SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

Draft Final Project Report

Title: DUST SAMPLING FOR ENGINEERING CONTROL

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EXECUTIVE SUMMARY

It may be considered to be good occupational hygiene practice to be able to monitor a condition and then be able to act upon the information immediately. In this way the working place can be restored to healthy conditions far quicker than if there is a time delay between monitoring and corrective action because a laboratory analysis is required before samples can be evaluated. In order to be able to evaluate in situ samples a real-time monitor is needed. Real-time monitoring is in itself something of a misconception because once a sample has been collected and evaluated it immediately becomes an historical value. As such, the lapsed time between sample collection and sample reporting, may have little bearing on any perceived required action since the constancy of pollutant levels may be questionable and/or not really known. This project examined dust monitoring techniques, especially real-time monitoring, with a view to implementing engineering controls with a minimum of delay.

There are two broad techniques that may be used to sample the atmosphere for particulate content. These may be summarized as

- indirect methods, which require laboratory analyses before any sample evaluation can take place, and
- direct readings which can be used to evaluate conditions in situ, provided the correct parameter is being monitored.

A review of the instrumentation and methodology reveals several shortcomings, notably with respect to cumbersome equipment, technique, inadequate development and in instances, interpretation difficulties. To address these issues may be overly costly and time consuming.

However, in the interim, the fundamental need to measure dust concentrations for direct engineering control remains.

On the basis of the present study, in conjunction with previous SIMRAC work, a three-fold strategy is proposed. The main points are outlined below.

1. The real-time monitor which appears to be practical at this stage is the pressure differential monitor. Although this monitor has not yet been fully developed or marketed the concept is basic and simple. Experimental work with such a monitor could commence with a minimum of delay since the basic components like filter cassette,

micro-manometer and data logger are all at hand. After a development/testing period a decision could be made as to whether to develop the concept commercially or not.

2. In the past mines made use of konimeters for dust control purposes. Since most mines still have this equipment, the technique could conceivably be rapidly re-introduced. As only trends and not absolute values are required, the techniques could be very usefully deployed at minimum cost to industry. Results need not be formally reported but could be used internally.

3. As an alternative to the konimeter (or in addition) standard gravimetric sampling equipment could be used for control sampling. In a previous research project [1] it was shown that short duration samples (10-15 minutes) are very useful in identifying localities or operations where high dust levels are generated. Consecutive short duration samples are capable of not only indicating trends but also "peak" concentrations.

Whatever technique is introduced in the interim period it is considered important to implement dust sampling for control purposes. If dust is controlled at source, exposure of workers will also be controlled. Should the pressure differential monitor eventually prove to be unsuitable and should no other real-time monitor emerge, then at least some system of monitoring for engineering control purposes would already be in place that could be continued with.

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1. INTRODUCTION.

Before dust sampling or dust surveys are undertaken the reason(s) therefor should be clearly understood. Very often the reason for the sample collection will determine the method or technique to be employed. The main reasons for dust sampling are listed below.

- To determine worker exposure. These are full shift samples and the results can be used to determine personal risk or also for epidemiological studies.
- Occupational sampling. These are similar to the above samples but the results of a number of samples, for a given occupation, are used to estimate exposure levels for a given occupation in terms of an 8-hour Time Weighted Average concentration.
- Activity sampling. The results of a number of full shift samples for a given activity e.g. tramming, lashing rock in workings, etc are used to determine dust levels arising from a given activity.
- Area sampling. Full shift samples are collected by samplers placed strategically within the workings to determine representative dust levels for all persons working within the area. However, the results of a previous project [2] indicated poor correlation between area samples and personal samples.
- Compliance testing. In this application environmental conditions are measured and the results compared with laid down standards.

The above five reasons for dust sampling are all conducted over a full shift and the results expressed in terms of an 8-hour Time Weighted Average dust concentration. The need for a real-time monitor for this type of sampling is thus remote.

A sixth reason to conduct dust monitoring is for engineering control purposes. Such sampling is undertaken to source high dust levels which may emanate from uncontrolled operations or bad workplace practices. Furthermore, the effectiveness and continued effectiveness of control measures put in place should be able to be assessed with this technique. Real-time samples, if realistic and practical to obtain, could be considered for this application. Control dust sampling is thus seen to be the only sampling not expressed in terms of an 8-hour Time Weighted Average.

It is common practice in occupational hygiene assessments that pollutant samples, either dust, gases or vapours, are collected in a specific manner using specific techniques and then returned to an analysing laboratory for evaluation. Thereafter the concentrations of the various pollutants are determined for the conditions as measured, but there are inevitable delays between sampling and evaluation. Notwithstanding any delays for laboratory evaluation, these indirect monitoring methods have been shown to provide valuable information with respect to the determination of dust formed and liberated at specific workplaces or by specific work processes. These indirect methods have also been successfully deployed in ascertaining the effectiveness of control measures introduced to improve workplace conditions.

It is considered that there would be an advantage in being able to make in situ measurements of airborne pollutants, including dust, so that corrective action could be instituted with as little delay as possible. In this way the working environment could be made healthier in less time than the present follow-up system permits. Clearly, the success of direct reading monitors would hinge on how well or how accurately such monitors could detect and report on pollutant levels, and how intelligently such observations were interpreted. Of concern is the fact that almost all the direct reading monitors measure aerosols and not just the dust in question.

There would be a lot of merit in being able to differentiate dust from other airborne particulates. Even if the actual toxic content of the dust was not known, as would be the case if the monitor did not collect a physical sample which could be analysed in a laboratory, the environmental control officer or occupational hygienist would be in a better position than is the case at present, to source any unacceptable dust levels and ensure the implementation of engineering control measures with a minimum of delay.

2. METHODOLOGY

In order to determine what real-time monitors are available a "Dialog" international literature search was conducted over a four-month period. An authoratative book on air sampling was widely consulted and, in addition, local suppliers/manufacturers' representatives were contacted for information. Finally, advertisements in a wide range of journals and trade literature were carefully perused and where instruments of interest were noted the local representatives or the suppliers were contacted.

3. THE PRINCIPLE TECHNIQUES FOR PARTICULATE MONITORING

There are basically seven techniques which can be employed to monitor particulates. They can be divided into indirect and direct techniques.

a) Indirect
- particle counting on glass slides
- personal gravimetric dust sampling

b) Direct
- light scattering (pseudo direct method)
- deposition on a quartz crystal
- beta radiation attenuation on a filter
- deposition on an oscillating filter
- pressure differential across a filter.

3.1 Description of techniques

3.1.1 Particle counting on glass slides (konimeter)[3]

The konimeter is a simple, hand-held sampling device in which the release of a spring-loaded plunger draws a 5 mℓ sample into the instrument through a narrow jet discharging at right-angles and in close proximity to a glass slide coated with a mixture of petroleum jelly, xylol and dioxan. Particles in the air sample are collected by impaction on the slide in the form of a "spot" and after each sample the glass slide is rotated a few degrees to bring a clear space on the slide opposite the jet. Each slide can nominally accommodate 58 samples. The slide is removed from the instrument in a laboratory and treated by

(i) a first ignition at 550°C,
(ii) immersion in hot, 50 percent hydrochloric acid, and
(iii) a second ignition at 550°C.

The above treatment is performed to eliminate carbonaceous matter and soluble salts before the sample spots are identified and counted under a microscope (X150) using dark-field illumination. A graticule with two 18° sectors is positioned over one spot at a time for counting purposes. Only particles inside the two sectors are counted, particles larger than 5 μm are excluded, particles smaller than about 0,25 μm cannot normally be seen at this magnification, and counts are converted to a number concentration per millilitre.

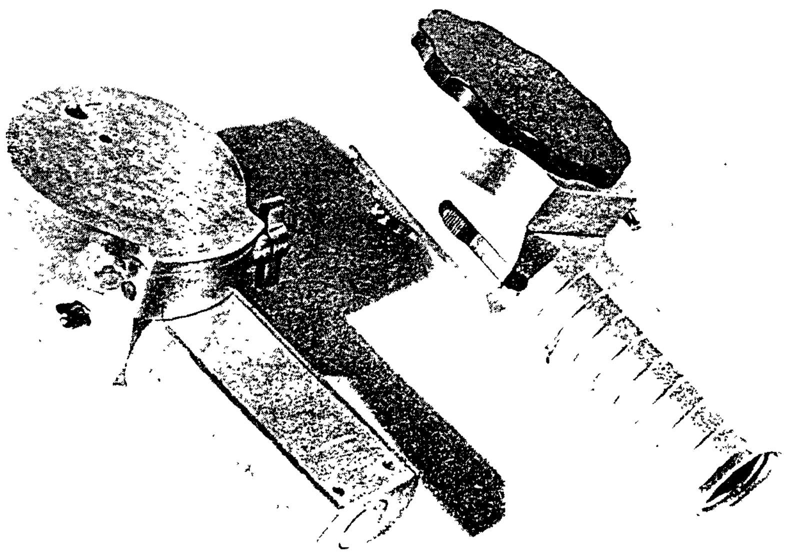


Figure 1. WITWATERSRAND KONIMETER

3.1.2 Personal gravimetric dust sampling

The title personal sampler is non-specific but is taken to mean one of the sets of equipment approved by the Department of Minerals and Energy to measure full-shift exposure. The sampling head incorporates a cassette containing a suitable filter (e.g. glass fibre, silver membrane, cellulose nitrate, etc.), the outlet side of which is connected by a flexible tube to a pump and battery unit, while the intake side is connected to a 10 mm cyclone elutriator. The pump draws air through the sampling head at a fixed flow rate of 1,9 ℓ/min. At this flow rate the elutriator has a retention characteristic defined by the penetration curve for respirable aerosols, published by the American Conference of Governmental Industrial Hygienists [4].

Obviously, full shift samples i.e. 8-hour Time Weighted Average samples, would not present useful data for engineering control purposes because peak values, however high, are averaged in the analysis and thus go undetected and the technique of short duration sampling, proposed in a previous research project[1] would need to be deployed.

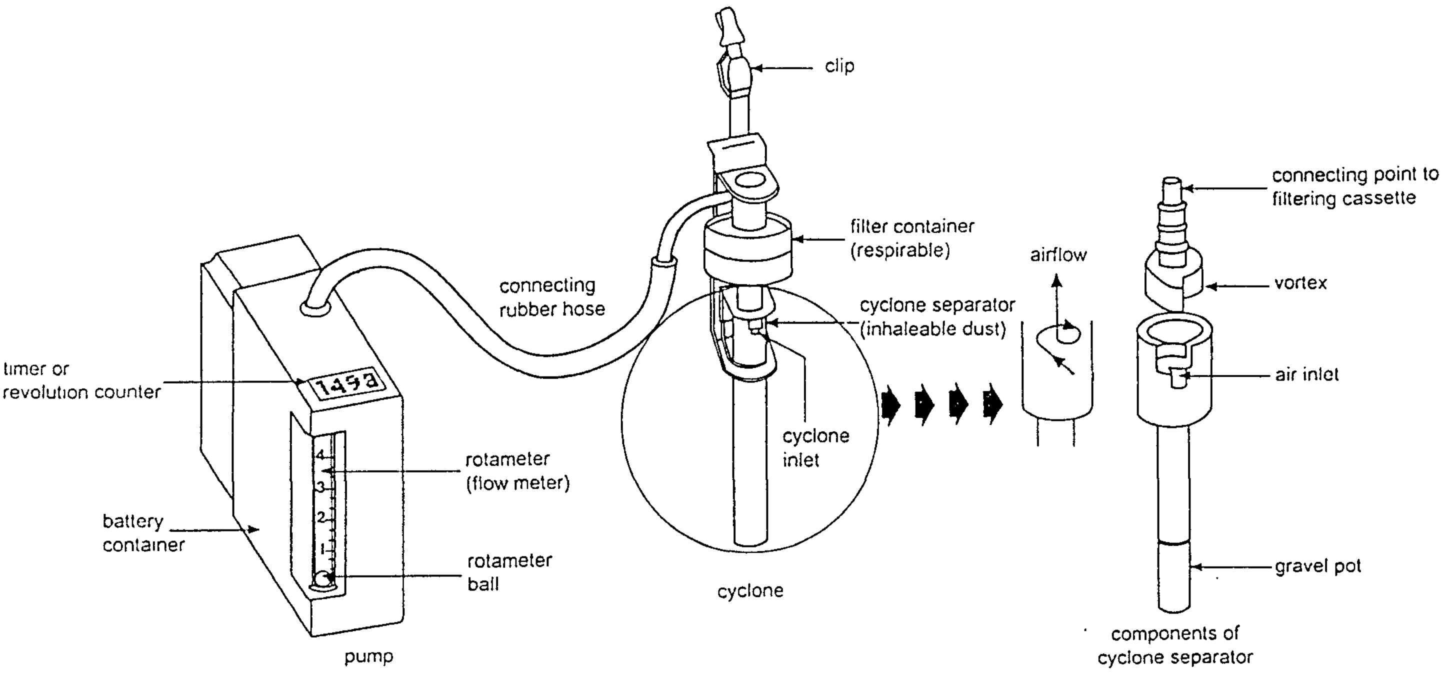


Figure 2. SCHEMATIC ILLUSTRATION OF A TYPICAL PERSONAL SAMPLING PUMP WITH FILTER, CASSETTE AND SEPARATING CYCLONE

3.1.3 Light scattering

SIMSLIN.

This is a light-scattering sampler with parallel gravimetric sampling that was developed in the United Kingdom. It is named after the British research establishment in which it was developed (Safety in Mines Scattered Light Instruments). Infra-red radiation emitted by a small laser diode is focused onto a column of air drawn into the instrument through an horizontal elutriator at a flow rate of 625 mℓ/min. A fraction of the incident light scattered between 12° and 20° to the forward direction by particulates in the sampled air is focused onto a detector to produce a signal proportional to the dust concentration in the column. The detector output is fed through appropriate circuitry to a digital display which is updated every second; a second display shows the cumulative average respirable dust concentration in mg/m^3, updated every 15 minutes. Data from the instrument can be fed into three separate channels simultaneously, namely

- a conventional chart recorder,
- a data transmission line, and
- an internal digital recording system (SIMSTOR).

After passing through the cylindrical photometer unit, respirable dust in the sample stream is collected on a filter for weighing and analysis. Since the filter collects the same dust that causes the scattered light reading, comparison of the values provides a simple method of calibrating the photometer.

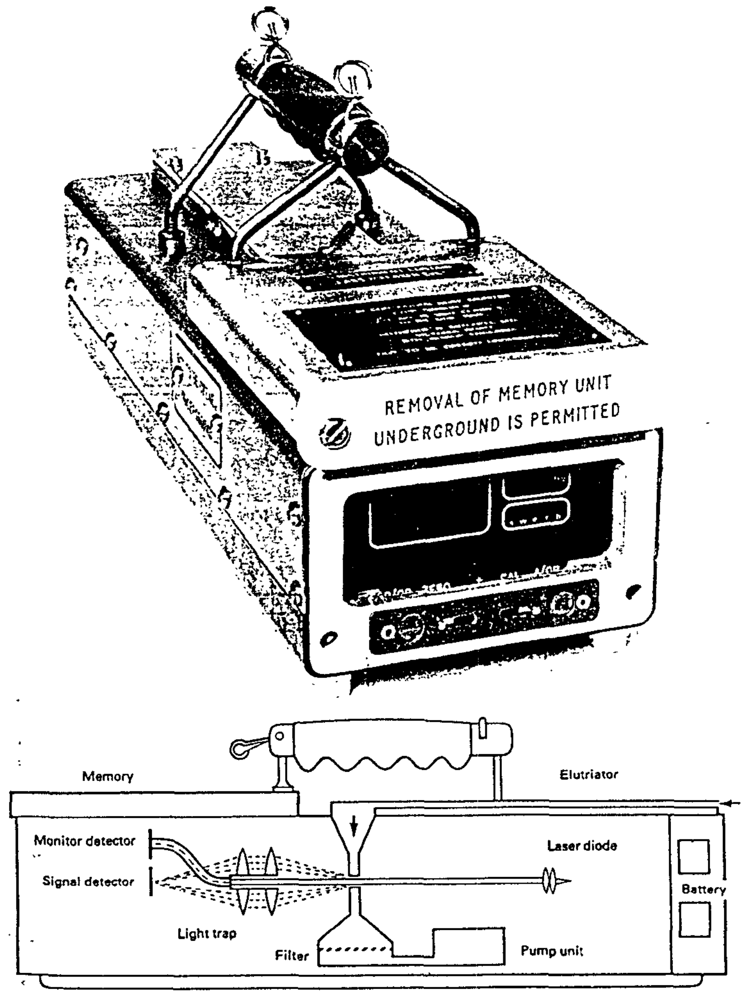


Figure 3. <u>SIMSLIN AND SCHEMATIC ARRANGEMENT</u>

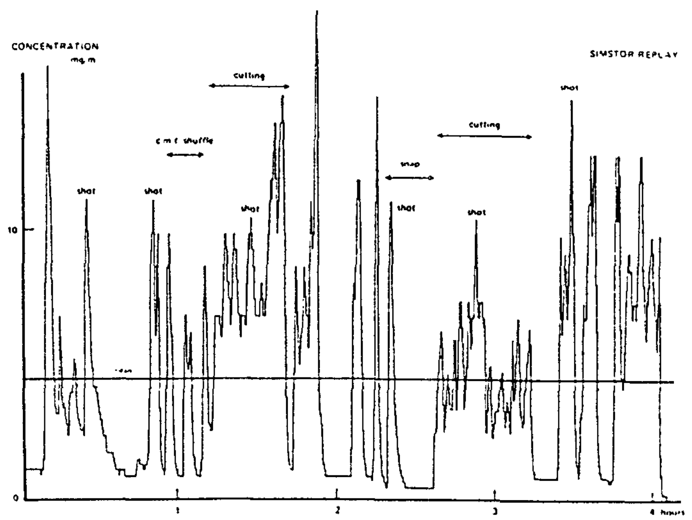


Figure 4. <u>TYPICAL OUTPUT FROM SIMSLIN</u>

Grimm : Laser mini dust monitor

The instrument is used to simultaneously monitor dust concentration and particle size distribution and has a built-in dust collector. Dust laden air is drawn through an isokinetic sampler (1) (see Figure 5), via an optional separating cyclone (9), into the measuring chamber (2) by a pump (3), in a defined volume, onto a filter (8). A laser diode (4) serves as a light source in the measuring chamber. If dust enters the chamber light scattering occurs, which is measured by diode (5). All signals generated from this diode are classified in the pulse-height analyser (6). These results can be corrected by the K-value (correction factor), established from simultaneous gravimetric dust sampling, and displayed digitally every 5 seconds in mg/m^3 (7). The pulse-height analyser (6) can also classify particles by size and indicates the mass in sizes over 1 μm, 2 μm, 5 μm or 10 μm as a dust concentration each second.

All measured values are continuously transmitted to the storage card (10). This card can easily be read in an office or laboratory using an optional slotcard (12) or via the built-in RS 232 cable on a PC. Sampling results can be displayed numerically and graphically. The necessary software program is readily available.

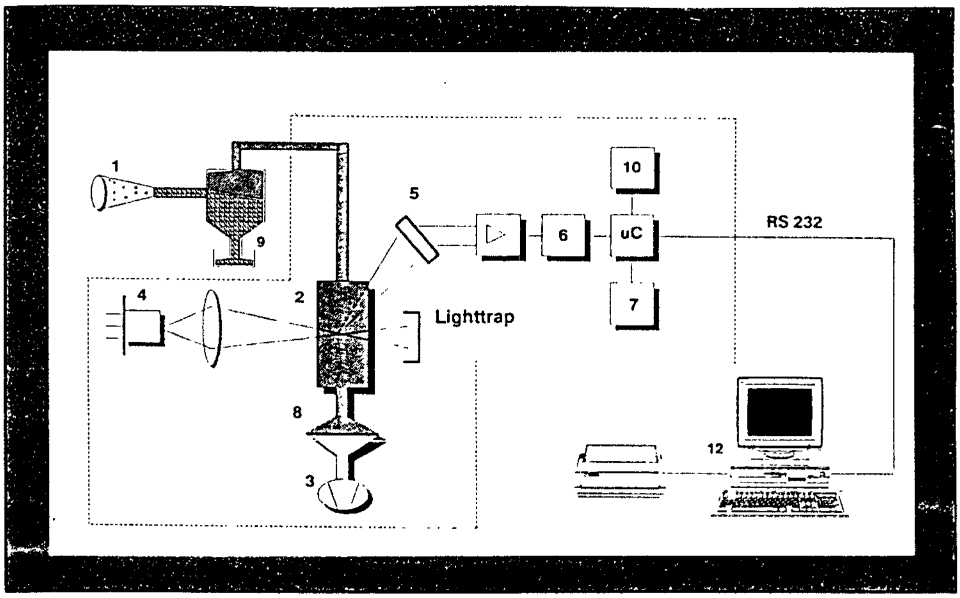


Figure 5. FUNCTION PRINCIPLES OF LASER MINI DUST MONITOR

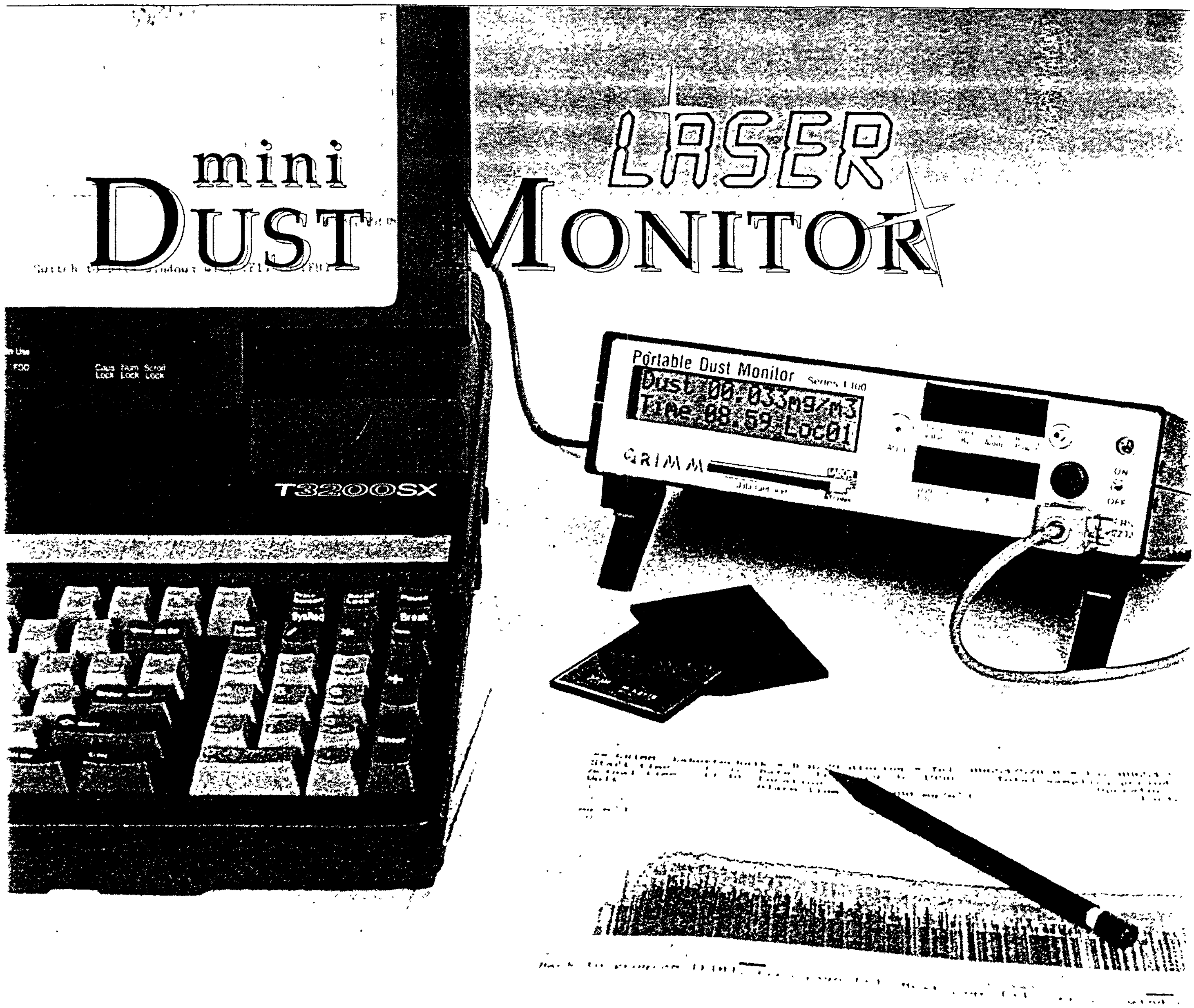


Figure 6. LASER MINI DUST MONITOR

Sigrist dust emission monitor.

If a ray of light falls on pollution in the form of dust, light is diffused in all directions and its intensity can be measured. Because the light is scattered in all directions by the dust particles, the light beam is attenuated as it passes through the air sample. Either the attenuation of the light beam or the scattered light can be taken as a measure of the dust content. The intensity of such stray light emerging nearly parallel to the primary ray (angle of approximately 15°) may be about 1000 times as great as that of the stray light emerging at right angles. This optimum stray light quantity in the forward scatter position permits extremely sensitive dust detections. It is thus possible to register 0.005 mg/m^3 in a measuring range of 0 - 0,5 mg/m^3. The dust emission monitor measures the 15° scattered light to determine the concentration of the dust particles and is thus classified as a 15° scattered light photometer.

The intensity of the stray (scattered) light produced is not dependent only on the number of dust particles present, but it is also affected by the degree of homogeneity and heterogeneity in their composition. Measuring processes using forward scattered stray light are subject, as a rule, to considerable distortion caused by the primary source, when compared to methods utilizing light diffused at right-angles. Since such primary light distortions are themselves not constant, they can only be eliminated to a restricted degree by electronic compensation.

This monitor eliminates all but a minimum residue of distorting primary light by means of an appropriate optical layout. The residual distortion is lower than the amount of stray light that could be caused by dust concentrations of 0.02 mg/m^3. The amount of stray light produced is directly linearly proportional to the amount of dust, so that measurements recorded over a given period of time can be integrated.

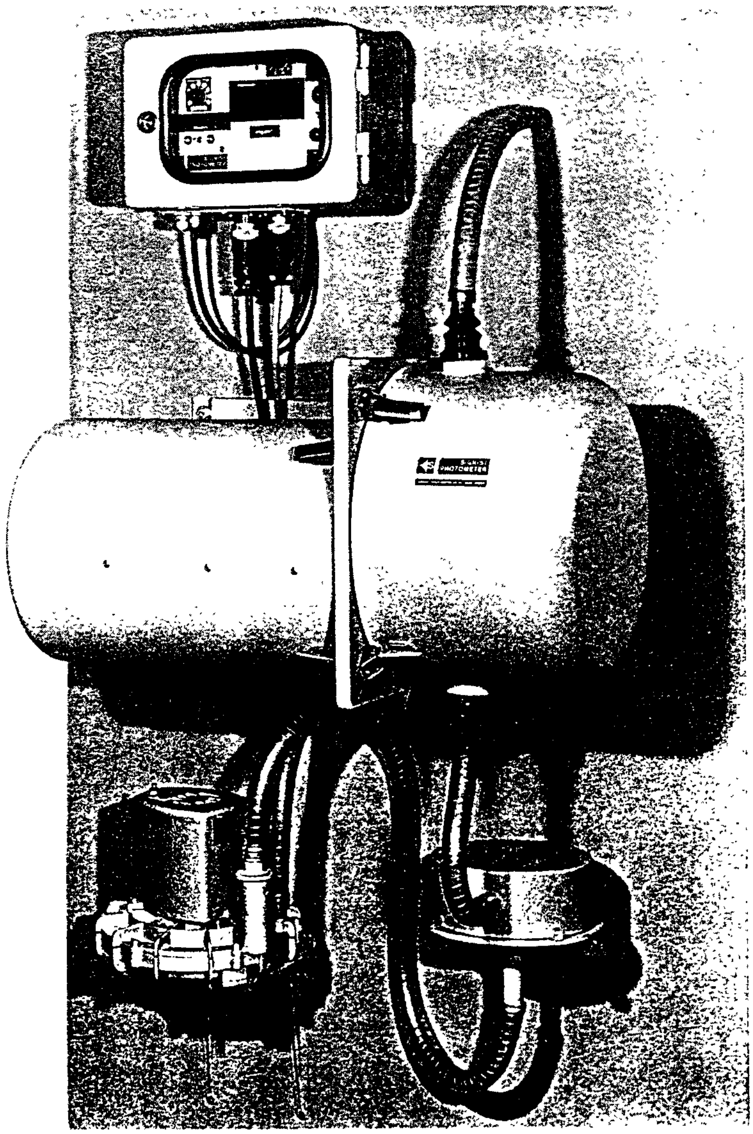


Figure 7. SIGRIST DUST MONITOR

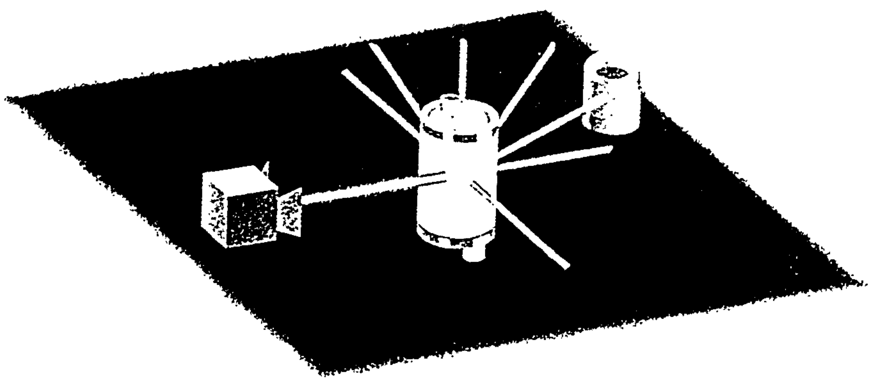


Figure 8. MEASURING PRINCIPLE OF SIGRIST DUST MONITOR

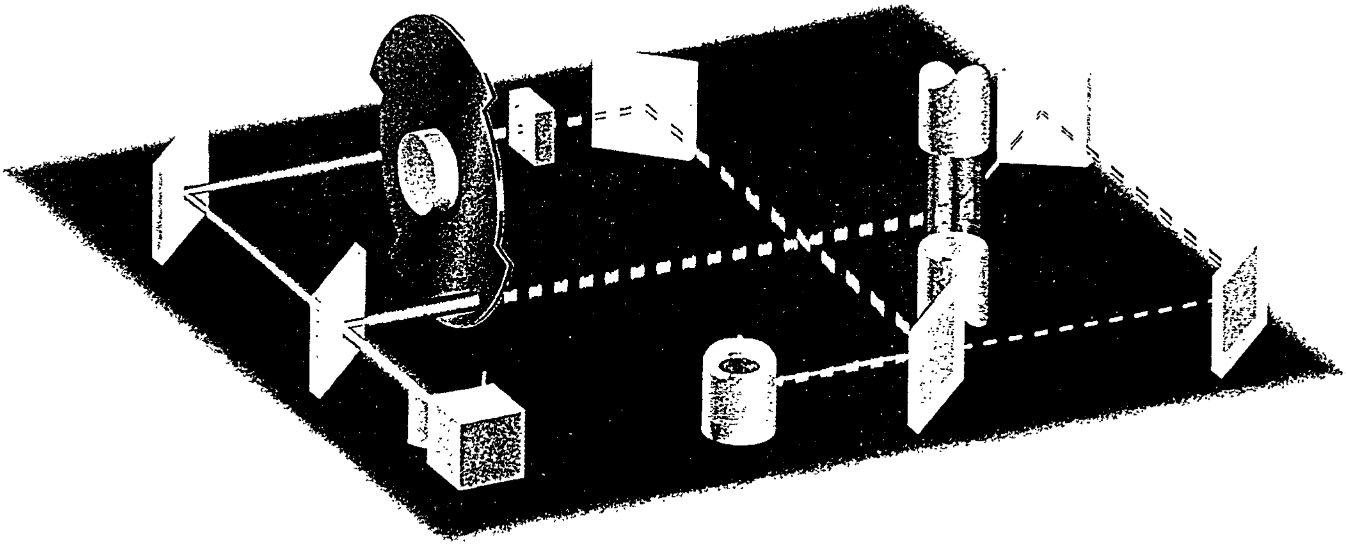


Figure 9. MEASURING METHOD OF SIGRIST DUST MONITOR

This emission monitor employs an alternating light dual beam method. The light beam produced by the light source is divided into two beams by a semi transparent mirror. One beam enters the sample, where the dust particles create scattered light in all directions. The 15° scattered light serves as the measurement signal. The other beam passes through a stable standard which then provides the reference signal.

A chopper disk lets the measuring beam and the reference beam through to the photodetector, alternately. The chopper disk also has a third position in which both beams are blocked; this is the zero value.

The photodetector thus receives three signals one after the other, namely

the measurement light with zero value,
the reference light with zero value, and
the zero value alone.

Identical amounts of light will result in steady direct current. If the signals are unequal, the direct current produced by the photocell pulsates. The microprocessor calculates the reading from these three signals. This measuring method of using just one light source and one photodetector eliminates measuring errors resulting from ageing of the components and should provide long-term stability.

TM digital (Hund)

This is a sophisticated version of the tyndalloscope widely used in German coal mines for many years. In essence, a beam of monochromatic light with a wavelength of 94 nm passes along a sensing chamber open to the atmosphere. The presence of airborne particulates in the path of the beam causes the beam to scatter and the intensity of the scattered light at a measuring angle of 70° with respect to forward direction, is measured with photocells and displayed on a digital readout. This arrangement assures the measurement of respirable particles in the airborne dust. A uniform accuracy of 0.01 to 99.99 units of intensity from the forward scattering ensures the registering of respirable particles without the necessity for preliminary separation of coarse particles. The instrument is designed to give a volume-proportional signal related to the concentration of fine dust in the beam according to its deposition probability in the human lung.

The instrument is zeroed by filling the chamber with filtered air and is calibrated with a standardized light-scattering device. Averaging takes place over random intervals of between 5 seconds and approximately 8 hours (max) in battery mode. Continuous measurement of current values takes place every second. There is also continuous output of the analogue measured signal as an impressed voltage within the range 0 - 4 V with simultaneous averaging. The flow through the measurement chamber is isokinetic. The unit is either battery or mains operated and software for the production of output graphs is available.

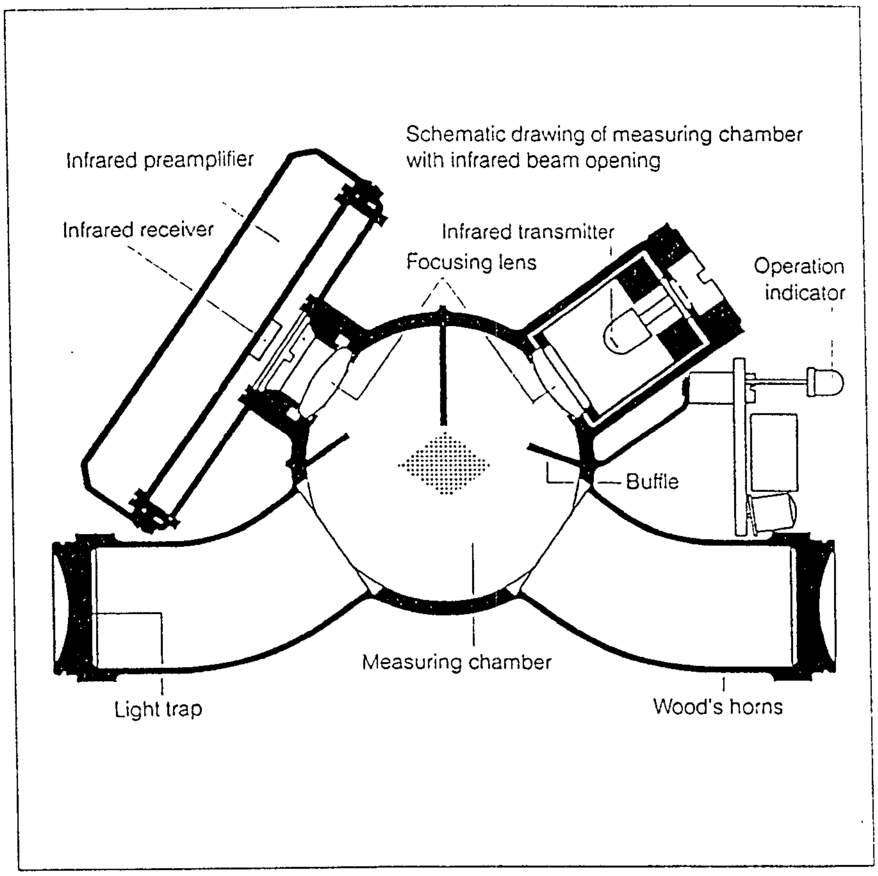
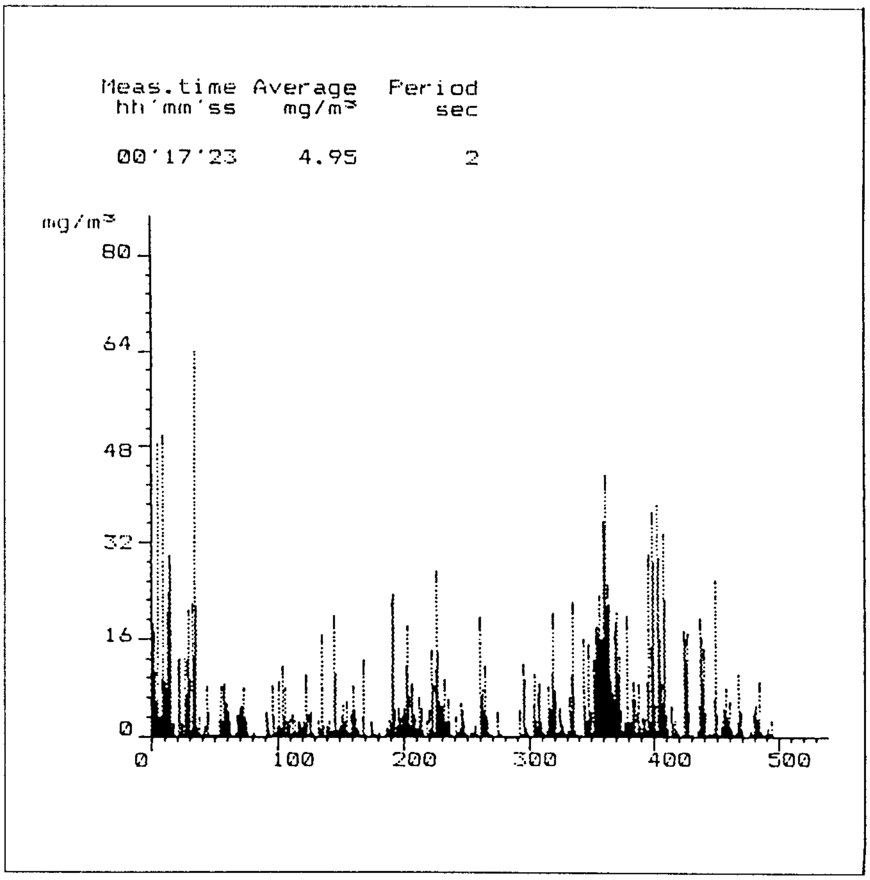


Figure 10. PRINCIPLE OF MEASUREMENT OF THE HUND TYNDALLOMETER



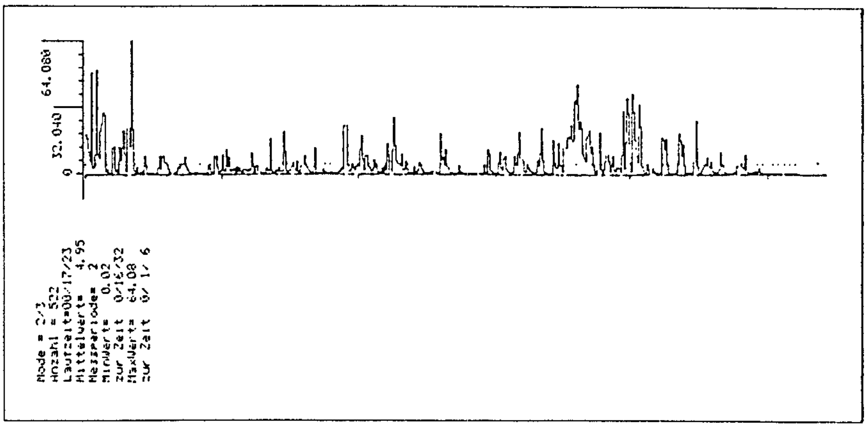


Figure 11: TYPICAL OUTPUT FROM THE HUND TYNDALLOMETER

Figure 12. <u>HUND TYNDALLOMETER</u>

Hand-held aerosol monitor (HAM) - HAM tyndallometer

The general principle of operation of the hand-held aerosol monitor (HAM) is light scattering by small particulates which are detected and related to mass concentration. The general arrangement is shown in Figure 13.

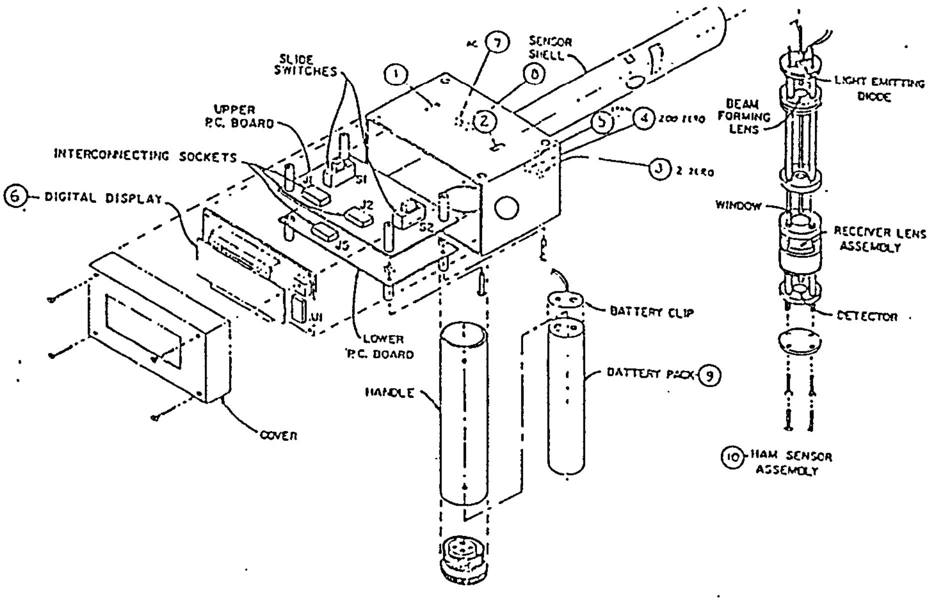


Figure 13. <u>GENERAL ARRANGEMENT OF HANDHELD AEROSOL MONITOR</u>

According to Mie theory for light scattering by spherical particles of arbitrary size and composition, the power scattered into unit solid angle by a single particle is dependent on particle size, composition and scattering angle, and the collection solid angle of the optical system (in steradiens).

Figure 14 shows the dependence on the particle diameter for forward scattering at 5° by a water droplet. Three distinct regions are evident, i.e.

- d^6 for d<0,1 μm
- d^3 for 0,3 μm <d < 2 μm, and
- d for d > 2 μm.

In the second region, or d^3, the scattering roughly follows a volume relationship. Therefore, for a constant particle density, the scattered power is approximately proportional to particle mass.

The HAM instrument was designed to collect forward scattered light at 10-15°. This narrows the region of mass response slightly.

To extend the scattering result to polydisperse particles, a lognormal distribution is weighted by the scattering from individual particles. Integrating over an entire distribution with a particular mean diameter and geometrical standard deviation gives the total scattered power per unit incident intensity. Dividing by the third moment or volume of the distribution produces response per unit volume.

The HAM can be used to evaluate aerosols directly or from within a system such as a duct by drawing the gas through the sampling head by means of a pump. Having passed through the head, the gas can then be passed through a standard filter for mass and compositional evaluation, analysis and calibration of the instrument.

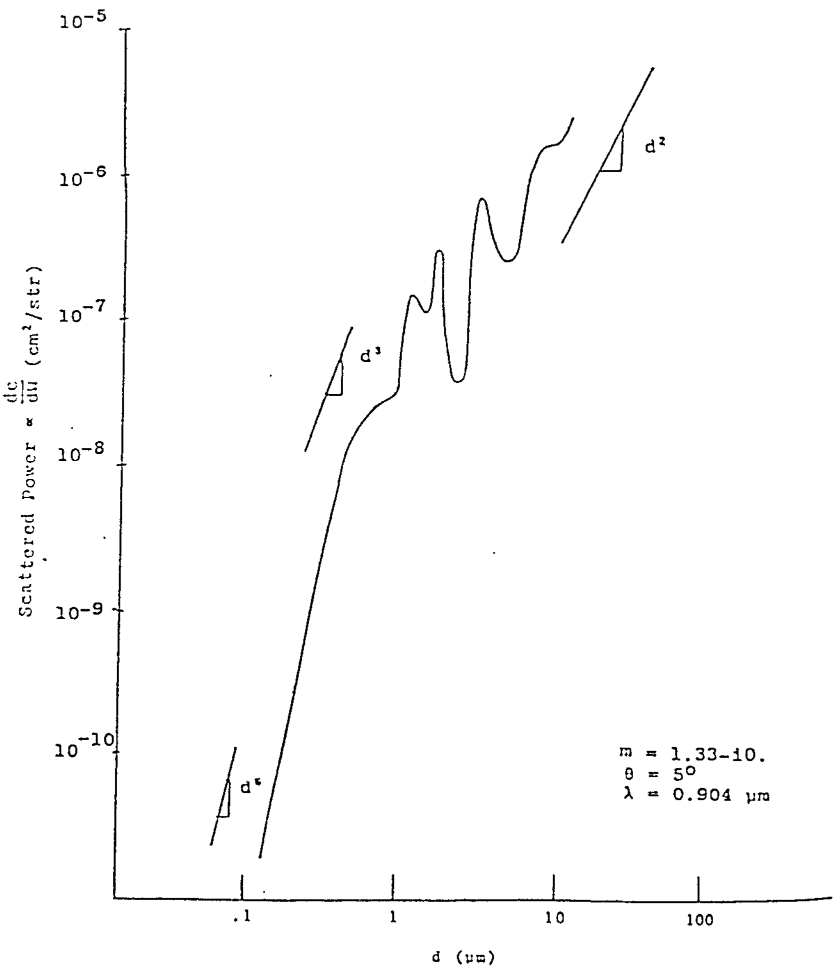


Figure 14. FORWARD SCATTERED POWER VS DIAMETER OF PARTICLE

Casella airborne particulate monitor

This instrument is similar to other light scattering monitors. It makes use of a beam of infra-red light projected forward into a measuring chamber. The light within the chamber is blocked from reaching the receiver by a modified Woods horn. When dust particles pass through the measurement chamber the light beam is scattered forward within a narrow angle to the receiver. The narrow angle of the scatter reduces the instrument's sensitivity to variations in the refractive index of measured particles.

Features of this monitor are listed below

- hand-held
- stainless steel probe
- twin purge on probe to assist in preventing inaccurate readings through the build-up of contamination on the optical lenses
- choice of ranges 0.01 - 19.99 mg/m^3 & 0.1 - 199.9 mg/m^3
  or 0.1 - 199.9 mg/m^3 & 1.0 - 1999 mg/m^3
- high sensitivity ± 10 μg/m^3

A standard cyclone is used to separate coarse particles and a standard gravimetric dust sampling pump is used to aspirate the instrument.

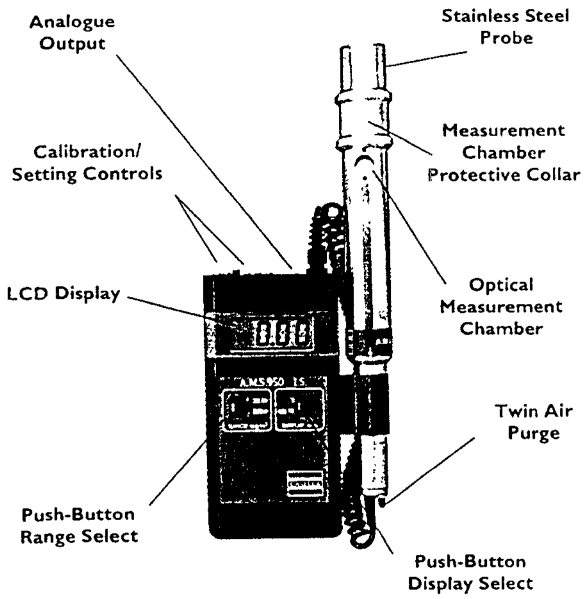


Figure 15. <u>CASSELLA AIRBORNE PARTICULATE MONITOR</u>

3.1.4 Deposition of dust on quartz crystal

The TSI mass monitor measures the respirable mass concentration of airborne particulates deposited on a quartz crystal by electrostatic precipitation from an aspirated sample stream[3]. The change in resonant frequency of the piezoelectric crystal is monitored continuously to detect the increased mass loading on the crystal, and the output is processed internally to give respirable mass concentrations on a digital readout. A second crystal, not exposed to the sample stream, compensates for frequency changes induced by temperature, pressure and humidity variation. The instrument does not use a radioactive source and is insensitive to materials being sampled i.e. welding fumes are monitored as accurately as quartz dust. Airborne particulates in the size range 0.01 μm to 10 μm and in the mass concentration range 0.01 mg/m^3 to 10 mg/m^3 are collected and monitored. An internal calibration check allows accuracy to be checked during each measurement without the need for a standard source. Pollutant concentration is displayed every 10 seconds.

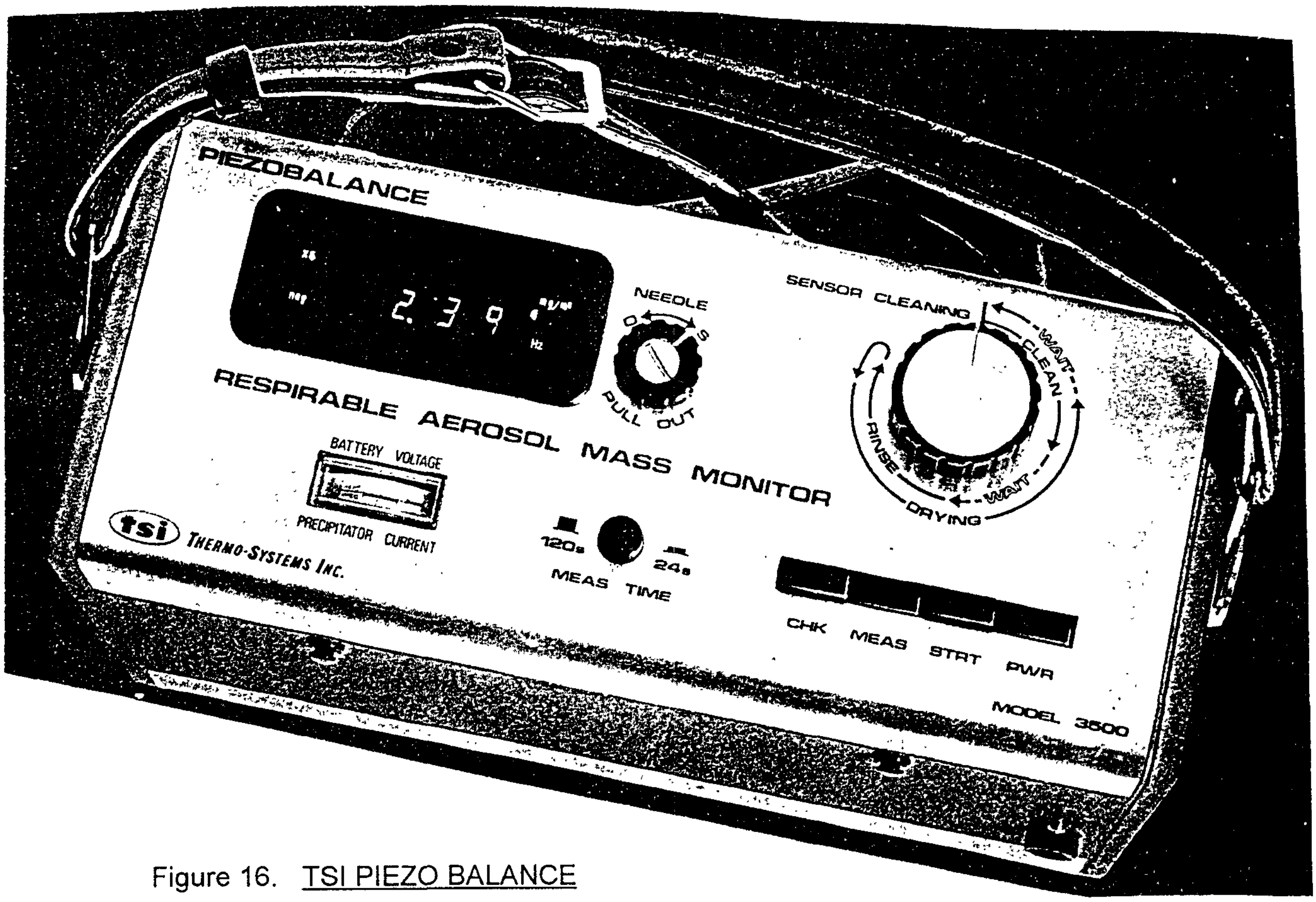


Figure 16. TSI PIEZO BALANCE

3.1.5 Beta Radiation attenuation on a filter

When β radiation (i.e. high energy electrons) passes through matter a certain fraction of the incoming radiation is attenuated, primarily owing to absorption. For β particles with energies less than 1 MeV the absorption mechanism is inelastic collision with orbital electrons. Thus, the correlation of the attenuation with mass depends on the relationship between the number of electrons per atom (atomic number) and the mass of the nucleus (atomic mass). The ratio of atomic number to atomic mass for naturally occurring elements, except hydrogen, is between 0.4 and 0.5. Accordingly, the attenuation of the β particles with energies less than 1 MeV is essentially independent of the chemical composition and depends only on the area density of the absorbent material[(5)]. Samples are collected at 1.2 m^3/hour (0.0003 m^3/s) for a preselectable time period, which can range from 15 minutes to 12 hours. The filter strip is then advanced to a new position. During the collection period the attenuated β radiation (from a Kr^{85} source) through the deposition area of the filter strip (1.34 cm^2), is monitored by an ionization chamber. Using suitable electronics the output of the instrument at any instant of time is made proportional to the attenuation and it is recorded. At the beginning of each sampling period, the mass of the filter is balanced out by a separate sensor.

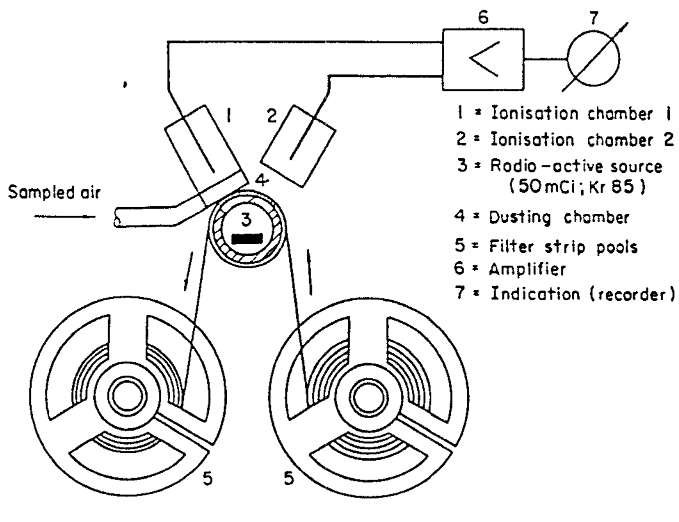
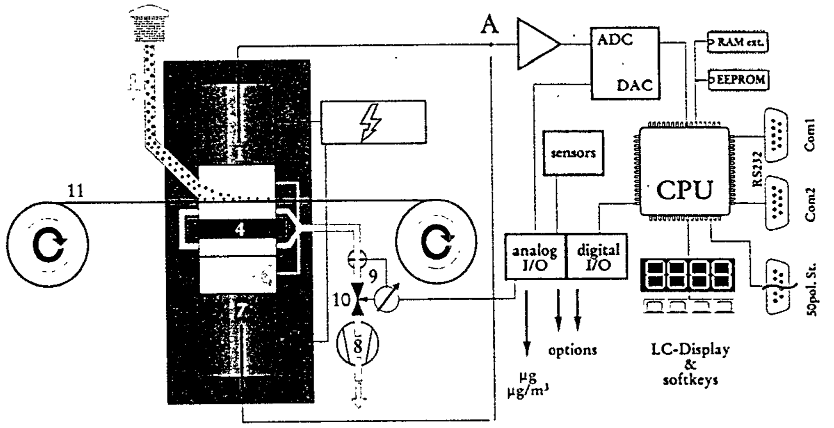


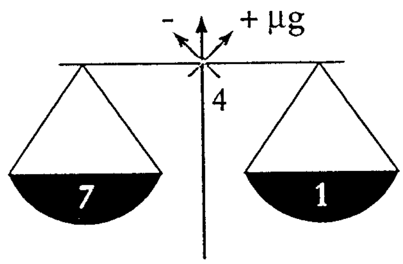
Figure 17. <u>SCHEMATICS OF THE β RADIATION PARTICULATE MASS MONITOR</u>

The Eberline particulate monitor

This particulate monitor utilizes the radiometric principle of β attenuation by a two-beam compensation method. The β source, Krypton-85, is orientated in such a way that two β beams (180°) emanate from the source. One beam passes through the measuring path and the other through the compensation path. The compensation path (4-5-6-7) serves to reduce the different influences e.g. ambient temperature, and pressure fluctuations, during the measurement (Figure 18). In the measuring path the particulate sampling in the measuring chamber is done between the β source and the measuring ionization chamber (4-2-1). Owing to this process a high measurement of stability is achieved, because for each measurement value a reference value is determined in a separate measuring section. This reference section is interconnected physically with the measurement section, with an equal effect from ambient temperature and pressure, which is a basic condition for precise and steady compensation. Ambient air is drawn through the sample system and dust particles are deposited on the filter. The accumulation of the dust mass is measured and indicated simultaneously. This continuous accumulation of a dust layer weakens the intensity of the β-ray in the measuring path and changes the ionization current. The electric signal at output A increases. The ionization currents produced in the two ionization chambers are combined to give a differential signal, which passes over an amplifier to the microprocessor and the output signal is provided as analogue as well as digital and the continuous and compensated signal ("arm balance") is displayed.

The supply voltages of the ionization chambers (1 and 7) are of opposite polarities, since output current number 1 supplies a positive signal and number 7 a negative signal.





1 *Measuring ionization chamber*
2 *Particulate collection and measurement*
3 *Vacuum chamber*
4 *Beta source*
5 *Compensation chamber II*
6 *Compensation chamber I*
7 *Compensation ionization chamber*
8 *Vacuum pump*
9 *Air flow rate measurement*
10 *Air flow rate control*
11 *Filter tape*

Figure 18. OPERATION OF THE EBERLINE PARTICULATE MONITOR

Size selective inlets

For ambient air particulate measurements the influence of particles for health-related criteria several size selective inlets can be connected at the sampling tube of the FH 62 I-R.

TSP sampling inlet
(1 m^3/h)
for total suspended particulate measurements/inhalable particles

Inhalable sampling inlet PM-10
(1 m^3/h)
for fine dust particles < 10 μm aerodynamic diameter/thoracic

Fine sampling inlet PM-2.5
(1 m^3/h)
for fine dust particles < 2.5 μm aerodynamic diameter/respirable

Sampling inlet PM-1.0
(1 m^3/h)
for fine dust particles < 1.0 μm aerodynamic diameter/respirable

Preseperation cyclone Z4
(1 m^3/h)
for work place monitoring according the requirements of the Johannesburg Convention

Heated sampling tube
(option)

For gentle heating of the sampled air the inlet is temperature controlled. Due to possible condensation in the sampling tube or instrument, an inlet heater can be used selectable to remove high relative humidity effects.

Figure 19. THE EBERLINE PARTICULATE MONITOR

3.1.6 Deposition of dust on an oscillating filter

The development of this instrument was undertaken under contract to the United States Bureau of Mines (USBM)[6]. The sensor was called "The Resonant Filter Membrane Mass Monitor" (RFM3). Its objective was to measure the mass of dust, in real time, collected on a vibrating filter. The sensor was designed around the principle that the frequency of the oscillating filter would shift in direct proportion to the mass of the dust deposited on the filter.

Figure 20. COMPONENTS OF THE RESONANT FILTER MEMBRANE MASS MONITOR (RFM3)

A second system developed in the same programme of work uses a tapered element oscillating microbalance (TEOM) as the principle of measurement. It uses a filter mounted on the end of a vibrating element. As dust is collected on the filter the frequency of oscillation of the element changes in direct proportion to the mass of dust collected on the filter. Because of the sensitivity of the sensor, real-time mass concentrations can be determined in a matter of minutes.

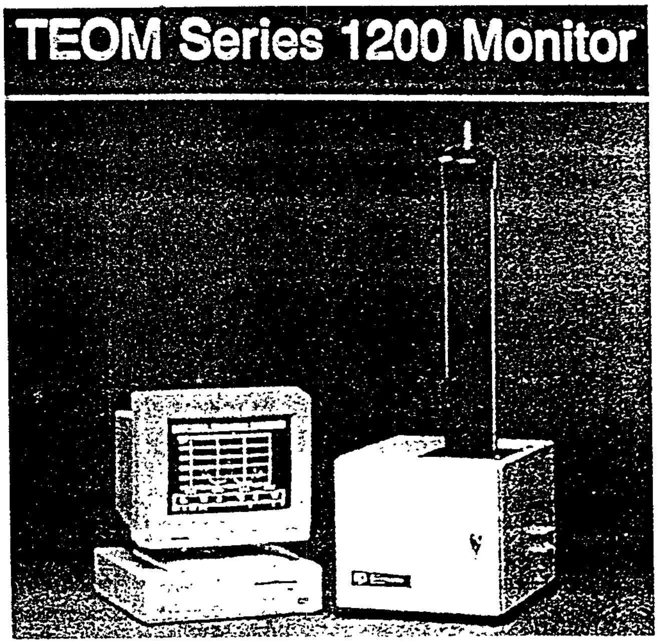


Figure 21. COMMERCIALLY AVAILABLE TAPERED ELEMENT OSCILLATING MICROBALANCE

3.1.7 Differential pressure as a means of estimating respirable dust mass on collection filters

The USBM [(7)] has studied various types of respirable dust sampling filters to determine if the differential pressure across them at a constant sampling rate can be used to estimate accumulated dust mass. Results suggest that glass fibre depth filters that allow the dust particles to penetrate well into the filter material, have considerable merit.

The correlation between differential pressure and dust mass using 37 mm glass fibre filters is linear provided they are loaded with not more than approximately 5mg of dust. Under these conditions the relationship between differential pressure and dust mass can be approximated by the equation $\Delta p = 24.91\ (M)$ where Δp is measured in Pascals and M is dust mass in mg. Most of the data fall within ± 25 percent of the regression line and have a correlation coefficient, R^2, of 0.89. The density of the dusts tested varied from approximately 1.3 to 2.5 kg/m^3. Particle size effects were studied using cyclones to load different filters at three different flow rates to provide three relative particle size distributions from common dust environments. The resulting differential pressures were then measured at a flow rate of 2 ℓ/min.

4. DISCUSSION

4.1 Aerosols

Since all the instruments described essentially sample aerosols a brief discussion on aerosols is deemed to be appropriate. An aerosol consists of particles and the gas in which they are suspended. Technically, the word aerosol should only be applied to describe a dispersion of solid or liquid particles in a gas.[8] It has, however, passed into more common use to describe pressurized airspray cans used for dispensing such domestic products as paint, hair lacquer, or insecticides. These latter two products can be ignored in the workings of mines. The toxicologically significant classes of aerosol are named and defined below [8] for the purpose of understanding exactly what may be indicated by the various monitors available.

(a) Dusts

Aerosols consisting of inorganic or organic solid materials are called dusts and vary widely in particle shape and size. Dusts are formed by mechanical disintegration of a parent material by grinding, sanding, sawing, drilling, handling, transporting and blasting. If the particle shape is roughly spherical the dust is called compact (e.g. coal dust), otherwise it is called fibrous (e.g. asbestos, cotton). The significance of the shape lies in the influence it has in determining particle behaviour and destination in the body. Particle shape and size are thus critical factors.

(b) Fumes

Fumes are collections of particles suspended in a gas (usually air) the size of each of which is below 0.1 μm. Their formation by combustion, sublimation or condensation is usually accompanied by a chemical change such as oxidation. The commonest fumes of significance toxicologically are those associated with oxides of metals.

(c) Smokes

Smokes are collections of particles which are below 0,5 μm in size. Smokes are formed during the combustion of organic materials and arise from incomplete combustion.

(d) Mists and fogs

Mists and fogs are liquid droplets formed by the condensation of vapours or the atomization of liquids around particulate nuclei in air, or by the uptake of liquid by hygroscopic (i.e. absorbent) particles.

All aerosols are temporally unstable, i.e. they experience change with the passage of time. Some important aerosol characteristics which can change are

- total mass concentration of a contaminant (sum of mass concentrations in the vapour and particle phases),
- fraction of a contaminant in the particle or vapour phase, and
- particle size distribution.

A wide variety of aerosol instabilities must be considered in air sampling because they may influence sampling strategy, the occurrence of artifacts in samples and extrapolation of measured aerosol characteristics to earlier or later times.

4.2 Real-time aerosol monitoring

Real-time aerosol monitoring instrument usage in the occupational health field has increased over the last 20 years [9]. Much of this increased usage is due to the availability of more sophisticated and well-characterized instruments. However, for a wide variety of reasons, these instruments are not used as much as they might be. Some difficulties stem from the wide range of particle sizes that can be found in industrial settings. The particle diameter can range from 0.001 μm for condensation nuclei to 200 μm and more for dust particles thrown into the air. If there is an interest in the mass of these particles, the range covers 15 orders of magnitude. Whereas in the workings of mines there is little interest in particles greater than 10 μm the range of masses in mine workings still covers several orders of magnitude. There are many physical mechanisms including diffusion, convection, impaction, gravitational settling, electrostatic drift, condensation and evaporation that can govern the behaviour of particles.

The importance of these various mechanisms changes in different parts of this large size range. Thus, it is rare to find instruments that can operate effectively over more than two orders of magnitude in particle size. In addition, particles in the workplace can have a range of chemical properties. To effectively measure workplace aerosols, **it is necessary to determine the aerosol and the appropriate aspect of the aerosol that is to be measured.** For occupational hygiene purposes, this typically means relating the aerosol measurement to the aerosol toxicity. In spite of all the potentially confounding variables, it is often possible to use relatively simple and limited

instruments to provide useful information. The single most common aerosol measurement in workplaces is respirable dust mass. An instrument that has a usable response in the 0.2 - 10 μm size range can be adequately tailored for these types of measurements. Apart from the physical aspects of an aerosol, there are a number of other reasons why real-time monitors are often not used. First of all, **there are very few aerosols present in today's work environment that pose an immediate danger to health**. This means that the immediacy of information is not as critical as it is for some gases, for example.
Quite often a toxic aerosol is a component or small part of the aerosol present and a **species-specific method of detection is required**. No direct-reading aerosol instruments meeting this requirement were found.

There are some physical aspects of the instrumentation itself that prevent its widespread use. There is no simple, rapid aerosol detector equivalent to the detector tubes used for gases, except the Sartorius konimeter which features a suitable microscope integrated into a konimeter sampling arrangement and which permits a particle count to be made immediately after the sample collection. It could not be established if this instrument is still being manufactured. Most of the available instruments are burdened by high initial costs and a number of instruments have suffered reliability problems in field use, thus creating a negative attitude among users. Furthermore, the complexity of aerosol properties and behaviour, combined with the necessity to interpret the dynamics of the workplace air, militate against attempts to make real-time measurements.

4.3 INDIRECT MONITORING

These are typically methods that require laboratory evaluation before any assessment of airborne dust conditions can be done. However, since the aerosol of major concern, dust from the various mining operations (e.g. gold, coal, etc), does not pose an **immediate** threat to workers' health, a delay of a few hours for sample assessment should not be seen as a serious disadvantage. There are many instances, in keeping with good, world-wide occupational hygiene practices, when laboratory evaluation of samples is not only unavoidable but totally necessary and even desirable. Such instances may include gas analyses, particularly less common but highly toxic gases, urine and blood analyses. High toxic levels in any of these latter samples are likely to be much more life threatening than high respirable dust levels in the immediate short term, but instantaneous evaluation is neither possible nor available yet.

4.3.1 The konimeter

Until the recent introduction of gravimetric sampling dust sampling was extensively conducted in non-coal mines, using konimeters. Essentially, this type of sampling was conducted to determine workplace dust levels, to source unsatisfactory dust levels, to determine the effectiveness of measures introduced to control dust emissions and to study trends [(10)]. The technique was not suitable for determining personal, full shift exposures because of the very short sample collection time - each "spot" sample was collected over about 0.25 seconds. Used in a structured test this sampling instrument can be used to determine dust levels at specific operations and to determine trends in dust emissions at such operations. As already noted, exposure to high concentrations of dust does not pose an immediate threat to health since there is a long latency period for any effects. Therefore, reasonable delays in evaluating results can be tolerated. In addition, most mines are still equipped with these instruments and dust sampling for engineering control purposes could be introduced with a minimum of delay. The results of such sampling need not be formally reported but used only for internal purposes.

4.3.2 Gravimetric dust sampling

The standard equipment is capable of providing full shift sampling at a constant flow rate of 1.9 ℓ/min. The results of such sampling are well suited to epidemiological studies and occupational dust exposure investigations. Because the result of the sampling is an eight-hour **average**, any high peak concentrations go undetected, thus rendering the present technique unsuitable for control purposes. However, it was shown in a recent research project [(3)] that if the standard equipment is deployed over much shorter time intervals, i.e. 10 to 15 minutes, the source of high concentrations can readily be identified. With conscientious observation the reasons for the high dust levels can usually be noted and reported (see Figure 22 for an actual example on the use of short duration sampling, the high dust levels reported and the observer's comments). Even though the laboratory evaluation was only available 24 hours after the sampling, the results of malpractices observed could be confirmed, quantified and

LOCALITY		STOPE 2	
Position	Ref.	Dust Concentration mg/m^3	
Return			
Face	1	1,67	
Face	2	2,15	
Face	3	6,53	
Face	4	30,67	
Face			
Face			
Ave. face		10,26	
Old area	5	2,12	
Old area	6	1,60	
Old area	7	1,87	
Ave. old area		1,86	
Intake			
Intake			
Traverse		1,48	
Integrated		1,42	
Full shift		1,35	

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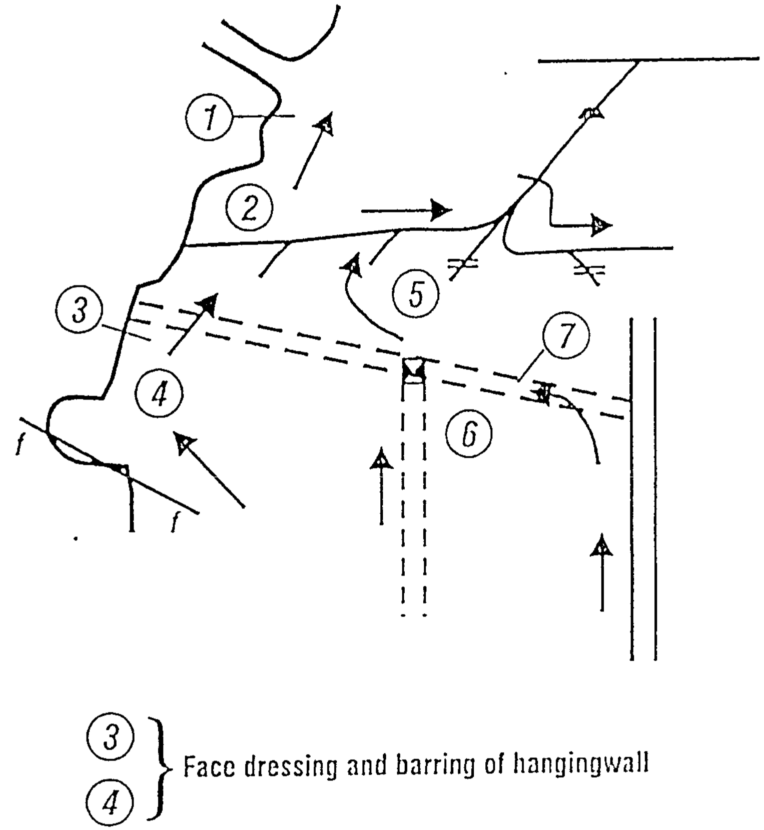

FIGURE 22. SHORT DURATION DUST SAMPLING

reported and management alerted to tighten up on dust control measures. To fully characterize the health hazard the samples need to be analysed for toxic content. In this case no further dust sampling was necessary to determine the reason for high dust emanations or its source. Additional dust sampling could be undertaken to determine if steps taken to control dust emission were effective. Shown in Figure 23 are the results of several successive 15 minute samples collected at a specific operation in a mine plant. The results clearly show that during a specific phase of the operation very high levels of dust were being generated. Figure 24 clearly shows that the two hour averages give no indications of peak dust concentrations nor at what point in the operation the high dust levels are generated. A tyndallometer set to sample every second showed wide fluctuations in concentration levels, exacerbated by mist and no clear trend was obvious. The over-sensitive response clouded the part of the operation when high dust levels were generated. Once again, even though there was a delay in obtaining results the problem was clearly identified and evaluated. Control measures were able to be planned and, once implemented their effectiveness could be ascertained.

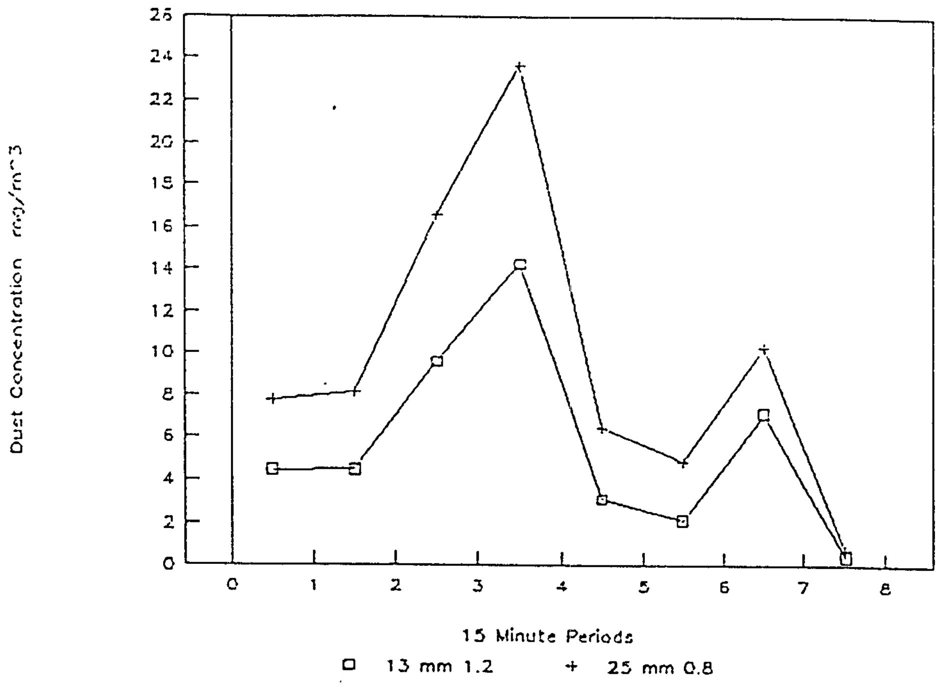

Figure 23. DUST CONCENTRATIONS FOR 15 MINUTE PERIODS FOR 13 mm 1.2μm AND 25 mm 0.8μm POROSITY FILTERS

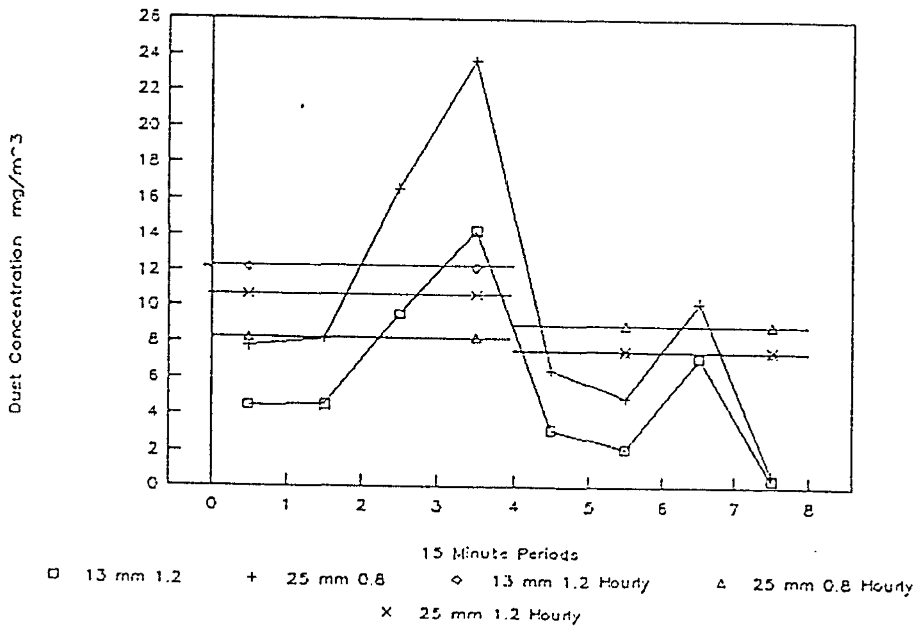

Figure 24. DUST CONCENTRATIONS FOR ALL FILTERS TESTED OVER TWO HOUR SAMPLE PERIOD

4.4 DIRECT MONITORING

This type of monitoring can be split into two categories, viz. pseudo-direct and actual direct. The pseudo-direct approach includes all light scattering dust measurements. In the direct approach actual dust depositions are physically measured.

4.4.1 Light scattering (tyndallometer)

Most of the real-time monitors fall into this category and are considered to be pseudo-direct reading monitors because they do not monitor actual dust deposition but equate dust mass to the amount of light scattering. As seen in Section 3 infra-red beams, laser beams and photo-electric cells have all been deployed in this technique. In general, these instruments are hand-held or at least very portable. Most are robust and some have probes which can be extended to monitor in awkward places such as in pipes.

The technique is basically one of **aerosol** monitoring, i.e. all airborne contaminants will be shown as an airborne mass concentration whether the pollutant is dust, water vapour, oil mist, etc. Direct comparisons with other sampling methods, such as gravimetric (or konimeter), are thus not always valid. Tyndallometer readings sometimes grossly exceed values obtained from other sampling methods. In addition, tyndallometers, in general, do not actually collect dust on a filter so that no actual physical sample is available and there is thus no dust on which pollutant analysis can be performed to establish actual toxicity. Nevertheless, tyndallometers can provide useful information but the results observed must be treated with a great deal of circumspection.

A tyndallometer could be used, exercising common sense and an understanding of the technique, by **experienced personnel** for trouble shooting such as testing the effectiveness of engineering dust controls. In the hands of an inexperienced operator, readings could be misinterpreted, especially if the use of this instrument is attempted on a routine basis where immediate action is required and it is considered that the delay for laboratory evaluation of samples is unacceptable. (The issue of high dust concentrations of non-toxic dust will not be addressed here.) The possibility for misinterpretation is clearly seen in Figure 25 and the corresponding continuous tyndallometer trace shown in Figure 26.[1] None of the respirable dust samples collected on the 13 mm filters (short duration) would attract undue attention. The traverse sample, collected on a 25 mm filter during the **same time** that the tyndallometer was operated, gave a result of 0.924 mg/m^3. If the dust levels had been sustained at between 12 and 16 mg/m^3 for approximately 15 minutes, as indicated by the tyndallometer trace, the average dust concentration for the traverse sample could have been expected to be in the range of 2.5 - 3 mg/m^3. Since this was not the case it is possible that it is not mineral dust that had registered on the tyndallometer. The high reading on the tyndallometer could have resulted in an observer expending a great deal of energy and time on solving a non-existent problem. The matter of poor correlation between aerosol concentrations and actual dust concentrations cannot be taken lightly as the occurrence appears to be more frequent than at first thought. In a series of correlations performed at three separate underground sites (Figure 27) aerosol concentrations were almost **always** found to exceed dust concentrations. However, a conversion factor could not be derived.

LOCALITY		STOPE 1					
Position	Ref.	Dust Concentration mg/m³					Rotating Sponge
		13 mm Ø		25 mm Ø			
		Total	Res	Total	Res		mg/m³
Return	R		2,340				
Face	1		2,260				
Face	2		1,480				
Face	3		2,060				
Ave. face			1,930				
Old area							
Old area							
Ave. old area							
Intake	4		1,500				
Intake							
Traverse					0,924		0,876
Integrated							1,532
Full shift					0,765		

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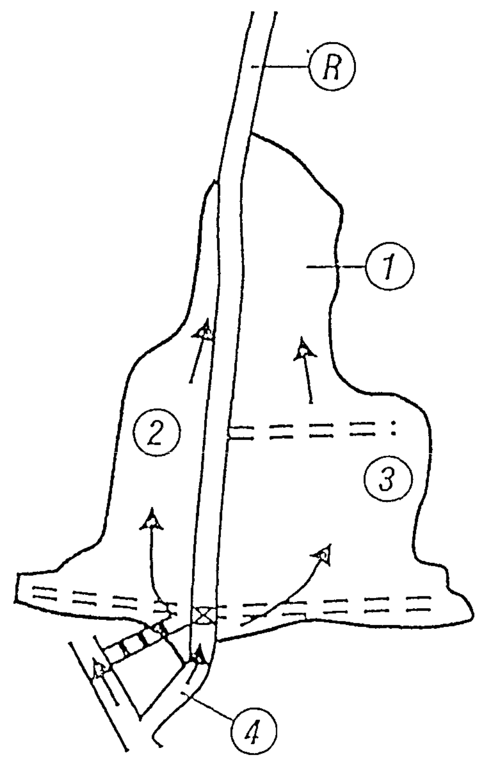


FIGURE 25. SHORT DURATION DUST SAMPLING (II)

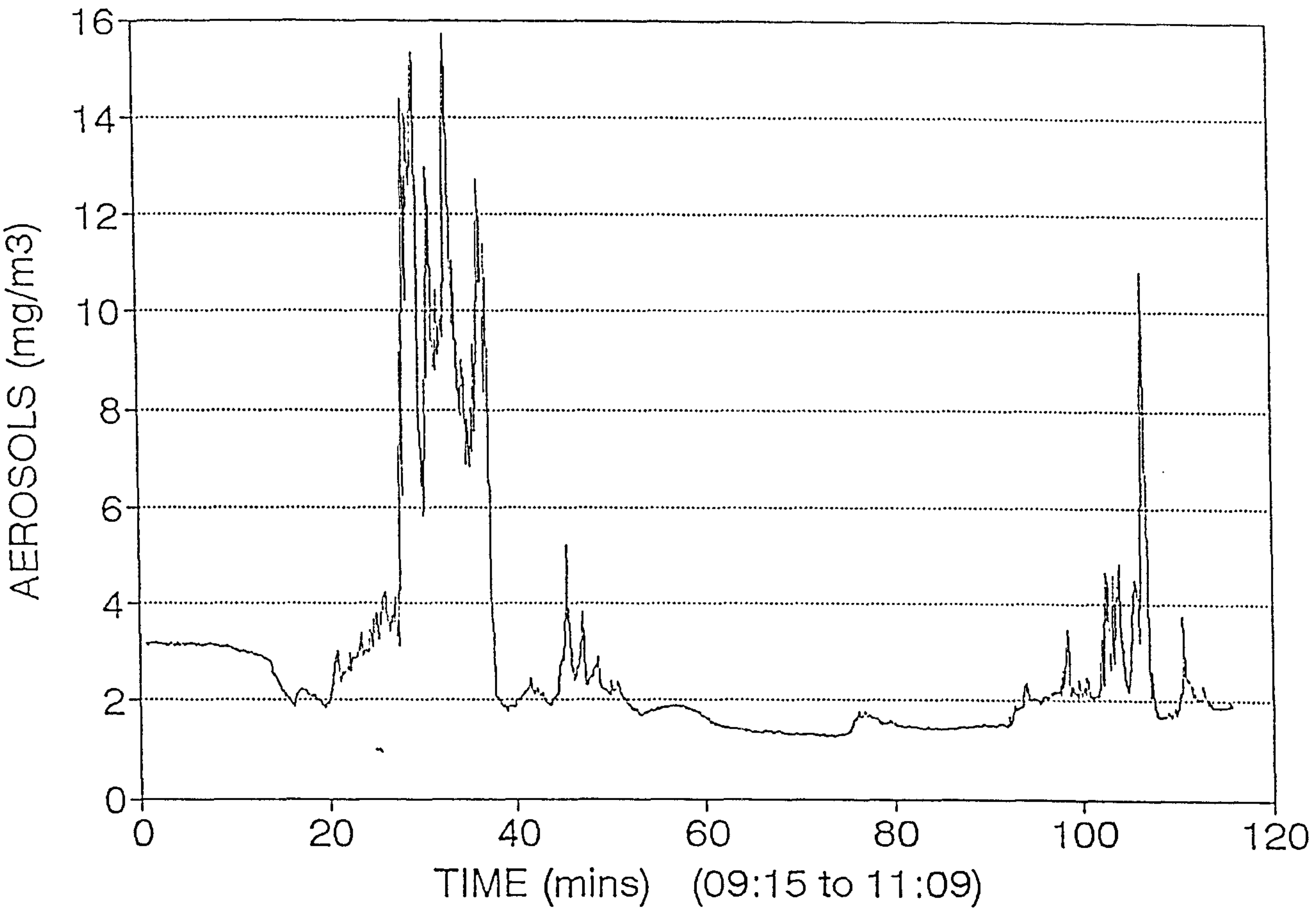
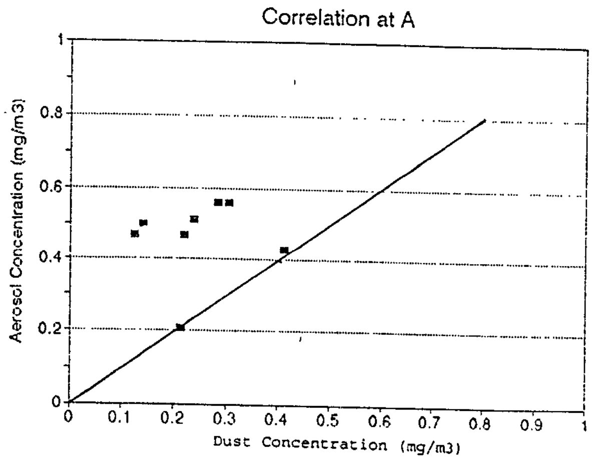
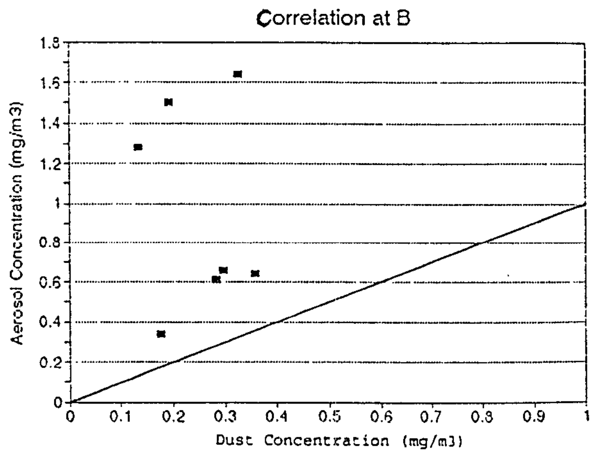


Figure 26. SHORT DURATION DUST SAMPLING - TYNDALLOMETER SURVEY





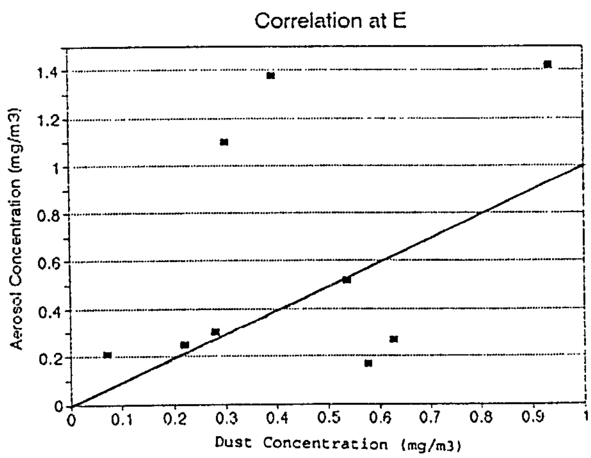


Figure 27. COMPARISON OF DUST AND AEROSOL MEASUREMENTS AT THREE SEPARATE LOCALITIES

Irrespective of the light scattering instrument (or tyndallometer) used they all monitor aerosols and a correct and practical interpretation of results will always be under some suspicion.

4.4.2 Deposition of dust on a quartz crystal

This instrument, although fully portable, was found to be too delicate to withstand the rigours of field work. The manufacturers, therefore, withdrew the instrument from the market 10 - 15 years ago but are currently investigating re-manufacturing with revised specifications. Developments should be monitored.

4.4.3 Beta radiation attenuation of dust on a filter

At present these units are somewhat large for underground field work. The collecting principle is sound, but, as is true for the tyndallometer, distinguishing mineral dust from other aerosol components could be a problem. The instrument is complex and requires a radioactive source, which may not receive official approval very readily.

4.4.4 Deposition of dust on an oscillating filter

When developments in real-time monitoring started the United States Bureau of Mines initiated an accelerated research programme, [6] with $1 million for the development of instrumentation to monitor the mine environment and parameters used to control dust continuously. Under this programme, three major efforts were launched. These are listed below.

- A contract was awarded for research aimed at the development of new, or novel, particulate mass-measuring technology.
- A contract was awarded for the modification and "ruggedisation" of commercially available technology.
- An in-house effort was initiated to develop methodology for real-time measurement of parameters used to control dust. This included the measurement of water pressure and quantity, air velocity, machine tram speed,

and power usage.

The contract for the development of a novel sensor for measuring the mass concentration of dust in the environment was awarded in 1992. The objective of the novel sensor, called, "The Resonant Filter Membrane Mass Monitor (RFM3) was to measure the mass of dust, in real time, collected on a vibrating filter. The principle of operation has already been described (see Section 3). The initial development phase of the contract was completed in 1994. The contract for the modification and "ruggedisation" of commercially available equipment was awarded to a company that manufactures systems for measuring minute quantities of dust collected during environmental sampling. The systems use a tapered element oscillating microbalance as the principle of operation. The operation of the system has also already been described (see Section 3). The commercially available units are relatively large and sensitive to shock and vibration, making them unsuitable for use in underground mine environments. Consequently, the primary objective of the contract was to reduce the unit's size, make it suitably rugged for use in mine environments, and develop technology that would eliminate measurement bias due to environmental moisture (water droplets). The initial phase of the contract was to determine and demonstrate that the system could be modified to withstand the rigour of a mine environment and the forces of shock when mounted on a piece of operating mine equipment. The contract reached its second phase during which modified systems were due to be tested and evaluated in several underground mines. No further information is available, especially since the recent downsizing of the USBM.

4.4.5 Differential pressure as a means of estimating respirable dust mass collection on filters.

The method, previously described (see Section 3, appears to be very promising. The concept is very straightforward, but further experimental work is needed for different filters. Since the basic components to produce an experimental model, viz. pressure transducer and relevant electronics and a data logging system, together with dust sampling pumps and filter cassettes, are already possessed by CSIR: Mining Technology, it would only cost man hours to conduct suitable experiments. At the conclusion of such experiments a decision could be made on whether or not to approach a commercial firm to package the sampling arrangement.

5. CONCLUSIONS AND RECOMMENDATIONS

The underground environment is not only loaded with mineral dust but also other contaminants such as water vapour, oil mists, diesel soot, cement dust, etc. This makes monitoring for mineral dust problematical, especially with real-time monitors since other pollutants have been found to have an influence on sampling results. By far the largest group of real-time samplers fall into the light-scattering category. These are generally portable instruments but are only pseudo-direct reading samplers since scattered or stray light is converted to a mass concentration and dust may not be physically collected, weighed, or analysed. These light-scattering instruments, or tyndallometers, should be deployed with care and readings treated with a great deal of caution to avoid erroneous interpretation of results. Direct reading instruments vary in operating principle. Some are not fully portable, some are no longer manufactured or are being re-introduced, and development on some has ceased. Whilst it is conceded that not every available instrument was investigated, the main operating principles will not be altered and these were all investigated and reported on.

The most promising monitoring technique appears to be that of measuring the pressure differential over a filter as a gauge of dust collected. Although not fully developed overseas, the concept appears to be sound and since the basic filters and pumps, mini pressure meter and logging system are already to hand, the basic experimental phase would only comprise man-hours. At the conclusion of the experimental phase a decision could be made on whether or not to pursue the development of such a device. Until a possible new real-time dust monitor is developed mines still have a need to conduct dust sampling for engineering control with existing equipment. Although it may be considered to be good occupational hygiene practice to be able to react with a minimum of delay to unsatisfactory dust conditions, for which a real-time dust monitor would unquestionably be needed, the dust encountered in mines is not of such a nature (lethally toxic) that short delays in dealing competently with bad conditions cannot be tolerated. A real-time monitor would thus be viewed as a piece of equipment that would be "nice to have." The above considerations open the way for the use of indirect methods for control sampling. Although the konimeter is not recognised by the Department of Minerals and Energy (DME), and its use vigorously discouraged by the DME, the konimeter played a very useful role in dust control in the past and most mines are equipped to re-introduce such sampling. On the other hand, conventional gravimetric dust samplers have been shown to provide very usable information about sources of and processes leading to dust emanation/generation when used in a short duration sampling mode. As was shown in a previous research project [1] this technique can readily be introduced in mines for control dust sampling.

Of fundamental importance, irrespective of strategy or technique, is that mines re-establish the capability and the capacity to measure dust for engineering control purposes.

6. ACKNOWLEDGEMENT

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