correlation to coal workers' pneumoconiosis. Arch Environ Health *46*(6):366-372.

David Y, Pantes ER [1991]. Coal 1990. Mining Eng 519-528.

Davis A [1976]. Bronchogenic carcinoma in chronic obstructive pulmonary disease. JAMA *235*:621-622.

Davis JMG [1980]. The relationship between the mass and composition of coal mine dust and the development of pneumoconiosis. In: Rom WE, Archer VE, eds. Health implications for new energy technologies. Ann Arbor, MI: Ann Arbor Science Publishers, Inc., pp. 283-292.

Davis JMG, Ottery J, LeRoux A [1977]. The effect of quartz and other non-coal dusts in coalworkers' pneumoconiosis, part II: Lung autopsy study. In: WH Walton, ed. Inhaled Particles IV. Oxford, England: Pergamon Press, pp. 691-700.

Davis JMG, Chapman J, Collings P, Douglas AN, Fernie J, Lamb D, Ruckley V [1983]. Variations in the histological patterns of the lesions of coal workers' pneumoconiosis in Britain and their relationship to lung dust content. Am Rev Respir Dis *128*(1):118-124.

Daykin T [1991]. Black lung may grow in wake of dust fraud. Lexington Herald-Leader, April 21; sect. E:1.

Dickman ML, Schmidt CD, Gardner RM, Marshall HW, Day WC, Warner HR [1969]. On-line computerized spirometry in 738 normal adults. Am Rev Respir Dis *100*:780-790.

Demange M, Gendre JC, Herve-Bazin B, Carton B, Peltier A [1990]. Aerosol evaluation difficulties due to particle deposition on filter holder walls. Ann Occup Hyg *34*(4):399-403.

Demers LM, Rose M, Bartlett GL [1988]. The effects of coal mine dust particles on the metabolism of arachidonic acid by alveolar macrophages. In: Frantz RL, Ramani R, eds. Respirable dust in the mineral industries: health effects, characterization, and control. University Park, PA: Pennsylvania State University.

Dieffenbach A [1988]. Trends in coal mine dust exposures for longwall miners: 1981-1987. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Respiratory Disease Studies.

Dieffenbach A [1988]. Memorandum of January 7, 1988, from Al Dieffenbach, Division of Respiratory Disease Studies, to Mike Attfield and Rickey Althouse Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health, Centers for Disease Control, Public Health Service, U.S. Department of Health and Human Services.

Dinkelis SS, Kukharenko TA, Derr EA, Chernova TG, Myakishev IA, Abaeva SD [1981]. Relationship between pathogenicity and physicochemical properties of bituminous coal dusts. J Hyg Epidemiol Microbiol Immunol *25*(4):393-399.

Divers EF, Cecala AB [1990]. Dust control in coal preparation and mineral processing plants. U.S. Department of Interior, Bureau of Mines, Information Circular 9248.

Dobreva M, Burilkov T, Kolev K, Lalova P [1977]. Characteristics of lung dusts and their relation to dust exposure and pathological findings in the lungs. In: Walton WH, ed. Inhaled particles IV. Proceedings of an International Symposium organized by the British Occupational Hygiene Society, Edinburgh, September 22-26, 1975, Oxford, England: Pergamon Press.

Dockery DW, Ware JH, Ferris BG Jr, Glicksberg DW, Fay ME, Spiro A III, Speizer FE [1985]. Distribution of forced expiratory volume in one second and forced vital capacity in healthy, white, adult never-smokers in six U.S. cities. Am Rev Respir Dis *131*:511-520.

Dockery DW, Speizer FE, Ferris BG, Ware JH, Louis TA, Spiro A [1988]. Cumulative and reversible effects of lifetime smoking and simple tests of lung function in adults. Am Rev Respir Dis *137*:286-292.

Dodgson J, Cowie AJ, Paris I, Whittaker W [1977]. A study of the importance of dust composition in relation to pneumoconiosis in coalminers. Roxburgh Place, Edinburgh, Scotland. Institute of Occupational Medicine. CEC contract no. 6253-32/8/018.

DOE [1989]. Coal production 1988. Washington DC: U.S. Department of Energy, Office of Coal, Nuclear, Electric, and Alternate Fuels, DOE/EIA-0118 (88).

Douglas AN, Robertson A, Chapman JS, Ruckley VA [1986]. Dust exposure, dust recovered from the lung, and associated pathology in a group of British coal miners. Br J Ind Med *43*:795-801.

Doyle HN [1970a]. A model for evaluating coal mine dust standards. J Occup Med *12*(9):370-374.

Doyle HN [1970b]. Dust concentrations in the mines. In: Proceedings of the Symposium on Respirable Coal Mine Dust. Washington, DC: U.S. Department of Interior, Bureau of Mines Information Circular 8458.

Driscoll KE, Lindenschmidt RC, Maurer JK, Higgins JM, Ridder G [1990a]. Pulmonary response to silica or titanium dioxide: inflammatory cells, alveolar macrophage-derived cytokines, and histopathology. Am J Respir Cell Mod Biol *2*:381-390.

Driscoll KE, Maurer JK, Crosby LL [1990b]. Overload of lung clearance is associated with activation of alveolar macrophage tumor necrosis factor and fibronectin release. J Aerosol Med *3*(Suppl 1):S83-S91.

EIA [1991]. Coal data: reference. Washington, DC: U.S. Department of Energy, National Energy Information Center, Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, Publication No. DOE/EIA-0064 (90).

Eisen EA [1987]. Standardizing spirometry: problems and prospects. In: Rosenstock L, ed. Occupational Medicine: State of the Art Review *2*(2):213-225.

Eisen EA, Wegman DH, Louis TA [1983]. Effects of selection in a prospective study of forced expirations in Vermont granite workers. Am Rev Respir Dis *128*:587-591.

Eisen EA, Robins JM, Greaves IA, Wegman DH [1984]. Selection effects of repeatability criteria applied to lung spirometry. Am J Epi *120*:734-742.

Elisburg D [1980]. Respiratory disability in coal miners. JAMA *244*(19):2158.

Emmett PC, Aitken RJ, Hannan WJ [1978]. Measurements of the total and regional deposition of inhaled particles in the human respiratory tract. J Aerosol Sci *13*:549-560.

Enterline PE [1967]. The effects of occupation on chronic respiratory disease. Arch Environ Health *14*:189-200.

Enterline PE [1972]. A review of mortality data for American coal miners. Ann N Y Acad Sci *200*:260-272.

Epler GR, Saber FA, Gaensler EA [1980]. Determinations of severe impairment (disability) in interstitial lung disease. Am Rev Respir Dis *121*:647.

Epstein DM, Miller WT, Bresnitz EA, Levine MS, Gefter WB [1984]. Application of ILO classification to a population without industrial exposure: findings to be differentiated from pneumoconiosis. Am J Roentgenol *142*:53-58.

Fairman PR, O'Brien RJ, Swecker S, Amandus HE, Shoub EP [1977]. Respiratory status of surface coal miners in the United States. Arch Environ Health *32*:211-215.

45 Fed. Reg. 13678 [1980]. Department of Labor: standards for determining coal miners' total disability or death due to pneumoconiosis.

45 Fed. Reg. [1980]. Department of Labor, Mine Safety and Health Administration, 30 CFR Part 71, Respirable Dust; Operator Sampling Procedures. Vol. 45, No. 236, December 5, 1980, Rules and Regulations.

Fed. Reg. 35(65), April 3, 1970, pp. 5544-5550.

54 Fed. Reg. 2332 [1989]. U.S. Department of Labor, Occupational Safety and Health Administration: air contaminants; final rule. (To be codified at 29 CFR 1910).

57 Fed. Reg. 46126 [1992]. U.S. Department of Labor, Coast Guard. Controlling the marine asbestos hazard; proposed rule.

Fels AOS, Cohn ZA [1986]. The alveolar macrophage. J Appl Physiol *60*:353-369.

Ferris BG [1978]. Epidemiology standardization project: respiratory questionnaires. Am Rev Respir Dis 118:7-53.

Ferris BG, Anderson DO, Zickmantel R [1965]. Prediction values for screening tests of pulmonary function. Am Rev Respir Dis *91*:252-261.

Fiserova-Bergerova V [1990]. Application of toxicokinetic models to establish biological exposure indicators. Ann Occup Hyg *34*(6):639-651.

Fletcher CM, Oldham PD [1949]. The problem of consistent radiological diagnosis in coalminers' pneumoconiosis. Br J Ind Med *6*:168-183.

Fletcher CM, Peto R, Speizer FS, Tinker CM [1970]. A follow-up study of the natural history of obstructive bronchitis. In: Orie NGM, Van der Lende R, eds. Bronchitis III. Royal Vangorcum, Assen, p. 115.

Fletcher CM, Peto R, Tinker C, Speizer FE [1976]. The natural history of chronic bronchitis and emphysema: an eight-year study of early chronic obstructive lung disease in working men in London. New York, NY: Oxford University Press, pp. 1-9, 70-105.

Fletcher CM, Peto R [1977]. The natural history of chronic airflow obstruction. Br Med J *1*:1645-1648.

Fox AJ, Collier PF [1976]. Low mortality rates in industrial cohort studies due to selection for work and survival in the industry. Br J Prev Soc Med *30*(4):225-230.

Foxman B, Higgins ITT, Oh MS [1986]. The effects of occupation and smoking on respiratory disease mortality. Am Rev Respir Dis *134*:649-652.

Freedman AP, Robinson SE, Johnston RJ [1980], Non-invasive magnetopneumographic estimation of lung dust loads and distribution in bituminous coal workers. J Occup Med *22*:613-618.

Freedman AP, Robinson SE, Green FHY [1982]. Magnetopneumography as a tool for the study of dust retention in the lungs. Ann Occup Hyg *26*:319-335.

Freedman AP, Robinson SE [1988]. Noninvasive magnetopneumographic studies of lung dust retention and clearance in coal miners. In: Frantz RL, Ramani RV Ramani, eds. Respirable dust in the mineral industries: health effects, characterization and control, pp. 181-186.

Freedman AP, Robinson SE, Street MR [1988]. Magnetopneumographic study of human alveolar clearance in health and disease. Ann Occup Hyg *32*(1):809-820.

Friedman GD, Klatshky AL, Siegelaub AB [1976]. Lung function and risk of myocardial infarction and sudden cardiac death. N Engl J Med *294*:1071-1075.

Fubini B, Giamello E, Volante M, Bolis V [1990]. Chemical functionalities at the silica surface determining its reactivity when inhaled—formation and reactivity of surface radicals. Toxicol Ind Health *6*(6):571-598.

GAO [1990]. Black lung program: further inprovements can be made in claims adjudication. Washington, DC: U.S. General Accounting Office. GAO/HRD-90-75, p. 36

Gauld SJ, Hurley JF, Miller BG [1985]. The effect of non-response in a longitudinal study of coalminers respiratory health and exposure to dust. In: Proceedings of the VIth International Symposium on Inhaled Particles. Cambridge: British Occupational Hygience Society.

Gauld SJ, Hurley JF, Miller BG [1988]. Differences between long-term participants and non-responders in a study of coalminers' respiratory health and exposure to dust. Ann Occup Hyg *32*(Suppl 1):545-551.

Ghio AJ, Crapo RO, Elliott CG [1990]. Reference equations used to predict pulmonary function: survey at institutions with respiratory disease training programs in the United States and Canada. Chest *97*:400-403.

Ghio AJ, Castellan RM, Kinsley KB, Hankinson JL [1991]. Changes in forced expiratory volume in one second and peak expiratory flow rate across a work shift among unexposed blue collar workers. Am Respir Dis 143(6):1231-1234.

Gilson JC, Hugh-Jones P [1949]. Lung function in coal-workers' pneumoconiosis. British Mine Research Council Special Report Series No. 290.

Given PH [1984]. An essay on the organic geochemistry of coal. In: Gobarty ML, Larsen JW, Wender I, eds. Coal science. Vol. 3. New York, NY: Academic Press, pp. 70-86.

Glindmeyer HW, Diem JE, Jones RN, Weill H [1982]. Noncomparability of longitudinally and cross-sectionally determined annual change in spirometry. Am Rev Respir Dis *125*:544-548.

Gold WM, Boushey HA [1988]. Pulmonary function testing. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 611-682.

Goldberg SA, Raymond LD, Taylor CD [1976]. Mining enforcement and safety administration procedure for analysis of respirable dust from coal mines. Proceedings of the Symposium on Silica, March 12-13, Pittsburgh, PA.

Goldberg SA, Tomb TF, Kacsmar PM, Baber JJ, Busa MJ [1984]. MSHA's procedure for determining quartz content of respirable coal mine dust. U.S. Department of Labor, Mine Safety and Health Administration.

Goldman HI, Becklake MR [1959]. Respiratory function tests: normal values at median altitudes and the prediction of normal results. Am Rev Tuber *79*:457-463.

Grayson RL [1990]. The potential role of particle characteristics on coal mine respirable dust standards. Unpublished paper presented at the Society for Mining, Metallurgy, and Exploration, Inc., Salt Lake City, Utah, February 26-March 1, 1990.

Grayson RL, Andre RA, Simonyi T [1988]. Seeking the "rtank factor" in CWP incidence: Role of respirable dust particle purity. Unpublished paper presented at the VIIth International Pneumoconiosis Conference, Pittsburgh, PA, August 23-26, 1988.

Grayson RL, Watts CM, Yuan S, Dean J, Nutter RS [1990]. The mine management support system: a knowledge-based system for better management of underground coal mines. West Virginia University, Morgantown, WV. Paper presented at the SME Annual Meeting, Salt Lake City,^S Utah, February 26-March 1.

Green FHY, Althouse R, Weber KC [1989]. Prevalence of silicoses at death in underground coal miners. Am J Ind Med *16*:605-615.

Green SO [1987]. Scrubbers and remote control allow North River No. 1 mine to extend cutting depth of continuous miners. Mining Eng *39*(8):781-784.

Greskevitch MF, Turk AR, Dieffenbach AL, Roman JM, Groce DW, Hearl FJ [1992]. Quartz analyses of the bulk dust samples collected by the National Occupational Health Survey of Mining. Appl Occup Environ Hyg 7(8):527-531.

Gross P, Tuma J, deTreville RTP [1971]. Emphysema and pneumoconiosis. Arch Environ Health *2*:194-199.

Gross P, Braun DC, deTreville RTP [1972]. The pulmunary response to coal dust. Ann N Y Acad Sci *200*:155-165.

Guidotti TL [1979]. Coal workers' pneumoconiosis and medical aspects of coal mining. South Med J *72*(4):456-466.

Gunderson EC, Anderson CC [1980]. Development and validation of methods for sampling and analysis of workplace toxic substances. Cincinnati, OH: U.S. Department for Health and Human Services, Public Health Service, Centers Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 80-133.

Halperin WE, Ratcliffe J, Frazier TM, Wilson L, Becker SP, Schulte PA [1986]. Medical screening in the workplace: proposed principles. J Occup Med *28*(8):547-552.

Hankinson JL [1986]. Pulmonary function testing in the screening of workers: guidelines for instrumentation, performance, and interpretation. J Occup Med *28*(10):1081-1092.

Hankinson JL, Bang KM [1991]. Acceptability and reproducibility criteria of the American Thoracic Society as observed in a sample of the general population. Am Rev Respir Dis *143*:516-521.

Hankinson JL, Reger RB, Fairman RP, Lapp NL, Morgan WKC [1977]. Factors influencing expiratory flow rates in coal miners. In: Walton WH, ed. Inhaled Particles IV. Oxford, England: Pergamon Press, pp. 737-755.

Hankinson JL, Reger RB, Morgan WKC [1977]. Maximal expiratory flows in coal miners. Am Rev Respir Dis *116*:175-180.

Hankinson JL, Wagner GR [press]. Medical screening using periodic spirometry for detection of chronic lung disease. Occupational Medicine: State of the Art Reviews.

Hansen JE, Wasserman K [1988]. Disability evaluation. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 699-718.

Hearl FJ, Hewett P [1993]. Problems in monitoring dust levels with mines. Occupational Medicine: State of the Art Reviews *8*(1):93-108.

Heederik D, Miller BG [1988]. Weak associations in occupational epidemiology: adjustment for exposure estimation error. Int J Epidemol *17*(4 Suppl):970-974.

Heederik D, Boleij JSM, Kromhout H, Smid T [1991a]. Use and analysis of exposure monitoring data in occupational epidemiology: an example of an epidemiological study in the Dutch animal food industry. Appl Occup Environ Hyg *6*(6):458-463.

Heederik D, Kromhout H, Burema J [1991b]. Letter to the editor: assessment of long-term exposures to toxic substances in air. Ann Occup Hyg *35*(6):671-673.

Heppleston AG [1970]. Emphysema in relation to dust exposure. In: Shapiro A, ed. Proceedings of the International Conference. Johannesburg, South Africa: Oxford University Press, pp. 312-314.

Heppleston AG [1988]. Prevalence and pathogenesis of pneumoconiosis in coal workers. Environ Health Perspect *78*:159-170.

Hewett P [1991]. Limitations in the use of particle size-selective sampling criteria in occupational epidemiology. Appl Occup Environ Hyg *6*(4):290-300.

Hewett P [1993]. Memorandum of March 25, 1993, from Paul Hewett, Division of Respiratory Disease Studies, to Eileen Kuempel, Division of Standards Development and Technology Transfer, National Institute for Occupational Safety and Health, Centers for Disease Control, Public Health Service, U.S. Department of Health and Human Services.

Heyder J, Gebhart J, Rudolf G, Schiller CF, Stahlhofen W [1986]. Deposition of particles in the human respiratory tract in the size range 0.005-15 um. J Aerosol Sci *17*:811-825.

Higgins RI, Dewell P [1968]. A gravimetric size-selecting personal dusts sampler. Alvechurch, Birmingham: British Cast Iron Research Association, BCIRA Report 908.

Higgins ITT, Higgins MW, Lockshin MD, et al. [1968]. Chronic respiratory disease in mining communities in Marion County, West Virginia. Br J Ind Med *25*:165-175.

Higgins ITT, Oh MS, Whittaker DE [1981]. Chronic respiratory disease in coal miners: follow-up study of two mining communities in West Virginia. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Respiratory Disease Studies.

Higgins MW, Keller JB [1970]. Predictors of mortality in the adult population of Tecumseh. Arch Environ Health *21*:418-424.

Higgins MW, Keller JB, Becker MH, Landis JR, Rotman H, Weg JG, Higgins I [1982]. An index of risk for obstructive air-ways disease. Am Rev Respir Dis *125*:144-151.

Higgins RD, Dewell P [1967]. A gravimetric size-selecting personal dust sampler. In: Davies CN, ed. Inhaled particles and vapors II. Oxford, England: Pergamon Press.

Hill AB [1965]. The environment and disease: association or causation. Proc Roy Soc Med *58*:295-300.

Hinds WC [1982]. Aerosol technology. New York, NY: John Wiley and Sons.

Hinds WC, Bellin P [1988]. Effect of facial-seal leaks on protection provided by half-mask respirators. Appl Ind Hyg *3*(5):158-163.

Hodous TK, Attfield MD [1990]. Progressive massive fibrosis developing on a background of minimal simple coal workers' pneumoconiosis. In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, Ohio: U.S. Department of Health and Human Service, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Hodous TK, Hankinson JL [1990]. Prospective spirometric study of new coal miners. In: Li Y, Yao P, Schlipkoter HW, Idel H, Rosenbruch M, eds. International Symposium on Pneumoconioses, ISP '88. Shenyang, PR China, May 30-June 2, 1988.

Howe LC [1987]. Increased productivity by applying deep cut technology. Paper presented at the Coal Convention '87, sponsored by the American Mining Congress, Cincinnati, OH, May 3-6, 1987.

HSE [1993]. General Methods for the gravimetric determination of respirable and total inhalable dust, MDHS 14 (revised). In: HSE series: methods for the determination of hazardous substances. London, England, ISBN 0-11-882046-X.

Hurley JF, Burns J, Copland L, Dodgson J, Jacobsen M [1982]. Coalworkers' simple pneumoconiosis and exposure to dust at 10 British coalmines. Br J Ind Med *39*:120-127.

Hurley JF, Maclaren WM, Alexander WP, Cowie AJ, Collins HRR, Ewing A, et. al [1984]. Factors influencing the occurrence of progressive massive fibrosis in British coalminers. Edinburgh, Scotland: Institute of Occupational Medicine. CEC contract no. 7256-34/016/08.

Hurley JF, Jacobsen M [1986]. Occupational hygiene implications of new results on progressive massive fibrosis in working coalminers. Ann Am Conf Gov Ind Hyg *14*:85-89.

Hurley JF, Soutar CA [1986]. Can exposure to coalmine dust cause a severe impairment of lung function? Br J Ind Med *34*:150-157.

Hurley JF, Alexander WP, Hazledine DJ, Jacobsen M, Maclaren WM [1987]. Exposure to respirable coal mine dust and incidence of progressive massive fibrosis. Br J Ind Med *44*:661-672.

Hurley JF, Maclaren WM [1987]. Dust-related risks of radiological changes in coal miners over a 40-year working life: report on work commissioned by NIOSH. Edinburgh, Scotland: Institute of Occupational Medicine. Report no. TM/87/09.

Hurley JF, Maclaren WM [1988]. Factors influencing the occurrence of progressive massive fibrosis (PMF) in miners and ex-miners. Ann Occup Hyg *32*(1):575-583.

Hutchinson J [1846]. On the capacity of the lungs and on the respiratory function, with a view of establishing a precise and easy method of defecting disease by the spirometer. Med Chir Soc *29*:138-252.

Hwang CY [1988]. Measurements of respirable dust concentrations by using various samplers in underground coal mines. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: Health effects, characterization and control, pp. 51-59.

Hyatt RE, Kistin AD, Mahan TK [1964]. Respiratory disease in southern West Virginia coal miners. Am Rev Respir Dis *89*:387-401.

IARC [1987]. IARC Monographs on the evaluation of the carcinogenic risk of chemicals to humans: Silica and some silicates. Vol. 42. Lyon, France: World Health Organization, International Agency for Research on Cancer.

ICDA [1968]. Eighth revision international classification of diseases, adapted for use in the United States. Washington, DC: U.S. Department of Health, Education, and Welfare, Public Health Service, National Center for Health Statistics. PHS Publication No. 1693.

ILO [1959]. Meeting of experts on the international classification of radiographs of the pneumoconioses. Occup Health Safety *1959*:63-69.

ILO [1970]. International classification of radiographs of pneumoconiosis. Revised 1968. Occupational Safety and Health, Series no. 22. Geneva, Switzerland: International Labour Office.

ILO [1972]. ILO U/C international classification of radiographs of pneumoconioses 1971. Geneva, Switzerland: International Labour Office.

ILO [1980]. Guidelines for the use of ILO international classification of radiographs of pneumoconiosis, revised. Geneva, Switzerland: International Labour Office.

Irwig L, Rocks P [1978]. Lung function and respiratory symptoms in silicotic and nonsilicotic gold miners. Am Rev Respir Dis *117*:429-4435.

ISO [1991a]. Air quality—assessment of performance of instruments used for the health-related sampling of particles at workplaces. Brussels, Belgium: Draft technical report, CEN/TC137/WG3/N 100.

ISO [1991b]. Air quality—particle size fraction definitions for health-related sampling. Brussels, Belgium: draft ISO standard, ISO/TC 146/CD 7708.

Jaakkola MS, Ernst P, Jaakkola JJK, N'gan'ga LW, Becklake MR [1991]. Effect of cigarette smoking on evolution of ventilatory lung function in young adults: an eight year longitudinal study. Thorax *46*:907-913.

Jacobson M [1971]. Respirable dust in bituminous coal mines in the U.S. In: Walton WH, ed. Inhaled particles III. Vol. 2. Surrey, United Kingdom: Unwin Brothers Limited, pp. 745-756.

Jacobson M, Lamonica JA [1969]. Personal respirable dust sampler. Washington, DC: U.S. Bureau of Mines, Technical Progress Report 17.

Jacobsen M [1972]. The basis for the new coal dust standards. Mining Eng *133*:269-278.

Jacobsen M [1973]. Progression of coal workers' pneumoconiosis in Britain in relation to environmental conditions underground. Proceedings of the Conference on Technical Measures of Dust Prevention and Suppression in Mines. Luxemburg, October 11-13.

Jacobsen M [1976]. Dust exposure, lung diseases, and coal miners' mortality. [Dissertation]. University of Edinburgh, p. 178.

Jacobsen M [1983]. Coalworkers' pneumoconiosis: results from epidemiological studies in Britain. Paper presented at the VIth International Pneumoconiosis Conference, Bochum, FRG, September 20.

Jacobsen M, Rae S, Walton WH, Rogan JM [1970]. New dust standards for British coal mines. Nature *227*:445-447.

Jacobsen M, Rae S, Walton WH, Rogan JM [1971]. The relation between pneumoconiosis and dust exposure in British coal mines. Vol. 2. In: Walton WH, ed. Inhaled Particles III. Surrey, United Kingdom: Unwin Brothers Limited, The Gresham Press, pp. 903-917.

Jacobsen M, Burns J, Attfield MD [1977]. Smoking and coalworkers' simple pneumoconiosis. Vol. 2. In: WH Walton, ed., Inhaled Particles IV. Oxford, England: Pergamon Press, pp. 759-771.

Jacobsen M, Dodgson J [1981]. Long-term experience in collecting and using occupational health data in the coal industry. Ann Occup Hyg *24*(4):391-398.

Jacobsen M, Maclaren WM [1982]. Unusual pulmonary observations and exposure to coal mine dust: a case-control study. Ann Occup Hyg *26*(1-4):753-765.

Jafari B, Dalal NS, Vallyathan AV, Green FYH [1988]. Detection of organic free radicals in coal-dust exposed lung tissue and correlations with their histopathological parameters. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: health effects, characterization and control. University Park, PA: The Pennsylvania State University, pp. 223-225.

Jain BL, Patrick JM [1981]. Ventilatory function in Nigerian coal miners. Br J Ind Med *38*:275-280.

Jankowski RA, Babbitt CA [1986]. Using barriers to reduce dust exposure of longwall face workers. Pittsburgh, PA: U.S. Bureau of Mines. NTIS no. PB-87-139-572.

Jankowski RA, Kissell FN, Daniel JH [1986]. Longwall dust control: an overview of progress in recent years. Mining Eng *38*(10):953-958.

Jankowski RA, Organiscak JA, Jayaraman NI [1990]. Dust sources and controls on high tonnage longwall faces. Unpublished manuscript presented at the Society for Mining, Metallurgy, and Exploration, Inc. annual meeting in Salt Lake City, Utah, February 26-March 1, 1990.

Jayaraman NI, Volkwein JC, Kissell FN [1990]. Update on continuous miner dust scrubber applications. Mining Eng *42*(3):281-284.

Johnson CC [1969]. HEW's eight point program to combat coal miner's pneumoconiosis. Ind Med *38*(9):14.

Jones CO, Gauld S, Hurley JF, Rickmann AM [1981]. Personal differences in the breathing patterns and volumes and dust intakes of working miners. Institute of Occupational Medicine, Roxburgh Place, Edinburgh, Scotland. Report no. TM/81/11, CEC contract 7246-12/8/002.

Jones WJ [1986]. Biological degradation of low-rank coal. Quarterly technical progress report. Grand Forks, ND: U.S. Department of Energy, Office of Fossil Energy, Morgantown Energy Technology Center, Grand Forks Project Office. Report no. DOE/FC/10625-2029.

Kaegi E, Baynton M [1981]. Respiratory disorders associated with coal mining. Edmonton, Alberta: Alberta Wokers' Health, Safety and Compensation, Medical Services Branch, Occupational Health and Safety Division.

Kalliomaki K, Kalliomaki PL, Moilnen M [1988]. Magnetopneumography and its application to occupational hygiene. Ann Occup Hyg *32*(Suppl 1):821-825.

Kannel WB, Hubert H, Lew EA [1983]. Vital capacity as a predictor of cardiovascular disease: The Framingham Study. Am Heart J *105*:311-315.

Kanner RE, Morris AH [1975]. Clinical pulmonary functions testing. Salt Lake City, UT: Intermountain Thoracic Society.

Kauffmann F, Drouet D, Lellouch J, Brille D [1982]. Occupational exposure and 12-year spirometric changes among Paris area workers. Br J Ind Med *39*:221-232.

Kellie SE, Attfield MD, Hankinson JL, Castellan RM [1987]. Spirometry variability criteria–association with respiratory morbidity and mortality in a cohort of coal miners. Am J Epidemiol *125*(3):437-444.

Kenny LC [1992]. Report of progress towards the development of a performance standard for aerosol sampling instruments used in occupational hygiene. J Aerosol Sci *23*(7):773-779.

Key MM [1971]. Pulmonary reactions to coal dust. New York, NY: Academic Press, pp. 179-185.

Key MM [1972]. Health standards and standard setting in the United States. Ann N Y Acad Sci *200*:707-716.

Kibelstis JA, Morgan EJ, Reger R, Lapp NL, Seaton A, Morgan WKC [1973]. Prevalence of bronchitis and airway obstruction in American bituminous coal miners. Am Rev Respir Dis *108*:886-893.

Kilburn KH [1980]. Occupational chronic bronchitis. In: Last JM, ed. Public health and preventive medicine. New York, NY: Appleton-Century-Crofts, p. 620.

Kilburn KH [1984]. Particles causing lung disease. Environ Health Perspect *55*:97-110.

Kilburn KH [1986]. Chronic bronchitis and emphysema. In: Merchant JA, ed. Occupational respiratory diseases. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 86-102.

Kim H [1989]. The characteristics of airborne coal mine dust and its implications to coal workers' pneumoconiosis [Dissertation]. Morgantown, WV: West Virginia University.

Kirby WA, Lakey JR, Sarjant RJ [1954]. A study of coal extracts by infra-red spectroscopy. Fuel *33*:480.

Kleinerman J [1979]. Pathology standards for coal workers' pneumoconiosis. Arch Pathol Lab Med *103*(8):374-432.

Knight G [1985]. Letters to the editor: definitions of alveolar dust deposition and respirable dust sampling. Ann Occup Hyg *29*(4):526-528.

Knight G [1986]. Letters to the editor: author's reply. Ann Occup Hyg *30*(4):520-521.

Knight G, Kirk B [1982]. Comparison of respirable dust specifications with recent lung data. Am Ind Hyg Assoc J *43*:575.

Knudson RJ, Lebowitz MD, Holberg CJ, Burrows B [1983]. Changes in the normal maximal expiratory flow-volume curve with growth and aging. Am Rev Respir Dis *127*:725-734.

Knudson RJ, Slatin RC, Lebowitz MD et al. [1976]. The maximal expiratory flow-volume curve. Am Rev Respir Dis *113*:587.

Kory RC [1963]. Clinical spirometry: recommendation of the section on pulmonary function testing, committee on pulmonary physiology, American College of Chest Physicians. Dis Chest *43*:214.

Kory RC, Callahan R, Boren HG [1961]. The veterans administration–army cooperative study of pulmonary function. Am J Med *30*:243-258.

Kuller LH, Ockene JK, Townsend M, Browner W, Meilan E, Wentworth DN [1989]. The epidemiology of pulmonary function and COPD mortality in the multiple risk factor intervention trial. Am Rev Respir Dis *140*:S76-S81.

Kuller LH, Ockene J, Meilahn E, Svendsen KH [1990]. Relation of forced expiratory volume in one second ($FEV_1$) to lung cancer mortality in the multiple risk factor intervention trial (MRFIT). Am J Epidemol *132*(2):265-274.

Lainhart WS [1969]. Roentgenographic evidence of coal workers' pneumoconiosis in three areas in the United States. J Occup Med *11*:399-408.

Lamb D [1975]. Physiological/pathological correlations in coal workers' pneumoconiosis. Bull Physiopathol Respir *11*:471-478.

Lamb D [1976]. A survey of emphysema in coal workers and the general population. Proc R Soc Med *69*(1):14.

Langnuir AD [1963]. The surveillance of communicable diseases of national importance. N Engl J Med *268*:182-192.

Lapp NL, Seaton A [1971]. Pulmonary function in coal workers' pneumoconiosis. New York, NY: Academic Press, Inc., pp. 153-177.

Lapp NL, Morgan WKC [1975]. Cardio-respiratory function in United Stated coal workers. Bull Physiopathol Respir *11*:527-559.

Larsen JW [1981]. Coal structure. Chapter 1. Vol. 70 In: American Institute of Physics Proceedings, pp.1-27.

Last JA [1985]. Changes in the collagen pathway in fibrosis. Fundam Appl Toxicol *5*:210-218.

Last JA, Wu J, Chen J, Gelzleichter T, Sun WM, Armstrong LG [1990]. Particle-cell interactions: lung fibrosis. J Aerosol Med *3*(Suppl 1):S61-S74.

Last JM, ed [1988]. A dictionary of epidemiology. International Epidemiology Association. New York, NY: Oxford University Press.

LeBouffant L et al. [1988]. Compared in vitro and in vivo toxicity of coal mine dusts–relationship with mineralogical composition. Ann Occup Hyg *32*(1):611-620.

Lee C, Mutmansky JM [1988]. Statistical analysis of the elemental characteristics of airborne coal mine dust. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: health effects, characterization and control, pp. 111-123.

Lee CW [1986]. Statistical analysis of size and elemental composition of airborne coal mine dust [Dissertation]. State College, PA: Pennsylvania State University, Department of Mineral Engineering.

Lee HB [1969]. Bloodletting in Appalachia. Morgantown, WV: West Virginia University Press.

Lehnert BE [1990]. Alveolar macrophages in a particle "overload" condition. J Aerosol Med *3*(Suppl 1):S9-S30.

Lehnert BE, Valdez YE, Holland LM [1985]. Pulmonary macrophages: alveolar and interstitial populations. Exp Lung Res *9*:177-190.

Lehnert BE, Valdez YE, Tietjen GL [1989]. Alveolar macrophage-particle relationships during lung clearance. Am J Respir Cell Mol Biol *1*:145-154.

Lieben J, Pendergrass E, McBride WW [1961]. Pneumoconiosis study in central Pennsylvania coal mines: I. Medical phase. J Occup Med *3*:493-506.

Leidel N, Busch K, Lynch J [1977]. Occupational exposure sampling strategy manual. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, DHEW (NIOSH) Publication No. 77-173.

Leiderman S, Halbert L, Preefer D, Forwalter D, Silver P [1983]. Review of claims filed under the Black Lung Benefits Amendments of 1981. Washington, DC: U.S. Department of Labor, Employment Standards Administration.

Leigh J, Outhred KG, McKenzie HI, Wiles AN [1982]. Multiple regression analysis of quantified aetiological, clinical, and post mortem pathological variables related to respiratory disease in coal workers. Ann Occup Hyg *26*:383-400.

Leigh J, Outhred KG, McKenzie HI, Glick M, Wiles AN [1983]. Quantification of pathoplogy of emphysema, pneumoconiosis, and chronic bronchitis in coal workers. Br J Ind Med *40*:258-263.

Lemen RA, Dunnom DD, Wagner WD, Mazzuckelli LF [1986]. Recommended standards for occupational exposure to silica. In: Goldsmith DF, Winn DM, Shy CM, eds. Silica, silicosis, and cancer, pp. 505-509.

Levy BS, Halperin WE [1988]. Screening for occupational disease. 2nd ed. In: Levy BS, Wegman DH, eds. Occupational health: recognizing and preventing work-related disease. Boston, MS: Little, Brown, and Co., pp. 75-86.

Lewis BC [1990]. Longwall mining: future concerns that must be addressed. Mining Eng, October 1990, pp. 1170-1172.

Lewis FA [1983]. Heath hazard evaluation report: Pennsylvania Power and Light, Martins Creek Steam Electric Station, Martins Creek, Pennsylvania. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. NIOSH Report No. HETA 81-472-1380, NTIS PB-85-178556/XAB.

Lewis TR, Green FHY, Moorman WJ, Burg JR, Lynch DW [1989a]. A chronic inhalation toxicity study of diesel engine emissions and coal dust, alone and combined. J Am Coll Toxicol *8*(2):345-375.

Lewis TR, Morrow PE, McClellan RO, Raabe OG, Kennedy GL, Schwetz BA, et al. [1989b]. Contemporary issues in toxicology. Toxicol Appl Pharmacol *99*:377-383.

Lewitter FI, Tager IB, McGue M, Tishler PV, Speizer FE [1984]. Genetic and environmental determinants of level of pulmonary function. Am J Epidemiol *120*(4):518-529.

Liddell FDK [1973]. Mortality of British coalminers in 1961. Br J Ind Med *30*:15-24.

Liddell D, Miller K [1983]. Individual susceptibility to inhaled particles. Scand J Work Environ Health *9*:1-8.

Liden G, Kenny LC [1991]. Comparison of measured respirable dust sampler penetration curves with sampling conventions. Ann Occup Hyg *35*(5):485-504.

Liden G, Kenny LC [1992]. The performance of respirable dust samplers: sampler bias, precision and accuracy. Ann Occup Hyg *36*:1-22.

Liden G, Kenny LC [1993]. Optimization of the performance of existing respirable dust samplers. J Appl Environ Ind Hyg *8*(4):386-391.

Lieben J, Pendergrass E, McBride WW [1961]. Pneumoconiosis study in central Pennsylvania coal miners. I. Medical phase. J Occup Health *3*:493-506.

Lilienfeld AM, Lilienfeld DE [1980]. Foundations of epidemiology. 2nd ed. New York, NY: Oxford University Press.

Lioy PJ, Lippmann M, Phalen RF [1984]. Rationale for particle size-selective air sampling. In: Particle size-selective sampling in the workplace: report of the ACGIH Technical Committee on Air Sampling Procedures. Ann Am Conf Ind Hyg 11:27-34.

Lippmann M [1970]. Respirable dust sampling. Am Ind Hyg Assoc J *31*:138-159.

Lippmann M [1985]. Development of particle size-selective threshold limit values. Ann Am Conf Ind Hyg *12*:27-34.

Lippmann M [1991]. Research needs: retrospective exposure assessment for occupational epidemiology. Appl Occup Environ Hyg *6*(6):550-554.

Lippmann M, Harris WB [1962]. Size-selective samples for estimating respirable dust concentrations. Health Phys *8*:155.

Lippmann M, Albert RE [1969]. The effect of particle size on the regional deposition of inhaled aerosols in the human respiratory tract. Am Ind Hyg Assoc J *30*:257-275.

Lippmann M, Timbrell V [1990]. Particle loading in the human lung—human experience and implications for exposure limits. J Aerosol Med *3*(Suppl 1):S155-S168.

Liu BYH, Pui DYH, Rubow KL, Szymanski WW [1985]. Electrostatic effects in aerosol sampling and filtration. Ann Occup Hyg *29*(2):251-269.

Llewellyn RL, Washburn HL, Halvorsen WJ [1981]. Coal preparation. Chapter 18. 2nd ed. In: Crickmer DF, Zegeer DA, eds. Elements of practical coal mining. Baltimore, MD: Port City Press, Inc., pp. 569-602.

[check letter for month, day, and year] Lorberau C [1990]. Memorandum to Henry S. Chan, Division of Standards Development and Technology Transfer, National Institute for Occupational Safety and Health, Centers for Disease Control, Public Health Service, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control.

Love RG [1983]. Lung function studies before and after a work shift. Br J Ind Med *40*:153-159.

Love RG, Miller BG [1982]. Longitudinal study of lung function in coalminers. Thorax *37*:193-197.

Lyons JP, Campbell H [1981]. Relation between progressive massive fibrosis, emphysema, and pulmonary dysfunction in coalworkers' pneumoconiosis. Br J Ind Med *38*:125-129.

Lyons JP, Ryder RC, Seal RME, Wagner JC [1981]. Emphysema in smoking and nonsmoking coalworkers with pneumoconiosis. Bull Eur Physiopathol Respir *17*:75-85.

Maclaren WM, Hurley JF, Collins HPR, Cowie AJ [1989]. Factors associated with the development of progressive massive fibrosis in British coalminer: a case-control study. Br J Ind Med *46*:597-607.

Maclaren WM, Soutar CA [1985]. Progressive massive fibrosis and simple pneumoconiosis in ex-miners. Br J Ind Med *42*:734-740.

Maly ER [1988]. Generation of free oxygen radicals from human polymorphonuclear granulocytes by cytokines from human mononuclear cells, treated with quartz dust DQ12 or coal mine dust TF-1—new aspects in pathogenesis of pneumoconiosis. Zbl Bakt Hyg B *187*:142-165.

Manfreda J, Johnson B, Cherniack R [1984]. Longitudinal changes in lung function: comparison of exployees of hard rock mining industry and general population. Am Rev Respir Dis *4*(4):142.

Marek K [1974]. Respiratory function impairment in coal workers' pneumoconiosis. In: Zaharski WW, ed. Coal workers' pneumoconiosis. Hanover, Germany: The University Press of New England, pp. 31-47.

Marek K, Kujawska A [1975]. Evolution of functional respiratory disorders in different types of pneumoconiosis. Bull Physiopathol Respir *11*:597-610.

Marine WM, Gurr D, Jacobsen M [1988]. Clinically important respiratory effects of dust exposure and smoking in British coal miners. Am Rev Respir Dis *137*:106-112.

Mark D [1990]. The use of dust-collecting cassettes in dust samplers. Ann Occup Hyg *34*(3):281-291.

Martin JC, Daniel-Moussard H, LeBouffant L, Policard A [1971]. The role of quartz in the development of coal workers' pneumoconiosis. Ann N Y Acad Sci *200*:127-141.

Mastin JP, Stettler LE, Shelburne JD [1988]. Quantitative analysis of particulate burden in lung tissue. Scanning Microsc *2*(3):1613-1629.

Matalo N, Melville RK, Gorishek WM, Dixon JA [1972]. High incidence of gastric carcinoma in a coal mining region. Cancer *3*(29):733-737.

Matte TD, Fine L, Meinhardt TJ, Baker EL [1990]. Guidelines for medical screening in the workplace. Occupational Medicine: State of the Art Reviews 5(3):439-456.

Mauderly JL, Cheng YS, Snipes MB [1990]. Particle Overload in Toxicological Studies: Friend or Foe? J Aerosol Med 3(Suppl 1):S169-S187.

McBride WW, Pendergrass E, Lieben J [1963]. Pneumoconiosis study of western Pennsylvania bituminous-coal miners. J Occup Med 5:376-388.

McBride WW, Pendergrass EG, Lieben J [1966]. Pneumoconiosis study of Pennsylvania anthracite miners. J Occup Med *8*:365-376.

McCawley MA [1984]. Performance considerations for size-selective samplers. In: Particle size-selective sampling in the workplace: report of the ACGIH technical committee on air sampling procedures. Ann Am Conf Ind Hyg *11*:23-100.

McCawley M, Wu Z, Peng K, Hearl F, Dosemeci M, Chen A, McLaughlin J, Blot W [1992]. Different estimations of dust exposure for mining operations. Presented at the Proceedings of the Society for Mining Engineers (SME), February 24-27, 1992, Phoenix, Arizona.

McClelland JJ, Organiscak JA, Jankowski RA, Pothini BR [1987]. Water infusion for coal mine dust control: three case studies. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, Report No. RI 9096.

McClelland JJ, Jankowski RA [1988]. Investigation of dust sources and control technology for Longwall Plow Operations. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines Information Circular, Report No. IC 9173.

McFeters JJ [1981]. Industrial hygiene study of TVA workers in coal-fired power plants. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. Report No. PB-83-139-295.

McLintock JS, Rae S, Jacobsen M [1971]. The attack rate of progressive massive fibrosis in British coalminers. In: Walton WH, ed. Inhaled particles III. Vol. II. Surrey, United Kingdom: Unwin Brothers Limited, The Gresham Press, pp. 933-950.

Mellish ML, Adler L, Stein RR, Martin TW, Snyder K, Murphy JN, Luxbacher GW, Sadik WA [1990]. Coal 1989. Mining Eng 475-482.

Meijers JMM, Swaen GMH, Slangen JJM, Vliet KV, Sturmans F [1991]. Long-term mortality in miners with coal workers' pneumoconiosis in the Netherlands: a pilot study. Am J Ind Med *19*:43-50.

Meiklejohn A [1951]. History of lung diseases of coal miners in Great Britain: Part I. 1800-1975. Br J Ind Med *8*:127-137.

Meiklejohn A [1952]. History of lung diseases of coal miners in Great Britain: Part III, 1920-1952. Br J Ind Med *9*:208-220.

Melandri C, Prodi V, Tarroni G et al. [1977]. On the deposition of unipolarly charged particles in the human respiratory tract. In: Walton WH, ed. Inhaled Particles IV. Oxford, England: Pergamon Press, pp. 193-201.

Melville AWT, Parin I, Hurley JF, Soutar CA [1979]. Pneumoconiosis, lung function and exposure to airborne dust: epidemiological research to compare responses of working coalminers with responses of ex-miners. Edinburgh, Scotland: Institute of Occupational Medicine. NTIS no. PB-84-114-081.

Mercer TT [1973]. Aerosol Technology in Hazard Evaluation. New York, NY and London, England: Academic Press.

Mercer TT [1978]. Respirable fraction of airborne dust: quantitative descriptions, formal definitions, and performance characteristics of samplers matched to them. J Test Eval *6*(1):9-19.

Merchant, JA, Taylor G, Hodous TK [1986]. Coal workers' pneumoconiosis and exposure to other carbonaceous dusts. In: JA Merchant, ed. Occupational Respiratory Diseases. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 86-102.

Mermelstein R, Dasenbrock C, Takenaka S, Mohr U, Kilpper R, MacKenzie J [1989]. Lung response to test toner upon 2-year inhalation exposure in rats. Toxicol *9*:548.

Mermelstein R, Kilpper R [1990]. Xerox exposure limit for respirable dust (N.O.S.). Paper presented at the American Industrial Hygiene Conference, Orlando, Florida, May 13-18, 1990.

Meyer MB, Luk GD, Sotelo JM, Cohen BH, Menkes HA [1980]. Hypothesis: the role of the lung in stomach carcinogenesis. Am Rev Respir Dis *121*:887-892.

Miller BG, Jacobsen M [1985]. Dust exposure, pneumoconiosis, and mortality of coalminers. Br J Ind Med *42*:723-733.

Miller BG, Jacobsen MG, Steele RC [1981]. Coalminers' mortality in relation to radiological category, lung function and exposure to airborne dust. CEC contract no. 7246.16/8/001.

Miller BG, Kinnear AG [1989]. Pneumoconiosis in coalminers and exposure to dust of variable l quartz content. Report: GRA&I, issue 14. CEC contract no. 7260-04/025/08.

Miller FJ, Martonen TB, Menache MG, Graham RC, Spektor DM, Lippmann M [1988]. Influence of breathing mode and activity level on the regional deposition of inhaled particles and implications for regulatory standards. Ann Occup Hyg *32*(1):3-10.

Miller WF, Scacci R [1981]. Pulmonary function assessment for determination of pulmonary impairment and disability evaluation. Clin Chest Med *2*(3):327-341.

MMWR [1990]. Silicosis: cluster in sandblasters—Texas, and occupational surveillance for silicosis. Mordidity and Mortality Weekly Report *39*(25):433-437.

Moorman WJ, Lewis TR, Wagner WD [1975]. Maximum expiratory flow-volume studies on monkeys exposed to bituminous coal dust. J Appl Physiol *39*:444-448.

Moorman WJ, Hornung RW, Wagner WD [1977]. Ventilatory functions in germfree and conventional rats exposed to coal. Proc Soc Exp Biol Med *155*:424-428.

Morgan A, Moores SR, Holmes A, Evans JC, Evans NH, Black A [1980]. The effect of quartz, administered by intratracheal instillation, on the rat lung—I the cellular response. Environ Res *22*:1-12.

Morgan WKC [1968]. The prevalence of coal workers pneumoconiosis. Am Rev Respir Dis *98*:306-310.

Morgan WKC [1975]. Coal workers' pneumoconiosis. In: Morgan WKD, Seaton A, eds. Occupational lung diseases. Philadelphia, PA: W.B. Saunders Co., pp. 149-215.

Morgan WKC [1976]. Respiratory problems in coal miners. JAMA *235*(13):1324-1325.

Morgan WKC [1978]. Industrial bronchitis. Br J Ind Med *35*:285.

Morgan WKC [1980]. Respiratory disability in coal miners, letter. JAMA *244*(19):2158-2159.

Morgan WKC [1983]. Coal and the lung [letter]. Thorax *38*:878.

Morgan WKC [1986]. On dust, disability, and death. Am Rev Respir Dis *134*:639-641.

Morgan WKC, Burgess DB, Jacobsen G, O'Brien RJ, Pendergrass EP, Reger RB, Shoub EP [1973]. The prevalence of coalworkers' pneumoconiosis in U.S. coal miners. Arch Environ Health *27*:221-226.

Morgan WKC, Handelsman L, Kibelstis J, Lapp NL, Reger RB [1974]. Ventilatory capacity and lung volumes of U.S. coal miners. Arch Environ Health *28*:182-189.

Morgan WKC, Lapp NL [1976]. Respiratory disease in coal miners. Am Rev Respir Dis *113*:531-559.

Morgan WKC, Lapp NL [1988]. Clinically important respiratory effects of dust exposure and smoking in British coal miners. Am Rev Respir Dis *138*:1643-1644.

Morgan WKC, Lapp NL, Seaton D [1980]. Respiratory disability in coal miners. JAMA *243*(23):2401-2404.

Morgan WKC, Seaton A, Burgess DB, Lapp NL, Reger R [1972]. Lung volumes in working coal miners. Ann N Y Acad Sci *200*:478-493.

Morris JF, Koski A, Johnson LC [1971]. Spirometric standards for healthy nonsmoking adults. Am Rev Respir Dis *103*:57-67.

Morris JF, Temple WP, Koski A [1973]. Normal values for the ratio of one-second forced expiratory volume to forced vital capacity. Am Rev Respir Dis *108*:1000-1003.

Morrow PE, Gibb FR, Gazioglu KM [1967]. A study of particulate clearance from the human lungs. Am Rev Respir Dis *96*(6):1209-1221.

Morrow PE [1977a]. In: Brain JD, Proctor DF, Reid LM, eds. Respiratory defense mechanisms. Part II. New York, NY: Marcel Dekker, pp 491-544.

Morrow PE [1977b]. Clearance kinetics of inhaled particles. In: Brain JD, Proctor D, Reid L, eds. Respiratory defense mechanisms. New York, NY: Marcel Dekker.

Morrow PE [1988]. Possible mechanisms to explain dust overloading of the lungs. Fundam Appl Toxicol *10*:369-384.

Morrow PE [1992]. Contemporary issues in toxicology—dust overloading of the lungs: update and appraisal. Toxicol Appl Pharmacol *113*:1-12.

Morrow PE, Bates DV, Fish BR, Hatch TF, Mercer TT [1966]. Task Group on Lung Dynamics, International Commission on Radiological Protection. Deposition and retention models for internal dosimetry of the human respiratory tract. Health Phy *12*:173-207.

Morrow PE, Gibb FR, Beiter H, Kilpper RW [1979]. Pulmonary retention of neutron-activated coal dust. Arch Environ Health, May/June, pp. 178-183.

Morrow PE, Muhle H, Mermelstein R [1991]. Chronic inhalation study findings as a basis for proposing a new occupational dust exposure limit. J Am Coll Toxicol *10*(2):279-290.

Morrow PE, Yuile CL [1982]. The disposition of coal dusts in the lungs and tracheobronchial lymph nodes of dogs. Fundam Appl Toxicol *2*:300-305.

Mosquera JA [1988]. Massive melanoptysis: a serious unrecognized complication of coal worker's pneumoconiosis. Eur Respir J *1*:766-768.

MSHA [1984]. MSHA's procedure for determining quartz content of respirable coal mine dust. Washington, DC: Mine Safety and Health Administration, Informational Report IR 1152.

MSHA [1988a]. Injury experience in coal mining, 1987. Washington, DC: U.S. Government Printing Office, Informational Report No. IR 1164.

MSHA [1988b]. Mine injuries and worktime, quarterly. Closeout edition 1988. Denver, CO: U.S. Department of Labor, Mine Safety and Health Administration, Division of Mining Information Systems.

MSHA [1989a]. Coal mine health inspector procedures. MSHA Handbook Series No. 89-VI. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration.

MSHA [1989b]. Coal mine safety and health, detail listing for designated and nondesignated occupations of producing longwalls.

MSHA [1989c]. Infrared determination of quartz in respirable coal mine dust. Pittsburgh, PA: Mine Safety and Health Administration.

MSHA [1991]. Injury experience in coal mining, 1990. Mine Safety and Health Administration, Information Report no. IR-1205.

MSHA [1992]. Review of the program to control respirable coal mine dust in the United States. U.S. Department of Labor, Mine Safety and Health Administration, 60 pp.

Muhle H, Bellman B, Heinrich U [1988]. Overloading of lung clearance during chronic exposure of experimental animals to particles. Inhaled particles VI. Ann Occup Hyg *32*(Suppl 1):141-147.

Muhle H, Creutzenberg, Bellman B, Heinrich U, Mermelstein R [1990a]. Dust overloading of lungs: investigations of various materials, species differences, and irreversibility of effects. J Aerosol Med *3*(Suppl 1): S111-S128.

Muhle H et al. [1990b]. Subchronic inhalation study of toner in rats. Inhalation Toxicol *2*:341-360.

Muhle H, Bellmann B, Creutzenberg O, Dasenbrock C, Ernst H, Kilpper R et al. [1991]. Pulmonary response to toner upon chronic inhalation exposure in rats. Fundam Appl Toxicol *17*:280-299.

Muir D [1975]. Pulmonary function in miners working in British collieries: epidemiological investigations by the national coal board. Bull Physiopath Respir *11*:403-414.

Muir DCF, Burns J, Jacobsen M, Walton WH [1977]. Pneumoconiosis and chronic bronchitis. Br Med J *2*:424-427.

Mundell R Lindsay et al. [1984]. Respirable dust control on longwall mining operations in the United States. U.S. Department of Labor, Mine Safety and Health Administration, Report no. IR 1151

Musk AW, Bevan C, Campbell MJ, Cotes JE [1979]. Factors contributing to the clinical grade of breathlessness in coalworkers with pneumoconiosis. Bull Europ Physiopath Respir *15*:343-353.

Musk AW, Cotes JE, Bevan C, Campbell MJ [1981]. Relationship between type of simple coalworkers' pneumoconiosis and lung function—a nine-year follow-up study of subjects with small rounded opacities. Br J Ind Med *38*:313-320.

Mutmansky JM, Lee C [1984]. An analysis of coal and geologic variables related to coalworkers' pneumoconiosis. In: Proceedings of the Lakeview Conference, Center for Generic Respirable Disease Studies, October 8, 1984, Lakeview, West Virginia.

Mutmansky JM, Lee C [1987]. Statistical analysis of the size and elemental composition of airborne coal mine dust. Washington DC: Bureau of Mines, Interim Report.

Naeye RL, Mahon JK, Dellinger WS [1971]. Rank of coal and coal workers pneumoconiosis. Am Rev Respir Dis *103*:350-355.

Nagelschmidt G [1965]. The study of lung dust in pneumoconiosis. Am Ind Hyg Assoc J *26*:1.

Nathan CF [1987]. Secretory products of macrophages. J Clin Invest *79*:319-326.

Nathan SP, Lebowitz MD, Knudson RJ [1979]. Spirometric testing. Chest 76:384-388.

NCA [1989a]. Coal in the news; NCA: U.S. coal production to top 1 billion tons by 2000. J National Coal Assn, May 1989.

NCA [1989b]. Steady growth forecast for U.S. coal production. Chem Engineering Progress, June, pp. 10-11.

Nemery B, Veriter C, Brasser L, Frans A [1987]. Impairment of ventilatory function and pulmonary gas exchange in non-smoking coalminers. Lancet 1427-1429.

Nicas M, Simmons BP, Spear RC [1991]. Environmental versus analytical variability in exposure measurements. Am Ind Hyg Assoc J *52*(12):533-557.

Niewiadomski G, Tomb T, Parobeck P [1990]. Monitoring and controlling quartz dust exposure in U.S. coal mines: current MSHA program and experience. In: Proceedings of the VIIth International Pneumoconioses Conference, Part I, Pittsburgh, Pennsylvania. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

NIOSH [1972]. NIOSH medical survey of surface coal mine workers at eight surface coal mines in six states of the U.S. in 1972 and 1973. Morgantown, WV: U.S. Department of Heatlth, Education, and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. [Unpublished data set].

NIOSH [1974]. Criteria for a recommended standard: occupational exposure to crystalline silica. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. DHEW (NIOSH) Publication No. 75-120.

NIOSH [1981]. Health hazard evaluation report: Colorado Springs Public Utilities, Colorado Springs, CO. Cincinnati, OH: U.S. Department of Health and Human Services, Center for Disease Control, Public Health Service, National Institute for Occupational Safety and Health, NIOSH Report No. HETA-81-034,035-934, NTIS Report No. PB-83-126-383.

NIOSH [1984]. NIOSH manual of analytical methods. 3rd rev. ed. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 84-100, NTIS No. PB-85-179-018/A22.

NIOSH [1987a]. NIOSH guide to industrial respiratory protection. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) publication No. 87-116.

NIOSH [1987b]. NIOSH respirator decision logic. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 87-108.

NIOSH [1988a]. NIOSH comments on the Mine Safety and Health Administration proposed rule on safety standards for underground coal mine ventilation: 30 CFR Part 75, April 28, 1988. NIOSH policy statements. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1988b]. NIOSH comments on the Occupational Safety and Health Administration's advance notice of proposed rulemaking on generic standard for exposure monitoring: 29 CFR Part 1910, December 20, 1988. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1988c]. NIOSH comments on the Occupational Safety and Health Administration notice, proposed rules, Coal Dust, Federal Register, Vol. 53, No. 109, June 7, 1988. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1988d]. NIOSH testimony on the Occupational Safety and Health Administration's proposed rule on air contaminants, August 1, 1988. NIOSH policy statements. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1988e]. Trends in coal mine dust exposures for longwall miners: 1981-1987. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1989]. NIOSH comments on the Mine Safety and Health Administration report, "Belt Entry Ventilation Review: Report of Findings and Recommendations," 30 CFR Part 75, November 22, 1989. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1990a]. NIOSH comments on the Mine Safety and Health Administration's proposed rule on air quality, chemical substances, and respiratory protection standards. 30 CFR parts 56, 57, 58, 70, 71, 72, 75, and 90. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH [1990b]. NIOSH testimony for occupational safety and health on the Mine Safety and Health Administration report, "Belt Entry Ventilation Review," 30 CFR part 75. Presented at the MSHA Public Hearing, April 18, 1990. Reston, Virginia.

NIOSH [1991]. Current Intelligence Bulletin 54: environmental tobacco smoke in the workplace, lung cancer and other health effects. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 91-108.

Oberdorster G, Green FHY, Freedman AP [1984]. Clearance of exp 59 $Fe_3O_4$ particles from the lung of rats during exposure to coal mine dust and diesel exhaust. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, NTIS no. DE-84-000-887.

Oberdorster G, Morrow PE, Spurny K [1988a]. Size dependent lymphatic short term clearance of amosite fibres in the lung. Ann Occup Hyg *32*(1):149-156.

Oberdorster G, Ferin J, Morse P, Corson NM, Morrow PE [1988b]. Volumetric alveolar macrophage (AM) burden as a mechanism of impaired AM mediated particle clearance during chronic dust overloading of the lung. J Aerosol Med *1*:A207.

Oboler SK, LaForce MF [1989]. The periodic physical examination in asymptomatic adults. Ann Intern Med *110*:214-226.

Ogden TL [1988]. The ISO and ACGIH standardized size fractions and their relation to human deposition data. Ann Occup Hyg *32*(1)413-421.

Oldham PD, Cole TJ [1983]. Estimation of the FEV. Thorax *38*:662-667.

Olofson J, Skoogh BE, Bake B, Svardsudd K [1987]. Mortality related to smoking habits, respiratory symptoms, and lung function. Eur J Respir Dis *71*:69-76.

Olson RC, Roepke WW [1984]. Respirable dust sources of longwall mining examined. Mining Eng, August, pp. 1158-1163.

Ondrey R, Stoltz R, Atchison D, Gerbec E [1988]. Dust sampling roof bolting operations. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: health effects, characterization and control. University Park, PA: The Pennsylvania State University, pp. 264-268.

Orenstein AJ, ed. [1960]. Proceedings of the Pneumoconiosis Conference held at the University of Witwatersrand, Johannesburg. February 9-24, 1959. Boston, MA: Little Brown, p. 619.

Organiscak JA, Listak JM, Janowski RA [1985]. Factors affecting respirable dust generation from longwall roof supports. U.S. Department of the Interior, Bureau of Mines. Information Circular 9019, NTIS No. PB85-236453.

Organiscak JA, Jankowski RA, Kelly JS [1987]. Dust controls to improve quality of longwall intake air. Government Reports Announcements and Index (GRA&I) Issue 14. NTIS No. PB-87-167-573.

Organiscak JA, Doyle-Coombs DM, Cecala AB [1988]. Effect of shearer web depth on dust generation and methane liberation. U.S. Department of the Interior, Bureau of Mines Report of Investigations, Report RI 9180.

Orie NGM, Sluiter HJ, De Vries K, Tammeling GJ, Witkop J [1961]. The host factor in bronchitis. In: Orie NGM, Sluiter HJ, eds. Bronchitis. Royal Vangorcum, Assen, pp. 43-59.

Ortmeyer CE [1974]. The mortality of Appalachian coal miners, 1963 to 1971. Arch Environ Health *29*(2):67-72.

Ostiguy GL [1979]. Summary of task force report on occupational respiratory disease (pneumoconiosis). Can Med Assoc J *121*:414-421.

Parkes RW [1982]. Pneumoconiosis due to coal and carbon. 2nd ed. In: Occupational lung disorders. London, England: Butterworths, pp. 175-232.

Parkes WR, Williamson RGB [1976]. Coronary artery disease and coalworkers' pneumoconiosis. Br Med J, November 27, pp. 1319-1320.

Parobeck PS [1975]. Effect of the 2.0 mg/m$^3$ coal mine dust standard on underground environmental dust levels. Am Ind Hyg Assoc J, August, pp. 604-609.

Parobeck PS, Tomb TF [1974]. Respirable dust levels—surface work areas of underground coal mines and surface coal mines. Work Environ Health *11*:43-48.

Parobeck PS, Jankowski RA [1979]. Assessment of the respirable dust levels in the nation's underground and surface coal mining operations. Am Ind Hyg Assoc J *40*:910-915.

Pern PO, Love RG, Wightman AJA, Soutar CA [1984]. Characteristics of coalminers who have suffered excessive loss of lung function over 10 years. Bull Eur Physiopathol Respir *29*:487-493.

Petersen MR, Lapp NL, Amandus HE [1975]. The relationship of several ventilatory capacities and lung volumes to age, height, and weight. J Occup Med *17*(6):355-356.

Petersen M, Castellan RM [1984]. Prevalence of chest symptoms in nonexposed blue-collar workers. J Occup Med *26*(5):367-374.

Petersen M, Hankinson J [1985]. Spirometry reference values for nonexposed blue-collar workers. J Occup Med *27*(9):644-650.

Petersen MR, Hodous TK [1988]. Lung volume reference values for blue collar workers not exposed to occupational respiratory hazards. J Occup Med *30*(8):626-632.

Peto R, Speizer FE, Cochrane AL, Moore F, Fletcher CM, Tinker CM [1983]. The relevance in adults of air-flow obstruction, but not of mucus hypersecretion, to mortality from chronic lung disease. Am Rev Respir Dis *128*:491-500.

Pezerat H, Buignard J, Cherrie JW [1992]. Man-made mineral fibers and lung cancer: an hypothesis. Toxicol Ind Health *8*(1/2):77-87.

Phalen RF, Hinds WC, John W, Lioy PJ, Lippmann M, McCawley MA, et al. [1986]. Rationale and recommendations for particle size-selective sampling in the workplace. Appl Ind Hyg *1*:3-14.

Phalen RF, Hinds WC, John W, Lioy PJ, Lippmann M, McCawley MA [1988a]. Particle size-selective sampling in the workplace: rationale and recommended techniques. Ann Occup Hyg *32*(Suppl 1):403-411.

Phalen RF, Stuart BO, Lioy PJ [1988b]. Rationale for and implications of particle size-selective sampling. In: Advances in air sampling. Chelsea, MI: Lewis Publishers, pp. 3-15.

PHS [1985]. The health consequences of smoking. Cancer and chronic lung disease in the workplace. A report of the Surgeon General. Rockville, MD: U.S. Department of Health and Human Services, Public Health Service, Office on Smoking and Health, DHHS (PHS) Publication No. 85-50207.

Piacitelli GM, Amandus HE, Dieffenbach A [1990]. Respirable dust exposures in U.S. surface coal mines (1982-1986). Arch Environ Health *45*(4):202-209.

Potts JD, McCawley MA, Jankowski RA [1990]. Thoracic dust exposures on longwall and continuous mining sections. Appl Occup Environ Hyg *5*(7):440-447.

Pratt PC [1968]. Role of silica in progressive massive fibrosis. Arch Environ Health *16*:734-737.

Pride NB [1986]. Smoking, allergy and airways obstruction: revival of the "Dutch Hypothesis". Clin Allergy *16*:3-6.

Prinz B, Stolz R [1990]. Effect of the measuring strategy on the determination of respirable dust concentration in the breathable air at underground workplaces. In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Service, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Pritchard JN [1989]. Dust overloading—a case for lowering the TLV of nuisance dusts? J Aerosol Sci *20*(8):1341-1344.

Puskar MA, Harkins JM, Moomey JD, Hecker LH [1991]. Internal wall losses of pharmaceutical dusts during closed-face 37 mm polystyrene cassette sampling. Am Ind Hyg Assoc J *52*:280-286.

Quanjer PH ed. [ ]. Standardization of lung function testing. Bull Eur Physiopatol Respir 19(Suppl 5):1S-9S.

Raabe OG [1984]. Size-selective sampling criteria for thoracic and respirable mass fractions. In: Particle size-selective sampling in the workplace: report of the ACGIH Technical Committee on Air Sampling Procedures. Ann Am Conf Ind Hyg *11*:23-100.

Rae S, Walker DD, Attfield M [1971]. Chronic bronchitis and dust exposure in British coal miners. In: Walton WH, ed. Inhaled particles III. Old Working, Surrey: Unwin Brothers, pp. 883-894.

Rappaport SM [1984]. The rules of the game: an analysis of OSHA's enforcement strategy. Am J Ind Med *6*:291-303.

Rappaport SM [1985]. Smoothing of exposure variability at the receptor: implications for health standards. Ann Occup Hyg *29*(2):201-214.

Rappaport SM [1991a]. Assessment of long-term exposures to toxic substances in air: review. Ann Occup Hyg *35*(1):61-121.

Rappaport SM [1991b]. Exposure assessment strategies. In: Rappaport SM, Smith TJ, eds. Exposure assessment for epidemiology and hazard control. Chelsea, MI: Lewis Publishers, Inc., pp. 219-249.

Rappaport SM [1991c]. Selection of the measures of exposure for epidemiology studies. Appl Occup Environ Hyg *6*(6):448-457.

Rappaport SM, Spear RC, Selvin S [1985]. The influence of exposure variability on dose-response relationships. In: Proceedings of the Sixth International Symposium on Inhaled Particles, Cambridge, British Occupational Hygiene Society. Oxford, England: Pergamon Press.

Rappaport SM, Spear RC, Selvin S [1988]. The influence of exposure variability on dose-response relationships. Ann Occup Hyg *32*(Suppl 1):529-537.

Reichel G, Ulmer WT [1978]. Results obtained by the various investigation centres: coalmine; active staff. In: Research report: chronic bronchitis and occupational dust exposure. Deutsche Forschungmeinschaft. Boppard: Harald Boldt Verlag, pp. 237-247.

Reisner KM, Last JA [1986]. Early cellular events in pulmonary fibrosis. Exp Lung Res *10*:331-355.

Reisner MTR [1971]. Results of epidemiological studies of pneumoconiosis in West German coal mines. In: Walton WH, ed. Inhaled particles III. Vol. 2. London, England: Unwin Brothers Limited, pp. 921-929.

Reisner MTR [1975]. Cumulative dust exposures and pneumoconiosis responses in German coal mines. Paper presented at the International Conference on Pneumoconiosis, Johannesburg, South Africa, 1969.

Reisner MTR, Bruch J, Kriegseis W, Prajsnar D, Robock K, Rosmanith J, Scharmann A, Schlipkoter HW, Strubel G, Weller W [1982]. Specific harmfulness of respirable dusts from West German coal mines, VI: comparison of experimental and epidemiological results. Ann Occup Hyg *26*(1-4):527-539.

Reisner MTR, Kuhn L, Kriegseis KW, Scharmann A, Strubel G, Rinn G [1988]. Effects of particle size of coalmine dusts in experimental anthraco-silicosis: I. influence of size of mineral composition and surface properties of dists from same origin. Ann Occup Hyg *32*(1):585-592.

Reisner MTR, Robock K [1977]. Results of epidemiological, mineralogical, and cytological studies on the pathogenicity of coalmine dusts. In: Walton WH, ed. Inhaled Particles IV. Oxford, England: Pergamon Press, pp. 703-715.

Reno SJ, Ashe HB, Levadie BTH [1966]. A comparison of count and respirable mass dust sampling techniques in the granite industry. Paper presented at the American Industrial Hygiene Conference, Pittsburgh, Pennsylvania.

Reynolds HY [1988]. Bronchoalveolar lavage. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 597-610.

Rice WS [1987]. Face automation impact on the work force. Paper presented at the Coal Convention '87, sponsored by the American Mining Congress, Cincinnati, OH, May 3-6, 1987.

Richards RJ, Curtis CG [1984]. Biochemical and cellular mechanisms of dust-induced lung fibrosis. Environ Health Perspect *55*:393-416.

Robertson A, Bolton RE, Chapman JS, Davis JMG, Dodgson J, Gormley IP, Jones AD, Miller BG [1984]. Animal inhalation experiments to investigate the significance of high and low percentage concentrations of quartz in coalmine dusts in relation to epidemiology and other biological tests. Edinburgh: Institute of Occupational Medicine, IOM Report TM/84/5.

Robertson A, Hurley JF, Brown PW, Collins HPR, Dodgson J, Maclaren WM [1987]. A case-control study of the reasons for unusual radiological changes of pneumoconiosis among individual mine workers. Edinburgh: Institute of Occupational Medicine, Report no. TM/87/11.

Robins TG [1991]. Coal dust particle size and respiratory disease. In: NIOSH Grants Research and Demonstration Projects: Annual Report Fiscal Year 1991. Cincinnati, OH: U.S. Department for Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 92-109.

Robinson James, Paxman Dalton G, Rappaport Stephen M [1991]. Implications of OSHA's reliance on TLVs in developing the air contaminants standard. Am J Ind Med *19*:3-13.

Robock K, Reisner MTR [1982]. Specific harmfulness of respirable dusts from West German coal mines—I. results of cell tests. Ann Occup Hyg *26*(1-4):473-479.

Robock K, Bauer HD [1990]. Investigations into the specific fibrogenicity of mine dusts in hardcoal mines of countries in the European community. Part I. In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, Ohio: U.S. Department of Health and Human Service, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Rockette HE [1977a]. Cause-specific mortality of coal miners. J Occup Med *19*:795-801.

Rockette HE [1977b]. Mortality among coal miners covered by the UMWA health and retirement funds. Unpublished paper. Morgantown, WV: U.S. Department of Health, Education, and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Respiratory Disease Studies.

Roepke W [1989]. Linear cutting concept improves health and safety for miners. Paper presented at the 40th Annual Earthmoving Industry Conference, Peoria, Illinois, April 11-13, 1989. SAE Technical Papers Series. Warrendale, PA: Society for Automotive Engineers, Inc., Report No. 890978.

Rogan JM, Attfield MD et al. [1973]. Role of dust in the working environment in development of chronic bronchitis in British coal miners. Br J Ind Med *30*:217-226.

Rom WN [1991]. Relationship of inflammatory cell cytokines to disease severity in individuals with occupational inorganic dust exposure. Am J Ind Med *19*:15-27.

Rom WN, Kanner RE, Renzetti AD, Shigeoka JW, Barkman HW, Nichols M et al. [1981]. Respiratory disease in Utah coal miners. Am Rev Respir Dis *123*:372-377.

Rosbury KD, Zimmer RA [1983]. Cost-effectiveness of dust suppressants on surface coal mine haul roads. Paper presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia.

Rosmanith J, Weller W, Reisner MTR, Kuhn L, Strubel G [1988]. Effects of particle size of coalmine dusts in experimental anthraco-silicosis: II. retention and penetration of the dust. Ann Occup Hyg *32*(1):593-601.

Roy TM, Collins LC, Snider HL, Anderson WH [1989]. Cigarette smoking and federal black lung benefits in bituminous coal miners. J Occup Med *31*(2):98-101.

Roy TM, Walker JF, Snider HL, Anderson WH [1989]. Resting gas exchange in nonsmoking bituminous coal miners with simple pneumoconiosis. Respiration *55*:28-32.

Ruckley VA, Fernie JM, Chapman JS, Collings P, Davis JMG, Douglas AN, Lamb D, Seaton A [1984a]. Comparison of radiographic appearances with associated pathology and lung dust content in a group of coalworkers. Br J Ind Med *41*:459-467.

Ruckley VA, Gauld SJ, Chapman JS, Davis JMG, Douglas AN, Fernie JM, et al. [1984b]. Emphysema and dust exposure in a group of coal workers. Am Rev Respir Dis *129*:528-532.

Ryder R, Lyons JP, Campbell H, Gough J [1970]. Emphysema in coalworkers' pneumoconiosis. Br Med J *3*:481-487.

Ryder RC, Dunnil MS, Anderson JA [1971]. A quantitative study of bronchial mucous gland volume, emphysema, and smoking in a necropsy population. J Pathol *104*:59-71.

Samet JM [1978]. A historical and epidemiologic perspective on respiratory symptoms questionnaire. Am J Epidemiol *108*:435-446.

Samet JM [1986]. Definitions and methodology in COPD research. In: Hensley M, Saunders N, ed. Clinical Epidemiology of Chronic Obstructive Lung Disease. New York, NY: Mercel Decker, Inc., pp. 1-22.

Scarano D, Fadali MA, Lemole GM [1972]. Carcinoma of the lung and anthracosilicosis. Chest *62*:251-254.

Schlick DL, Fannick NL [1971]. Coal in the United States. In: Key MM, Kerr LE, Bundy M, eds. Pulmonary reactions to coal dust. New York, NY: Academic Press.

Schraufnagel DE, Claypool WC, Fahey PJ, Jacobs ER, Rubin DB, Snider GL [1987]. Interstitial pulmonary fibrosis. Am Rev Respir Dis *136*:1281-1284.

Schreider JP, Culbertson MR, Raabe OG [1985]. Comparative pulmonary fibrogenic potential of selected particles. Environ Res *38*:256-274.

Schulte PA [1991]. Contribution of biological markers to occupational health. Am J Ind Med *20*:435-446.

Schwartz J [1989]. Lung function and chronic exposure to air pollution: a cross-sectional analysis of NHANES II. Environ Res *50*:309-321.

Schoenberg Janet B, Beck Gerald J, Bouhuys Arend [1978]. Growth and decay of pulmonary function in healthy blacks and whites. Respir Physiol *33*:367-393.

Seaton A [1983]. Coal and the lung. Thorax *38*:241-243.

Seaton A [1991]. Cigarette smoking and small irregular opacities. Br J Ind Med *49*(6):453-454.

Seaton A, Lapp NL, Morgan WK [1972]. Relationship of pulmonary impairment in simple coal workers' pneumoconiosis to type of radiographic opacity. Br J Ind Med *29*:50-55.

Seaton A, Dick JA, Dodgson J, Jacobsen M [1981]. Quartz and pneumoconiosis in coalminers. Lancet *5*:1272-1275.

Seixas N, Robins TG, Moulton LH [1988]. The use of geometric and arithmetic mean exposures in occupational epidemiology. Am J Ind Med *14*:465-477.

Seixas NS, Robins TG, Rice CH, Moulton LH [1990]. Assessment of potential biases in the application of MSHA respirable coal mine dust data to an epidemiologic study. Am Ind Hyg Assoc J *51*(10):534-540.

Seixas NS, Robins TG, Moulton LH, Rice CH, Attfield MD, Zellers ET [1991]. Estimation of cumulative exposures for the national study of coal workers' pneumoconiosis. Appl Occup Environ Hyg *6*(12):1032-1041.

Seixas NS, Robins TG, Attfield MD, Moulton LH [1992]. Exposure-response relationships for coal mine dust and obstructive lung disease following enactment of the Federal Coal Mine Health and Safety Act of 1969. Am J Ind Med *21*:715-734.

Seixas NS, Robins TG, Becker M [1993]. A novel approach to the characterization of cumulative exposure for the study of chronic occupational disease. Am J Epi *137*(4):463-471.

Selikoff I, Key MM, Lee DHK [1972]. Coal workers' pneumoconiosis. Ann N Y Acad Sci *200*.

Selvin S, Rappaport SM [1989]. A note on the estimation of the mean value from a lognormal distribution. Am Ind Hyg Assoc J *50*:627-630.

Shennan DH, Washington JS, Thomas DJ, Dick JA, Kaplan YS, Bennett JG [1981]. Factors predisposing to the development of progressive massive fibrosis in coal miners. Br J Ind Med *38*:321-326.

Shigenaga MK, Gimeno CJ, Ames BN [1989]. Urinary 8-hydroxy-2'-deoxyguanosine as a biological marker of *in vivo* oxidative damage. Proc Natl Acad Sci *86*:9697-9701.

Shulman SA, Groff JH, Abell MT [1992]. Performance of laboratories measuring silica in the proficiency analytical testing program. Am Ind Hyg Assoc J *53*(1):49-56.

Silicosis and Silicate Disease Committee [1988]. Diseases associated with exposure to silica and nonfibrous silicate minerals. Arch Pathol Lab Med *112*:673-720.

Silver K, Hattis D, Attfield MD [1991]. Methodology for quantitative assessment of risks from chronic respiratory damage: lung function decline and associated mortality from coal dust. NTIS No. PB92-115658/XAB.

Skelly R, Loy L [1979]. Illustrated surface mining methods. New York, NY: McGraw-Hill, Inc., pp. 1-87.

Skillrud DM, Offord DP, Miller RD [1986]. Higher risk of lung cancer in chronic obstructive pulmonary disease. Ann Intern Med *105*:503-507.

Smith TJ [1985]. Development and application of a model for estimating alveolar and interstitial dust levels. Ann Occup Hyg *29*:495-516.

Smith TJ [1990]. Occupational exposure and dose over time: limitations of cumulative exposure. Presented at the 1st Seminar on Occupational Exposure Assessment: On the Concepts of Exposure and Dose. Linkoping, Sweden.

Snider GL [1988]. Chronic bronchitis and emphysema. In: Murray JF, Nadel JA, eds. Respiratory medicine. Philadelphia, PA: W.B. Saunders Company, pp. 1069-1106.

Soderholm SC [1986]. Rationale of ACGIH recommendations for size-selective sampling. Ann Occup Hyg *30*(4):518-520.

Soderholm SC [1989]. Proposed international conventions for particle size-selective sampling. Ann Occup Hyg *33*(3):301-320.

Soderholm SC [1991a]. Why change ACGIH's definition of respirable dust? Appl Occup Environ Hyg *6*(4):248-250.

Soderholm SC [1991b]. Correction. Ann Occup Hyg *35*(3):357-358.

Soderholm SC, McCawley MA [1990]. Should dust samplers mimic human lung deposition? Appl Occup Environ Hyg *5*(12):829-835.

Solu S [1972]. Disability of coal mine workers. Chest *61*(3):306-307.

Sorensen JB, Morris AH, Crapo RO, Gardner RM [1980]. Selection of the best spirometric values for interpretation. Am Rev Respir Dis *122*:802-805.

Soutar CA [1987a]. Occupational bronchitis. In: Harrington M, ed. Recent advances in occupational health. Volume 3. London: Churchill Livingstone.

Soutar CA [1987b]. Update on lung disease in coalminers. Br J Ind Med *44*:145-148.

Soutar CA, Coutts I, Parkes WR, Dodi IA, Gauld S, Castro JE, Turner-Warwick M [1983]. Histocompatibility antigens in coal miners with pneumoconiosis. Br J Ind Med *40*:34-38.

Soutar CA, Hurley JF [1986]. Relationship between dust exposure and lung function in miners and ex-miners. Br J Ind Med *43*:307-320.

Soutar CA, Maclaren WM, Annis R, Melville AWT [1986]. Quantitative relations between exposure to respirable coalmine dust and coalworkers' simple pneumoconiosis in men who have worked as miners but have left the coal industry. Br J Ind Med *43*:29-36.

Soutar CA, Campbell SJ, Gurr DC, et al. [1988]. Cross-sectional studies of respiratory disease in British coalminers. Final Report. Edinburgh, Scotland: Institute of Occupational Medicine. Report No. TM/88/06.

Spear RC [1991]. Individual versus group differences in exposure and risk. In: Rappaport SM, Smith TJ, eds. Exposure assessment for epidemiology and hazard control. Chelsea, Michigan: Lewis Publishers, Inc., pp. 283-295.

SSA [1986]. Social Security Administration disability evaluation under Social Security. Washington, DC: U.S. Department of Health and Human Services, Social Security Administration. SSA Publication No. 05-10089.

SSA [1989]. Social Security Administration bulletin—annual statistical supplement, 1989. Washington, DC: U.S. Department of Health and Human Services, Social Security Administration, ISSN0037-7910.

Stahlhofen W, Gebhart J, Hayder J, Philipson K, Camner P [1981]. Intercomparison of regional deposition of aerosol particles in the human respiratory tract and their long-term elimination. Exp Lung Res *2*:131-139.

Stahlhofen W, Rudolf G, James AC [1989]. Intercomparison of experimental regional aerosol deposition data. J Aerosol Med *2(3)*:285-308.

Stefanko R [1983]. Coal mining technology, theory and practice. Kingsport, Tennessee: Kingsport Press, pp. 40-44, 285-338.

Stein RR, Martin TW [1989]. Coal mining equipment. Mining Engineering, May, p. 338.

Stettler LE, Tucker JH, Riley RD, Platek SF, Mastin JP, Green FHY, Zuchelkowski E [1988]. Silica lung particle size determination in coal miner lungs. Cincinnati, OH: U.S. Department for Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, NTIS no. PB89-142988, pp. 19-47.

Stobbe TJ, Plummer RW, Kim H, Dower JM [1986]. Characterization of coal mine dust. Ann Am Conf Gov Ind Hyg *14*:689-696.

Stobbe TJ, Hyunwook K, Plummer RW [1990]. Mineral content variability of coal mine dust by coal seam sampling location and particle size. Part I. In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Stober W, Morrow PE, Hoover MD [1989]. Compartmental modeling of the long-term retention of insoluble particles deposited in the alveolar region of the lung. Fund Appl Toxicol *13*:823-842.

Strachan DP [1992]. Ventilatory function, height, and mortality among lifelong non-smokers. J Epidemiol Comm Health *46*:66-70.

Stuart BO, Lioy PJ, Phalen RF [1984]. Use of size-selection in establishing TLVs. In: Particle size-selective sampling in the workplace: report of the ACGIH Technical Committee on Air Sampling Procedures. Ann Am Conf Ind Hyg *11*:85-96.

Stuart BO, Lioy PJ, Phalen RF [1986]. Particle size-selective sampling in establishing threshold limit values. Appl Ind Hyg *1*:138-144.

Suratt PM, Winn WC, Brody AR, Bolton WK, Gile RD [1977]. Acute silicosis in tombstone blasters. Am Rev Respir Dis *115*:521-529.

Susskind H, Acevedo JC, Iwai J, Rasmussen DL, Heydinger DK, Pate HR et al. [1988a]. Heterogeneous ventilation and perfusion: a sensitive indicator of lung impairment in nonsmoking coal miners. Eur Respir J *1*:232-241.

Susskind H, Brill AB, Harold WH [1988b]. Clearance of TC-99M DTPA aerosol from coal miners' lungs. Ann Occup Hyg *32* (Suppl 1):157-169.

Takemura T, Rom WN, Ferrans VJ, Crystal RG [1989]. Morphologic characterization of alveolar macrophages from subjects with occupational exposure to inorganic particles. Am Rev Respir Dis *140*:1674-1685.

Task Group on Lung Dynamics [1965]. Deposition and retention models for internal dosimetry of the human respiratory tract. Health Phys *12*:173-207.

Taylor Charles D, Jankowski Robert A [1982]. How the six cleanest U.S. longwalls stay in compliance. Proceedings of the 1st Mine Ventilation Symposium, The University of Alabama, University (Tuscaloosa), Alabama, March 29-31, pp. 67-69.

Theriault Gilles, Peters John M, Johnson William M [1974]. Pulmonary function and roentgenographic changes in granite dust exposure. Arch Environ Health *28*:23-27.

Thurlbeck WM [1976]. Chronic airfow obstruction in lung disease. Vol. 5. In: Bennington JL, ed. Major problems in pathology. Philadelphia, PA: W.B. Saunders Co.

Tockman MS, Anthonisen NR, Wright EC, Donithan MG [1987]. Airways obstruction and the risk for lung cancer. Ann Intern Med *106*:512-518.

Tokuhata GK, Dessduer P, Pendergrass EP, Hartman T, Digon E, Miller W [1970]. Pneumoconiosis among anthracite coal miners in Pennsylvania. Am J Pub Health *60*:441-451.

Tomb TF [1990]. Measurement strategies in U.S. underground coal mines. In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, Ohio: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Tomb TF, Treaftis HN, Mundell RL, Parobeck PS [1973]. Comparison of respirable dust concentrations measured with MRE and modified personal gravimetric sampling equipment. Washington, DC: Bureau of Mines, Report of Investigations 7772.

Tomb TF, Ondrey RS [1976]. Determining the feasibility of area sampling to enforce the respirable dust standard in underground coal mines. Pittsburgh, PA: Pittsburgh Technical Support Center, Mining Enforcement and Safety Administration, Informational Report 1037.

Tomb TF, Treaftis HN, Gero AJ [1983]. Characteristics of underground coal mine dust aerosols. Aerosols Mining Ind Work Environ 2(1):395-405.

Tomb TF, Parobeck PS, Gero AJ [1986a]. MSHA's revised quartz enforcement program. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: health effects, characterization and control, pp. 9-14.

Tomb TF, Peluso RG, Parobeck PS [1986b]. Quartz in United States coal mines. Ann Am Conf Gov Ind Hyg *14*:513-519.

Tomb TF, Ondrey RS, Stoltz RT, Haney RA, Chiz Novakowski DL, Atchison DJ, Gerbec EJ [1990]. Evaluation of respirable dust control on longwall mining operations. Paper presented at the SME Annual Meeting, Salt Lake City, Utah, February 26-March 1. Society for Mining, Metallurgy, and Exploration, Inc.

Treaftis HN, Parobeck PS [1984]. Quality assurance program for field health laboratories. U.S. Department of Labor, Mine Safety and Health Administration. Report no. IR 1149.

Trotter JA [1981]. The organization of actin in spreading macrophages.

Turner, Scott, Cohen BS [1984]. Effects of electrostatic charge on aerosol collection with polystyrene filter cassettes. Am Ind Hyg Assoc J *45*:745-748.

Tweeddale PM, Alexander F, McHardy GJR [1987]. Short term variability in $FEV_1$ and bronchodilator responsiveness in patients with obstructive ventilatory defects. Thorax *42*:487-490.

Ulfvarson U [1983]. Limitations to the use of employee exposure data on air contaminants in epidemiologic studies. Int Arch Occup Environ Health *52*:285-300.

Ullah MI, Cuddihy U, Saunders KB, Addis GJ [1983]. How many blows really make an FEV1, FVC, or PEFR? Thorax *38*:113-118.

Ulmer WT [1975]. Chronic obstructive airway disease in pneumoconiosis in comparison to chronic obstructive airway disease in non-dust exposed workers. Bull Physiopathol Respir *11*:415-427.

Valiante DJ, Rosenman [1989]. Does silicosis still occur? J Am Med Assoc *262*:3003-3007.

Vallyathan V, Green FHY, Rodman NF, Boyd CB, Althouse R [1985]. Lung carcinoma by histologic type in coal miners. Arch Pathol Lab Med *109*:419-423.

Vallyathan V, Althouse R, Green FHY [1990]. Coal workers' pneumoconiosis lesions and their correlation to dust load. In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, Ohio: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Vallyathan V, Schwegler D, Reasor M, Stettler L, Clere J, Green FHY [1988a]. Comparative in vitro cytotoxicity and relative pathogenicity of mineral dusts. Ann Occup Hyg *32*(1):279-289.

Vallyathan V, Shi Xianglin, Dalal NS, Irr W, Castranova V [1988b]. Generation of free radicals from freshly fractured silica dust. Am Rev Respir Dis *138*:1213-1219.

Villnave JM, Corn M, Francis M, Hall TA [1991]. Regulatory implications of airborne respirable free silica variability in underground coal mines. Am Ind Hyg Assoc J *52*(3):107-112.

Vincent JH, Johnston AM, Jones AD, Bolton RE, Addison J, Beckett ST [1985]. Kinetics of deposition and clearance of inhaled mineral dusts during chronic exposure. Br J Ind Med *42*:707-715.

Vincent JH, Mark D [1988]. On the biologically-relevant sampling of airborne particles. Ann Occup Hyg *32*(1):423-434.

Volkwein JC, Covelli A, Thimons ED [1979]. Dust protection afforded by enclosed cabs on surface and underground mine machinery. Bureau of Mines Metal and Nonmetal Health and Safety Program, Technical Progress Report 109.

Vollmer WM [1988]. Longitudinal versus cross-sectional estimation of lung function decline—further insights. Stat Med *7*:685-696.

Vostal JJ [1986]. Factors limiting the evidence for chemical carcinogenicity of diesel emissions in long-term inhalation experiments. In: Ishinishi N, Koizumi A, McClellan RO, Stober W, eds. Carcinogenic and mutagenic effects of diesel engine exhaust. Amsterdam: Elsevier Science.

Wagner GR, Spieler EA [1990]. Is the U.S. coal miner chest x-ray surveillance program succeeding in controlling lung disease? In: Proceedings of the VIIth International Pneumoconiosis Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, Ohio: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Wagner GR, Attfield MD, Kennedy RD, Parker JE [1992]. The NIOSH B reader certification program: an update report. J Occup Med *34*(9):879-884.

Wagner GR, Attfield MD, Parker JE [1993]. Chest radiography in dust-exposed miners: promise and problems, potential and imperfections. Occupational Medicine: State of the Art Reviews 8(1):127-141.

Wallace W et al. [1990]. Mutagenicity of diesel exhaust soot dispersed in phospholipid surfactants. Environmental Hygiene II, Springer-Verlag.

Wallace WE, Vallyathan V, Keane MJ, Robinson V [1985]. In vitro biologic toxicity of native and surface-modified silica and kaolin. J Toxicol Environ Health *16*:415-424.

Wallace WE et al. [1988]. The effect of lecithin surfactant and phospholipase enzyme treatment on some cytotoxic properties of respirable quartz and kaolin dusts. In: Frantz RL, Ramani RV, eds. Respirable dust in the mineral industries: health effects, characterization and control. pp. 154-166.

Wallace WE, Keane MJ [1988]. Characterization of surface properties affecting the activity of the "free silica" fraction of respirable dusts. Final report prepared for the Bureau of Mines, Pittsburgh, PA, by the National Institute for Occupational Safety and Health, Morgantown, WV, pp. 48-70. NTIS no. PB89-142988.

Wallace WE, Keane MJ, Mike PS, Hill CA, Vallyathan V [1989]. Mineral surface-specific differences in the adsorption and enzymatic removal of surfactant and their correlation with cytotoxicity. In: Mossman BT, Gegin RO, eds. Effects of mineral dusts on cells. NATO ASI Series, Vol. H30. Heidelberg: Springer-Verlag, pp. 49-56.

Wallace WE, Harrison J, Keane MJ, Bolsaitis P, Eppelsheimer D, Poston J, Page SJ [1990]. Clay occlusion of respirable quartz particles detected by low voltage scanning electron microscopy x-ray analysis. Ann Occup Hyg *34*(2):195-204.

Wallaert B, Lassalle P, Fortin F, Aerts C, Bart F, Fournier E, Voisin C [1990]. Superoxide anion generation by alveolar inflammatory cells in simple pneumoconiosis and in progressive massive fibrosis of nonsmoking coal miners. Am Rev Respir Dis *141*:129-133.

Walton, WH, Dodgson J, Hadden GG, Jacobsen M [1975]. The effect of quartz and other non-coal dusts in coalworkers' pneumoconiosis, part 1: epidemiological studies. In: Walton WH, ed. Inhaled Particles IV, part 2. New York, NY: Pergamon Press, pp. 669-690.

Waseem M, Bansal SK, Gupta GSD, Kaw JL [1982]. Cytotoxic and hemolytic action of coal-quartz mixtures. Arch Environ Health 37(6):352-357.

Watts WF, Niewiadomski [1990]. Respirable dust trends in coal mines with longwall or continuous miners sections. In: Proceedings of the VIIth International Pneumoconioses Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Watts WF, Parker DR [1987]. Respirable dust levels in coal, metal, and nonmetal mines. Bureau of Mines Information Circular 9125.

Weber K, Tucker J, Stettler L, Wallace W [1988]. Final report: research on health effects and particle characterization to improve silica dust control in underground coal mines. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. NTIS No. PB89-142-988.

Webster JB, Chiaretta CW, Behling J [1990]. Dust control in high productivity mines. In: Proceedings of the Society for Mining, Metallurgy, and Exploration, Inc. Salt Lake City, Utah, February 26-March 1.

Weeden RP [1991]. TLVs and the contribution of science to policy. Am J Ind Med *19*:684-685.

Weeks JL [1990]. Characteristics of chronically dusty longwall mines in the U.S. In: Proceedings of the VIIth International Pneumoconioses Conference, August 23-26, 1988, Pittsburgh, PA. Cincinnati, OH: U.S. Department of Health and Human Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 90-108.

Weeks JL [1991]. Tampering with dust samples in coal mines (again). Am J Ind Med *20*:141-144.

Weeks JL, Fox M [1983]. Fatality rates and regulatory policies in bituminous coal mining, United States. Am J Public Health *73*(11):1278-1280.

Weeks JL, Wagner GR [1986]. Compensation for occupational disease with multiple causes: the case of coal miners' respiratory diseases. Am J Public Health *76*(1):58-61.

Weeks JL, Levy BS, Wagner GR [1991]. Preventing occupational disease and injury. Washington, DC: American Public Health Association.

Weiss W [1991]. Cigarette smoking and small irregular opacities. Br J Ind Med *48*:841-844.

WHO [1973]. WHO Technical Report Series, No. 535. Geneva, Switzerland: World Health Organization.

WHO [1980]. International classification of impairments, disabilities, and handicaps. Geneva, Switzerland: World Health Organization, pp. 10-11, 26-31, 86-87.

WHO [1986a]. Early detection of occupational diseases. Geneva, Switzerland: World Health Organization.

WHO [1986b]. Recommended health-based limits in occupational exposure to selected dusts (silica, coal). Technical Report Series 745. Geneva, Switzerland: World Health Organization.

Whong WZ, Long R, Ames RG, Ong TM [1983]. Role of nitrosation in the mutagenic activity of coal dust: a postulation for gastric carcinogeneses in coal miners. Environ Res *32*:298-304.

Wiedermann CJ, Adamson IYR, Pert CB, Bowden DH [1988]. Enhanced secretion of immunoreactive bombesin by alveolar macrophages exposed to silica. J Leukocyte Biol *43*:99-103.

Winter ML, Liehr JG [1991]. Free radical-induced carbonyl content in protein of estrogen-treated hamsters assayed by sodium boro[$^3$H]hydride reduction. J Biol Chem *226*(22):14446-14450.

Wolff RK, Henderson RF, Snipes MB, Griffith, Mauderly WC, Cuddihy RC, McClellan R [1987]. Alterations in particle accumulation and clearance in lungs of rats chronically exposed to diesel exhaust. Fundam Appl Toxicol *9*:154-166.

Worth G [1984]. Emphysema in coal workers, editorial. Am J Ind Med *6*:401-403.

Wu Z-L, Chen JK, Ong T, Matthews EJ, Whong W-Z [1990]. Induction of morphological transformation by coal-dust extract in BALB/3T3 A31-1-13 cell line. Mutat Res *242*:225-230.

Wyngaarden JB, Smith LH Jr. [1982]. Cecil's textbook of medicine, 16th ed. Philadelphia, PA: W.B. Saunders, p. 398.

Xu L, Colinet JF, Mutmansky JM [1990]. Dust control in high-productivity coal mines: observations and strategies in high-quartz sections. In: Society for Mining, Metallurgy, and Exploration, Inc., for presentation at the SME Annual Meeting, Salt Lake City, Utah, February 26-March 1.

Yu CP, Morrow PE, Chan TL, Yoon KJ [1988]. A non-linear model of alveolar clearance of insoluble particles from the lung. Inhal Toxicol *1*:97-107.

Zey JN, Donohoe M [1983]. Health hazard evaluation report: Culley Generating Station, Yankeetown, IN. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control, Public Health Service, National Institute for Occupational Safety and Health, NIOSH Report No. HETA 81-112-1372, NTIS No. PB-85-163-467/XAB.