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**The Effect Of Changes In Shift Patterns On The Risk  
Of Pneumoconiosis**

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# EXECUTIVE SUMMARY

## Objectives

The overall aim of the study was to investigate how the risks of pneumoconiosis vary for different patterns of exposure in coalminers. Five exposure scenarios with the following shift patterns were investigated:

- The baseline. A dust concentration of  $3 \text{ mg.m}^{-3}$ , for a shift pattern of 5 days/week, 8 hrs/day (and 2 days off).
- Pattern 1. A dust concentration of  $2.5 \text{ mg.m}^{-3}$ , for a shift pattern of 6 days/week, 8 hrs/day (and 1 day off).
- Pattern 2. A dust concentration of  $2.45 \text{ mg.m}^{-3}$ , for a shift pattern of 3 days/week, 14 hrs/day (and 3 days off).
- Pattern 3. A dust concentration of  $2.5 \text{ mg.m}^{-3}$ , for a shift pattern of (1 day on 8 hrs/day) + (4 days on 12 hrs/day + 1 day on 8 hrs/day) + (5 days on 8 hrs/day) + (1 day on 8 hrs/day (overtime)).
- Pattern 4. A dust concentration is  $0.54 \text{ mg.m}^{-3}$ , for a shift pattern of continuous work for 28 days at 8 hrs/day to be followed by 7 days off.

We investigated the influence of the change in shift patterns on the risk of category 2 pneumoconiosis by means of a mathematical model. This model describes the exposure-dose relationship, where the dose is the burden of coalmine dust in the human lungs. For humans, the pulmonary adverse effect of coal dust is the impairment of normal functions of the alveolar region (i.e. the blood-air barrier). This region is normally kept clean and sterile by scavenging cells, the macrophages, which ingest foreign matters and clear them from the lung. However, coal dust is predominantly retained in the interstitial space, i.e. the [matrix](#) of supporting [tissue](#) of the lung and therefore is prevented from being removed by macrophages. The accumulation of coal dust in the interstitial space eventually impairs normal lung functions.

## Main Findings

Our calculations indicate that,

- in all cases, a reduction in the level of airborne concentration with respect to the different shift patterns ( Pattern 1 to 4) would lead to a reduction in pneumoconiosis in comparison to the pneumoconiosis level obtained when the airborne concentration is at  $3 \text{ mg.m}^{-3}$  while allowing for the shift pattern to change correspondingly.
- when compared to the baseline scenario, Pattern 1 and 3 yield the same level of pneumoconiosis as the baseline level while pattern 2 and 4 give a much reduced level of pneumoconiosis.

Our model simulations have also indicated that the clearance of coal dust from the lungs is also a sensitive factor affecting the risk of pneumoconiosis.

## Recommendations

The coal mine dust concentration in the air in coal mines should be reduced according to the proposed time-weighting model in order to reduce Pneumoconiosis Risk or maintain the level of risk at the baseline level.

# 1 INTRODUCTION

## 1.1 BACKGROUND

A new legislative package, developed by HSE with industry stakeholders, will be introduced with a time-weighted model for exposure limits, intended to be adaptable to the shift patterns common in current working mines whilst ensuring long-term exposure is controlled.

There is a need to assess how these new measures may affect the risk of pneumoconiosis in miners.

## 1.2 OBJECTIVES

The overall aim of the study was to investigate how the risks of pneumoconiosis vary for different patterns of exposure in coal miners. A mathematical model, describing the exposure-dose relationship, was applied to assess the effects of changes in exposure concentrations on the risk of developing pneumoconiosis. Specifically, five exposure scenarios, taken from the examples set out in the package to illustrate the effect of the time-weighting model, with the following shift patterns were investigated:

- The baseline. A dust concentration of  $3 \text{ mg.m}^{-3}$ , for a shift pattern of 5 days/week, 8 hrs/day (and 2 days off).
- Pattern 1. A dust concentration of  $2.5 \text{ mg.m}^{-3}$ , for a shift pattern of 6 days/week, 8 hrs/day (and 1 day off).
- Pattern 2. A dust concentration of  $2.45 \text{ mg.m}^{-3}$ , for a shift pattern of 3 days/week, 14 hrs/day (and 3 days off).
- Pattern 3. A dust concentration of  $2.5 \text{ mg.m}^{-3}$ , for a shift pattern of (1 day on 8 hrs/day) + (4 days on 12 hrs/day + 1 day on 8 hrs/day) + (5 days on 8 hrs/day) + (1 day on 8 hrs/day (overtime)).
- Pattern 4. A dust concentration is  $0.54 \text{ mg.m}^{-3}$ , for a shift pattern of continuous work for 28 days, at 8 hrs/day to be followed by 7 days off.

## 2 METHODS

Existing estimates of pneumoconiosis risk are based on cumulative exposure to coalmine dust and do not take account of the time period or shift pattern over which the exposure is accumulated. For example, the risk of pneumoconiosis for exposure to  $1 \text{ mg.m}^{-3}$  dust for 5 years would be the same as for exposure to  $5 \text{ mg.m}^{-3}$  dust for one year. It is therefore not possible to estimate changes in pneumoconiosis risk directly for different scenarios which result in the same total lifetime exposure, although the scenarios should result in different lung burdens in coalminers due to the varying deposition and clearance rates of dust over varying time periods.

In this report, a multi-stage approach for estimating the pneumoconiosis risk, taking into account the total lung burdens from the different exposure scenarios was adopted. The approach is summarised below:

1. For each scenario, the exposure pattern constructed was for 35 years exposure with a fixed number of holidays, annual and public, per year. The holidays were assumed to be constant between years and different patterns of exposure.
2. The lung burden arising from 35 years of exposure for each of the scenarios, including the baseline scenario, was simulated.
3. The final lung burden, following cessation of working life-time exposure (35 years) was estimated.
4. The concentration level over baseline exposure pattern that would give the same final lung burden in a given scenario was then calculated.
5. The pneumoconiosis risk based on this concentration level using the standard risk equation was estimated.
6. The sensitivity of this approach on the change in the clearance rate of dust from the lung was demonstrated.

### *Construction of exposure pattern*

For each scenario, the pattern of exposure was constructed. This was based on the number of days worked during a tour of duty, and the number of rest days that followed. It was assumed that in each calendar year, there would be 28 days of annual holiday. These would comprise 3 weeks holiday in August each year, when the colliery would have been closed; 3 days holiday over the Christmas/New Year period and the remaining holidays spread randomly throughout the year. An annual exposure profile for each scenario was constructed using this information. It was assumed that the annual exposure profile was repeated each year over a working lifetime of 35 years.

### *Estimation of lung burden*

The exposure profiles were used to estimate the lung burden following 35 years exposure under each scenario. Lung burdens were calculated using the exposure–dose mathematical model for dust deposition and clearance in the lung developed by Kuempel *et al* (2001a,b). This model was calibrated using data from US miners and validated with similar UK data (Tran and Buchanan, 2001). Full details of the lung burden model are given in Appendix.

Mathematical modelling was used to calculate, for each scenario, an estimate of the final lung burden. This was compared to the final lung burden for the baseline scenario, and adjustments made to the concentration in the baseline scenario (higher or lower depending on whether the final lung burden for that scenario was higher or lower than for the baseline), in order to determine the concentration value that would provide a final lung burden under the baseline

scenario which was of the same level as that in the scenario being analysed. This concentration was then used for the calculation of pneumoconiosis risk for that scenario.

*Calculation of pneumoconiosis risk*

Risks of pneumoconiosis were calculated using the equation:

$$P_{\text{CAT2}} = - (a/R) + ((b \times C_{AV} \times R \times Y \times H) / (1631 \times 40)) \quad (1)$$

where

$R$  = mean percentage carbon (=86 percent)

$C_{AV}$  = average dust concentration ( $\text{mg.m}^{-3}$ )

$Y$  = number of years worked (= 35)

$H$  = number of hours worked per year (=1740)

$a = 53$

$b = 0.01667$

from, Kenny *et al* (2004), describing the risk of developing category 2 pneumoconiosis.

### 3 RESULTS

#### *Baseline scenario*

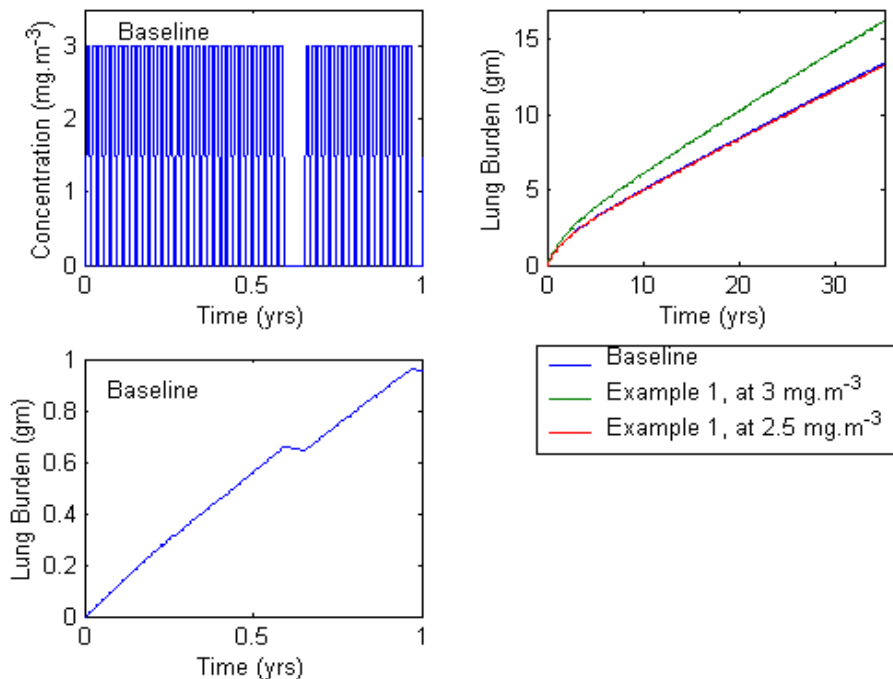
We first consider the baseline scenario. Here, a worker is exposed 5 days a week, 8 hours a day. He will be working for 35 years with 28 days holidays per year. For a given year, his pattern of exposure is given in Figure 1a, which shows exposure to concentrations of  $3 \text{ mg.m}^{-3}$  for 5 working days followed by zero exposure in the 2 rest days that follow. Larger gaps in exposure are seen for the 3-week holiday period in August and the winter holidays. The lung burden associated with this one year exposure pattern is shown in Figure 1c, clearly showing the effect of lung clearance during the holiday periods.

We assume that there are 35 consecutive years of this pattern of exposure, with the time course of the lung burden over this lifetime exposure given in Figure 1b.

#### *Scenario Pattern 1*

Pattern 1 assumes that a miner works for 6 days a week, 8 hours a day, with one rest day. If this shift pattern occurred with the same concentration level as the baseline exposure ( $3 \text{ mg.m}^{-3}$ ) the final lung burden will be higher (Figure 1b). A reduction in the level of concentration for this pattern of work to  $2.5 \text{ mg.m}^{-3}$  leads to the same level of lung burden as in the baseline scenario. This example shows that, for the alternative shift pattern, a reduction of  $0.5 \text{ mg.m}^{-3}$  would help maintain the pneumoconiosis risk at the baseline level.

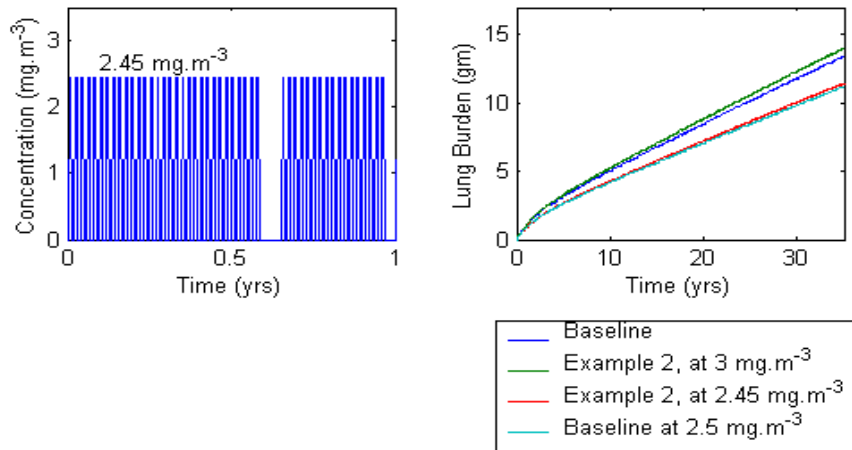
The results show that the lung burden for scenario pattern 1 at  $2.5 \text{ mg.m}^{-3}$  is the same as for the baseline scenario at  $3 \text{ mg.m}^{-3}$ . Therefore, for the calculation of pneumoconiosis risk, the equivalent baseline concentration of  $3 \text{ mg.m}^{-3}$  should be used for this scenario pattern.



**Figure 1. (a) Baseline pattern; (b) lung burden for Pattern 1 after 35-years exposure; (c) Build up of lung burden for a 1-year exposure at baseline pattern.**

*Scenario Pattern 2*

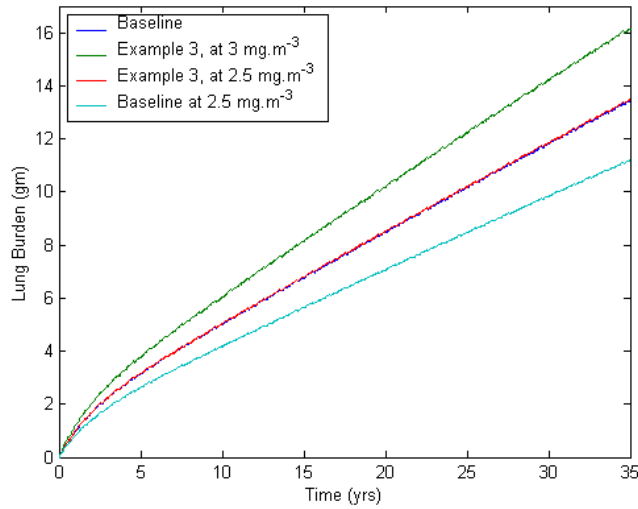
In this scenario the pattern assumes a miner has a 3 day working week (4 days off), with each shift consisting of 14 hours per day at an average concentration of  $2.45 \text{ mg.m}^{-3}$ . The exposure pattern for this scenario is shown in Figure 2a. Using the same methods as above, the final lung burden after 35 years exposure at  $2.45 \text{ mg.m}^{-3}$  was calculated to be 11.18 gm. This burden is equivalent to a final lung burden of a hypothetical miner following the baseline pattern of exposure but exposed at  $2.5 \text{ mg.m}^{-3}$ . Therefore, for the calculation of pneumoconiosis risk, the equivalent baseline concentration of  $2.5 \text{ mg.m}^{-3}$  should be used for scenario pattern 2.



**Figure 2. (a)Pattern for Example 2; (b) Lung burden for Example 2 after 35-years of exposure.**

*Scenario pattern 3*

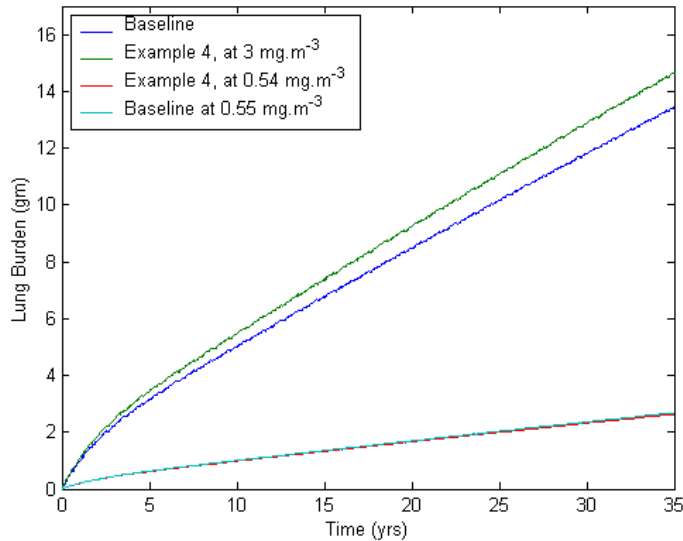
Scenario pattern 3 assumes that the miner is exposed for 1 day at 8 hrs/day, 4 days at 12 hrs/day, 1 day at 8 hrs/day, 5 days at 8 hrs/day and 1 day at 8 hrs/day (overtime) at a concentration of  $2.5 \text{ mg.m}^{-3}$ . This pattern of exposure leads to a final lung burden equivalent to a hypothetical baseline exposure of  $3 \text{ mg.m}^{-3}$  (Figure 3).



**Figure 3. Lung burden accumulation for Example3 and the baseline exposure at 3 mg.m<sup>-3</sup> and 2.5 mg.m<sup>-3</sup>**

*Scenario pattern 4*

For this pattern of exposure, a miner is assumed to be work continuously for 28 days, at 8 hrs/day to be followed by 7 rest days, at an average dust concentration of 0.54 mg.m<sup>-3</sup>. The final lung burden from this pattern of exposure is much lower than for the baseline scenario, or any of the other scenarios (Figure 4). The equivalent baseline exposure, which produces the same lung burden, as the exposure pattern given in example 4 is 0.55 mg.m<sup>-3</sup>.



**Figure 4. Lung burden for the baseline pattern of exposure and the pattern of Example 4 at different airborne concentrations.**

*Pneumoconiosis Risk for the different patterns of exposure*

The risks of category 2 pneumoconiosis were calculated using Equation (1). The risks were calculated for the baseline scenario at 3 mg.m<sup>-3</sup> and for the ‘equivalent baseline concentrations’ for each of the scenarios. The results are shown in Table 1. In all cases, as indicated by the final lung burden (Figure 1b, 2b, 3 and 4), if the airborne concentration is maintained at 3 mg.m<sup>-3</sup>, the final lung burdens will exceed that of baseline exposure. Consequently, the risk of category 2 pneumoconiosis will be higher than baseline. However, if the suggested change in dust level is applied for each scenario, a reduction in pneumoconiosis in 2 cases is achieved (compared to baseline) and in 2 cases, the risk is maintained at baseline level. The results are summarised in Table 1.

**Table 1. Risk for Category 2 Pneumoconiosis for all scenarios**

	Scenario Conc. (mg.m <sup>-3</sup> )	Equivalent Baseline Conc. (mg.m <sup>-3</sup> )	P <sub>CAT2</sub>	Percentage Reduction (%)
Baseline	3.0	-	3.40	-
Example 1	2.5	3.0	3.40	0
Example 2	2.45	2.5	2.73	10.69
Example 3	2.5	3.0	3.40	0
Example 4	0.55	0.55	0.12	96.48

*Model sensitivity to Dust Clearance*

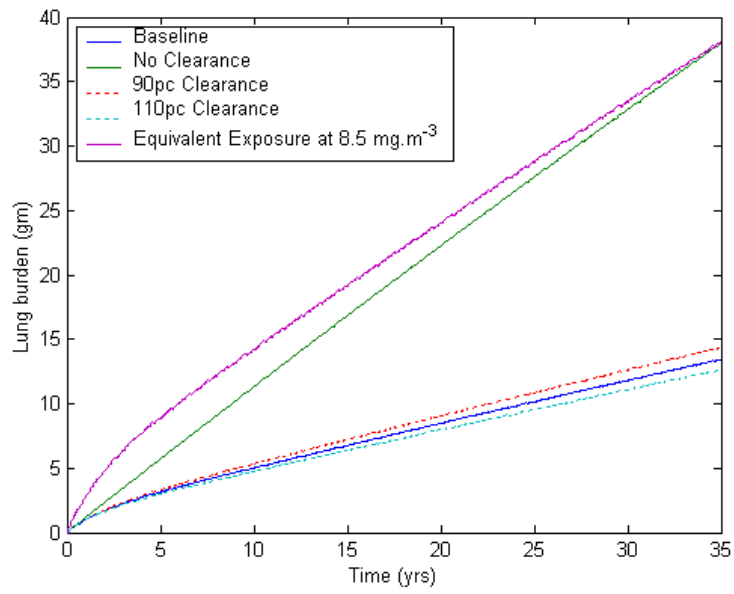
The sensitivity of the dust clearance parameter in the model was investigated. A Dust clearance rate of 0.001 day<sup>-1</sup> was used in the baseline model. The baseline exposure pattern (5 days/week and 8 hrs/day) was used for comparative purposes.

A 10 percent increase or decrease in the clearance rate results in an inverse final lung burden of a magnitude of 6-7 percent (Table 2).

Miners with existing lung diseases (Chronic Obstructive Pulmonary Disease) or smokers tend to have negligible dust clearance mechanisms. With zero clearance, the final burden is predicted to be 37.92 gm compared with 13.41 for a miner with normal clearance (Figure 5). This is equivalent to a final lung burden, for a worker with normal clearance, achieved with exposure to 8.5 mg m<sup>-3</sup>. In this case, the Risk for Category 2 Pneumoconiosis for individuals with negligible clearance is as high as 11 percent (compared to 3.4 percent for the baseline scenario with normal clearance).

**Table 2. Influence of dust clearance on final lung burden**

Scenarios	Final Lung Burden (gm)	Percentage Change
10 percent reduction in clearance	14.35	+ 7
Baseline clearance	13.41	-
10 percent increase in clearance	12.59	-6
Zero clearance	37.92	+183



**Figure 5. Model sensitivity to dust clearance parameters**

## 4 CONCLUSIONS

The impact of changes in control limits, for coalmine dust due to different shift patterns, on the risk of developing category 2 pneumoconiosis were investigated. In this approach, which applies a mathematical model describing the cumulative lung burden, has demonstrated that:

- In all Examples, the reduction in the dust concentration required by the proposed time-weighting model would lead to either a reduction in Pneumoconiosis Risk or at least maintenance of the level of Risk at the baseline level.
- The approach is sensitive to the clearance rate of dust from the lung and individuals with negligible dust clearance are likely to accumulate more lung burden which will lead to a higher Risk of pneumoconiosis.

## 5 APPENDICES

### *The Model*

Briefly, the model is described by 3 compartments representing, the alveolar region ( $X_1$ ), the interstitium ( $X_2$ ) and the lymph nodes ( $X_3$ ). The rate of dust accumulation in each compartment is described by a differential equation.

Mathematically, the model is described as:

$$\begin{aligned}\frac{dX_1}{dt} &= Dose - K_t \cdot X_1 - K_i \cdot X_1 \\ \frac{dX_2}{dt} &= K_i \cdot X_1 - K_{ln} \cdot X_2 \\ \frac{dX_3}{dt} &= K_{ln} \cdot X_2\end{aligned}\tag{A.1}$$

where  $dX_i/dt$  is the rate of dust accumulating in compartment  $i$  (mg/day).

$Dose = Fractional-deposition \times Volume-inhaled \times Concentration$ , is the deposited dose in the alveolar region (mg/day).  $Fractional-deposition$  is the percentage of inhaled dust that reaches the alveolar region.  $Volume-inhaled$  is the volume of air inhaled ( $m^3$ ) either via the nose or mouth-beathing;  $Concentration$  is the airborne concentration ( $mg/m^3$ ).

$K_s$  are rate parameters ( $day^{-1}$ ).  $K_i$  is the interstitialisation rate,  $K_{ln}$  is the dust translocation rate to the lymph nodes and  $K_t$  is the pulmonary clearance rate of dust.

As observed in animal experiments, pulmonary clearance becomes impaired at high lung burden. So, the clearance rate  $K_t$  is dependent on the lung burden,  $X_1$ .

If  $X_1$  is less than the minimum critical burden,  $X_{min}$  then,

$$K_t = K_{t0}$$

otherwise,

$$K_t = K_{t0} \cdot e^{-B \left( \frac{X_1 - X_{min}}{X_{max} - X_{min}} \right)^C}\tag{A.2}$$

Where,  $X_{max}$  is the lung burden such that  $K_t$  declines by 50 percent of its original value ( $K_{t0}$ ).

Similarly,  $K_{ln}$  increases with high interstitialised burden ( $X_2$ ).

$$K_{ln} = K_{ln0} \cdot e^{B_i \cdot X_2}\tag{A.3}$$

Where,  $B$  and  $C$  are parameters governing the extent of impairment of clearance and  $B_i$  relates the increase in the rate of translocation rate to the interstitialised lung burden  $X_2$  and  $K_{ln0}$  is the original value.

### *Model Parameters*

The model, initially, had three different parameter sets. Each set represented different hypotheses about the exposure-dose relationship (Kuempel *et al*, 2001a,b). The three assumptions are: (i) 'Severe Overload', when 90 percent of the clearance rate became impaired; (ii) 'Moderate Overload', with 50 percent impairment of clearance; (iii) 'No Overload with high sequestration', in which alveolar clearance is effective but the amount of dust in the alveolar

region is small in proportion to the amount retained in the interstitial region. The model, with different hypotheses, was calibrated and tested with autopsy data from US coalminers and validated using a similar dataset of autopsy data from UK coalminers (Tran and Buchanan, 2001). The model, representing the 3<sup>rd</sup> hypothesis gave the best fit of all the three hypotheses. This model is also in concordance with the observations from Nikula *et al* (2001). The model parameters, representing this hypothesis, are listed in the Table below.

Fractional Deposition	0.12
Volume Inhaled (m <sup>3</sup> /hr)	1.69
$X_{\min}$ (mg)	105
$X_{\max}$ (mg)	10500
$B$	$1 \times 10^{-4}$
$C$	1.0
$B_l$	$1 \times 10^{-9}$
$K_t$	$1 \times 10^{-3}$
$K_i$	$4.7 \times 10^{-4}$
$K_{ln}$	$1 \times 10^{-5}$

The fractional deposition is for particles with Mass Median Aerodynamic Diameter (MMAD) of 0.5  $\mu\text{m}$ . The human subject is assumed to be a male Caucasian 1.76 m in height, involved in heavy manual work, and predominantly mouth breathing (IRCP, 1994). The volume inhaled is for an 8-hr shift.

#### *Model simulation*

The model, was exercised to simulate the benchmark exposure regime and the accumulation of coalmine dust. Figure A1 shows the accumulation of dust in the alveolar, interstitial and lymph node regions. The first order removal of dust from the alveolar region ( $X_1$ ) to the mucociliary escalator (for clearance) and to the pulmonary tissues: i.e. the interstitium, is described by the first equation in A1 and ensures that  $X_1$  reaches a steady state (see Figure A1). However, the human model predicts an increasing burden in the interstitium (compartment  $X_2$ ) as dust becomes increasingly imbedded in the matrix of supporting tissues of the lung (i.e. the interstitial space) and therefore unavailable for clearance, in another word, sequestered. Finally, a second source for particle sequestration is in the lymph nodes ( $X_3$ ).

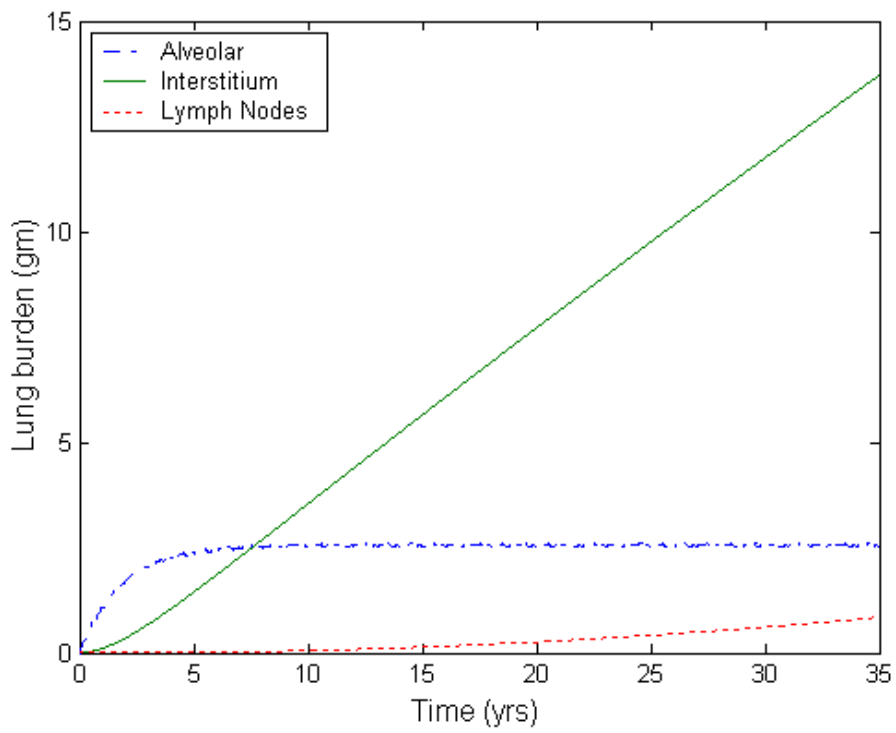


Figure A1. The 3 compartments of the exposure-dose model for the retention and clearance of coalmine dust in humans.

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