GRAVIMETRIC DUST SAMPLING — FUNDAMENTAL CONCEPTS AND PRINCIPLES*

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One of the fundamental problems of mining, from the health point of view, is that it produces airborne dust and, as every miner knows, excessive dust exposure may lead to lung disease, commonly termed pneumoconiosis ('dusty lung'). The solution is obvious: reduce the dust exposure of mineworkers to levels which are considered acceptable.

A considerable amount of time, effort and expense is directed towards dust sampling on South African mines. For such efforts to be fruitful, however, they must be based on sound principles of dust measurement and dust control, and their effectiveness verified by medical studies. After all, the success of a dust control programme is ultimately measured in terms of an overall reduction in the incidence of pneumoconiosis.

The introduction of gravimetric dust sampling throughout the South African mining industry as an alternative to present methods is currently the subject of considerable attention. Discussion on this subject obviously requires a basic understanding of the method and familiarity with terminology used to describe it.

This paper sets out the fundamental principles and concepts underlying gravimetric sampling for respirable dust and examines its role in providing an improved measure of the health hazard from dust exposure.

Principles of dust sampling for hazard evaluation

Nearly thirty years ago, world dust experts gathered in Johannesburg to discuss the need to improve dust sampling and control techniques in order to mitigate the effects of dust exposure. That historic International Pneumoconiosis Conference in 1959 recommended the principles under which dust sampling should be conducted in order to assess the health hazard from dust exposure. The main principles have remained virtually unchanged to the present day and have gained widespread international acceptance. They are as follows:-

- measurements of the **respirable** dust fraction
- **gravimetric** assessment of the collected dust
- **long-period sampling** to give average dust levels over a shift.

Each of these principles is now examined in more detail.

Respirable dust

Dust particles are conveniently sized by reference to their diameter, generally expressed in microns (μm). The diameter of an irregular particle estimated using a microscope and graticule by the projected area method is the 'geometric' diameter. It has physical meaning and is most commonly used to denote actual particle size. The aerodynamic equivalent diameter (AED) is a hypothetical but valuable concept used to denote the diameter of a spherical particle of unit density having the same falling velocity as the particle in question.

For example, an irregular quartz particle (density 2 600 kg/m^3) with a diameter of 3,1 μm will have an equivalent (AED) diameter of about 5 μm; a coal particle (density 1 100 kg/m^3) but 3,8 μm in size will also have an AED of 5 μm. Both particles will behave in exactly the same manner aerodynamically when breathed into the lungs, despite being physically different in size. The equivalent diameter concept therefore classifies particles aerodynamically, regardless of their shape, size or density.

Respirable dust was originally defined in qualitative terms by the British Medical Research Council (BMRC) in 1952 as 'that fraction of dust reaching the alveoli'. (Alveoli are air sacs deep in the lung where gas exchange takes place; damage in this region, caused by deposited dust particles, may lead to pneumoconiosis).

The BMRC selected the horizontal elutriator (MRE 113A) as the practical device for measuring respirable dust with the fraction of dust penetrating this sampler constituting the respirable fraction. The rationale behind this was that the dust collection efficiency of the horizontal elutriator could be made to simulate fairly closely the dust deposition characteristics of the alveolar portion of the lung.

Here, therefore, was a practical method of measuring that fraction of a dust cloud which could pose long-term health risks.

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From experimental studies of dust deposition, it was decided to set a value of 50% penetration at 5 µm AED. Respirable dust was therefore defined numerically by a penetration curve **(Figure 1)** whose maximum particle size is 7,1 µm AED.

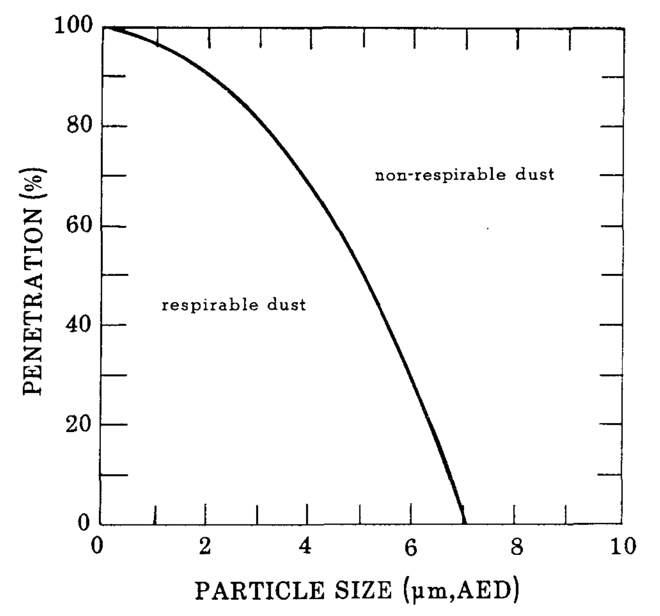

Figure 1 ***BMRC/JOHANNESBURG RESPIRABLE DUST CURVE***

A formula for the penetration curve defining the respirable fraction* is given below:-

$$P = 1 - (\frac{d^2}{D})$$

where P = penetration of dust to the lung (%)

d = size of particle (µm, AED)

D = maximum size of particle (7,1 µm AED)

(* equivalent to the dust collected by the MRE 113A filter)

Values of P for varying dust size are set out in **Table 1.**

Table 1 ***QUANTITATIVE DEFINITION OF RESPIRABLE DUST (BMRC/JOHANNESBURG DEFINITION)***

P (%)	90	80	70	60	50	40	30	20	10	0
d (µm)	2,2	3,2	3,9	4,5	5,0	5,5	5,9	6,3	6,9	7,1

Respirable dust as defined in **Table 1** is therefore not simply all particles less than a stated size (as is so often quoted) but an increasing proportion of dust particles smaller than ~ 7 µm (AED). This description approximates to the fraction of dust penetration to the lung, in the course of which larger particles are selectively removed.

Several points should be emphasized:-

- the penetration function is a theoretical curve and not an exact simulation of the deposition curve for dust in the lung
- particle size is expressed in aerodynamic equivalent diameters e.g. a 5 µm (AED) quartz particle will appear under the microscope to be only 3,1 µm in size
- other definitions of respirable dust have also been recognised e.g. U.S. ACGIH definition
- the BMRC definition was adopted at the International Conference on Pneumoconiosis held in Johannesburg in 1959. It is therefore frequently referred to as the 'Johannesburg' curve.
- the Government Mining Engineer in South Africa has recognised the Johannesburg definition of respirable dust for local use.

Gravimetric assessment

'Gravimetric' means 'measurement by mass' and refers to the mass of dust collected after a period of sampling dusty air. The mass of dust is typically determined by measuring the weight increase of a filter using a microbalance. Strictly speaking, 'gravimetric' refers to the analytical rather than the sampling process, but the term 'gravimetric dust sampling' has, through common usage, been taken to mean 'dust sampling followed by gravimetric assessment'.

Gravimetric means measurement by mass and is the mass of dust collected after a period of sampling dusty air

Dust levels measured gravimetrically are expressed in terms of concentration by dividing the mass of dust (mg) by the volume of air sampled (m^3) giving a mass concentration in mg/m^3. (This is quite distinct from number concentration e.g. konimeter dust 'counts' expressed in particles per millilitre of air sampled, or p/mℓ).

The principle of measuring the mass concentration of respirable dust was founded on the results of epidemiological research, particularly on coal mines. Epidemiology is the science of relating medical manifestations of disease with the agent or process presumed to cause the disease. It typically requires detailed study of a select group of workers over a long time, during which two aspects are monitored:

- average dust exposures of workers in occupational groups
- medical and occupational histories of these workers.

From such studies, the relationship between dust exposure (obtained from dust measurements and occupational histories), and clinical evidence of the disease is hopefully clarified and the results are expressed in a family of exposure (or dose) — response curves. An example is given in **Figure 2.**

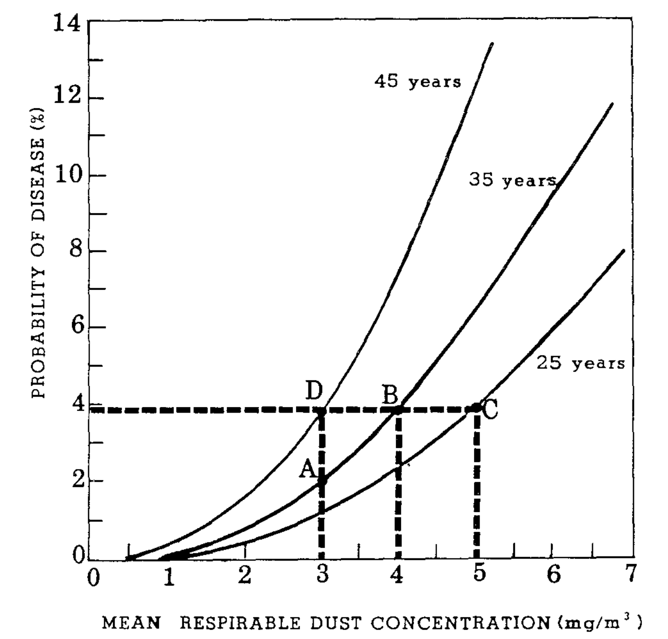

Figure 2 ***HYPOTHETICAL EXPOSURE-RESPONSE CURVES SHOWING PROBABILITY OF CONTRACTING PNEUMOCONIOSIS AFTER 25, 35 OR 45 YEARS EXPOSURE TO DIFFERENT DUST CONCENTRATIONS***

The classic epidemiological study was the so-called '25 pit scheme' conducted in the U.K. over 15 years. During this period, detailed chest x-rays and dust exposure levels of all miners were accumulated, the object being to provide a quantitative link between dust exposure and coal-workers' pneumoconiosis.

Poor correlation was initially obtained when particle number was the parameter used to measure dust concentrations, despite this being of respirable size. It was only after gravimetric sampling was undertaken that good correlation was found between mass concentration of respirable dust (measured by the MRE 113A instrument) and progression of the disease.

This was a major breakthrough because for the first time a quantitative relationship for the health hazard of respirable coal dust was available in terms of a controllable parameter. It was, furthermore, developed not from theory or animal studies but from clinical and environmental evidence gleaned from a group of coal mineworkers in the course of normal work.

The link also provided a logical basis for dust control:-

- establish a link between dust exposure and dust disease
- control that dust parameter which correlates with the disease to an acceptable level
- observe a reduction in the prevalence of the disease with time.

The relationship between silica dust exposure and silicosis has, unfortunately, not received the same depth of study as coal dust. However, there is general consensus that mass is a better indicator than surface area for estimating the harmful effect of respirable silica.

Long-period sampling

Epidemiological studies reveal two factors which are paramount in determining whether or not a mineworker contracts pneumoconiosis:-

- his cumulative exposure to respirable dust
- the time period over which this occurs.

These points are illustrated graphically in **Figure 2** which comprises a set of hypothetical exposure — response curves relating the probability of contracting pneumoconiosis after 25, 35 or 45 years exposure to different mean respirable dust concentrations. For a given exposure period (say 35 years), risk increases rapidly with increase in mean dust concentration (curve AB). However, a miner would suffer the same risk of 4% (point B) whether it was after 25 years at 5 mg/m^3 (point C), 35 years at 4 mg/m^3 (point B) or after 45 years at 3 mg/m^3 (point D).

Dust levels during a shift vary tremendously, so in order to obtain a reliable mean concentration, measurements require the use of a long-period sampler. A full shift is usually considered the most practical period of measurement and this has the advantage of monitoring a mineworker's total exposure.

Gravimetric dust standards

Having discussed the principles of gravimetric dust sampling, it is important to understand how gravimetric dust levels are interpreted, and what degree of dust exposure is acceptable. The answers, of course, depend on what dust standard is permitted. Without benchmark standards, it is difficult to quantify whether or not a given working environment is potentially unhealthy. Conversely, a healthy environment can only be effectively defined in terms of specified levels of pollutants.

Dust levels measured gravimetrically are expressed in terms of concentration by dividing the mass of the dust (mg) by the volume of the air sampled m^3), giving a mass concentration in mg/m^3

Pneumoconiosis is a long-term disease in that it may not appear before 15 to 20 years of cumulative dust exposure. It is daily exposure to respirable dust over many years rather than the occasional peak level in a shift that is most likely to lead to the disease. Respirable dust standards must obviously be formulated on this basis.

However, what are harmful dust levels? Epidemiological studies again provide the answer in the form of the exposure — response curve **(Figure 3).**

There is no evidence that a lower level exists below which respirable dust causes no injury. (The so-called 'zero risk' standard of 2 mg/m^3 legislated for the U.S. coal mining industry does in fact represent a finite but negligible risk).

Gravimetric standards therefore represent a balance between what is considered an acceptable risk (expressed in per cent probability of contracting the disease after a specified time) and the likely impact on the mining industry of adopting that value.

Toxicity

Mine dusts have different health effects on the body depending on their mineralogical or chemical make-up e.g. asbestos, coal, quartz, diesel soot, metal fumes. Different standards therefore apply depending on the type of airborne dust. For pneumoconiosis type diseases, the respirable size fraction is also specified.

Concentration

The amount of dust inhaled in a given time increases directly with concentration. Gravimetric standards are generally expressed in terms of an average concentration over the work shift e.g. 3 mg/m^3.

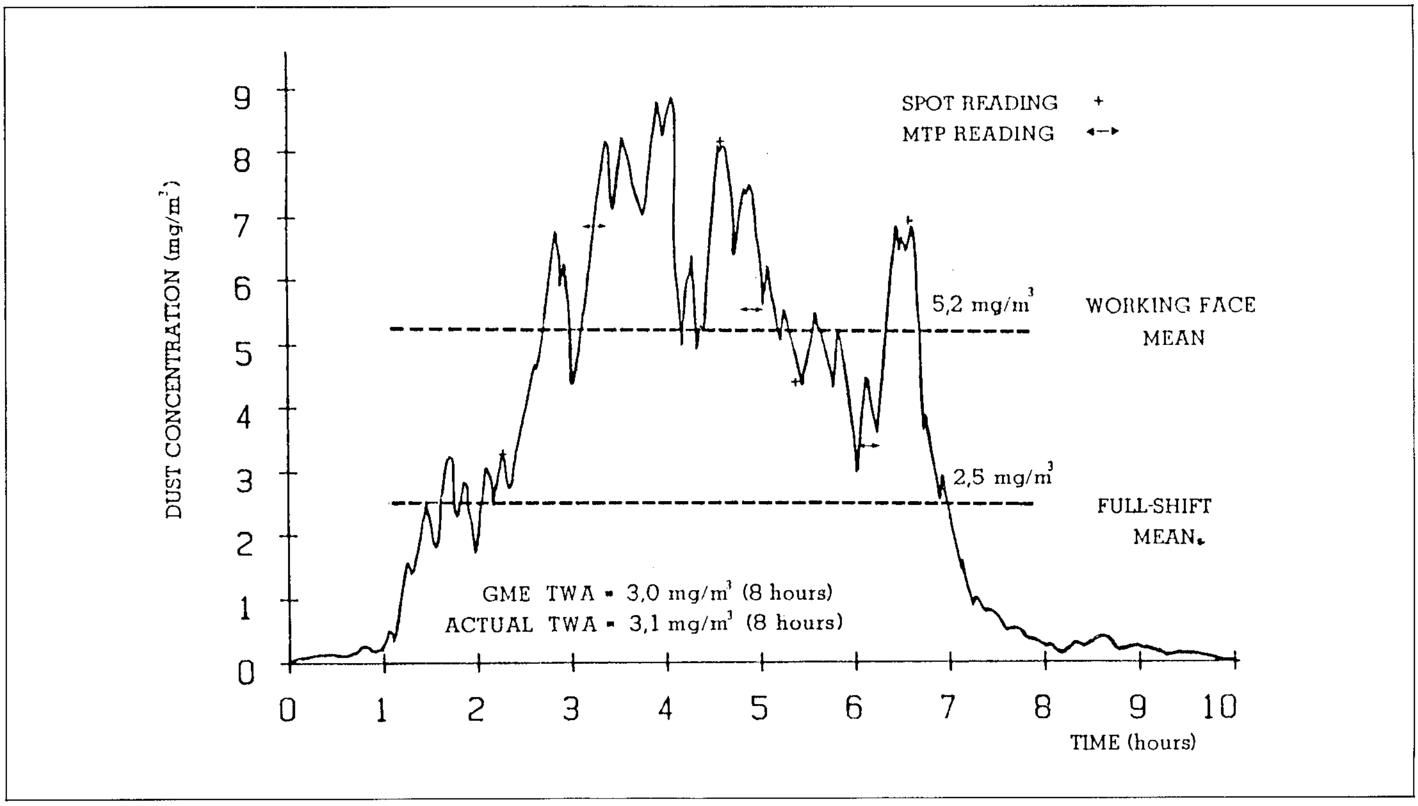

Figure 3: ***HYPOTHETICAL DUST PROFILE OVER A FULL SHIFT ILLUSTRATING THE CONCEPTS OF FULL-SHIFT MEAN CONCENTRATION AND TIME-WEIGHTED AVERAGE (TWA) CONCENTRATION***

Although standards should be set at realistic levels, bearing in mind the degree of dust control attainable with current technology, they should also require a measure of improvement on existing levels i.e. the standard should be seen as a target. Dust standards have historically been tightened as improvements in control technology appear and as social pressures come to bear on mining industries.

Gravimetric dust standards are usually specified in terms of three criteria:-

- toxicity — how harmful?
- concentration — how much present?
- exposure — how much inhaled?

Exposure

The amount of dust inhaled at a given concentration increases with time of exposure to the dust. Gravimetric standards normally refer to an 8-hour shift (40 hour week). Dust concentration and time together give the dust **exposure** or **dose:-**

- Dust exposure = concentration x time

For example, two coal mineworkers whose full-shift mean respirable dust concentrations are 3 mg/m^3 and 4 mg/m^3, but whose shift times (bank-to-bank) are 8 hours and 6 hours respectively, will experience the same dust exposure (24 $\frac{\text{mg.hrs}}{\text{m}^3}$)

Both workers consequently suffer the same health risk from respirable dust, despite the fact that the mean dust concentrations differ.

Clearly, dust exposure can be decreased by:-

- reducing the average dust concentration
- reducing the period of exposure
- a combination of the above two.

The three criteria for gravimetric dust standards are illustrated in **Figure 3** which shows a hypothetical profile of dust concentrations experienced by a miner during his shift.

Assume that the miner collected his personal gravimetric sampler from the lamphouse at 05h30 and returned it at 15h30, still running at a flow rate of 2,0 ℓ/min. After gravimetric analysis, the mass of respirable dust on the filter amounted to 3,0 mg. The following then applies:-

Sampling period = 10 hours

Air volume sampled = 1,2 m^3

Full-shift mean dust concentration $= \frac{3}{1{,}2} = 2{,}5\ \text{mg/m}^3$

Dust exposure (concentration x time) $= 2{,}5 \times 10 = 25\ \frac{\text{mg.hr}}{\text{m}^3}$

Assume, also, that the Government Mining Engineer (GME) has set a respirable dust standard of 3,0 mg/m^3 over an 8 hour period. Are dust conditions within the law?

Maximum dust exposure allowed by GME $= 3{,}0 \times 8 = 24\ \frac{\text{mg.hr}}{\text{m}^3}$

This particular shift is therefore fractionally above what is allowed.

The same conclusion could be reached by comparing the permissable dust concentration, 3,0 mg/m^3 (over 8 hours), with the calculated figure of 2,5 mg/m^3 (over 10 hours), after weighting this to 8 hours (2,5 mg/m^3 for 10 hours is equivalent to 3,1 mg/m^3 for 8 hours). Again, the time-weighted average concentration for the shift is marginally higher than the allowable level, based on the stipulated 8 hour period.

An important point to note is that although the full-shift mean concentration (2,5 mg/m^3) is apparently within the dust standard (3,0 mg/m^3), after weighting for the shift period (10 hours) it actually exceeds the standard. This emphasises the need to assess dust exposure and not just dust concentration.

Several other points are evident from **Figure 3:-**

- dust levels experienced by miners may vary by orders of magnitude during a shift (and even between shifts). A statistical approach is therefore required to obtain reliable estimates of dust exposure
- any attempt to measure dust exposure (or mean dust concentration) with one reading from a short-term sampler (e.g. modified thermal precipitator over 15 minutes, or a konimeter over < 1 second) will lead to totally erroneous results
- any attempt to measure meaningful improvements resulting from dust control measures will require comparisons based on average dust concentrations measured over a good proportion of the shift
- travelling and/or waiting time may be a significant fraction of the total shift period during which the miner is in 'fresh' air. In the example, the working face mean dust concentration of 5,2 mg/m^3 reduces to 2,5 mg/m^3 when averaged over a full shift
- personal gravimetric dust sampling can be used as a cost-effective screening tool to identify dusty sections. In the above example, extra dust control measures are probably not required, although spot dust measurements during the middle of the shift may have created the impression that dust conditions are hazardous.

Summary

The average mass concentration of respirable dust, measured over as long a period as possible, gives the most reliable measure of hazard dust exposure. These three principles of gravimetric sampling form the most rational foundation for programmes designed to measure and control the hazard from long-term exposure to respirable dust.

Gravimetric dust standards, selected on the basis of epidemiological studies that quantify the relationship between dust exposure and dust disease, provide the key to reduce the prevalence of pneumoconiosis in the mining industry.

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