4 HEALTH EFFECTS OF EXPOSURE TO RESPIRABLE COAL MINE DUST

This chapter describes the adverse health effects associated with exposure to respirable coal mine dust. Epidemiological studies of underground and surface coal miners in the United States and other countries are discussed. Also discussed are animal studies that add to our understanding of particle deposition and retention in the lungs and associated disease responses. This chapter emphasizes studies that (1) were performed since the passage of the Federal Coal Mine Health and Safety Act of 1969 [P.L. 91-173], (2) used standardized methods of exposure monitoring and disease classification, and (3) investigated exposure-response relationships between respirable coal mine dust exposure and disease. Several published review articles contain further discussion of health effects studies of coal miners [Attfield and Wagner 1992b; Petsonk and Attfield 1994; Cotes and Steel 1987; Merchant et al. 1986; Morgan and Lapp 1976; Morgan 1975].

4.1 DESCRIPTION OF OCCUPATIONAL RESPIRATORY DISEASES IN COAL MINERS

4.1.1 Historical Perspective

"Black lung" was recognized as a disease of British coal miners in the mid-17th century [Davis 1980]. The term "pneumonokoniosis" was introduced in 1866 and was shortened to "pneumoconiosis" in 1874 [Meiklejohn 1951]. The term means "dusty lung." The term "silicosis" was introduced in 1870 to describe pneumoconiosis resulting from silica [NIOSH 1974]. Investigations into the etiology of black lung disease began in the 1900s. By 1907, chest X-rays were used to study lung disease in coal miners, but their quality permitted detection of only gross pathological changes until about 1930 [Meiklejohn 1952 a,b].

The causative agent of pneumoconiosis in coal miners was thought to be silica until studies in the United Kingdom provided evidence that exposure to coal dust containing minimal silica could also cause pneumoconiosis [Collis and Gilchrist 1928; Gough 1940]. These investigators found pneumoconiosis among coal trimmers, who were responsible for the loading and distribution of coal (previously washed and separated from rock) into the holds of ships. King et al. [1956] later reported that the severity of pneumoconiosis (based on both radiographic and pathologic data) was related to the total dust in the lungs of U.K. coal miners but not to the silica content of the coal.

In the United States, few studies of pneumoconiosis in coal miners were performed before the 1960s [Dressen and Jones 1936; Flinn et al. 1941]. In the early 1960s, studies of pneumoconiosis were conducted among coal miners in central and western Pennsylvania [Lieben et al. 1961; McBride et al. 1963] and in seven states in the Appalachian region [Lainhart et al. 1968] (Section 4.2.1.1). By

the early 1970s, investigators suggested that CWP was not a single disease but a composite of disorders, each varying in incidence and severity depending on geographic area, occupational exposure, and individual susceptibility [Naeye and Dellinger 1972].

In the Federal Coal Mine Health and Safety Act of 1969, CWP was defined 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 as "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)]. CWP has been medically defined as a parenchymal lung disease produced by deposits of coal dust in the lung and the response of the host to the retained dust [Weeks and Wagner 1986; Wyngaarden and Smith 1982].

4.1.2 Simple CWP and PMF

Diagnosis of CWP is generally based on chest X-ray findings and a history of working in coal mines (usually for 10 or more years) [Attfield and Wagner 1992b; Balaan et al. 1993]. The radiographic patterns are often the same for CWP and silicosis; thus, these diseases are distinguishable only by work history or pathological examination [Attfield and Wagner 1992b; Wagner et al. 1993b]. The radiographic appearance of simple CWP 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 PMF [Balaan et al. 1993; McLintock et al. 1971; Cochrane 1962].

PMF is associated with significant decreases in lung function, oxygen-diffusing capacity, and arterial blood gas tension (PaO_2) [Attfield and Wagner 1992b; Rasmussen et al. 1968]. PMF is also associated with breathlessness (at rest or with exercise), chronic bronchitis and recurrent chest illness, right ventricular hypertrophy, and episodes of right heart failure [Cotes and Steel 1987]. Coal miners with silicotic lesions or PMF have an increased risk of tuberculosis and other mycobacterial infections [Petsonk and Attfield 1994]. PMF may progress, even in the absence of further dust exposure [Stewart 1948; Parkes 1982; Merchant et al. 1986]. This disease is also associated with increased mortality [Atuhaire et al. 1985; Miller and Jacobsen 1985].

4.1.2.1 Radiographic Classification of Simple CWP and PMF

The opacities on the chest X-ray are classified according to their size, shape, profusion, and extent [ILO 1980] (Table 4-1). These classifications are used in the diagnosis of simple CWP and PMF.

4.1.2.1.1 Simple CWP

Simple CWP is characterized by the presence of small opacities <10 mm in diameter on the chest X-ray. These opacities are usually seen first in the upper lung zones, but the middle and lower zones may become involved as the disease progresses [Balaan et al. 1993]. The profusion of small opacities is classified as major category 1, 2, or 3. Category 0 is defined as the absence of small opacities, or as small opacities that are 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 if an adjacent main category was seriously considered during the classification process (e.g., 1/2 was

Table 4–1. Summary of ILO classification of radiographs pertaining to simple CWP and PMF

Features	Codes	Definitions
Technical quality of radiographs	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:		
Profusion		The category of profusion is based on assessment of the concentration of opacities by comparison with the standard radiographs.
	0/- 0/0 0/1 1/0 1/1 1/2	Category 0: Small opacities are absent or are less profuse than the lower limit of category 1.
	2/1 2/2 2/3 3/2 3/3 3/+	Categories 1, 2 and 3: These represent increasing profusion of small opacities as defined by the corresponding standard radiographs.
Extent	RU RM RL LU LM LL	The zones in which the opacities are seen are recorded. The right (R) and left (L) thorax are both divided into three zones—upper (U), middle (M), and lower (L). 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:		
Round	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 appearance on standard radiographs: p = diameter up to about 1.5 mm q = diameter exceeding about 1.5 mm and up to about 3 mm 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: s = width up to about 1.5 mm t = width exceeding about 1.5 mm and up to about 3 mm u = width exceeding 3 mm and up to about 10 mm
Mixed	p/s p/t p/u p/q p/r q/s q/t q/u q/p q/r r/s r/t r/u r/p r/q s/p s/q s/r s/t s/u t/p t/q t/r t/s t/u 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.

(Continued)

Table 4-1 (Continued). Summary of ILO classification of radiographs pertaining to simple CWP and PMF

Features	Codes	Definitions
Parenchymal abnormalities (continued):		
Large opacities		The categories are defined in terms of the dimensions of the opacities.
	A	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.
	B	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.
	C	Category C: One or more opacities whose combined area exceeds the equivalent of the right upper zone.
Symbols*	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 about the classification should be recorded—especially if some cause other than pneumoconiosis is thought to be responsible for a shadow that could be interpreted by others as pneumoconiosis; comments should also be recorded to identify radiographs whose technical quality may materially affect the reading.

Adapted from ILO [1980].
*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.

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). The diameters of these opacities are ≤1.5 (p or s), 1.5 to 3 mm (q or t), or 3 to 10 mm (r or u).

4.1.2.1.2 PMF (complicated CWP)

PMF (or complicated CWP) is classified radiographically as category A, B, or C when large opacities with a combined area of 1 cm or larger are found on the chest X-ray. PMF usually develops in miners already affected by simple CWP, but it may also develop in miners with no previous radiographic evidence of simple CWP [Hodous and Attfield 1990; Hurley et al. 1987].

An unusual presentation of PMF or Caplan's nodule(s) may be difficult to distinguish from a primary or metastatic neoplasm [Lapp and Parker 1992]. When large opacities occur bilaterally on a background of simple CWP, a diagnosis of PMF is reasonably certain; however, when the radiographic background of simple CWP is sparse or absent, or when there are multiple crops of peripherally situated nodules (Caplan's syndrome), it may be difficult to differentiate between PMF and neoplasm [Lapp and Parker 1992].

4.1.2.1.3 Pleural abnormalities

Pleural abnormalities on the chest X-ray (including pleural thickening of the chest wall or diaphragm, obliteration of the costophrenic angle, and pleural calcification) should also be recorded according to the International Labour Office (ILO) classification [ILO 1980].

4.1.2.1.4 Interpretation of chest X-rays

Individuals who interpret chest X-rays under the Federal Mine Safety and Health Act of 1977 [30 USC 843] must be either an A or B reader [42 CFR Part 37]. A person can become an A reader by attending a NIOSH-approved course on interpretation of chest X-rays for pneumoconioses. Certification as a B reader requires passing an examination that tests proficiency in interpretation of chest X-rays for pneumoconioses [Wagner et al. 1992; Morgan 1979]. B readers are therefore considered to have more expertise than A readers in interpreting chest X-rays. Several studies have examined the variability between readers in interpreting radiographic appearances of pneumoconioses [Collins and Soutar 1988; Attfield et al. 1986; Felson et al. 1973; Fletcher and Oldham 1949]. Attfield and Wagner [1992a] discuss training, certification, and quality assurance.

4.1.2.2 Pathological Classification of CWP and PMF

The primary histopathological lesion of CWP is the coal macule [Cotes and Steel 1987]. The macular lesion of CWP has been defined as "a focal collection of coal-dust-laden macrophages at the division of respiratory bronchioles that may exist within alveoli and extend into the peribronchiolar interstitium with associated reticulin deposits and focal emphysema" [Kleinerman et al. 1979]. The primary lesion of CWP is focal, like that of silicosis; but it differs in the amount and nature of dust, the quantity and disposition of fibrous tissue, and the presence of focal emphysema [Heppleston 1992]. Coal macules range in size from 1 to 5 mm and may be rounded, irregular, or stellate [Attfield and Wagner 1992b]. Macular lesions are usually symmetrically distributed in both lungs, with a greater concentration in the upper lobes [Merchant et al. 1986]. Dust-laden macules occur in the region of the first-, second-, and third-order respiratory bronchioles [Attfield and Wagner 1992b]. Macrophages found in both the air spaces and the connective tissue around the respiratory bronchioles may contain dust [Merchant et al. 1986]. The proportion of dust, cellular material, or collagen varies depending on the rank of coal dust inhaled [Cotes and Steel 1987].

Focal emphysema has been defined as the emphysematous changes that are focal in nature and consist of dilation and destruction of alveoli adjacent to the respiratory bronchioles where dust has aggregated [Kleinerman et al. 1979]. Focal emphysema usually involves a region of 1 to 2 mm around the dust-laden macule [Merchant et al. 1986; Attfield and Wagner 1992b].

The macule is a discrete lesion of connective tissue and dust, but it is not necessarily palpable [Kleinerman et al. 1979]. In addition to macules, a variety of nodular lesions are found in coal miners' lungs; these may or may not be related to occupational exposures [Kleinerman et al. 1979]. These nodules are classified according to size and etiology and include the following categories: micronodular CWP (up to 7-mm diameter), macronodular CWP (7- to 20-mm diameter), silicotic nodule, PMF, Caplan's lesion, and infective granuloma (histoplasmosis, tuberculosis) [Kleinerman et al. 1979]. The nodular lesions of simple CWP are palpable because they contain collagen and are sometimes calcified [Merchant et al. 1986].

The National Coal Workers' Autopsy Study [30 CFR 37 Subpart—Autopsies] uses lesions ≥1 cm as the anatomical definition of PMF—a definition consistent with the radiographic definition of opacities ≥1 cm [ILO 1980]. The American College of Pathologists has recommended using lesions ≥2 cm as a more appropriate anatomical definition of PMF for pathological studies [Kleinerman et al. 1979]. The lesions of PMF are solid, heavily pigmented, and rubbery to hard; a PMF lesion may also contain a cavity containing opaque black liquid [Kleinerman et al. 1979; Merchant et al. 1986]. PMF lesions usually occur in the apical posterior portions of the upper lobes or the superior segments of the lower lobes [Kleinerman et al. 1979]. Histologically, the periphery is composed of irregular reticulin and collagen interspersed with black pigment [Merchant et al. 1986]. Blood vessels and airways transversing the lesion are destroyed [Merchant et al. 1986]. PMF generally occurs on a background of simple CWP, and lesions of simple CWP in this case are usually nodular rather than macular [Merchant et al. 1986]. PMF is asymmetrical, in that one lung may be more severely affected than the other [Kleinerman et al. 1979].

4.1.2.3 Relationship Between Chest X-rays, Pathology, and Lung Dust Content

Rossiter [1972a,b] reported a correlation between the radiographic category of simple CWP and the weight of the dust in the lungs of coal miners. Later studies provided information about the types of radiographic opacities and particles in the lungs. Ruckley et al. [1984] reported that the size (radiographic type) of opacity was related to the lung dust weights (see Section 4.1.2.1 for a discussion of radiographic opacities). Miners with the smallest opacities (p) had greater lung dust weights than miners with the largest opacities (r) [Ruckley et al. 1984]. The relationship between the profusion of r-type opacities and lung dust weight was poor, although few cases were examined [Fernie and Ruckley 1987]. Among miners with predominantly p-type opacities, total lung dust provided the best correlation with radiographic profusion; of the pathologic lesions, the number of pinhead nodules (<1-mm diameter) correlated with radiographic profusion [Fernie and Ruckley 1987].

Several investigators have reported a relationship between increasing severity of pathological lesions and increasing mean weight of lung dust [King et al. 1956; Nagelschmidt 1965; Douglas et al. 1986]. However, the percentage of quartz in the total dust was similar (about 6%) for most lesions [King et al. 1956; Nagelschmidt 1965]. These findings suggest that coal dust is more closely associated than silica with the development of simple CWP and PMF. An exception to the above

pattern—a decreased amount of total dust and increased amount of silica found in the most severe pathological lesion [King et al. 1956]—might have been related to the additional factor of tuberculosis infection [King et al. 1956]. Douglas et al. [1986] found that miners with PMF had retained more dust in their lungs per unit of dust exposure (during life) than miners without PMF. This finding suggests greater deposition and/or less clearance of dust in the lungs of miners who developed PMF. Among miners of high-rank coal (88.8% to 94% carbon), the composition of lung dust was similar for different pathological lesions [Douglas et al. 1986; 1988]. But among miners of low-rank coal (81.1% to 87% carbon), the proportion of ash* in retained dust was higher than that in the airborne dust to which they had been exposed—and this proportion increased with increasing severity of pathological lesions.

Gough et al. [1950] reported that chest X-rays did not always detect slight pathological grades of pneumoconiosis (see Sections 4.1.2.1. and 4.1.2.2 for discussions about radiographic opacities and pathological lesions). More recently, Attfield et al. [1994] reported that increasing pathological grade of coal macules was associated with a greater likelihood of detecting an abnormality on the chest X-ray (predominant types of opacities were m [mixed], p, and q) [Attfield et al. 1994]. However, there was also a probability (up to 33%) that the chest X-ray would indicate no abnormality (category 0), even when moderate and severe grades of macules were present [Attfield et al. 1994]. Caplan [1962] reported that radiographic appearances were more closely associated with the profusion of nodules than with other types of dust foci. Similarly, Attfield et al. [1994] found better association between the presence of micro- and macro-nodules and the detection of radiographic abnormality: only 0% to 9% of the cases with moderate and severe grades of micro- and macro-nodules had a normal chest X-ray (category 0). Micro- and macro-nodules tended to be associated with the appearance of q- and r-type opacities on the chest X-ray [Ruckley et al. 1984; Attfield et al. 1994]. Douglas et al. [1988] found that three types of PMF lesions were equally associated with the radiographic appearance of large opacities.

4.1.3 Silicosis

Silicosis may develop when inhaled respirable crystalline silica is deposited in the lungs. The disease may be chronic, complicated, accelerated, or acute. The clinical diagnosis of silicosis is based on (1) recognition by the physician that the silica exposure is adequate to cause the disease, (2) the presence of chest radiographic abnormalities consistent with silicosis, and (3) the absence of other illnesses (e.g., tuberculosis or pulmonary fungal infection) that may mimic silicosis [Balaan and Banks 1992].

4.1.3.1 Chronic Silicosis

Chronic silicosis commonly involves 15 or more years of exposure to silica [Parker 1994]. The characteristic microscopic feature is the silicotic 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 that often exhibit a feature known as onion skinning. The peripheral zone consists of more randomly oriented collagen fibers mixed with dust-laden macrophages and lymphoid cells. Chronic silicosis

*Ash is the solid residue remaining after coal is burned; quartz, kaolin, and mica are common constituents of ash.

is often asymptomatic and may manifest itself as a radiographic abnormality with small, rounded opacities of less than 10 mm in diameter, predominantly in the upper lobes [Parker 1994]. Lung function may be normal or show mild restriction [Parker 1994]. Chronic silicosis is associated with a predisposition to tuberculosis and other mycobacterial infections and with progression to complicated silicosis [Balaan and Banks 1992].

4.1.3.2 Complicated Silicosis

Complicated silicosis, or PMF, occurs when the nodules coalesce and form large conglomerate lesions [Weber and Banks 1994]. Complicated silicosis is characterized radiographically by the presence of nodular opacities >1 cm in diameter on the chest X-ray [Parker 1994]. Complicated silicosis typically causes respiratory impairment that may first manifest itself as exertional dyspnea; this disease commonly involves reduced carbon monoxide diffusing capacity, reduced arterial oxygen tension at rest or with exercise, and marked restriction on spirometry or lung volume measurement [Parker 1994; Balaan and Banks 1992]. Recurrent bacterial infection may occur, and tuberculosis is a concern. Distortion of the bronchial tree may lead to airway obstruction and productive cough. Pneumothorax, a life-threatening complication, may occur because the fibrotic lungs may be difficult to re-expand [Parker 1994; Balaan and Banks 1992]. Hypoxemic respiratory failure with cor pulmonale is a common terminal event [Parker 1994].

4.1.3.3 Accelerated Silicosis

In accelerated silicosis, the duration of exposure is usually 5 to 10 years [Parker 1994]. The lung nodules seen are at an earlier stage of development than those in chronic silicosis [Silicosis and Silicate Disease Committee 1988]; but otherwise, the lung nodules in accelerated silicosis have no specific distinguishing morphologic feature. Symptoms, radiographic findings, and physiologic measurements are similar to those seen in the chronic form [Parker 1994]. Disease progression is likely even if the worker is removed from the workplace [Balaan and Banks 1992]. Autoimmune diseases, including scleroderma and rheumatoid arthritis, are commonly associated with accelerated silicosis [Parker 1994; Balaan and Banks 1992].

4.1.3.4 Acute Silicosis

Acute silicosis may develop within 6 months to 2 years of intensive exposure to fine particles of nearly pure silica—such as those present during sandblasting or drilling. Because acute silicosis is characterized by the filling of lung alveoli with lipoproteinaceous material, it is also known as silicotic alveolar proteinosis [Silicosis and Silicate Disease Committee 1988]. 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 risk of tuberculosis or other mycobacterial infection is greater in acute silicosis than in the chronic or accelerated forms [Parker 1994; Weber and Banks 1994].

4.1.4 Mixed-Dust Pneumoconiosis

In coal mining, particularly surface coal mining, the typical worker is exposed to a mixture of dusts over a working lifetime rather than 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

Table 4-2. Terms and diagnostic criteria for describing airways disease*

Disease	Diagnostic criteria	Definition
Asthma	Clinical features	Acute, episodic airflow limitation reversible spontaneously or on treatment† [Fletcher and Pride 1984; ATS 1987b; Tecelescu 1990]
Chronic bronchitis	Symptoms	Chronic or recurrent bronchial hypersecretion‡ (i.e., almost daily sputum for 3 months of the year for at least 3 years) [Fletcher and Pride 1984; ATS 1987b; Tecelescu 1990]
Emphysema	Pathologic features	Dilatation of air spaces distal to the terminal bronchiole with destructive changes in the alveolar walls [Fletcher and Pride 1984; ATS 1987b]
COPD	Lung function deficit with or without other clinical features	Main feature is chronic airflow limitation (largely irreversible) that may, in certain circumstances, be primarily in peripheral airways [Fletcher and Pride 1984; ATS 1987b; Snider 1989; Tecelescu 1990]

Adapted from Becklake [1992].
*Based on definitions proposed by the 1959 Ciba Guest Symposium [Ciba 1959; Fletcher and Pride 1984], the American Thoracic Society [ATS 1987b], and other commentators [Snider 1989; Tecelescu 1990].
†Some definitions included the feature of airway hyperresponsiveness [ATS 1987b].
‡Assessed by clinical history or respiratory symptoms questionnaire.

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 and 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. Except in the case of acute silicosis (which has a distinctive radiologic presentation similar to pulmonary edema and other diseases that fill air space with fluids and cells), the chest X-ray alone cannot indicate 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 X-ray showing pneumoconiosis in a coal miner may represent CWP, silicosis, or mixed-dust pneumoconiosis [Cotes and Steel 1987].

4.1.5 COPD

COPD refers to three disease processes—chronic bronchitis, emphysema, and asthma—that are all characterized by airway dysfunction [Barnhart 1994; Becklake 1992]. Airflow limitation (of varying degree and reversibility) and shortness of breath (nonspecific symptom) are underlying features of COPD [Becklake 1992]. Asthma is characterized by reversible airflow obstruction; chronic bronchitis and emphysema may have partially reversible airflow limitation [Barnhart 1994]. Lung function tests are used to establish the presence of COPD [Becklake 1992]. Table 4-2 lists definitions and diagnostic criteria for COPD and other airways diseases. A major cause of COPD

is cigarette smoking; but air pollution and occupational exposure to dust, particularly among smokers, can also cause COPD [Samet 1989; Fletcher et al. 1976]. Chronic bronchitis is characterized by symptoms of chronic mucus hyper-secretion [Becklake 1992]. Chronic bronchitis can also be associated with airflow obstruction and abnormalities in gas exchange [Barnhart 1994]. Pathologically, chronic bronchitis involves hypertrophy and hyperplasia of bronchial mucous glands and the lack of cartilaginous support of the airways [Kilburn 1986]. Occupational or industrial bronchitis is chronic bronchitis that is caused or aggravated by occupational exposure to dust [Morgan and Lapp 1976].

Emphysema is defined as the abnormal, permanent enlargement of air spaces [Barnhart 1994] distal to the terminal bronchiole, accompanied by destruction of their walls [ATS 1962]. Either pathological features or computed tomography can be used to determine the presence of emphysema [Becklake 1992]. The several types of emphysema are classified in terms of lung structure [Thurlbeck 1976].

4.2 EPIDEMIOLOGICAL STUDIES

4.2.1 Studies of Simple CWP, PMF, and Silicosis

4.2.1.1 U.S. Studies from the 1960s

Before 1970, the average concentration of respirable dust for most job categories in underground coal mines exceeded 2 mg/m^3, and the average concentration for some jobs at the working face (where the coal is extracted) exceeded 6 mg/m^3 [Attfield and Wagner 1992b] (Figure 4-1).

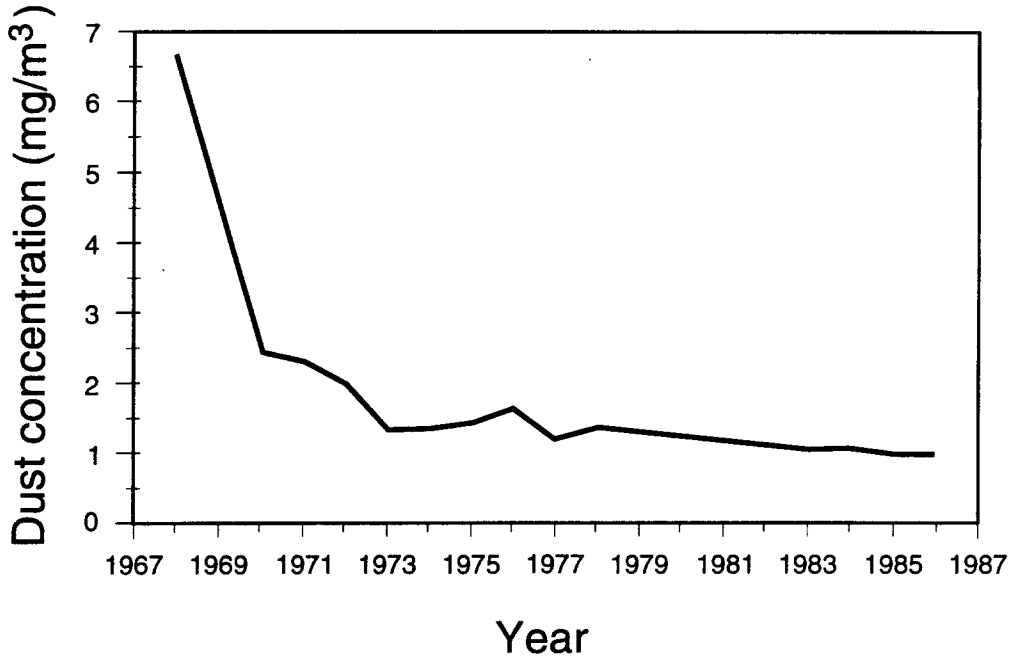

Figure 4-1. Reported trends in dust concentrations for continuous miner operators, 1968–87. (Source: Attfield and Wagner [1992b].)

U.S. studies from the 1960s have reported prevalences of simple CWP category 1 or greater ranging from 4% to 46% (Table 4-3). In these studies, the factors associated with the higher prevalences of simple CWP and PMF were (1) exposure to dust of higher-rank coal, (2) greater number of years worked in mining (especially years worked underground), and (3) increasing age of the miner. Because the mean number of years worked in mining and the mean ages were similar across the various studies (Table 4-3), these factors probably do not account for the different prevalences observed among miners in different regions of the United States. Instead, these differences have generally been attributed to the various ranks of coal mined in these regions.

Lainhart [1969] observed that the prevalence of pneumoconiosis[†,‡] increased as coal rank increased. He reported the following prevalences of pneumoconiosis among miners in the following regions of increasing coal rank: Utah, 4.8%; Illinois and Indiana, 7.5%; and Appalachia, 11.1%. Miners in each region had no significant differences in mean age or mean number of years worked underground. The overall rate of participation in the study was also similar for each region, ranging from 91.7% to 97.5%.

McBride et al. [1963, 1966] observed that the prevalence of pneumoconiosis[†,§] increased with increasing number of years worked. Among working bituminous coal miners in western Pennsylvania, the prevalence of pneumoconiosis was 3%, 8%, 14%, 18%, and 26%, respectively, for groups with <20, 20-24, 25-29, 30-39, and ≥40 years of experience [McBride et al. 1963]. Among working anthracite coal miners in Pennsylvania, the prevalence of pneumoconiosis was 10%, 21%, 39%, 56%, and 50%, respectively, for the same years of experience.

The prevalence of pneumoconiosis was higher among retired coal miners than among working coal miners with a similar number of years of experience. Among retired bituminous coal miners, the prevalence of pneumoconiosis was 24%, 22%, and 32%, respectively, among those with <30, 30-39, and ≥40 years of experience. Among retired anthracite coal miners, the prevalence of pneumoconiosis was 52%, 80%, and 80%, respectively, for the same years of experience. McBride et al. [1963, 1966] also observed increasing prevalence of pneumoconiosis with increasing age.

4.2.1.2 U.S. Studies from 1970 to Present

The National Study of Coal Workers' Pneumoconiosis and the Coal Workers' X-Ray Surveillance Program were established in response to the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-73).** The National Study of Coal Workers' Pneumoconiosis is an epidemiological research study [Attfield et al. 1984a,b], and the Coal Workers' X-Ray Surveillance Program is a medical screening and surveillance program [Althouse et al. 1986, 1992]. NIOSH administers these ongoing programs, both of which began about 1970. Results from successive cross-sectional surveys (or rounds) of these studies have shown general downward trends in the prevalence rates of simple CWP among U.S. underground coal miners (Table 4-4 and Figure 4-2).

[†]Pneumoconiosis is defined here as simple CWP (category 1 or greater) or complicated CWP (PMF).

[‡]The 1959 International Radiological Classification of Chest Films was used [ILO 1959].

[§]The U.S. Public Health Service modification of the International Radiological Classification of Chest Films was used [Ashford and Enterline 1966].

**This Act was later amended by the Federal Mine Safety and Health Act of 1977 [30 USC 801-962].

Table 4–3. Prevalence of CWP (category 1 or greater) and PMF for some U.S. studies undertaken between 1961 and 1970, in order of coal rank

Study (by coal rank)	Prevalence: CWP (category 1 or greater)	Prevalence: PMF	Mean age (years)	Mean tenure (years): All work in coal mining	Mean tenure (years): Work underground	Comments
High rank:						
Eastern Pennsylvania [McBride et al. 1966]	22	9.6	55	26	——	*
Eastern Pennsylvania [Tokuhata et al. 1970]	34	——	45	——	22	*,†
Medium-high rank:						
Central Pennsylvania [Lieben et al. 1961]	25	8.3	47	27	——	*
Southern West Virginia [Hyatt et al. 1964]	46	7.2	52	——	25	*,‡
Southern West Virginia [Enterline 1967]	14	5.4	44	——	——	§
Medium rank:						
Appalachia [Lainhart 1969]	10	3.0	47	——	22	**
Eastern West Virginia [Enterline 1967]	6	1.1	43	——	——	§
Northern West Virginia [Higgins et al. 1968]	7	0.9	48	——	19	*,‡
Western Pennsylvania [McBride et al. 1963]	9	3.7	47	26	——	*
Medium/low rank:						
Illinois/Indiana [Lainhart 1969]	6	1.5	48	——	20	**
Utah [Lainhart 1969]	4	0.7	51	——	20	**

Adapted from Attfield and Castellan [1992].
*The 1959 ILO classification was used.
†Exact figure for average age is not given; figure given here has been estimated from age distribution data.
‡Group contains both current miners and ex-miners and could not be subdivided [ILO 1959].
§Radiographic classification is not stated but is probably the ILO 1959 scheme, given that the study was undertaken from 1963 to 1964.
**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 1970], but Morgan [1968] states that the ILO 1959 classification system was used.

Table 4–4. Adjusted summary prevalence estimates for combined small opacities from the Coal Workers' X-ray Surveillance Program and the National Study of Coal Workers' Pneumoconiosis

Category	Study*	Reader	Adjusted summary prevalences (%)†			
			Round 1	Round 2	Round 3	Round 4
CWP category 1 or greater:						
All participants	CWXSP‡	First	22.4	7.1	6.0	5.5
		Second	13.8	5.9	5.7	3.0
Tenure >4 years	CWXSP§	First	35.0	20.3	11.4	7.8
		Second	22.1	18.2	9.2	4.0
Common tenure distribution	CWXSP**	First	19.5	11.7	8.7	7.2
		Second	10.7	9.9	7.3	3.6
Epidemiological data, common tenure distribution**	NSCWP		6.6	5.1	3.6	2.3
CWP category 2 or greater:						
All participants	CWXSP‡	First	6.5	1.8	1.1	0.8
		Second	4.5	1.2	0.6	0.3
Tenure >4 years	CWXSP§	First	10.8	5.7	2.2	1.2
		Second	7.5	3.8	1.3	0.5
Common tenure distribution	CWXSP**	First	4.0	2.0	1.2	1.0
		Second	2.4	1.2	0.7	0.4
Epidemiological data, common tenure distribution**	NSCWP		1.5	1.2	0.5	0.3

Source: Attfield and Althouse [1992].

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

†Dates for various rounds of the CWXSP are as follows: round 1, 1970–73; round 2, 1973–78; round 3, 1978–81; round 4, 1981–86.

Dates for various rounds of the NSCWP are as follows: round 1, 1969–71; round 2, 1972–75; round 3, 1977–81; round 4, 1985–88.

‡All participants = summary rates based on all mandatory and voluntary X-rays.

§Tenure >4 years = summary rates based on all miners with more than 4 years of tenure in mining.

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

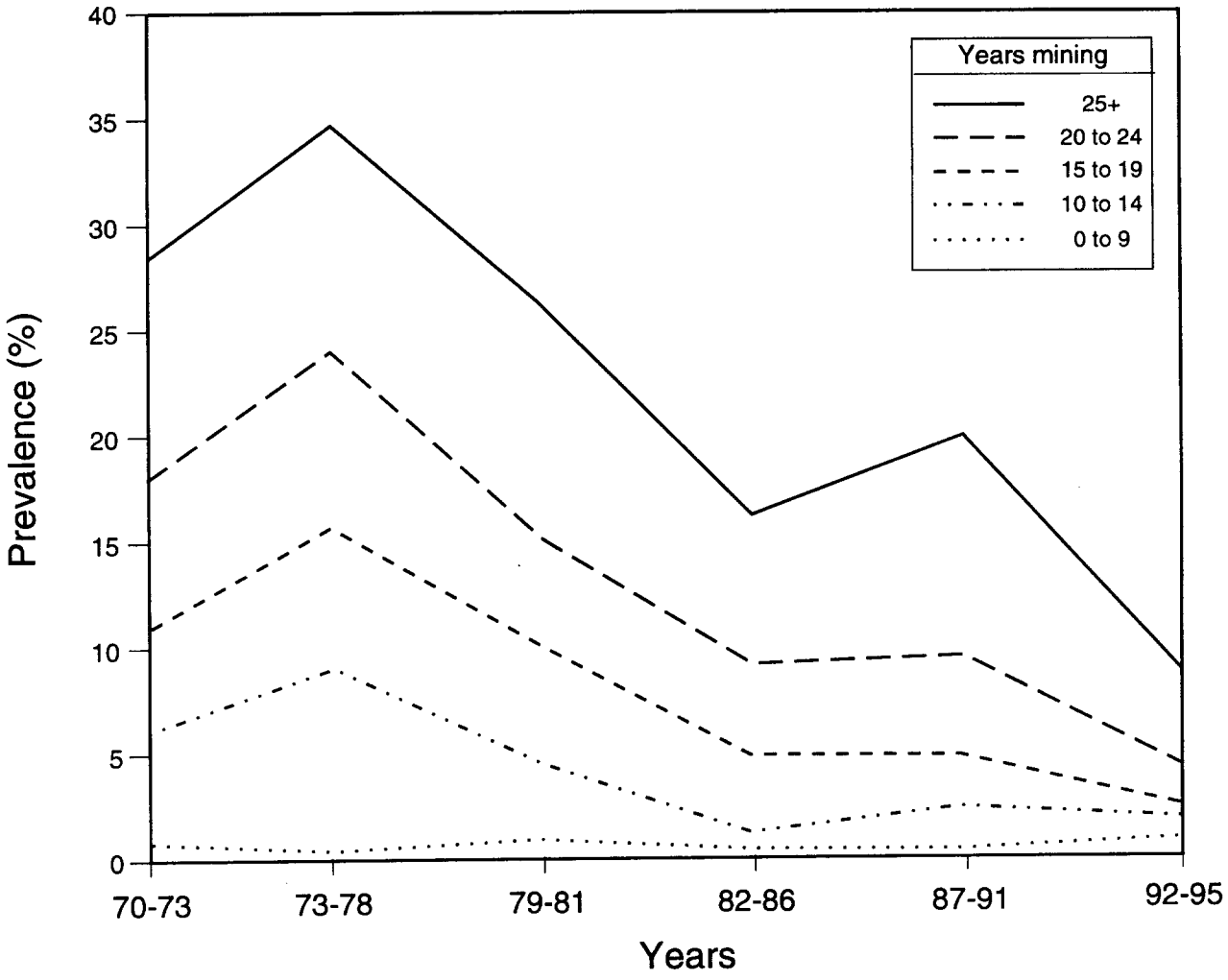

Figure 4–2. Prevalence of CWP category 1 or higher identified in the Coal Workers' X-ray Surveillance Program from 1970 to the present, by tenure in coal mining. The number of miners examined during each round is 71,446 (1970–73), 115,386 (1973–78), 58,294 (1979–81), 25,154 (1982–86), 13,920 (1987–91), and 11,678 (1992–95). (Source: Althouse, unpublished data.)

Thirty-one mines were originally selected for inclusion in the National Study of Coal Workers' Pneumoconiosis from the different mining regions across the continental United States, but many of those mines are no longer in production. The original criteria for selecting mines in round 1 included an expected mine life of 10 years, a workforce of at least 100 miners, geographical and geological spread, and accessibility to a field examination trailer [Attfield and Castellan 1992]. Rounds 1, 2, and 3 were conducted at nearly the same group of mines, but round 4 was organized differently from the previous rounds. The objective of round 4 was a followup study of miners and ex-miners who had participated in earlier rounds. Round 4 examinations were given at three of the original mine sites and in 22 mining communities. Participation rates for the National Study of Coal Workers' Pneumoconiosis were 90%, 75%, 52%, and 70% for rounds 1, 2, 3, and 4, respectively. Participation rates for the Coal Workers' X-ray Surveillance Program were 50%, 44%, 32%, and 30% for rounds 1, 2, 3, and 4, respectively. Recent improvements in the Coal Workers' X-ray

Surveillance Program have resulted in increased participation [Wagner et al. 1993a]. Because both programs consisted of successive cross-sectional studies (rounds), disease prevalences for the corresponding rounds of each study may not be strictly comparable because of differences in X-ray standards, X-ray readers, groups of miners studied, and tenure distributions that occurred in the successive rounds. The UICC††/Cincinnati classification of radiographs for pneumoconioses [Bohlig et al. 1970] was used for round 1 of the National Study of Coal Workers' Pneumoconiosis. The 1971 ILO U/C classification [ILO 1970] was used for rounds 2 and 3, and the 1980 ILO classification [ILO 1980] was used for round 4. The 1980 classification is also currently used for the ongoing Coal Workers' X-Ray Surveillance Program. Although the UICC/Cincinnati [Bohlig et al. 1970] classification included small rounded opacities (and excluded small irregular opacities), the 1980 ILO classification [ILO 1980] recommends classification of the profusion of all small opacities.

Morgan et al. [1973b] reported prevalences of simple CWP and PMF among 9,076 U.S. coal miners examined during round 1 of the National Study of Coal Workers' Pneumoconiosis (1969-71). For all regions combined, the prevalence of simple CWP category 1 or greater was 21.2%, and the prevalence of PMF was 2.5%. Prevalences were higher among miners of high-rank coal. The highest prevalence of PMF observed was 14% among miners of anthracite coal [Morgan et al. 1973a,b].

Analyses of round 4 of the National Study of Coal Workers' Pneumoconiosis (1985-88) included determining the prevalence of simple CWP and PMF among 3,194 underground miners and ex-miners who had been previously examined in round 1 (1970-75) [Attfield and Seixas 1995; Attfield 1992]. The prevalence of simple CWP category 1/0 or greater was 6.8% for the whole cohort and less than 5% among miners with 0 to 19 years of experience working underground. Among miners with 20 or more years of experience, the prevalence of category 1/0 increased steadily, reaching about 25% among miners who hadworked 30 or more years (Figure 4-3). The prevalence of simple CWP category 2 or greater increased gradually, reaching 2% among miners with 25 to 29 years of experience, then rising to 10% among miners with 30 or more years of experience (Figure 4-3). The prevalence of PMF was about 0.8%. Prevalences were higher among miners of high-rank coal and among ex-miners who had left work for health reasons.

About one-third (1,206) of the miners who participated in round 4 had started mining after 1969, thus having worked under the conditions mandated by the Federal Coal Mine Health and Safety Act of 1969 (P.L. 91-173). A respirable coal mine dust standard of 3.0 mg/m^3 was in effect until 1972, when it was reduced to 2.0 mg/m^3. Of these miners, 2% (21/1,206) had chest X-rays indicating simple CWP category 1 or greater (including 3 miners with category 2 or greater) at round 4 (1985-88). In the logistic regression model used to investigate exposure-response, separate coefficients were included for exposure both before 1970 and after. These coefficients were similar in magnitude and statistically significant, indicating that the influence on the development of simple CWP was similar per unit of dust exposure, whether that exposure occurred before 1970 or after.

††International Union Against Cancer.

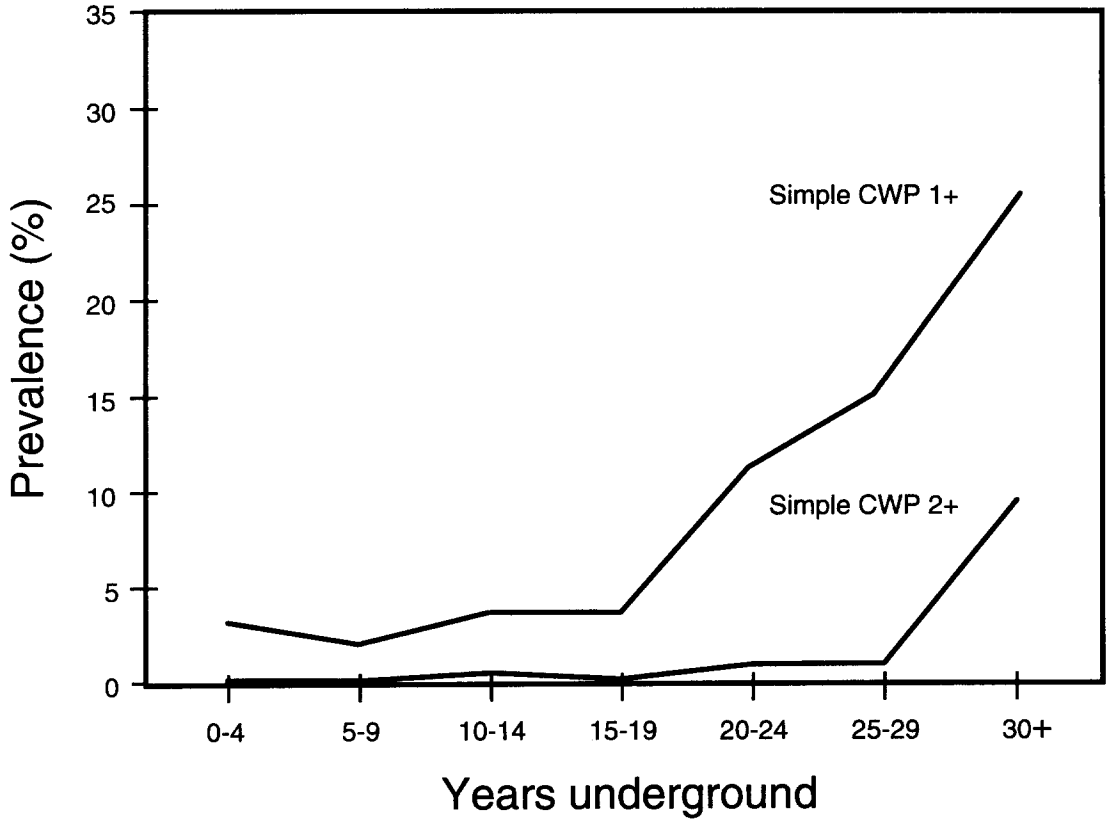

Figure 4–3. Prevalences of simple CWP category 1 or greater (1+) and category 2 or greater (2+) as detected by the median reading of chest X-rays for miners who worked in underground mines for various periods. (Adapted from Attfield and Seixas [1995].)

4.2.1.3 Studies Outside the United States

4.2.1.3.1 U.K. studies

Several important factors in the development of PMF have been determined from studies of coal miners in the United Kingdom. These factors include (1) cumulative dust exposure [Hurley et al. 1984, 1987]; (2) coal rank [Hurley and Maclaren 1987; Bennett et al. 1979; McLintock et al. 1971]; (3) residence time of dust in the lungs [Hurley et al. 1982; Maclaren et al. 1989]; and (4) radiographic category of simple CWP at the beginning of the study interval [Hurley et al. 1987; Hurley and Jacobsen 1986; Shennan et al. 1981; McLintock et al. 1971; Cochrane 1962]. The risk of PMF among miners with initial simple CWP category 2 or 3 is three to four times that of miners with initial simple CWP category 1 (Figure 4-4) [Hurley and Jacobsen 1986; Cochrane 1962].

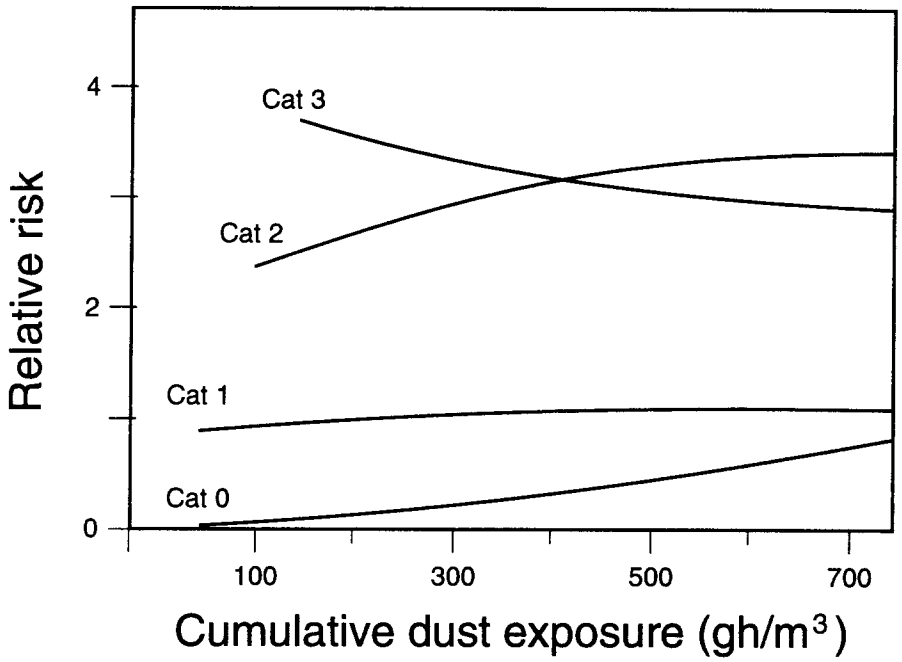

Figure 4–4. Relative risks of PMF over a 5-year period in miners with various cumulative exposures to respirable coal mine dust and various radiographic categories of CWP at the beginning of the period (relative to a miner with CWP category 1 and cumulative exposure to 200 gram hours per cubic meter [gh/m^3]). (Source: Hurley et al. [1987].)

The incidence of PMF among ex-miners in the United Kingdom was about 2.5 times that of working miners of similar ages [Maclaren and Soutar 1985]. However, miners and ex-miners had similar incidences of either simple CWP or PMF when differences in the distributions of age, dust exposure, simple CWP (at the beginning of the study), and mine (where employed) were considered [Soutar et al. 1986; Hurley and Maclaren 1988]. Among 1,902 ex-miners who had not developed PMF within 4 years of leaving mining, 172 (9%) developed PMF after leaving mining [Maclaren and Soutar 1985]. Of those 172 miners with PMF, 32% had no evidence of simple CWP (category 0) when they left mining.

Hurley and Maclaren [1987] investigated the risk of PMF among more than 30,000 U.K. coal miners during 5-year intervals (representing 52,264 risk intervals). The probability of radiographic change (developing simple CWP or PMF, or progressing to a higher category) was determined using a logistic regression model with covariates of age, cumulative exposure to respirable coal mine dust, and initial CWP category (at the beginning of the study interval). The 5-year exposure intervals occurred during the calendar years of 1953 through 1977, with a range of cumulative coal mine dust exposure from 12 to >519 gh/m^3.

The 5-year incidences of PMF among working British coal miners (during the period 1952-77) were 0.2%, 4.4%, 12.5%, and 13.9% for miners with CWP category 0, 1, 2, or 3, respectively, at the beginning of a 5-year interval [Hurley et al. 1987]. The 4.4% incidence of PMF among miners with initial CWP category 1 is three to four times higher than previous estimates [Maclaren and Soutar 1985; Shennan et al. 1981; McLintock et al. 1971]. At the beginning of the 5-year study intervals, most miners (47,087 of 52,264) 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].

4.2.1.3.2 German studies

In a study of German coal miners, Reisner [1971] reported a relationship between increasing residence time of dust in the lungs and the development of pneumoconiosis (based on the 1930 Johannesburg radiographic classification). In this 10-year study (beginning in 1954) at 10 mines in the Ruhr region, Reisner [1971] also reported an exposure-response relationship between cumulative dust exposure (computed as the summation of the monthly products of average workplace tyndallometric fine dust concentration and number of shifts worked) and the development of pneumoconiosis. In a study of German miners who had worked at least 5 years underground and had left mining in 1980 or 1985, Vautrin et al. [1990] reported a relationship between years worked underground and increasing prevalence or incidence of simple CWP (radiographic classification based on ILO [1980]). Among miners who worked 28 to 30 years, the cumulative incidence of simple CWP category 1/1 or greater was 16.6%, and that of simple CWP category 2/2 was 2.7% [Vautrin et al. 1990].

4.2.1.4 Studies of the Rapid Development of PMF

Researchers have known since the 1960s that the risk of PMF increases as the category of simple CWP increases [Cochrane 1962]. The risk of developing PMF was shown to rise steeply among miners with simple CWP category 2 [Cochrane 1962]. Therefore, a logical occupational health strategy for the prevention of PMF (which was included in the Federal Coal Mine Health and Safety Act of 1969 [Public Law 91-173]) was to identify miners who had sufficient dust exposure to develop simple CWP category 1. These miners were then offered the option of working in a low-dust environment ($\leq$1 mg/m^3) with increased frequency of environmental monitoring in the expectation that further disease progression would be prevented.

Studies from the 1970s and 1980s have confirmed that the risk of developing PMF increases as the category of simple CWP increases [McLintock et al. 1971; Hurley and Jacobsen 1986; Hurley et al. 1987; Hurley and Maclaren 1987; Hodous and Attfield 1990]. These studies have also shown that even miners with minimal simple CWP (radiographic evidence of simple CWP category 1 at the beginning of a 5-year interval) or without simple CWP (category 0) have a measurable risk of having PMF detected on their chest X-rays by the end of the 5-year period. The risk of PMF among miners without evidence of simple CWP (category 0) increased with increasing cumulative exposure to respirable coal mine dust. Thus, reducing exposures to respirable coal mine dust is the key factor in preventing PMF in all miners.

Hurley et al. [1987] found that the cumulative exposure to respirable coal mine dust in U.K. coal miners was the "most important single factor determining PMF risks" for two reasons. First, miners with simple CWP (category 1 or greater) are at higher risk of developing PMF than those without it, and the risk of developing simple CWP increases as exposure to respirable coal mine dust increases. Second, miners without radiographic evidence of simple CWP (category 0) have a higher risk of developing PMF with increased cumulative exposures to respirable coal mine dust [Hurley et al. 1987].

Hodous and Attfield [1990] studied 5-year film pairs representing chest X-rays of U.S. coal miners taken from 1969 through 1988 in the National Study of Coal Workers' Pneumoconiosis or the Coal Workers' X-ray Surveillance Program. The objective was to identify X-rays that showed PMF on the later but not the earlier film and to determine the category of simple CWP on the earlier film. Although there were more than 1,300 films showing PMF, most had only one X-ray on file. Of the 69 confirmed PMF cases with two or more films on file, 14% (10 cases) had no evidence of simple CWP (category 0) on the previous film, and 43% (30 cases) showed simple CWP category 1. Also, the earlier films showed 33% (23 cases) of simple CWP category 2 and 9% (6 cases) of simple CWP category 3. These findings in U.S. miners are consistent with the findings of the U.K. studies [Hurley and Maclaren 1987; Hurley et al. 1987].

Pathology studies of coal miners have shown that chest X-rays do not always detect early stages of pneumoconiosis, particularly when the lesions are macular [Gough et al. 1950; Ruckley et al. 1984; Attfield et al. 1994]. Thus, it is possible that early stages of simple CWP may not have been detected on the initial chest X-rays.

4.2.1.5 Studies of the Role of Silica

The composition and the amount of dust retained in the lungs influence the development of fibrotic lung diseases such as pneumoconiosis and silicosis. Noncoal minerals (especially silica) are associated with more severe lesions (i.e., examination of lesions in miners' lungs at autopsy indicate that coal particles were associated with soft macules, and quartz was associated more with PMF lesions [Davis et al. 1977]). Among workers 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 coal mine dust components that might coat the silica particles and reduce their toxicity to the alveolar macrophages, and (2) a greater rate of deposition (i.e., higher doses in shorter periods) in the workers exposed to dust with higher percentages of crystalline (free) silica.

Silica exposure may be a factor in the rapid development of PMF. In several U.K. studies, the rapid progression of simple 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 a relatively high respirable silica content [Seaton et al. 1981; Jacobsen and Maclaren 1982; Hurley et al. 1982; Robertson et al. 1987]. On 65% of the X-rays showing PMF in U.S. coal miners [Hodous and Attfield 1990], the r-type small opacities were predominant—a condition that may indicate silicosis [Ruckley et al. 1984].

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

4.2.1.6 Radiographic Small Opacities Among Nonminers

In a study of 1,422 U.S. workers in nondusty jobs, Castellan et al. [1985] found a low prevalence of radiographic small opacities, which is compatible with radiographic appearances of simple CWP. Among workers with fewer than 5 years of experience in jobs with possible respiratory hazards, 3 of 1,422 workers (0.21%) showed radiographic evidence of category 1/0 or 1/1. The study population consisted of 50.6% men and 49.4% women; 52.5% were whites, and 44.2% were blacks. The mean age of the whole group was 33.8 years (range 16 to 70 years). The mean age of persons with radiographic opacities was 47.5 years [Castellan et al. 1985]. By comparison, the mean age of the coal miners who participated in round 1 of the National Study of Coal Workers' Pneumoconiosis was 44 years [Attfield and Morring 1992b], and the mean age of those who participated in round 4 was 31 years [Attfield and Seixas 1995].

In a study of 200 hospitalized patients, Epstein et al. [1984] reported that 36 patients (18%) had small opacities of profusion category 1/0 or greater by ILO standards [ILO 1980]. Of these 36 patients with positive X-rays, 22 patients had no known dust exposure or medical condition that would explain the X-ray findings. 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 the 22 patients with radiographic small opacities and without known dust exposure or medical conditions was 55.7 years (compared with 41.5 years among patients with negative X-rays).

Because the Castellan et al. [1985] study was based on a worker population, the findings from that study are probably more applicable to coal miners than the findings of the Epstein et al. [1984] study. That is, the prevalence of small opacities expected among workers *without* exposures to respirable dust is probably closer to those reported by Castellan et al. [1985]. A study population of hospitalized patients (such as the one used in the Epstein et al. [1984] study) is likely to be a poor representation of a current worker population (especially those working in strenuous jobs such as coal mining). The study population in Castellan et al. [1985] was also larger (1,422 workers) than in Epstein et al. [1984] (200 hospitalized patients).

4.2.2 Studies of COPD in Coal Miners

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], gold miners [Cowie and Mabena 1991; Irwig and Rocks 1978], and other workers exposed to organic and inorganic particles

‡‡Ten percent of all coal miners who died during the period 1971-80.

[Kilburn 1980, 1984]. Nonoccupational factors that affect lung function include age, race, gender, height, weight, physical activity, and altitude. Decrements in FEV_1 have been associated with reduced life expectancy in studies of coal miners [Ortmeyer et al. 1974, 1973] and other populations [Strachan 1992; Foxman et al. 1986; Peto et al. 1983; Fletcher and Peto 1977; Higgins and Keller 1970].

4.2.2.1 Chronic Bronchitis

Several cross-sectional studies from the United States and the United Kingdom have found that respiratory symptoms (including cough, phlegm, wheezing, and breathlessness) are related to either duration of exposure [Rom et al. 1981; Hankinson et al. 1977a; Kibelstis et al. 1973; Hyatt et al. 1964] or cumulative exposure to respirable coal mine dust [Seixas et al. 1992; Marine et al. 1988; Rae et al. 1971]. Dust exposure and cigarette smoking each contribute to the development of respiratory symptoms and decrements in lung function. Increasing severity of bronchitic symptoms has been associated with loss in FEV_1 after accounting for dust exposure, smoking, age, height, and weight [Rogan et al. 1973]. Rogan et al. [1973] suggest that once early bronchitic symptoms develop, the disease may progress and ventilatory capacity may deteriorate independently of factors initiating the disease process.

Rae et al. [1971] found a statistically significant association between increasing exposure to respirable coal mine dust and increasing prevalence of bronchitis (based on symptoms of cough and phlegm) among U.K. coal miners; a twofold greater prevalence of bronchitis was found among smokers than nonsmokers. A relationship between chronic bronchitis and dust exposure, smoking, and alcohol consumption was reported in a cross-sectional study [Leigh et al. 1986] and a longitudinal study [Leigh 1990] of Australian coal miners.

In an autopsy study of U.S. miners, Naeye and Dellinger [1972] found that the miners had more bronchiolar goblet cells than the comparison group; yet the number of these cells did not correlate with the miners' radiographic category. Similarly, emphysema, dyspnea, and cor pulmonale did not correlate with the radiographic category. In an autopsy study of U.K. coal miners, Douglas et al. [1982] reported that the maximum mucous gland-wall ratio correlated with lifetime occupational exposure to coal mine dust.

4.2.2.2 Emphysema

Autopsy studies of U.K. coal miners have shown a significant increase in emphysema among coal miners compared with nonmining comparison populations [Ryder et al. 1970; Cockcroft et al. 1982b]. Ryder et al. [1970] found that emphysema was more frequent among coal miners with either simple CWP or PMF. Cockcroft et al. [1982b] found that the severity of centrilobular emphysema (the predominant type observed) was related to the amount of dust in the simple foci in the lungs. Cockcroft et al. [1982b] attempted to overcome bias in case selection by using similar methods to select coal miners and nonminers aged 50 to 70 who had died of ischemic heart disease; furthermore, these investigators accounted for age and smoking habits by stratification. Irregular opacities on chest X-rays have been associated with the pathological signs of emphysema and interstitial fibrosis, and with reduced gas transfer factor and reduced total lung capacity [Cockcroft et al. 1982a,b; Cockcroft and Andersson 1987].

In a pathological 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 centriacinar emphysema at autopsy among miners with pathologically determined fibrotic lesions. The prevalence of any emphysema among miners studied was 47% in those with no fibrotic lesions, 65% 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.

In a pathology study of 886 Australian coal miners, Leigh et al. [1982, 1983] determined that emphysema is related to coal dust exposure (using years of coal face work as a surrogate for exposure). A recent study of Australian coal miners provides further evidence of an association between emphysema and coal dust in the lungs of both smokers and lifelong nonsmokers [Leigh et al. 1994]. The extent of emphysema in smokers was significantly related to both coal dust content of the lungs and to smoking. In nonsmokers, the extent of emphysema was significantly related to both the coal dust content of the lungs and age. There was no evidence of a relationship between the silica content of the lungs and emphysema, though the silica content of the lungs was significantly related to the degree of lung fibrosis.

4.2.2.3 Decreased Lung Function

Several studies have shown that coal miners reported more respiratory symptoms and had poorer lung function than control groups [Enterline and Lainhart 1967; Higgins and Cochrane 1961; Higgins et al. 1968; Higgins 1972; Higgins et al. 1981]. Exposure to respirable coal mine dust has been associated with deficits in ventilatory function (including FEV_1 and vital capacity, VC) whether or not simple CWP was present [Hankinson et al. 1977a; Morgan 1978]. The presence of small, irregular radiographic opacities has been associated with deficits in FEV_1 and FVC among U.K. coal miners—in addition to those deficits attributable to age, height, weight, smoking habits, and dust exposure [Collins et al. 1988]. Complicated CWP (PMF) has been associated with ventilatory impairment [Morgan et al. 1974] and with decreased resting arterial blood gas tension (Pa_{O2}) [Rasmussen et al. 1968]. Maclaren et al. [1989] reported that miners with dyspnea had a greater risk of developing PMF.

Other measures of lung function (i.e., residual volume [RV] and total lung capacity [TLC]) have been shown to be elevated in miners with simple CWP [Morgan et al. 1971, 1974]. Cigarette smoking and bronchitis were also found to be associated with increased TLC and RV, regardless of the category of simple CWP [Hankinson et al. 1977b]. More recently, FEV_1 and maximum expiratory flow rates were shown to be significantly lower, and RV was significantly higher among nonsmoking coal miners than among nonsmoking steelworkers [Nemery et al. 1987]. These lung function indices were similar among the coal miners, whether or not simple CWP was present [Nemery et al. 1987].

Diffusing capacity has been shown to be either normal or slightly decreased among miners with simple CWP [Cotes et al. 1971; Cotes and Field 1972; Ulmer and Reichel 1972]. Diffusing capacity was reduced among coal miners who smoked, regardless of their duration of exposure to coal mine

dust [Kibelstis 1973]. Diffusing capacity was reduced among nonsmoking miners with simple CWP and p-type opacities [Seaton et al. 1972].

4.2.2.3.1 Quantitative estimates of dust-related loss of lung function

4.2.2.3.1.1 Cross-sectional studies

Decrements in FEV_1 and FVC have been shown to be related to coal mine dust exposure (independent of the effects of smoking) in cross-sectional epidemiological studies [Attfield and Hodous 1992; Seixas et al. 1992; Marine et al. 1988; Soutar et al. 1988; Rogan et al. 1973]. The average decrement in FEV_1 from exposure to respirable coal mine dust has been estimated in 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]. A re-analysis of the Rogan et al. [1973] data by Marine et al. [1988] showed a 36% greater loss for nonsmokers and a 56% greater loss for cigarette smokers than originally estimated. Table 4-5 lists the estimated average losses of FEV_1 from coal mine dust exposure reported in several studies.

Two studies of 4,059 British coal miners followed for 22 years indicated that exposure to coal mine dust on pulmonary function can be clinically significant [Hurley and Soutar 1986; Soutar and Hurley 1986]. An "excess effect" of exposure to coal mine dust was observed in a subgroup of 199 miners who had left the coal industry before normal retirement age, taken other jobs, and reported symptoms of chronic bronchitis at the 22-year followup 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.

Soutar et al. [1988] found that miners with the first level of breathlessness (troubled by shortness of breath when hurrying on level ground or walking up a slight hill) had lower lung function than predicted normal values in that region. Average decrements in FEV_1 among miners with the first level of breathlessness were 422, 343, and 215 ml, respectively, for miners in South Wales, Yorkshire, and Tyne and Wear. The second level of breathlessness (shortness of breath walking with other people of the same age on level ground) was associated with average FEV_1 decrements of 592, 491, and 386 ml, respectively, for the same regions. The third level of breathlessness (needing to stop for breath when walking at one's own pace on level ground) was associated with average losses of 942, 812, and 800 ml, respectively.

Soutar et al. [1993] examined clinically important dust-related deficits in lung function of U.K. coal miners analyzed previously [Soutar et al. 1988; Soutar and Hurley 1986]. Clinically important deficits of FEV_1 were defined as the average deficit associated with a severe grade of exertional dyspnea (having to stop for breath when walking at one's own pace on level ground). In two of the areas studied (Yorkshire and North East), no exposure-related deficits were demonstrated; however, age and cumulative dust exposure were highly correlated. In the third area (South Wales), significant exposure-related deficits were observed. The mean FEV_1 of miners in South Wales with severe exertional dyspnea was 942 ml less than that predicted for nonsmokers of the same age and stature. This deficit is close to the value of <65% of predicted normal FEV_1 used by Marine et al. [1988] to indicate a clinically important deficit.

Table 4–5. Estimated average loss of lung function (FEV_1) associated with exposure to respirable coal mine dust

References	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]†	0.69	124
Seixas et al. [1992]‡	3.39	610
Soutar and Hurley [1986]§	0.76	137
Marine et al. [1988]**	0.94 (smokers)	169
	1.02 (nonsmokers)	184

*Note: Cumulative exposure of 180 gh/m^3 corresponds to 45 years (2,000 hr/year) at a mean concentration of 2 mg/m^3 of respirable coal mine dust.
†U.S. miners working before 1970; average of 18 years underground.
‡U.S. miners new to mining since 1970; average of 13 years underground.
§British miners working during the 1950s; 22 years of followup.
**British miners working during the 1950s; 10 years of followup.

4.2.2.3.1.2 Longitudinal studies

Longitudinal studies have demonstrated an association between cumulative exposure to respirable coal mine dust and the rate of decline in FEV_1 [Seixas et al. 1993; Leigh 1990; Attfield 1985; Love and Miller 1982]. 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 gh/m^3 had an FEV_1 loss of 42 ml in 11 years, with an additional FEV_1 loss of 122 ml among smokers. In a study of 1,470 U.S. coal miners, Attfield [1985] found that the dust-related FEV_1 loss was 36 to 84 ml over 11 years, with an additional FEV_1 loss of 100 ml among smokers.

In a longitudinal study of new coal miners (those who began working in mining since 1970), the average loss related to dust exposure was 13.8 ml per gh/m^3 during the first 3 to 4 years of mining (at round 2 of the National Study of Coal Workers' Pneumoconiosis), with no additional exposure-related loss over approximately the next 13 years (between rounds 2 and 4 of the National Study of Coal Workers' Pneumoconiosis) [Seixas et al. 1993]. Thus, the average exposure-related loss was 3.39 ml per gh/m^3 over the 15- to 17-year period. Another U.S. study reported an average FEV_1 loss of 67 ml per year for the first 2 years of mining, with an average FEV_1 loss of 14.4 ml per year for the next 5 years [Hodous and Hankinson 1990]. However, dust exposure estimates were not provided. The results of the latter two studies suggest (1) a nonlinear relationship between the rate of decline in FEV_1 and coal mine dust exposure, with the greatest rate of decline in FEV_1 occurring during the first few years of mining, and (2) a reduction in the rate of decline associated with subsequent coal mine dust exposures.

In a longitudinal study of lung function in 384 coal miners from France, the average rates of decline for FEV_1 and FVC ranged from 47 ml/year for living nonsmokers to 78 ml/year (measured during

life) for deceased smokers [Dimich-Ward and Bates 1994]. The rate of decline in FEV_1 after retirement decreased among coal miners who had never smoked but increased among smokers [Dimich-Ward and Bates 1994].

Such factors as past dust exposure, smoking, and alcohol consumption were associated with decreased FEV_1 and chronic bronchitis in a longitudinal study of Australian coal miners [Leigh 1990]. The mean loss of FEV_1 in 15 years was 0.81 L [Leigh 1990].

4.2.2.3.2 Smoking

The roles of dust exposure and smoking in the development of COPD among coal miners has been the subject of much debate [Attfield and Hodous 1992; Morgan 1986, 1983, 1980; Cochrane 1983; Seaton 1983]. Morgan [1986] has suggested that the effects of smoking and dust exposure are different in that smoking causes severe losses in lung function in a small percentage of individuals and dust exposure causes small losses in lung function in the majority of individuals. Findings from two exposure-response studies of lung function in U.S. miners [Attfield and Hodous 1992; Attfield and Hodous 1989] did not support that suggestion.

Attfield and Hodous [1992] found that both dust exposure and smoking caused shifts in the distribution of FEV_1 values. Loss of FVC was also related to cumulative dust exposure, although the magnitude of the FVC loss was slightly smaller than that for FEV_1. In an earlier analysis of lung function in the same coal miner population reported by Attfield and Hodous [1992] (but without dust exposure data), Morgan et al. [1974] found that the number of years underground was associated with similar losses in both FEV_1 and FVC. Thus, the number of years worked was not associated with a reduction in the FEV_1/FVC ratio [Morgan et al. 1974]. Attfield and Hodous [1992] found an exposure-related loss of the FEV_1/FVC ratio that was statistically significant but small in magnitude.

Among U.K. coal miners, Soutar and Hurley [1986] found that cumulative dust exposure was related to losses in both FEV_1 and FVC. Smoking was associated with a reduction in the ratio of FEV_1/FVC (i.e., FEV_1 was reduced more than FVC), but dust exposure was not related to this ratio (i.e., FVC was reduced at least as much as FEV_1) [Soutar 1987; Soutar and Hurley 1986].

4.2.2.3.3 Dust characteristics

Some studies have shown that the coal rank of the dust to which miners are exposed may affect lung function. Morgan et al. [1974] reported greater decrements of FEV_1 and FVC and greater RV among miners exposed to higher-rank coal (an effect observed in smokers, ex-smokers, and those who never smoked). Because the study did not include dust exposure data, the results could reflect differences in the extent of dust exposure. In a study that did include exposure data [Attfield and Hodous 1992], miners exposed to higher-rank eastern coal had greater decrements in FEV_1 than those with the same cumulative exposure to lower-rank western coal.

Some evidence suggests that exposure to coal mine dust of larger particle size than the respirable fraction may affect the development of COPD. Potts et al. [1990] suggested that thoracic dust, which is deposited primarily in the bronchial airways, may be important in the development of

bronchitis and loss of lung function. Thoracic dust concentrations can vary by location in underground coal mines, and thoracic dust concentrations may be five to seven times higher than respirable dust levels [Potts et al. 1990; Burkhart et al. 1987]. Two U.K. studies investigated the correlation between "total" or "inspirable" dust and respiratory disease [Cowie et al. 1981; Mark et al. 1988]. Both studies found that estimated concentrations of the coarse fractions of dust provide no better correlations with disease than concentrations of the respirable fraction.

4.2.3 Predicted Prevalence of Simple CWP, PMF, and Decreased Lung Function Among U.S. and U.K. Coal Miners

In several epidemiological studies of U.S. and U.K. coal miners, statistical models (primarily linear or logistic regression) have been used to estimate the prevalence of simple CWP, PMF, or specific decrements in lung function. The models for simple CWP and PMF have generally included covariates for age and coal rank, and the models for decreased lung function have generally included covariates for age, height, and smoking.

4.2.3.1 Predicted Prevalence of Simple CWP and PMF

Both U.S. and U.K. studies indicate that the risk of developing PMF is greater than the previous risk estimates that were used as a basis for the current U.S. standard for coal mine U.S. and U.K. estimates indicate that 7/1,000 (0.7%) to 89/1,000[§§] (8.9%) miners who were exposed to respirable coal mine dust for 40 years at the current MSHA PEL of 2 mg/m^3 will develop PMF by the age of 58 (Table 4-6); 65 to 316 miners/1,000[§§] will develop simple CWP category 1 or greater. The range of estimates quoted reflect the higher risks predicted for exposure to dust of higher-rank coal as well as possible variations in exposure conditions and differences between the populations of coal miners studied. The risk estimates from the U.S. studies are consistently higher than those from the U.K. studies, even though the various studies are similar in magnitude. However, the estimated reductions in simple CWP or PMF are comparable in the U.S. and U.K. studies. Up to threefold reductions in the prevalence of simple CWP and PMF are predicted if exposures are reduced from a mean concentration of 2 to 1 mg/m^3[***] over a 40-year working lifetime (Table 4-6).

4.2.3.2 Predicted Prevalence of Decreased Lung Function

In addition to the risk of simple CWP and PMF, epidemiological studies have shown that coal miners have an increased risk of developing COPD. COPD may be detected from decrements in certain measures of lung function, especially FEV_1 and the ratio of FEV_1/FVC. Decrements in lung function associated with exposure to coal mine dust are severe enough to be disabling in some miners, whether or not pneumoconiosis is also present [Hurley and Soutar 1986; Soutar and Hurley 1986]. A severe or disabling decrement in lung function is defined here as an FEV_1 <65% of expected normal values; an impairment in lung function is defined as an FEV_1 <80% of predicted

[§§]Range of mean prevalences.

[***]Measured using the current MSHA sampling method (Section 5.1 and Appendix J); 1 mg/m^3 is equivalent to 0.9 mg/m^3 when measured using the NIOSH recommended sample criteria (Sections 5.2 and 5.4).

Table 4-6. Predicted prevalence of simple CWP and PMF among U.S. or U.K. coal miners at age 58 following exposure to respirable coal mine dust over a 40-year working lifetime

Study and coal rank	Mean concentration of respirable coal mine dust (mg/m^3)	Predicted prevalence (cases/1,000)		
		CWP≥1*	CWP≥2	PMF
Attfield and Seixas [1995]:†				
High-rank bituminous	2.0	253 (204-308)‡	89 (60-130)	51 (30-85)
	1.0	116 (88-150)	29 (16-51)	16 (7-36)
Medium/low-rank bituminous	2.0	144 (117-176)	31 (20-49)	14 (7-27)
	1.0	84 (64-110)	17 (9-30)	9 (4-19)
Attfield and Morring [1992b]:§				
Anthracite	2.0	316 (278-356)	142 (118-172)	89 (69-113)
	1.0	128 (108-152)	46 (35-60)	34 (24-48)
High-rank bituminous (89% carbon)	2.0	282 (250-317)	115 (94-141)	65 (49-85)
	1.0	119 (100-142)	41 (31-54)	29 (20-41)
Medium/low-rank bituminous (83% carbon)	2.0	121 (108-136)	40 (33-49)	22 (17-29)
	1.0	74 (62-89)	24 (18-31)	17 (12-24)
Medium/low-rank bituminous (Midwest)	2.0	89 (73-108)	28 (20-39)	15** (9-26)
	1.0	63 (52-77)	20 (14-27)	14** (9-21)
Medium/low-rank bituminous (West)	2.0	67 (52-86)	15** (8-26)	13** (7-24)
	1.0	55 (44-68)	14** (10-21)	12** (8-20)
Hurley and Maclaren [1987]:				
High-rank bituminous (89% carbon)	2.0	89	29	18
	1.0	40	12	7

See footnotes at end of table.

(Continued)

Table 4-6 (Continued). Predicted prevalence of simple CWP and PMF among U.S. or U.K. coal miners at age 58 following exposure to respirable coal mine dust over a 40-year working lifetime

Study and coal rank	Mean concentration of respirable coal mine dust (mg/m^3)	Predicted prevalence (cases/1,000)		
		CWP≥1*	CWP≥2	PMF
Medium/low-rank bituminous (83% carbon)	2.0	65	16	7
	1.0	28	7	3

*Abbreviations: CWP≥1 = simple pneumoconiosis category 1 or greater; CWP≥2 = simple pneumoconiosis category 2 or greater; PMF = progressive massive fibrosis.

†Attfield and Seixas [1995] define the coal rank groups as follows:

1. High-rank bituminous (89%-90% carbon): central Pennsylvania and southeastern West Virginia
2. Medium/low-rank bituminous (80%-87% carbon): medium-rank—western Pennsylvania, northern and southwestern West Virginia, eastern Ohio, eastern Kentucky, western Virginia, and Alabama
3. Low-rank: western Kentucky, Illinois, Utah, and Colorado

‡The 95% confidence intervals, where available, are given in parentheses under the point estimates for prevalence (cases/1,000).

§In Attfield and Morring [1992b], the predicted prevalences for CWP category 1 or CWP category 2 did not include high categories.

**Attfield and Morring [1992b] define the coal rank groups as follows:

1. Anthracite: two mines in eastern Pennsylvania (about 93% carbon)
2. Medium/low-volatile bituminous (89%-90% carbon): three mines in central Pennsylvania and three mines in southeastern West Virginia
3. High-volatile "A" bituminous (80%-87% carbon): 16 mines in western Pennsylvania, north and southwestern West Virginia, eastern Ohio, eastern Kentucky, western Virginia, and Alabama
4. High-volatile Midwest: four mines in western Kentucky and Illinois

normal values [Boehlecke 1986; Marine et al. 1988; ATS 1991; Soutar et al. 1993]. An exposure-response relationship between respirable coal mine dust exposure and decrements in lung function has been observed in cross-sectional studies [Attfield and Hodous 1992; Seixas et al. 1992; Marine et al. 1988; Rogan et al. 1973] and confirmed in longitudinal studies [Seixas et al. 1993; Attfield 1985; Love and Miller 1982].

Table 4-7 presents the predicted prevalence of decreased lung function among miners at age 58 who have worked 40 years at a mean concentration of 2 or 1 mg/m^3 of respirable coal mine dust. The predicted prevalences are based on studies of U.S. miners [Attfield and Hodous 1992] and U.K. miners [Marine et al. 1988] and are reasonably consistent. These studies show that among miners who never smoked and who were exposed for 40 years at the current MSHA PEL of 2 mg/m^3 for respirable coal mine dust, an estimated 16 to 63/1,000††† will have FEV_1 <65% of predicted normal values at age 58. Among smokers with the same exposures, an estimated 80 to 173/1,000 will have FEV_1 <65% of predicted values at age 58. These predicted prevalences include the background prevalence (predicted from the model at zero exposure). See Section 7.3.2.1 for further discussion on background prevalence. Excess (i.e., exposure-attributable) risk estimates computed from these studies are provided in Section 7.3.2.2.

†††Range of mean prevalences (range of point estimates).

Table 4-7. Predicted prevalences of decreased lung function* among U.S. or U.K. coal miners at age 58 following exposure to respirable coal mine dust over a 40-year working lifetime

Study and region†	Mean concentration of respirable coal mine dust (mg/m^3)	Lung function decrement (% FEV_1)	Predicted prevalence (cases/1,000)	
			Miners who never smoked	Smokers
Attfield and Hodous 1992:				
East	2.0	<80	141	369
		<65	22	102
	1.0	<80	123	336
		<65	18	87
West	2.0	<80	125	340
		<65	16	80
	1.0	<80	108	309
		<65	13	68
Marine et al. 1988‡	2.0	<80	153	372
		<65	63	173
	1.0	<80	125	314
		<65	52	159

*Decreased lung function is defined as FEV_1 <80% of predicted normal values. Clinically important deficits are FEV_1 <80% (which approximately equals the lower limit of normal [LLN], or the 5th percentile) [Boehlecke 1986; ATS 1991] and FEV_1 <65% (which has been associated with severe exertional dyspnea) [Soutar et al. 1993; Marine et al. 1988].

†Attfield and Hodous [1992] define the following coal ranks and regions:

East: Anthracite (eastern Pennsylvania) and bituminous (central Pennsylvania, northern Appalachia [Ohio, northern West Virginia, western Pennsylvania], southern Appalachia [southern West Virginia, eastern Kentucky, western Virginia]), Midwest [Illinois, western Kentucky], and South [Alabama].

West: Colorado and Utah.

‡Conversion from gh/year to mg-yr/m^3; assumed 1,920 hr/year for U.S. miners.

4.2.4 Surface Coal Miners

4.2.4.1 Health Hazard Evaluations Among Drillers at U.S. 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 in 1979 when a driller who had worked at this mine for 5 years was hospitalized and diagnosed as having silico-proteinosis, a type of silicosis. Among the other nine miners evaluated in the HHE, two cases of CWP category 1 were identified; both involved surface coal miners who had worked as drillers—one for 4 years and the other for 6 years.

In 1982, MSHA requested that NIOSH conduct an HHE at three surface coal mines to evaluate the respiratory status of surface coal miners who were drillers and driller helpers [Cornwell and Hanke 1983]. 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 simple CWP category 2 in the driller group and one case of simple CWP category 1 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.

4.2.4.2 Medical Evaluations of Miners at U.S. Bituminous Surface Coal Mines, 1972–73

During 1972–73, 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; the participation rate was 95.5%. Table 4-8 shows the prevalence of simple CWP 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 simple CWP than miners who had never worked underground or on drill crews.

4.2.4.3 Medical Evaluations of Miners at U.S. Anthracite Surface Coal Mines, 1984–85

During 1984–85, 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]; the participation rate 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 4-9 shows the prevalence of simple CWP among anthracite surface coal miners. The results indicate a higher risk of developing simple CWP among miners who 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 simple CWP 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 Sections 4.2.1.1 and 4.2.1.2). The results of the Amandus et al. [1989] study are consistent with those of the Amandus et al. [1984] study. Both found an excess prevalence (relative to "background" [Castellan et al. 1985]) of simple CWP among surface coal miners who never worked in underground coal mines or on surface coal mine drill crews. Both studies also found that surface coal miners who never worked underground coal but did work on surface drill crews were at risk of developing CWP category 2 or higher.

4.2.4.4 Study of U.K. Surface Coal Miners

A recent study of surface ("opencast") coal miners in the United Kingdom was performed to determine miners' exposures to respirable dust and quartz and to assess their respiratory health [Love et al. 1992]. Concentrations of respirable coal mine dust and respirable quartz were reported to be generally below 1 and 0.1 mg/m^3, respectively. The investigators found that the duration of employment in the dustiest opencast jobs was significantly related to the probability of having radiographic category 0/1 or greater. Age and smoking were controlled in the analyses. The relative risk of category 0/1 doubled for every 10 years worked in those jobs compared with workers of the

Table 4-8. Prevalence of simple CWP among bituminous surface coal miners

Group	Number of workers	Prevalence			
		CWP 1		CWP ≥2	
		%	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 underground or on drill crew; ≤10 years on surface coal mine jobs	516	0.8	4	0.0	0
Never worked underground 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	3.7	3	0	0
Drill crew member for >10 years; never worked in an 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 surface coal miners	1,348*	4.2	56	0.6	8

Adapted from Amandus et al. [1984].
*Of the original 1,438 X-rays, two or more readers determined that 90 were unreadable.

same age who were not exposed to dusty work. The relationship between years worked and category 0/1 or 1/0 remained after excluding 198 men with previous underground work experience. Duration of employment was not associated with chronic bronchitis or measures of lung function (FEV_1, FVC, or FEV_1/FVC). The relationship between years worked and small opacities on the chest X-ray was similar for both rounded and irregular opacities.

4.2.5 Studies of Mortality Among Coal Miners

Studies from the United States [Attfield et al. 1985; Ortmeyer et al. 1973, 1974], the United Kingdom [Miller and Jacobsen 1985; Atuhaire et al. 1985; Cochrane et al. 1979], and the Netherlands [Meijers et al. 1991] indicate that mortality from occupational respiratory diseases (PMF, chronic bronchitis, or emphysema) and accidents is elevated among coal miners relative to the general population. Miners with radiographic evidence of PMF had higher mortality rates than miners with or without simple CWP [Atuhaire et al. 1985; Cochrane et al. 1979; Ortmeyer et al. 1974; Cochrane 1973].

Table 4-9. Prevalence of simple CWP among anthracite surface coal miners

Group	Number of workers*	Prevalence			
		CWP 1		CWP ≥2	
		%	Number	%	Number
Surface miners with previous dust exposure	537	7.1	38	1.1	6
Surface miners with no previous dust exposure	516	3.5	18	1.0	5
Never worked on surface coal mine drill crew	448	2.7	12	0	0
Worked 1-9 years on surface coal mine drill crew	46	4.3	2	2.2	1
Worked >10 years on surface coal mine drill crew	22	18.2	4	18.2	4

Adapted from Amandus et al. [1989].
*Of the 1,073 workers who originally participated, 20 were not included in the analyses.

Regional or coal rank differences have also been reported, with higher standardized mortality ratios (SMRs) for all-cause mortality among miners in the anthracite coal regions of the United States [Ortmeyer et al. 1974]. Miners with decreased lung function (FEV_1/FVC <70% of predicted normal values) had elevated mortality [Ortmeyer et al. 1974]. Mortality rates for ischemic heart disease were lower in coal miners than in the general population [Costello et al. 1975].

4.2.5.1 Mortality Related to Exposure to Respirable Coal Mine Dust

Most studies of mortality in U.S. coal miners did not include exposure information [Rockette 1977; Costello et al. 1974; Enterline 1972]. Attfield et al. [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 [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.

Mortality attributed to pneumoconiosis, chronic bronchitis, or emphysema has been related to cumulative exposure to respirable coal mine dust in both U.S. and U.K. coal miners [Miller and Jacobsen 1985; Kuempel et al. 1995]. In the U.K. study [Miller and Jacobsen 1985], 22-year survival rates were determined for 19,500 coal miners who were medically examined between 1953 and 1958. Within 10-year age categories, significant relationships were observed between increasing cumulative exposure category and increasing mortality from all nonviolent causes, pneumoconiosis, chronic bronchitis, or emphysema as the underlying cause of death. Mortality from all nonviolent causes was significantly elevated among miners with PMF compared to miners without radiographic evidence of pneumoconiosis. Survival was also slightly decreased (2% to 3%) among miners with simple CWP category 1 compared to those without pneumoconiosis.

In the U.S. study [Kuempel et al. 1995], significant exposure-response relationships were observed between cumulative exposure to respirable coal mine dust and mortality from pneumoconiosis, chronic bronchitis, or emphysema as an underlying or contributing cause of death. The study included 8,878 miners who were medically examined during the period 1969-71 and followed through 1979. SMRs for pneumoconiosis mortality increased with increasing cumulative exposure category. The effects of age and smoking were controlled by inclusion of these factors as covariates in the proportional hazards models. Pneumoconiosis mortality was significantly elevated among miners with either simple CWP or PMF and among miners exposed to dust of higher-rank coals. On the basis of these analyses, miners with working lifetime exposures to respirable coal mine dust at a mean concentration of 2 mg/m^3 have an increased risk of dying from pneumoconiosis, chronic bronchitis, or emphysema.

4.2.5.2 Studies of Lung Cancer and Stomach Cancer Among Coal Miners

Most studies have reported that mortality from lung cancer is lower than expected among coal miners when compared with general population rates [Liddell 1973; Costello et al. 1974; Armstrong et al. 1979; Rooke et al. 1979; Ames and Gamble 1983; Atuhaire et al. 1985; Miller and Jacobsen 1985; Kuempel et al. 1995], although some studies have reported elevated lung cancer mortality among coal miners [Enterline 1972; Rockette 1977]. Mortality from lung cancer was not associated with cumulative exposure to respirable coal mine dust in the two studies that evaluated this relationship [Miller and Jacobsen 1985; Kuempel et al. 1995]. In a study of lung cancer by histologic type, Vallyathan et al. [1985] found little difference in the pathologic features of lung cancer in coal miners and in men from the general population who smoke cigarettes. Vallyathan et al. [1985] also found no relationship between lung cancer and years in coal mining.

Some studies have reported that mortality from stomach cancer is elevated among U.S. coal miners when compared with general population rates [Stocks 1962; Enterline 1964; Matalo et al. 1972; Rockette 1977]. Miller and Jacobsen [1985] found a marginally significant relationship between cumulative exposure to respirable coal mine dust and mortality from cancers of the digestive system among U.K. coal miners.

Factors including diet, cigarette smoking, chewing tobacco, and coal dust exposure may play a role in the development of stomach cancer [Wu 1990; Ames and Gamble 1983; Ong et al. 1983; Whong et al. 1983; Ames 1982]. Coal dust cleared from the lungs via mucociliary clearance may enter the stomach, where it undergoes nitrosation or other chemical interactions and forms carcinogenic compounds [Ong et al. 1983; Meyer et al. 1980]. The nitrites and nitrates may enter the stomach from diets containing preserved meats or vegetables, or from the use of tobacco. Laboratory studies have shown that nitrosated extracts of coal dusts and tobacco are mutagenic in the Ames assay [Stamm et al. 1994], induce sister-chromatid exchanges in human peripheral lymphocytes [Tucker et al. 1984; Tucker and Ong 1985], and cause transformation of mouse fibroblasts [Wu et al. 1990]. Reduction in exposures to respirable coal mine dust, tobacco, and foods containing nitrites and nitrates may help reduce the risk of gastric cancer among coal miners.

SMRs for lung cancer [Liddell 1973; Costello et al. 1974; Armstrong et al. 1979; Rooke et al. 1979; Meijers et al. 1991] and heart disease [Costello et al. 1975] have generally been lower than expected among coal miners. Stomach cancer mortality rates were elevated among coal miners in some

studies in the United States [Stocks 1962; Enterline 1964; Matalo et al. 1972; Rockette 1977]. Miller and Jacobsen [1985] found an association between cancers of the digestive organs and coal mine dust exposure in U.K. coal miners, but the effect was not observed independently of pneumoconiosis.

4.3 ANIMAL AND HUMAN STUDIES OF LUNG DUST BURDEN AND CELLULAR MECHANISMS

Although researchers have conducted extensive epidemiological studies of coal miners (including determination of exposure-response relationships), animal and cellular studies have provided additional useful information on the toxicity of respirable coal mine dust and components of that dust (e.g., silica or diesel exhaust). The animal studies of particle deposition and lung clearance have provided information on dose-response relationships. These studies have enhanced our understanding of disease mechanisms. Further research may provide the methods for earlier identification of disease and more effective medical intervention and treatment.

4.3.1 Alveolar Clearance Mechanisms

Both a sequestration and an overload hypothesis have been proposed to model the accumulation of dust in lungs following continuous exposure to particulates. The sequestration hypothesis was first proposed by Soderholm [Soderholm 1981; Vostal et al. 1982]. Later studies by Vincent et al. [1985, 1987] provided support for this model. The sequestration model predicts that some fraction of dust is sequestered or retained in the lungs even at low exposures. This sequestered dust is unaffected by clearance mechanisms and may be trapped in lymphatic tissue, in the interstitial spaces of alveolar walls, or within macules. Sequestration of dust does not necessarily render it nontoxic. Indeed, some proposed models assume that once particulates have entered the alveolar wall, they exhibit greater fibrogenicity than dust in the alveolar spaces.

The normal clearance of particles from the alveolar or pulmonary region of the lungs by alveolar macrophages is regarded as a first-order process [Task Group on Lung Dynamics 1966; Vincent et al. 1985; Morrow 1992]. However, first-order clearance models do not adequately represent the clearance kinetics under the following conditions: (1) when clearance is by dissolution, (2) when the lung is overloaded with particles, or (3) when cytotoxic dust is cleared [Morrow 1992]. At initial dust exposure, deposition exceeds clearance and the lung burden rises. As clearance increases in response to the added burden, the model from the Task Group on Lung Dynamics [1966] predicts that the lung burden begins to level off to a constant, steady-state value, and eventually clearance equals deposition. Recent studies have shown that the pulmonary clearance of retained particles by alveolar macrophages becomes progressively reduced until it essentially ceases; then the lung burden increases linearly at a rate approximately equal to the rate of deposition [Morrow 1988].

The phenomenon of overloading of lung clearance is consistent with overloading or saturation in other biological systems [Witschi 1990]. The overloading of lung clearance has been observed in studies of several animal species (including rats, mice, and hamsters) exposed to various insoluble, respirable particles, including diesel exhaust [Strom et al. 1988; Wolff et al. 1987], carbon black [Strom et al. 1989; Muhle et al. 1990a,b], test toner (polymer pigmented with carbon black) [Bellmann et al. 1991; Muhle et al. 1990c, 1991], titanium dioxide [Muhle et al. 1990a,b], mineral

dusts [Vincent et al. 1985], and amosite fibers [Bolton et al. 1983]. The exposure-dose-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].

As the lung burden increases, alveolar macrophages become activated and release reactive oxygen species and cellular factors that stimulate pathogenic events [Driscoll et al. 1990a]. Activated or overloaded alveolar macrophages may release the following cellular factors: arachidonic acid metabolites [Demers et al. 1988], superoxide anion (O_2-) [Wallaert et al. 1990], platelet- activating factor [Kang et al. 1991], interleukins [Lapp and Castranova 1993], fibronectin, and tumor necrosis factor (TNF) [Vilcek et al. 1986; Driscoll et al. 1990b]. Coal dust-exposed alveolar macrophages from coal miners released significantly increased concentrations of TNF and interleukin-6 after 24-hr culture [Gosset et al. 1991].

Leukotriene B_4, interleukin-8, platelet-activating factor, and platelet-derived growth factor all enhance chemotaxis. In addition, platelet-activating factor and platelet-derived growth factor enhance the production of reactive oxygen species and increase the release of lysosomal enzymes from pulmonary phagocytes [Lapp and Castranova 1993]. Thus, these mediators may play an important role in dust-related inflammation and pathogenesis.

TNF has been the subject of much research. Its functions include (1) stimulating adhesion of polymorphonuclear leukocytes (PMNs) to endothelial cell surfaces (which induces chemotaxis and direct activation of PMNs), (2) indirectly activating fibroblast growth, and (3) inducing mononuclear phagocytes to produce and release cytokine interleukin-1 (IL-1) (which has been suggested to cause fibroblast proliferation and collagen synthesis) and induce the production of reactive oxygen species that 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 and/or other indicators could be acquired or genetically controlled [Borm et al. 1988; Schraufnagel et al. 1987].

Overloading of alveolar clearance has been observed in animal studies to be characterized by the following responses, which may also be relevant in the pathogenesis of dust-related lung diseases: 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, 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 [Morrow et al. 1991; Muhle et al. 1991; Bowden 1987; Campbell and Senior 1981].

The composition of the dust and the surface properties of the particles influence the cellular response. Kuhn and Demers [1991] reported that rat alveolar macrophages exposed to freshly fractured coal dust‡‡‡ produced markedly increased levels of prostaglandin E_2 and thromboxane B_2, whereas those

‡‡‡Freshly-fractured silica particles in the coal mine dust produce increased levels of silicon-based radicals [Dalal et al. 1988, 1989b].

exposed to aged coal dust did not. The harmfulness of the coal dust has been attributed to the proportion of clean silica surface area [Kriegseis and Scharmann 1982; Le Bouffant et al. 1988, 1982]. The cytotoxicity (as assayed by erythrocyte hemolysis) of the silica has been shown to decrease after the particles are incubated in dipalmitoyl lecithin, which is a major component of lung surfactant coating alveoli surfaces [Wallace et al. 1988; Cilento and Georgellis 1991].

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]. For example, in a chronic inhalation study of respirable test toner (a dust with low solubility and low acute toxicity that is used in photographic processes) in rats, retardation of particle clearance progressively increased with lung burdens of toner above approximately 1.0 mg/g 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 at 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 at 1.4 mg/m^3 respirable dust (4 mg/m^3 total dust) (Table 4-10). Signs of lung overloading persisted 15 months after cessation of exposure [Muhle et al. 1990b].

4.3.2 Studies of Alveolar Clearance in Animals and Relevance to Dust-Exposed Workers

The finding from animal studies that alveolar-macrophage-mediated clearance can become saturated following long-term exposure to insoluble particles may be relevant to working lifetime exposures of coal miners. Coal miners may accumulate lung dust burdens of more than 10 mg/g of lung over a working lifetime under the current MSHA PEL of 2 mg/m^3 for respirable coal mine dust [Pritchard 1989]. Table 4-11 shows that 5 to 15 mg of dust/g of lung was retained in the lungs of British coal miners with cumulative exposures similar to those of U.S. miners exposed for 40 to 45 years at about 2 mg/m^3 of respirable coal mine dust. At 15 mg of retained dust/g of lung, slight to moderate fibrosis occurred in all animals in the chronic inhalation study (Table 4-10). With 15 mg of retained dust/g of lung, coal miners had developed PMF; and with 5 mg/g, coal miners had developed minimal fibrosis (Table 4-11).

A comparison of the lung dust burdens that caused overloading of alveolar clearance in animal studies and the lung dust burdens found in coal miners suggests that overloading may occur in the lungs of coal miners exposed at the current PEL of 2 mg/m^3 for respirable coal mine dust. However, these comparisons do not take into account additional factors that may be important—such as duration of exposure, dust composition (e.g., silica content), or differences in clearance rates or lung morphology of animals and humans.

4.3.3 Biological Factors in Individual Susceptibility to Fibrosis

The process of lung fibrosis is a multi-faceted, cascading process involving various inflammatory cells (e.g., macrophages, polymorphonuclear leukocytes, and lymphocytes) and distinct mediators [Lehnert 1990; Bowden 1987]. Thus, it is not known why some coal miners develop simple CWP or PMF and others with similar exposures do not [Lassalle et al. 1990]. Differences in individual susceptibility probably play a role [Borm et al. 1992, 1988].

Table 4-10. Findings of chronic inhalation study* of test toner in F-344 rats

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

Adapted from Mermelstein and Kilpper [1990].
*Study duration was 24 months (6 hr/day, 5 days/week).

Table 4-11. Cumulative exposure, retained dust levels, and disease in British coal miners

Coal rank (% carbon)	Number of miners	Mean cumulative exposure (gh/m^3)*	Mean dust retained 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

Based on data from Douglas et al. [1986].
*In U.S. coal miners, estimates of cumulative exposure to respirable coal mine dust range from 122 to 180 gh/m^3 (i.e., 35 years of exposure at 2 mg/m^3 and 1,740 hr/year equals 122 gh/m^3; or, 45 years of exposure at 2 mg/m^3 and 2,000 hr/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 and 9 mm in diameter.
PMF: Fibrotic dust lesions 10 mm or more in diameter.

Bronchoalveolar lavage in humans has been used to recover alveolar macrophages to study the differences in factors released from alveolar macrophages of dust-exposed miners and unexposed controls. In coal miners who worked underground for a mean of 17 years and had no clinically detectable pneumoconiosis, a statistically significant increase in alveolar macrophages with surface

ruffling (an indicator of alveolar macrophage activation) was observed [Lapp et al. 1991]. Significant increases in surface ruffling were also observed in alveolar macrophages from coal miners with pneumoconiosis [Takemura et al. 1989] and in rats chronically exposed to coal dust [Castranova et al. 1985; Lewis et al. 1989]. 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 alveolar macrophages than comparison workers [Takemura et al. 1989].

Lassalle et al. [1990] compared the secretion of the cytokines TNF-alpha and IL-1 by alveolar macrophages from French coal miners and control subjects (11 nonminers living in the same area). A total of 40 coal miners were studied—19 with simple CWP; 11 with PMF; and 10 without CWP, including 5 retired coal miners. Alveolar macrophages were harvested by bronchoalveolar lavage. The investigators found that the alveolar macrophages from patients with CWP spontaneously secreted higher levels of TNF-alpha and IL-1 than did alveolar macrophages from controls. Among miners without radiographic evidence of simple CWP or PMF, high levels of both TNF-alpha and IL-1 were secreted from alveolar macrophages of working miners—but not from those of retired miners. Kuhn et al. [1991] also found that the alveolar macrophage production of eicosanoids and cytokines was lower in former U.S. coal miners than in working miners.

Rom [1991] reported that among individuals exposed to inorganic dust (including some coal miners), only those with respiratory impairment had alveolar macrophages that released significantly increased amounts of the oxidants superoxide anion and hydrogen peroxide. Furthermore, occupational exposures were similar among individuals with or without impairment, which indicates possible differences in individual susceptibility.

Chronic smokers may have impaired clearance of particles deposited in the lungs and persistent inflammatory responses [Mauderly et al. 1990; Bohning et al. 1982]. The slowing of particle clearance from the alveolar region of the lung would promote sequestration of larger lung dust burdens in smokers than 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 impaired alveolar clearance of tracer particles; the magnitude of this impairmant was similar to the magnitude of impairments reported for human smokers [Bohning et al. 1982]. However, epidemiological 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 a simple reflection of dust exposure: patterns of deposition or clearance may differ between miners who develop pneumoconiosis and those who do not. Pathological studies have shown that miners with PMF (or complicated CWP) accumulated more dust in their lungs *and* more dust per unit of dust exposure than miners without PMF [Douglas et al. 1986].