MEASURING DUST EXPOSURE WITH THE THERMAL PRECIPITATOR IN COLLIERIES AND FOUNDRIES

BY

S. A. ROACH*

From the Pneumoconiosis Research Unit, Llandough Hospital, Nr. Cardiff

(RECEIVED FOR PUBLICATION OCTOBER 6, 1958)

The standard thermal precipitator has been modified for field surveys of airborne dust exposure so as to make it more portable. A microprojector is used when assessing the samples and for coal-mine dusts the counts are restricted to the range 0-5 to 5 microns.

In industrial environments the dust concentration appears to vary with a standard deviation of more than 50% of the mean. Part of this variability is due to errors of the thermal precipitator. The standard error of a count of a sample is about 10% to 15% in practical work and the combined effect of this and other errors is that the standard error of a single result is about 15%. However, in practice this can be neglected since the dust concentration itself is so variable. A more important source of error is the bias, due to overlapping among the particles on the cover glasses. The count may give a serious underestimate of the number of airborne particles if high sample densities are used.

The product of average concentration and duration of exposure is probably a good index of the dose of dust retained in a man's lungs. The duration of exposure is measured by a simple time study made at the same time as the concentration is measured.

Samples are taken near workers chosen at random to give unbiased estimates of the dust exposure. Ideally successive samples are taken alongside different workers. However, in a survey at a colliery it was not possible to do this and each day had to be spent with one collier. The mean dust exposure of the coal-getters was 2,860 particle-hours per shift, of those on stone work 2,250 particle-hours per shift, and the remainder had a mean dust exposure of 1,010 particle-hours per shift.

In a survey at a steel works successive samples could be taken alongside different workers. It was found that the dustiness was unrelated to the apparently dusty processes and as the dust was very fine it was suspected that it was the normal atmospheric pollution of the neighbourhood. This was confirmed by samples taken outside.

The cost of such surveys is found to lie between £1 and £2 per sample taken and consequently alternative instruments are being developed which can run unattended for long periods. In future research studies respiratory ventilation as well as dust exposure may be measured over many years, which, combined with periodic medical examinations, would enable the relation between dust exposure and its effects on the men to be determined.

In surveys of airborne dust conducted by the Pneumoconiosis Research Unit we aim to measure the amount of dust inhaled at work. Up to the present time most of the dust sampling has been done with the thermal precipitator (Green and Watson, 1935; Watson, 1936). This paper describes in detail the use of this instrument and the factors affecting its accuracy. Two surveys, one in a colliery and another in a steel foundry, are used to illustrate the differences in the techniques adopted and the results obtained.

Sampling with the Thermal Precipitator

The Apparatus.—The standard apparatus is fairly portable (Fig. 1a) but when set on its tripod it is easily knocked over and it cannot readily be operated while moving about. This is a serious disadvantage when

*Present address: Occupational Health Unit, London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1.
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measuring the dust exposure of colliers since they may spend as much as two hours walking along a dusty underground roadway to and from their work and many of those employed on haulage work move about all the time. The modified apparatus illustrated in Fig. 1b uses a cap lamp battery with an ammeter, switch, and rheostat incorporated in the top cover plate. It is more portable than the standard instrument and easier to use in confined spaces. The thermal precipitator head is usually hung from a roof support when sampling in collieries but it can be fastened to a person’s jacket or held in the hand for sampling close to the worker’s face. A small reversible aspirator (Wright, 1954) replaces the can of water, jet, and measuring cylinder, used in the standard apparatus. The total weight of the modified equipment is 10 lb. compared with 24 lb. for the standard equipment.

Counting and Sizing the Dust.—A high power microscope with a travelling stage and a microprojector is used for counting and sizing the dust (Fig. 2). In the microprojector there are two front-silvered mirrors, which reflect the light on to a matt white card on the table in front of the observer where the image of the particles is easily seen. This makes viewing comfortable and free from eyestrain. Using a 2 mm. objective and x10 eyepiece the magnification is about 2,500 times. A chain drive and flexible coupling control the fine focus and horizontal traverse. Back-lash is reduced by using spring mounts for the chain wheel bearings. A foot switch operates a counter leaving the hands free to

Fig. 1a.—Standard equipment.
Fig. 1b.—Portable equipment.

Fig. 2.—Microprojector for counting dust samples.
operate the controls. To reduce extraneous light the lamp and light beam are hooded and a curtain is hung between the operator and the microscope. The lamp base has screw controls for centering the light.

The size of the particles is estimated by comparing their area visually with those of a series of circles either on an eyepiece graticule or on the screen of the microprojector. Two graticules are illustrated in Fig. 3. The number of circles used depends upon the detail with which the size distribution is required (Patterson and Cawood, 1936; Fairs, 1943; May, 1945; Watson, 1952; Hamilton, Holdsworth, and Walton, 1954). The deposits are traversed beneath the microscope and the particles which pass through the graticule rectangle are counted.

**The Size of Important Particles.**

—When determining the number and size distribution of samples
in detail, eight samples can be assessed each day. More samples can be assessed if the sizing is simplified, and by using the graticule illustrated in Fig. 3b, 20 samples can be assessed each day. In addition, with simpler size analyses the results can be summarized and assimilated much more quickly. Consequently it is desirable to limit the sizing to no more than is essential for assessing the amount of dust of sizes likely to be retained by the lung.

When dust is inhaled the large particles are deposited in the upper respiratory tract and bronchi; only the small particles are carried into the alveoli where some of them are deposited. The probability of a particle reaching an alveolus and being deposited there depends mainly on its size and weight. The proportions of inhaled dust of different sizes deposited in the alveoli have been estimated theoretically by Findeisen (1935) and by Landahl (1950). Their results agree in general with the conclusions from indirect experiments on human subjects (see, for example, Brown, 1931 a and b; Van Wijk and Patterson, 1940; Landahl and Herrmann, 1948; Wilson and LaMer, 1948; Wilson, Sylvester, Laskin, LaBelle, and Stokinger, 1948; Davies, 1949; Brown, Cook, Ney, and Hatch, 1950; Landahl, Tracewell, and Lassen, 1951, 1952). They also agree in general with the results obtained by examining the size of the dust found in lungs after death (Gessner, Rüttner, and Bühler, 1949; Bedford and Warner, 1950; Cartwright and Nagelschmidt, 1951).

These studies show that very little dust is deposited in the alveoli of sizes greater than 5 microns in diameter and in coal-miners' lungs the greatest volume of dust lies in particles with diameters less than 5 microns and larger than 0·5 microns.
Thus in collieries the restricted count, 0·5 to 5 microns, is used, and this probably gives a good index of the volume of the dust likely to be retained by the lung. The count is obtained by using two circles on the graticule, one 0·5 and the other 5 microns diameter, and counting only those particles whose area lies between the area of these two circles. The result is then expressed as the number of particles per ml. of sizes 0·5 to 5 microns diameter. In other industries, where little is known about the nature and size of the dust, a full count and size distribution will help to assess the probable hazard and often to identify the source of pollution.

Variability of Counts

The Amount of Variability.—When a series of thermal precipitator samples is taken in an industrial environment the results are found to vary considerably.

The frequency distribution of counts gives the lop-sided, hump-shaped curve shown in Fig. 4a. However, if we take the logarithms of the concentrations we find the curve is usually roughly symmetrical and similar in shape to a normal distribution curve (Fig. 4b). Thus, by using the logarithms of the concentrations the extent of the variations in dustiness can be described in terms of the normal distribution.

The curves in Fig. 4 are for a lognormal distribution with a standard deviation of 0·3 log particles per ml. and an arithmetic mean concentration of 1,000 particles per ml.

Some of the variability in the results is due to the difference between the dustiness of different jobs but there is also a large variability in the dustiness from time to time in one place even when the work appears to be done at a steady rate. Fig. 5 shows the results of sampling alternately with two thermal precipitators at a coal-face during a coal-getting shift. Each sample was taken for a period of three minutes. A set of low concentrations occurred during the mid-shift break but apart from this the dust concentration fluctuated in a more or less random fashion from one sample to the next around the mean level of 1,550 particles per ml. Oldham (1953) analysed many sets of samples of this kind from different collieries and showed that within any given shift the logarithms of the concentrations at any one place are distributed about the mean with a standard deviation of 0·22 log particles per ml. When all places and shifts are included a standard deviation of 0·44 log particles per ml. has been found. This variation corresponds to standard deviations of the order of 50% and more of the mean.

Some of the variability arises in errors inherent in the thermal precipitator and in the way the samples are assessed. These errors are of various kinds, some of which can be studied separately.

Random Errors

Errors in Counting.—The size of the errors which
occur when counting a number of particles is illustrated in Fig. 6. This shows the results of a series of experiments in which two observers simultaneously counted the particles in a traverse across a sample using a microprojector. At the end of each traverse both observers wrote down the number of particles they had counted. The average difference between the two observers was 3.3 particles, about 5% of the count. Although this difference is small, it is perhaps surprising that the two observers counted the same number in only 11 out of 80 traverses. The main reason is that there is often a difference of opinion between observers on whether particles are larger or smaller than the graticule circles (Heywood, 1946; Watson and Mulford, 1954). Usually at least two traverses are counted on a sample, one on each of the two coverglasses on which the sample is distributed, which means that errors in counting of this kind are unlikely to give a standard error of more than 2% in the total count.

Number of Particles Counted.—Only a small fraction of all the deposited particles are counted (0.2% to 2.0%), a proportion determined by the width of the graticule within which the particles are counted in a traverse across the deposits and the number of traverses counted.

An important source of error is the variability of the number of particles in different traverses across the deposits. This is illustrated by the example in Fig. 7 which is a summary of the results of counting the particles in 184 traverses, each at a different point along the length of one deposit. The frequency histogram shows how the number of particles counted varied from 20 to 80. The mean count was 47 particles per traverse.

During the sampling, as the dust is precipitated, successive particles are equally likely to arrive and be deposited anywhere along the length of the sample. Under these circumstances, it can be shown that by chance alone we would expect to find that the number of particles in different traverses varies in a Poisson distribution. If the counting were perfect this means that the counts on different traverses would vary around the mean with a standard deviation equal
to the square root of the mean. Since the number counted on a traverse usually lies within the range 15-150 particles this irreducible variation would result in a standard deviation of 10% to 25% of the mean. In practice there is a further variation due to errors in counting. The dotted curve in Fig. 7 is the frequency distribution of counts expected from the Poisson distribution when the mean is 47. The additional variation shown by the actual counts is due in part to errors in counting and in part to the uneven deposition of the dust caused by the wire in the precipitator head not being perfectly straight and parallel to the two coverglasses.

If there were no counting errors the coefficient of variation would theoretically be larger for deposits with a low density than for deposits with a high density. The smooth curve in Fig. 8 shows the theoretical relation. Sometimes the particles are counted in two traverses at different points on the deposit and from the difference between such pairs of results an estimate can be made of the coefficient of variation of counts of a sample. The results of 1,000 pairs of counts from deposits of widely different densities were analysed to estimate this coefficient of variation. The results are illustrated in Fig. 8. It can be seen that in practice although the coefficient of variation did fall as the number counted increased, over the usual working range of 20 to 150 particles per traverse the coefficient was fairly constant at about 20%. If, as is usual in our work, an estimate of the number of particles on the sample is based on the mean of two such counts, one from each of the two deposits, then the standard error of such an estimate would be about 10% to 15% of the mean, this error being due to a combination of errors in counting and variations in the number of particles per traverse.

Beadle and Kerrich (1955) analysed the results of a comparison of counts by different observers counting the same samples. They showed that the bias between their observers was very small and the coefficient of variation fell from 17% for counts of
50 particles to 8% for counts of 250 particles and then remained roughly constant at 8% up to counts of 750 particles. These results are similar to those found by us where we have used similar densities.

A technician sometimes regards the difference between his successive counts of the same deposit as being due to his lack of care in avoiding mistakes and may in consequence produce results which agree to an extent which is unlikely to have occurred by chance. This may be done quite unconsciously and therefore as a routine no more than one traverse is counted across each deposit at any one time. When comparing repeat counts by the same observer Beadle and Kerrich (1955) found the coefficient of variation was less than the minimum variation predicted from the Poisson distribution. They were unable to account for this effect. Our experience suggests that this may have been due to the fact that the repeat counts were done with knowledge of the first counts.

**Volume of Air Sampled.**—The measurement of the volume of air drawn into the thermal precipitator for each sample may be in error. This affects the results since the concentration of airborne dust is given by the ratio of the estimated total number of particles deposited, derived from the traverse counts, to this volume of air. With the standard apparatus the volume of air aspirated through the thermal precipitator head is commonly measured with a 50 ml. measuring cylinder. When training technicians it is found that they sometimes misread the volume by 1 ml. or 5 ml. but it is difficult to judge to what extent such mistakes are likely to occur in practice with an experienced observer. Beadle and Kerrich (1955) measured the extent to which these mistakes may occur in the laboratory. They made 972 observations and in 49 of these (5%) a mistake was made of between 10 and 110 ml. in volumes varying between 75 and 570 ml. An error of 10 — ml. was most common.

With the Wright reversible aspirator, used in the modified apparatus, the volume aspirated at each cycle is fixed at about 20 ml., and is measured once at the start of the shift and again at the end. This has the advantage that the volume is measured in the laboratory, away from the distractions of underground conditions, so that there is less likelihood of mistakes. The main source of error with this aspirator is from loss of water through the air outlet nozzle when reversing the bottles, especially if insufficient time is allowed for the aspirator to empty completely. After continuous use throughout a shift it is sometimes found that up to 2 ml. has been lost. In such cases the mean of the readings before and after the shift is used.

With both forms of aspirator the volume of air aspirated will be incorrect if there is a leak between the aspirator and the thermal precipitator head. This point can be checked in the laboratory with the aid of a bubble flowmeter.

**Overall Repeatability.**—The combined effect of all these errors on the repeatability of the results can be measured by taking samples simultaneously with two thermal precipitators side by side.

In experiments designed to measure the magnitude of the errors which occur in practice there are two important difficulties to overcome. First, it is necessary to exclude all possibility of spurious agreement. The memory of a previous result should be of no help to the observer in determining a particular value. The second difficulty is that in any experiment designed specifically to estimate errors the observers tend to be particularly careful. This cannot be avoided entirely but the longer the trial.

![Graph](#)

**FIG. 8.—**The variability of counts on thermal precipitator samples.
becomes the less likely is the effect to be important.

In the series illustrated in Fig. 9 there were 470 pairs of samples taken in a variety of collieries. The two instruments were operated by different observers. The samples were then coded and each was counted independently by three different observers, care being taken to ensure that the two samples of each pair were widely separated in the list of samples. Each observer made only one count of each deposit. Steps were taken to conceal the purpose of the trial from the observers until all the results were brought together.

The results illustrated show the scatter about the line of perfect agreement. From such pairs of results we can estimate the error of a measurement of the dust concentration made with the thermal precipitator. The results expressed in terms of the standard deviation about the mean are given in Table 1. It can be seen that there is a tendency for a lower standard error, in percentage terms, the higher the concentration, although in general we may expect to find a standard error of about 15%. Beadle and Kerrich (1955), sampling in gold mines in South Africa and counting all the particles that could be seen after igniting the slides to remove carbon, found in a similar experiment that the standard error of a single sample was 13%. Burdekin and Dawes (1956), reporting on a comparison of two thermal precipitators, found a standard error of a single observation of about 25%.

**Importance of Repeatability.**—If the errors in measuring a concentration with the thermal precipitator were the only cause of variations in the results found in sampling in a colliery we would expect to
find the standard deviation of the concentrations to be about 15%, so that the standard deviation of the logarithms of the concentrations would be between 0.06 and 0.07 log particles per ml. In fact, as has been noted, the standard deviation found is 0.22 log particles per ml. when considering a single place during a single shift and 0.44 log particles per ml. when including all places and shifts. Thus, it can be seen that the errors of measurement, although quite large by some standards, have a negligible effect on the variability of the results obtained at different times and different places. In the past it has been recommended that enough particles should be counted to reduce the error of estimation of each sample to less than 5% (Watson, 1936; Transvaal Chamber of Mines, 1947). However, in practical work where it is desired to estimate the mean concentration at a particular place, or its variability, or the dust exposure of a worker or group of workers, the effort needed to achieve this precision is better spent in taking more samples. Large errors can be tolerated in the estimation of individual samples without appreciably affecting the precision of the mean concentration.

Systematic Errors

Overlapping.—The most important systematic error in thermal precipitator measurements is that due to overlapping amongst the particles deposited on the coverglasses. Particles covered by larger ones are not seen and since clumps or aggregates of particles are counted as single particles those aggregates formed by particles depositing near one another are also counted as single particles.

The bias in the count due to this overlapping increases with the density of the deposits and with the mean size of the particles (Roach, 1958). When sampling in a coal-mine Roach found that this bias amounted to 20% of the count at densities commonly used and recommended.

Contamination.—Another important source of bias is extraneous contamination of the coverglasses. They may become contaminated with dust while putting them into the thermal precipitator head and while taking them out. More contamination occurs if the plug holders and screw cap in the thermal precipitator head are not kept clean or if the screw cap is left off between samples. This leads to the number of particles deposited being overestimated. All particles less than 5 microns in diameter drawn into the thermal precipitator head are deposited on the coverglasses in a zone about 2 mm. wide (Green and Watson, 1935; Prewett and Walton, 1948), but when a deposit is examined under the microscope it is usually found that there is also a small amount of dust on the rest of the coverglass.

Fig. 10 illustrates the effect of this contamination on the density of the deposits. Two deposits were examined, one with little and the other with excessive contamination. The number of particles in unit area was determined at different points across the deposits. It can be seen that with the contaminated deposit (Fig. 10b) the edges of the deposit were ill-defined and there would have been considerable difficulty in determining how much of the dust was from the sample.

When excessive contamination is suspected it is our practice to examine the coverglass with a 16 mm. objective at a point away from the deposit and if it is found that there are more than 50 particles per sq. mm. the sample is rejected. To minimize the effect of contamination on the count the length of the traverse made across the sample is limited so as to span the sample dust and no further.

An example of the combined effect of the bias due to overlapping and contamination which normally occurs is illustrated in Fig. 11. This gives the expected errors for the count 0.5 to 5 microns for samples of dust of the kind obtained at a colliery. The continuous line gives the relationship between the number of particles counted and its expected bias. When the number counted is very high the number deposited is seriously underestimated, due to the large amount of overlapping whereas when the number counted is very low the extraneous contamination is a relatively large proportion of the count and the count is biased high. The dotted curves are the 95% confidence limits of the true mean plotted against the corresponding value of the mean.

Other Errors.—In addition to the biases from overlapping and contamination, which are inherent in the instrument, there are other biases which are more easily avoided. For example, the technician may tend to read the volume of each sample systematically high or low or the observer assessing the samples may consistently underestimate or overestimate the size of the particles. These biases are corrected as far as possible when training the technicians.

The measuring cylinder used in the sampling may not be accurate. Errors are reduced by using...
cylinders made to British Standard Specification 604. A 50 ml cylinder of this kind will not be in error by more than 0.5 ml at any point on the scale. Ten such cylinders were compared with an accurate burette and none was found with an error of more than 0.2 ml at any point on the scale. On the other hand when six cylinders were tested which had no such guarantee of accuracy, it was found that at 20 ml they were in error by between 0.6 and 1.2 ml.

The Time Factor

In determining the dust exposure of a group of workers their duration of exposure is measured as well as the average concentration to which they are exposed. This is done to derive an index of the amount of dust retained in the lungs.

It has been found by field studies that in all diseases due to accumulations of dust in the lungs the greatest incidence of pneumoconiosis occurs amongst men who have been exposed for the longest time to the highest concentration (Sayers, Bloomfield, Dallavalle, Jones, Dreessen, Brundage, and Britten, 1935; Dreessen, Dallavalle, Edwards, Miller, Sayers, Easom, and Trice, 1938; Flinn, Dreessen, Edwards, Riley, Bloomfield, Sayers, Cadden, and Rothman, 1939; Dreessen, Dallavalle, Edwards, Sayers, Easom, and Trice, 1940; Flinn, Seifert, Brinton, Jones, and Franks, 1941; Dreessen, Page, Hough, Trasko, Jones, and Franks, 1942; Bedford and Warner, 1943; Roach, 1953). Since men with pneumoconiosis have more dust in their lungs than others (Gough, 1947; King, Maguire, and Nagelschmidt, 1956) the logical conclusion is that the dust accumulates gradually in the lungs over a period of many years.

In the absence of evidence to the contrary, it seems likely that over the working range the rate of accumulation of the dust is simply proportional to
the concentration of dust inhaled (Wright, 1953). Consequently, the product of average concentration and duration of exposure is probably a good index of the dose of dust permanently retained in a man's lungs. The average concentration of particles between 0.5 and 5 microns is measured with the thermal precipitator and the duration of exposure in hours is measured by a simple time study done at the same time. The product of the two gives the dust exposure in particle-hours per ml. between 0.5 and 5 microns, or "particle-hours", for short.

Sampling Procedures
When measuring the dust exposure of groups of workers the samples are taken as close to the workers as practicable. To get the greatest possible coverage with the least number of samples each sample should be taken alongside a different worker. However, it is sometimes difficult to get from one worker to another and a series of samples may be taken alongside one worker before proceeding to the next. It may be necessary to stay with one worker for a whole shift, in which case a different worker is chosen each day. Whatever sampling procedure is adopted, the workers sampled on a particular shift are chosen at random from the population in order to obtain an unbiased estimate of their average dust exposure.

In control sampling where the primary purpose is to check that conditions have not deteriorated, sampling procedures have been developed based on measuring the dustiness at fixed positions, at times of maximum dustiness and in the dustiest positions, so that an ample safeguard is given that the average levels are below the level measured. These procedures are simple and practical but they are of little use for precise measurement of the average dust exposure of the men or how the dust exposure varies from one man to another (Oldham and Roach, 1952).

A Survey in a Colliery
The Sampling Procedure.—The object of this survey was to test the sampling procedure and practicability of measuring the dust exposure of coal-miners over a long period. For the purposes of the survey their dust exposure was considered to begin when they entered the cage which takes them underground and to cease when they left the cage again at the end of the day’s work.

Colliers often arrive early or work overtime and the men at this colliery took from 20 minutes to two hours to travel between the pit bottom and their place of work.

A sampling procedure was therefore tried in which the technician was provided each day with a
list of six coal-getters chosen at random from the whole population. The technician went underground with one of these men and travelled with him to his place of work, taking samples on the way. He then travelled from one collier to the next at hourly intervals during the main part of the shift, from 8 a.m. to 2 p.m., and came out of the pit with the last collier on his list.

With this procedure each technician was able to take samples alongside 30 different colliers each week, but he had to be willing and able to travel considerable distances underground each day. It is necessary in this work to leave the technicians unsupervised for most of their work so that it is essential for reliable results that their task be light and simple.

The next method tried was to treat the men in each district of the colliery as a separate population so that the technician had to travel only over a limited area each day. This procedure was found to be an improvement, but only at the expense of added complications in the book-keeping as it became necessary to keep week-by-week records of the placing of the men in the different districts. The difficulties of keeping a tally on the jobs the men actually do over an extended period are considerable. For instance, over a year it was found that of 234 men who were visited, 79 (34%) were doing a different job from the one allocated to them in the colliery books.

The procedure finally adopted was that described by Oldham and Roach (1952). Each shift a technician went underground with a collier chosen at random from the whole population, stayed with him for the whole of the shift, and returned to the surface with him. This was the simplest and least laborious of the methods tried.

A list of the men employed on the underground staff was obtained from the colliery. The men were met at the start of their shift at the lamp room on the surface and accompanied underground. The job they did during the shift and where they worked was noted by the technicians so that the dust exposure associated with a particular type of job or district could be assessed at the end of the survey. If a collier was absent his dust exposure on that day was recorded as zero and the technician did not go underground. Samples were normally taken one after the other throughout the shift, but if the concentration was expected to be high, short-period samples of fixed duration were taken at intervals of 20 minutes, beginning at a time chosen at random within the first 20 minutes.

The survey lasted 55 weeks including a break of two weeks for the colliery summer holidays. The names of the men on the books at the start of the survey were placed in a random order and they were dealt with serially. During the survey it was found that of the 377 men selected, 49 (13%) were no longer employed at the colliery. Of the remaining 328, still employed, 109 were absent (33%) on the days when their dust exposure was to be estimated. A collier was not informed beforehand that he was due for a visit by the technician so that his attendance or otherwise was not affected. It has been found that when a worker is asked beforehand if he expects to be at work a few days ahead, he will often make a special effort to turn up and this may bias the estimation of his dust exposure.

**Variability of the Dustiness.**—The frequency distribution of the dust concentrations shown by the 2,725 samples obtained is illustrated in Fig. 12. The arithmetic mean was 288.7 particles per ml. The dots
in the diagram refer to the number of results at that particular level of concentration and the continuous line is a frequency distribution curve fitted to these frequencies on the assumption that the parent distribution is of log normal form. The standard deviation was 0.44 log particles per ml. The continuous curve describes the distribution well.

The highest concentration recorded in the survey was 6,190 particles per ml., more than 20 times the mean, and there were eight samples which showed concentrations more than 10 times the mean. On the other hand there were 28 samples for which the concentration was so low (less than 5 particles per ml.) that the dust on the sample was too sparse to count.

**Duration of Exposure.**—The colliers were supposed to spend seven and a half hours underground each shift. However, colliers who become ill or have an accident and those who need to come out to mend or get a piece of equipment may leave the mine before the end of the shift. Some men also work overtime. There is thus a considerable variation in the duration of exposure, illustrated by the summary given in Table 2. The shortest time spent underground was 0.8 hours and the longest 9.5 hours. The average time spent underground was 7.52 hours.

Time studies were done to measure the time spent travelling to and from the place of work, and on half the days the time spent working and resting between spells of work was also measured. In a number of jobs the work is machine minding, particularly those connected with the transport of trucks and roof supports between the pit bottom and the coal-face. In these jobs the observer could not distinguish clearly between the working and resting periods. This type of job was done on 19 days out of the 110 when detailed time studies were attempted.

The time spent in these different activities varied considerably as is illustrated by the results given in Table 3. The mean time spent working, during which the greatest dust exposure occurs, was 4.32 hours; the mean times spent travelling and resting were respectively 1.34 hours and 1.82 hours. On at least 10% of occasions the length of these periods was either less than half of the mean or more than one and a half times the mean.

**Dust Exposure in Particle-hours.**—On three occasions the colliers chosen, although usually employed underground, were sent to work on the surface clearing away a stock of coal. Their dust exposures were 290, 280, and 30 particle-hours. Excluding these figures, we give in Table 4 the mean dust exposures for each month. The number of shifts sampled each month varied because of annual leave and sickness absences in the colliery and among the sampling staff. There seems to be no steady trend either upwards or downwards in the dust exposure per shift over the period covered. However, the dust exposure per shift did vary a great deal. The minimum was 70 particle-hours per shift and the maximum was 17,090 particle-hours per shift, representing a range of more than 200-fold in the dust exposure. The mean dust exposure of all the
shocks sampled was 1,549 particle-hours per shift.

There is a very great variety of occupations underground and to study each of them thoroughly would take considerably longer than a year. The results are divided into three groups. The first includes coal-getters and their assistants, that is, the men who dig the coal and shovel it on to the conveyors; the second includes all the rippers, repairers, packers, and their assistants, that is, the men who work on stone; and the third group includes all the other workers such as labourers, transport workers, and specialists of various kinds who together account for about half the underground population.

The results of the measurements in these three occupational groups are shown in Table 5. The dustiest occupation is that of the coal-getters for whom the mean dust exposure was 2,860 particle-hours per shift. In the dustiest shift the collier’s dust exposure was 17,090 particle-hours, the highest recorded. He was working in a rib end (a short extension of the face beyond the junction where it meets the return airway of the face) where the ventilation was very poor. The dust he produced while digging the coal would normally be swept away by the ventilation current, but on this occasion remained in the relatively stagnant air around him and led to his having a very high dust exposure.

Stone work was a less dusty occupation than that of coal-getting. The mean dust exposure per shift for the stone workers was 1,370 particle-hours. A dust exposure of 2,250 particle-hours per shift was exceeded in seven shifts out of 44. On six out of these seven occasions the man was working at the ripping lip in the return roadway of one of the faces during the coal-getting shift, whereas out of the remaining 37 occasions only three were spent at the return end during the coal-getting shift. The return ends of longwall faces are usually the most dusty places during the coal-getting shift as the airborne dust made by all the coal-getters along the face is drawn by the ventilation current to the return end.

The remaining occupational group under “others” in Table 5 had a lower dust exposure per shift worked than either the coal-getters or the stone workers. Their mean dust exposure was 1,010 particle-hours per shift. This group included a large number working on the night and afternoon shifts, when no coal-getting was in progress and others who worked some distance from the coalface.

**Variations in Dustiness along the Face.**—That the dustiness is greatest at return ends is illustrated by the results for the coal-getters. During the survey a note was always made of where the men were working and for the coal-getters the distance to the main intake road to the face was recorded. The mean concentrations at these different positions are summarized in Table 6. They exclude the dust measurements made while travelling to and from work and while resting during the mid-shift break. The dustiness was greatest towards the return end although the increase is not as great as might be expected. Some dust enters the face with the intake air. Also on some faces there is in addition to the main intake air, a further, although much smaller, supply of air half-way along from the loader gate. Another complicating factor is that the coalface itself, although bounded on three sides by solid rock, namely, the roof, floor, and coal itself, is bounded on the fourth side by a series of stone packs at right angles to the face between which the roof is allowed to fall and there is some leakage of air through this loosely packed material which only partially mixes with the air passing the colliers.

Fig. 13 illustrates the results of a survey at another colliery with a more simple layout of the faces where there is a much clearer demonstration of the increase of dustiness towards the return end. In general, the more complicated the ventilation
MEASURING DUST EXPOSURE WITH THERMAL PRECIPITATOR

DUST EXPOSURE ON LONGWALL FACES DURING THE COAL-GETTING SHIFT

<table>
<thead>
<tr>
<th>Distance from Intake Road (yards)</th>
<th>Mean Concentration (particles/ml. 0.5 to 5 microns)</th>
<th>Number of Shifts Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>280</td>
<td>6</td>
</tr>
<tr>
<td>20-40</td>
<td>340</td>
<td>1</td>
</tr>
<tr>
<td>40-60</td>
<td>390</td>
<td>6</td>
</tr>
<tr>
<td>60-80</td>
<td>340</td>
<td>7</td>
</tr>
<tr>
<td>80-100</td>
<td>420</td>
<td>4</td>
</tr>
<tr>
<td>100-120</td>
<td>400</td>
<td>8</td>
</tr>
<tr>
<td>120-140</td>
<td>390</td>
<td>11</td>
</tr>
<tr>
<td>140-160</td>
<td>720</td>
<td>2</td>
</tr>
<tr>
<td>160-180</td>
<td>490</td>
<td>2</td>
</tr>
<tr>
<td>&gt;180</td>
<td>500</td>
<td>1</td>
</tr>
</tbody>
</table>

The results from 34 shifts are shown, four more than in Table 5 for coal-getters, due to the inclusion of shifts where the travelling dust exposure was not known and the exclusion of shifts where the collier did not work on a longwall face and where the collier worked in the rib end.

system, the more dust entering with the intake air and the wider the face, the more difficult is it to detect the increase in dustiness along the length of the face.

A Survey in a Steel Works

Object of the Survey.—In the melting shop of a large steel works employing about 10,000 people there were 16 smelting furnaces. These furnaces deteriorate with use and are then partially or completely dismantled and rebuilt. There were complaints from the men doing this work that their job was particularly dusty.

A survey was made of the dust exposure of these furnace dismantlers and repairers and of other groups working in the bar and strip mills where it was expected there would be little or no dust.

The men in each of the occupational groups worked within 400 yards of one another and it was practicable to get from one to another within 10 minutes. It was therefore possible in this instance to adopt the more efficient sampling procedure of moving from worker to worker between successive samples.

Method of Sampling.—Names were chosen at random from a works list of the men employed in different occupations and samples were taken along side each of these men using the standard thermal precipitator (Fig. 1a). For each sample the tripod was placed as close as possible to the worker without interfering with his work. As soon as the apparatus had been set up a sample of 10 minutes' duration was taken and then the sampler moved on to the next man on the list. In order to cover as many workers as possible only a short time was spent with each one, just sufficient to take one sample. It was found that it took about 20 minutes to complete each sample. The duration of exposure began when the workers clocked in and finished when they clocked out. Since they all clocked in and out within a few minutes of each other their durations of exposure were effectively equal. The survey lasted three weeks.

Results.—The mean concentrations of dust of all sizes are shown in Table 7. The samples were counted for total number of particles using a 2 mm. oil-immersion objective in the microscope. Particles as small as 0.1 microns diameter can be seen with this arrangement. In all three of the occupational groups the mean concentration was very high but of the three groups it was the bar mill workers who were exposed to the highest concentration and not, as was expected, the bricklayers.

The Source of the Dust.—It seemed possible that the dust in the bar mill came from the smoke from the pre-heating furnace. At the time of the sampling a note was made of where in the mill the particular worker was working. We could thus determine where in the mill the highest concentration existed. Table 8 gives the results, showing that there is no clear trend of dustiness along the length of the mill. This finding and also the finding that the mill as a whole was more dusty than the steel melting shop suggested that very little of the airborne dust in the works came from the demolition and building operations.

It was concluded that probably most of the dust came from outside and entered with the ventilating air. Further, it was found that the dust in the samples was very fine, as would be expected if it was
the normal atmospheric pollution of the neighbourhood. The fineness of the dust is illustrated in Table 9 where the diameter at the median projected area is given for 20 samples taken at random from all the samples taken and compared with samples from 20 collieries. The mean size at the steel works was 0.77 microns and in the collieries was 10.5 microns.

**Table 8**

**Mean Concentration at Different Positions in the Bar Mill**

<table>
<thead>
<tr>
<th>Distance from Furnace (yards)</th>
<th>Number of Samples Taken</th>
<th>Mean Concentration (particles/ml., all sizes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100</td>
<td>14</td>
<td>15,550</td>
</tr>
<tr>
<td>100-200</td>
<td>14</td>
<td>27,170</td>
</tr>
<tr>
<td>200-300</td>
<td>10</td>
<td>6,890</td>
</tr>
<tr>
<td>300-420</td>
<td>4</td>
<td>10,050</td>
</tr>
</tbody>
</table>

Measurements made of the dust concentrations in the air entering the works confirmed that high concentrations of fine dust were entering from outside. Samples were taken around the works on the windward side. The results ranged from 6,000 to 39,000 particles/ml and the average concentration was 16,860 particles/ml. The dust was again very fine. The dust, or smoke, appeared to come in part from bonfires of rubbish in the yards and from the smoke of the steam locos working in the large shunting yards behind the works.

Chest radiographs were taken of the men and a summary of the readings for the furnace dismantlers and repairers is given in Table 10. All those who had had two or more years' experience in mine or factory, other than at the steel works, were rejected from the analysis. It can be seen that about 8% of the men were classified as category 1 or more. The prevalence of such radiological abnormalities in 12 British collieries was given by Cochrane, Davies, Chapman, Rae, Rinsler, and Williams (1956) and in these the prevalence ranged from 18% to 62%. Thus, the risk of pneumoconiosis at the steel works must be relatively low. Presumably the particles were so small that, despite their large numbers, the total weight of dust retained in the workers' lungs was comparatively low.

However, the dismantlers maintained that theirs was a very dusty job and the worst dust conditions occurred when they were breaking down the roof of a furnace. Samples were therefore taken to cover the period when a roof was being broken down. The results are given in Table 11.

**Table 9**

**Mean Size of Dust in 20 Samples from Steel Works and in Samples from Coalface at 20 Different Collieries**

<table>
<thead>
<tr>
<th>Steel Works</th>
<th>Collieries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median Diameter in Microns</td>
<td>No. of Samples</td>
</tr>
<tr>
<td>&lt;0.3</td>
<td>0</td>
</tr>
<tr>
<td>0.3-</td>
<td>3</td>
</tr>
<tr>
<td>0.5-</td>
<td>4</td>
</tr>
<tr>
<td>0.7-</td>
<td>6</td>
</tr>
<tr>
<td>0.9-</td>
<td>3</td>
</tr>
<tr>
<td>1.1-</td>
<td>2</td>
</tr>
<tr>
<td>1.3-</td>
<td>2</td>
</tr>
<tr>
<td>&gt;1.5</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
</tr>
</tbody>
</table>

The area median diameter is given, that is, the size at which the total projected area of all larger particles is equal to the total projected area of all smaller particles.

**Table 10**

**Prevalence of Pneumoconiosis in Furnace Dismantlers and Repairers (P.R.U. Classification)**

<table>
<thead>
<tr>
<th>Category of Radiograph</th>
<th>No. of Men</th>
<th>% of Men</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>149</td>
<td>92</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>162</td>
<td>100</td>
</tr>
</tbody>
</table>

The mean period of exposure was 11.7 years, varying from one month to 33 years.

**Table 11**

**Dust Concentrations When Breaking Down Roof of a Furnace**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Activity</th>
<th>Number of Particles per ml. with Diameter in Microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>42,200, 5,450, 0</td>
</tr>
<tr>
<td>2</td>
<td>Dismantling</td>
<td>26,300, 5,230, 0</td>
</tr>
<tr>
<td>3</td>
<td>Dismantling</td>
<td>53,800, 7,660, 60</td>
</tr>
<tr>
<td>4</td>
<td>None</td>
<td>30,400, 4,970, 0</td>
</tr>
</tbody>
</table>

Samples 1 and 4 were taken immediately before and after the operation. During the second and third sample the roof was being broken in. Since it could be seen that the billowing cloud of dust was not reaching the thermal precipitator during sample 2, the instrument was put inside the furnace for sample 3, just outside the range of the falling brickwork. This sample gave 60 particles larger than 5.
microns in diameter per ml. where none were found in the other samples. Assuming these particles were collected only when the heavy cloud of dust enveloped the instrument as the roof fell in, a period of six seconds, then since the sample lasted 10 minutes, 100 times as long, the peak concentration of this coarse dust was of the order of 60 × 100, that is, 6,000 particles per ml. Thus, when a roof is broken down a spectacular cloud of coarse dust is produced but it lasts for a few seconds only.

This operation and similar ones no doubt gave rise to the belief amongst dismantlers that they were exposed to a particularly high risk of pneumoconiosis.

Discussion

The thermal precipitator is widely used at the present time. It is fairly reliable, although not very accurate. Because of the high variability of the dustiness existing in industrial areas a high precision can only be obtained with it by taking large numbers of samples. At the same time it is necessary to employ an experienced technician both to operate the instrument and to count and measure the size of the dust in the samples. Consequently, in practice the precision achieved in a survey using this instrument is limited by the amount of time and money available for technicians to take and assess the samples. Taking into account wages, expenses, the cost of materials, and the wear and tear on the instruments, the total cost of such a survey is usually found to lie between £1 and £2 per sample taken.

Much of the expense of these surveys is due to the time spent taking the large numbers of samples needed to cover the wide fluctuations in dustiness from time to time. Consequently, instrument development at the present time is directed to producing instruments which will run unattended for long periods and give readings of the average concentration over the whole of the run. Instruments such as the long-running thermal precipitator (Hamilton, 1956), the drum pump sampler (Lloyd, Winder, and Gillard, 1951), the liquid trap sampler (Barker, O'Connor, and Winder, 1954), and the automatic sedimentation cell (Davies, 1954) are examples of these.

Where the time of exposure is very variable its measurement must be given as much attention as the measurement of concentration. This is particularly important in collieries. It has been shown in an earlier paper (Roach, 1954) that not only do colliers vary amongst themselves but also the duration of exposure of colliers in different collieries is markedly different; this is an additional reason for making careful measurements when comparing one colliery with another.

In surveys of dust exposure the samples are taken alongside selected individuals and the first few workers often have some misgivings that they should be picked out from their fellows in connexion with a study of a disease about which they know very little. Such fears are allayed when it is explained how a particular worker comes to be chosen and the men are soon reassured when they see the sampler taking samples alongside their fellow workers. In practice, it is found that wage-earners lose interest in the conduct of these surveys after a few days. This lack of interest is not discouraged since it is essential that the workers' habits are not altered by the sampling.

The procedure used has to be sufficiently simple to be performed by the field survey personnel under the distracting conditions met with in industry and at the same time has to yield unbiased and accurate estimates of concentration and duration of exposure. This is most simply done by choosing a representative group of men from a works list with the aid of random sampling numbers and taking the dust samples alongside each in turn. A sample of the population consisting of the first few names given in a works list, the first few names in a list in order of works number, or in alphabetical order is often unreliable. With the first two of these we have found that the men are then placed in order to some extent according to seniority, so that selection of the first few men does not give a representative sample, and in the last it was found that foreign names were more commonly found in the last few letters of the alphabet. Foreign workers seem to be placed in particular jobs or are placed together because of language difficulties, so that sampling, for example, only those men whose names begin with a letter in the upper half of the alphabet would have given a biased sample.

This sampling procedure may be modified in several ways so as to give a higher accuracy in the averages for the same number of samples taken. For instance, extra samples can be taken in conditions where the dustiness is likely to be excessive or particularly variable. Similarly, for sampling in order to check on the control of dustiness by dust prevention and suppression devices, more samples can be taken in places where the dustiness is near the upper permissible level than those which are much less dusty. Control chart techniques are likely to be used to help do this systematically (Tomlinson, 1957). Another way in which control sampling can be improved is by measuring the dust exposure of the men rather than relying solely on measuring the dust concentration at a fixed place.

The assessment of airborne dust samples is often done by counting the particles by eye under the microscope. No matter how much the procedure is
simplified this is a tedious and time-consuming activity. It is hoped that automatic counting machines will be developed in the future to do the counting more rapidly, cheaply, and objectively (Walton, 1954).

Although the main features of pneumoconiosis are known, the relative importance of the various factors which influence the deposition and retention of dust and its effect on the lung is but vaguely understood. For example, the harder the men work the greater will be the rate of inhalation and the greater will be the proportion of dust caught in the upper respiratory tract, particularly of the larger sizes. At the same time, a greater volume of lung is used in breathing with the result that the dust deposited in the alveoli will be finer and more widespread. To investigate the importance of these particular factors it is likely that in field studies of pneumoconiosis measurements of respiratory ventilation will have to be taken in addition to measurements of dust exposure.

The practical problem of determining the relations between dust exposure and its effects on the men is beset by two major difficulties. First, since pneumoconiosis is the result of exposure to dust for 10 to 20 years, the prevalence of pneumoconiosis in a group of workers can be related to the dust conditions prevailing only if these conditions have remained unaltered for many years. Secondly, although breathlessness is associated with pneumoconiosis it is not known how much of the one is caused by the other. Both these difficulties can be overcome by field surveys which last for many years, tracing the dust exposure of the men from the time they enter the industry and measuring the progressive effect of the accumulations of dust with periodic medical examination (see, for example, Fay, 1957).

Thanks are due, first to my technicians, Messrs. B. P. Pryce, R. P. Pryce, W. J. Davies, R. D. Evans, and J. Williams, who took and assessed most of the dust samples.

On statistical aspects, Mr. P. D. Oldham gave much help and advice and Mr. R. G. Carpenter analysed some of the results. Many of the ideas and methods presented in this paper were developed in conversations with Mr. Oldham.

Dr. B. M. Wright was responsible for many ingenious features of the apparatus and Messrs. V. Gubb and F. Hyett also helped in this.

None of this work would have been possible without the cooperation of the managers and employees of the mines and steel works where the field work was undertaken.

Dr. R. S. F. Schilling, of the London School of Hygiene and Tropical Medicine, and Mr. J. R. Hodkinson, of the Safety in Mines Research Establishment, made many valuable suggestions in the preparation of this paper.

Finally, I would like to thank Dr. J. C. Gilson, Director of this Unit, and also Dr. A. L. Cochrane without whose continual encouragement this material would not have been published.

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Measuring Dust Exposure with the Thermal Precipitator in Collieries and Foundries

S. A. Roach

Br J Ind Med 1959 16: 104-122
doi: 10.1136/oem.16.2.104

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