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A METHOD FOR MEASURING THE POTENTIAL ALPHA ENERGY (WORKING-LEVEL VALUES) OF AIRBORNE RADIOACTIVITY IN COALMINES

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SUMMARY

Following findings that airborne radioactivity could reach potentially dangerous levels in metal mines a method has been developed and tested for measuring the hazard in working levels due to low airborne concentrations of mixed radon and thoron daughters in coalmines. The measurement is made on a sample of respirable dust collected throughout a shift. The alpha-decay of the sample is measured for two periods, the second ending four hours after the end of sampling, and the working-level values of the two radioactive series are obtained. The method is sensitive to 1 mWL or less, and the figures are a reasonably accurate measure of the average exposure of the worker through the shift. The sampling equipment used is the MRE gravimetric sampler, which is electrically safe in a methane-air mixture.

Field trials in a colliery over a period of eight months show: (1) no secular change of total working levels; (2) random variation with time within ± 30% of the mean; (3) no difference between the working levels given by total and respirable dust samples; (4) little, if any, variation between different faces in the same seam; (5) little, if any, variation with barometric pressure; (6) an average face working-level value of about 25 mWL, about 70% of this being the radon component. The method is now being used to survey the airborne radioactivity hazard in British coalmines.

1. RADIOACTIVITY IN COAL MINES

It is well known that airborne radioactivity can reach hazardous levels in mines even where no obviously radioactive minerals are being extracted. The isotopes of the gas emanation, radon($^{222}_{86}$Em, or Rn) and thoron ($^{220}_{86}$Em, or Tn), occur in the decay chains of 238-uranium and thorium, which are present in small quantities in all rocks. The gases diffuse through the rock and contribute to the radioactivity of the air. In mines, this process is always more important than at the surface because of the larger area of rock exposed and the generally lower ventilation, and where the concentrations of the radioactive elements in nearby rocks have been increased by natural processes, the airborne concentrations are also increased.

Although coal seams are usually less radioactive than other sedimentary strata, enhancement of both uranium and thorium can occur, especially where the coal measures are overlaid by igneous rocks. As far as uranium is concerned, Ode (1963) cites various sources which suggest that soluble uranium salts in percolating groundwater are reduced to an insoluble form in the coal beds. This is consistent with the finding that the highest coal seam in a series is often the most radioactive. It is also often found that lower-rank coals are the more active, with some lignites having a uranium content of 0.1%. Davidson and Ponsford (1954) even refer to a coal seam in East Germany which was said to be mined for its uranium content. The presence of uranium can also make marine shales in coal measures relatively highly radioactive. As far as thorium is concerned, Parks (1963) quotes a finding that a coal seam rich in zircons had a high thorium content. Similarly, Knowles (1961) found that in one sample of medium-fine sandstone from the Yorkshire coal-measures, zircons were the source of over half the alpha-activity, although they constituted only about 0.2% of the mineral. Thorium and zirconium are chemically similar, and so an association is reasonable. Ode (1963) refers to some Ruhr coals with a zirconium content of 0.7% (the mean abundance in the crust is about 0.02%), but gives no information on thorium content, and there seems no other information

on the presence of this element in coal.

Duggan, Howell & Soilleux (1968) measured radon concentrations in twelve British coalmines and found a maximum concentration of 14 pCi l^{-1}, with a median for the twelve mines of 2 pCi l^{-1}. Their method was to take a gas sample in the mine, and to measure the radioactivity of the gas later, making corrections for the thoron present. The results are consistent with measurements in U.S. coalmines, such as those by Lucas and Gabrysh (1966). For comparison, a typical surface value is 0.1 pCi l^{-1}.

2. THE HEALTH HAZARD

Thoron and radon are not particularly dangerous in themselves. Being isotopes of an inert gas, they are breathed in and out with the air, giving only a very small radiation dose to the walls of the respiratory tract. However, they decay to atoms of non-volatile radioactive elements, and these daughter atoms quickly attach themselves to solid surfaces, usually airborne dust. If the free atoms are inhaled before they are captured, they are likely to attach to the walls of the tract. In addition, some of the dust will be deposited in the airways, and the daughter atoms attached to it are therefore likely to decay further in close contact with the airway walls while the dust is being cleared. The resulting alpha close to the walls is potentially dangerous. The decay schemes involved are shown in Figure 1.

The dose therefore depends on several factors, including the concentrations of the parent gases and their various daughters, the proportions of the daughters attached to dust, the deposition of the dust in the respiratory tract, and the proportion of attached atoms decaying before the dust is cleared. In practice, however, Archer, Wagoner & Lundin (1973) have shown lung cancer incidence amongst uranium miners to correlate well with the potential alpha energy of the radon daughters in the air, i.e. the

total energy that would be released per unit volume of air as alpha radiation if all the short-lived daughter atoms decayed away. The unit of potential alpha energy is the working level (WL), one working level being equal to 1.3×10^5 MeV l^{-1} potential alpha energy. This is usually applied only to the radon decay scheme, because in uranium mines the contribution of other isotopes is negligible, and the "short-lived daughters" concerned are 218-polonium (RaA) to 214-polonium (RaC') inclusive. When thoron daughters are present in sufficient concentrations to make them important, however, the definition can be extended to include thoron daughters, in which case one working level equals a potential alpha energy of the thoron daughters from 212-lead (ThB) to 208-lead of 1.3×10^5 MeV l^{-1} (Jacobi, 1972a). The short half-life of 216-polonium (ThA) means that very few atoms are present at any one time, so that the contribution of those that are present can be ignored. The thoron working level is an overestimate of the radiological hazard compared with the radon working level because an appreciable proportion of ThB (half-life 10.6 hr) will have been cleared from the respiratory system before alpha-emission occurs. The degree of overestimate is hard to calculate. Jacobi (1972b) estimates it to be 15-40 times for daughters deposited in the bronchial region, and 1.5 - 2 times for the much smaller deposit in the pulmonary region. In the relatively dusty conditions of coalmines, the ratios might be smaller. Because of this uncertainty, Duggan (1973) has questioned the use of working level as a unit for thoron daughter measurement at all, but in the present uncertain state of thoron daughter dosimetry we have used working levels for convenience, although the results must be interpreted with the knowledge that the radon-daughter working level probably represents substantially more actual hazard than the thoron-daughter working level.

One working level is present when 100 pCi l^{-1} of radon is in radioactive equilibrium with its daughters, so that the maximum of 14 pCi l^{-1} of radon recorded by Duggan et al. (1968) would

correspond to 0.14 WL if radioactive equilibrium existed, but probably less than that in reality. The present US Department of Labour regulations permit miners to be continuously exposed to 0.3 WL throughout their working lives, but there is evidence that this standard allows a smaller safety margin than is usual in occupational hygiene. For example, Duggan, Soilleux, Strong & Howell (1970) found median concentrations between 0.15 and 2 WL in four haematite mines in Cumberland, where Boyd, Doll, Faulds & Leiper (1970) found increased incidence of lung cancer.

The measurements of Duggan et al. (1968) are therefore low, but not low enough to permit complacency. Doll (1958) and Goldman (1965) found that British coal miners were less likely than other comparable groups to develop lung cancer, confirming that any direct hazard is probably small. On the other hand, the possibility that radiation exposure at low levels may have a synergistic effect in association with other factors, such as dust, cannot be neglected. Available data suggest that between 0.1 and 1% of respirable-size dust particles emit alpha particles between deposition and clearance.

As a precautionary measure, therefore, a method has been developed to permit regular monitoring of the hazard from airborne radioactivity in coalmines, and the rest of this memorandum describes the method. It is proposed to use it to survey radioactivity levels in a sample of British coalmines, with a closer study of any areas or circumstances where high levels are found. It is not thought that airborne radioactivity is a direct danger in any British coalmines, but the survey will make certain of this, and provide data for any future study of synergistic effects.

3. THE MEASUREMENT PROBLEM IN COALMINES

The need to monitor radon daughters in uranium mines has led to the development of a number of practical measurement methods. Many of the commoner ones are developments of that of Kusnetz (1956), which involves filtering 100 to 250 litres of air in a five to ten minute period, and measuring the alpha activity of the filter at

some time between 40 and 90 minutes after sampling. If the filter is efficient, all the radon daughter atoms, whether attached to dust or not, are caught on the filter, and knowledge of the decay characteristics of the isotopes involved permits calculation of the radioactivity of the air. The relative proportions of the isotopes remain unknown, but the resultant error in the derived WL-value was claimed by Kusnetz to be always less than 12%, although Groer (1972) put the possible disparity at 25%. Other methods involve taking a gas sample, whose radon content can later be measured, or having two filters in series, with a decay chamber between, which permits the radon and daughter concentrations to be measured separately. Measurements in uranium mines are made frequently of radon gas only, on the grounds that preventive measures require knowledge of the local sources of radon, but measurement of the hazard itself must involve measurement of the daughters.

The main practical problem of measurement in British coalmines is the requirement that equipment should be electrically safe in flammable atmospheres. This eliminates all readily-available high-volume electrical air-sampling equipment and sensitive alpha-radiation meters, so that Kusnetz's method cannot easily be used. Air-sampling equipment driven by compressed air is available, but few coalmines today have compressed air supplies at the coal-face, and a gas cylinder of sufficient size is cumbersome. This is why Duggan et al. (1968) only measured radon from a gas sample, and not radon daughters. Also a routine method for coalmines needs to be sensitive, because of the low radioactivity levels involved. It also became apparent early in the project that thoron daughters often make an important contribution to the total working level in coalmines, so that the chosen method must be able to take this component into account. Cost is also important, particularly as radioactivity is evidently not a very serious direct health problem.

For these reasons a new method has been developed, meeting all these requirements, and based on measuring the alpha activity of the shift-long respirable dust samples taken routinely in a sample

of coalmines as part of the Pneumoconiosis Field Research, using the Casella gravimetric dust sampler, Type 113A (Dunmore, Hamilton & Smith, 1964). Under this programme, volunteer mineworkers carry the samplers with them, so that a measure is obtained of the respirable dust concentration in their vicinity during their time underground on a particular shift - usually about seven hours. The choice of the PFR samples for this method was made for organisational reasons. If necessary, the method could be used, with minor changes, on the routine dust samples taken at all pits by the National Coal Board. The alpha activity of the dust sample is measured when the instrument has been brought to the surface, and from this the WL-values can be obtained, as will now be shown. We assume for the moment that all the activity is on the respirable dust. Field work to test this assumption is described later.

4. THEORETICAL BASIS OF METHOD

The object of this section is to relate the alpha-count from the dust on the filter after sampling to the WL-value in the air sampled. An error of up to 20% has been regarded as acceptable.

4.1 List of Symbols

A'	alpha-decay rate of sample taken over a period (sec^{-1})
A	total number of alpha decays in time specified by subscript
b	ratio of airborne activity concentrations of RaB
c	ditto for RaC and RaA
Dec	rate of decay of isotope
Form	rate of formation of isotope
k	sampling-time correction factor = $\left\{1-\exp(-2.52 \times 10^4/\tau_{TB})\right\}/\left\{1-\exp(-T/\tau_{TB})\right\}$ (T and τ in sec)
N(t)	number of undecayed atoms of RaC on filter present at time t which were formed on the filter from RaB
n	rate of collection of atoms of an isotope on the filter
p_R	c/τ_{RA}
q_R	$(b\tau_{RB} + \tau_{RA}) / \tau_{RA}(\tau_{RB} + \tau_{RC})$
p_T	γ / τ_{TB}
q_T	$1 / (\tau_{TB} - \tau_{TC})$
T	sampling time
t	time
V	volume sampling rate
w	number of working levels
χ	airborne activity concentration ($pCi\ l^{-1}$)
γ	activity concentration ratio of ThC to ThB
ν	number of atoms of an isotope per litre
τ	mean lifetime of atom

Subscripts:

R	radon daughter series
RA	RaA
RB	RaB
RC	RaC
T	thoron daughter series
TA	ThA
TB	ThB
TC	ThC
Tot	both series together
50	time interval 50-135 min after end of sampling
135	Do. 135-240 min

4.2 Alpha Count from Radon Daughters

As mentioned above, the sampling time is usually about 7 hr. Consider first, however, a sample taken in a very short time δt from an atmosphere with x_{RA} pCi l^{-1} of RaA, bx_{RA} pCi l^{-1} of RaB and cx_{RA} pCi l^{-1} of RaC. (If the series is in radioactive equilibrium, $b = c = 1$).

Each second the sampler collects Vx_{RA} pCi of RaA, or $3.7 \times 10^{-2} Vx_{RA} \tau_{RA} = n_{RA}$ atoms of RaA, and in the same time $bn_{RA} \tau_{RB}/\tau_{RA}$ atoms of RaB and $cn_{RA} \tau_{RC}/\tau_{RA}$ atoms of RaC. If the sample is then allowed to decay for a time $t \gg \tau_{RA}$, so that all the RaA has decayed, the alpha count from the sample will be given by

$$\alpha\text{-count} = \text{Dec}(RC') = \text{Dec}(RC)$$

since $\tau_{RC'} \ll \tau_{RC}$. Then

α-count = Dec(RC originally present in sample) + Dec(RC formed on filter from RaB)

$$= \frac{cn_{RA}}{\tau_{RC}} \frac{\tau_{RC}}{\tau_{RA}} \delta t \exp(-t/\tau_{RC}) + N(t)/\tau_{RC} \qquad (1)$$

$N(t)$ can be determined as follows

$$\text{Rate of increase of RaC} = \frac{dN(t)}{dt}$$

$$= \text{Form(RC)} - \text{Dec(RC)}$$

$$\text{Form (RC)} = \text{Dec (RC)}$$

$$= \text{Dec (RB originally present in sample)} + \text{Dec (RB formed on filter from RaA)}$$

$$= \left(b \frac{n_{RA}}{\tau_{RB}} \frac{\tau_{RB}}{\tau_{RA}} \delta t + \frac{n_{RA}}{\tau_{RB}} \delta t\right) \exp(-t/\tau_{RB})$$

assuming $t \gg \tau_{RA}$ (4.5 min) so that all the RaA can be assumed to have decayed at $t = 0$.

$$\therefore \text{Form(RC)} = n_{RA} \delta t \left(\frac{b}{\tau_{RA}} + \frac{1}{\tau_{RB}} \right) \exp(-t/\tau_{RB})$$

Then rate of increase of RaC which was formed from RaB

$$\frac{dN(t)}{dt} = n_{RA} \delta t \left(\frac{b}{\tau_{RA}} + \frac{1}{\tau_{RB}} \right) \exp(-t/\tau_{RB}) - N(t)/\tau_{RC} \qquad (2)$$

Solving this gives us $N(t)$

$$N(t) = n_{RA} \delta t \frac{\tau_{RC}}{\tau_{RA}} \frac{(b\tau_{RB} \quad \tau_{RA})}{(\tau_{RB} - \tau_{RC})} \left\{ \exp(-t/\tau_{RA}) - \exp(-t/\tau_{RC}) \right\}$$

Substitution in (1) gives

$$\alpha\text{-count} = n_{RA}\ \delta t \left\{ (p_R - q_R) \exp(-t/\tau_{RC}) + q_R \exp(-t/\tau_{RB}) \right\} \qquad (3)$$

where p_R and q_R are constants determined by the degree of radioactive disequilibrium. They are defined in the list of symbols above.

Equation (3) gives the α-count from a sample taken in a very short time, t sec before the measurement of count-rate. The count-rate A'_R from a long-period sample taken over a time T, ending t sec before the measurement of count-rate, is given by integration of (3) from t to t + T. This gives

$$A'_R = n_{RA} \left\{ \tau_{RC}(p_R - q_R) \left[1 - \exp(-T/\tau_{RC}) \right] \exp(-t/\tau_{RC}) \right.$$
$$\left. + q_R \tau_{RB} \left[1 - \exp(-T/\tau_{RB}) \right] \exp(-t/\tau_{RB}) \right\} \qquad (4)$$

Now $\tau_{RC} = 1.706 \times 10^3$ sec (28.43 min) ; $\tau_{RB} = 2.32 \times 10^3$ sec (38.67 min).

If $T > 3.9\,\tau$, $\exp(-T/\tau) < 0.02$, and so if T > 2½ hr,

$\exp(T/\tau_{RB}) \ll 1$ and $\exp(-T/\tau_{RC}) \ll 1$. Then

$$A'_R = n_{RA} \left\{ \tau_{RC} (p_R - q_R) \exp(-t/\tau_{RC}) + q_R \tau_{RB} \exp(-t/\tau_{RB}) \right\} \qquad (5)$$

The count-rate A'_R is independent of T because each isotope is decaying as fast as it is sampled and is formed from its parent. Taking $\tau_{RA} = 0.264 \times 10^3$ sec and τ_{RB} and τ_{RC} as given above, we can write (5) as

$$A'_R = n_{RA} \left\{ 2.320\ (14.30b + 1.628) \exp(-t/\tau_{RB}) \right.$$
$$\left. -1.706\ (14.30b + 1.628 - 3.786c) \exp(-t/\tau_{RC}) \right\} \qquad (6)$$

4.3 WL-Value of Radon Daughters

Each picocurie of an isotope gives 3.7×10^{-2} disintegrations per second, so that the numbers of atoms present per litre are

$\nu_{RA} = 3.7 \times 10^{-2}\ x_{RA}\ \tau_{RA}$; $\nu_{RB} = 3.7 \times 10^{-2}\ b\ x_{RA}\ \tau_{RB}$;

$\nu_{RC} = 3.7 \times 10^{-2}\ c\ x_{RA}\ \tau_{RC}$.

The alpha-energies that will be given by the decay to ^{210}Pb can be obtained from Figure 1; and from the definition of the

working level, the WL value of the radon daughters is

$$w_R = \left\{13.7\ \nu_{RA} + 7.7\ (\nu_{RB} + \nu_{RC})\right\} / 1.3 \times 10^5$$
$$= 1.0298 \times 10^{-3}\ x_{RA}\ (1 + 4.937b + 3.631c)$$

taking τ values as before. From the definition of n_{RA}, taking $V = 4.17 \times 10^{-2}$ l sec^{-1} (2.5 l min^{-1}),

$$w_R = 2.529 \times 10^{-3}\ n_{RA}\ (1 + 4.937b + 3.631c) \qquad (7)$$

From (6) and (7), w can be found from the alpha count-rate A' provided b and c are known. Series of measurements of these ratios in uranium mines were given by AYER (1954) and GEORGE and HINCHCLIFFE (1972). Typical values found by Ayer in well-ventilated mines were $b = 0.45$ and $c = 0.35$, and these give us values within a few per cent of those given by his extreme values. We shall therefore assume $b = 0.45$ and $c = 0.35$, giving

$$A'_R = n_{RA} \left\{18.71\ \exp(-t/\tau_{RB}) - 11.50\ \exp(-t/\tau_{RC})\right\} \qquad (8)$$

$$w_R = 1.136 \times 10^{-2}\ n_{RA} \qquad (9)$$

$\tau_{RB} = 38.67$ min and $\tau_{RC} = 28.43$ min. The half-life of the alpha-count from radon daughters therefore varies with time, but is about half an hour.

4.4 Alpha Count from Thoron Daughters

Although ThA is an alpha emitter, it has a very short half-life, so that the number of atoms of ThA deposited on the sides of the respiratory tract is very much less than the number of atoms of ThB. The dose from ThA can therefore be ignored, and the dangerous decays are the routes from ThC to ThD (^{208}Pb). By an analogous treatment to the radon-daughter case, we obtain an equation analogous to (3); the alpha count-rate from a sample taken in a small time δt is

$$\alpha\text{-count} = n_{TB}\ \delta t \left\{(p_T - q_T)\ \exp(-t/\tau_{TC}) + q_T\ \exp(-t/\tau_{TB})\right\} \qquad (10)$$

The count-rate from a sample taken for a period T is

$$A'_T = n_{TB} \left\{\tau_{TC}\ (p_T - q_T) \left[1 - \exp(-T/\tau_{TC})\right] \exp(-t/\tau_{TC})\right.$$
$$\left. + \quad q_T\ \tau_{TB} \left[1 - \exp(-T/\tau_{TB})\right] \exp(-t/\tau_{TB})\right\} \qquad (11)$$

$\tau_{TB} = 5.527 \times 10^4$ sec (921.2 min) and $\tau_{TC} = 5.247 \times 10^3$ sec (87.45 min),

so that although $\exp(-T/\tau_{TC}) \ll 1$ if T = 7 hr, $\exp(-T/\tau_{TB})$ remains appreciable. We can most conveniently accommodate variations in T by introducing a sampling-time factor k defined in the list of symbols above. If T = 7 hr, k = 1; k = 1.13 if T = 6 hr and 0.901 if T = 8 hr. This simple correction cannot be used if T < 5.7 hr, because $\exp(-T/\tau_{TC})$ then becomes important.

Substituting the τ values in (11) gives

$$A'_T = n_{TB}\left\{0.4047k \exp(-t/\tau_{TB}) - 0.09492(1.105-\gamma) \exp(-t/\tau_{TC})\right\} \quad (12)$$

τ_{TB} = 921.2 min and τ_{TC} = 87.45 min. The effective half-life varies considerably with t and γ, but is initially of the order of an hour. In practice, of course, the total count-rate A' from the dust sample will be given by

$$A' = A'_R + A'_T \quad (13)$$

4.5 WL-Value for Thoron Daughters

Using the extension of the WL definition to thoron daughters given above, we can now proceed as in the radon case. ThC can decay by two routes, but the mean α-decay energy per atom is 7.89 MeV. $\nu_{TB} = 3.7 \times 10^{-2} x_{TB} \tau_{TB}$ and $\nu_{TC} = 3.7 \times 10^{-2} \gamma x_{TB}\tau_{TC}$, and the WL-value is

$$w_T = 2.245 \times 10^{-6} x_{TB}(\tau_{TB} + \gamma \tau_{TC})$$

Substituting as before

$$w_T = 1.456 \times 10^{-3} n_{TB}(1 + 0.0949\gamma) \quad (14)$$

w_T can now be found in principle from Equations (12) and (14). There are very few measurements of γ in mines, although some results of DUGGAN (1973) suggest that it is usually much less than unity. We shall not assume a value at this stage. The total WL-value is now

$$w_{Tot} = w_R + w_T \quad (15)$$

4.6 Determination of w_T in Practice

In practice, we measure the total number of disintegrations occurring between two values of t, t_1 and t_2. An expression for

this count can be derived by integrating Equation (13) with respect to time, using Equations (8) and (12). This gives an expression for the number of disintegrations, which can be determined for particular values of t_1 and t_2, in terms of three unknowns n_{RA}, n_{TB} and γ, which are required in order to determine w from Equations (15), (9) and (14). In principle, we could take three different time intervals and determine the unknowns from the three simultaneous equations obtained, but because of sampling errors we have found it more accurate to use two time intervals, treating γ as an unknown variable, and accept a spread in possible WL-values due to the possible range of values of γ.

Counting cannot begin immediately after sampling, because the sampler must be brought up to the surface, and also because we have assumed $t \gg \tau_{RA}$. In the light of field experience we have fixed our counting intervals as $t_1 = 50$ min to $t_2 = 135$ min and $t_1 = 135$ min to $t_2 = 240$ min. If A_{50} and A_{135} respectively are the number of disintegrations in the sample in these time intervals,

$$w_R = 1.540\times10^{-6}A_{50} - 1.588\times10^{-6}(A_{135} - 0.1449A_{50})\frac{(k - 0.1035 + 0.0936\gamma)}{(k - 0.0299 + 0.0271\gamma)} \qquad (16)$$

$$w_T = 8.041\times10^{-7}(1 + 0.0949\gamma)\frac{(A_{135} - 0.1449A_{50})}{(k - 0.0299 + 0.0271\gamma)} \qquad (17)$$

The total w is the sum of these two. We have found that changes of γ between 0 and 1.5 (the maximum likely range) make little difference to w_R and w_T, and even less difference to the sum of the two. It is convenient to calculate the WL-values for $\gamma = 0$, 1.0 and 1.5, taking the 1.0 value as standard and the others as indicating the range of uncertainty due to ignorance of γ. For this range of γ, and sampling times between 5.7 and 9.0 hr, the ratio of the bracketed terms including k and γ in (16) does not vary by more than 2%, so that the equations can be written:

$$(\gamma = 0) \qquad \left.\begin{aligned} w_R &= 1.753 \times 10^{-6} \,(A_{50} - 0.837\, A_{135}) \\ w_T &= \frac{8.041 \times 10^{-7}}{k - 0.030}\,(A_{135} - 0.1449\, A_{50}) \end{aligned}\right\} \qquad (18)$$

$$(\gamma = 1) \qquad \left.\begin{aligned} w_R &= 1.768 \times 10^{-6} \,(A_{50} - 0.892\, A_{135}) \\ w_T &= \frac{8.804 \times 10^{-7}}{k - 0.003}\,(A_{135} - 0.1449\, A_{50}) \end{aligned}\right\} \qquad (19)$$

$$(\gamma = 1.5) \qquad \left.\begin{aligned} w_R &= 1.776 \times 10^{-6} \,(A_{50} - 0.917\, A_{135}) \\ w_T &= \frac{9.186 \times 10^{-7}}{k + 0.011}\,(A_{135} - 0.1449\, A_{50}) \end{aligned}\right\} \qquad (20)$$

Practical sampling procedure is discussed in the final section.

5. RELATION OF MEASURED EXPOSURE TO TRUE EXPOSURE

Because atoms already on the filter are decaying while sampling continues, concentrations of airborne radioactivity sampled near the beginning of the shift obviously have less influence on the w figure calculated than concentrations sampled near the end. This is particularly important with the PFR sampling procedure, because the dust samples we use are taken from the time the volunteer worker enters the pit to the time he leaves, including his journey underground to and from his workplace, which typically lasts 30–60 min each way, and during which the radioactivity exposure of the man is likely to be lower than when he is at the coalface. We can assess the effect of this "time-weighting" of the radioactivity sample using Equation (4) and its thoron analogue, Equation (11). If $^{n}_{RA}$ is constant during sampling, Equation (4) can represent the count-rate at the end of the sampling period due to radon daughters collected during a time T which ended a time t before the end of the sampling period, if we take the values of b and c as before. Since the count-rate A'_R and also w_R are both proportional to $^{n}_{RA}$ for a given collection-time (and similarly A'_T, w_T, and $^{n}_{TB}$), Equations (4) and 11) can be used to calculate the percentage contribution to the calculated w of different parts of the sampling-time. We can also calculate the figures for any combination of radon and thoron daughters. Table 1 shows the periods contributing the last 25%, 50%, 75% and 90% of w_{Tot}, assuming constant conditions over a seven-hour shift with b = 0.45, c = 0.35, γ = 0.5, for radon and thoron daughters separately, and for a combination giving $w_R = 3w_T$.

Table 1. The periods before the end of sampling in a seven-hour shift which contribute the stated percentages to the final calculated WL under constant conditions of (a) pure radon daughters, (b) pure thoron daughters, (c) mixture with $w_R = 3w_T$

	25%	50%	75%	90%	100%
(a)	21 min	44 min	78 min	120 min	420 min
(b)	96	195	300	370	420
(c)	25	50	118	240	420

The table shows that for this combination of radon and thoron, found in our results to be typical, the first five hours of sampling contribute roughly a quarter to the final w measurement, the next hour another quarter, and the final two half-hours about a quarter each. A higher proportion of radon daughters shortens the effective sampling time. This gives us some idea of the likely effect of varying conditions on the computed w. The WL-value obtained is obviously not a shift mean, but is reasonably representative. For example, Duggan et al. (1968) found that radon concentration may vary by a factor of two from one part of a coalmine to another. If the worker were exposed to z WL while he was working, for the middle five hours of the shift, say, z/2 WL while he was travelling underground to and from his workplace, one hour each way, the time-weighting effect would cause our method to underestimate his integrated shift exposure by about 13% (we would measure only 5.25z WL-hours instead of 6z). This error is acceptable, but must be borne in mind in interpreting results. This is discussed further in the light of our field results in section 7.7.

6. PRACTICAL SAMPLING PROCEDURE

The preceding two sections show that the WL-value can in principle be determined by alpha-monitoring the shift dust sample after it has been taken from the mine. Practical measurements were taken at Linby colliery, in the Nottinghamshire coalfield, to assess (1) how results from respirable and total dust samples compared, (2) the general magnitude and variation with time and place in a mine (so that sampling strategy for a wider survey could be planned), and (3) how our results compared with those obtained by other methods.

As already mentioned the respirable dust samples were taken by volunteer miners using the MRE Gravimetric Dust Sampler, with which they sampled the environment wherever they happened to be working on a particular shift. Our samples were obtained in seven different districts in the colliery, usually on the return side of a face, with two other samples being taken at the shaft bottom, one in the return air, and the other in intake air. For about half the trial the end of sampling was timed accurately at the shaft bottom, but measurements of the decay of the count-rate showed that an error of three minutes in this timing would lead to an error of less than 5% in the final calculated WL-value. For the latter part of the trial, therefore, the time of end of sampling was estimated from the time of the volunteer's arrival at the pit-top. A counter on the side of the instrument records the volume sampled in litres, and k was determined from this reading using Table 2. (The sampling-rate on these instruments is adjusted before use to be within two per cent of 2,5 l min^{-1}).

Total dust measurements were made using a similar sampler adapted to draw air directly through the nosepiece on to the filter, without passing through the elutriator. Both respirable and total dust samples were taken on 50 mm Sartorius MF500 cellulose membrane filters.

The alpha meter used was a zinc sulphide scintillator probe Type DP2 with a PCM3 monitor (both manufactured by Nuclear Enterprises Ltd., Beenham, Berks.). The output from the monitor

was taken to a programmable counter-timer. For counting, the dust-covered filter was placed against the screen of the probe, the operator switched on the counter-timer fortyfive minutes after the end of sampling, and the counters then recorded the counts for 50 - 135 and 135 - 240 min after sampling. The overall efficiency of the probe is stated by the manufacturers to be 22½% for alphas of approximately the energy measured. Measurements with a small radioactive source showed the probe to be slightly more sensitive in the central area exposed to the filter than at the periphery, so that the effective efficiency in our use is close to 25%. The counts were therefore corrected for background (about twenty counts an hour), and then multiplied by 4.0 to obtain A_{50} and A_{135}. The thickness of the dust sample was usually small compared with the range of alpha particles in carbon (about 40 μm) and so absorption should not have been a problem. A programmable calculator was used to obtain w_R and w_T from A_{50} and A_{135} for the three values of γ, using Equations (18), (19) and (20). The results were expressed in thousandths of a working level (mWL).

A few short-period respirable dust samples were taken for evaluation by Kusnetz's method in places from which the travelling time to the shaft bottom was sufficiently short. Each sample was taken for five minutes with a Hexhlet sampler, sampling at 50 l min^{-1}, and driven by a compressed nitrous oxide cylinder. The count was made between 70 and 90 min after sampling, taking a correction factor of 75 from Kusnetz (1956). Comparison with the results of Duggan et al. (1968) was also possible.

7. FIELD-TRIAL RESULTS AND DISCUSSION

The results at Linby colliery are given in Table 3. In this analysis, the figures quoted are for $\gamma = 1.0$. The effect of γ can be seen in the Table, where the differences are given between the $\gamma = 1.0$ and the $\gamma = 0$ values. In all cases this difference was greater than, and of opposite sign to, the difference between the $\gamma = 1.0$ and $\gamma = 1.5$ values. Taking a lower value of γ increased

the calculated w_R and w_{Tot} and decreased w_T. These changes were, however, relatively small.

Because both the seam worked and the individual face might affect radioactivity, we give most attention to the 26 samples from the High Main seam and, within that seam, to the 11 samples from the 18s district. The purpose of the measurements was to allow intelligent planning of more extensive sampling. The results are sufficient for this, and permit some more general inferences about factors that might influence the airborne radioactivity concentration. These more general conclusions must be tentative, however, because of the small number of samples, the large number of interacting possible influences, and because the method of choosing sampling-positions and times was probably too inexact for statistical precision.

7.1 Weight and Size-Range of Dust

Figure 2 shows the High Main seam samples with w_{Tot} plotted against dust weight. The 18s district samples are distinguished from the others on the figure, although in this case there is no clear difference between their activities and those from the rest of the seam. It can be seen that there is no strong correlation of w_{Tot} with the amount of dust caught. This is not surprising, since the rock is probably more radioactive than the coal, and the airborne emanation is therefore more likely to come from steady seepage from the rock than from sudden release in coal-cutting. Also, there is no significant difference between the mean w_{Tot} obtained on the 13 shifts sampled by respirable dust (mean 25.4 mWL, S.D. on mean 1.6) and the mean of the total-dust samples (mean 27.6 mWL, S.D. on mean 1.0), so that the standard respirable-dust samples can obviously be used to assess the hazard with sufficient accuracy for our purpose. As the elutriator would be expected to remove the free daughter atoms as well as those attached to the larger dust particles, the inference is that neither of these components makes an appreciable contribution to the hazard. The absence of significant numbers of free atoms in the dusty atmosphere of the coal mine is not surprising, and the indication that the

daughter atoms attach mainly to the smaller dust particles agrees with the results of other workers (e.g. Blanc, Fontan, Chapuis, Billard, Madelaine & Pradel, 1967). The respirable range in coalmines includes most of the particles numerically, and usually most of the dust surface area as well.

7.2 Atmospheric Pressure

Pohl-Ruling and Pohl (1969) found that changes of atmospheric pressure affected the radon concentrations in mines. Figure 3 shows the w_{Tot} values for the High Main seam plotted against pressure measured at the surface. There is some suggestion of decrease of WL value with increasing pressure, but the effect is negligible for our purposes. It might be expected that the direction and rate of change of atmospheric pressure might be more influential than its actual magnitude, but classification of the 18s results on this basis gives the following mean values : pressure decreasing (four cases) 30.2 mWL; pressure steady (four cases) 24.9 mWL; pressure increasing (three cases) 29.9 mWL. Any effect of pressure can therefore be neglected for our purpose.

7.3 Variability with Time

Figure 4 shows the total WL-value plotted against date of sampling. There is no obvious secular change. The mean of these values is 26.5 mWL, with a standard deviation of 4.8 mWL. The distribution is consistent with a normal distribution, and so 90% of the individual values would be expected to lie within 7.9 mWL of the mean, i.e. within 30% of the mean. This seems to describe the true situation adequately, and is a guide to the number of samples required to specify the applicable WL-value (considered below). It assumes, however, that there is no real difference between values obtained at the different faces in this seam, or different positions near a particular face, and so this must be considered.

7.4 Place-to-Place Variation in the Mine

Inspection of the 18s district figures (Table 3) shows no clear difference between the intake side, the face, and the return side,

although there is only one sample each for the first two positions. The 3s figures, with fewer samples, might lead to a different interpretation. Overall, in the High Main seam, the mean of the three intake-side samples is 23.2 mWL, of the two face samples 24.0 mWL, and of the 22 return-side samples 27.2 mWL. A buildup of airborne radioactivity along the face is therefore possible, but small compared with the day-to-day variability. An alternative explanation for this result is discussed in 7.7.

Figure 5 shows the mean WL-values for the various positions in the colliery plotted against the distance the ventilation air has travelled through the colliery to reach the position. For clarity, for the six High Main districts only the means and the number of samples in each district are shown. The standard deviations of the WL-values in the two districts with reasonable numbers of samples (18s and 3s) are both about 4 mWL. The air at the bottom of the mine intake shaft is obviously relatively non-radioactive. The lower values in the Victoria seam relative to the High Main seam values might be due to different geological conditions, or to the shorter time the air had been underground. The distance given for the bottom of the return shaft is the average of the distances through all the districts, although a greater volume probably flows through the shorter pathways than through the longer. The w differences between different districts in the High Main seam may be real, but the small number of samples prevents certainty.

7.5 The Radon Contribution

Generally speaking, all the above discussion about variations of the total WL-values applies also to the radon component. However, the mean percentage radon contribution in the High Main samples (73%) is substantially higher than in the Waterloo samples (58%), which itself is higher than the intake shaft bottom proportion (53%) and the surface value (mean of three samples at Edinburgh 45%). Within the High Main samples, the higher total WL values usually have high radon percentage contributions. A given

percentage variability about the mean in the radon component would, of course, make a greater absolute contribution to changes in total WL than the same percentage variability about the mean in the thoron component. This is insufficient to explain the between-seam variations, however, which indicate that the uranium series is more variable in occurrence in this colliery than the thorium series.

7.6 Comparison with Kusnetz's Method and Duggan's Results

As already mentioned, five samples were taken at Linby using Kusnetz's method, discussed in section 3 above. Close agreement with results by our method cannot be expected, mainly because, in our experience, a large part of the count in this period would come from the thoron-daughter component, which is not taken into account in Kusnetz's method.

The results are shown in Table 4. It can be seen that, except for the results at the return shaft bottom, our results give considerably higher values than those given by Kusnetz's method.

Table 4. Results from Kusnetz's method.

Location	Measured activity
Return shaft bottom	16.8 mWL
Do	12.5
Intake shaft bottom	0.4
V1 return side	4.0
41s return side	6.1

Comparison is also possible with the measurements of Duggan et al. (1968), whose "Mine A" was, in fact, Linby (M.J. Duggan, personal communication), where they measured a range of radon concentrations of 5 - 12 pCi l^{-1}. We can calculate the range of radon working levels this corresponds to if we assume values for the disequilibrium ratios b and c. For the b = 0.45, c = 0.35 we assumed, these radon concentrations correspond to 17 - 55 mWL, compared with our range (excluding the intake shaft-bottom result) of 2.9 - 28.4 mWL. For Ayer's (1954) extreme values of b = 0.15, c = 0.06, Duggan's range would be 10 - 24 mWL.

Considering the time interval between the measurements, the agreement is satisfactory.

The degree to which the calculated WL-values account for the details of the observed decay can be seen from Figure 6, which shows the five-minute totals that would be expected for one particular sample from the WL-values calculated in the usual way, and the five-minute totals actually observed. This is not an entirely independent check on the theory, but confirms that there is unlikely to be any alpha-emitter other than those considered making a significant contribution to the count. The line shown is for $\gamma = 1.0$, but the lines that assume $\gamma = 0$ and $\gamma = 1.5$ are not significantly different from it.

7.7 Conclusions from Field Results

Because of the small number of samples and the *ad hoc* sampling procedure, the above generalisations about influences on the WL-value must be regarded as tentative, as already stated. However, the results show that for our purposes the WL-value can be regarded as varying randomly in time, with about 90% of individual values lying within 30% of the long-term mean. The results suggest that the radioactivity level may be about the same in different workings of the same seam, but it would be safer until more data accumulates to regard each district as a unit. As mentioned in section 5 above, a lower concentration of airborne radioactivity in the roadways from the shaft bottom to the workplace than at the workplace itself will lead to an underestimate of exposure. The field results imply that this might be important if the workmen return to shaft bottom in the incoming, low-activity air, but not if they return in the outgoing air. If it could be arranged for samplers to travel back from the workplace in the return air, the accuracy of the calculated exposures would therefore be improved. At Linby, workers on the return side of faces usually travel in the return air, and those on the intake side in the intake air, and this might account for the apparent build-up along the face at Linby

discussed in 7.4 above, although the overall effect on results seems to be small.

One unexpected result obtained was a quick method of calculating w_{Tot} from the original alpha count. If the count obtained for the 50 min to 135 min period, uncorrected for background, counter efficiency, or sampling period, is divided by 200, the figure obtained is remarkably close to w_{Tot} in mWL. The maximum departure of this crude result from the properly-calculated value for any of the 36 shifts so far sampled at Linby and elsewhere, including those on the surface, is 13%. No such easy method exists for the radon component alone.

8. PRACTICAL SAMPLING STRATEGY FOR THE WIDER SURVEY

The field work has confirmed the practicability of the method. It is possible to estimate reasonably accurately the shift-exposure to airborne radioactivity of a worker by subsequent alpha-monitoring of the shift respirable dust sample, using the procedure described in section 6, with the additional condition that the exposure of workers near the coalface is best sampled by workers who return to the surface in the return air. As far as frequency and distribution of samples are concerned, the practical radioactivity sampling strategy now being applied in the ten collieries regularly surveyed by the Pneumoconiosis Field Research involves measurement of three samples from each face area, taking the mean as the value for that face. For samples distributed normally about a mean of 25 mWL with a standard deviation of 4 mWL, a reasonable model of the Linby results, 96% of the mean face values so obtained should lie within 20% of the true mean, and 72% within 10%. It is planned that this survey should be repeated from time to time. In some coalfields, igneous intrusions intersect the workings, and special samples will be taken at collieries where this occurs. If necessary, the method can be used with the dust samples taken during working in all collieries by the NCB. However, from the survey of the ten PFR collieries a picture will be built up of the radioactivity exposure of a sample of British coalminers.

Acknowledgements

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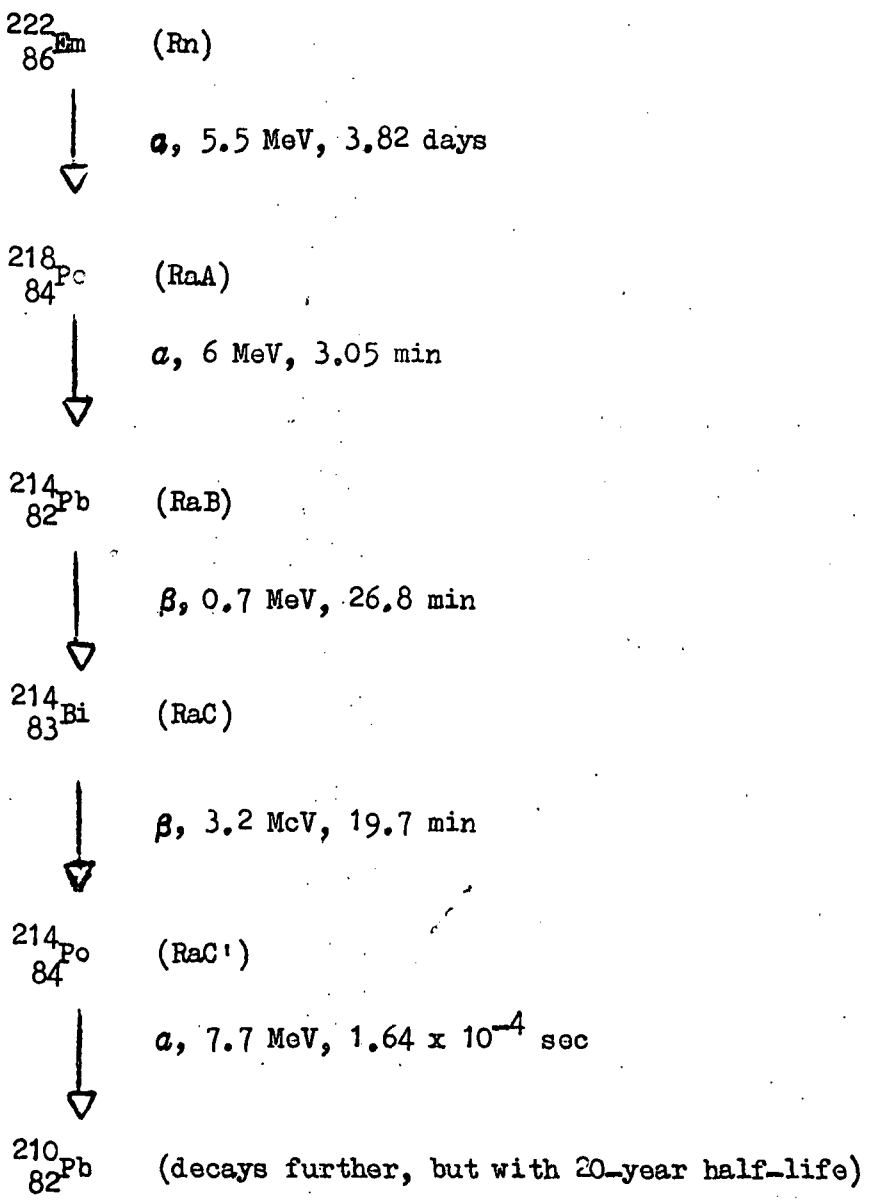
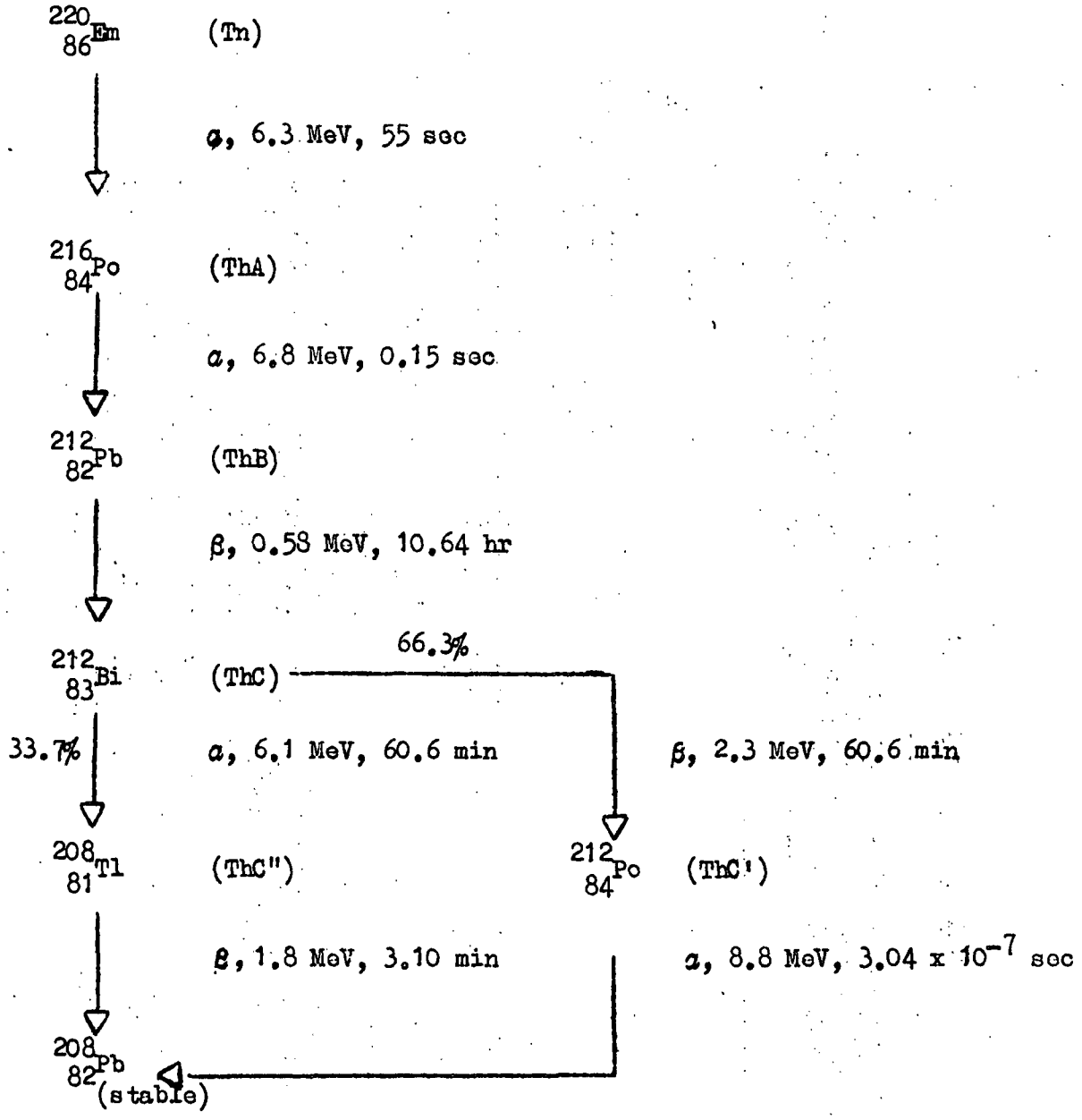
Figure 1. The decay of radon. Types and energies of the principal emissions, and half-lives, are shown.



+ next sheet

Figure 1 (cont.) The decay of thoron



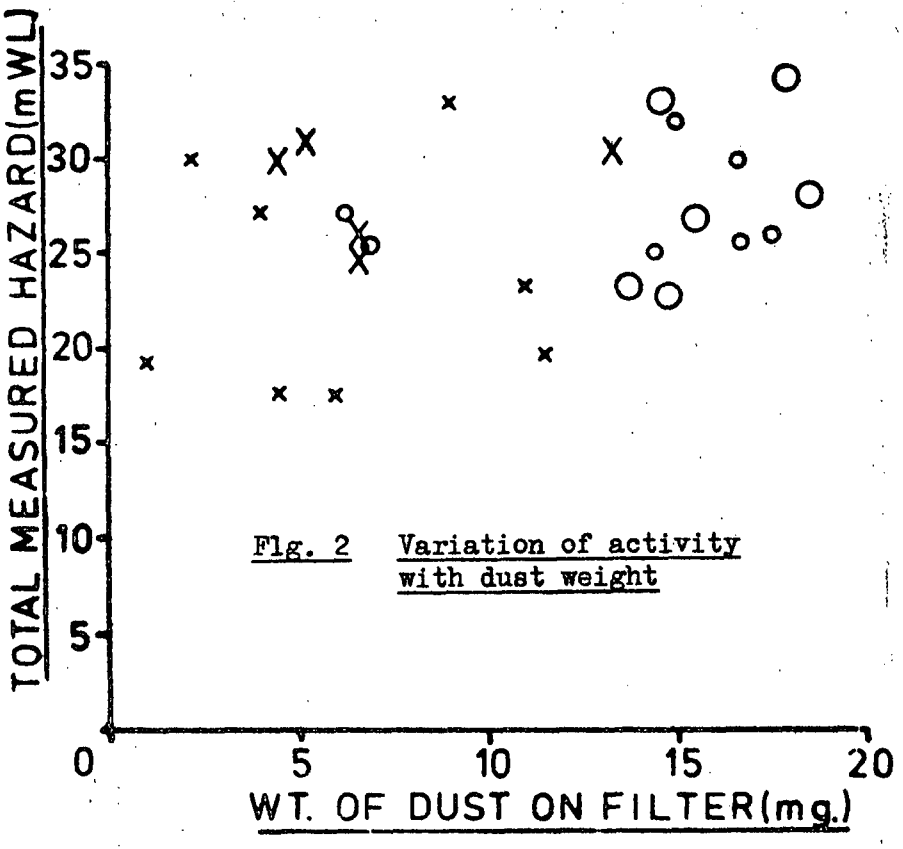


Fig. 2 Variation of activity with dust weight

× Respirable Dust samples.

o Total Dust samples.

18s district samples drawn large.

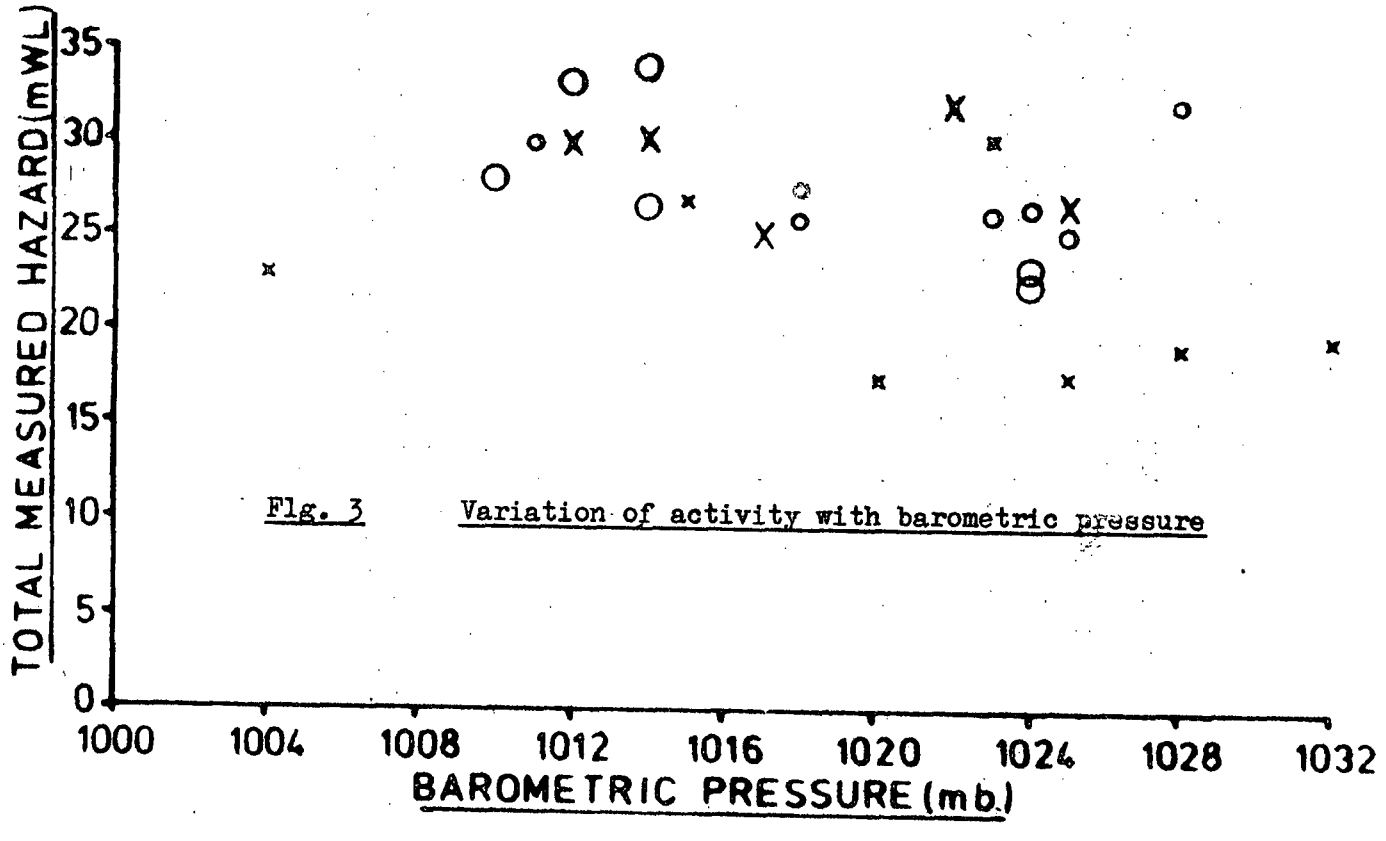


Fig. 3 Variation of activity with barometric pressure

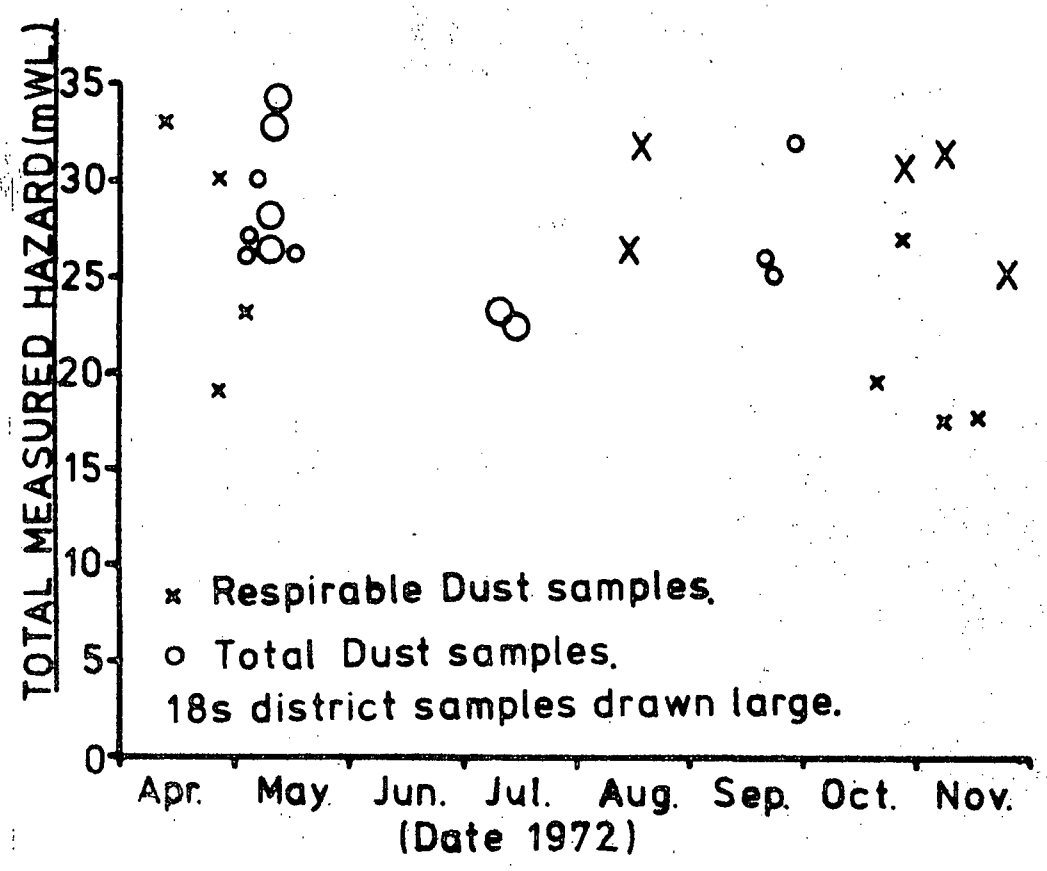


Fig. 4 Change of activity with date

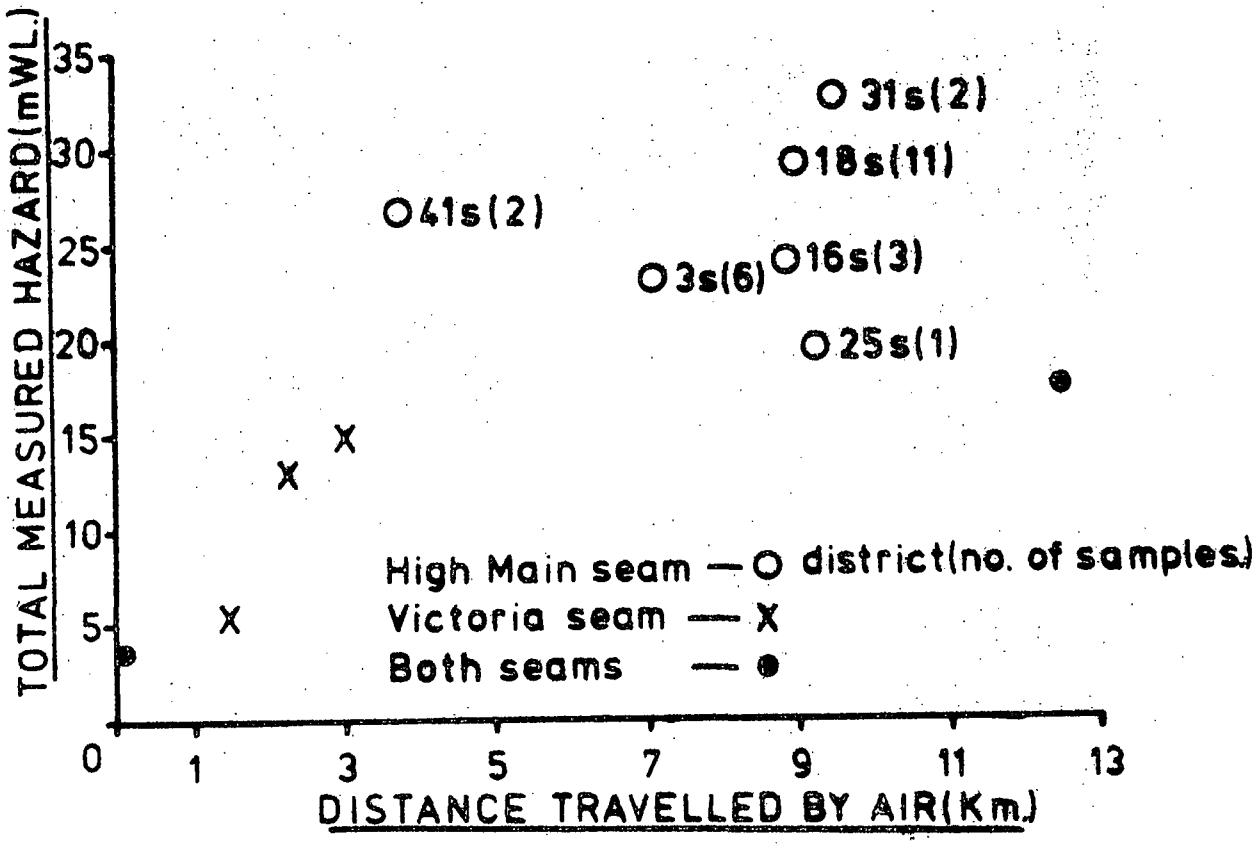


Fig. 5 Build-up of activity through the mine

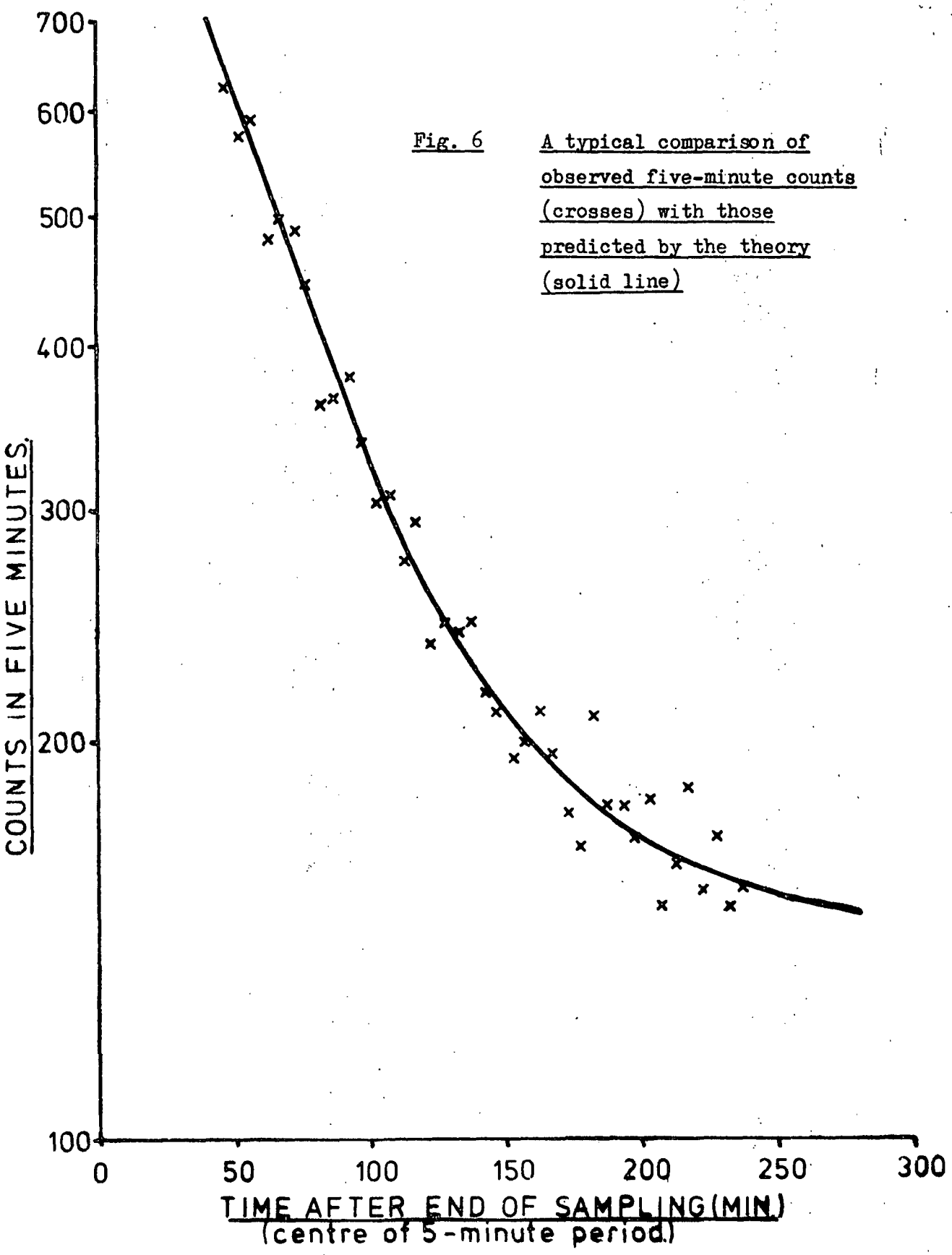


Fig. 6 A typical comparison of observed five-minute counts (crosses) with those predicted by the theory (solid line)

TABLE 2. Sampling-time Correction Factor k.

The volume sampled (litres) is followed by the corresponding value of k.

850,000	876,000	901,000	926,000	951,000
1,186	1,157	1,130	1,105	1,082
851,000	877,000	902,000	927,000	952,000
1,185	1,156	1,129	1,104	1,081
852,000	878,000	903,000	928,000	953,000
1,183	1,154	1,128	1,103	1,080
853,000	879,000	904,000	929,000	954,000
1,182	1,153	1,127	1,102	1,079
854,000	880,000	905,000	930,000	955,000
1,181	1,152	1,126	1,101	1,078
855,000	881,000	906,000	931,000	956,000
1,180	1,151	1,125	1,100	1,077
856,000	882,000	907,000	932,000	957,000
1,179	1,150	1,124	1,099	1,076
857,000	883,000	908,000	933,000	958,000
1,178	1,149	1,123	1,099	1,075
858,000	884,000	909,000	934,000	959,000
1,177	1,148	1,122	1,098	1,074
859,000	885,000	910,000	935,000	960,000
1,175	1,147	1,121	1,097	1,073
860,000	886,000	911,000	936,000	961,000
1,174	1,146	1,120	1,096	1,073
861,000	887,000	912,000	937,000	962,000
1,173	1,145	1,119	1,095	1,072
862,000	888,000	913,000	938,000	963,000
1,172	1,144	1,118	1,094	1,071
863,000	889,000	914,000	939,000	964,000
1,171	1,143	1,117	1,093	1,070
864,000	890,000	915,000	940,000	965,000
1,170	1,142	1,116	1,092	1,069
865,000	891,000	916,000	941,000	966,000
1,169	1,141	1,115	1,091	1,068
866,000	892,000	917,000	942,000	967,000
1,168	1,140	1,114	1,090	1,067
867,000	893,000	918,000	943,000	968,000
1,166	1,138	1,113	1,089	1,066
868,000	894,000	919,000	944,000	969,000
1,165	1,137	1,112	1,088	1,065
869,000	895,000	920,000	945,000	970,000
1,164	1,136	1,111	1,087	1,065
870,000	896,000	921,000	946,000	971,000
1,163	1,135	1,110	1,086	1,064
871,000	897,000	922,000	947,000	972,000
1,162	1,134	1,109	1,085	1,063
872,000	898,000	923,000	948,000	973,000
1,161	1,133	1,108	1,084	1,062
873,000	899,000	924,000	949,000	974,000
1,160	1,132	1,107	1,084	1,061
874,000	900,000	925,000	950,000	975,000
1,159	1,131	1,106	1,083	1,060
875,000				
1,158				

TABLE 2 (continued)

976,000		1000 1,000		1026,000		1052 1,000		1076,000	
	1,059		1,038		1,018		0,999		0,980
977,000		1002,000		1027,000		1052,000		1077,000	
	1,058		1,037		1,017		0,998		0,980
978,000		1003,000		1028,000		1053,000		1078,000	
	1,058		1,036		1,016		0,997		0,979
979,000		1004,000		1029,000		1054,000		1079,000	
	1,057		1,036		1,015		0,996		0,978
980,000		1005,000		1030,000		1055,000		1080,000	
	1,056		1,035		1,015		0,996		0,977
981,000		1006,000		1031,000		1056,000		1081,000	
	1,055		1,034		1,014		0,995		0,977
982,000		1007,000		1032,000		1057,000		1082,000	
	1,054		1,033		1,013		0,994		0,976
983,000		1008,000		1033,000		1058,000		1083,000	
	1,053		1,032		1,012		0,993		0,975
984,000		1009,000		1034,000		1059,000		1084,000	
	1,052		1,031		1,012		0,993		0,975
985,000		1010,000		1035,000		1060,000		1085,000	
	1,052		1,031		1,011		0,992		0,974
986,000		1011,000		1036,000		1061,000		1086,000	
	1,051		1,030		1,010		0,991		0,973
987,000		1012,000		1037,000		1062,000		1087,000	
	1,050		1,029		1,009		0,990		0,973
988,000		1013,000		1038,000		1063,000		1088,000	
	1,049		1,028		1,009		0,990		0,972
989,000		1014,000		1039,000		1064,000		1089,000	
	1,048		1,027		1,008		0,989		0,971
990,000		1015,000		1040,000		1065,000		1090,000	
	1,047		1,027		1,007		0,988		0,970
991,000		1016,000		1041,000		1066,000		1091,000	
	1,046		1,026		1,006		0,988		0,970
992,000		1017,000		1042,000		1067,000		1092,000	
	1,046		1,025		1,005		0,987		0,969
993,000		1018,000		1043,000		1068,000		1093,000	
	1,045		1,024		1,005		0,986		0,968
994,000		1019,000		1044,000		1069,000		1094,000	
	1,044		1,023		1,004		0,985		0,968
995,000		1020,000		1045,000		1070,000		1095,000	
	1,043		1,023		1,003		0,985		0,967
996,000		1021,000		1046,000		1071,000		1096,000	
	1,042		1,022		1,002		0,984		0,966
997,000		1022,000		1047,000		1072,000		1097,000	
	1,041		1,021		1,002		0,983		0,966
998,000		1023,000		1048,000		1073,000		1098,000	
	1,041		1,020		1,001		0,982		0,965
999,000		1024,000		1049,000		1074,000		1099,000	
	1,040		1,019		1,000		0,982		0,964
1000,000		1025,000		1050,000		1075,000		1100,000	
	1,039		1,019		0,999		0,981		0,964

TABLE 2 (continued)

110	1,000	0,963	110	2,000	0,962	110	3,000	0,961	110	4,000	0,961	110	5,000	0,960	110	6,000	0,959	110	7,000	0,959	110	8,000	0,958
110	9,000	0,957	111	0,000	0,957	111	1,000	0,956	111	2,000	0,955	111	3,000	0,955	111	4,000	0,954	111	5,000	0,953	111	6,000	0,953
111	7,000	0,952	111	8,000	0,951	111	9,000	0,951	112	0,000	0,950	112	1,000	0,949	112	2,000	0,949	112	3,000	0,948	112	4,000	0,947
112	5,000	0,947	112	6,000	0,946	112	7,000	0,946	112	8,000	0,945	112	9,000	0,944	113	0,000	0,944	113	1,000	0,943	113	2,000	0,942
113	3,000	0,942	113	4,000	0,941	113	5,000	0,940	113	6,000	0,940	113	7,000	0,939	113	8,000	0,938	113	9,000	0,938	114	0,000	0,937
114	1,000	0,937	114	2,000	0,936	114	3,000	0,935	114	4,000	0,935	114	5,000	0,934	114	6,000	0,933	114	7,000	0,933	114	8,000	0,932
114	9,000	0,931	115	0,000	0,931	115	1,000	0,930	115	2,000	0,930	115	3,000	0,929	115	4,000	0,928	115	5,000	0,928	115	6,000	0,927
115	7,000	0,927	115	8,000	0,926	115	9,000	0,926	116	0,000	0,925	116	1,000	0,924	116	2,000	0,923	116	3,000	0,923	116	4,000	0,922
116	5,000	0,922	116	6,000	0,921	116	7,000	0,920	116	8,000	0,920	116	9,000	0,919	117	0,000	0,919	117	1,000	0,918	117	2,000	0,917
117	3,000	0,917	117	4,000	0,916	117	5,000	0,916	117	6,000	0,915	117	7,000	0,914	117	8,000	0,914	117	9,000	0,913	118	0,000	0,913
118	1,000	0,912	118	2,000	0,911	118	3,000	0,911	118	4,000	0,910	118	5,000	0,910	118	6,000	0,909	118	7,000	0,909	118	8,000	0,908
118	9,000	0,907	119	0,000	0,907	119	1,000	0,906	119	2,000	0,906	119	3,000	0,905	119	4,000	0,904	119	5,000	0,904	119	6,000	0,903
119	7,000	0,903	119	8,000	0,902	119	9,000	0,902	120	0,000	0,901	120	1,000	0,900	120	2,000	0,900	120	3,000	0,899	120	4,000	0,899
120	5,000	0,898	120	6,000	0,898	120	7,000	0,897	120	8,000	0,896	120	9,000	0,896	121	0,000	0,895	121	1,000	0,895	121	2,000	0,894
121	3,000	0,894	121	4,000	0,893	121	5,000	0,892	121	6,000	0,892	121	7,000	0,891	121	8,000	0,890	121	9,000	0,890	122	0,000	0,889
122	1,000	0,889	122	2,000	0,888	122	3,000	0,887	122	4,000	0,887	122	5,000	0,886									

TABLE 2 (concluded)

1226,000	0,886	1251,000	0,873	1276,000	0,860	1301,000	0,848	1326,000	0,836
1227,000	0,886	1252,000	0,872	1277,000	0,860	1302,000	0,847	1327,000	0,835
1228,000	0,885	1253,000	0,872	1278,000	0,859	1303,000	0,847	1328,000	0,835
1229,000	0,885	1254,000	0,871	1279,000	0,859	1304,000	0,846	1329,000	0,834
1230,000	0,884	1255,000	0,871	1280,000	0,858	1305,000	0,846	1330,000	0,834
1231,000	0,884	1256,000	0,870	1281,000	0,858	1306,000	0,845	1331,000	0,834
1232,000	0,883	1257,000	0,870	1282,000	0,857	1307,000	0,845	1332,000	0,833
1233,000	0,883	1258,000	0,869	1283,000	0,857	1308,000	0,844	1333,000	0,833
1234,000	0,882	1259,000	0,869	1284,000	0,856	1309,000	0,844	1334,000	0,832
1235,000	0,882	1260,000	0,868	1285,000	0,856	1310,000	0,843	1335,000	0,832
1236,000	0,881	1261,000	0,868	1286,000	0,855	1311,000	0,843	1336,000	0,831
1237,000	0,880	1262,000	0,867	1287,000	0,855	1312,000	0,842	1337,000	0,831
1238,000	0,880	1263,000	0,867	1288,000	0,854	1313,000	0,842	1338,000	0,830
1239,000	0,879	1264,000	0,866	1289,000	0,854	1314,000	0,842	1339,000	0,830
1240,000	0,879	1265,000	0,866	1290,000	0,853	1315,000	0,841	1340,000	0,829
1241,000	0,878	1266,000	0,865	1291,000	0,853	1316,000	0,841	1341,000	0,829
1242,000	0,878	1267,000	0,865	1292,000	0,852	1317,000	0,840	1342,000	0,828
1243,000	0,877	1268,000	0,864	1293,000	0,852	1318,000	0,840	1343,000	0,828
1244,000	0,877	1269,000	0,864	1294,000	0,851	1319,000	0,839	1344,000	0,828
1245,000	0,876	1270,000	0,863	1295,000	0,851	1320,000	0,839	1345,000	0,827
1246,000	0,876	1271,000	0,863	1296,000	0,850	1321,000	0,838	1346,000	0,827
1247,000	0,875	1272,000	0,862	1297,000	0,850	1322,000	0,838	1347,000	0,826
1248,000	0,875	1273,000	0,862	1298,000	0,849	1323,000	0,837	1348,000	0,826
1249,000	0,874	1274,000	0,861	1299,000	0,849	1324,000	0,837	1349,000	0,825
1250,000	0,874	1275,000	0,861	1300,000	0,848	1325,000	0,836		

TABLE 3. The results at Linby.

The WL-values given are those for $\gamma = 1.0$, with the differences from the values for $\gamma = 0$ in brackets (for sign, see text).

Seam	District	Date	Position	Total or Respirable	Barometric pressure (mb)	Volume sampled (l)	Dust weight (mg)	WL R (mWL)	WL T (mWL)	WL Tot (mWL)	$100 \times \frac{WL\ R}{WL\ Tot}$
High Main	18s	22 Nov	i	R	1017 ↑	1099	6.6	17.8(0.9)	7.2(0.4)	25.0(0.4)	71
		9 Nov	f	R	1014 ↓	1086	13.3	23.2(0.9)	7.2(0.4)	30.4(0.5)	77
		25 Oct	r	R	1012 ↓	1062	4.5	21.2(1.1)	8.6(0.5)	29.8(0.6)	71
		8 May	r	T	1014 ↓	1048	15.4	18.7(1.0)	7.9(0.5)	26.7(0.5)	70
		9 May	r	T	1010	1062	18.5	20.9(0.9)	7.1(0.4)	28.0(0.5)	75
		10 May	r	T	1012 ↑	1068	14.6	25.5(1.0)	7.6(0.5)	33.0(0.5)	77
		11 May	r	T	1014 ↓	1061	16.9	25.4(1.1)	8.5(0.5)	34.0(0.6)	75
		10 Jly	r	T	1024	1061	13.7	15.4(0.9)	7.5(0.5)	22.9(0.5)	67
		11 Jly	r	T	1024	1025	14.8	16.2(0.8)	6.1(0.4)	22.3(0.4)	73
		16 Aug	r	R	1025	1080	6.6	19.0(0.9)	7.2(0.4)	26.2(0.6)	73
		18 Aug	r	R	1022 ↑	1101	5.2	25.4(0.8)	6.3(0.4)	31.7(0.4)	80
	3s	8 Nov	i	R	1025	1069	4.3	9.1(1.1)	8.7(0.5)	17.7(0.6)	51
		15 Nov	f	R	1020	1102	6.0	9.8(1.0)	7.8(0.5)	17.6(0.5)	56
		3 May	r	T	1018	1047	6.2	18.2(1.1)	9.0(0.6)	27.3(0.6)	67
		4 May	r	T	1018	1085	6.9	18.3(0.9)	7.5(0.5)	25.8(0.5)	71
		15 May	r	T	1024	1159	17.5	18.4(0.9)	7.8(0.5)	26.1(0.5)	70
		21 Sept	r	T	1025	1177	14.4	17.5(0.9)	8.4(0.5)	25.9(0.4)	68
	16s	1 May	r	R	1004	1138	10.9	16.3(0.8)	6.6(0.4)	22.9(0.4)	71
		25 Apr	r	R	1028 ↓	1004	0.9	13.5(0.7)	5.5(0.3)	19.0(0.4)	71
		26 Apr	r	R	1023	1081	2.2	25.4(0.6)	4.6(0.3)	30.0(0.4)	68
	31s	13 Apr	r	R	1016	1129	8.9	28.4(0.6)	4.7(0.3)	33.1(0.3)	86
		27 Sept	r	T	1028	1176	14.9	21.0(1.3)	11.1(0.7)	32.1(0.6)	65
	41s	25 Oct	i	R	1015	1066	3.8	15.3(1.4)	11.5(0.7)	26.9(0.7)	57
		19 Sept	r	T	1023	1284	16.6	17.5(0.9)	8.4(0.4)	25.9(0.4)	68
	25s	19 Oct	r	R	1031 ↓	1083	11.5	12.8(0.8)	6.6(0.4)	19.4(0.4)	66
	3s 18s Mixed	5 May	r	T	1011	1094	16.6	22.7(0.9)	7.2(0.4)	25.8(0.5)	71
Waterloo	V1	17 Aug	i	R	1016	922	4.7	2.9(0.3)	2.5(0.2)	5.4(0.2)	55
		27 Oct	f	R	996 ↓	1114	4.4	8.2(0.6)	5.1(0.3)	13.2(0.3)	62
		26 Oct	r	R	1009 ↓	1103	4.4	8.1(0.8)	6.7(0.4)	14.8(0.4)	55
Shaft Bottom		11 Oct	i	R	1010 ↑	1073	0.3	2.0(0.2)	1.9(0.1)	3.8(0.1)	51
		9 Nov	r	R	1004 ↓	1005	0.6	9.4(1.0)	8.0(0.5)	17.3(0.5)	54

Abbreviations: i = intake; f = face; r = return; ↑ = rising; ↓ = falling

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