Gravimetric Dust Sampling with Quartz Analysis and its Use in Metal and Mineral Mines

By G. KNIGHT* and T. S. COCHRANE†

SYNOPSIS

Gravimetric sampling with quartz analysis is the basis of a dust measuring system developed for Canadian hard-rock mines. The system incorporates the following features:

(a) size selection to simulate the selectivity of the two major regions of the lung, the bronchial tract and the alveolae;
(b) long-period sampling to give full shift exposure;
(c) direct ashing without change in tare weight, using silver membrane filters of 25-mm diameter and 5 μm pore size;
(d) gravimetric assessment of the total dust collected;
(e) X-ray diffraction assessment of the most hazardous component, quartz.

Preliminary results indicate that the Canadian Mining Personal Dust Sampler (CAMPEDS) developed for routine use in mines has certain advantages. Also, the results show X-ray analysis of full-shift airborne dust samples weighing less than 0,5 mg is feasible.

Problem areas in the measuring system have been identified and development work is continuing.

INTRODUCTION

At the Johannesburg Pneumoconiosis Conference[1] in 1959 world dust experts concerned with the measurement, control and effects of industrial dust recognized the need to improve dust sampling and assessment techniques. To obtain dust values suitable for correlation with clinical observations they recommended that a measuring system should have the following basic characteristics:

(a) aerodynamic size selection;

(b) the collection of only the respirable dust fraction;

(c) long-period sampling (full shift);

(d) gravimetric assessment of the dust collected;

(e) assessment of surface area of quartz dust in the sample.

Since that Conference, the measurement technology in the coal mines of Europe has advanced to the stage of development and acceptance of size-selective two-stage long-period dust samplers and gravimetric assessment of the respirable dust fraction.[2,3] However, no acceptable method for the assessment of the surface area of quartz particles has been developed.

In hard-rock mines similar advances in measurement technology have not been realized. It is difficult to develop dust sampling and assessment procedures that are applicable over the wide range, 0 to 100 per cent, of free silica (mainly quartz) and the related range of threshold limit values.[4] Successful application of a gravimetric procedure in hard-rock mines requires high accuracy in the handling and weighing of filters and a quick method of measuring the quartz content of the samples.

There are as yet no methods for measuring the surface area of quartz when mixed with other dusts; however, both infrared absorption and X-ray diffraction can be used to measure quartz in terms related to its mass or volume rather than surface area. The use of these techniques is encouraged by Goldstein and Webster's[5] conclusion, from intra-tracheal injection of sized quartz particles, that mass may be a better indicator than surface area of the harmful effect of quartz in the respirable size range.

PRELIMINARY STUDIES

Prior to 1970, thousands of dust measurements were taken in simulated dust clouds in the Mines Branch laboratory and in hard-rock mines using a variety of sampling instruments and assessment techniques. Mine environmental conditions were appraised and dust measurement systems evaluated.[6,7] General conclusions of primary significance for hard-rock mines were:

(i) The significant components of dust in the mine air are the total respirable dust, the respirable combustible dust, the respirable incombustible dust and the respirable quartz dust.

(ii) The correlation between number count and mass dust values is poor. Figure 1 shows a comparison between results obtained by the two techniques under laboratory and under mine conditions. It is found that the two techniques agree in classifying working places in high-quartz mines (65 per cent quartz in ore) as either acceptable or non-acceptable in 75 per cent of the cases, provided that 300 ppml is assumed to be equivalent to 0,1 mg/m^3 of respirable quartz. Any other conversion relation leads to agreement in less than 75 per cent of the cases.

(iii) The total respirable dust and the combustible and incombustible components can be determined by weighing and the quartz content by X-ray analysis.

(iv) Dust exposure can best be determined using personal samplers. Experiments were conducted where samplers of the same type were worn by a miner and set up at a fixed position in the working place. Results showed that the personal sampler often indicated dust concentrations as much as 50 per cent higher than that in a fixed position; the average indicated value was 25 per cent higher (Fig. 2). In short, there are considerable difficulties in using a fixed-position sampler to take samples that are representative of one man's exposure. While the relationship between each man's exposure and that of a

*Research Scientist, Elliot Lake Laboratory, Mining Research Centre, Mines Branch, Department of Energy, Mines and Resources, Elliot Lake, Ontario.

†Head, Mining Research Centre, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Ontario.

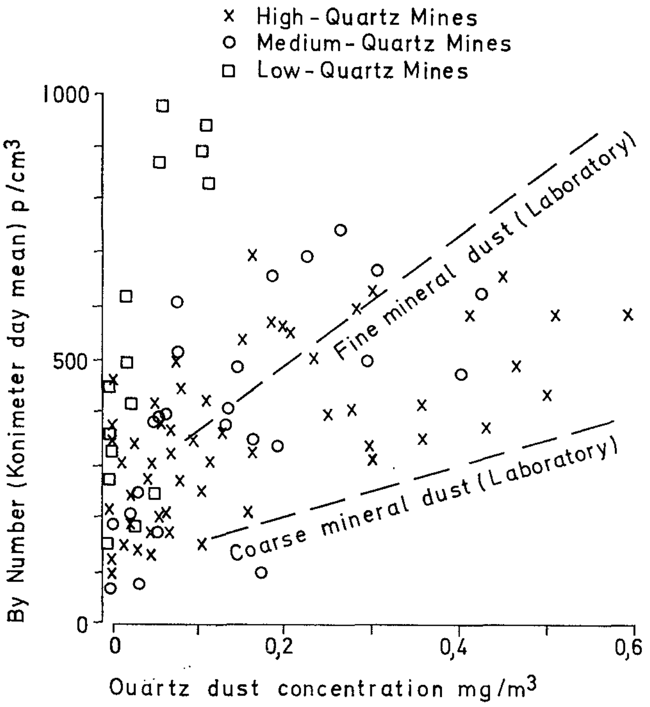

Fig. 1. Comparison of konimeter and respirable quartz dust concentrations.

fixed-position sampler could be determined, this would require a considerable amount of effort and is probably worthwhile only if there are a large number of miners to be monitored, for example, at a longwall coal face.[8]

(v) Gravimetric assessment is of little value for determining compliance with threshold limit dust concentration below 0,5 mg/m^3 without developments in protection of filters during handling. The repeatability of weighing of unhandled filters is about 0,1 mg, of filters loaded and unloaded about 0,03 mg, and of those taken underground somewhat greater. Occasional errors of up to 0,2 mg occur due to loss of loose pieces of filter or to contamination. The weight of sample less than 0,5 mg needs

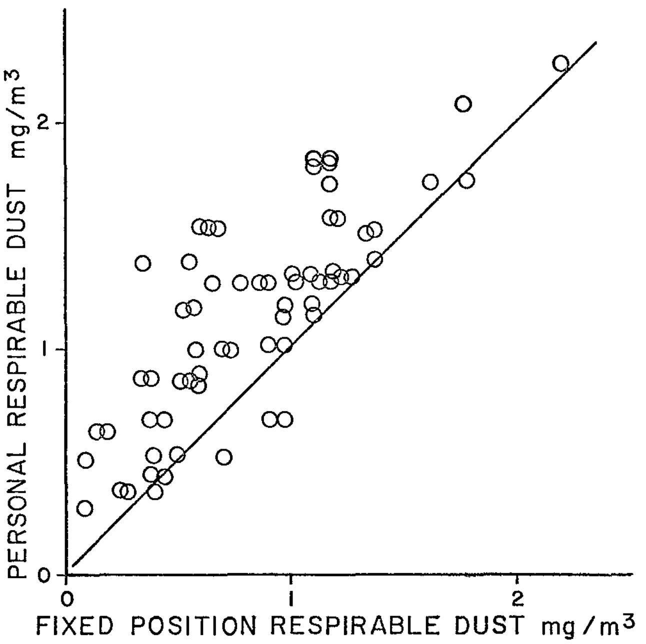

Fig. 2. Comparison of personal and fixed-position samples.

to be verified by visual observation of the appearance of the dust deposit and scanned for absence of physical damage.

(vi) The percentage of quartz in respirable airborne dust varies greatly, mainly because the proportion of dust of mineral origin varies greatly. Thus the total respirable dust, even if it could be weighed accurately, would be a poor indicator of the possible hazard due to quartz.

DESIGN CRITERIA

As a result of experience to date the following criteria are proposed for an improved dust sampling system:

(a) Short-period sampling should be changed to full-shift personal dust sampling rather than to full-shift fixed-position dust sampling. This would have the advantage that the man's total job would be monitored.

(b) On the supposition that there would be a large number of samples, of the order of thousands per year, handling should be reduced to a minimum. Quartz analysis should be undertaken directly on the dust deposit collected on a filter.

(c) X-ray diffraction equipment has a wider range of capability than infrared absorption in analysis of all minerals and would in the final analysis provide a larger body of supporting data.[9]

CANADIAN MINING PERSONAL DUST SAMPLER (CAMPEDS)

The Casella personal gravimetric dust sampler[10] was the only instrument on the market which collected dust on 25-mm diameter filters and for this reason was chosen for preliminary experiments in collecting samples for mass and quartz determinations. Experience with the instrument showed that it was capable of collecting full-shift samples in most mining situations. The exception was in mines with high diesel usage where sampling often had to be limited to as little as three hours. This was not considered to be a serious long-term problem as the observation of high average dust concentrations of over 2 mg/m^3 during a shift from diesel exhausts, led to research into their origin and recognition of the need for their control.[11]

The Casella sampler was mechanically adequate as a fixed-position sampler but not as a personal sampler for mine use. Four main problems were evident:

(i) the harness was not strong enough;
(ii) the pump was easily damaged;
(iii) the hoses pulled off readily; and
(iv) the instrument was too bulky.

The SIMPEDS dust sampler[12,13] which combined the pump with the cap lamp battery appeared not to show the disadvantages of the Casella. However, the concept of a filter protected by foam to collect the dust was not found to be applicable to direct X-ray analysis for quartz on the filter. Without the foam to collect any dust knocked off the filter, the chances of loss from the dust deposit were too high.

It was observed that underground the cap lamp battery gets much less rough usage than the cap lamp and consequently is a more suitable mounting for the sampling head. Also, a sampling head in the battery would result in less weight and drag on the safety hat. The question was 'Is a sample taken at cap battery level equivalent to or related to a sample taken at the breathing zone?' A few tests were carried out with miners wearing two dust samplers, one on the lapel and one on the belt.[6] Reasonable agreement was found between the two samplers provided neither sampler was covered by outer clothing. The cap lamp battery dust sampler was acceptable when worn outside all clothes and if mounted near the breathing zone on a bracket when riding.

It was decided to combine the best features of the Casella and the SIMPEDS and incorporate them into a cap lamp battery sampler. For identification purposes the sampler was called the Canadian Mining Personal Dust Sampler (CAMPEDS). Prototypes were built and tested in mines. The first CAMPEDS using a Casella 13040 cyclone was described in an earlier report.[7] A sketch of the second model using a smaller impactor size selector combined with a filter holder in a cassette and a pump design based on the commercial SIMPEDS is shown in Fig. 3. This second CAMPEDS has the advantage that the filter need only be handled in the laboratory, thus decreasing the chance of damage.

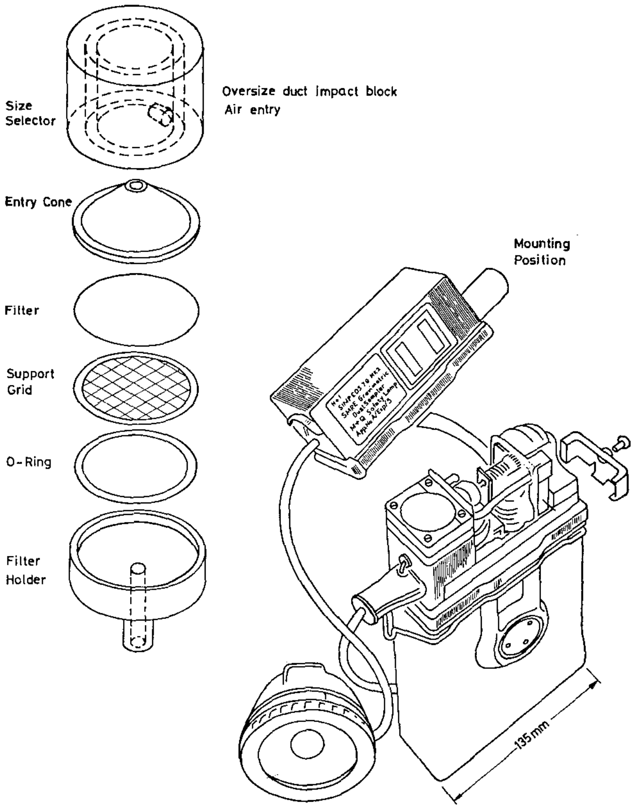

Fig. 3. The modified filter holder and size selector for the SIMPEDS pump.

The CAMPEDS as designed can be used for various purposes with very minor changes:

(a) normal design: 2 *l*/min with size selection equivalent to MRC specifications for most hardrock mining conditions. The CAMPEDS impact size selector has had its dimensions adjusted such that it gives the same estimate of respirable dust as does the Casella 113A gravimetric sampler with a horizontal elutriator[2] in a laboratory coal dust cloud with the respirable-sized fraction about 50 per cent of the total;

(b) low flow-rate design for high-diesel mines or other conditions where the filter overloads during a full shift; a smaller entry orifice and adjustment of the pump stroke; and

(c) total dust-collector design for assessment of materials such as arsenic in smelters; the same as (a) except that the impact block is omitted.

Further, the small sampling head casette could be fitted with any other pump with a suitable smoothed flow for fixed-position sampling in mines or elsewhere, or for personal sampling when cap lamps are not used. While the components of the CAMPEDS can be mass-produced cheaply in plastic, experience has shown that conductive materials are necessary to prevent electrostatic charges from altering the size selection characteristics of the sampler.

SAMPLE EVALUATION

Weighing techniques have been well developed for dust samples from coal mines. The silver membrane filters used in the CAMPEDS can be ashed to an accuracy of $\pm$ 0,03 mg by heating them on a stainless steel 'table' at a temperature of 480 to 500°C. The loss in weight, termed the 'respirable combustible dust', includes carbon dioxide lost from carbonates as well as organic materials. Weighing is done using a Mettler grammatic balance with a readability of 0,01 mg.

The starting point for studies on X-ray analysis was Dr. Leroux's work[14,15,16] on analysis of thin dust layers. Full details of the studies on X-ray analysis are given in a research report.[17] In brief, the studies consisted of the development of the X-ray technique in conjunction with the dust-sampling instrument modifications and sampling in mines.

Filter material and pore size

The choice of filter material and its pore size is a compromise between X-ray and dust sampling requirements. For X-ray analysis the requirements are low backgrounds under the quartz peaks, a linear calibration and a dust deposit of high surface density; for dust sampling, high collection efficiency, low air resistance, low moisture absorption, ease of handling, strength, and little or no weight loss on ashing. Two filter materials, namely, silver membrane and polycarbonate membrane, give low background levels under some of the stronger quartz diffraction lines; however, the polycarbonate is difficult to handle and the silver membrane is preferable on most counts. The large pore sizes, 3 and 5 μm, have the advantages of low resistance to airflow and of permitting the dust to be collected in a higher density deposit. However, while they are efficient in collecting all the dust, some dust at the start of sampling enters into the pores and is screened from the X-ray beam by the highly absorbent silver. This results in a non-linear calibration which is, however, more sensitive than the linear calibrations associated with the lower surface densities obtainable with the finer pore sizes, 0,8 and 0,4 μm.

Diameter and flow rate

The combination used is that which will permit the collection of the thickest deposits possible in a full shift without over-loading the pump and causing a significant drop in flow rate. It has been found that 25-mm diameter filters of 5 μm pore size can be used at 2 *l*/min in most metal mining situations for eight hours. A 22-mm diameter dust deposit is collected. When particulates from diesel engines exceed 2 mg/m^3, however, sampling times must be limited to three hours. Smaller-diameter filters can be used at this flow rate for a full shift on only a few sites and are thus not suitable for routine use.

X-ray wavelength

In selecting the X-ray wavelength, a compromise must be made between absorption, peak-to-background ratio, intensity and resolution. Absorption increases generally with wavelength and limits the thickness of sample for which a linear calibration is an acceptable approximation. The peak-to-background ratio for a given quantity of quartz determines the total count required for a given statistical accuracy and affects the sensitivity; generally, the peak-to-background ratio increases with increasing wavelength. The intensity of the X-ray output is inversely proportional to counting time for the same accuracy. High-output tubes are available with three target materials, Mo, Cu and Cr, which give X-ray wavelengths of about 0,7, 1,5 and 2,25 Å, respectively.

It is clear that a molybdenum target gives much less intensity and resolution than does a copper or a chromium target. The poor resolution using the molybdenum $K\alpha$ radiation increases greatly the problems of interference from other minerals; also, this radiation is applicable to a limited range of samples.

With Cu $K\alpha$ radiation, absorption exceeds only 25 per cent in full-shift iron-free samples if the mass exceeds 5 mg. With samples of mass up to this level, the underestimation of the quartz content is less than 25 per cent. In samples containing iron, 25 per cent absorption corresponds to an iron content of 0,5 mg.

Chromium radiation offers the advantages of greater resolution and greater peak-to-background ratio than copper radiation. However, it suffers from a slight loss in intensity and some decrease in its linear range due to increased absorption. Further studies are required to determine the extent of absorption problems and to develop a simple technique for absorption corrections following Leroux's method.[18]

X-ray settings

X-ray settings are a compromise between intensity and resolution. However, the gains in resolution that can be made by limiting the width of slits and the take-off angle are mostly minor compared with the great loss in intensity. The gain in resolution obtained by the use of 'Soller' slits in the incident beam is worthwhile at angles below $30°2\theta$ but not at $45°2\theta$ (2θ is the angle between the incident and the diffracted beams). If these slits were readily replaceable it would be advantageous to remove them at high angles. The diverging slit should be just large enough to illuminate the width of the dust deposit. The components of the tube tunnel have been machined to permit the use of the full 12-mm length of the electron beam on the target. The receiving slit is set to its maximum useful width, 0,4 mm, and a diffracted beam graphite monochromator is used to eliminate the $K\beta$ radiation and the possible high background caused by sample fluorescence. The monochromator gives a useful gain of 1,5 times in intensity over the use of an Ni filter to eliminate the $K\beta$ radiation. The step size used in step scanning is a compromise between the accuracy and the number of steps, with which is associated the time spent on computation. If the step size is too large the peak height varies with the relative position of the peak and the step. A step of $0{,}10°2\theta$ with the wide receiving slit and the monochromator keeps this variation to within 10 per cent and is probably a maximum usable value. The value used, $0{,}08°2\theta$, was set by the equipment available, with simple modifications. A six-rise cam and clutched drive motor are used instead of the original components to minimize waste of time during stepping.

A scintillation detector was used with a wide window, 0,5 to 1,75 times peak value on the analyser. Narrow windows did not improve the peak-to-background ratios. Preset count times of 10 to 40 seconds are used and the data are printed on paper tape.

Calculation of quartz content

Calibration was carried out using samples collected in a pure quartz dust cloud to overcome the problems of uneven distribution and entry of dust into the pores of the filter and screening from the X-rays.[19] Permanent samples were prepared from a quartz-in-resin mixture and calibrated against the pure quartz samples. These permanent samples eliminate errors due to variations in X-ray intensity with time (the tube output decreases by 50 per cent during its useful life) and mechanical drift of the set-up.

Because the filter samples are occasionally distorted, it is not feasible to determine the peak at given angles and a computer program is used to:

1. find a statistically significant peak;
2. determine the shoulders;
3. select a background region on either side, rejecting adjacent peaks if any;
4. calculate net peak height, area and corresponding masses using the net peak height and area from the standard sample.

It was found that repeat measurements on one sample indicated about four times the error expected from the formula given by Klug and Alexander[20] and it appeared that one main factor causing discrepancy was statistical fluctuations in the shoulder positions.

FIELD RESULTS

General

A few hundred samples have been taken with the CAMPEDS prototype sampler which is combined with the cap lamp battery. It has been used in three underground mines with the mine staff issuing and receiving the samplers on surface and changing the filters. The results of a survey in one mine are shown in Fig. 4 as number of samples

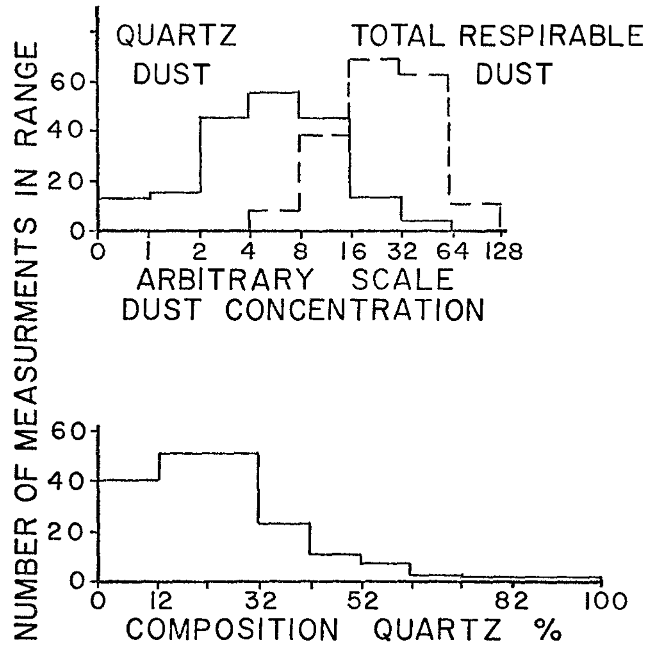

Fig. 4. Frequency distributions of respirable dust concentrations and composition found in one survey at one mine.

occurring in each concentration or per cent quartz range as marked. The distributions of dust concentrations are approximately log-normal and the characteristics are shown in Table I.

TABLE I

RESULTS OF A MINE SURVEY USING CAMPEDS

	Total respirable dust at ratio to mean	Respirable quartz dust as ratio to mean
Arithmetic mean	1	1
Median	0,85	0,74
20% exceed . .	2	2
10% exceed . .	2,3	3

Duplicate samples on personnel were not taken in this series and it is difficult to interpret the high results, that is, the 20 per cent exceeding twice the mean, and to decide whether they indicate random variations or that a few men were exposed to much higher dust concentrations than the average.

Composition of airborne dust in mines

Measurements were made of three components of the respirable portion of the dust, namely, combustible, ash and quartz. Figure 5 shows the results on samples from one mine. It can be seen that the results tend to lie on a line between 100 per cent combustible dust and 50 per cent quartz.

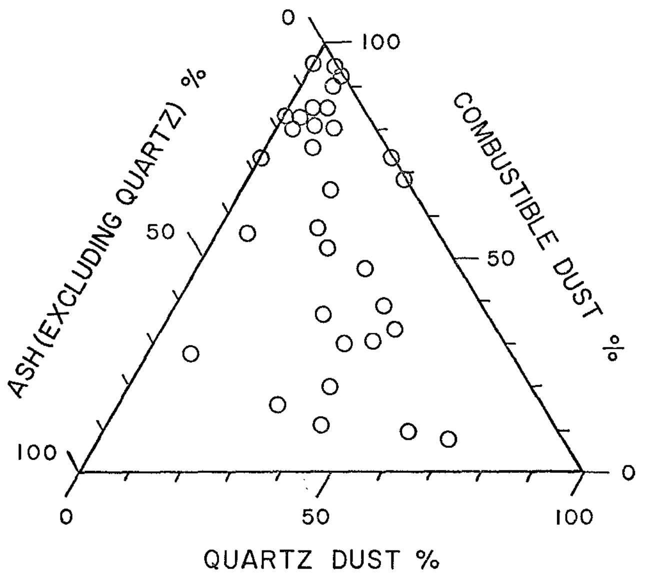

Fig. 5. Composition of the respirable portion of the airborne dust in a high-quartz mine.

The notable exceptions to this were samples in which the mass of ash was so small that weighing errors could account for the discrepancy. Similar results, with a different quartz percentage, were obtained in other mines. Table II shows the ranges and mean compositions found and compares them with the quartz in the ore.

TABLE II

COMPOSITION OF THE RESPIRABLE AIRBORNE DUST IN VARIOUS MINES: RANGES AND MEANS

Mine	Combustible Dust %	Ash %	Quartz as % of Total Dust	Quartz as % of Ash	Quartz in ore %
A Range	—	—	0–100		99+
Mean*	—	—	80		
Mean*	—	—	50		
B Range	—	—	0–100		65
Mean	—	—	25		
C Range	8–91	9–92	0–70	0–100	65
Mean	57	43	22	52	
D Range	5–100	0–95	0–15	0–30	30
Mean	49	51	7,5	15	
E Range	19–96	6–81	0–2	0–30	10
Mean	50	50	1,5	3	
F Range			0–15		15
Mean			1,2		
G Range			0–12		10
Mean			1,7		

*The two means given here were obtained before and after the mean dust concentration dropped from 0,3 mg/m³ to 0,1 mg/m³ during a concentrated effort on dust control.

It is apparent that the measured compositions are very variable and that on the average the proportion of quartz in the total respirable dust is much less than that in the ore, and that in the ash is often less than in the ore. While errors in weighing account for some of the variation in composition, it is clear that the main factor is the lack of correlation between the different sources of dust. Table III shows results on the composition of dust produced in given operations, obtained by subtracting the concentration in the air entering the working place from those in the air leaving.

TABLE III

COMPOSITION OF THE RESPIRABLE DUST PRODUCED DURING SOME TYPICAL MINING OPERATIONS

Operation	Combustible dust %	Mineral dust %
Drilling (jack leg)	90	10
Mucking (comp. air)	80	20
LHD (diesel)	70	30
Slushing	10	90
Chute pulling	50	50
Crushing	n.d.*	100
Ore and waste passes	n.d.*	100

*n.d. – not detectable

Quartz analysis of airborne dust from mines

Interference has been found to be very common and is the factor controlling the sensitivity and accuracy of X-ray analysis.[19] To understand the X-ray results it is necessary to understand that there are two forms of error in calculated peak height or area due to interference by diffraction lines from other minerals. In form 1 the lines are close together, unresolved and result in a high estimate for quartz. In form 2 the lines are far enough apart to be resolved but the quartz line lies on the tail of the next and results in too high a value for the assumed linear background being subtracted, thus giving a low estimate for the quartz. Form-1 errors cannot usually be detected from the scan while the adjacent peaks giving form-2 errors are readily apparent if the interfering peak is sharp. However, if it is diffuse or multiple, it may result in non-obvious high background on one side of the quartz peak. While form-1 errors may be predictable from the minerals present, we have often found that after allowing for the known minerals in the sample there are one or more lines of medium intensity which have not been explained and could be due to unidentified components. On a few occasions one very strong quartz line has been found which is not confirmed on any other of the quartz lines. The most likely cause of this phenomenon is contamination by a few coarse quartz crystals of which one happens to be aligned to give a strong signal.

A selection of dust samples with the mass determined from four quartz diffraction lines (Miller indices 1, 0, 0; 1, 0, 1; 1, 1, 2; 2, 1, 1) is shown in Table IV. It is usually necessary to confirm an indication of a significant quantity by repeating the analysis on at least one other diffraction line.

DISCUSSION

It has been shown that long-period dust sampling with collection on a filter for subsequent gravimetric assessment and X-ray diffraction analysis for quartz is technically feasible in hard-rock mines. The gravimetric assessment is of value for non-mineral dust in all mines and for mineral dust in mines with low quartz content in the ore, but is insufficiently sensitive for mineral dust in mines with high quartz content in the ore.

TABLE IV

COMPARISON OF QUARTZ ANALYSES USING SOME OF THE DIFFRACTION LINES AVAILABLE

	Mass of Dust Estimated in mg using the Diffraction Lines Indicated							
	1, 0, 0		1, 0, 1		1, 1, 2		2, 1, 1	
Mine	Height	Area	Height	Area	Height	Area	Height	Area
A			0,017	0,019	0,025	0,024		
			0,030	0,031	—	—		
				0,014		0,015		0,001
				0,022		0,01		0,022
		0,01		0,01		0,06		0,01
B	0,023	0,049	0,006	0,007	0,007	0,002	0,010	0,003
	0,110	0,093	0,20	0,305	0,175	0,15	0,185	0,165
	0,185[1]	0,160[1]	0,064	0,077	0,057	0,053	0,050	0,041
C				0,24		0,00		
				0,32		0,27		
D		0,86		0,45		0,24[1]		0,60
		0,30		0,24		0,11[1]		0,26
E		1,03[2]		0,83[2]		0,36[1]	0,81	1,16
F		0,32		0,04		0,02		
				0,05		0,03		0,04
G				0,06		0,12		0,04
H		3,14		0,26		0,15		0,21
H′		0,24		0,21		0,16		0,14
H′ [3]		0,64		0,15		0,13		0,09

Footnotes:

[1] Adjacent peak detected.

[2] Percentage of quartz in the crushed ore determined by X-ray diffraction:

24% 64% 15% 35%

respectively, for each of the four lines. These figures compare with the 30 to 40 per cent found by other techniques.

[3] Sample H′ from a coal mine was ashed and re-analyzed with the results given in this line.

The change in instrument and period of sampling necessitate changes in the mine dust sampling procedures. These will be discussed under four headings: instrument performance, procedures, analysis of results (statistics) and dust standards.

Instrument performance

While the field trials of the CAMPEDS were judged to be successful, instrument problems did occur and may be identified as follows:

1. Acceptance. About 1 per cent of the men have refused to carry the dust sampler in this voluntary programme.
2. Contaminated samples. About 1 per cent of the samples appeared to have been significantly contaminated due to either inversion of the cyclone and transfer of the oversize dust to the filter or to deliberate dusting by personnel.
3. Mechanical failures. The most common has been a damaged lamp cord, the dust sampler portion has required little maintenance.
4. Underestimations. The dust concentration can be underestimated for two reasons:
   (a) The dust is knocked off the filter by rough handling. This has occurred on about 10 per cent of the very heavy samples and can readily be detected and allowances made.
   (b) The dust sampler is screened by clothing and air recirculates through the instrument. This can be overcome only by inspection and training.

Sampling procedures

The practice of using specialists to take dust samples and to record conditions has been generally successful. Short-period samples are taken and the samplers spend a short time at each working place. However, with long-period samplers, two visits to each working place are necessary to place and retrieve the instruments, and a third during the working period to record conditions. This means that the specialists are not able to cover as many working places.

Procedures for involving the miners or underground staff for placing and retrieving the samplers must be considered. During the course of our studies, miners were asked on occasion to place and retrieve samplers, usually with success, but sometimes samplers were forgotten and left underground. The placing and retrieval of dust samplers by the underground staff (shifters) in the Canadian mines does not fit in with their routine duties. The most reasonable way to obtain full-shift samples covering the working period would be to have personal dust sampling instruments worn by the miner. A few hundred samples have been taken in this fashion using either the separate sampler or the CAMPEDS prototype which is combined with the cap lamp battery. The procedures adopted by management staff for using the dust sampler should be as follows:

1. Issue sampler to miner at start of shift; check that it is running; note time.
2. Return of sampler by the miner to special lamp rack at end of shift; put on charge in normal manner.
3. Switch off samplers; note time; record miner's work, working place and time underground.
4. Record elapsed running time indicated by instrument.
5. Check and record flow rate through used filter.
6. Change filter cassette.
7. Check and record flow rate through clean filter.
8. If necessary, adjust flow rate or carry out other maintenance as required.
9. Designate miner to wear sampler for next shift.
10. Visit miner wearing the sampler during his working period both to check sampler and to note conditions for dust and ventilation control.

This dust sampling method with the CAMPEDS is a feasible routine dust sampling system for measuring the total personal dust exposure of a miner during one shift and for examining the whole job and not just the main operation.

Routine dust measurements as described would estimate dust exposure over the full shift. The requirements for dust sampling for engineering control still have to be considered. Having decided that a particular job required improved dust control, short-period samplers could be used to study its components. However, as the existing short-period samplers give very poor correlation with the gravimetric and quartz assessment techniques, it would be preferable to use the latter for dust control purposes. By running the long-period dust sampler continuously during one aspect of a particular job and turning off during others, it is possible to measure as little as 10 per cent of the required dust level, and thus break down the day's work into significant sections. Of course, to get meaningful measurements it is necessary to measure the dust in the intake air over the same periods unless it is very much lower than that produced by the operation.

Analysis of results

An accurate dust exposure estimate for one miner would require measurements over many shifts because of the great variability in dust concentration from one shift to the next, and would result in a tremendous mass of data for each mine. This is probably not necessary and the main requirement is

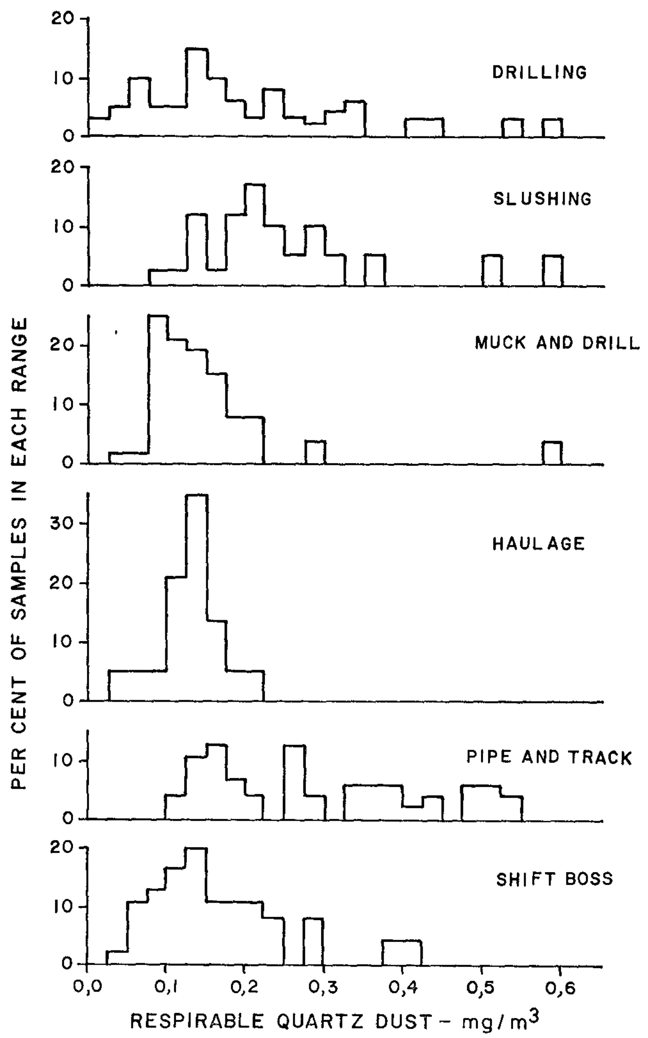

Fig. 6. Respirable quartz by occupations

to get reasonable estimates of exposure for each class of men, such as drillers, and for each section of the mine. The data may then be used for deciding on dust control requirements.

It is clear that the results of dust surveys in a mine will indicate a very great variability in dust levels. It has been found that the highest shift-mean concentration is about 10 times the average shift-mean concentration. The distribution of concentrations approximate a log-normal distribution. The same variability is also apparent for most jobs in the mine when considered separately, as shown in Fig. 6. A study in which three to six personal samples were taken on each of about 20 men showed that the distribution of the means for individual men was about half as wide as the distribution for all the separate samples, that is, the maximum mean concentration for an individual man is about half of the maximum single-shift mean concentration (Table V, line 2). However, in this study, because of the small number of samples for each man, the highest mean concentrations were unduly influenced by the single high values included.

TABLE V

VARIABILITY OF SHIFT MEAN OF RESPIRABLE QUARTZ DUST CONCENTRATIONS FOR INDIVIDUAL MINERS WAERING PERSONAL SAMPLERS (A FEW SELECTED SAMPLES)

Number of shifts	Mean	Range
5	0,11	0,06 – 0,15
3	0,25	0,03 – 0,53
3	0,14	0,01 – 0,37
3	0,14	0,09 – 0,24
6	0,16	0,11 – 0,30
6	0,07	0,04 – 0,10
4	0,04	0,02 – 0,06
6	0,17	0,07 – 0,25
6	0,12	0,06 – 0,23
5	0,05	0,03 – 0,07

The following conclusions may be drawn from these surveys:

1. The average dust exposure of most men is less than twice the average shift mean dust concentration found.
2. Miners returning high dust concentrations, above twice the mean value, should be resampled to check that the exposure is not excessive.
3. The results should be averaged over each operation and and mine section to decide on the need for improved dust control.
4. The 10 per cent of shifts worked at high concentrations contribute some 25 per cent of the total dust exposure.
5. Attempts should be made to elucidate and control the factors leading to the high dust concentrations that occur on one shift in ten.

More samples are required to be able to undertake a complete statistical analysis of the variability of dust samples and to develop more than the *ad hoc* procedure given.

Dust standards

Dust standards have not been promulgated in Canada for the gravimetric dust sampling technique with quartz analysis. A review of existing standards throughout the world using both this and other types of dust sampling equipment suggests that upper and lower dust levels can be defined on which there would be general agreement. Concentrations above the upper level would be hazardous over a working lifetime and concentrations below the lower level would be safe. Target levels could be established for total respirable airborne dust in mines and for the two main constituents; for example

	Upper level	Lower level	Target
Total respirable dust	5 mg/m^3	1,5 mg/m^3	2 mg/m^3
Respirable combustible dust (diesel exhaust and oil mist not coal)	3 mg/m^3	0,5 mg/m^3	1 mg/m^3
Respirable quartz dust	0,5 mg/m^3	0,05 mg/m^3	0,1 mg/m^3

These target levels are those met with in the majority of mines visited and represent a dust level that can be obtained with present techniques. These dust concentrations assume a working lifetime of 35 years at eight hours per day, five days a week. For other working hours the concentrations should be adjusted to give the same exposure levels.

ACKNOWLEDGEMENTS

The authors wish to thank the personnel of the McIntyre Research Foundation, the Mines Accident Prevention Association of Ontario and the many mining companies, who were and are involved in these studies. Any advances made must be attributed to their co-operative efforts.

REFERENCES

1. ORENSTEIN, A. J. (Ed.). *Proceedings of the pneumoconiosis conference*, Johannesburg, 1959. Churchill 1960. pp. 617-621.
2. DUNMORE, J. H., HAMILTON, R. J., and SMITH, D. S. G. An instrument for the sampling of airborne dust for subsequent gravimetric assessment. *J. Sci. Inst.*, vol. 41, 1964, pp. 669-672.
3. JACOBSEN, M., and PAROBECK, P. S. Respirable mine dust sample processing laboratory. *U.S. Bur. Mines Inf. Circ.* No. 8504, 1971.
4. Threshold limit values of airborne contaminants and changes for 1974. American Conference of Government Industrial Hygienists, Cincinnati, 1974.
5. GOLDSTEIN, B., and WEBSTER, I. Intratracheal injection into rate of size graded silica particles. *Brit. J. Ind. Med.*, vol. 23, 1966.
6. KNIGHT, G., NEWKIRK, T. E., and YOURT, G. R. Full shift assessment of respirable dust exposure. *C.I.M.M. Bull.*, vol. 67 (744), 1974, pp. 61-72.
7. KNIGHT, G., KOWALCHUK, R., and YOURT, G. R. Development of a dust sampling system for hardrock mines based on gravimetric and quartz (by X-ray diffraction) assessment. *A.I.H.A. J.*, vol. 35, 1974, pp. 671-680.
8. JACOBSEN, M., RAE, S., WALTON, W. H., and ROGAN, T. M. The relation between pneumoconiosis and dust exposure in British coal mines, in Walton, W. H. (Ed.). *Inhaled particles and vapours, III.* Pergamon, Oxford, 1971.
9. Powder diffraction data. Joint Committee on Powder Diffraction Standards, Swarthmore, Penn., 1974.
10. Casella Ltd., London, U.K., Model 13040.
11. DAINTY, E. D., and BROWN, G. K. Federal certification and research concerning environmental aspects of diesel powered machines in coal mines. Pres. 76th Annual CIMM Meeting, Montreal, 1974.
12. HARRIS, G. W., and MAGUIRE, B. A. A gravimetric dust sampling instrument (SIMPEDS): Preliminary results. *Ann. Occup. Hyg.*, vol. 11, 1968, pp. 195-201.
13. MAGUIRE, B. A., and BARKER, D. A gravimetric dust sampling instrument (SIMPEDS): Preliminary underground trials. *Ann. Occup. Hyg.*, vol. 12, 1969, pp. 197-201.
14. LEROUX, J., LENNOX, D. H., and KAY, K. Direct quantitative X-ray analysis by diffraction absorption technique. *Anal. Chem.*, vol. 25, 1953, p. 740.
15. LEROUX, J. Direct quantitative X-ray analysis with molybdenum $K\alpha$ radiation by the diffraction absorption technique. *Norelco Reporter*, vol. 4, 1957, p. 107.
16. LEROUX, J., and POWERS, C. A. Direct X-ray diffraction quantitative analysis of quartz in industrial dust films deposited on silver membranes. *Staub*, vol. 29, No. 5, 1969, pp. 197-200.
17. KNIGHT, G. Guide to gravimetric sampling with quartz analysis in metal and mineral mines. *Mines Branch Technical Bulletin*, in process, 1974.
18. LEROUX, J. Quartz in airborne dust. *American Conference of Governmental Industrial Hygiene in 'Analytical Techniques for Quartz'*, Cincinatti, 1973, p. 55.
19. KNIGHT, G., STEFANICH, W., and IRELAND, G. Laboratory calibration of a technique for determination of respirable quartz in mine air. *A.I.H.A. J.*, vol. 33, No. 7, July 1972, pp. 469-475.
20. KLUG, H. P., and ALEXANDER, L. E. *X-ray diffraction procedures.* Wiley, New York, 1962, p. 272.