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HISTORICAL RESEARCH REPORT

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DUST-RELATED RISKS OF RADIOLOGICAL CHANGES IN COALMINERS OVER A 40-YEAR WORKING LIFE:

REPORT ON WORK COMMISSIONED BY NIOSH

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SUMMARY

This study provides estimates, using data from the Pneumoconiosis Field Research (PFR) of the National Coal Board in Britain, of the prevalence of simple pneumoconiosis (CWSP) and of progressive massive fibrosis (PMF) in coalminers at various stages of a 40-year working life. It considers in particular the risks associated with work at dust concentrations of 2 mg m^{-3}, and it explores the sensitivity of these estimates to variations in the proportion of men who transfer to work at concentrations of 1 mg m^{-3} once CWSP category 1 or more is diagnosed. Several simplifying assumptions were made, the most important being that men left the industry only after an attack of PMF, and that PMF is irreversible.

Data from 52 264 intervals at risk were used to estimate the probabilities of radiological changes over five-year periods, for various combinations of age, dust exposure, and carbon content of the coal, using logistic regression methods. These estimates were applied in turn to the eight successive five-year periods which comprise a 40-year working life, to give estimates of the required long-term risks.

Results suggest that for coal of carbon content 86.2%, typical of conditions in Britain, the 40-year risks of PMF incidence at 2 mg m^{-3} dust concentration are 1.19% for PMF, and 3.67% for simple pneumoconiosis category 2 or more (including PMF). Corresponding estimates for coal of 83% carbon, more typical of conditions in the USA, were 0.71% for PMF, and 2.49% for category 2 or 3 CWSP or PMF. The transfer to lower dust concentrations of men with simple pneumoconiosis had negligible effect on the estimated risks.

The long-term risks of category 2 or more CWSP associated with work at high dust concentrations (say 6 to 7 mg m^{-3}) were on average similar to estimates from previous PFR studies. However at lower dust levels, say 1 to 4 mg m^{-3}, the risks estimated now were higher than those reported previously. On the other hand the new estimates of the long-term risks of PMF were lower than preliminary estimates reported last year.

Results reinforce the conclusion from other recent studies of PMF, that the limitation of dust exposures for all miners is the only reliable way of limiting PMF. We think that the concentration-specific estimates of long-term PMF risks described are the most reliable indices of their kind available to date. They provide a sound basis for control strategies aimed directly at preventing PMF.

1. INTRODUCTION

Early in 1984 this Institute published results, based on about 50 000 observations of men at risk from 25 years of the Pneumoconiosis Field Research (PFR) in Britain, estimating the probabilities that working miners without progressive massive fibrosis (PMF) would develop the disease over five-year periods of risk (HURLEY *et al.*, 1984). The risk estimates took account of a man's age, cumulative exposure to respirable dust, and attained category of coalworkers' simple pneumoconiosis (CWSP) at the start of the five-year risk periods, and of the colliery where he was employed at that time. All four characteristics were shown to be related to the risks of a PMF attack. Also, the colliery-related differences in risk were clearly associated with the carbon content of the coal at the 24 pits included in the research. The results have since been revised on a slightly smaller but more highly validated dataset (HURLEY *et al.*, 1987). The main results were unchanged.

Meanwhile, the study was extended to give first estimates of the risks of a PMF attack, in miners, over a 35-year working life. The age- and exposure-specific prevalence of the four major categories of CWSP was estimated using substantially the same dataset as HURLEY *et al.* (1984). The estimates of attained category of CWSP, together with appropriate values of age and cumulative exposure, were then combined repeatedly with five-year risk estimates of PMF incidence to give estimates of the 35-year risks of a PMF attack. Results were reported to the 1985 ACGIH Conference in Pittsburgh, USA (HURLEY and JACOBSEN, 1986).

The US National Institute of Occupational Safety and Health (NIOSH) subsequently commissioned an extension of the work reported at Pittsburgh. The objectives of this further exercise, and the assumptions about coalmining and PMF on which NIOSH wanted the risk estimates to be based, are recorded in full in Appendix 1. The first objective was to provide age-specific estimates of the prevalence of PMF and of CWSP at any time during a 40-year working life from age 18 onwards, assuming that occurrence of PMF was the sole reason for leaving the industry in that period. Risks were to be estimated on the assumption that in general, miners would be exposed to a respirable dust concentration of 2 mg m^{-3}. However, miners were assumed eligible for an X-ray every five years and if CWSP category 1 or more was found, the man could transfer to work in reduced dust conditions of 1 mg m^{-3}. The second objective was to examine how sensitive are the estimates of PMF and of CWSP prevalences to changes in the proportion of men with CWSP category 1 or more who transfer to lower dust conditions.

The present report summarises the methods used in carrying out the commissioned work, and the results of it. Some remarks on the findings and on their implications are also included. Details are included in the various Appendices.

2. SUBJECTS AND METHODS

2.1 Strategy, subjects and data

In order to estimate the prevalence of radiological abnormality among miners in the course of a 40-year working lifetime, the entire period was divided into eight successive five-year intervals. The strategy adopted was first to examine change in radiological category over five-year periods, and then to apply the estimated risks of radiological changes, in succession, to the eight five-year periods of a 40-year working life. Change from PMF was not considered because it was assumed that the condition was irreversible, and so it was possible and convenient to base estimates of five-year radiological changes on the same set of 52 264 risk periods as used by HURLEY *et al.*, (1987),

Subjects and data are described fully by HURLEY *et al.*, and are summarised again in Appendix 2 to the present report. Briefly, the data refer to 52 264, approximately five-year, periods when miners then employed in the coal industry in Britain and participating in the PFR were at risk of developing PMF for the first time. The risk periods do not all refer to different individuals, but were generated from the attendance of about 30 000 miners at two or more successive PFR medical surveys between 1953 and 1978. Estimates of individuals' cumulative exposures to respirable coalmine dust up to the start of the periods where they were at risk, and during the risk periods themselves, were derived from detailed work history records linked to results from an intensive programme of environmental sampling at the 24 research collieries. Radiographs were classified in accordance with the ILO scheme(s) by one or more doctors from the National Coal Board's panel of radiological specialists. Some of the readings used were intended originally for clinical rather than for epidemiological purposes.

2.2 Methods

The work was carried out in four stages. First, general estimates were made of the probabilities of change in radiological category over five-year periods, and of how these probabilities depend also on age, dust exposure and the carbon content of the coal. Then the experience of the hypothetical mining population, as described in the NIOSH commission, was followed through to identify the values of age, cumulative dust exposure and percent carbon experienced by various subgroups of the men at the start of each five-year period. Exposure calculations assumed 1 631 working hours per year. Three values of percent carbon were considered: 83%, 86.2% and 89%, corresponding approximately to the mean value plus or minus one standard deviation in the data set of 52 264 risk periods.

In the third stage, the various combinations of age, exposure and percent carbon in the NIOSH mining population at the start of each five-year period were linked together with the general estimates of age-, exposure- and carbon-specific risks of radiological change, to give specific estimates of how various subgroups progressed or regressed in each five-year period. Finally, the experience of the entire hypothetical mining population was considered through the eight successive five-year risk periods, estimating the changes in radiological status in each interval and taking these attained prevalences as starting points for the succeeding risk period. The entire process was carried out assuming various proportions of men with CWSP who transfer to more favourable dust conditions.

Full details of the methods are given in Appendix 3.

3. RESULTS

3.1 Estimates of the prevalence of radiological abnormality over a 40-year working life

Table 1 shows estimated prevalences of CWSP categories 0, 1, 2 and 3, and of PMF, at five-yearly intervals from age 18 to age 58 years, in miners exposed to dust concentrations of 2 mg m^{-3} throughout their time at work (i.e. assuming that no miners with CWSP transferred to the lower conditions of 1 mg m^{-3}).* The results show that at older ages, the prevalence of PMF approximately doubles every five years and varies substantially with variations in carbon content. Prevalence of CWSP of various categories also varies positively with age and carbon content, but in a less dramatic way.

Comparisons of Table 1 with estimated prevalences at other dust concentrations may be of interest. Appendix 4 includes additional relevant results, referring to dust concentrations of 1.0, 1.5, 2.5 and 3.0 mg m^{-3}, assuming as in Table 1 that no miners with CWSP transferred to lower dust conditions.

3.2 Effect of varying the level of participation in the five-yearly X-ray scheme

Table 2 shows the estimated percentage prevalences of CWSP and of PMF at age 58 years for various levels both of participation in the five-yearly X-ray scheme, and of transfer of men with CWSP to lower dust concentrations. The results show clearly that the levels of participation and of transfer do not influence the prevalence of radiological abnormality, to any practically significant extent.

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* Throughout this report dust concentrations refer to average shift concentrations measured close to where men are working throughout a shift and during travel to and from pit bottom. They are therefore not the same as the fixed-point measurements made in British collieries for control purposes.

TABLE 1 Probabilities (%) that a man will have simple pneumoconiosis (categories 1, 2, 3) or PMF assuming a working life of 40 years from age 18 to age 58, and exposure to an average dust concentration of 2 mg m^{-3}, tabulated by coal rank (measured by percent carbon) and age.

Coal rank (% carbon)	Radiological Category	Age							
		23	28	33	38	43	48	53	58
83.0	CWSP Ø	99.96	99.71	99.15	98.26	97.02	95.41	93.41	91.02
	CWSP 1	0.04	0.27	0.75	1.47	2.42	3.58	4.94	6.49
	CWSP 2	0.00	0.02	0.09	0.23	0.46	0.78	1.17	1.63
	CWSP 3	0.00	0.00	0.00	0.01	0.02	0.05	0.09	0.15
	PMF	0.00	0.00	0.01	0.03	0.08	0.19	0.38	0.71
86.2	CWSP Ø	99.96	99.64	98.95	97.83	96.26	94.20	91.65	88.59
	CWSP 1	0.04	0.32	0.91	1.78	2.92	4.31	5.94	7.75
	CWSP 2	0.00	0.03	0.12	0.33	0.65	1.09	1.63	2.23
	CWSP 3	0.00	0.00	0.01	0.02	0.04	0.08	0.15	0.25
	PMF	0.00	0.00	0.01	0.05	0.14	0.31	0.64	1.19
89.0	CWSP Ø	99.96	99.58	98.74	97.38	95.45	92.93	89.80	86.06
	CWSP 1	0.04	0.38	1.06	2.08	3.40	5.01	6.86	8.88
	CWSP 2	0.00	0.04	0.17	0.44	0.87	1.45	2.13	2.86
	CWSP 3	0.00	0.00	0.01	0.03	0.06	0.12	0.22	0.36
	PMF	0.00	0.00	0.02	0.08	0.22	0.49	0.99	1.84

TABLE 2 Probabilities (%) that a man will have simple pneumoconiosis (categories 1, 2, 3) or PMF at age 58 after a working life of 40 years exposed to an average dust concentration of 2 mg m^{-3}, by percentage of men with category 1 or more simple pneumoconiosis or PMF who opt to transfer to lower dust conditions (1 mg m^{-3}). (Figures shown assume a coal rank of 83% carbon.)

Percentage participating	Percentage transferring	Radiological category				
		CWSP 0	CWSP 1	CWSP 2	CWSP 3	PMF
0	0	91.02	6.49	1.63	0.15	0.71
20	50	91.03	6.48	1.63	0.15	0.71
	100	91.04	6.48	1.62	0.15	0.71
40	50	91.04	6.48	1.62	0.15	0.71
	100	91.05	6.47	1.62	0.15	0.71
60	50	91.05	6.47	1.62	0.15	0.71
	100	91.07	6.46	1.62	0.15	0.71
80	50	91.05	6.47	1.62	0.15	0.71
	100	91.08	6.45	1.62	0.15	0.71
100	50	91.06	6.46	1.62	0.15	0.71
	100	91.09	6.44	1.61	0.14	0.70

4. DISCUSSION

4.1 Reliability of data and of methods

The reliability of the data has been discussed in detail by HURLEY *et al.* (1987). The main points are summarised again in Appendix 5, Sections A5.1 to A5.3. Section A5.4 of that Appendix includes discussion of several aspects of the methodology used in constructing estimates of long-term risk from the data available for study.

4.2 Comparisons of current with previous risk estimates

4.2.1 Risks over five- or ten-year periods

The present estimates of the risks of a PMF attack over a five-year period were based on the full dataset of 52 264 intervals rather than on a sample, as in HURLEY *et al.* (1987) but included a less comprehensive set of explanatory variables. Estimates of the effect of cumulative exposure, age, and CWSP category were however very similar on both occasions.

Earlier dust-specific estimates of the short-term risks of CWSP changes refer to ten-year rather than to five-year periods (JACOBSEN *et al.*, 1971; JACOBSEN, 1973). They were based on film readings by more doctors, and under more controlled conditions, but included fewer working miners than the present study, and they refer to dust exposure during the 10-year study periods rather than to estimated lifetime exposures.

Nevertheless, the two sets of estimates are similar, in qualitative terms. They both show that exposure to dust increases the chances of radiological progression among men with category 0 CWSP at the start of the risk periods. Progression from category 1/0 has also been shown to be dust-related (JACOBSEN, 1973). However at higher categories of CWSP it appears from both studies that the dominant influence on progression is the severity of attained simple pneumoconiosis.

4.2.2 Estimates of risks over a working life

Earlier PFR studies also provided estimates of the risks that miners would develop category 2 or more CWSP over a 35-year working life at various dust concentrations (JACOBSEN *et al.*, 1971; JACOBSEN, 1973; HURLEY *et al.*, 1982). For the purposes of comparison, the results from the present study (Table 1 and Appendix 4) were extended to provide new estimates of the 35-year risks of category 2 or more CWSP, or PMF, over a similar range of dust concentrations (Figure 1). Figure 2 shows the new estimates, for coal of carbon content 86.2%, in relation to earlier results. At high dust concentrations (6 to 7 mg m^{-3}) the various estimates are similar, but the new results suggest that at lower dust concentrations (say 1 to 4 mg m^{-3}) the risks are higher than estimated previously (Figure 2). The inclusion of PMF as part of the new response is not sufficient to explain the difference.

Figure 3 shows that the present estimates of the long-term risks of PMF are however lower than the preliminary estimates of HURLEY and JACOBSEN (1986). The data and methods of the present study are in some important respects better than those used in the preliminary work (see Appendix A5.4) and so we consider that the preliminary estimates have now been superseded and are no longer relevant.

4.3 Percent carbon

The present results showed substantial differences in the risks of a PMF attack, over five-year periods and long-term, according to the percent carbon of the coal at the colliery where a man was surveyed. Differences in PMF risks according to coalfield or region within Scotland, England and Wales are well-known, and have been described for example by McLINTOCK *et al.* (1971), SHENNAN *et al.* (1981) and by ROBERTSON *et al.* (1987). That these differences are related to percent carbon was shown clearly by HURLEY *et al.* (1987).

Because coal mined in the USA is generally of lower rank than in Britain, estimates of PMF risks for coal of 83% carbon content may be the set most relevant to US conditions.

4.4 Transfer factor

It is noteworthy that the estimated risks are practically unaffected by variations in the proportions of men with CWSP category 1 who subsequently transfer to work in lower dust conditions.

4.5 Relevance to ex-miners

The present results refer to miners while employed in the coal industry. MACLAREN and SOUTAR (1985) showed that PMF could develop for the first time after men had left the industry, and indeed that the crude attack rate may be higher in ex-miners than in men who remain at work as miners. It appears however that when cumulative exposure is taken into account, the dust-related attack rate of PMF is similar in miners and in ex-miners (HURLEY and MACLAREN, in press). Thus the present results may well apply to ex-miners also.

4.6 Further work

We think that it is desirable to carry out further analysis to establish whether and to what extent the dust-specific estimates reported here would differ if radiological category at more than one earlier survey had been taken into account (Appendix A5.4.2).

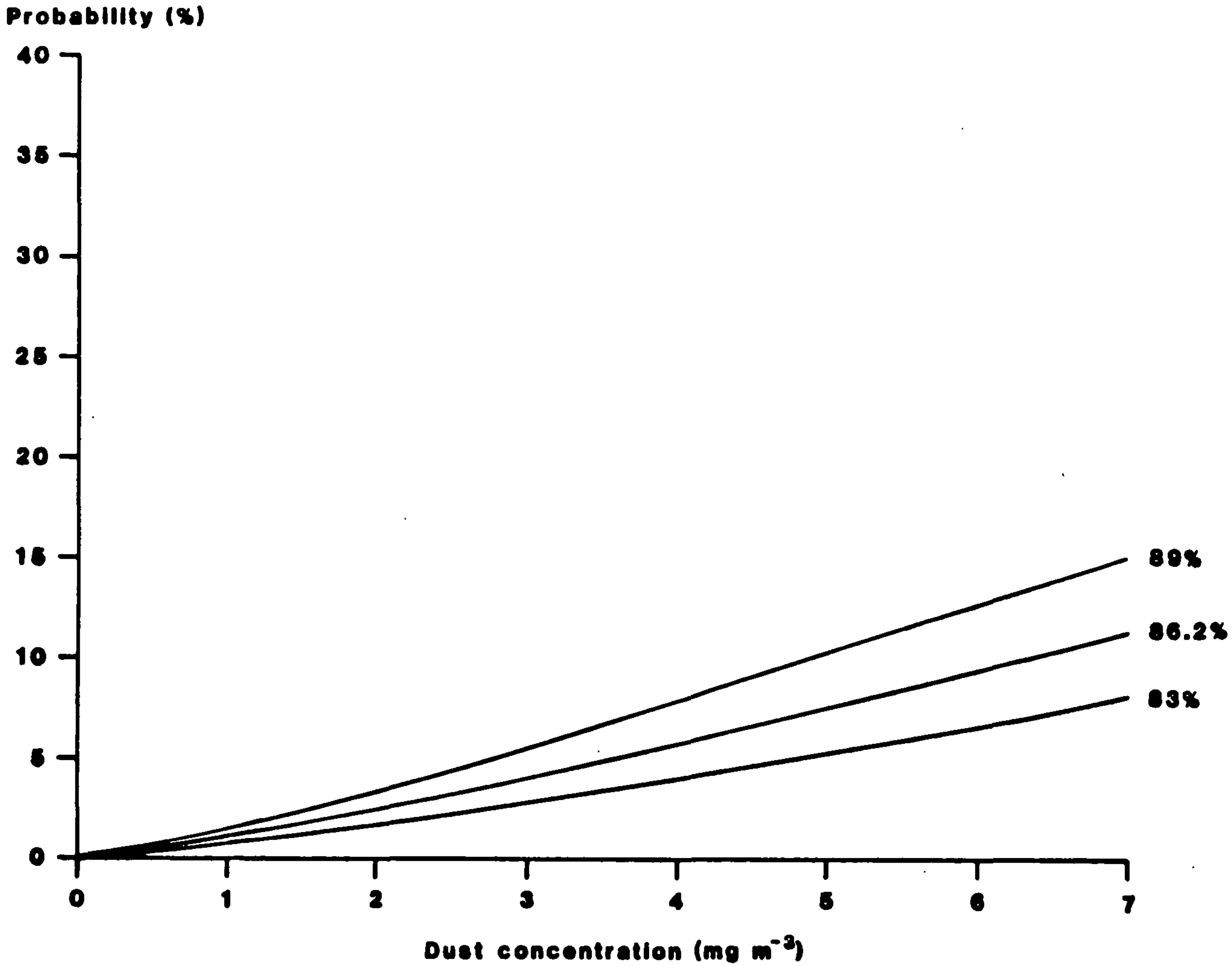

Figure 1 Estimates of the proportion (%) of miners with category 2 or more CWSP, or PMF, after 35 years' work from age 18 onwards at various dust concentrations. Estimates refer to three values of percent carbon, and assume 1 631 hours worked per year.

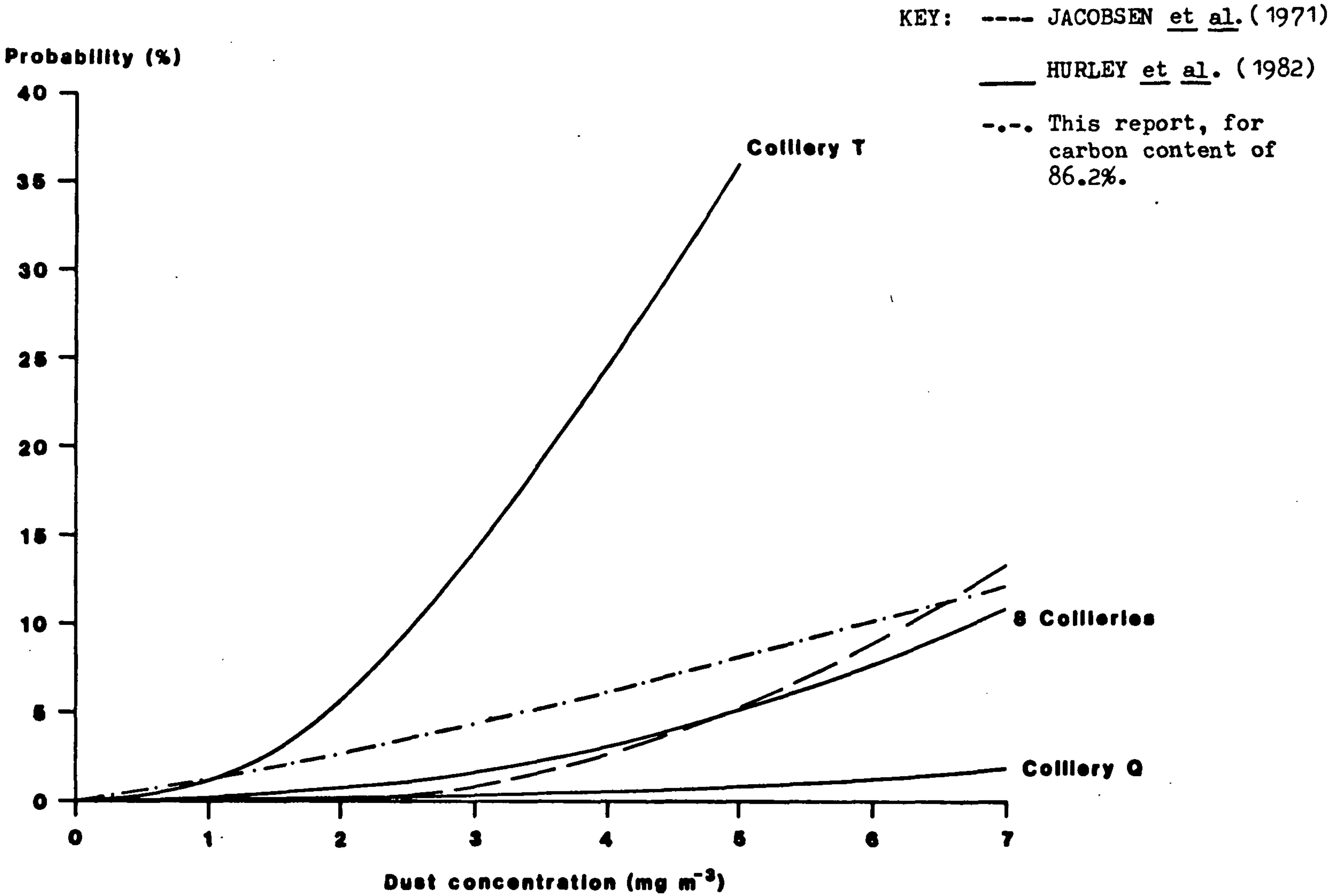

Figure 2 Estimates from various studies of the concentration-specific risks of showing category 2 or more CWSP after 35 years' work, at 1 740 hours per year.

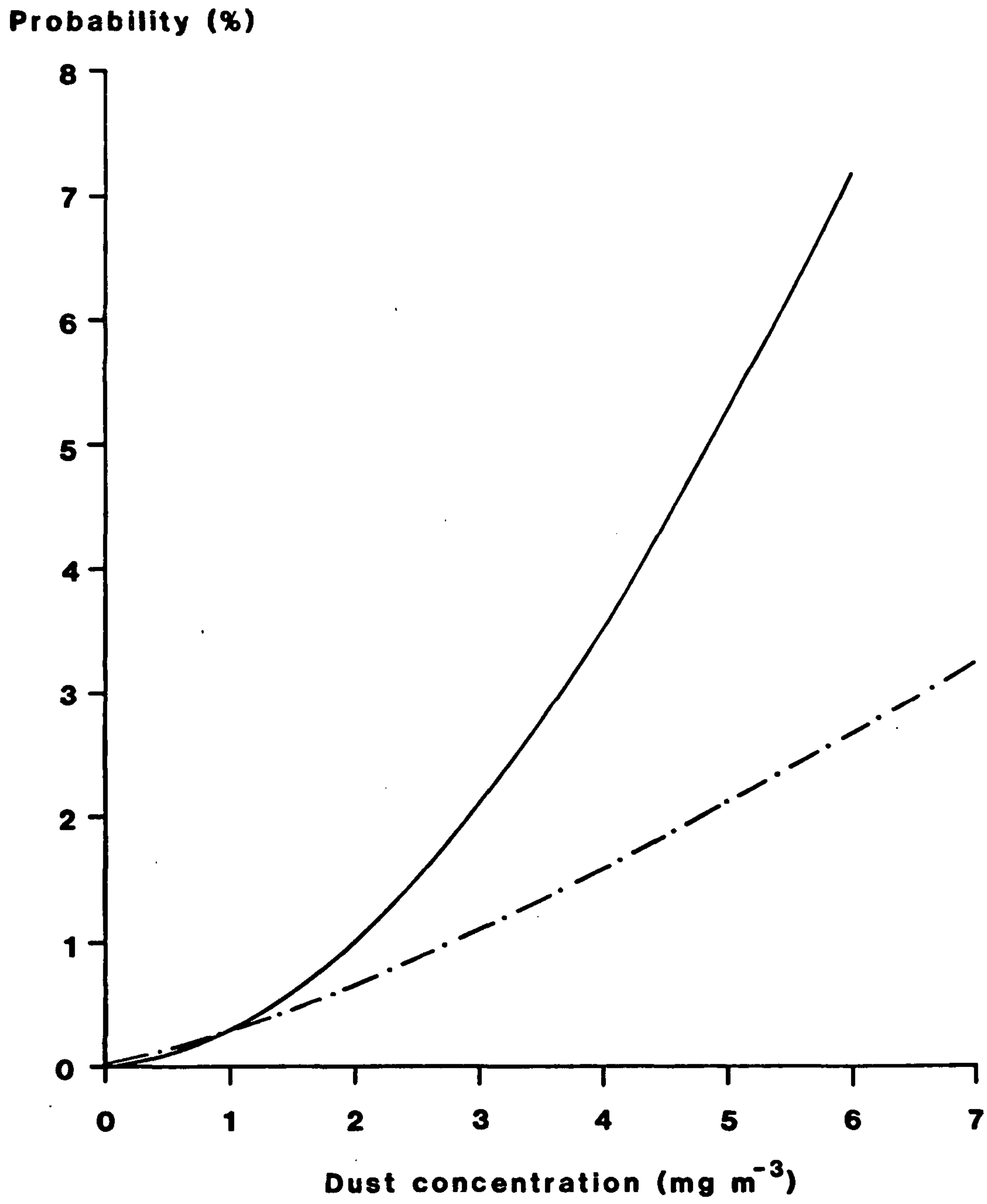

Figure 3 Estimates from two analyses of the concentration-specific risks of PMF incidence over a 35-year working life, at 1 631 hours worked per year

(a) ____ HURLEY and JACOBSEN (1986).

(b) —·—·— This report.

5. CONCLUSIONS

5.1 The risk of developing categories 1, 2 or 3 of coalworkers' simple pneumoconiosis after 40 working years' exposure to 2 mg/m^3 respirable dust containing 83% carbon is estimated as 8.3%. The estimated risk of contracting PMF under the same conditions is 0.7%.

5.2 If a man develops category 1 simple pneumoconiosis following exposure over periods less than 40 working years to precisely 2 mg/m^3 respirable dust, then reducing his exposure to 1 mg/m^3 for the remainder of that 40-year working life will not reduce appreciably his chances of developing further radiological changes, including the development of PMF.

5.3 It follows that if miners' risks of developing pneumoconiosis, including PMF, are to be reduced appreciably to less than the levels estimated above (5.1), then it will be necessary to restrict their dust exposures to less than 2 mg/m^3 throughout their working lives.

5.4 These findings reinforce our more general main conclusion from other recent discussions of the data used for the analyses reported here (HURLEY and JACOBSEN, 1986; HURLEY *et al.* 1987): limiting exposure to dust is the only reliable way of limiting the risks to miners of radiological changes, particularly PMF.

ACKNOWLEDGEMENTS

We are grateful to British Coal who funded the long-term research programme on coalworkers' respiratory health which made this study possible; again to British Coal, and to the Commission of the European Communities, for financial support to recent research on PMF which made possible preliminary estimates of long-term PMF risks; to NIOSH, for posing the present version of the PMF problem and for funding this most recent part of the work; to the many people who contributed their time and expertise to the PFR research programme over the years; to present-day colleagues at the Institute of Occupational Medicine, especially Dr. Michael Jacobsen, for discussions in the course of the work; and to Dr. Michael Attfield of ALOSH for comments on an earlier draft.

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APPENDIX 1

THE NIOSH COMMISSION

A1.1 Background

In April 1986, the US National Institute of Occupational Safety and Health asked this Institute to prepare a report on the predicted incidence of simple and complicated pneumoconiosis, assuming current US federal dust limits and health protection measures, and using the latest epidemiological results from the Pneumoconiosis Field Research.

The original text of NIOSH's request, which specifies requirements and assumptions, is given in section A1.2. Section A1.3 contains some remarks on certain details of the specification.

A1.2 Text of the commission

OBJECTIVES

Based on current US federal disease prevention measures, and given the latest information from the PFR, undertake the following analyses:

(i) *Estimate the percentage of miners who will have simple and complicated CWP at normal retirement age. This will include both miners who remained in mining for all of their working lives, and those who retired early due to contracting PMF.*

(ii) *Estimate the prevalence of simple and complicated CWP among all miners and ex-miners of any age between starting work and normal retirement.*

(iii) Explore the effectiveness of the X-ray program in preventing disease, given various levels of participation and transfer to low dust areas.

Details of the federal requirements and assumptions to be made are described below.

CURRENT FEDERAL DISEASE PREVENTION MEASURES

(i) The maximum dust level for coal miners in general is 2 mg/m^3. Sampling is based on personal measurement and should reflect actual exposure. As discussed below, miners with early signs of CWP can opt to transfer to a job where the dust level is 1 mg/m^3 or less.

(ii) Miners are eligible for an X-ray every five years. If an X-ray is read as 1/0 or greater, he then can transfer at his option to a low dust area (1 mg/m^3). (Miners also receive a pre-employment X-ray, and one after just three years work, but these should be ignored in this analysis.)

ASSUMPTIONS

Exposures

Assume the worst case that a miner receives 2 mg/m^3 all of his working life unless he transfers, in which case he receives 1 mg/m^3.

Tenure

Assume a worst case working life of 40 years, starting at age 18. If a person contracts PMF, assume that he retires from mining on receipt of compensation. Assume that it takes five years to get benefits.

Participation and transfer

Currently many miners do not participate in the X-ray program, and of those that do, many do not exercise their transfer option, at least at once. However, for the purposes of this investigation, the critical question is - of those with category 1/0+ at any examination (presence of CWP known or unknown to the miner), and who have not yet opted for transfer, what percentage do transfer? This percentage is obviously dependent on both participation and action by the participants. (For example, 100% transfer can only be obtained if everyone gets an X-ray, and everyone with CWP opts to transfer.) This percentage should vary from 0 to 100 by increments of 10 percent, so that the effect of these factors can be explored in detail.

Workforce composition

Assume a stable industry with a uniform age distribution, and hiring equaling retirement. Assume the worst case where every entrant to mining either works their full life in mining, or, if they leave mining, their departure is due to contracting PMF. Ignore deaths from any cause.

A1.3 Remarks

A1.3.1 Progression and regression of PMF

For the purposes of this study PMF was regarded as an irreversible condition; also, no attempt was made to estimate the prevalence of the different categories of PMF among retired miners.

A1.3.2 Workforce composition

An idealized population of working miners was assumed, in which each man begins work at age 18 free from simple pneumoconiosis or PMF, and continues working for a period of 40 years. The only cause of early retirement would be the development of PMF.

APPENDIX 2

SUBJECTS AND DATA

Subjects and data are from the Pneumoconiosis Field Research (PFR) of the National Coal Board in Britain, and are described in slightly greater detail in HURLEY *et al.* (1986).

A2.1 Collieries

Six rounds of medical surveys at approximately five-year intervals, were carried out at selected collieries in the British coalfields between 1953 and 1977 inclusive as part of the PFR. These collieries were chosen specifically to include examples of all the major variations in mining conditions in Britain (FAY and RAE, 1959).

Twenty-four pits were included in the first phase of the research, comprising three rounds of surveys: PFR 1, PFR 2 and PFR 3. Ten of these collieries were included in PFR 4 and PFR 5, and only two had been surveyed for a sixth time when the second phase of the research was ended in 1977.

A2.2 Subjects and intervals at risk

The PFR was designed to include all industrial workers employed at the research collieries at the time of medical surveys. In all, 53 382 coalminers participated. For the present analyses of radiological changes we first excluded 22 848 (42.8%) who had attended only one medical survey. Men recorded as showing PMF at their earliest survey were further excluded, since change from PMF was not under investigation. The remaining men were considered in the study in the first instance until the latest PFR survey they attended or, for men who experienced an attack of PMF, until the earliest survey where the response was diagnosed. Results therefore refer to radiological changes in men while employed in the mining industry, as required by the NIOSH statement of work.

The amount of relevant information available for men at risk varies, even among those at risk for the same length of time. This feature arises because of differences in individuals' patterns of survey attendance. Consider, for example, two miners who attended PFR 1 and PFR 5. Suppose that one man also attended PFR 2, 3 and 4, and that the other did not. Then for the first man there is information on radiological changes over four separate five-year periods, while for the second man there is information about a single 20-year period only.

More generally, it was possible to divide each man's total time at risk in the study into distinct and non-overlapping periods by considering the times between the pairs of successive medical surveys he attended. These periods, or person-intervals, were adopted as the basic unit of analysis in the study since each such interval provided new information on radiological changes. Note that each man's total time at risk gave rise to one person-interval fewer than the number of PFR surveys he attended. Methods of analysis did not distinguish between intervals which refer to the same coalminer and those which refer to other men.

Of the 54 395 person-intervals thus generated, 53 011 (97%) referred to periods of approximately five years' duration. Results in this paper are restricted to these approximately five-year intervals. Detailed validation of the data led to the exclusion of 747 (1.4%) of the five-year intervals, leaving a set of 52 264 for analyses of five-year radiological changes.

A2.3 <u>Age</u>

Each miner's date of birth was recorded at every survey he attended, discrepancies being resolved during subsequent data processing.

A2.4 Radiological classifications

A full-sized postero-anterior chest radiograph of each man was also taken at every survey attended.

Shortly after the surveys concerned, at least two of four Medical Officers in the research team read all films from PFR 1, PFR 2 and from four collieries of PFR 3 to provide an agreed ("definitive") classification of each radiograph (FAY and ASHFORD, 1960). Earlier films from the same man were available for reference throughout. Classification of simple pneumoconiosis referred to the four major categories of CWSP only (ILO, 1959). Films taken subsequently were classified clinically by any one of five or six doctors in the Coal Board's Radiological Service to provide assessments of PMF and CWSP on scales comparable to the earlier readings (JACOBSEN *et al.*, 1977).

A2.5 Exposure to respirable dust

The details have been summarised frequently, for example by HURLEY *et al.* (1982). The strategy was based on a system of occupational groups at the research collieries, so that within each group the men were exposed to similar dust concentrations. Groups were re-defined or closed, and new groups formed, to reflect changes in the work of the colliery through time.

Histories of individuals' work at the research collieries from 1953 onwards were recorded as shifts worked per week, including overtime, in the various occupational groups. Details of coalmining work before the research programme began or subsequently at non-research pits were recorded at medical survey interviews and later summarised as years and months worked in six main classes of coalmining activity. Times were converted to hours by assuming that one calendar year's employment was equivalent to 1 740 hours at work. (Estimates in Appendix 3 of 40-year risks under current conditions assume 1 631 hours worked per year, equivalent to 225 shifts at 7.25 hours each, reflecting shorter working hours now compared with the research period of 1953-1977.)

Dust concentrations were monitored using sampling instruments close to the men throughout selected working shifts. On this basis the average concentrations of respirable coalmine dust, in gravimetric units, were determined for all occupational groups and five-year inter-medical-survey periods. A series of side-by-side instrument comparisons was carried out to convert earlier particle count measurements to gravimetric units (DODGSON *et al.*, 1971).

There was no direct monitoring of the dust concentrations to which men were exposed before the research began, or at non-research collieries subsequently. Separately for men at each research colliery and each time-period, the average concentrations to which they were exposed in each of the six broad classes of coalmining activity were estimated by assuming that dust concentrations elsewhere were similar to those at the research pit in the corresponding time-period, and that concentrations prior to the research were similar to those experienced during the first 10 years of monitoring.

Finally, the men's exposures to respirable coalmine dust in any inter-survey period were estimated by forming the product of an individual's time worked in any occupational group or broad class of coalmining activity with the corresponding average dust concentration, and summing appropriately. The exposure units are gramme hours per cubic metre of sampled air (g hour m^{-3}).

A2.6 Percent carbon

Percent carbon is one important measure of the rank of the coal being mined (DODGSON *et al.*, 1971). Data refer to collieries rather than to individuals. Values in the 24 PFR collieries (and in the 10 pits included in the second phase of the research) ranged from 81.1% to 94.0% carbon.

REFERENCES: see main report.

APPENDIX 3

ESTIMATING PREVALENCE OF CWSP AND OF PMF THROUGHOUT A WORKING LIFE: METHODS AND RELATED RESULTS

A3.1 Introduction

As indicated in the main report, the strategy adopted was to consider a 40-year working life as a linked series of eight successive five-year periods; to examine changes in radiological category over the five-year periods; and then to apply the estimates of changes to the eight periods in succession, and so provide estimates of the prevalence of CWSP and of PMF after 40 years in the industry, or at the end of any earlier five-year period.

In practice, the work was carried out in four stages. First, general estimates were made of the probabilities of change in radiological category over five-year periods, and of how these probabilities depend also on age, dust exposure and the carbon content of the coal. Details are given in Section 2.

The second stage involved following through the experience of the hypothetical mining population as described in the NIOSH commission, to identify the values of age, cumulative dust exposure and percent carbon experienced by various subgroups of the men at the start of each five-year period. Further details are given in Section 3.

In the third stage, the various combinations of age, exposure and percent carbon in the NIOSH mining population at the start of each five-year period were linked together with the general estimates of age-, exposure- and carbon-specific risks of radiological change, to give specific estimates of how various subgroups progressed or regressed in each five-year period. Details are given in Section 4.

Finally, the experience of the entire hypothetical mining population was considered through the eight successive five-year risk periods, estimating the changes in radiological status in each interval and taking these attained prevalences as starting points for the succeeding risk period. The entire process was carried out assuming various proportions of men with CWSP who transfer to more favourable dust conditions. Details of the methods are given in Section 5; results were included in the main report.

A3.2 Regression functions for estimating change in radiological status over five-year periods

A3.2.1 Aims, assumptions and general approach

The first task was to provide general regression functions for estimating the probabilities of moving from any of the four main categories of CWSP to any other, or of developing PMF, over five-year periods, taking account of dust exposure and other relevant factors. Equivalently, we aimed to estimate the radiological category in which a man would end a five-year period, taking account among other things of his radiological category at the start.

Change from PMF was not studied, since it was assumed that the condition is irreversible. (In practice, instances are found in PFR data where a man is identified as showing PMF at one survey, while his film from a later occasion is classified as showing CWSP only. Such instances are rare, and it is unclear whether they arise solely because of errors in film readings, or whether regression of PMF can on occasion be a real phenomenon.)

Estimates were based on the dataset of 52 264 intervals (HURLEY *et al.*, 1986; see Appendix 2). Radiological category at the end of the approximately five-year periods was used to construct four dichotomous response variables:

Response 1: presence/absence of PMF or CWSP categories 1, 2 or 3;
Response 2: presence/absence of PMF or CWSP categories 2, 3;
Response 3: presence/absence of PMF or CWSP category 3;
Response 4: presence/absence of PMF.

Relations between each of the four responses and a set of explanatory characteristics including age, dust exposure and CWSP category at the start of the risk periods, were examined in separate analyses using multiple logistic regression methods (COX, 1970), implemented through programs in the GENSTAT language (ALVEY *et al.*, 1977). But first, some preliminary work was necessary to decide on a suitable set of explanatory variables for the logistic modelling.

A3.2.2 Selecting an appropriate model

Five explanatory characteristics were considered in the analyses: age; cumulative dust exposure (on the log scale), and attained category of CWSP, all as measured at the start of the study intervals; percentage of carbon in the coal being mined; and the length (in years) of the risk interval. In the regression equations, CWSP category was used to distinguish the four groups from which change in radiological status was being assessed. Preliminary investigation to choose an appropriate regression model was necessary in order to see to what extent the effect of age, dust exposure and other factors differed for men in the various CWSP categories. (In principle, the regression equation for each response could contain an intercept and four distinct slopes for each CWSP category; possible interactions between other variables, for example an age-exposure interaction, were not considered.)

The model-building exercise was carried out by grouping together risk intervals with common values of interval length, age (correct to within five years), dust exposure (correct to within 50 g hour m^{-3}), percent carbon (24 values: one per colliery), and CWSP category. By this method, preliminary analyses were based on 4 844 groups while using information from all 52 264 distinct intervals at risk. Several different logistic regression models were explored for each of the four responses, with a view to selecting an appropriate model.

The results of Table A3.1 summarise the findings. It is clear that all five main explanatory variables are highly significant statistically. However, the pattern of significant interaction terms of other variables with CWSP varies according to the response of interest.

The first course of action adopted was to retain in analyses of each response only those terms statistically significant at the 0.15 level. However, use of the corresponding equations in the later part of the work, along lines described in Section A3.4 below, resulted in some small negative estimates of the probability of five-year change from one category of CWSP to another, possibly arising from the inclusion of different sets of interaction terms in analyses of the four responses.

Though unimportant practically, such negative estimates were undesirable. In order to minimise the problem, it was decided to use the same explanatory variables for analyses of each of the four radiological responses. On the basis of the exploratory work, the model adopted for all responses included interactions with CWSP of all other variables except interval length, i.e. in the chosen model the influence of age, dust exposure and percent carbon on radiological category at the end of an interval varied according to the men's CWSP category at the start. Within this common framework the problem of later negative estimates of transition probabilities largely disappeared (Appendix A3.4.4).

A3.2.3 Fitting the chosen model using the full dataset

For each of the four responses, the chosen common logistic model was then fitted to the full dataset of 52 264 individual risk intervals. Starting values for the process of estimating the coefficients using iteratively reweighted least squares were obtained from results of the earlier model-selection exercise using grouped data.

Table A3.2 gives the resulting maximum likelihood estimates of the logistic regression models. The first five rows of the Table give the coefficients appropriate to initial category 0 of CWSP. The succeeding rows show the quantities which must be added to obtain corresponding coefficients for other categories of CWSP. Thus, for example, the intercept for men with CWSP category 2 in the regression equation for PMF is given by -32.90 + 22.32, and the coefficient of age is given by 0.0557 - 0.0167.

A series of such calculations was carried out to give the results of Table A3.3, which shows the fitted regression functions within each initial category of CWSP. Figures A3.1 to A3.4 show plots of the fitted functions for men with initial CWSP categories 0 to 3, respectively. To produce these graphs, interval length, age and percent carbon were set to five years, 40 years of age and 86.2% respectively, values which were close to the mean values in the full dataset of 52 264 intervals at risk.

A3.3 Starting values of age, exposure and carbon content for each five-year period, for the various groups of men in the NIOSH population

The general regression estimates of the probabilities of radiological change over five-year periods depended on age, respirable dust exposure, and percent carbon in the coal being mined. In order to apply these general estimates separately to each of the eight five-year periods which constitute the 40-year working life of the NIOSH population, it was necessary to determine the values of age and exposure experienced by various subgroups of the population at the start of each period; and to select a number of values of percent carbon also.

It was assumed that the carbon content of the coal being mined did not vary over a 40-year working life. Three specific values of percent carbon were chosen, as a basis for three separate sets of long-term risk estimates: 83%, 86.2%, and 89%. These values were approximately the mean percent carbon plus or minus one standard deviation in the dataset of 52 264 intervals at risk.

By assumption, men entered the industry at age 18 years, and so trivially their ages at the start of subsequent five-year periods were 23, 28, 33 and so on.

If there were no transfer of men with CWSP to lower dust conditions, the calculation of attained dust exposure would have been almost as straightforward. Based on the experience of men in the PFR in recent years, it was assumed that one year's work in mining corresponds to 1 631 working hours. Thus, five years' exposure at 2 mg m^{-3} dust concentration amounts to 16.31 g hour m^{-3} exposure units. However the situation is complicated by the fact that at any of the stages from age 23 onwards, a man may choose to have a chest X-ray. Should CWSP categories 1, 2 or 3 or PMF be diagnosed, the man has the option of transferring to a workplace involving exposure to a dust concentration of 1 mg m^{-3} rather than 2 mg m^{-3}. In addition, if PMF is diagnosed, the man will only have five more years of work in the industry.

Figure A3.5 shows the various groups of men which may appear throughout a working life of 40 years. The bold continuous line along the centre of the diagram shows the group of men who continue to work in a dust concentration of 2 mg m^{-3}. The other, lighter, continuous lines which branch off at each stage represent groups of men who transfer to a dust concentration of 1 mg m^{-3}. The dashed lines represent groups of men who develop PMF - these men leave the industry five years after diagnosis by chest X-ray. Some men with PMF will continue to work in a dust concentration of 2 mg m^{-3} - these groups of men are shown by long dashed lines. Men with PMF who transfer to a lower dust concentration of 1 mg m^{-3} are shown by short dashed lines. (It is not actually necessary to distinguish between the two PMF groups for the purposes of the present study, since progression of PMF was not being investigated, and the possibility of regression of PMF was disallowed. They are shown here only for completeness.)

The relative sizes of the different groups of men will depend on two factors: first, the level of participation in the five-yearly X-ray scheme, and secondly, the proportion of men with CWSP categories 1, 2 or 3 or PMF, who opt to transfer to lower dust conditions. Variations in these proportions, and their implications, will be considered in Section A3.5. At present it is sufficient to note that some men may start a five-year period with combinations of age and exposure corresponding to any of the 28 branching points in Figure A3.1, and so estimates of the probabilities of change specific to these values of age and exposure are required.

A3.4 Estimates of the five-year risks of radiological change, for various groups of men in the NIOSH population

The present Section describes how the specific starting values from Section A3.3 were combined with the general equations of Section A3.2 to give estimates of the risks of radiological change appropriate to subgroups of the NIOSH population over particular five-year periods. It is clear from Figure A3.5 that, for any given level of percent carbon, 28 sets of estimates of five-year changes are required. Each set of probabilities was organised as a transition matrix, showing the (age-, exposure- and carbon-specific) chances of change from relevant starting categories of CWSP to any other, or to PMF. It was necessary to take special steps with two particular problems: negative entries in the transition matrices, and the derivation of the transition matrix for the first transition.

A3.4.1 Calculation of transition matrices: general approach

The general approach was as follows. An interval length of five years and one of the three selected values of percent carbon, together with an appropriate combination of age and exposure from a branching point in Figure A3.5, were substituted directly into the general equations of Section A3.2. For every such combination of starting values, and for every associated category of CWSP at the start of the intervals, this procedure yielded numeric estimates of the respective probabilities that each of the four radiological response variables would be present at the end of the interval. These probabilities were then arranged in a series of 4 x 4 matrices, whose general form was as follows:

Initial category of CWSP	Response variable CWSP 1, 2, 3 + PMF	CWSP 2, 3 + PMF	CWSP 3 + PMF	PMF
0	p_{11}	p_{12}	p_{13}	p_{14}
1	p_{21}	p_{22}	p_{23}	p_{24}
2	p_{31}	p_{32}	p_{33}	p_{34}
3	p_{41}	p_{42}	p_{43}	p_{44}

The subscripts refer to row and column position in the Table, and not to radiological category. For example, p_{32} denotes the probability that a man will have CWSP categories 2 or 3 or PMF at the end of a five-year interval, given that his initial radiological category was CWSP category 2. All entries in all such 4 x 4 matrices were non-negative.

For each combination of starting values, entries of the required transition matrix M giving probabilities of category-specific five-year radiological changes were then obtained from the above 4 x 4 matrix, as follows:

Initial radiological state	Final radiological state				
state	CWSP 0	CWSP 1	CWSP 2	CWSP 3	PMF
CWSP 0	$1-p_{11}$	$p_{11}-p_{12}$	$p_{12}-p_{13}$	$p_{13}-p_{14}$	p_{14}
CWSP 1	$1-p_{21}$	$p_{21}-p_{22}$	$p_{22}-p_{23}$	$p_{23}-p_{24}$	p_{24}
CWSP 2	$1-p_{31}$	$p_{31}-p_{32}$	$p_{32}-p_{33}$	$p_{33}-p_{34}$	p_{34}
CWSP 3	$1-p_{41}$	$p_{41}-p_{42}$	$p_{42}-p_{43}$	$p_{43}-p_{34}$	p_{44}
PMF	0	0	0	0	1

The entries of the last row of the matrix are held fixed throughout the calculation of prevalences, and express the fact that the possibility of regression of PMF is excluded for the purposes of this study.

A3.4.2 Calculation of transition matrices - an example

In order to illustrate the methods, consider the calculation of the transition matrix corresponding to an interval length of five years, age of 38 years, dust exposure of 65.24 g hour m^{-3} and percent carbon of 83%. Substitution of these values in the equations of Table A3.3 yields the following 4 x 4 matrix of probabilities:

Initial category of CWSP	Response variable CWSP 1, 2, 3 + PMF	CWSP 2, 3 + PMF	CWSP 3 + PMF	PMF
0	.016890	.001139	.000224	.000187
1	.716167	.162377	.020503	.014571
2	.987549	.753444	.065770	.047351
3	.999999	.999067	.848447	.055691

Performing the subtractions will produce the desired transition matrix:

Initial radiological state	Final radiological state CWSP 0	CWSP 1	CWSP 2	CWSP 3	PMF
CWSP 0	.983110	.015751	.000915	.000037	.000187
CWSP 1	.283833	.553790	.141874	.005932	.014571
CWSP 2	.012451	.234105	.687674	.018419	.047351
CWSP 3	.000001	.000932	.150620	.792756	.055691
PMF	0.0	0.0	0.0	0.0	1.0

A3.4.3 Negative entries in transition matrices

The elements of the transition matrices are estimates of probabilities, derived by subtraction. It was possible therefore that negative values of estimates would occur, though the true probabilities are necessarily non-negative. In practice negative estimates did occur, but only on three occasions. In each case, the dust exposure and age values were low (16.31 g hour m^{-3} and 23 years of age respectively), and the particular probability involved was that of progression from CWSP category 2 to category 3. The three instances refer, respectively, to the three values of percent carbon of 83%, 86.2% and 89%.

Figure A3.3 indicates why negative values occurred for this combination of starting values. The Figure shows that for men with CWSP category 2 with low dust exposures, the estimated probability of either progression to CWSP category 3 or to PMF is close to the probability of developing PMF alone. Clearly at very low ages and dust exposures, the estimated probability curves overlap, thus giving rise to negative "probabilities".

However, the negative estimates were small in magnitude (-0.0007, -0.0004, -0.00002), and it was decided not to adjust the matrices in any way, since the influence of these terms on the final prevalence estimates would be negligible.

A3.4.4 Derivation of the transition matrix for the first transition

The general approach was not applied to the first transition, since the general equations were considered inappropriate for estimating radiological change with zero dust exposure at the start of the intervals. The first transition matrix was therefore estimated directly from a subset of the 52 264 risk intervals. Estimates were based on the 2 279 intervals with starting CWSP category 0 and attained cumulative dust exposure of not more than 16.31 g hour m^{-3} at the end of the intervals concerned (i.e. five years work at dust concentrations of 2 mg m^{-3} or less).

Data descriptions quickly revealed that there was very little radiological change in the 2 279 intervals. Only four men showed progression, and then only to category 1. Multiple logistic regression of the presence of CWSP categories 1, 2 or 3 or PMF upon age, interval length and percent carbon showed that only the regression coefficient on age was statistically significant. Fitting an equation with a term for age only yielded the result:

$$\text{logit probability} = -9.51 + 0.0939 \times \text{age},$$

with the t statistic for the age coefficient equal to 2.67. Substitution of an age value of 18 gave a predicted probability of 0.0004, and accordingly the matrix used for the first transition was the following:

Initial radiological state	Final radiological state				
	CWSP 0	CWSP 1	CWSP 2	CWSP 3	PMF
CWSP 0	0.9996	0.0004	0.0000	0.0000	0.0000

(Rows 2 to 5 of the matrix were irrelevant for the first transition, since the initial radiological state was constrained to be CWSP category 0.)

A3.5 Methods of estimating the prevalence of CWSP and of PMF throughout a 40-year working life

In principle a man's radiological category could take any one of five values: CWSP categories 0, 1, 2 and 3, and PMF. It was assumed that all men had CWSP category 0 on entering the industry at age 18, with no previous dust exposure. The problem now was to estimate the proportions of men in the five radiological categories at the end of each of the eight five-year periods of a 40-year working life. Estimates were made corresponding to three distinct values of percent carbon: 83%, 86.2% and 89%, which were considered fixed throughout a working life. It simplifies the description of methods, and involves no loss of generality, to describe methods for any one fixed value of carbon content. Also, it is helpful to describe first the simple situation whereby no men with CWSP transfer to lower dust conditions, and describe subsequently the complications of non-zero transfers.

A3.5.1 Zero transfer factor

With obvious notation, we wish to estimate a series of column vectors $p^{(n)}$, $n = 2,\ldots,9$, whose elements $p_j^{(n)}$, $j = 1,\ldots,5$ show the proportions of men with radiological category j at the start of the n^{th} five-year period. By assumption, the vector $p^{(1)}$ of starting values has elements $p_1^{(1)} = 1$, $p_j^{(1)} = 0$ for $j = 2,\ldots,5$.

The age- and exposure-specific transition matrices of the previous section are central to the method of estimation. Since there is no transfer to lower dust conditions, there are no differences between men in respect of age or of cumulative dust exposure at the start of any particular five-year period, and so only a single transition matrix M(n) is relevant to the n^{th} five-year period. For example, M(5) is the transition matrix based on age 38 years at the start of the risk period, and exposure 8t mg hour m^{-3}, where t = 1 631 is time worked per calendar year.

The vectors $p^{(n+1)}$, $n = 1,\ldots,8$ were then estimated by the recursive procedure

$$p^{(n+1)} = M^T(n)\ p^{(n)} \qquad n = 1,\ldots,8$$

where the superscript T denotes the transpose of the transition matrix. Equivalently, the probability of showing radiological category j at the start of the $(n+1)^{th}$ period (or at the end of the n^{th} period) is

$$p_j(n+1) = \sum_{i=1}^{5} m_{ij}(n)p_i(n) \qquad j = 1,\ldots,5 \qquad n = 1,\ldots,8$$

where $m_{ij}(n)$ is the conditional probability of a man progressing (or regressing) to category j during the n^{th} five-year period, given that his category at the start of the period was i.

A3.5.2 Non-zero transfer factor

The situation is complicated when some men with CWSP working in conditions of 2 mg m^{-3} transfer to lower dust conditions of 1 mg m^{-3}. The various possible combinations of age and exposure were described in Figure A3.5. It is helpful to index the corresponding transition matrices (Section A3.4) by age and cumulative exposure also.

The relative sizes of the various groups of men at each branching point will depend on the proportion of men with CWSP working in conditions of 2 mg m^{-3} who transfer to lower dust conditions. In fact, π is the product of two factors: the level of participation in five-yearly surveys (of men who are still working in dust conditions of 2 mg m^{-3}), and the proportion of men identified with CWSP who then transfer to conditions of 1 mg m^{-3}. But only the product of the two factors is relevant. Furthermore, the transfer of men with PMF to lower dust conditions need not be considered in the detail shown in Figure A3.5. Since it is assumed that PMF is irreversible and progression of PMF is not being considered, it is irrelevant whether men with PMF stay exposed at 2 mg m^{-3}, at 1 mg m^{-3}, or leave the industry. For simplicity, we assume the same transfer factor among men with PMF working in conditions of 2 mg m^{-3}, and that all remain in the industry.

Given a value of the transfer factor π, the calculation of age-specific prevalences proceeds as follows. As before,

$$p^{(2)} = M^T(18,0)p^{(1)}$$

where M (18,0) is the first transition matrix, i.e. corresponding to age 18 and zero exposure. It is helpful now to distinguish two groups of miners, those who transfer to lower dust conditions and those who do not, represented by $p^{(2)1}$ and $p^{(2)2}$ respectively. In detail,

$$p^{(2)} = \begin{bmatrix} p_1{}^{(2)} \\ p_2{}^{(2)} \\ p_3{}^{(2)} \\ p_4{}^{(2)} \\ p_5{}^{(2)} \end{bmatrix} = \begin{bmatrix} 0 \\ \pi p_2{}^{(2)} \\ \pi p_2{}^{(3)} \\ \pi p_2{}^{(4)} \\ \pi p_2{}^{(5)} \end{bmatrix} + \begin{bmatrix} p_1{}^{(2)} \\ (1-\pi)p_2{}^{(2)} \\ (1-\pi)p_2{}^{(3)} \\ (1-\pi)p_2{}^{(4)} \\ (1-\pi)p_2{}^{(5)} \end{bmatrix} = p^{(2)1} + p^{(2)2}$$

Both groups experience the same transition probabilities, given by the elements of the matrix M (23,2t), since their exposure at the start of the period is the same. Thus

$$p^{(3)} = M^T(23,2t)\ p^{(2)} = M^T(23,2t)\ (p^{(2)1} + p^{(2)2})$$

$$= p^{(3)1} + p^{(3)2}$$

describes the state of the population as a whole at the start of the third five-year period.

Radiological change over the third five-year period requires construction of two transition matrices, M(28,3t) for the experience of $p^{(3)1}$, and M(28,4t), for the experience of group $p^{(3)2}$. However, it is useful for subsequent calculations to subdivide $p^{(3)2}$ further, according to who with CWSP transfers to lower dust conditions during the third interval, and who does not. The division of $p^{(3)2}$ is exactly analogous to the subdivision of $p^{(2)}$ earlier, and may be written as

$$p^{(3)2} = p^{(3)2,1} + p^{(3)2,2}.$$

The state of the population at the start of the fourth five-year periods is thus given by

$$\begin{aligned} p^{(4)} &= M^T(28,3t)p^{(3)1} + M^T(28,4t)p^{(3)2} \\ &= M^T(28,3t)p^{(3)1} + M^T(28,4t)p^{(3)2,1} + M^T(28,4t)p^{(3)2,2} \\ &= p^{(4)1} + p^{(4)2} + p^{(4)3}, \text{ say.} \end{aligned}$$

The general pattern may now be described. At the start of the n^{th} five-year risk period ($n>2$) it is necessary to distinguish n-1 distinct groups. The groups are identified by column vectors $p^{(n)k}$, $k = 1,\ldots,n-1$, which give the proportions of the total mining population which the group includes, by radiological category. The entire population is of the same age

$$a_n = 18 + 5(n-1),$$

but because of transfers at each stage there are between-group differences in accumulated dust exposures. Accumulated exposure for the k^{th} group is

$$d_{nk} = (n + k - 1)t \quad g \text{ hour } m^{-3}$$

where t is the number of hours worked per year, in thousands (in this study, 1.631).

Associated with each group $p^{(n)k}$ there is an age- and exposure-specific 5 x 5 transition matrix $M(a_n, d_{nk})$ giving conditional probabilities of radiological change. It is strictly unnecessary in estimating risks for the n^{th} risk period, but essential in estimating risks for the $(n + 1)^{st}$ period, to split the final group $p^{(n)n-1}$ as

$$p^{(n)n-1} = \begin{bmatrix} p_1^{(n)n-1} \\ p_2^{(n)n-1} \\ p_3^{(n)n-1} \\ p_4^{(n)n-1} \\ p_5^{(n)n-1} \end{bmatrix} = \begin{bmatrix} 0 \\ \pi p_2^{(n)n-1} \\ \pi p_3^{(n)n-1} \\ \pi p_4^{(n)n-1} \\ \pi p_5^{(n)n-1} \end{bmatrix} + \begin{bmatrix} p_1^{(n)n-1} \\ (1 - \pi) p_2^{(n)n-1} \\ (1 - \pi) p_3^{(n)n-1} \\ (1 - \pi) p_4^{(n)n-1} \\ (1 - \pi) p_5^{(n)n-1} \end{bmatrix}$$

corresponding respectively to the portions which are exposed at 1 mg m^{-3} and at 2 mg m^{-3} for the n^{th} interval.

Radiological status at the end of the n^{th} period and the start of the $(n+1)^{th}$ period is then given by

$$p^{(n+1)} = \sum_{k=1}^{n-1} M^T(a_n, d_{nk}) p^{(n)k},$$

while the n groups which need to be distinguished for the $(n+1)^{st}$ risk period are given by

$$p^{(n+1)k} = M^T(a_n, d_{nk})\ p^{(n)k} \quad k = 1,\ldots,n-2,$$

with the final two groups generated from

$$M^T(a_n, d_{n\ n-1})\ p^{(n)n-1}$$

by splitting $p^{(n)n-1}$ as indicated above.

REFERENCES: see main report.

TABLE A3.1 Residual degrees of freedom, -2 x log likelihood, and, in brackets, P values of added terms, for a series of fitted logistic regression equations to four response variables. (Note that the 10 models are nested - e.g. the first three models of the series are: constant, constant + β_1 x interval length, constant + β_1 x interval length + β_2 x $\log_e$ (dust + 1.0). P values are obtained by referring differences in successive values of -2 x log likelihood to tables of the Chi-square distribution. Appropriate degrees of freedom for tests are provided by corresponding differences in the residual degrees of freedom.)

Model	Residual degrees of freedom	Response variable			
		PMF	PMF + CWSP 3	PMF + CWSP 2, 3	PMF + CWSP 1, 2, 3
Constant	4843	3559	6189	15740	26400
+ interval length	4842	3523 (<0.0005)	6149 (<0.0005)	15690 (<0.0005)	26360 (<0.0005)
+ $\log_e$ (dust + 1.0)	4841	2759 (")	4769 (")	11680 (")	17330 (")
+ age	4840	2724 (")	4732 (")	11650 (")	17220 (")
+ percent carbon	4839	2625 (")	4577 (")	11350 (")	16840 (")
+ CWSP (3 terms)	4836	1954 (")	2352 (")	3351 (")	4737 (")
+ interval length x CWSP	4833	1953 (0.8<P<0.85)	2350 (0.6<P<0.7)	3349 (0.6<P<0.7)	4733 (0.3<P<0.4)
+ $\log_e$ (dust + 1.0) x CWSP	4830	1894 (<0.0005)	2272 (<0.0005)	3235 (<0.0005)	4621 (<0.0005)
+ age x CWSP	4827	1892 (<0.6<P<0.7)	2262 (0.01<P<0.025)	3229 (0.1<P<0.15)	4604 (0.0005<P<0.001)
+ percent carbon x CWSP	4824	1880 (0.005<P<0.01)	2250 (0.005<P<0.01)	3214 (0.001<P<0.005)	4602 (0.5<P<0.6)

TABLE A3.2 Estimated regression coefficients (with associated standard errors and t statistics) of the predictor variables shown, which were used to model four radiological responses viz:

(a) presence or absence of PMF;
(b) presence or absence of PMF or category 3 CWSP;
(c) presence or absence of PMF or categories 2 or 3 CWSP;
(d) presence or absence of PMF or categories 1, 2 or 3 CWSP,

in a set of 52264 man-intervals. (Responses were measured at the end of man-intervals, predictor variables at the start.)

Predictor variable	Radiological response											
	PMF			PMF + CWSP 3			PMF + CWSP 2, 3			PMF + CWSP 1, 2, 3		
	coeff.	(s.e.)	t	coeff.	(s.e.)	t	coeff.	(s.e.)	t	coeff.	(s.e.)	t
Constant	-32.90	(2.20)	-14.93	-31.93	(2.47)	-12.94	-24.84	(1.55)	-16.05	-15.546	(0.598)	-26.01
Length of man-interval (L)	0.3932	(0.0536)	7.33	0.4049	(0.0538)	7.53	0.2801	(.0370)	7.58	0.1397	(0.0264)	5.29
Age (A)	0.0557	(0.0119)	4.70	0.0563	(0.0133)	4.23	0.01982	(0.00799)	2.48	0.01369	(0.00300)	4.56
$\log_e$ (dust exposure + 1.0) (D)	1.490	(0.161)	9.26	1.395	(0.178)	7.84	1.227	(0.109)	11.27	1.2257	(0.0405)	30.28
Percent carbon (PC)	0.1685	(0.0235)	7.17	0.1628	(0.0265)	6.14	0.1297	(0.0170)	7.62	0.06173	(0.00647)	9.55
Indicator for CWSP cat. 1 (C_1)	16.36	(2.85)	5.74	16.45	(3.15)	5.22	16.38	(1.83)	8.96	8.77	(1.36)	6.46
Indicator for CWSP cat. 2 (C_2)	22.32	(2.92)	7.63	19.93	(3.04)	6.56	20.93	(2.49)	8.40	21.51	(8.37)	2.57
Indicator for CWSP cat. 3 (C_3)	14.88	(5.00)	2.98	24.30	(4.84)	5.02	31.5	(19.3)	1.63	67.5	(34.0)	1.99
$A \times C_1$	-0.0207	(0.0154)	-1.34	-0.0328	(0.0169)	-1.94	-0.02447	(0.00957)	-2.56	-0.02206	(0.00714)	-3.09
$A \times C_2$	-0.0167	(0.0160)	-1.04	-0.0183	(0.0166)	-1.10	-0.0113	(0.0130)	-0.86	-0.0143	(0.0426)	-0.33
$A \times C_3$	-0.0024	(0.0278)	-0.09	-0.0634	(0.0272)	-2.34	-0.029	(0.114)	-0.25	-0.286	(0.200)	-1.43
$D \times C_1$	-1.405	(0.215)	-6.53	-1.354	(0.235)	-5.77	-1.083	(0.135)	-8.03	-0.8501	(0.0972)	-8.74
$D \times C_2$	-1.273	(0.232)	-5.48	-0.880	(0.238)	-3.69	-1.049	(0.189)	-5.54	-0.680	(0.432)	-1.57
$D \times C_3$	-2.036	(0.361)	-5.64	-2.374	(0.401)	-5.93	-2.98	(1.55)	-1.92	-3.20	(2.11)	-1.52
$PC \times C_1$	-0.0640	(0.0304)	-2.10	-0.0601	(0.0338)	-1.78	-0.0696	(0.0201)	-3.46	0.0075	(0.0150)	0.50
$PC \times C_2$	-0.1297	(0.0312)	-4.16	-0.1180	(0.0326)	-3.62	-0.0989	(0.0272)	-3.64	-0.1166	(0.0880)	-1.33
$PC \times C_3$	-0.0060	(0.0540)	-0.11	-0.0218	(0.0556)	-0.39	-0.050	(0.209)	-0.24	-0.298	(0.324)	-0.92

TABLE A3.3 Estimated intercepts and logistic regression coefficients of the predictor variables shown, which were used to model four radiological responses viz:

(a) presence or absence of PMF;
(b) presence or absence of PMF or category 3 CWSP;
(c) presence or absence of PMF or categories 2 or 3 CWSP;
(d) presence or absence of PMF or categories 1, 2 or 3 CWSP,

in a set of 52264 man-intervals; tabulated by CWSP status at the start of each man-interval, and response variable. (Responses were measured at the end of man intervals, predictor variables at the start.)

Response variable	Initial category of CWSP	Intercept	Predictor variable			
			Length of man-interval (years)	Age (Years)	$\log_e$ (dust exposure + 1) ($\log_e$ (g hour m^{-3} + 1))	Percent carbon (%)
PMF	0	-32.90	0.3932	0.0557	1.490	0.1685
	1	-16.54	0.3932	0.0350	0.085	0.1045
	2	-10.58	0.3932	0.0390	0.217	0.0388
	3	-18.02	0.3932	0.0533	-0.546	0.1625
PMF or CWSP 3	0	-31.93	0.4049	0.0563	1.395	0.1628
	1	-15.48	0.4049	0.0235	0.041	0.1027
	2	-12.00	0.4049	0.0380	0.515	0.0448
	3	-7.63	0.4049	-0.0071	-0.979	0.1410
PMF or CWSP 2, 3	0	-24.84	0.2801	0.01982	1.227	0.1297
	1	-8.46	0.2801	-0.00456	0.144	0.0601
	2	-3.91	0.2801	0.00852	0.178	0.0308
	3	6.66	0.2801	-0.00918	-1.753	0.0797
PMF or CWSP 1, 2, 3	0	-15.546	0.1397	0.01369	1.2257	0.06173
	1	-6.776	0.1397	-0.00837	0.3756	0.06923
	2	5.964	0.1397	-0.00061	0.5457	-0.05487
	3	51.954	0.1397	-0.27231	-1.9743	-0.23627

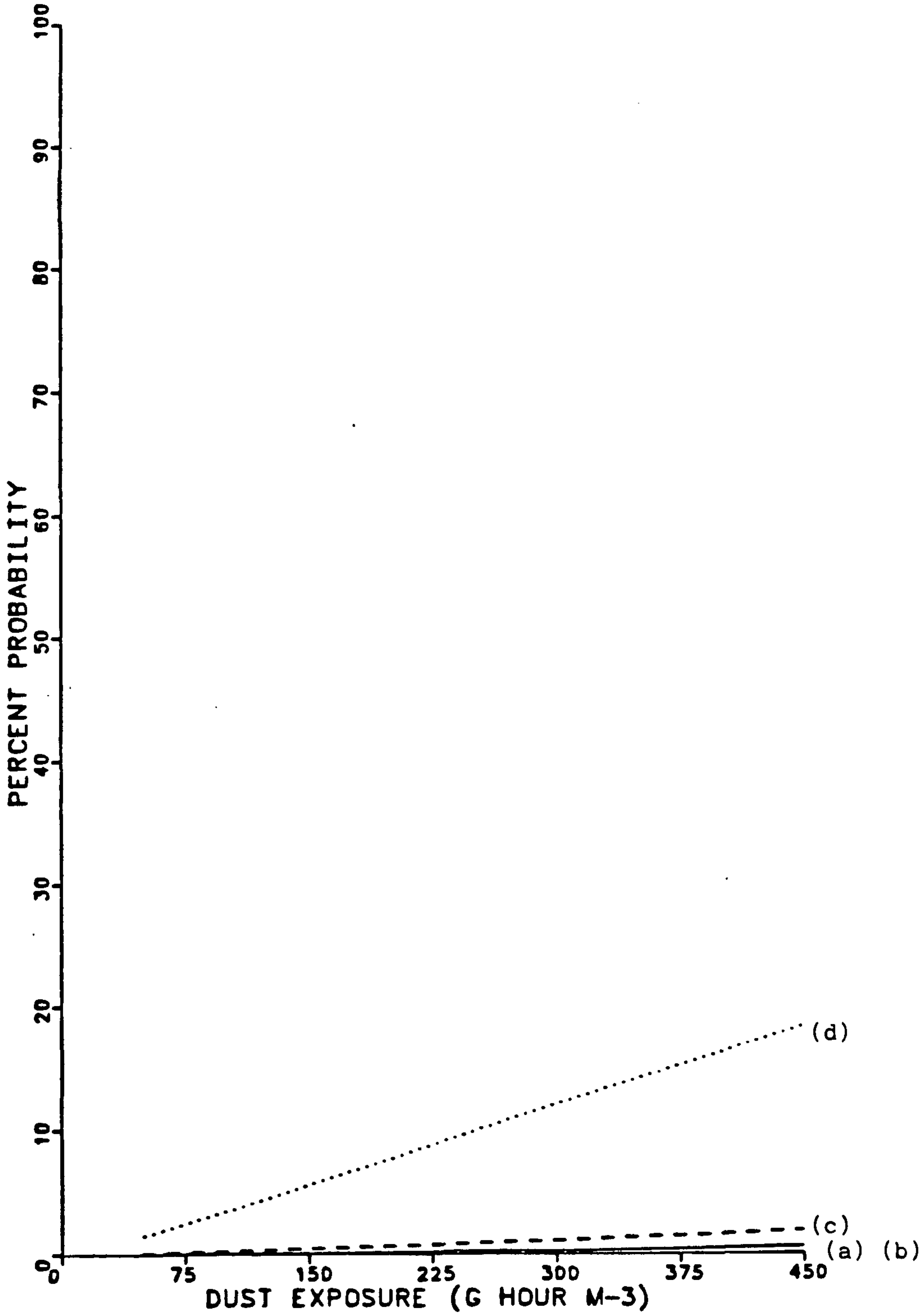

Figure A3.1 Estimated probabilities (percent) that a man aged 40 years with CWSP category 0 will, after five years:

(a) have developed PMF;
(b) have progressed to CWSP category 3 or developed PMF;
(c) have progressed to CWSP categories 2 or 3 or developed PMF;
(d) have progressed to CWSP categories 1, 2 or 3 or developed PMF,

assuming a percentage carbon value of 86.2%.

(Note: in this Figure, curves (a) and (b) are indistinguishable, and are shown by a single solid line.)

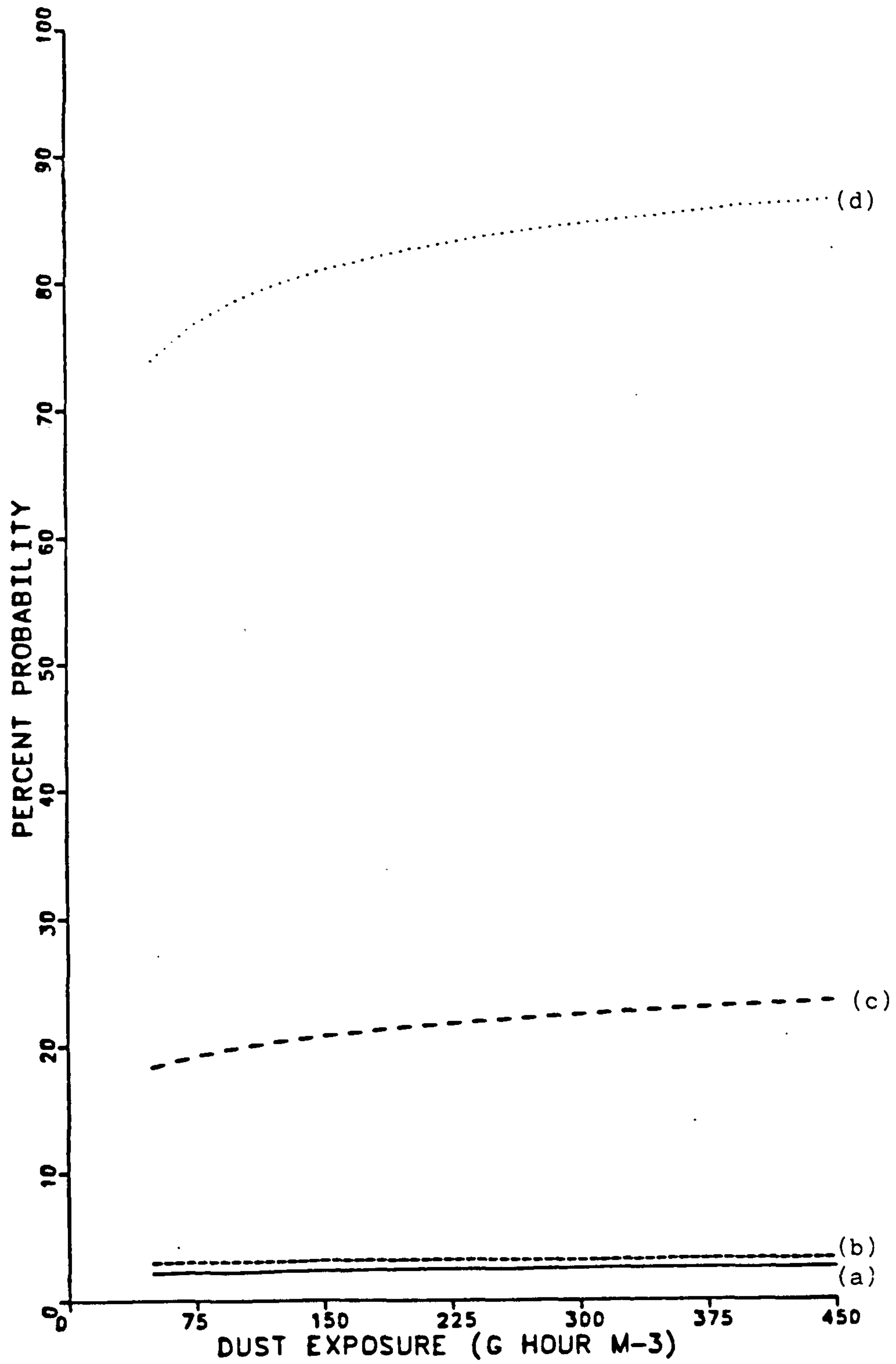

Figure A3.2 Estimated probabilities (percent) that a man aged 40 years with CWSP category 1 will, after five years:

(a) have developed PMF;
(b) have progressed to CWSP category 3 or developed PMF;
(c) have progressed to CWSP categories 2 or 3 or developed PMF;
(d) have remained in CWSP category 1, progressed to CWSP categories 2 or 3 or developed PMF,

assuming a percentage carbon value of 86.2%.

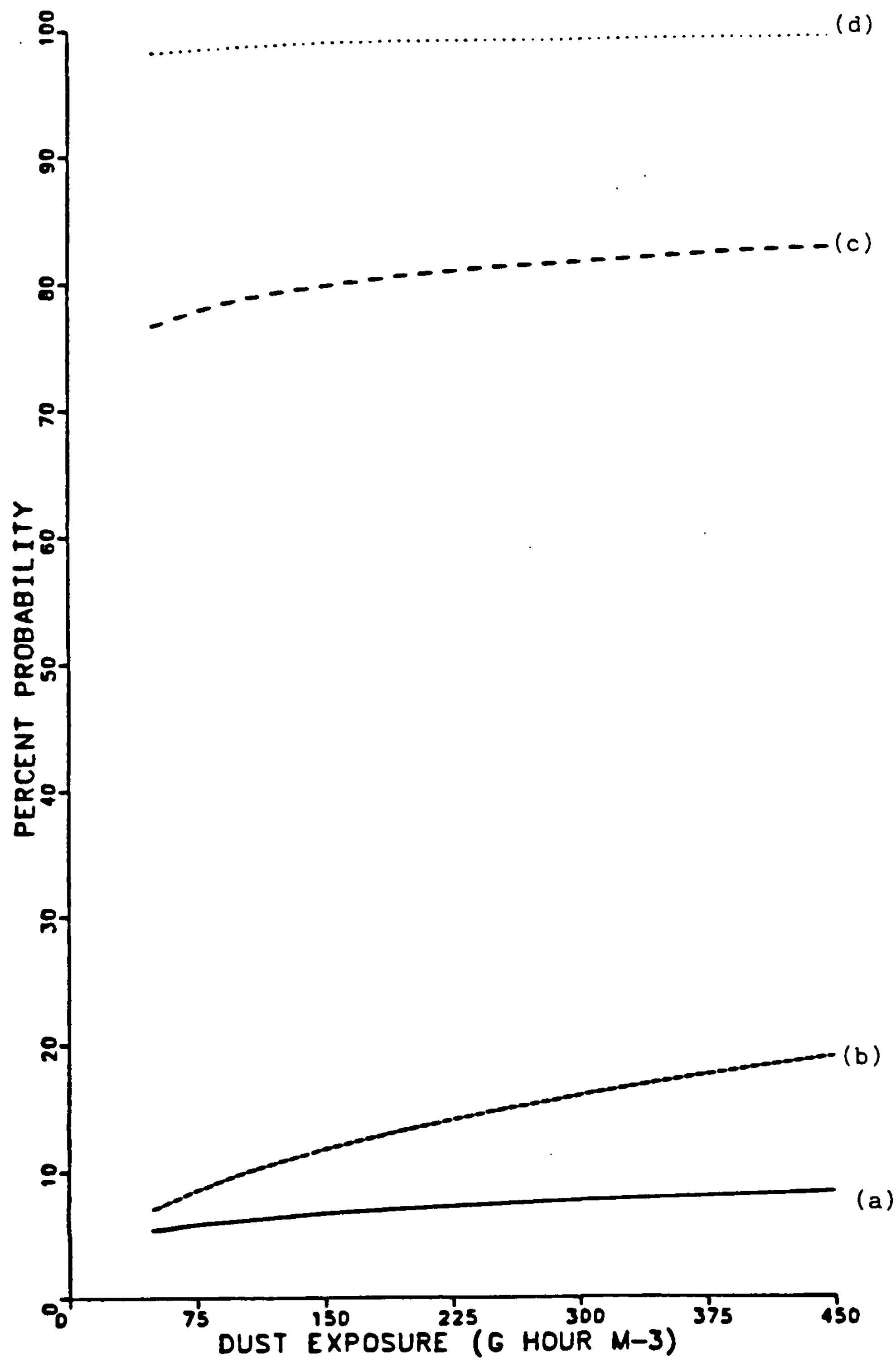

Figure A3.3 Estimated probabilities (percent) that a man aged 40 years with CWSP category 2 will, after five years:

(a) have developed PMF;
(b) have progressed to CWSP category 3 or developed PMF;
(c) have remained in CWSP category 2, progressed to CWSP category 3 or developed PMF;
(d) have regressed to CWSP category 1, remained in CWSP category 2, progressed to CWSP category 3 or developed PMF,

assuming a percentage carbon value of 86.2%.

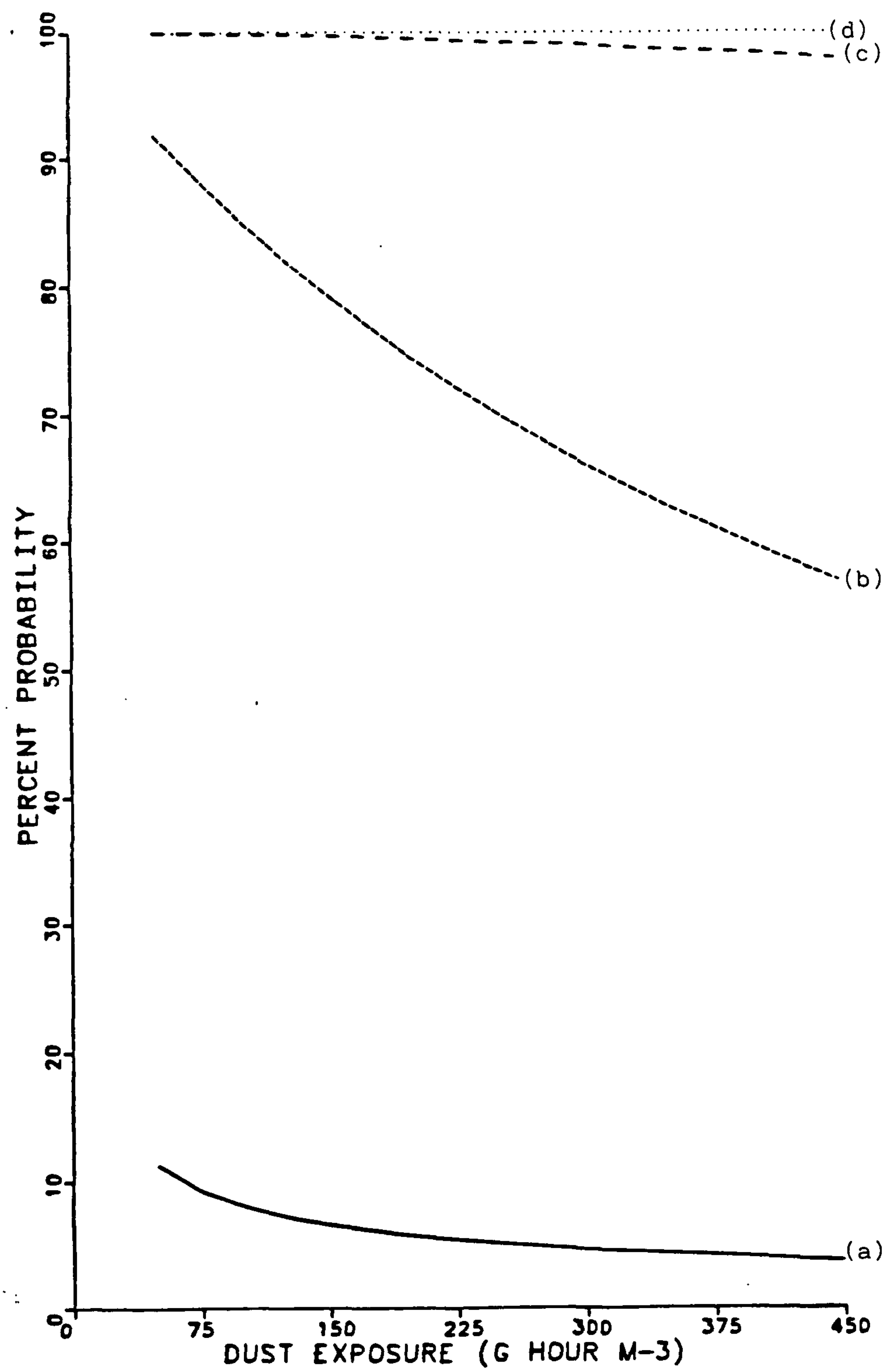

Figure A3.4 Estimated probabilities (percent) that a man aged 40 years with CWSP category 3 will, after five years:

(a) have developed PMF;
(b) have remained in CWSP category 3 or developed PMF;
(c) have regressed to CWSP category 2, remained in CWSP category 3 or developed PMF;
(d) have regressed to CWSP categories 1 or 2, remained in CWSP category 3 or developed PMF,

assuming a percentage carbon value of 86.2%.

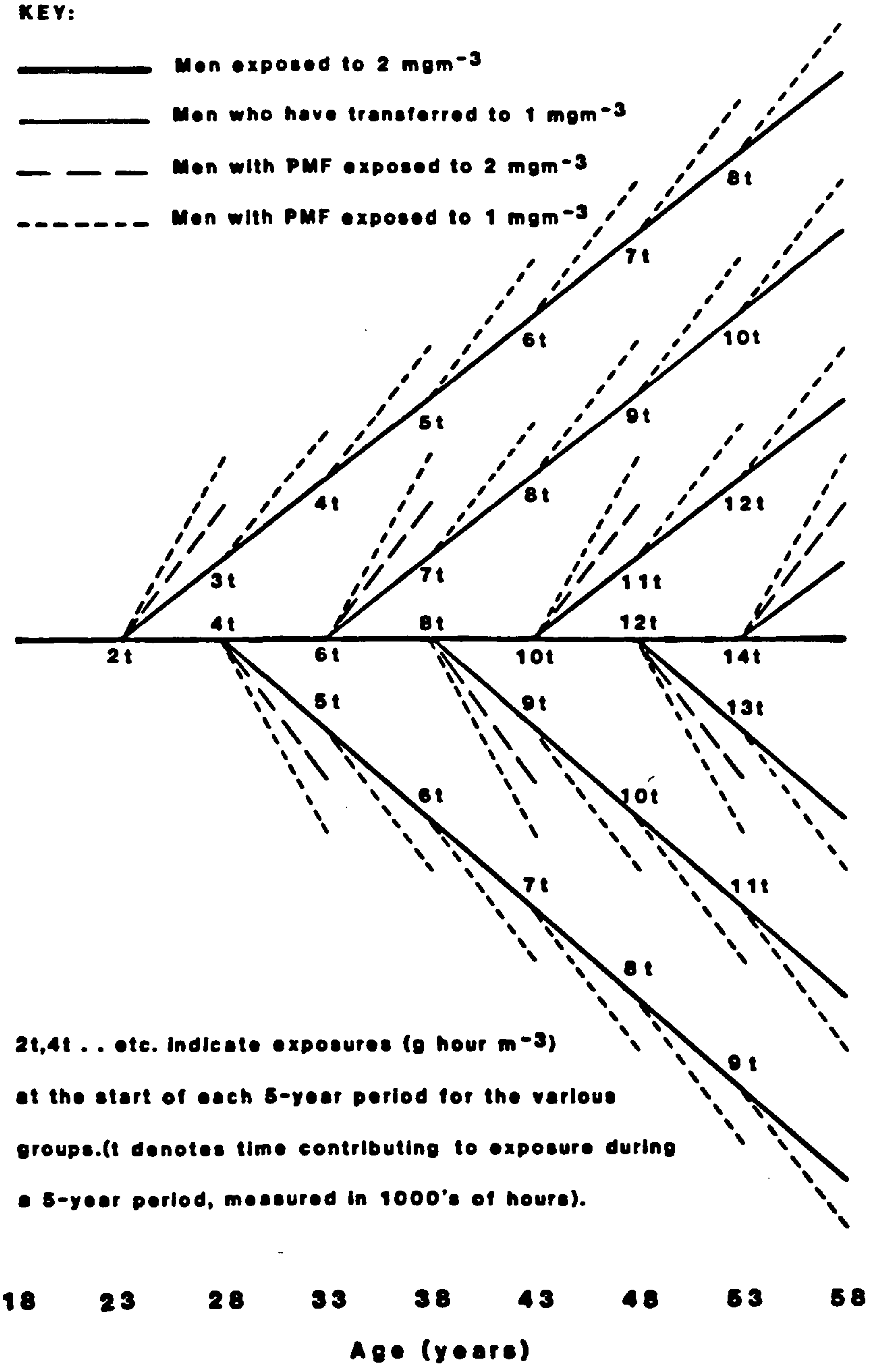

Figure A3.5 Development of various groups of miners according to exposure level and PMF status, throughout a working life of 40 years.

APPENDIX 4

ESTIMATED LIFETIME PROBABILITIES OF RADIOLOGICAL ABNORMALITY FOR A RANGE OF ASSUMED DUST CONCENTRATIONS

Tables A4.1 to A4.4 give estimated lifetime probabilities of simple pneumoconiosis and PMF by age and percent carbon, for four values of average dust concentration: 1.0, 1.5, 2.5 and 3.0 mg m^{-3} respectively.

These results complement Table 1 of the main report, and show how the estimated prevalences of radiological abnormality might be expected to vary with assumed dust concentration.

TABLE A4.1 Probabilities (%) that a man will have simple pneumoconiosis (categories 1, 2, 3) or PMF assuming a working life of 40 years from age 18 to age 58, and exposure to an average dust concentration of 1 mg m^{-3}, tabulated by coal rank (measured by percent carbon) and age.

Coal rank (% carbon)	Radiological category	Age							
		23	28	33	38	43	48	53	58
83.0	CWSP Ø	99.96	99.85	99.62	99.24	98.72	98.05	97.20	96.18
	CWSP 1	0.04	0.13	0.34	0.64	1.04	1.54	2.13	2.82
	CWSP 2	0.00	0.01	0.04	0.10	0.19	0.32	0.48	0.67
	CWSP 3	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.05
	PMF	0.00	0.00	0.00	0.01	0.03	0.07	0.15	0.28
86.2	CWSP Ø	99.96	99.82	99.53	99.05	98.39	97.51	96.41	95.07
	CWSP 1	0.04	0.16	0.41	0.78	1.27	1.88	2.60	3.43
	CWSP 2	0.00	0.02	0.06	0.14	0.27	0.46	0.68	0.94
	CWSP 3	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.09
	PMF	0.00	0.00	0.01	0.02	0.05	0.12	0.25	0.47
89.0	CWSP Ø	99.96	99.79	99.43	98.85	98.02	96.94	95.56	93.88
	CWSP 1	0.04	0.18	0.48	0.92	1.49	2.21	3.05	4.02
	CWSP 2	0.00	0.02	0.08	0.19	0.37	0.61	0.91	1.24
	CWSP 3	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.12
	PMF	0.00	0.00	0.01	0.03	0.09	0.20	0.39	0.73

TABLE A4.2 Probabilities (%) that a man will have simple pneumoconiosis (categories 1, 2, 3) or PMF assuming a working life of 40 years from age 18 to age 58, and exposure to an average dust concentration of 1.5 mg m^{-3}, tabulated by coal rank (measured by percent carbon) and age.

Coal rank (% carbon)	Radiological category	Age							
		23	28	33	38	43	48	53	58
83.0	CWSP Ø	99.96	99.78	99.39	98.77	97.91	96.78	95.37	93.68
	CWSP 1	0.04	0.20	0.54	1.04	1.70	2.52	3.50	4.61
	CWSP 2	0.00	0.02	0.06	0.16	0.32	0.54	0.81	1.13
	CWSP 3	0.00	0.00	0.00	0.01	0.02	0.03	0.06	0.10
	PMF	0.00	0.00	0.01	0.02	0.06	0.13	0.26	0.48
86.2	CWSP Ø	99.96	99.74	99.25	98.46	97.36	95.91	94.10	91.91
	CWSP 1	0.04	0.24	0.65	1.26	2.07	3.06	4.23	5.56
	CWSP 2	0.00	0.02	0.09	0.23	0.45	0.76	1.14	1.56
	CWSP 3	0.00	0.00	0.00	0.01	0.03	0.06	0.10	0.16
	PMF	0.00	0.00	0.01	0.03	0.09	0.21	0.43	0.81
89.0	CWSP Ø	99.96	99.69	99.10	98.14	96.78	94.99	92.75	90.04
	CWSP 1	0.04	0.28	0.76	1.48	2.42	3.58	4.93	6.44
	CWSP 2	0.00	0.03	0.12	0.31	0.61	1.01	1.50	2.03
	CWSP 3	0.00	0.00	0.01	0.02	0.04	0.08	0.14	0.23
	PMF	0.00	0.00	0.02	0.05	0.15	0.33	0.68	1.26

TABLE A4.3 Probabilities (%) that a man will have simple pneumoconiosis (categories 1, 2, 3) or PMF assuming a working life of 40 years from age 18 to age 58, and exposure to an average dust concentration of 2.5 mg m^{-3}, tabulated by coal rank (measured by percent carbon) and age.

Coal rank (% carbon)	Radiological category	Age							
		23	28	33	38	43	48	53	58
83.0	CWSP Ø	99.96	99.63	98.89	97.72	96.09	93.97	91.37	88.27
	CWSP 1	0.04	0.35	0.98	1.92	3.16	4.68	6.43	8.39
	CWSP 2	0.00	0.02	0.11	0.30	0.61	1.03	1.56	2.15
	CWSP 3	0.00	0.00	0.00	0.01	0.03	0.07	0.13	0.21
	PMF	0.00	0.00	0.01	0.04	0.11	0.25	0.52	0.97
86.2	CWSP Ø	99.96	99.55	98.63	97.16	95.10	92.42	89.12	85.22
	CWSP 1	0.04	0.41	1.18	2.32	3.80	5.60	7.67	9.93
	CWSP 2	0.00	0.03	0.16	0.43	0.86	1.44	2.15	2.91
	CWSP 3	0.00	0.00	0.01	0.02	0.05	0.11	0.21	0.35
	PMF	0.00	0.00	0.02	0.07	0.19	0.42	0.86	1.60
89.0	CWSP Ø	99.96	99.47	98.36	96.58	94.06	90.80	86.78	82.06
	CWSP 1	0.04	0.48	1.38	2.70	4.42	6.48	8.80	11.28
	CWSP 2	0.00	0.05	0.22	0.58	1.14	1.90	2.78	3.70
	CWSP 3	0.00	0.00	0.01	0.03	0.08	0.17	0.31	0.50
	PMF	0.00	0.00	0.03	0.11	0.29	0.66	1.33	2.46

TABLE A4.4 Probabilities (%) that a man will have simple pneumoconiosis (categories 1, 2, 3) or PMF assuming a working life of 40 years from age 18 to age 58, and exposure to an average dust concentration of 3 mg m^{-3}, tabulated by coal rank (measured by percent carbon) and age.

Coal rank (% carbon)	Radiological category	Age							
		23	28	33	38	43	48	53	58
83.0	CWSP 0	99.96	99.54	98.62	97.16	95.12	92.49	89.27	85.49
	CWSP 1	0.04	0.43	1.22	2.40	3.93	5.80	7.94	10.30
	CWSP 2	0.00	0.03	0.14	0.38	0.76	1.30	1.96	2.69
	CWSP 3	0.00	0.00	0.01	0.02	0.04	0.09	0.17	0.28
	PMF	0.00	0.00	0.01	0.05	0.14	0.32	0.66	1.24
86.2	CWSP 0	99.96	99.45	98.30	96.47	93.90	90.59	86.55	81.84
	CWSP 1	0.04	0.51	1.46	2.88	4.72	6.92	9.40	12.06
	CWSP 2	0.00	0.04	0.20	0.54	1.07	1.80	2.68	3.61
	CWSP 3	0.00	0.00	0.01	0.03	0.07	0.15	0.27	0.45
	PMF	0.00	0.00	0.02	0.09	0.24	0.54	1.10	2.03
89.0	CWSP 0	99.96	99.35	97.97	95.75	92.63	88.62	83.75	78.11
	CWSP 1	0.04	0.59	1.71	3.35	5.46	7.95	10.71	13.58
	CWSP 2	0.00	0.06	0.27	0.72	1.43	2.37	3.45	4.55
	CWSP 3	0.00	0.00	0.01	0.04	0.10	0.22	0.40	0.66
	PMF	0.00	0.01	0.04	0.14	0.37	0.84	1.69	3.11

APPENDIX 5

RELIABILITY OF DATA AND METHODS

A5.1 Representativeness of sample, and relevance to USA conditions

This was a large-scale study, with data from more than 30 000 coalminers, and a wide-ranging one, including substantial numbers of men from all the coalfields in Britain. And though the study involved examining radiological changes in working coalminers, long-term employment as a miner was not a requirement for inclusion: it was sufficient that a man had participated in two successive five-yearly medical surveys. We think therefore that the results reflect accurately the experience of working coalminers in Britain.

Relevance to conditions in the USA is necessarily less clear. However, when NIOSH in the USA and the PFR in Britain have investigated other issues of coalminers' respiratory health, the results have generally been in good agreement (ATTFIELD *et al.*, 1984; ATTFIELD, 1985).

A5.2 Dust exposure

Estimates of exposure were based on comprehensive environmental monitoring linked with detailed records of time worked. We think however that exposures experienced by men at some collieries prior to the research proper have been underestimated, as noted also by HURLEY *et al.* (1982) and MILLER and JACOBSEN (1985).

A5.3 Radiological classifications

The readings were carried out by the National Coal Board's group of medically qualified specialists in radiological classifications. Their shared experience helped to maintain consistency of classifications during the course of the research, despite changes in the ILO standards for film readings and in the composition of the group itself.

Most of the intervals at risk referred to the earlier part of the research where classifications required the agreement of at least two doctors of the group. (It was in this calendar period also that the need to distinguish PMF from tuberculosis was most required, and the agreement of at least two physicians experienced in the classification of radiographs provides reassurance that tuberculosis was not mistakenly identified as PMF in these films.) Subsequent classifications may be less exact since they were for clinical rather than for epidemiological purposes and each reading involved one doctor only.

A5.4 Epidemiological approach and statistical methods

The PFR was designed to include at the five-yearly medical surveys all industrial workers employed at the colliery concerned at time of survey. Thus, though the study has a longitudinal aspect, no attempt was made to include at later surveys all men who had attended at earlier ones. Such a design, with a discrete response variable, presents non-standard statistical problems and is an area of current development of statistical methods. The Markov-type approach adopted here, of studying five-year intervals, is consistent with that proposed by MUENZ and RUBINSTEIN (1985) in a recent review. It is also similar in concept to the well-established person-years-at-risk approach to mortality studies (CASE and LEA, 1955). There are however a few issues we wish to highlight because they are relevant to the reliability of the present work, and to comparisons of methods and results reported now with the methods and findings of the preliminary work reported by HURLEY and JACOBSEN (1986) at Pittsburgh.

A5.4.1 Estimating CWSP category

The two studies differed in their approach to estimating attained category of CWSP at the start of each five-year period. HURLEY and JACOBSEN (1986) used a cross-sectional approach to this problem. They related attained CWSP category at the start of the risk intervals to dust exposure and age as measured at the same time. They then used the resulting equations to give age- and dust-specific estimates of CWSP category at the start of the various five-year periods of a 40-year working life. This approach took no account of attained CWSP category at any earlier time.

The present study adopted an alternative, longitudinal approach. Radiological category at the end of the risk periods was considered as a response, and attained category at the start of the periods was included as one of the explanatory or predictor variables together with age, dust exposure and carbon content.

It had been well-known for many years that category of CWSP at one point in time was a major factor in predicting simple pneumoconiosis status at some later stage (see, for example, JACOBSEN *et al.*, 1971). Results from the present study confirmed decisively that CWSP category at the start of the risk periods was much the most influential characteristic in predicting CWSP category five years later (Table A3.1). Thus the current method of estimating attained CWSP category includes the single most important predicting factor. This difference, in the context of attained CWSP category being such an important influence on five-year risks of PMF (HURLEY *et al.*, 1987) is the main reason why we think that results from the present work are more reliable than the earlier findings of HURLEY and JACOBSEN (1986).

A5.4.2 The Markov assumption

Because attained category of CWSP at the start of the five-year risk periods is so influential in predicting radiological response at the end, it is reasonable to consider whether predictions could be improved still further by taking account also of CWSP category at even earlier surveys. Examining this issue is equivalent to checking the adequacy of the simple Markovian assumption (that while transitions during one five-year period may and do depend on attained category at the start of the period, they are otherwise independent of any pattern of radiological changes between earlier surveys).

This is an important issue on which there is little published evidence. However, in the work carried out since the present study was completed, ROBERTSON *et al.* (1987) showed that coalminers who progress two or more steps of CWSP on the 12-point ILO scale over approximately five-year periods are more likely than others to experience an attack of PMF in the succeeding five-year period. These results show that the differences in PMF risks are not explicable in terms of differences in age, starting category of CWSP, or region. The corresponding position on changes between categories of CWSP is unknown.

It appears that a more complex modelling of transitions may be appropriate, and we think it would be useful to construct estimates of five-year radiological changes which take account among other factors of transitions at earlier times. The required radiological information from at least one earlier survey is available for about 20 000 of the 52 264 risk intervals studied here. The further work is not trivial: it would lead to a substantially more complex breakdown of the hypothetical mining population than that of Fig. A3.5 of the present study. It would also need to consider to what extent the subset of 20 000 is representative of the entire dataset, and to what extent the estimates of long-term risk are sensitive to the changes in underlying models.

We would be surprised if the effect on long-term risk estimates of PMF were nearly as great as the difference between the preliminary estimates and those reported now. However, the only way to find out is to extend the present analyses, and we think it highly desirable that this should be done.

A5.4.3 Non-radiological explanatory variables

A third issue concerns the choice of other explanatory variables in estimating the risks of five-year radiological changes. This relates to the discussion above, because it is advisable with Markov systems to use as many relevant concomitant variables as possible in order to minimise the effect of ignoring information about earlier steps of the process (COX and MILLER, 1965).

HURLEY and JACOBSEN (1986) included age and dust exposure only. The present study also included percent carbon, which was clearly related to response (Table A3.1), and so made it possible to provide different estimates of long-term risks specific to the carbon content of the coal.

Neither study included exposure to respirable dust experienced during the risk periods. When other factors are taken into account, concurrent exposure is unrelated to the risks of PMF incidence (HURLEY *et al.*, 1987). It is however related to the chances of radiological progression, but demonstrably so only among men with category 1/0 or less CWSP (JACOBSEN *et al.*, 1971; JACOBSEN, 1973). Nor did either study consider whether the influence of exposure on radiological change varied with the time periods over which the exposure was accumulated: HURLEY *et al.* (1982) showed, in cross-sectional analyses, that there were time-related differences in the relation of exposure to presence of CWSP category 2/1 or more, but the effect on transitions has not been examined similarly. Finally, the risks of a PMF attack are related to a man's physique (MACLAREN, 1985), but these effects were also ignored. Relevant data were available for a subset of the risk periods only; estimation of five-year risks in relation to physique would have required added complexity in constructing long-term estimates also; and results from other analyses showed no evidence that the clearcut effect of physique was related to the effect of other factors examined then, especially CWSP (HURLEY *et al.*, 1984).

A5.4.4 Ordered categorical response

A fourth issue concerns the response variable used in the present study, that is, radiological category at the end of the risk periods. The four categories of severity of CWSP constitute an ordered categorical variable, and presence of PMF can be considered a further degree of severity. Statistical methods have been developed for the regression analysis of such data (McCULLAGH, 1980), but we were unable to implement them on such a large dataset, and with so many explanatory variables, as in the present study. The device adopted, of studying a series of nested binary responses using ordinary logistic regression methods, is a good alternative: indeed, this is the idea underlying the more exact approach, but McCullagh's proportional odds method takes account of the correlation between the response variables in the various nested analyses. Even with the simpler approach we were reaching the limits of what it was sensible to attempt, computationally, with these data and models.

REFERENCES: see main report.

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