MEASUREMENT STRATEGIES IN U.S. UNDERGROUND COAL MINES

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ABSTRACT

The 1969 Federal Coal Mine Health and Safety Act (ACT) mandated standards for occupational exposures to respirable coal mine dust. For mine environments where the respirable dust contains less than 5 percent quartz the standard is 2.0 milligrams of dust per cubic meter of air (mg/m^3), where the respirable dust contains more than 5 percent quartz the standard is adjusted according to the quartz percentage. The Act also required mine operators to carry out a dust sampling program. This paper presents an overview of the current methods used in the United States of America to assess exposures to respirable dust in coal mines, the sampling strategies used to enforce the mandatory dust standard, the sampling requirements of coal mine operators and a description of the laboratory used to process the more than 100,000 samples per year collected by the coal mine operators.

ENFORCEMENT PROGRAMS (STRATEGIES)

Since December of 1969, the United States of America has had a Federally mandated respirable dust standard of 2.0 mg/m^3 for its underground coal mine environments. Respirable dust, for the purpose of this standard, is defined as the fraction of dust recommended by the British Medical Research Council (BMRC) and adopted by the Johannesburg Pneumoconiosis Conference in 1959. The sampling efficiency curve representative of the respirable dust criteria adopted at that conference is shown in Figure 1. Particle diameters in this figure refer to equivalent spherical diameters, which are defined as the diameter of spherical particles of unit density having the same falling velocity as the particles in question.

Because of the recognized increased health risk associated with exposure to quartz (crystalline silicon dioxide), the mandated exposure standard is to be adjusted (reduced) when the quartz content in the respirable dust exceeds 5 percent. The adjusted standard is determined by dividing the percent quartz in the respirable dust into the number 10 (i.e., 10/% SiO_2).

In the United States there are two programs to enforce the mandatory respirable dust standard, a program conducted by the mine operators in accordance with mandated regulatory requirements and a program conducted by the Federal government. Under the operator's program each operator is required to collect five respirable dust samples from a "designated occupation," the occupation on a coal getting operation that previous sampling has shown to have the highest dust exposure, in each coal getting operation every two months. The samples must be collected on consecutive production shifts or on production shifts on consecutive calendar days.

The collected samples are sent by mail, within 24 hours after collection, to a central laboratory in Pittsburgh, Pennsylvania, where the amount of dust collected is determined by weighing. A data card, shown in Figure 2, is submitted with each sample. The dust concentration is determined for each sample using the weight of dust collected, the time over which the sample was collected and the flow rate of the sampling device (in all cases this is 2.0 liters of air per minute). All samples are required to be collected for a full production shift (portal-to-portal).

The dust concentrations determined from these five samples are averaged. The average concentration is then compared to the 2.0 mg/m^3 dust standard (or adjusted standard) to establish compliance or noncompliance with regulatory requirements. In addition to the five samples collected bimonthly on the designated occupation, the mine operator is

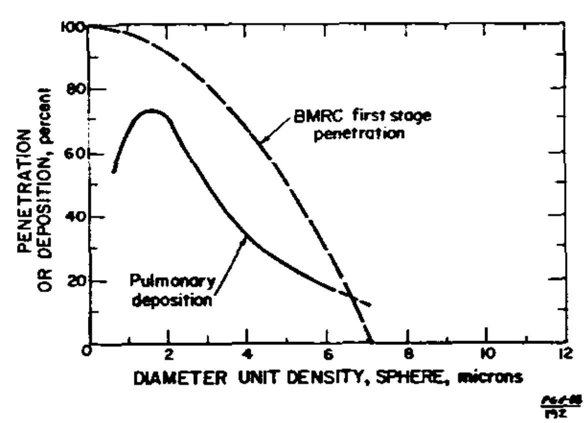

Figure 1. Comparison of BMRC respirable size criteria with pulmonary deposition curve.

also required to collect an additional sample bimonthly at specified locations throughout the mine. These locations are strategically selected so that the environment where miners normally work or travel is monitored for compliance with the respirable dust standard. If at any time it is determined from any of these samples that the respirable dust standard is exceeded, five additional samples are collected (either on consecutive days or consecutive production shifts) at the site where it was determined that the applicable standard may be exceeded. The dust concentrations determined from these samples are averaged and compliance is determined using the applicable standard for the area where the samples were collected. In accordance with regulatory requirements, the mine operator also submits to the Federal government a ventilation system and a methane and dust control plan which are to include: sources of dust generation in the outby areas of the mine, methods being used to control dust at these sources of dust generation and the specific location of places where samples will be collected to monitor the levels of dust in areas where miners normally work or travel. Also specified in the plan are the parameters characterizing the measures that are being used to control dust at the coal mining (getting) operation. The typical parameters specified include the quantity and velocity of air used to ventilate the face, the quantity and pressure of water and the number, type and location of nozzles used in the water spray system.

The Federal government's program to enforce the legislated respirable dust standard(s) consists of a mine inspector visiting each coal mining operation to approve, or check for compliance, that portion of the ventilation and dust control plan that describes the measures to be used by the mine operator to control respirable dust levels in the mine environment. To approve the "dust control" portion of the plan, an inspector will collect a personal sample on at least five miners working in the immediate area of the coal mining operation where the parameters described in the plan are being used to control the dust. If the type of mining is "room and pillar" employing continuous mining equipment, one sample must be collected from the environment of the continuous miner operator, one from the environment of the roof bolter operator and three from other occupations working in the immediate area. Typically these other three samples are representative of the environments of shuttle car operators, continuous miner operator helpers and laborers. If the mining operation is a longwall mining operation, the samples are representative of the shearer operators and shield (jack) setters.

The sampling equipment is normally mounted on the miners (referred to as personal sampling) prior to the start of the shift and removed after the shift is finished. After the samplers are removed from the miners, a mine data card is completed and the sample and data card taken to a local Federal enforcement laboratory for processing. The respirable dust samples collected are weighed to a tolerance of ±0.1 mg which is the same as for those samples collected by the mine operators. After the samples are weighed and the net weight of the collected dust determined, the concentration of dust, in mg/m^3, is calculated using the weight of the dust collected and the volume of air sampled.

To determine if the parameters being used to control dust are effective in reducing the respirable dust level in the environment to the applicable standard, the dust concentrations determined from the five samples are averaged. For the plan to be considered adequate, the average dust concentration must be below 2.0 mg/m^3 and the concentration of no individual sample can be greater than 2.0 mg/m^3. If the average concentration determined from the five samples exceeds 2.0 mg/m^3, the work area is found to be in noncompliance and the mine operator must improve the practices being used to control dust and specify these changes in his dust control plan.

If the average concentration determined from the five samples is below 2.0 mg/m^3, but one or more of the individual samples is greater than 2.0 mg/m^3, then sampling continues on all five occupations on subsequent production shifts. Sampling is continued until the average concentration determined from the individual occupation samples collected on

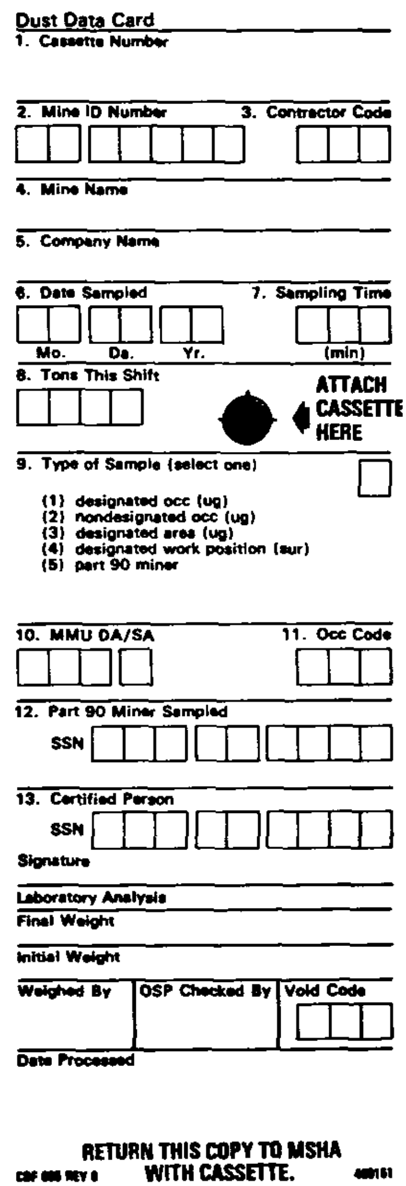
Dust Data Card
1. Cassette Number
2. Mine ID Number
3. Contractor Code
4. Mine Name
5. Company Name
6. Date Sampled
Mo. Da. Yr.
7. Sampling Time (min)
8. Tons This Shift
ATTACH CASSETTE HERE
9. Type of Sample (select one)
(1) designated occ (ug)
(2) nondesignated occ (ug)
(3) designated area (ug)
(4) designated work position (sur)
(5) part 90 miner
10. MMU DA/SA
11. Occ Code
12. Part 90 Miner Sampled
SSN
13. Certified Person
SSN
Signature
Laboratory Analysis
Final Weight
Initial Weight
Weighed By
OSP Checked By
Void Code
Date Processed
RETURN THIS COPY TO MSHA WITH CASSETTE.

Figure 2. Mine data card.

consecutive production shifts and the average concentration determined from samples collected on the same shift are both equal to or less than 2.0 mg/m^3. No more than five production shifts are sampled.

As previously discussed, the 2.0 mg/m^3 respirable dust standard is reduced whenever it is determined that the quartz content of the respirable dust exceeds 5 percent. Determination of the quartz percentage of the respirable dust is based on the analysis of a selected number of samples collected during the plan approval process. Those samples typically selected for analysis are the designated occupation sample, all roof bolter samples and any other sample that may be suspected of having a high quartz percentage.

After sampling has demonstrated that the procedures specified in the plan for controlling dust are adequate, subsequent inspections (up to three) during the year are limited to checking on conformance with the dust control plan; i.e., no dust samples are collected, only dust control procedures are evaluated.

RESPIRABLE DUST SAMPLING INSTRUMENTATION

To measure the respirable dust concentration of coal mine environments in the United States, a two-stage sampling instrument is used. The instrument, commonly referred to as a personal respirable coal mine dust sampler, is shown in Figure 3. The sampler was designed to be an instrument that was capable of sampling the environment to which a miner is exposed during his full work shift. Therefore, the instrument has the flexibility of either being mounted on a person (as shown in Figure 4) to obtain his exposure or of stationary mounting to obtain measurements of any general environment where it is located.

The sampler consists of a 10 mm diameter nylon cyclone, a filter and a pump. The 10 mm nylon cyclone, the first stage of the sampling system, separates the sampled aerosol into two fractions: a respirable fraction and a nonrespirable fraction. The particle selectivity curve that defines the separated fractions is shown on Figure 5.

The nonrespirable fraction is collected and retained in the cyclone (Figure 6) while the respirable fraction passes through the cyclone and is collected on a 37 mm diameter, 5 micrometer pore size, vinyl metricel membrane filter. The filter is preweighed by its manufacturer to a precision of ± 0.1 milligram. The cyclone and filter assembly, commonly referred to as the "sampling head," is designed to be mounted on the miner at his "breathing zone."

The pump, used to induce air into the sampling system, is

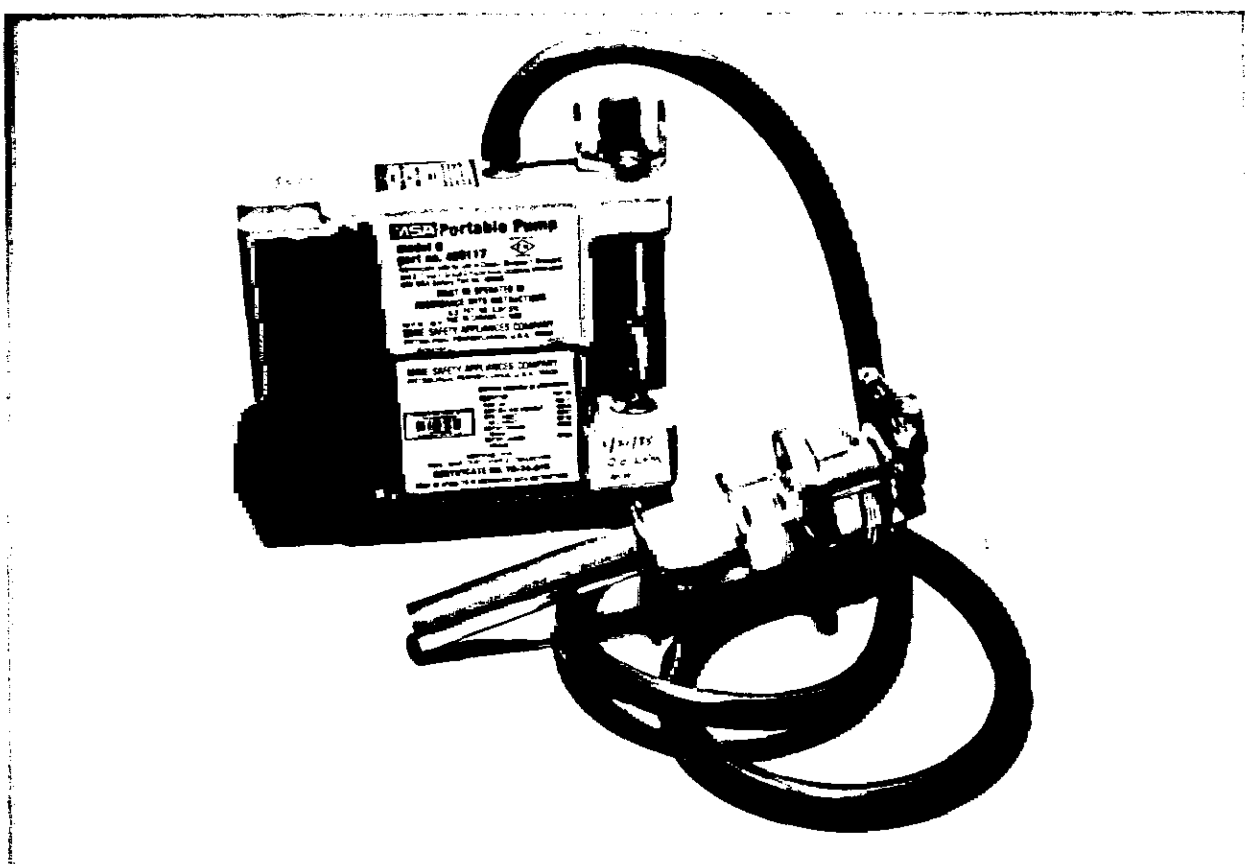

Figure 3. Personal respirable dust sampler.

Figure 4. Personal sampler worn by miner.

battery powered and can be easily worn by a miner during the performance of his duties. It weighs less than one kilogram and has overall dimensions of approximately 5 cm × 10 cm × 13 cm.

Air is sampled at the rate of 2.0 liters per minute (±0.1 liters per minute). Because the 2.0 mg/m^3 dust standard is based on measurement data obtained with an instrument that sampled with respect to the BMRC selectivity curve shown in Figure 1, respirable dust concentrations determined from measurements obtained with the personal coal mine dust sampler must be multiplied by a factor of 1.38 before the measurements can be used to determine compliance with the mandatory dust standard.

PROCESSING COAL MINE OPERATOR DUST SAMPLES

As a result of the Federally mandated regulatory program, approximately 110,000 dust samples are collected by mine operators each year. These samples and associated data are mailed to the Federal government's central processing laboratory located at Pittsburgh, Pennsylvania.

At the central processing laboratory, samples are processed in a "clean room" environment. The laboratory is maintained at a slight positive pressure to limit the entry of extraneous dust from surrounding work areas. The environment in the room where samples are weighed is maintained at 23° ± 1°C and 50 percent ±5 percent relative humidity.

Prior to weighing, samples are vacuum desiccated to remove moisture that may be present on the sample. The internal pressure of the desiccator chamber is reduced to 5 mm Hg and held at that pressure for 15 minutes.

Since January, 1985, respirable dust samples have been processed using the Automated Weighing System (AWS) shown in Figure 7. The AWS is a robotic system which has been designed for unattended weighing of filter capsules on a Mettler AE163 analytical balance.

The robotic arm (Figure 8) has the ability to rotate 360° around its central vertical axis, move up and down its vertical axis as well as in and out from the horizontal axis. At one end of the robotic arm is a "hand" with a pair of fingers which may be made to open and close as well as rotate 180° in wrist-like movements around the arm's horizontal axis. The system is designed so that the robot can sequentially process up to 200 samples from five trays without manual intervention. Processing time for 200 samples is approximately four hours.

Performed tasks are programmed into a power and event controller. The power and event controller zero's the balances before weighing each sample, switches a relay to select either of two balances, activates a solenoid to open and close a balance door and to sound an alarm buzzer when manual intervention with the AWS is required. Upon completion of a weighing, the controller activates a printer which prints the weight of each filter capsule and a sequence number on a 1 cm x 5 cm pressure sensitive label. The label is subsequently affixed to the data card.

The Mettler Model AE163 analytical balance used with the AWS is shown in Figure 9. This state-of-the-art analytical balance has a weighing precision of ±0.02 mg. Each balance is calibrated twice daily and checked with a Class M certified calibration weight. A radioactive deionizing unit is used to eliminate the presence of static charge on filter capsules. To isolate vibrations, the balances are positioned on a marble table weighing approximately 320 kg.

The AWS has been programmed to systematically weigh a sample twice on two different Mettler AE163 balances. One in eight of each filter capsule weighed is reweighed on the second balance. If the weight difference obtained between the two balances is within ±0.1 mg, the weighings are considered to be within tolerance and weighings are continued. If the weights are out of tolerance, an alarm sounds and both balances are recalibrated. The system then reweighs the last seven filters, performs another quality control check weighing and continues processing additional samples if the check weights are within the established tolerance.

As previously discussed, each respirable dust sample is

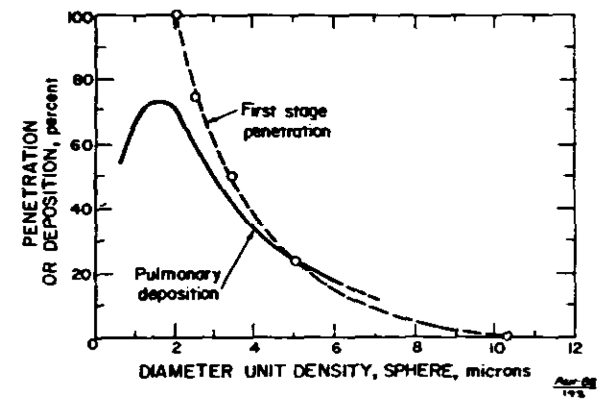

Figure 5. Comparison of the 10 mm diameter cyclone selectivity curve with pulmonary deposition curve.

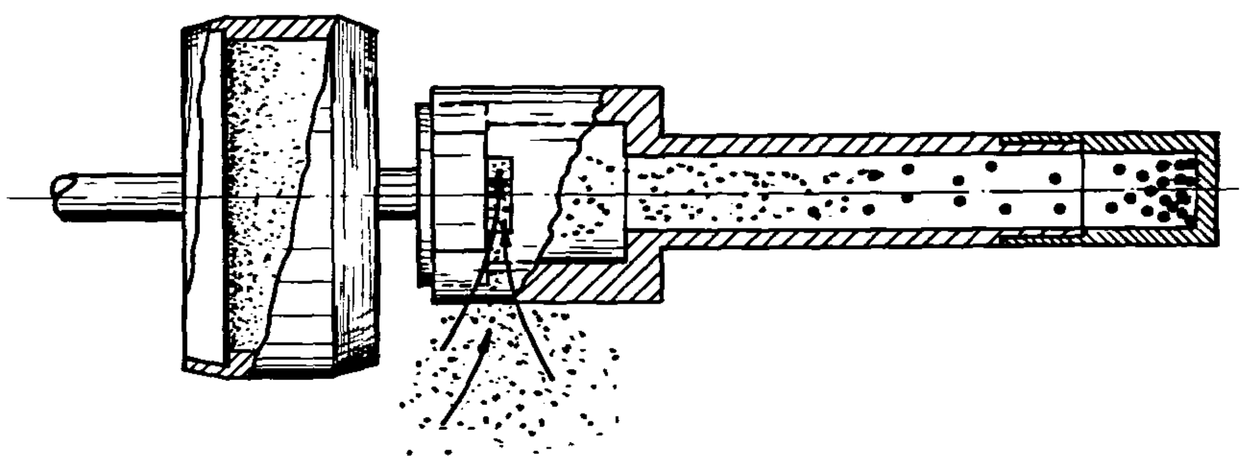

Figure 6. 10 mm cyclone with filter.

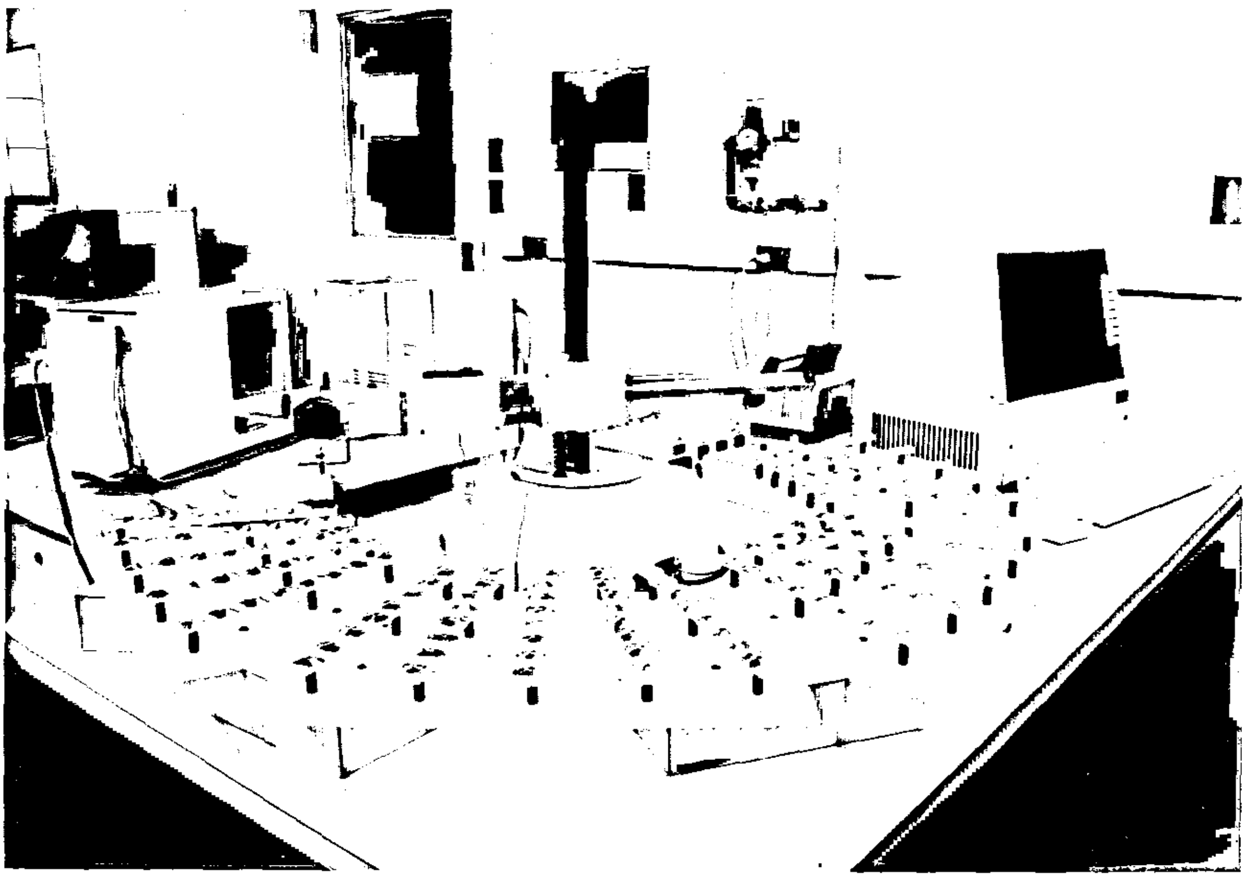

Figure 7. Automated weighing system.

accompanied by a mine data card (Figure 2). The data on each card is manually transcribed (Figure 10), in numeric notation, onto magnetic discs. Each card contains 62 keystrokes or digits. Data transcription is verified using a double entry system. Data retranscribed by a second operator is compared to that originally transcribed. The verifying operator is alerted to resolve errors or mismatched data. All disks generated during the day are then machine edited for completeness and accuracy. After editing, all data is accumulated and telecommunicated to an Information Systems Center in Denver, Colorado.

The information telecommunicated to the Information Systems Center is compiled and the respirable dust concentration for each sample calculated. A copy of all the data and sample results are mailed directly to the mine operators. The results are also telecommunicated to local enforcement offices which have interactive access to all dust data file information.

SUMMARY

The promulgation of a respirable dust standard for underground coal mine environments and the programs instituted to enforce that standard have resulted in a more healthful working environment for U.S. coal miners. As shown in Figure 11, occupational exposures have steadily decreased since promulgation of the respirable dust standard. However, as the data on this graph also depicts, the reduction of dust levels on longwall mining operations has not been as great as on the other types of mining operations. Work still needs to be done to develop methods to control dust on longwall mining operations.

The program requiring coal mine operators to sample their mine environments and to submit the samples to the Federal government for analysis has been effective in reducing underground respirable dust levels, and has provided the impetus for them to institute procedures to control dust.

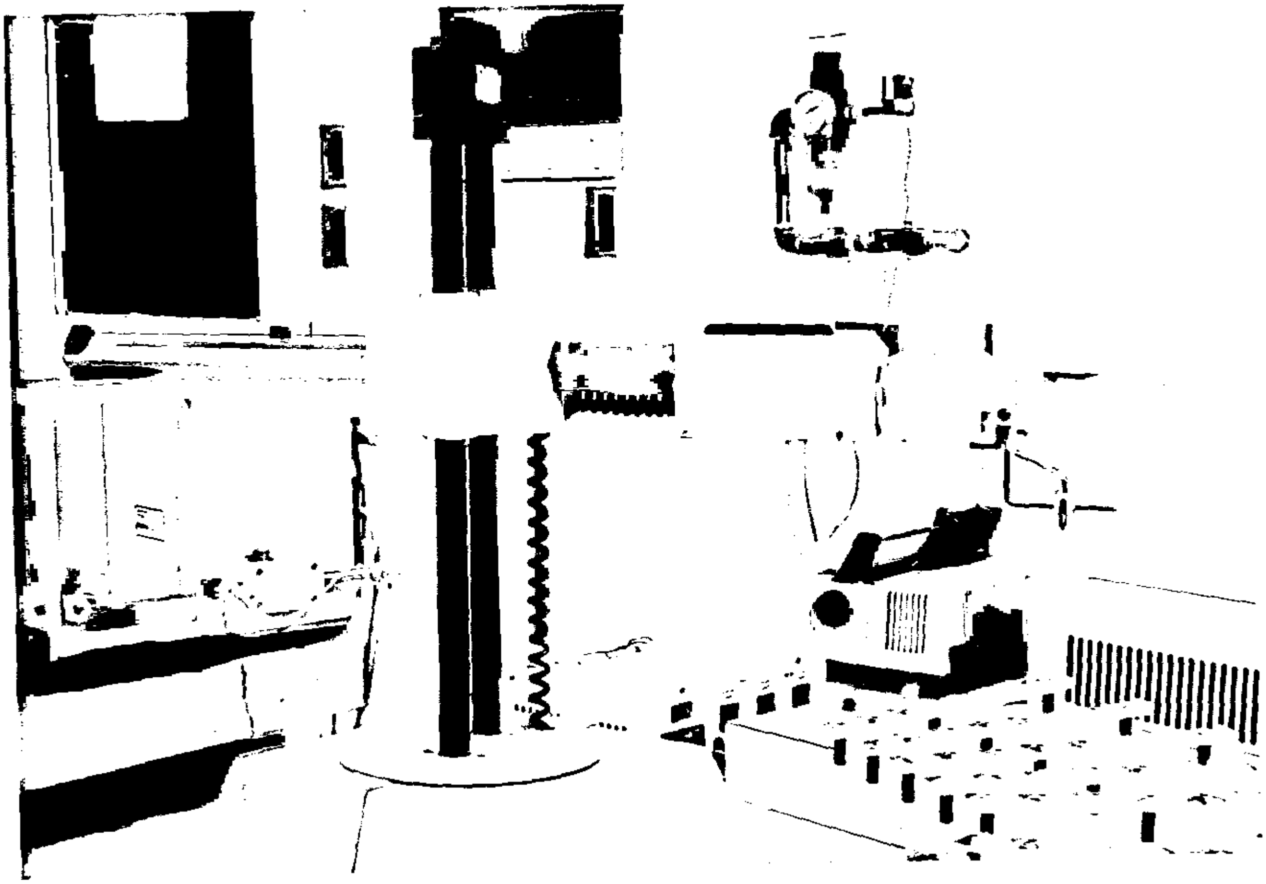

Figure 8. Robotic arm.

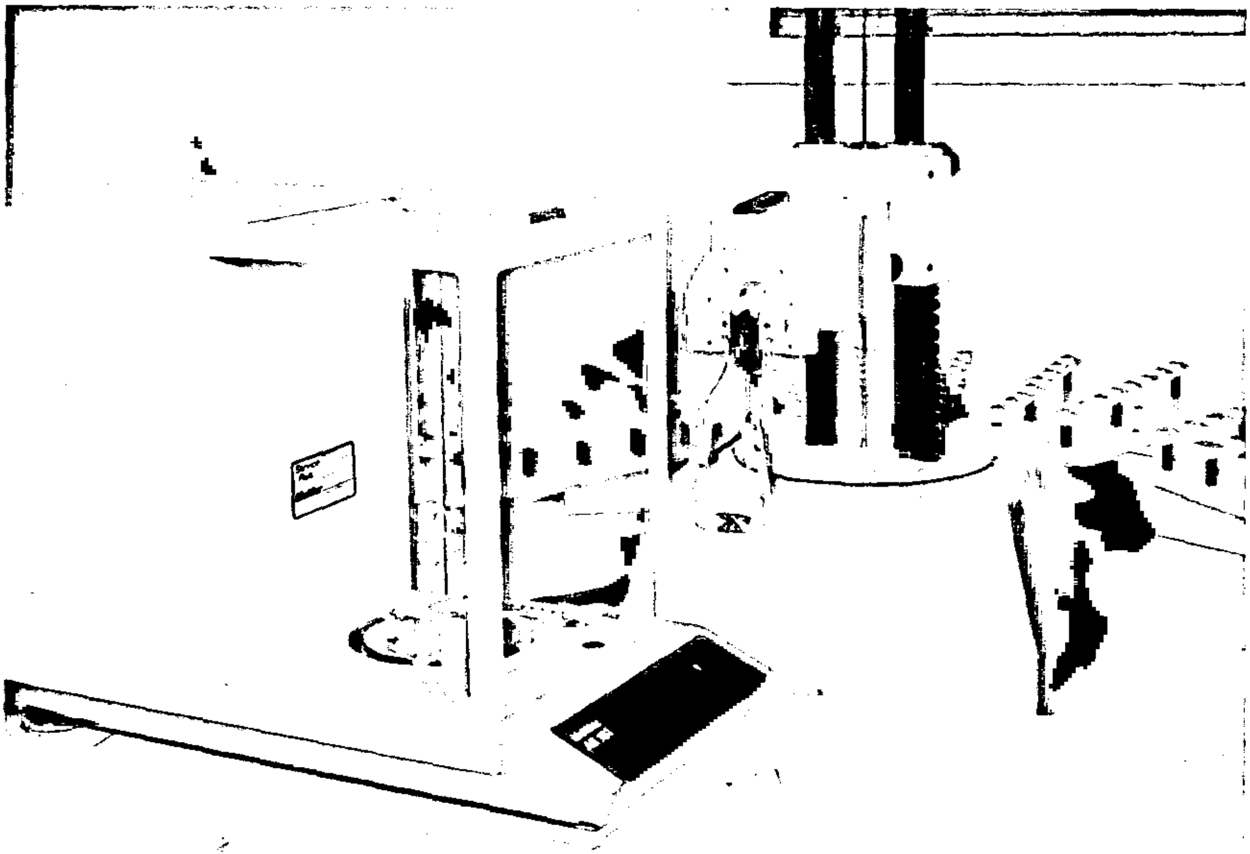

Figure 9. Analytical balance used with automated weighing system.

Figure 10. Data processing station.

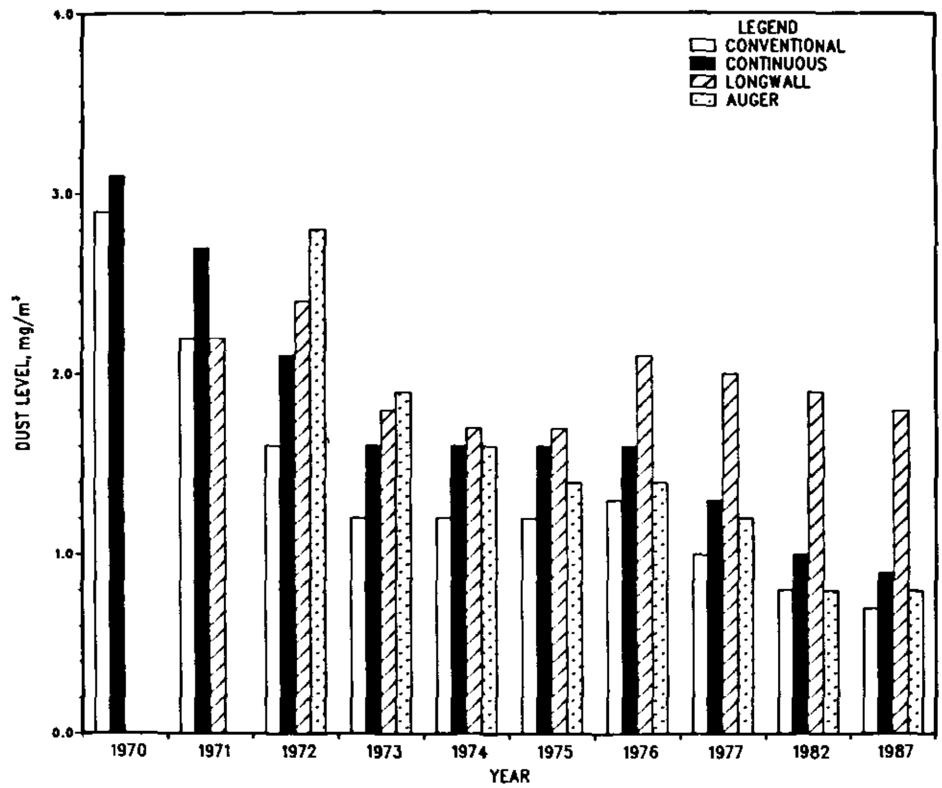

Figure 11. A yearly comparison of dust levels for four types of mining.

THE THRESHOLD LIMIT VALUE FOR VARIOUS FORMS OF AMORPHOUS SILICA

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Silica is the common name for silicon dioxide (SiO_2). In silica each silicon atom is covalently bound to four oxygen atoms which are arranged tetrahedrally around it. Each oxygen atom is bound to two silicon atoms. In the crystalline forms of silica the silicon and oxygen atoms are arranged in a highly ordered lattice which extends infinitely in all directions. Of course, the lattice is not truly infinite since it must end at the surface of the solid. The surfaces of crystalline silica particles or macroscopic pieces are bounded by flat surfaces joined at sharp straight edges. In some forms of crystalline silica such as tripoli or quartzite, the surfaces and edges may have been worn away to produce what appears to be amorphous particles.

All naturally occurring crystalline silica was formed by crystallization from aqueous solution or from molten magma. Depending on the temperature and pressure at which the crystallization takes place, one of three different geometrical arrangements of the silicon and oxygen atoms will be formed. The most common crystalline form of silica is quartz, which occurs as solid crystals from several inches in size down to microscopic dimensions. Other forms of crystalline silica are cristobalite and tridymite.

Under several natural and artificial conditions, silicon dioxide will form solids with no overall spatial ordering of the atoms. These products are amorphous silicas. Solid objects and particles of amorphous silica do not display flat faces and sharp edges. More importantly, amorphous silicas do not display X-Ray diffraction patterns as do the crystalline forms. The several forms of amorphous silica display different physical and chemical properties and substantially different toxicological characteristics.

The only naturally occurring form of amorphous silica is diatomaceous earth whose particles are the fossil skeletons of microscopic marine plants known as diatoms. While alive these organisms extract silica from the sea water and deposit it in complex regular forms with numerous voids. In California and other parts of the world there are very large deposits of the mineral diatomite or diatomaceous earth consisting almost entirely of fossilized diatoms, and which is a highly porous substance with a very low bulk density. The overlying and surrounding rock frequently contains quartz which contaminates the final product. Some deposits contain traces of cristobalite, apparently formed by metamorphism.

Fused quartz, or more properly, fused silica, is formed by the relatively slow solidification of molten quartz. In the melt there is no long range order. As it cools, the molten material becomes highly viscous and then solidifies so that the atoms become immobilized in their random positions. Fused silica is produced as lumps of glassy material but during crushing and grinding, respirable particles can be produced.

Glass or silica dissolves in sodium hydroxide to form a solution of sodium silicate, also known as water-glass. On acidification, this forms the insoluble flocculent precipitate of silicic acid (H_4SiO_4 or $Si(OH)_4$). As water is eliminated between nearby SiOH groups Si-O-Si bridges are formed. Depending on the dehydration process, precipitated silica or silica gel is produced. These both can be considered to be partially hydrated silicon dioxide. Silica gel can be dried to a very low moisture content to form a granular product which absorbs water and polar organic substances with great avidity.

Fumed silica is produced synthetically by a vapor phase hydrolysis of silicon tetrachloride in a flame of hydrogen and oxygen. It is a widely used filler in paints, plastics and rubber and as an antiskid and antislip agent.

Elemental silicon is produced by reacting coke and silica sand (crystalline) in an electric arc furnace. If iron is included in the charge, the product is ferrosilicon. In both cases, silicon monoxide is apparently produced as a byproduct which escapes from the furnace and is oxidized by ambient oxygen to produce what can be called silica fume. Although it is not a deliberately manufactured product, baghouse dust from silicon and ferrosilicon furnaces has been used in the same way as fumed silica. Although both fumed silica and silica fume are fumes in the usual industrial hygiene sense (they are finely divided solids produced by condensation from the gas phase) their mode of formation and worker exposure are different. As is discussed below, the toxic effects are also quite different.

Precipitated silica and silica gel could be considered to be the prototypical nuisance dusts. The ACGIH considers a material to be a nuisance dust if it causes no adverse health effects when exposures are kept under reasonable control (e.g. near or below 10 mg/m^3) and further does not alter the lung air spaces, does not form collagen to a significant extent and whose tissue reactions are potentially reversible.[3] Klosterkotter showed that silica gel injected intratracheally in rats did not cause fibrosis.[6] Schepers et al observed no fibrosis in guinea pigs and rabbits exposed by inhalation at 126 mg/m^3 for two years.[7] There were macrophage accumulations and mild proliferation of reticulin fibers. In a group of 165 workers exposed to precipitated silica estimated to be near or below 10 mg/m^3 for an average of 8.6 years, Wilson et al observed no serial changes in pulmonary function or chest radiographs.[9]

The TLV or 10 mg/m^3 (total dust) assigned to precipitated silica and silica gel was not chosen to avoid any known adverse health effect.[3] Rather it represents a recommendation for good industrial hygiene practice. Airborne exposure above this level may reduce visibility, may cause unpleasant deposits in the eyes and nasal passages and may cause injury to the skin and mucous membranes by purely mechanical action.

Fumed silica and silica fume display entirely different toxicities. This contrast illustrates the confusion created by misidentification of the toxic substance in epidemiological studies and the risk of predicting toxicity on the basis of chemical similarity. As noted above, both products are true fumes, ultrafine solid particulates formed in gas phase reactions. However, fumed silica appears to be only slightly more toxic than precipitated silica and silica gel. ASTM standard E1156-87 reviewed three studies involving a total of 353 workers exposed for up to 32 years to fumed silica concentrations from 1.6 to 53 mg/m^3.[1] No pulmonary dysfunction was observed except in smokers. Schepers exposed rats, rabbits and guinea pigs to fumed silica at 53 mg/m^3 for a year causing emphysema which reversed after exposure ceased and fibrosis which partially reversed.[7] Groth observed significant interstitial hyperplasia and collagen deposition in monkeys exposed to 15 mg/m^3 of fumed silica for 13 months.[4] However, the monkeys' lungs showed the presence of mineral dust which had apparently been inhaled in the wild or in captivity prior to purchase of the animals. No changes were observed in rats and guinea pigs similarly exposed.

On the other hand, several studies in the elemental silicon and ferrosilicon industries show that silica fume produces a unique complex of acute and chronic effects which are reversible after exposure ceases. The observations of Bowie at an African ferrosilicon plant are typical.[2] Brief high exposures to silica fume produce the symptoms of metal fume fever, which can persist for up to three months. Chronic exposure produces X-Ray and pulmonary function evidence of silicosis which regresses or disappears after cessation of exposure.

The TLV for fumed silica has been set at 10 mg/m^3; the value assigned to nuisance dusts.[3] No value has been established for silica fume but a TLV of 0.2 mg/m^3 (twice the TLV for quartz) seems reasonable.

It is tempting to speculate on the causes of the radical difference between the two silica fume materials. In the case of silica fume, the effects may be produced bv repeated high exposures but no airborne measurements are available to support this hypothesis. It is also possible that silicon and ferrosilicon workers are exposed to a much more freshly formed fume since they work at the tapping ports of the furnaces while the synthetic fumed silica may have aged for a few minutes before reaching the workers' breathing zones. Again there is no evidence to support this.

In contrast to the other forms of amorphous silica, the TLV for fused silica is based on very little actual data, animal or human. The Documentation references only two studies both published in the early 1950s; one an acute intraperitoneal injection in rabbits, the other an intratracheal instillation in rats.[3,8,5] No inhalation experiments in animals or epidemiological studies in exposed workers have been published since then. Both references indicated that fused silica was less active in inducing a tissue reaction than crystalline quartz but no comparisons with nonfibrogenic forms of amorphous silica were performed. On the basis of the fact that there was a tissue reaction at all, a TLV of 0.1 mg/m^3 was established; the same as for quartz.[3]

Fused quartz is now used in several advanced technological products such as ablative surfaces for rocket reentry vehicles and in fiber optics. It is anticipated that more workers will be exposed to this hitherto exotic material and it is unfortunate that more solid toxicological data is not available.

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COMPARISON OF THE SAMPLING STRATEGIES RECOMMENDED BY THE EUROPEAN COMMUNITIES FOR THE PROTECTION OF WORKERS FROM THE RISKS RELATED TO CHEMICAL AGENTS AT WORK, ASBESTOS, LEAD AND MINE DUST

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INTRODUCTION

The purpose of this paper is to evaluate the monitoring strategies implemented by the various European Directives on the exposures to airborne workplace contaminants.

Monitoring strategies to determine compliance with occupational health standards entail a number of requirements that are usually determined by consensus rather than through the scientific process.

Statistical models will be used to compare the proposed sampling strategies. Past research has shown that the concentration distribution of most air pollutants can be described as lognormal. Therefore, the analysis will be based on the lognormal distribution. Such distributions are completely defined by the geometric mean (GM, a measure of central tendency) and by the geometric standard deviation (GSD, a measure of the variability of exposures).

When a monitoring strategy provides consecutive shift or daily samples to determine compliance, the autocorrelation of the exposures should be taken into account.

DIRECTIVES OF THE EUROPEAN COMMUNITIES

The first Directive laid down by the Council of the European Communities is the Directive 80/1107/EEC of 27th November 1980 on the protection of workers from the risks related to exposure to chemical, physical and biological agents at work.[1] This is a global Directive providing for the laying down of individual Directives for specific agents.

Directive on Lead

The first of these individual Directives has been the Council Directive 82/605/EEC of 28th July 1982 regarding exposure to metallic lead and its ionic coumpounds at work.[2] Taking into account the biological half-life of the agent, the limit value for lead is based on the time-weighted average concentration over one week (40 hours). The strategy provides the following stages:

- initial designation if the sample exceeds 1/2 of the limit value;
- a quarterly sampling cycle in the first instance;
- the frequency of monitoring may be reduced to once a year if two consecutive measurements are below 2/3 of the limit value.

Directive on Asbestos

The Council Directive 83/477/EEC of 19th September 1983 relating to exposures to asbestos at work was the second individual Directive.[3] Here the limit values are measured or calculated in relation to an eight-hour reference period. The general rule is to measure the level of asbestos at least every quarter.

This frequency may be reduced to once per year when the results of the two preceding measurements have not exceeded 1/2 of the limit value. As the time-weighted average over 8 hours has a greater standard deviation than the average over 40 hours,[4] a lower action level has been chosen: namely 1/2 of the limit value instead of 2/3. If the concentration is lower than 1/4 of the limit value, monitoring is terminated.

Proposal for Modification of the Frame Directive 80/1107/EEC

On 6 June 1986, the Commission of the European Communities presented a proposal for modification of the Frame Directive 80/1107/EEC.[5] The strategy is similar to the one for asbestos, except that the action level has been lowered to 1/3 of the limit value and the decision to end sampling is taken when the concentration does not exceed 1/5 of the limit. This proposal has not been approved and Technical Committee TC 137 of the CEN (European Committee for Standardization) has been invited to draw up its own sampling scheme for the determination of airborne hazardous substances at the workplace.

Draft Proposal of the Safety and Health Commission for the Mining and other Extractive Industries of the E.C. to the Governments of the Member States to reduce the risk to health associated with the exposure to fibrogenic mineral dust in the non-coal mining and quarrying industries.

This draft proposal, in its last version (Doc. 5761/10/85) of 19 May 1988, provides for the same measuring strategy as the Directive on asbestos. Moreover, it provides for an alternative approach towards dealing with the problem of exposure fluctuation by interpreting the limit in terms of the mean exposure over one year. Daily levels are allowed to exceed the limit if they are compensated by the days of low exposure so that the one-year time-weighted average remains below the limit.

Intuitively, it would appear difficult to accurately characterize the exposure over one year with only one, two or three isolated estimates of daily exposures. For example, in West German underground coal mines, the exposure over one year is estimated from averaging the results of 12 monthly measurements.

STRATEGY EVALUATION

An evaluation of the sampling strategies has been conducted using a lognormal model.

For this model, a value of 1.7 has been chosen for GSD, a typical value for the distributions of one-shift respirable dust concentrations in European underground coal mines (although it can vary from 1.2 to 3.0 in other work environments). When GSD = 1.7, it means that 5% of the shifts have a concentration exceeding 2.8 times the geometric mean or 2 times the arithmetic mean. Low values of GSD indicate good dust control. When GSD > 2.5, it is likely that there are no functioning engineering controls.[6]

Thus dust measurements carried out for industrial hygiene purposes, even performed with the same instruments at the same place, can provide very different results, implying capricious decisions concerning both compliance and controls. It is clear that this can lead to all forms and kinds of injustice and may have little to do with the degree of chronic hazard.

For the study of the autocorrelation, we have used the time series made up by a string of consecutive measurements recorded by a recently developed respirable dust continuous measuring instrument [HUND, Wetzlar, West Germany] set up in the tailgate of a German longwall coal face.[7] Figure 1 shows the time series plot of the shift averages at the sampling point at 50 m from the face. It is seen that the range of the shift averages observed during a period of 138 consecutive shifts (4 shifts a day) exceeds a factor of 13.

Consider two concentrations, c(t) and c(t + h), at two shifts t and t + h, separated by the interval h. The autocorrelation between these two quantities is characterized by the variogram function Gamma (h) which in turn is defined as the expectation of the random variable

$$[c(t) - c(t + h)]^2/2.(4)$$

Figure 2 shows the experimental corresponding semi-variogram, to which the following theoretical model has been fitted:

$$\text{Gamma}(h) = 0.15 + 0.11\,(1.5\,h/40 - 0.5\,(h/40)^3),$$

where h is the time lag (i.e. the number of shifts between the sequences being compared). Using this model, allowing for the autocorrelation between the shift averages, GSD of the distribution of the five-shift average concentration over 5 days (one measurement every 4 shifts) can be estimated by using the following formula (Equation 12,(4)):

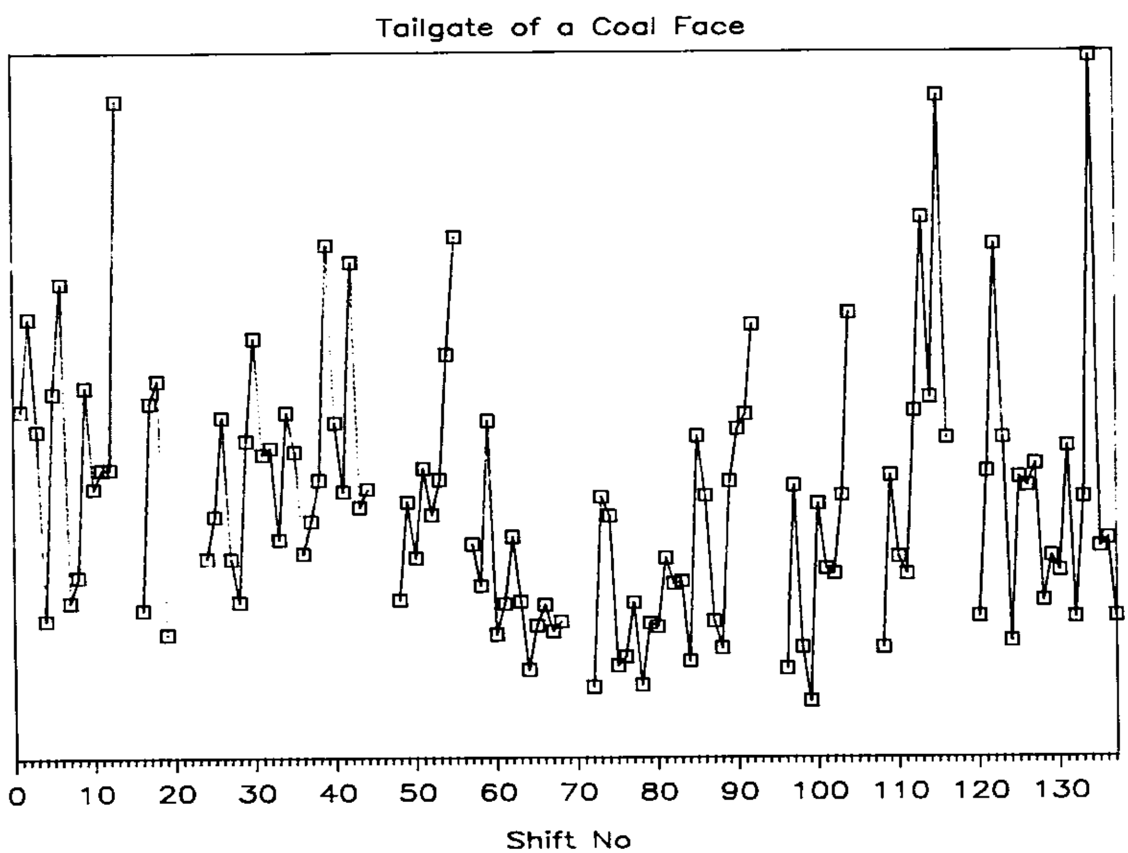

Figure 1. Respirable dust concentration.

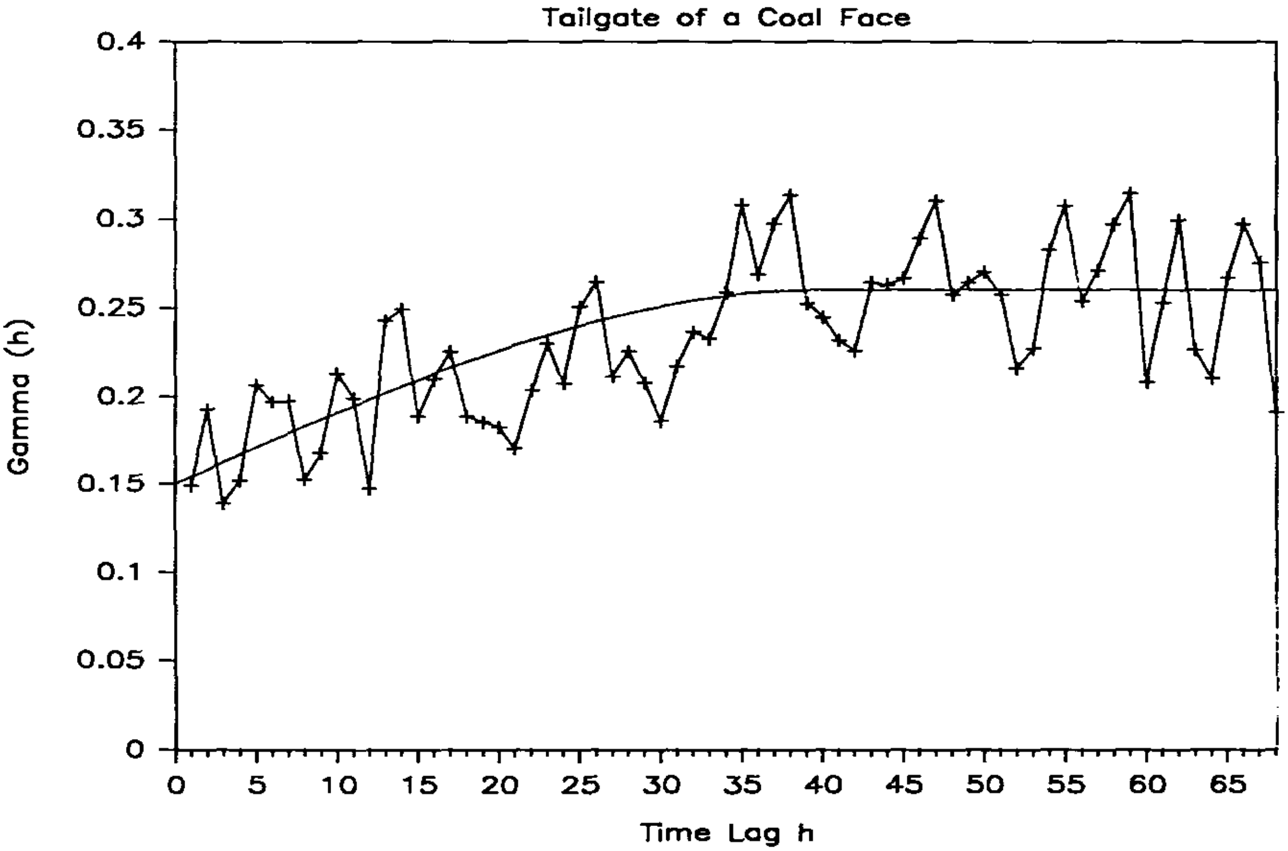

Figure 2. Semivariogram.

$$(\ln GSD)^2 = (\ln 1.7)^2 - 1/10\,(4Gamma(4) + 3Gamma(8) + 2Gamma(12) + Gamma(16)).$$

This leads to GSD = 1.4, instead of

$$GSD = \exp(((\ln 1.7)^2/5)^{0.5}) = 1.27$$

for the averages of five independent shift concentrations.

Figure 2 shows that, for this example, the time interval over which there is autocorrelation between the concentrations, covers 40 shifts (i.e., 10 days).

Note the pseudo-periodicity of the experimental semivariogram, with lower values at h = 8 and 12 shifts, showing a stronger autocorrelation between concentrations measured during the same shift at two or three days intervals. In this case, random sampling would be more appropriate.

Other work situations do not present any autocorrelation. Figures 3 and 4 show, by way of illustration, the respirable dust concentration in a mechanized road heading area.

The strategies were simulated for various values of the geometric mean with 1000 runs in each case. The results are illustrated in Figures 5 and 6 showing the operating characteristics of the monitoring strategies after a maximum monitoring duration of 5 years. From Figure 5, it is seen that the workplaces where the limit is exceeded more than 40% of the time are detected very quickly, usually in less than 5 years operation. Conversely, Figure 6 shows that the probability is very low for finding the workplace in compliance if the exposure exceeds the limit value during at least 40% of the shifts (i.e., with a mean greater than the health standard).

All this means that the compared strategies are extremely conservative. The probability of noncompliance if the mean is lower than the limit ("operator's risk" with all its associated engineering and administrative consequences) is much higher than the chance of finding the workplace in compliance if the mean is above the limit ("worker's risk"). This probability of escaping a citation being less than 5%.

The worker's risk with the Directive on Lead is higher than with the Directive on Asbestos and it is near-zero with the draft modification of the Frame Directive which appears to be the safest strategy but with the highest operator's risk, of unjustifiable expenses and labor problems.

CONCLUSION

As the design of monitoring strategies aims at keeping the "operator's" and "worker's" risks as low as possible, (0,05 being the goal for the last one) it may be concluded that the strategy provided in the Directive on Asbestos is the most efficient. Whilst this strategy allows for a reasonable level of risk for the worker's health, it imposes a lower sampling burden than the others. However the compliance outcome of these strategies is related to the fraction of days above the limit

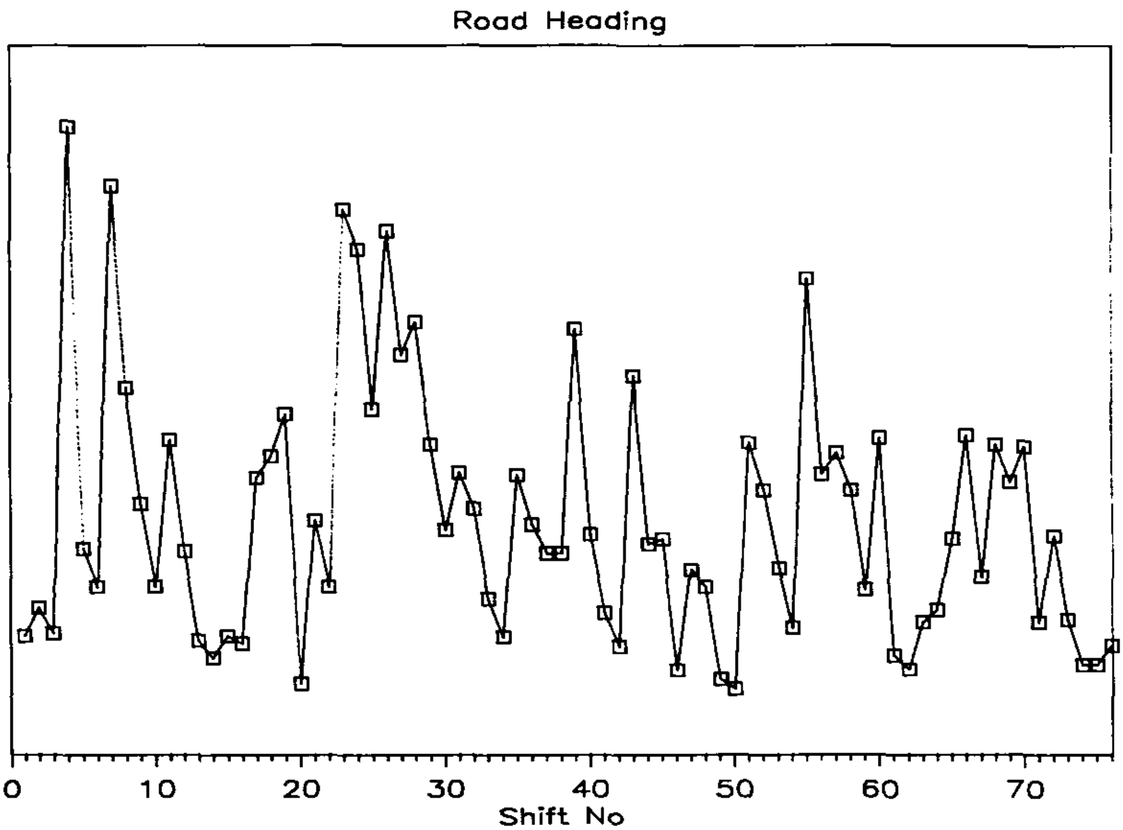

Figure 3. Respirable dust concentration.

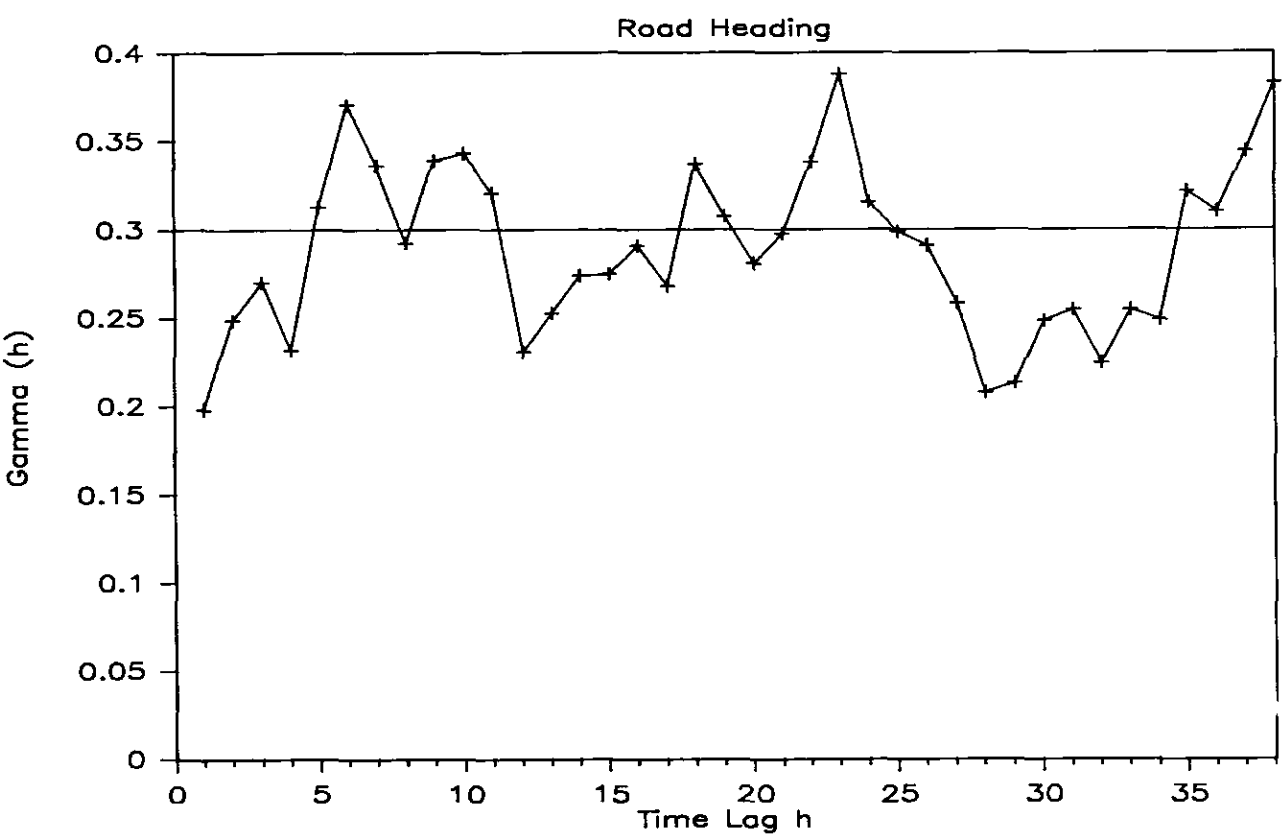

Figure 4. Semivariogram.

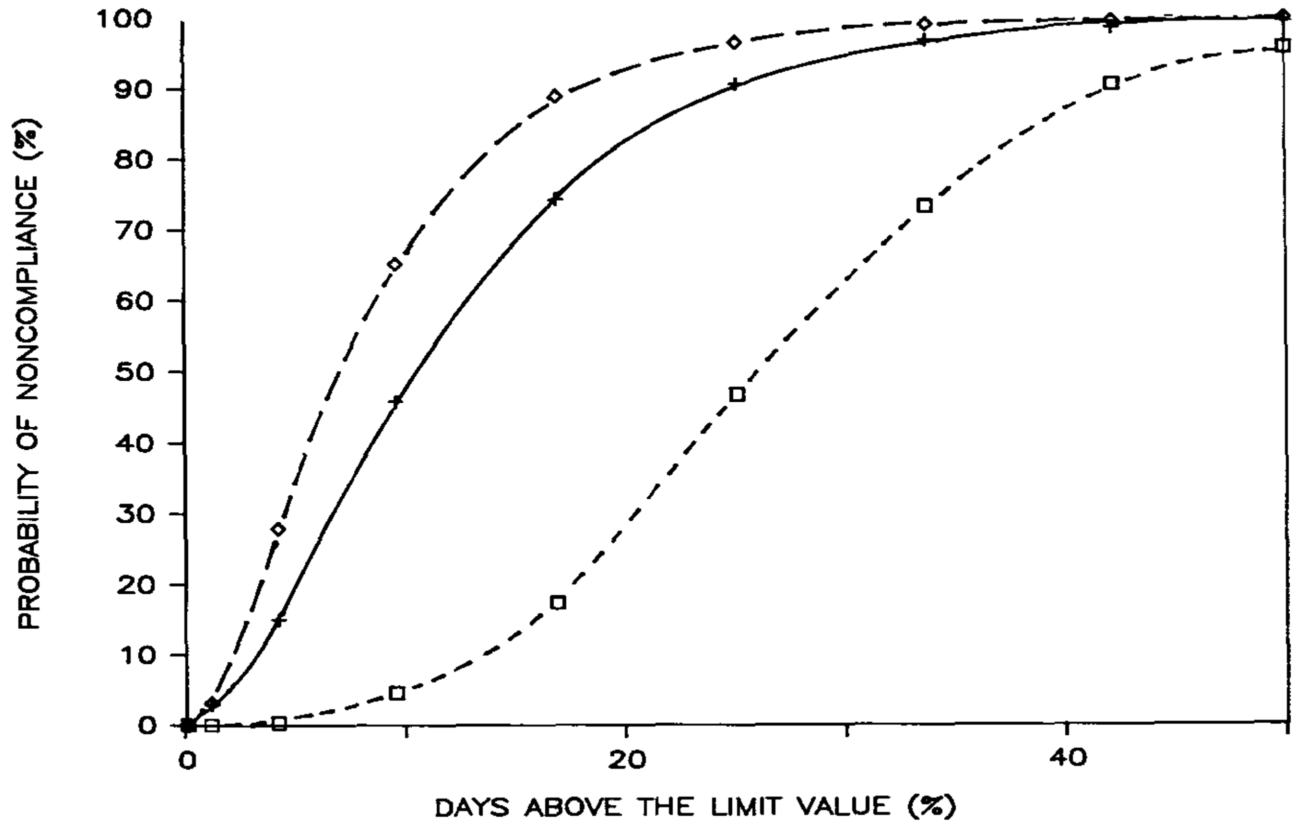

Figure 5. Operating characteristics.

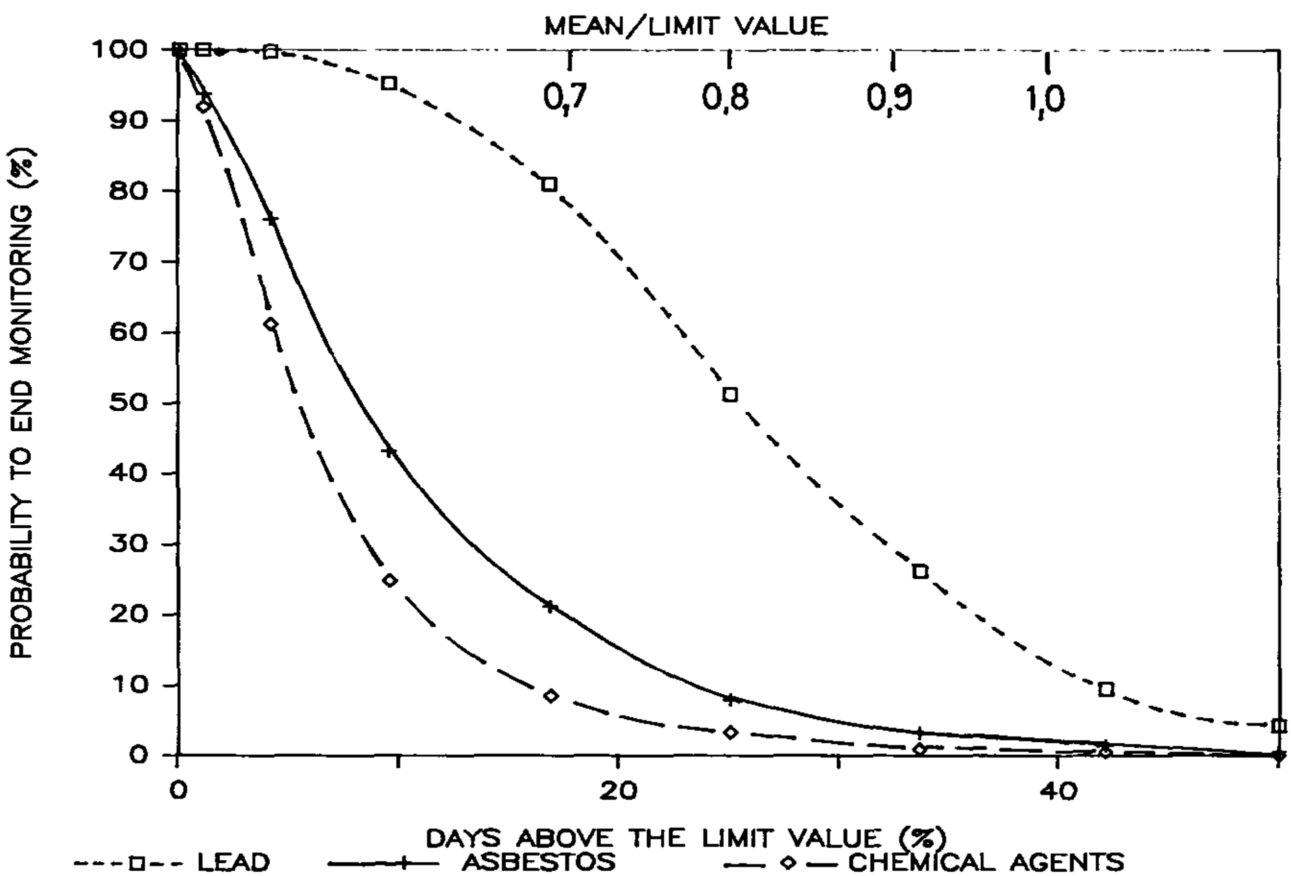

Figure 6. Operating characteristics.

value, whereas the chronic hazard is related to the average level of exposure. Therefore, the Safety and Health Commission for the Mining and Other Extractive Industries of the European Community in its draft proposal on the worker's protection from the risk due to the fibrogenic mineral dust in the non-coal mines and quarries, allows the operator to choose between the asbestos monitoring scheme and the compensation method, this last one being more expensive but with lower operator risk.

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ANALYSIS OF RESPIRABLE COAL MINE DUST SAMPLES BY INFRARED SPECTROSCOPY

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ABSTRACT

To control the health hazard associated with quartz in the United States coal mining industry, Federal regulation requires that whenever the quartz content of the respirable dust in the coal mine environment exceeds five percent, the applicable respirable dust standard be reduced. This regulation, which is applicable for both surface and underground mining operations, has been in force since the promulgation of the Federal Coal Mine Health and Safety Act in 1969. To enforce this regulation, the Mine Safety and Health Administration (MSHA) analyzes approximately 6,000 respirable coal mine dust samples per year for quartz content. The quartz content of these samples is determined using an infrared spectroscopic method.

This paper presents an overview of MSHA's quartz enforcement program, the analytical method used for quartz determination and efforts underway to enhance the sensitivity of the method.

INTRODUCTION

At the time of promulgation of the Coal Mine Health and Safety Act of 1969, the Congress of the United States of America stipulated that a limit be placed on the allowable quantity of quartz to which miners would be exposed. The requirement for this limit was based on work performed in the 1930's and 1940's[1,2] which showed that the presence of quartz increased the health hazard associated with exposure to coal dust. Based on this data, the United States Bureau of Mines in 1948 established a dust exposure limit when the dust in the environment was found to contain more than five percent quartz. The limit at that time, determined by multiplying the dust particle concentration by the percent quartz, was not to exceed five million particles per cubic foot of air.

When the United States Congress promulgated the Coal Mine Health and Safety Act in 1969, they directed that a formula be developed for lowering the applicable respirable dust standard when the quartz content of the dust to which miners are exposed is greater than five percent. Such a formula was developed on March 10, 1971, and was included in Parts 70.101, 71.101 and 90.101 of Title 30 of the Code of Federal Regulations. According to the formula, the applicable dust standard (mg/m^3) is determined by dividing the percent quartz into the number 10 (i.e., standard = 10/% quartz). This formula was continued under the Federal Mine Safety and Health Act of 1977 which amended the 1969 Act.

To enforce this standard, the quartz content of respirable coal mine dust samples is determined by the use of infrared absorption spectrophotometry. Three common methods available for the analysis of crystalline silica are the use of X-ray diffraction, visible absorption spectrophotometry and infrared absorption spectrophotometry. The advantage of using the infrared method over the others for the analysis of coal mine dust samples is that the sensitivity is greater than either that of the X-ray Diffraction Method[3] or the visible absorption spectrophotometric method, also referred to as the Talvitie method.[4,5] In addition, the X-ray method, although able to differentiate between different forms of free silica (quartz, cristobalite and tridymite), is affected by several compounds which have diffraction peaks that interfere with the major peak for quartz. The Talvitie method, which cannot distinguish between the crystalline forms, requires extensive sample preparation using various corrosive acids and is a time consuming procedure.

Since cristobalite, tridymite and amorphous silica, all of which would cause an interference in the infrared analysis for quartz, have not been detected in coal mine dust,[3] the infrared method is ideal for the determination of quartz in coal mine dust samples. From 1970 through 1980, quartz analysis was conducted by MSHA using a high temperature ashing (800°C) technique and the subsequent pelletizing of the ash with potassium bromide (KBr). This procedure required a sample mass of one to four milligrams, thus requiring the compositing (combining) of a number of samples from various coal mine operations to obtain a sample of sufficient weight for analysis.[6] In 1981, the method was upgraded to the current method which is known as the Low Temperature Ashing (LTA) Method. This LTA method allows for the analysis of individual coal mine dust samples containing from 0.5 to 2.5 mg of dust. The method, developed by the Bureau of Mines, has been ruggedized and evaluated.[3]

From 1970 through December of 1985, enforcement of the quartz standard in the United States was determined solely from the analysis of a single sample or composited samples collected by Federal mine inspectors. In December of 1985, MSHA's enforcement policy was revised so that the quartz content of the dust in the environment is based on a number of samples (up to three) collected over a period of several months and includes samples collected by the coal mine operators.

QUARTZ ENFORCEMENT PROCEDURE

The rudiments of MSHA's current quartz enforcement program require the analysis of selected respirable dust samples collected by mine inspectors during the approval or verification of mine operators' dust control plans. Samples typically selected for analysis are those collected on the designated occupation (DO), that occupation in an underground mining operation that has the highest respirable dust exposure, the roof bolting (RB) operation in underground mining and designated work positions (DWP) in the surface coal mining industry. If the analysis of any of these samples shows that the quartz content is in excess of five percent, the mine operator is notified of the option of collecting a sample for analysis on the mine entity representative of the original sample which was in excess of five percent quartz. If the difference between the quartz percentage of the operator's sample and the quartz percentage of the MSHA sample is within plus or minus two percent, (e.g., MSHA value seven percent, operator value five to nine percent) the results of the two analyses are averaged and the respirable dust standard is set accordingly. If the quartz determination of the operator's optional sample differs from the MSHA sample by more than plus or minus two percent, the operator is given the option of collecting a second sample on the mine entity. Following analysis of the operator's second sample, the average quartz percentage is determined from the three samples (MSHA sample plus the two samples submitted by the operator). If the operator elects not to collect a sample or if the samples submitted have insufficient dust for analysis (less than 0.5 milligrams), the standard is adjusted based on the analysis of the MSHA sample. At six month intervals, any entity on a reduced standard is automatically reevaluated by analyzing for quartz one of the mine operator's samples submitted for dust compliance, provided there is sufficient weight gain on the sample. Analysis of MSHA inspector samples, mine operator optional samples and six month operator samples accounts for the analysis of approximately 6,000 samples per year.

ANALYTICAL METHOD

Analysis of respirable coal mine dust samples for quartz is conducted in a central laboratory located in Pittsburgh, Pennsylvania. The operation of this laboratory is a function of MSHA's Pittsburgh Health Technology Center. The analytical method used for the analysis employs the principle of infrared spectrophotometry. The current LTA method allows for the analysis of the quartz content of a sample with a mass of 0.5 milligrams or greater. The method has a detection limit of 10 micrograms of quartz and a precision of 13 to 22 percent for quartz masses ranging from 25 to 160 micrograms.[3]

Samples are collected with approved respirable coal mine dust sampling assemblies equipped with a quartz-free, ashable filter medium. Following weighing of the filter to determine sample mass, the filter medium is ashed in a low-temperature ashing system. This ashing system, shown in Figure 1, operates at a temperature of approximately 120°C and utilizes radio frequency energy to generate an oxygen plasma which destroys the filter matrix and the carbonaceous material present in the sample.

Following ashing, isopropyl alcohol is added to the residue. The residue is dispersed in the alcohol using an ultrasonic generator. The suspension is filtered onto one half of a Gelman DM-450 vinyl metricel filter. The filtering is accomplished by washing the sample through a specially constructed, glass filter funnel on a vacuum manifold system, shown on Figure 2. The funnel is designed to produce a 10 millimeter diameter deposit. Once filtration is complete, the filters containing the ashed deposits are dried on a slide warmer for approximately 20 minutes at a temperature of approximately 42°C.

Analysis for quartz is then conducted using a dispersive infrared spectrophotometer. The DM-450 filter half containing the ashed residue is mounted in a sample holder and placed in the sample beam of the infrared spectrophotometer. A blank DM-450 filter half which has been treated with alcohol and dried is similarly mounted in the reference beam of the instrument. Following appropriate parameter setting of the infrared instrument, the sample is scanned in the absorbance mode from 1,000 to 710 cm^{-1}. Quartz absorbs infrared energy in the 800 cm^{-1} region. The clay mineral kaolinite, which is also found in coal mine dust, also absorbs infrared energy in this region.[3] Its presence causes a slight overestimation of the quartz content. To correct for this overestimation, the absorption for kaolinite is measured at 915 cm^{-1}. Thus, measuring the absorbance of infrared energy by the sample from 1,000 to 710 cm^{-1} allows for the quantification of kaolinite at 915 cm^{-1} and the correction for its interference with quartz absorbance at 800 cm^{-1}.

Figure 3 shows a sample of an infrared scan of a typical coal mine dust sample. As illustrated on the figure, the peak intensities at 915 and 800 cm^{-1} are determined by measuring the height from established baselines to the peak maximums. The baselines are drawn from 950 to 890 cm^{-1} for the 915 cm^{-1} kaolinite band and from 810 to 760 cm^{-1} for the 800 cm^{-1} quartz-kaolinite band. The measured net peak heights are converted into absorbance units and the interference due to kaolinite is determined from a calibration curve of kaolinite absorbance at 915 cm^{-1} versus kaolinite absorbance at 800 cm^{-1}. The calculated absorbance for kaolinite at 800 cm^{-1} is subtracted from the measured absorbance at 800 cm^{-1} (quartz-kaolinite) to give the absorbance due to quartz. The amount of quartz is determined from a calibration curve of absorbance of quartz at 800 cm^{-1} versus mass of quartz.

For MSHA's quartz enforcement program, -5 μm Minusil, a commercial product of the Pennsylvania Glass Sand Company, Berkeley Springs, West Virginia, is used as the quartz standard.[7] Kaolinite used for the standard is Hydrite UF, supplied by the Georgia Kaolin Company, Elizabeth, New Jersey.

Once the analysis and calculations are completed, the percent quartz in the coal mine dust sample is computed by using the following equation:

$$\text{quartz (percent)} = \frac{\text{mass of quartz } (\sigma g)}{\text{mass of coal mine respirable dust } (\sigma g)} \times 100$$

The percent quartz determined for a coal mine dust sample is truncated to the whole percent value which is subsequently used in the formula for the determination of the reduced coal mine dust standard when the quartz percentage is in excess of five percent (reduced standard = 10/% quartz).

To insure the integrity of the quartz analyses performed, MSHA conducts an internal quality assurance program. This program consists of the analysis of three specially prepared samples, containing varying known quantities of quartz, with each group of 20 to 25 samples analyzed. The mass of quartz on each of the three quality control samples is unknown to the analysts. These samples undergo the same processing as the coal mine dust samples; i.e., ashing, deposition by filtration and IR scanning. The analysis of these samples is used to verify that the process is controlled, assuring the reliability of analytical results.

IMPROVEMENTS TO ANALYTICAL CAPABILITY

In an effort to improve the sensitivity of the present analytical technique, MSHA recently acquired a Fourier transform infrared spectrophotometer (FTIR). A FTIR operates differently than a dispersive infrared spectrophotometer. A FTIR employs an interferometer to obtain information about the transmission of infrared energy of all wavelengths (simultaneously) emitted by the source and passing through the sample, whereas a dispersive spectrophotometer uses a monochromotor and slit system to divide the infrared radiation into frequency elements. The interferometer of the FTIR contains a fixed mirror and a moving mirror, the position of which is determined by a helium-neon laser. The information obtained from a sample is digitally stored as signal intensity versus mirror displacement as shown in Figure 4. This is known as an interferogram. The instrument's computer then performs a Fourier transform of the interferogram to produce the desired absorbance versus frequency (in wave numbers) spectrum as shown in Figure 5.

The FTIR has many advantages over the dispersive instrument. Since there are no entrance or exit slits in the FTIR, a greater amount of energy reaches the detector, resulting in increased sensitivity. The laser tracking of the moving mirror results in greater precision of the wavelength measurement, permitting multiple scans to be averaged and thereby increase the signal to noise ratio of the absorbance spectrum. Precise duplication of the analytical frequencies and computer control of the calculations with the FTIR reduce the errors associated with the electromechanical components of the dispersive instruments and the necessary manual measurements of frequencies and peak intensities.

Figure 1. Low-Temperature ashing system.

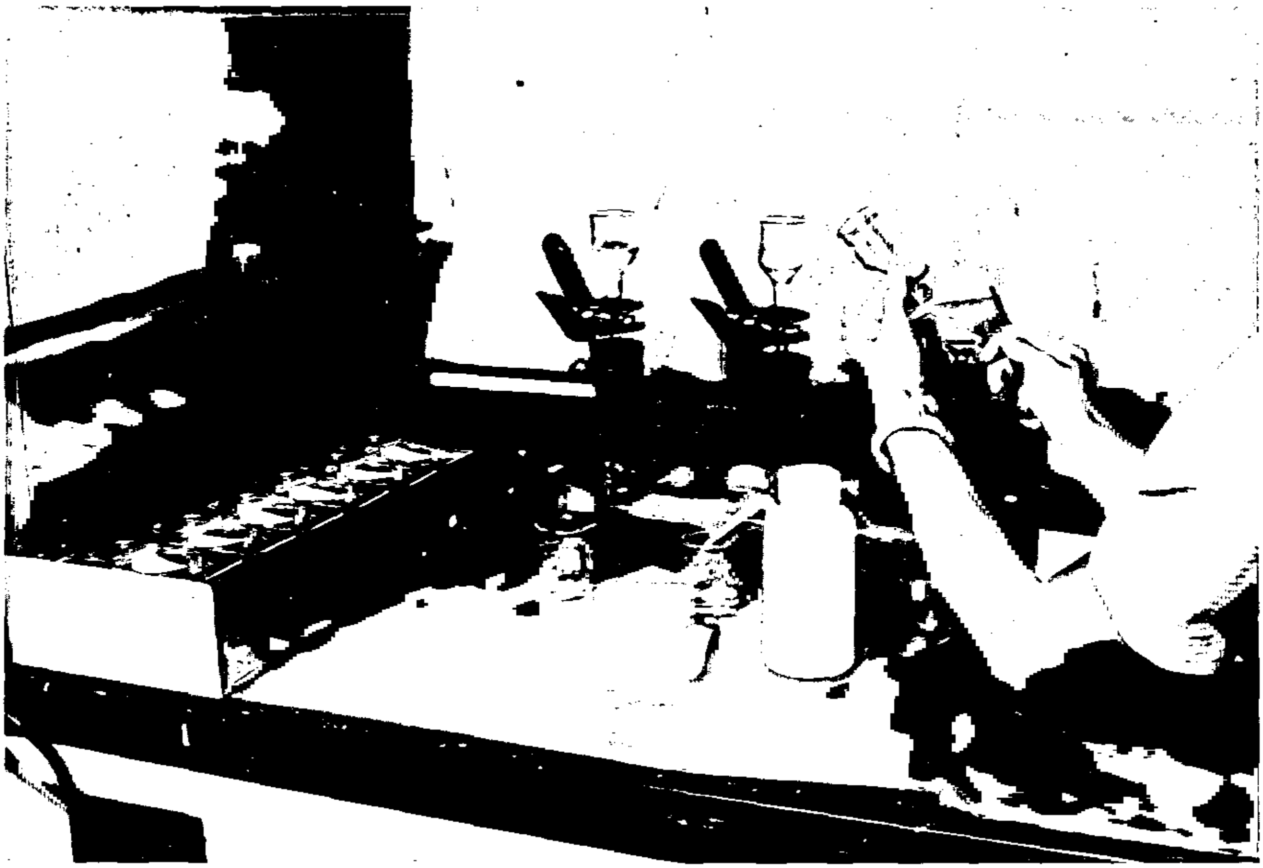

Figure 2. Vacuum filtration of ashed samples.

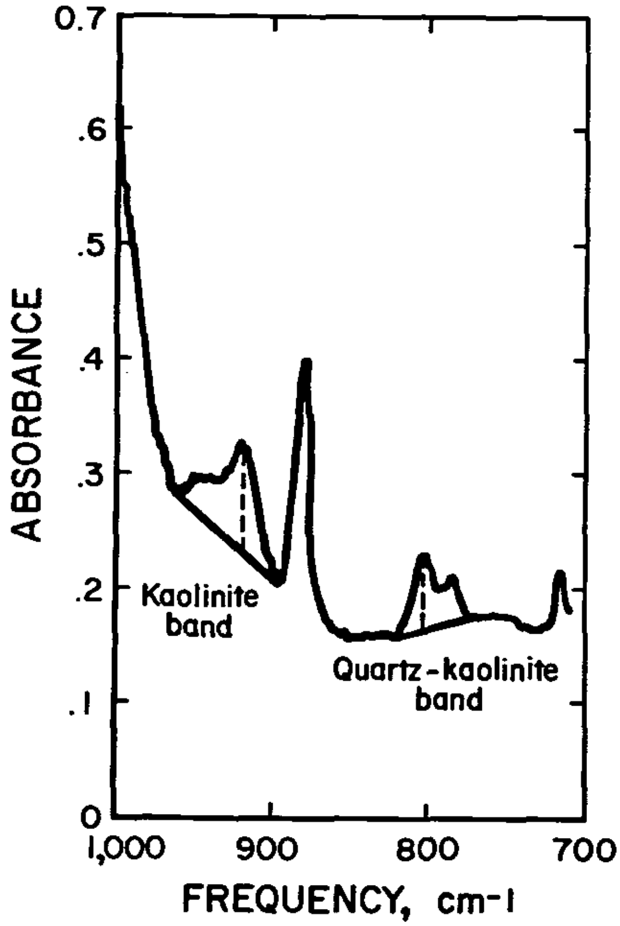

Figure 3. Infrared scan on dispersive IR of a coal mine dust sample showing manually drawn baselines and peak locations.

The current quartz analysis procedure employing dispersive IR is used to detect from 25 to 250 micrograms of quartz for coal dust sample masses ranging from 0.5 to 2.5 milligrams. With the FTIR, it is anticipated that 10 micrograms of quartz will be detectable in coal dust samples with as little mass as 0.2 milligrams. This factor is of considerable importance since many respirable coal mine dust samples obtained in the surface coal mining industry are of low mass, yet have greater than five percent of quartz. This system should allow for the analysis of such samples. The computerization of the data handling will, likewise, automate output and eliminate tedious and redundant tasks which are currently performed manually.

SUMMARY

The United States Congress realized the hazard associated with coal miners' exposure to quartz and, when issuing the Coal Mine Health and Safety Act of 1969 and the subsequent Coal Mine Safety and Health Act of 1977, stipulated that exposure to quartz be controlled. Exposure to quartz is controlled by reducing the applicable dust standard when the dust is found to contain quartz levels in excess of five percent.

To determine the quartz content of respirable coal mine dust, MSHA utilizes an infrared spectrophotometer to measure the absorbance of infrared energy by quartz in a dust sample. This analysis is conducted following the destruction of the combined sample and filter matrix by a low temperature ashing process and subsequent filter redeposition of the ash containing the quartz. Since the mineral kaolinite interferes with the quartz determination, a correction is made to the result obtained.

In order to automate the processing of samples and obtain a lower level of detection, the use of a FTIR to analyze coal

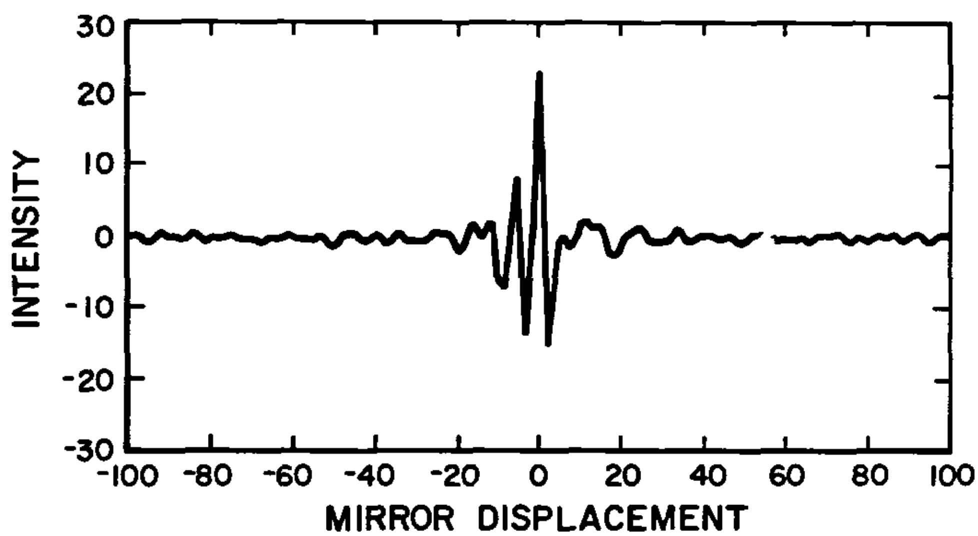

Figure 4. Interferogram of a pure quartz sample.

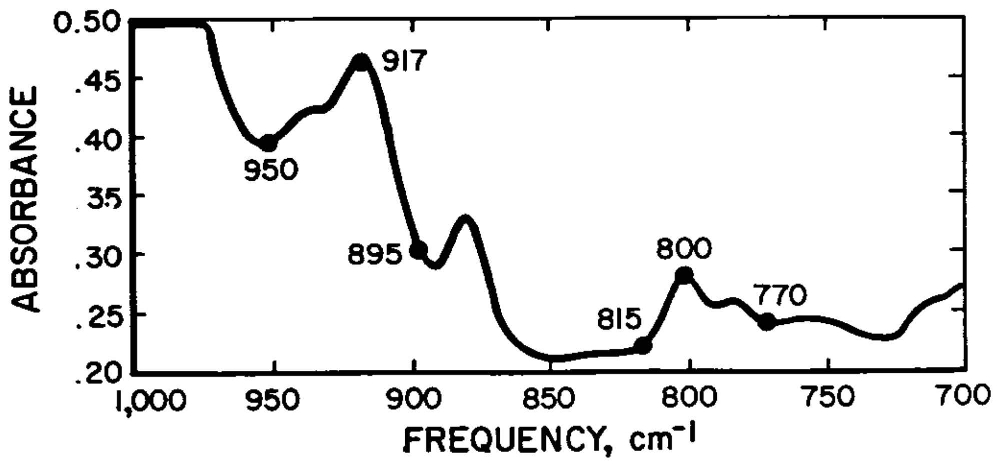

Figure 5. Absorbance spectrum from FTIR of a coal mine dust sample with kaolinite and quartz-kaolinite frequencies indicated.

mine dust for quartz content is being investigated. It is anticipated that a quartz mass of 10 micrograms will be detectable in respirable dust samples with masses as small as 0.2 milligrams.

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EFFECT OF THE MEASURING STRATEGY ON THE DETERMINATION OF THE RESPIRABLE DUST CONCENTRATION IN THE BREATHABLE AIR AT UNDERGROUND WORKPLACES

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INTRODUCTION

The dust conditions at the underground workplaces are permanently discussed worldwide. These discussions are always based on the absolute values of the respirable dust concentrations in the breathable air indicated in mg/m^3 (Figure 1). They provide information on the effective limits for the permissible respirable dust concentrations and on the results of the statutory dust measurements. These values are also used to reflect the state of the pneumoconiosis prevention and dust suppression in the various hardcoal mining countries.

In the following it is intended to show that the respective indicated absolute values are not suitable for a comparison of the dust load of miners in different countries, the reason for this being that the rules for the determination of the values, i.e. the measuring strategies, are not included in the discussions. The existing different measuring strategies have, however, significant effects on the magnitude of the measured absolute values. Thus, there is no uniform basis for an objective comparison. The measuring results are significantly influenced by the following parameters of the measuring strategy:

- the position of the measuring point;
- the time required for an individual measurement; and
- the frequency of the measurements.

Measuring Strategy in Different Countries

According to the measuring strategy effective in the Federal Republic of Germany (FRG) (Figure 2) since 1954 the respirable dust concentration has to be measured at the location of a working area at which the maximum dust concentration has to be expected. In this context it is generally assumed that in working faces this location is situated, seen in ventilation direction, at the face end respectively the end of the working area. Measurements are taken once a month under normal operating conditions. The measurement period corresponds to the time the miners stay at their workplaces. Over a period of five years each the preset limits for the dust exposition of the miners must not be exceeded. Higher individual shift values which have to be compensated over the 5 year period are, however, permissible.

The measuring strategy in the FRG is based on the following considerations:

1. For the people employed in the environment of the measuring point, the measuring result is sufficiently accurate.
2. The impact of dust on people employed on the intake side upstream the measuring point is overrated by the "high risk method."
3. By overrating higher urgency is attributed to the measures for a prevention of dust impact on the employees.
4. One monthly measurement over a 5 year period is sufficient as the dust load of each miner is determined with sufficient accuracy by 60 measurements in five years.

In Great Britain (GB) measuring values of a fixed measuring point located in the return airway approx. 70 m behind the face are used to assess the dust conditions at the workplaces in the face. The fact that it is only there that the measuring results are no longer influenced by the coarse dust or the unequal distribution of the respirable dust in the air is given as a reason for the choice of this location. The partial sedimentation of the dust between the face and the measuring point is considered by correction factors. Measurements are taken in monthly intervals. As in the FRG the time of a measurement corresponds to the time the miners stay at the workplace. The number of measurements in one month depends on the size of the measured individual fine dust concentration. At values < 15 mg/m^3 one measurement per month is sufficient. At values > 8 mg/m^3 the average has to be calculated from up to five subsequent measurements in one week.

The main point in the measuring strategy of the Soviet Union (USSR) is the monitoring of dust suppression in the face. When cutting coal with shearers the air-borne dust concentration with grain sizes of up to 74 μm without preseparator is determined directly behind the shearer, when ploughing the coal it is determined at the face end. The strategy for these dust measurements has the main objective to improve the efficiency of dust suppression measures. The measuring time per measurement amounts to a few minutes during the coalgetting process. The measurement is repeated in monthly intervals if the measuring result shows a value ≤ 10 mg/m^3. At higher values the measurement is repeated directly after improving dust suppression.

The measuring strategy in the United States of America provides for a measurement of the acting respirable dust concentration by means of "personal dust samplers" directly at the employee. For the measurement the person exposed to the highest dust load in the face may be chosen as representative for all employees of one face. This measuring method called "designated occupation" is also based on the "high risk"

	Tolerable Dust Concentration mg/m3	Dust Fraction	Quartz Valuation
RUHR	8.0	respirable	yes
SAAR	4.0	respirable	no
USA	2.0	respirable	yes
GB	5.0	respirable	no
USSR	2.0	inhalable	yes
RAG Ruhrkohle AG	Limit Values for Dust in Coal Mines		Arbeits-schutz

Figure 1.

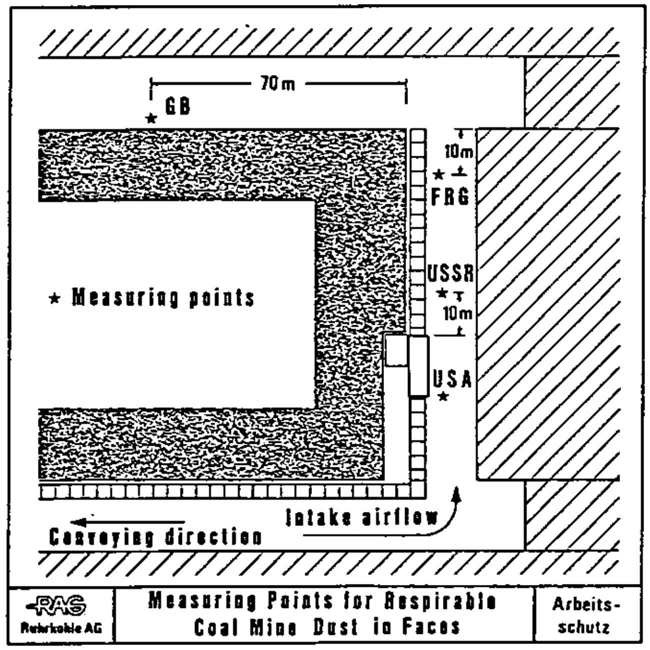

Figure 2.

process as the measuring strategy in the FRG. In faces the workplace of the shearer operator is mainly chosen as "designated occupation." This is justified if nobody is employed behind the shearer for more than two hours during the shift.

The respirable dust concentration at the workplace or the measuring point is assessed in two-monthly intervals by the averege of 5 measurements taken in 5 subsequent production shifts. If the limit is exceeded additional measurements have to be carried out in the following production shifts and a new average has to be calculated from 5 subsequent measuring values. The measuring series is interrupted if one average reaches or remains below the limit. The measuring time of each individual measurement corresponds to the shift length, i.e. working time plus travelling time.

The effect of the measuring strategy on the size of the measuring values can be illustrated by means of an example for respirable dust measurements in 10 faces of Ruhrkohle AG (Figure 3).

In each of these faces several measuring points were installed in regular intervals. The respirable dust concentration was measured over a longer time period in the first production shift of each day with the miners at their workplaces. In the diagram the monthly averages of the respirable dust concentrations in mg/m^3 are listed on the ordinate, the face length in % on the abscissa.

At the face entry, i.e. at face meter "0", the respirable dust concentration in the intake air of the face was listed.

In nine of the ten faces the respirable dust concentrations increase in different magnitudes towards the face end where they reached their highest values. The different increase is governed by work sequence, machine type, support, ventilation volume, ventilation velocity, etc. In one case—i.e. face 8—in contrast, the initial concentration is already so high that the sedimentation over the face length is higher than the concentration increase caused by the coalgetting operations.

According to the measuring strategy of the USA all employees in the face would be exposed to the dust concentrations of the intake air flow, i.e., the initial values of the graphs on the extreme left of the diagram, under the prerequisite that:

1. The shearer operator stands on the intake air side in front of the machine;
2. The dust produced by coalgetting is blown away from the site of the shearer operator; and
3. Bypasses the chock fitters.

A possible slight increase in the dust concentrations in the intake air flow towards the workplace of the operator by turbulences is negligible in this approach.

Applying the German measuring strategy these velues are contrasted by the concentrations of the fixed measuring points which in contrast to the USA are, however, located at the face end. This means (Figure 4) that in a comparison of the values up to 9 times higher values have to be assigned to the employees due to the German measuring strategy with the measuring point at the face end compared to the American strategy. Even in case of a subdivision of the face into two monitoring sections with measuring points in the center and at the end of the face up to 6 times higher values are still calculated for the employees in the lower face section according to the German measuring strategy. On average the concentrations at the face entry and the face end differ by the factor 3.9 and the concentrations at the face entry and the face center still by the factor 2.4.

The determination of the measuring values in Great Britain is again significantly different from the determination of the measuring values in the USA and the FRG. On the one hand additional dust sources between the face and the measuring point are registered, on the other the measuring result is corrected by a factor for sedimentation which was developed specifically for British mines. It may, however, hardly be applied worldwide.

CONCLUSION

From the mentioned comparison it may be derived that both the dust limits and the absolute respirable dust concentration figures cannot be referred to in a comparative representation of the dust conditions in different countries.

Also the dust suppression measures applied in the different countries have to be seen under this aspect. The measuring strategies of the FRG, GB and the USSR call for measures reducing the dust concentration in the entire return air section. In the United States dust suppression may center on the intake air section up to the coalgetting machine (Figure 5). This becomes particularly clear in the "shearer clearer" process. The dust produced by the coalgetting operations is kept away from the measuring point. Without doubt this process has the advantage of reducing the dust load for machine operators and chock fitters.

Face No.	USA / FRG Head - Tail	USA / FRG Head - Centre
1	1 : 2.1	1 : 1.6
2	1 : 5.4	1 : 2.8
3	1 : 2.7	1 : 1.7
4	1 : 4.3	1 : 2.0
5	1 : 6.0	1 : 3.1
6	1 : 3.1	1 : 1.8
7	1 : 8.8	1 : 6.0
8	1 : 0.7	1 : 0.8
9	1 : 2.3	1 : 1.9
10	1 : 3.4	1 : 2.3
	Ø 1 : 3.9	Ø 1 : 2.4

RAG Ruhrkohle AG | Factor of Respirable Coal Mine Dust in Faces: USA / FRG | Arbeitsschutz

Figure 4.

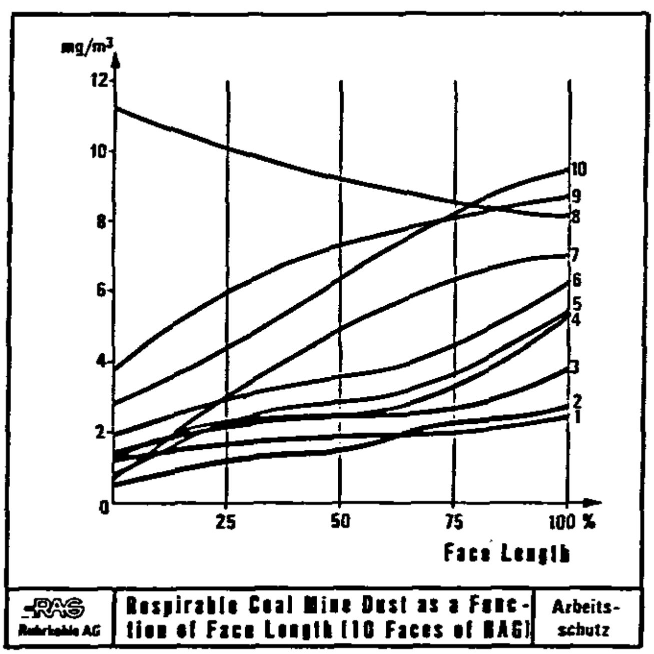

Figure 3.

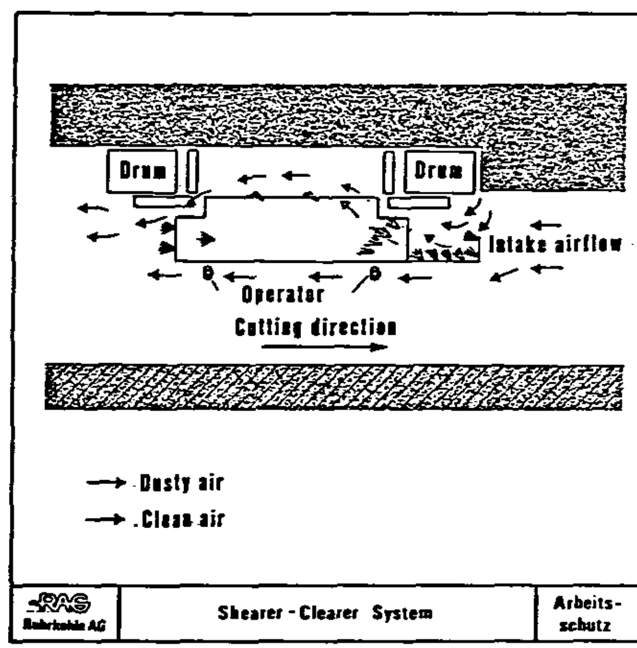

Figure 5.

These comments were intended to show that:

1. The different measuring strategies will inevitably have to result indifferent limits;
2. The measuring values and limits determined by one measuring strategy can only be compared in its scope of validity;
3. Identical absolute values of the different countries do not describe also identical dust conditions or dust impact;
4. Limits provide for a statement on the pneumoconiosis risk of the employees only in their scope of validity.

The comments of Dr. Bauer (FRG) on the impact of different measuring devices, tyndallometer, cycloneseparator, horizontal elutriator, on the result of respirable dust measurements underline the mentioned reservations against a comparison of measuring values and limits.

These comments are not intended to be an assessing statement on the measuring strategies but are only meant to explain the fact that measuring values and limits cannot be compared as long as they are based on different measuring strategies.

The uncritical comparison of measuring values and limits from different measuring strategy scopes involves two dangers:

1. That a race towards actually desirable but technically not feasible limits is started; and
2. That the statement on the pneumoconiosis risk of a mining region in relation to the dust impact is wrong if risk determinations are taken over from other measuring strategy scopes.

For an international comparison of the dust load to which the miners in the hardcoal mines are exposed, it is thus required to use identical reference measuring equipment and to apply an identical reference measurement strategy.

RESPIRABLE DUST AND FREE SILICA VARIATION IN MINE ENVIRONMENTS

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Regulations promulgated and enforced by the Mine Safety and Health Administration (MSHA) require that coal mine operators control respirable mine dust to prescribed concentrations.[5] Specifically, coal mine operators must regularly sample (bimonthly) respirable mine dust (RMD) in working mine sections. MSHA on a less frequent basis (once a year) also samples and evaluates RMD and its free silica (FS) content in working coal mines. Sampling is performed by MSHA and mine operators in order to: 1) establish permissible RMD levels in working mine sections when free silica is present; and 2) demonstrate compliance with permissible exposure limits prescribed in regulations. In non-coal mines the sampling frequency is less well defined.

Since passage of the Coal Mine Safety and Health Act of 1969 and the Mine Safety and Health Act of 1977, enormous resources have been focused on controlling RMD in mines with highly satisfactory results. The vast majority of U.S. coal and non-coal mines consistently meet the appropriate RMD Permissible Exposure Limits (see Formula 1) promulgated by MSHA.[12]

In the past five years, more inspector RMD samples have been analyzed for free silica. This has occurred because the analytical technique MSHA uses for the detection of free silica in coal mine dust has been refined and improved resulting in lower detection limits. The use of the "improved" analytical technique has suggested to many that MSHA has placed increased emphasis on enforcement of the coal mine respirable dust (containing free silica) standard. The standard for respirable dusts containing free silica used in coal mines invokes a "sliding scale" to determine the allowable RMD concentration. For % FS concentrations >5, Formula 1 is used to calculate the permissible RMD concentrations in coal mines.

$$\underset{(\text{for }\%\text{ FS} > 5)}{\text{RMD, mg/M}^3} = \frac{10}{\%\text{ FS}} \qquad (1)$$

The purpose of this investigation was to gain insight into the extent of FS variation in RMD samples collected from a sample of U.S. coal and non-coal mines. A second goal of this study was to determine the factors (mining operation variables, etc.) associated with this variation. Specifically, the following questions were addressed:

- How large is the sampling and laboratory error in measurements of respirable mine dust concentration (RMD), free silica (FS) and percent free silica (% FS)?
- Is the sampling and laboratory variability different in personal and machine samples, across occupations or mines?
- Is exposure to RMD and FS systematically different across occupations or mines?
- How large is the temporal variability in RMD, FS and % FS?

Thirteen mines, seven coal and six non-coal mines initially offered opportunities for dust sampling in this study. Of the thirteen mines originally volunteering for the investigation, ten (six coal and four non-coal) provided samples for analysis. Each participating mine was required to collect six air samples per day for five consecutive days. The six daily air samples were divided among five occupations with one miner wearing two samplers (paired sample). A total of 374 personal and area samples were collected in the participating mines during 55 sampling days.

Mine dust technicians from the participating companies were used to collect the air samples. Before these individuals were allowed to take part in the investigation they had to participate in a workshop presented by the study authors. Additionally, each participating mine was subjected to a site visit during the sample collection period to insure that the prescribed techniques for sample collection were being used. After collection all dust samples were forwarded to, and analyzed by an independent, accredited laboratory. Results of laboratory analyses of samples were transmitted to JHU for statistical analyses and interpretation of results.

All samples were collected using Mine Safety and Health Administration (MSHA) prescribed procedures with some minor modifications. The samples were analyzed at two commercial laboratories for respirable dust and free silica using the P7 analysis routine. The onsite dust technician or industrial hygienist responsible for sampling completed a standardized questionnaire. Data from questionnaires were analyzed by JHU investigators, as were the analytical results of dust samples.

LITERATURE REVIEW

The Mine Safety and Health Administration requires that coal mine operators conduct extensive sampling for respirable mine dust and airborne free silica. The goal of this sampling is to measure progress toward achieving promulgated dust standards and thus reduce the occurrence of pulmonary disease among the mining population. MSHA's strategy for controlling exposure to pneumoconiosis-producing dusts employs a sampling scheme which utilizes a worst-case scenario.

Although there is extensive scientific and technical literature which addresses the variability of measured mine dust concentrations resulting from the dust sampling process, few studies have sought to define the variability associated with sampling for respirable dust and its free silica content in mine environments. Factors affecting variability of airborne free silica dust, such as occupation, production rates, equipment operating time, and other mine and production variables have not been examined.

The most widely publicized investigation of measured dust concentration variability is a GAO report to Congress.[6] In this report, the GAO indicated that under certain conditions the error associated with respirable mine dust samples could be as great as 50%.

An investigation by the Bureau of Standards studied respirable mine dust sampling and analysis.[8] While focusing specifically on sampling and analysis (gravimetric) for respirable mine dust, each step in the sampling process was examined, e.g. dust weighing, pump flow variation, etc. It was concluded that under tightly controlled conditions with a "well-trained" technician, the average standard deviation associated with the process was ±0.39 mg/M^3, or 19% (@ the 2 mg/M^3 RMD concentration).

In 1976, NIOSH found that in high risk mine sections (those which had been repeatedly found to be in violation of the 2 mg/M^3 standard) the coefficient of variation for RMD measurements was 91.6%.[9]

In 1980, the National Research Council concluded that uncertainties associated with spatial and temporal variation in RMD estimates from machine mounted samplers precluded this method for estimating personal exposures.[10]

In 1983, a literature review by investigators at the Johns Hopkins School of Hygiene and Public Health concluded that the factors responsible for the variation in RMD had not been quantitated for free silica and estimates of free silica were at least as unreliable as those of RMD.[3] More specifically stated, "Because of the unavailability of data on free silica variation in coal mine respirable dust, the representativeness of a single sample analyzed for free silica can not be assessed." The authors went on to state that the use of a single air sample to determine free silica content of mine environments is meaningless.

Page and Jankowski compared RMD measurements made using a real-time aerosol monitor (RAM-1) and a standard gravimetric sampler at a longwall mining operation.[11] The authors reported ratios of paired RAM-Gravimetric sampler results, expressed as concentrations of RMD ratios of 0.41 to 1.63. The authors attributed this variation to differences in the aerosol cloud being sampled, air flow velocity at the filter face and cyclone orientation.

Burkhart, et al, in a presentation at the American Industrial Hygiene Conference in Dallas, Texas reported data from a limited number of air samples collected from bituminous coal mines in West Virginia.[2] The authors reported %FS concentrations ranging from 2 to 30% in five samples collected on five consecutive days. The samples reported were personal air samples collected on the operator of the continuous mining machine. The source of this variability was not discussed.

Breslin, et al, in a Bureau of Mines Circular reported that for both personal and fixed-point (area) samplers the coefficient of variation for RMD was typically less than 20%.[1]

Kissell, et al, reviewed several factors thought to contribute to RMD and FS variability.[7] The authors, while not specifically evaluating potential contributions to variation from mine sources, concluded that sampler position, geological variation in composition of coal, production factors such as deep or continuous cutting and failure to control known sources such as shuttle car loading, play an important role in RMD and FS sample results.

PAIRED SAMPLE ANALYSIS AND RESULTS

Sampling and laboratory variability for respirable mine dust, free silica and percent free silica were studied using 23 and 20 pairs of dust samples from coal and non-coal mines, respectively. Paired samples were defined for this study as two samples collected on the same occupation for the same time period and located not more than 14 inches apart. For this analysis, the ratios of the RMD and FS parameters were analyzed to determine variability. % FS was analyzed using the differences between the paired values. Figures 1-3 display the cumulative frequency distributions of RMD, FS and % FS, respectively. All three dust parameters exhibit large variability.

Results of this analysis are presented in Table I and are briefly summarized as follows:

Coal Mines

- The respirable mine dust *ratios* (larger to smaller values) exceeded 1.5 in half of the paired samples and 2.5 in 10% of the pairs.
- For free silica, 50% of the pair *ratios* exceeded 1.52; 10% exceeded 5.7.
- For % free silica, the *differences* (larger minus smaller) exceeded 1.3% in half of the pairs and 5.6% in one out of ten.

Non-Coal Mines

- The variability of respirable mine dust was somewhat less in non-coal mines with 50% of the samples having *ratios* greater than 1.13. 10% of samples demonstrated ratios of 6.19. (This was due to a few extreme outlier sample pairs.)

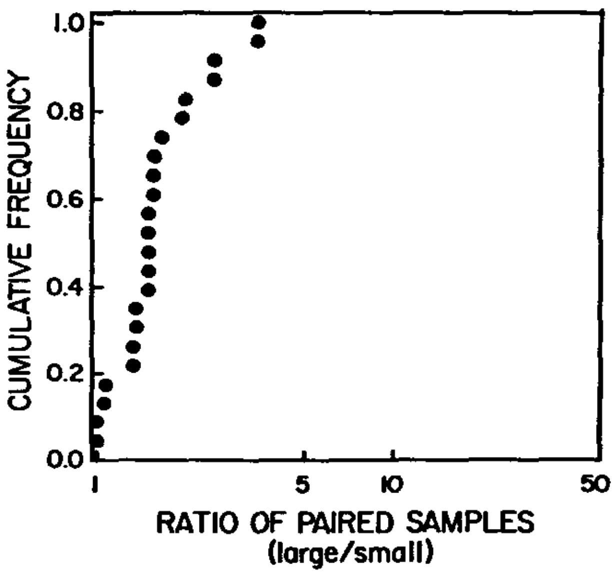


Figure 1. Cumulative distribution of RMD sample pair ratios.

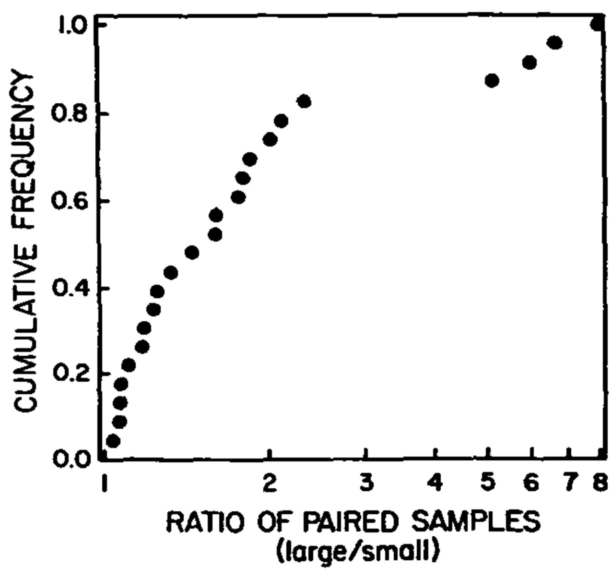


Figure 2. Cumulative distribution of FS sample pair ratios.

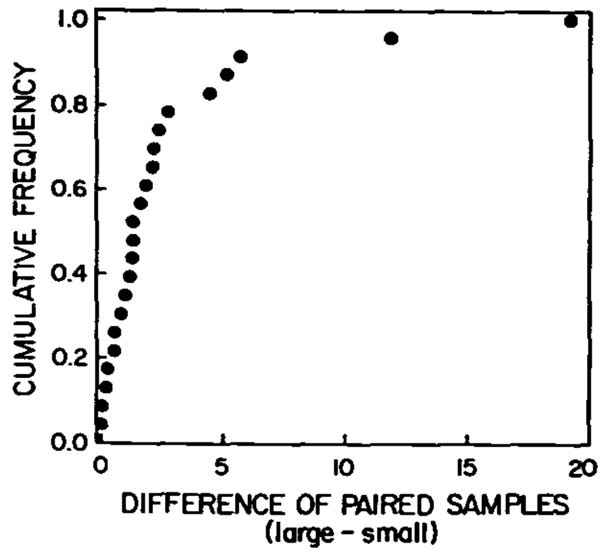


Figure 3. Cumulative distribution of % FS sample pair differences.

- For free silica, 50% of the respirable mine dust sample pair *ratios* exceeded 1.25 and 10% exceeded 2.0.
- The variability of % FS was slightly greater in non-coal mines. The *differences* in 50% of the samples were at least 1.7% free silica; 10% had differences equal to or greater than 7.7% free silica.

EFFECT OF INCREASED NUMBER OF SAMPLES ON VARIABILITY OF DUST PARAMETERS

The use of paired samples to measure variability in RMD, FS and % FS permits the prediction of variability reductions achievable by averaging increased numbers of samples. Figures 4 and 5 demonstrate the improvement in sample variability for the mean value of RMD and % FS. These figures were calculated from all paired samples and reflect the average variability improvement.

The achievement of a standard deviation of 0.2 (mg/m^3) for respirable mine dust in coal and non-coal mines would require eight sample pairs. (Figure 4) In both coal and non-coal mines, a standard deviation of 1.5% free silica can be achieved with six sample pairs. (Figure 5)

Table I
Selected Cumulative Percentages of Coal and Hardrock Mine Dust Parameters

	Coal Mine			Hardrock Mine		
	RMD	FS	%FS	RMD	FS	%FS
	(ratio)		(diff.)	(ratio)		(diff.)
50 percentile	1.50	1.52	1.31	1.13	1.25	1.67
80 percentile	1.96	2.20	3.47	1.25	1.60	5.05
90 percentile	2.50	5.72	5.58	1.50	2.00	7.69
95 percentile	3.33	6.56	10.98	6.19	2.67	9.21
100 percentile	3.50	8.00	19.23	13.00	3.00	18.06

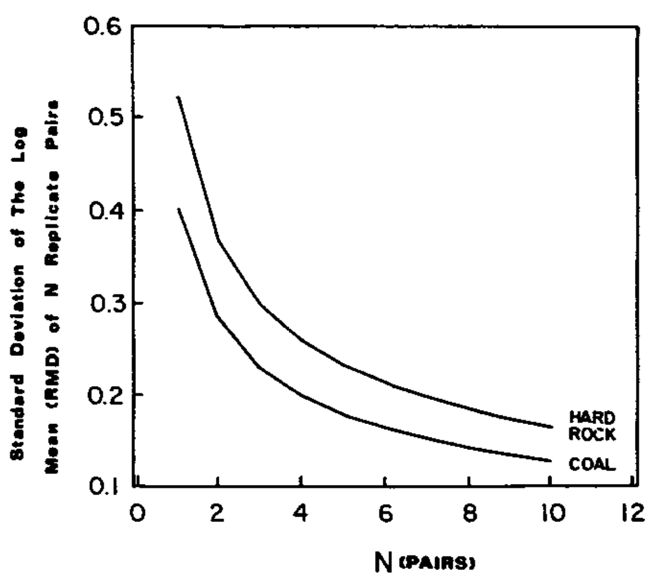


Figure 4. The effect of increased sample pairs on the variability of RMD estimates.

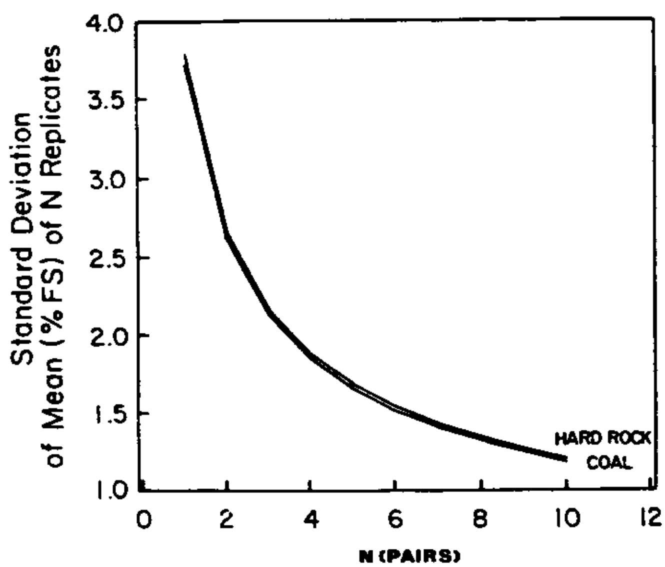


Figure 5. The effect of increased sample pairs on the variability of % FS estimates.

CONTRIBUTION OF STUDY PARAMETERS TO VARIATION

Linear regression analysis was used to determine the contribution to sample variability associated with study variables, i.e. production rate, sampler location, etc. The results demonstrate that for:

Coal Mines

- Sampler location was an important contribution to the demonstrated variability. Machine-mounted samples showed an improvement in variability for all measured parameters. The improvement in variability for machine-mounted samples when compared with personal samples was 40%, 20% and 5% for RMD, FS and % FS, respectively. The improvement in % free silica variability associated with machine mounted samples was not statistically significant.
- Sample variability for respirable mine dust, free silica, and % free silica did not appear to be related to occupational category.
- Respirable mine dust exposure variability across mines was greater than within mine variability for occupation categories. Respirable mine dust, free silica and % free

silica are more dependent on production and/or dust control within the mine than on occupational category. Exposure to free silica demonstrated a consistent pattern, regardless of the respirable mine dust concentration in the mine. Roof bolters were exposed to respirable mine dust levels containing 2–3% more free silica than continuous miner or standard shuttle car operators, and approximately 5% more free silica than center or offside shuttle car operators.

Non-Coal Mines

Regression analysis of non-coal mine results could not be performed because of differences in mining methods employed by participants. These differences did not permit comparison of data between mines.

COMPARISONS OF EXPOSURES BY OCCUPATION

The analytical results of all dust samples were used to address the question of whether dust (RMD, FS and % FS) exposure differs across occupations within a mine, and whether there are differences in dust exposure within occupations across mines.

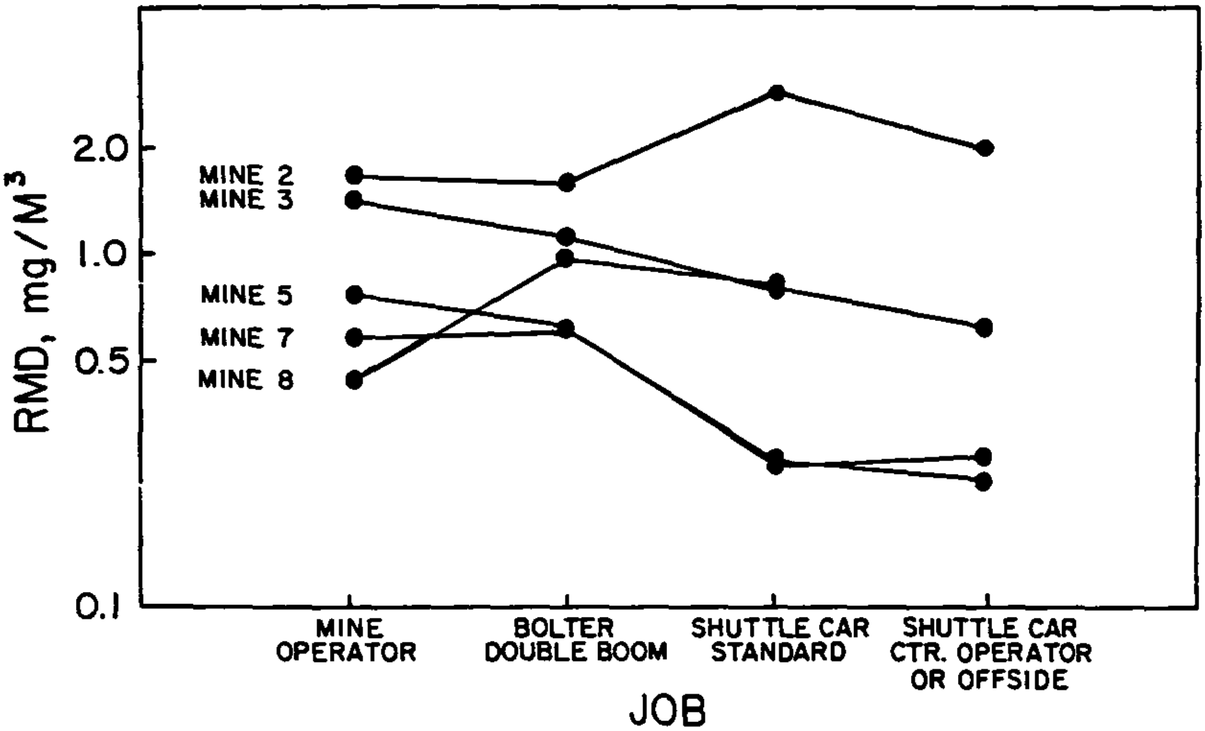
Because only coal mines have uniform job descriptions we have focused our analysis on coal mines. The geometric mean exposure and geometric standard deviation by occupation for coal mines are presented in Table II. Figures 6-8 display the mean exposures for the three variables RMD, FS, and % FS by job classification: mine operator, bolter (double boom), shuttle car operator-standard and shuttle car operator-center

Table II

Results of Air Sampling Analyses by Occupation and Mine for Coal Mines

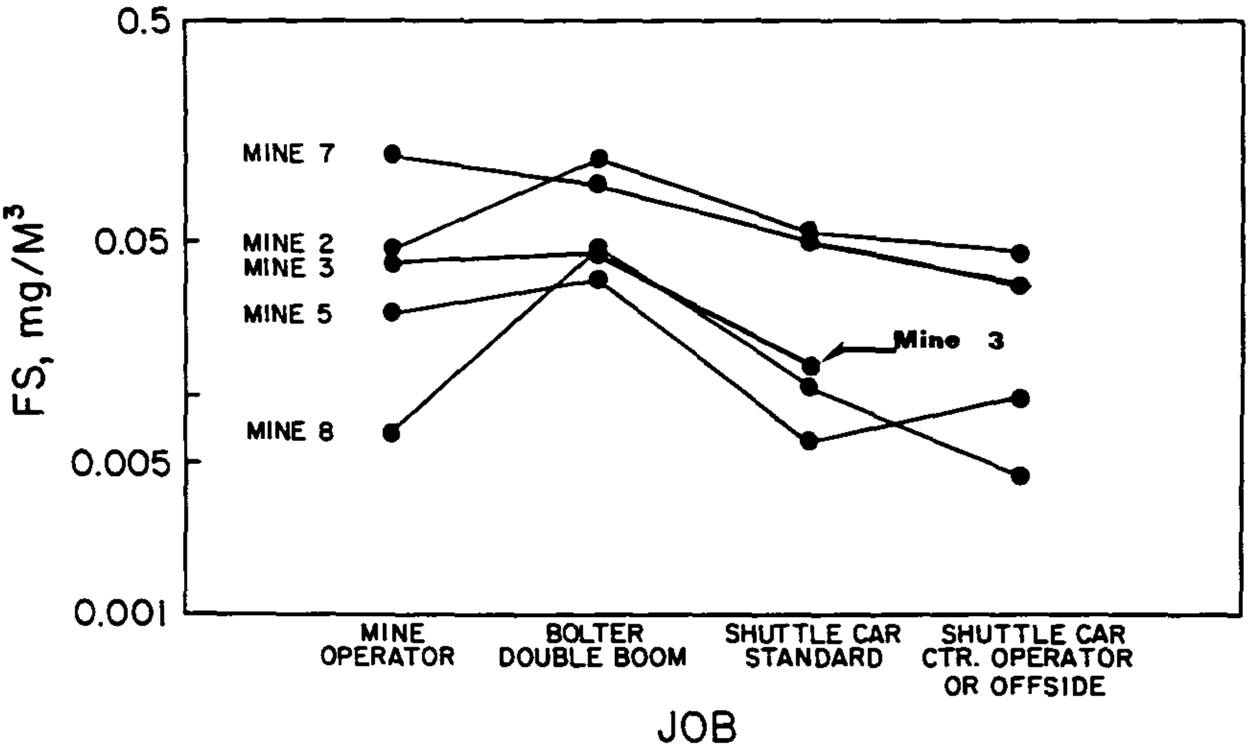
Mine ID	N	Occupation Code[1]	RMD (GM[2], mg/M^3)	G.S.D.[3]	FS (GM[2], mg/M^3)	G.S.D.[3]	%FS (Mean)	S[4]
2	8	1	1.67	1.58	0.045	1.41	2.95	1.45
	15	3	1.61	1.31	0.117	3.13	7.66	2.08
	6	4	2.52	1.86	0.054	2.97	1.93	0.89
	8	6	1.97	3.98	0.044	1.45	2.92	0.88
3	7	1	1.42	2.03	0.039	5.90	3.73	1.88
	12	3	1.12	1.74	0.048	1.69	6.41	3.15
	11	4	0.80	1.76	0.017	2.45	2.78	2.34
5	8	1	0.767	1.60	0.023	2.03	4.05	2.84
	12	3	0.620	1.09	0.033	2.03	5.56	1.34
	3	4	0.252	1.92	0.006	1.32	2.83	1.59
	9	6	0.268	2.36	0.010	1.77	4.42	3.82
7	7	1	0.580	2.46	0.121	3.11	27.7	25.7
	15	3	0.612	2.13	0.090	3.39	23.1	18.7
	5	4	0.261	1.44	0.050	1.48	21.5	12.1
	5	6	0.267	2.39	0.030	4.56	14.9	8.81
8	5	1	0.474	1.38	0.010	1.83	2.24	0.917
	12	3	0.975	1.98	0.047	1.85	5.04	1.59
	6	4	0.824	2.30	0.011	3.71	2.00	2.06
10	10	31	1.07	1.70	0.014	2.30	1.96	2.19
	10	32	1.21	1.49	0.36	2.55	4.34	3.68
	4	34	1.09	4.22	0.016	1.52	7.92	12.8

1. 1 – Continuous Mine Operator, 3 – Roof Bolter, 4 – Shuttle Car Operator (Standard), and Shuttle Car Operator (center and off-side).
2. GM – Geometric Mean
3. GSD – Geometric Standard Deviation.
4. S – Standard



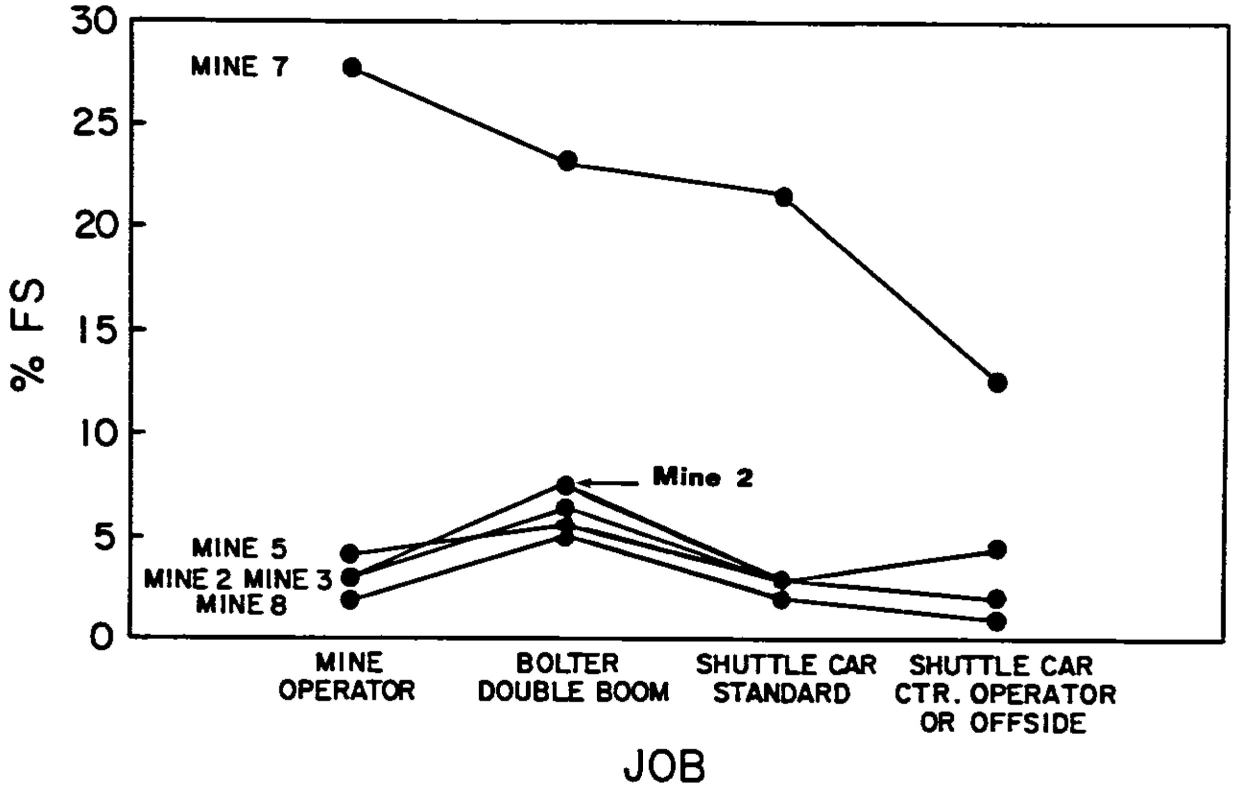
RMD Associated with Selected Jobs in Coal Mines, Expressed as Geometric Means (mg/M³).

Figure 6. Comparison of measured geometric mean exposures by occupation for RMD.



Free Silica Associated with Selected Jobs in Coal Mines, Expressed as Geometric Means (mg/M³).

Figure 7. Comparison of measured geometric mean exposures by occupation for FS.



%FS Associated with Selected Jobs in Coal Mines, Expressed As Geometric Means.

Figure 8. Comparison of measured geometric mean exposures by occupation for % FS.

or off side for coal mines (Mines 2, 3, 5, 7 and 8). Figures 6-8 demonstrate that dust exposure variability across mines is greater than the variability associated with occupations within a mine. RMD, FS and % FS levels are more dependent on the production and/or control of dust within the mine than on occupation.

% FS is more consistent than RMD or FS across all mines except mine 7 where the occupation-specific % FS averages range from 15 to 20% FS over the four occupations. This is three to four times as high as in the other mines. The occupational exposure to free silica does have a consistent pattern regardless of RMD concentrations in a mine. Bolters are exposed on average to RMD containing 2 to 3% more free silica than continuous miner and standard shuttle car operators, and about 5% more than center or offside shuttle car operators who are exposed to the lowest % FS.

TEMPORAL COMPONENT OF VARIATION

The results of the previous sections have been used in combination with the published precision of our laboratory procedures to characterize the contributions to variability in dust parameters of: laboratory analysis; sampling; time; occupation and mines. The analytical lab component is the variance among repeated lab analyses for the same sample. The sum of the laboratory and sampling variances for this investigation was estimated from the paired samples study. The sum of all components as well as the contributions of occupation and mine have been estimated by ANOVA. By combining the results for the ANOVA and the paired sample analysis the variability over time for a given occupation and mine can be estimated.

Table III summarizes the contributions to variability from each source for RMD, FS and % FS for coal mines in absolute units and as a percent of total.

For RMD the total variance across the 157 samples was 0.76. The analysis contributes 1%; sampling contributes 20%; variability over time for the same occupation and mine contributes 33%; while variability across mines/occupations added the largest fraction, 46%. The relative contributions for free silica are similar to those for RMD. For % FS, analysis again contributed little to variability although the specific amount could not be determined from the literature. The sampling and analysis together contributed 35% to the total variation; temporal variability was approximately 30% of the total; while variation from mines/occupations was 36%.

GENERAL CONCLUSIONS

- Occupation and mine, sampler position, laboratory analysis and repeated sampling time contributions to sample variance were estimated based on the paired sample results and published values for variance associated with

Table III

Decomposition of Variance for RMD, FS and % FS by Components: (1) Occupation and Mine; (2) Time; (3) Sampling; and (4) Laboratory for Coal Mine Data

RMD		FS		%FS		
		% of		% of		% of
Source	Variance	Total	Variance	Total	Variance	Total
Occupation and Mine	.35	46	.76	49	2.8	36
Time	.25	33	.42	27	2.3	29
Sampling	.15	20	.38	24	2.7	35
Laboratory	.01	1	.01	0		
Total	.76	100	1.57	100	7.8	100

laboratory analysis and air sampling techniques. The largest contributions to variance arose from sampling across mines and occupations, which accounted for 46% of the variability associated with respirable mine dust samples.

- The second important contributor to variance was the temporal variability of dust levels in mines, accounting for approximately 33% of total variability.

In summary, this investigation demonstrates that the largest contribution to variability results from sampling across mines.

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