A study of the dust exposure of South African white gold miners†

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SYNOPSIS

A study of the response of South African white gold miners to exposure to dust in their working environment yielded large quantities of dust data. Analysis of this data (presented in summarized form) reveals a variety of interesting relationships, including the shift-long exposure of different occupational groups, the dust levels due to various mining operations, relationships between different dust-measuring procedures and time trends in dust levels during the shift. The statistical probability of contracting silicosis at various levels of exposure to this dust is reported briefly. A new method of using microscope counts to estimate the respirable mass of dust samples is given in an appendix.

SINOPSIS

'n Studie van die uitwerking van Suid-Afrikaanse blanke goud myners na blootstelling aan stof in die werksomgewing het groot hoeveelhede stof data opgelewer. Ontleding van hierdie data (weergegee in opgesomde vorm) het 'n verskeidenheid van interessante verwantskappe aan die lig gebring wat die volgende insluit; blootstelling van verskillende beroeps groepe oor skof periodes, stof hoeveelhede as gevolg van verskeie bemynings bedrywe, verwantskappe tussen verskillende stof opname prosedures en die tyd tendens in stof hoeveelhede gedurende 'n skof. Die statistiese moontlikheid om silikosis op te doen as gevolg van blootstelling aan verskeie hoeveelhede stof word kortliks behandel. 'n Nuwe metode vir die gebruik van mikroskoop tellings om die hoeveelheid stof wat ingeasem kan word te skat, word in die bylae aangegee.

INTRODUCTION

That exposure to the dust in the underground working environment of the South African gold miner‡ can lead to silicosis has long been known. In 1956, an attempt to establish the dose-response relationship in this exposure was commenced. The dust exposure of a large number of miners was measured to give average dust exposures for various occupational groups. Then the medical and occupational histories of cohorts of men who started work in 1936 and 1946 were correlated. The emergence of a clear dose-response relationship is perhaps the best evidence of the reliability of the dust surveys. The details of this relationship have been reported at various conferences.[1, 2, 3]

However, the mass of dust data collected in the occupational dust survey which comprised the early stages of the investigation has never been published. Since this information may be of interest to numerous members of the South African mining community, as well as to epidemiologists, a summary of the data, with some of the analytical results, is presented in this paper.§

For the information of readers who have not read the proceedings of the conferences mentioned above, some of the findings concerning the probability of contracting silicosis at various levels of exposure are also presented.

DUST SAMPLING STRATEGY

Large numbers of airborne dust samples are taken in the South African gold mining industry every day. Some justification for the decision to undertake a special dust survey to measure the dust exposure of the miners is therefore necessary. Good reasons are not hard to find: (a) routine mine sampling is primarily concerned with dust control and the location of *trouble spots*, (b) it is known to be biased with respect to time coverage, most of the samples being taken between 0900 and 1100 hours.

It is not necessarily a criticism of this strategy to observe that the occupational dust survey needed to be more *people-orientated*. It was considered important that the shift-long (surface-to-surface) dust exposure of the miners should be evaluated for correlation with medical findings. The survey revealed variations in the dust level during the shift, which amply justified the decision to sample for the full shift and not rely on routine measurements.

A further point is that many of the measurements made in the survey and all those made routinely on the mines, rely on microscopic evaluation which is notoriously subjective and susceptible to operator bias. In the occupational dust survey all samples were evaluated under controlled conditions at a central laboratory. Few people would question that this was likely to yield results of greater precision [that is, less random variation].

The occupational dust survey was commenced in 1956, and all the samples were collected prior to 1960. Since the individuals whose medical histories were studied had commenced work either in 1936 or 1946, some assumptions with regard to their dust exposure had to be made:

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‡In this paper the term *miner* includes all underground workers included in the study.
§The full set of data has been submitted to the Chamber of Mines of S.A. in the form of a contract report (Corner House Laboratories Ref. A36/P233/70 — Chamber of Mines Contract 6/135/69).

1. It was assumed that dust conditions had not varied greatly in the year 1936-1960. This was justified by the fact that the mean dust levels reported to the Chamber of Mines had not altered appreciably in this period. The clear dose-response relationship which resulted from the study gives retrospective confirmation that this was a reasonable assumption.
2. It was assumed that miners doing the same type of work would be exposed to similar dust levels.

The decision to restrict the investigation to White miners was based on the belief that their careers followed more regular patterns than those of the Bantu and that their occupational and medical histories would thus be easier to trace.

Occupational Groups

Because of the second assumption mentioned above, it was necessary to group the miners whose dust exposure was measured according to their occupations.

Initially 33 such *occupational groups* were used. Some of these turned out to be too small for statistical analysis and they were recombined into 11 occupational groups. Similarity of work and dust level were taken into account in this re-classification. The occupations included in the 11 groups are shown in Table I.

For some analytical purposes the 11 groups were further reduced to two, referred to as the *production* and *non-production* workers. This classification is also indicated in Table I.

Selection of Mines and Underground Workers

Twenty gold mines were chosen for sampling. They were selected on a stratified random basis to include the various geographical areas and mining conditions [e.g. depth of working, reef dip-angle, mining method etc.]. The men to be sampled were selected at random from the White underground workers employed on these mines. The number of men chosen for sampling in each occupational group was related to:

(a) the total number of men employed in that occupation
(b) the average dust level found for that occupation, and
(c) the variation in dust levels within the occupation.

TABLE I

THE ELEVEN OCCUPATIONAL GROUPS

Occupational Group No.	Main Occupations in this Group	Short title for Group	Approximate n o.of men in industry in 1957	
1	Shaft-sinkers	Shaft-sinkers	120	PRODUCTION
2	Developers	Developers	1 430	
3	Stopers	Stopers	4 040	
4	Assistant Miners and Trammers Timbermen Locomotive Drivers Pipes and Tracks	Assistant Miners/ Trammers	1 690 490 210 910	
5	Shift Bosses Learner Officials	Shift Bosses	2 910 540	
6	Underground Managers Mine Overseers Study Officials Surveyors Samplers Ventilation Officials Native Labour Controllers Engineers	Other Officials	200 580 380 780 790 260 140 150	NON PRODUCTION
7	Underground Banksmen Skipmen/Onsetters	Banks/Skips	140 1 210	
8	Shaft Timbermen Winding Engine Drivers Pump Attendants	Workers near Shafts	1 190 490 390	
9	Boilermakers/Truck Repairers	Boilermakers	340	
10	Carpenters Electricians Fitters Masons Riggers Handymen	Other Artisans	90 990 1 050 80 390 120	
11	Sanitation Diamond Drillers Blasters Miscellaneous	Miscellaneous	30 90 30 270	
Total			22 520	

Obviously, only (a) was known at the commencement of the study. The sampling schedule was reviewed repeatedly during the survey and adjustments were made as necessary.

In all, 650 men were each followed through a single shift.

DUST SAMPLING AND ASSESSMENT TECHNIQUES

Three instruments were used to sample the airborne dust, viz:

(i) The Witwatersrand Konimeter[4]

(ii) The standard thermal precipitator[5] (STP), and

(iii) The modified thermal precipitator[6] (MTP).

The instruments were carried and operated by an observer who accompanied the miner whose exposure was being measured. All possible precautions were taken to ensure that the work patterns of the subject were typical of normal practice.

Konimeter Sampling

Konimeter samples were taken at ten-minute intervals throughout the shift. The operations in progress in the vicinity at the time of sampling were recorded. All samples were ignited, acid-treated and counted under the microscope according to standard procedures[7].

Standard Thermal Precipitator Sampling

The standard thermal precipitator samples were taken continuously throughout the shift. All samples were evaluated using high-power, light-field microscopy and the truncated multiple traverse method[8] of counting. Counts were made both before and after acid treatment. Calculations made from the counts yielded total surface area, respirable surface area and particles per millilitre in various groups.

A linear approximation of the sampling curve recommended by the 1959 Johannesburg Pneumoconiosis Conference[9] was used to estimate the respirable surface area, viz.

$y=1{,}02-0{,}17\,x$

where x is the particle diameter (projected area diameter)

and y is the sampling efficiency

The equation is corrected for particle density but not for particle shape.

Strict control of counting procedures was maintained via inter-microscopist checks and the use of a counting control chart[10].

Modified Thermal Precipitator Sampling

The modified thermal precipitators operated throughout the shift, individual samples being of ten-minute duration. The samples were evaluated on the photo-electric assessor[11] both before and after acid treatment. Since the sampling instruments were fitted with elutriators, the photo-electric assessor readings are a measure of the respirable surface area of the dust samples.

Respirable Mass Calculations

Despite the recommendations of the 1959 Johannesburg Pneumoconiosis Conference[9], most workers overseas have chosen to measure the *mass* of respirable dust rather than the *surface area.* This procedure has many advantages, inter alia, freedom from operator bias or subjectivity. It has not found favour in South Africa, largely because a very large air sample [2-3 m^3] would be required to give a readily measurable dust sample. It is of interest to be able to express approximate equivalents in respirable surface area values (in square microns per cubic centimetre) to respirable mass values (in milligrams per cubic metre). Conversion factors based on the Sichel-Joffe procedure for calculating respirable mass from microscope counts have therefore been calculated. [See Appendix I].

FREQUENCY DISTRIBUTION OF DUST COUNTS

The numbers of konimeter samples and modified thermal precipitator samples were about 22 000 each. About 650 standard thermal precipitator samples were obtained. Clearly the tabulation of all the results would provide readers with a severe case of numerical indigestion.

However, there is interesting information to be gleaned from these data. As a compromise, they are presented in this paper in the form of the moments

TABLE II

MOMENTS OF THE SHIFT-LONG MEAN DUST LEVELS—MEASURED BY KONIMETER (p/ml AFTER ACID TREATMENT)

Moments of Data	Occupational Group											All Groups
	Shaft Sinkers 1	Developers 2	Stopers 3	Assistant Miners/ Trammers 4	Shift Bosses 5	Other Officials 6	Banks/ Skips 7	Workers near shafts 8	Boiler-makers 9	Other Artisans 10	Miscel-aneous 11	
Number of samples	10	31	87	134	33	84	20	18	33	45	8	503
Mean	280	210	210	180	160	200	140	100	210	150	160	180
Standard Deviation	270	120	100	100	90	120	180	90	170	130	90	120
Range	50 800	50 600	0 600	0 650	50 350	0 750	0 850	0 400	0 700	0 850	0 350	0 850

(mean, standard deviation and range) of the various groups of figures. No attempt has been made to include the individual values of samples obtained from any instrument or by any type of sample evaluation.

Mean Shift-Long Dust Levels

The mean shift-long dust levels for the eleven occupational groups are probably the most interesting data. These dust levels, as measured by the konimeter, are tabulated and discussed in some detail. The konimeter samples have been chosen for this prominent display because konimeter sample values are most meaningful to personnel in the South African mining industry.

Examination of these figures reveals some interesting features, not all of them unexpected:

(a) In most cases the range of dust levels starts at zero. The exceptions are the Shaft-Sinkers, Developers and Shift Bosses (Groups 1, 2 and 5, respectively).

(b) Although the actual values range as high as 850 p/ml, the mean values do not exceed 250, and then only in the case of shaft-sinkers. A value of 280 p/ml would not normally be rated *high* in routine measurement.

(c) The exposure of boilermakers appears very high. This may, however, have been due to the presence of welding fumes in the samples. Although not siliceous particles, these would not have been effectively removed by conventional slide treatment procedures.

(d) The range of exposures in any occupational group is very wide. Among the factors which may have influenced this are:

(i) different mining methods [e.g. high- or low-speed development] are embraced by each occupational group, and

(ii) the efforts of individuals are of primary importance in determining the dust level of their environment.

Mean Daily Dust Exposures

In the evaluation of the dose-response relationship in exposure to dust, the dust level is clearly very significant. The duration of exposure to the dust is equally important, however, and the value *mean dust level* × *time of exposure* is thus a measure of the dust likely to have been inhaled in the course of a shift.

The figures given in Table II, corrected for the duration of the shift, are tabulated below in Table III. The figures given here are *mean particles per millilitre* × *shift length in hours*. The units are thus, strictly speaking, *particle-hours per millilitre*. This is not very intelligible, however, and the units are perhaps best viewed as *dust level-hours*. (The same units are used again in the final correlation, where the findings of the study are described.) The mean shift length for each occupational group is included in this table.

More interesting information may be derived from these figures:

(a) The effect of shift length on exposure is considerable, e.g. the mean dust level to which Group 5 (Shift Bosses) is exposed, is 0,57 times that to which Group 1 (Shaft Sinkers) is exposed. The ratio of time-weighted dust exposures is only 0,40.

(b) The relative ranges are increased as well, because the variation in length of shift within some occupational groups was by as much as three or four times.

Similar data obtained using the Standard Thermal Precipitator are tabulated in Appendix 1, various properties of the dust samples being distinguished, viz. Total particles per millilitre after acid treatment, particles 0,5 to 5 μm per millilitre after acid treatment, total and respirable surface area after acid treatment and respirable mass after acid treatment.

DUST LEVELS ASSOCIATED WITH DIFFERENT MINING OPERATIONS

The information on operations in progress at the times when konimeter samples were taken was evaluated in some detail. All operations were coded and classified by an experienced mining production official.

The mean dust levels based on konimeter samples associated with each type of operation and each of the 11 occupational groups, are reported in Table IV. The

TABLE III

MOMENTS OF THE DAILY DUST EXPOSURES IN ACTUAL UNITS—MEASURED BY KONIMETER (p/ml x HOURS, AFTER ACID TREATMENT)

Moments of Data	Occupational Group											All Groups
	Shaft Sinkers 1	Developers 2	Stopers 3	Assistant Miners/ Trammers 4	Shift Bosses 5	Other Officials 6	Banks/ Skips 7	Workers near Shafts 8	Boiler-makers 9	Other Artisans 10	Miscel-laneous 11	
Mean	2 130	1 780	1 560	1 360	860	810	1 030	760	1 230	800	1 030	1 190
Standard Deviation	1 740	1 030	830	870	470	560	1 310	790	920	590	570	900
Range	500 6 500	500 5 000	0 5 000	0 5 000	500 2 000	0 3 000	0 6 500	0 3 500	0 4 500	0 3 000	0 2 500	0 6 500
Mean Shift Length (hours)	7,7	8,0	7,8	7,7	5,2	4,0	7,5	6,5	6,3	5,7	7,2	6,7

TABLE IV

MEAN DUST LEVEL FOR EACH MINING OPERATION—MEASURED BY KONIMETER WITH STANDARD TREATMENT (p/ml) (NUMBERS OF SAMPLES ARE GIVEN IN BRACKETS)

OPERATION IN PROGRESS	OCCUPATIONAL GROUP											
	1 Shaft-sinkers	2 Developers	3 Stopers	4 Assistant Miners/ Trammers	5 Shift Bosses	6 Other Officials	7 Banks/ Skips	8 Workers near shafts	9 Boiler-makers	10 Other Artisans	11 Miscell-aneous	Mean Total
TRAVELLING/WAITING 1. In shafts and at stations	230 (73)	110 (102)	130 (344)	130 (813)	120 (176)	160 (443)	70 (72)	90 (106)	160 (234)	140 (261)	110 (93)	130 (2 717)
2. Between shafts and working places	150 (5)	160 (84)	140 (349)	150 (432)	150 (78)	200 (250)		70 (13)	150 (60)	170 (108)	120 (43)	150 (1 425)
3. Between working places		250 (107)	210 (150)	190 (343)	180 (100)	190 (155)			170 (54)	130 (114)	140 (19)	190 (1 043)
4. Between working places and miner's box		180 (97)	200 (235)	190 (110)	120 (10)	200 (20)				100 (7)	110 (12)	170 (494)
5. At miner's box or equivalent	130 (6)	180 (223)	180 (790)	150 (507)	190 (36)	230 (24)					100 (38)	170 (1 629)
6. In officials' U/G tea rooms					170 (14)	130 (20)				60 (5)		130 (49)
7. Waiting elsewhere	110 (12)	280 (107)	180 (153)	170 (554)	130 (27)	170 (61)		90 (23)	170 (177)	170 (193)	150 (26)	160 (1 333)
IN STOPES 10. Examining/watering down			230 (246)	340 (98)	220 (36)	310 (30)						250 (410)
11. Barring		130 (5)	270 (247)	240 (168)	150 (39)	200 (25)						210 (484)
12. Lashing/tramming/tipping			230 (818)	240 (233)	250 (128)	290 (233)						240 (1 419)
13. Blowing out, washing, plugging, marking holes			210 (137)	290 (30)		190 (5)						180 (176)
14. Drilling		130 (10)	240 (721)	240 (100)	310 (89)	250 (227)						250 (1 150)
15. Scraping			290 (255)	250 (34)	320 (44)	540 (72)						340 (412)
16. Support work at face		160 (12)	230 (170)	170 (13)	340 (22)	270 (24)						250 (241)
17. Work in back areas			290 (37)	200 (118)	260 (18)	190 (33)						240 (208)
18. Charging up/lighting up		100 (6)	210 (403)	410 (28)	60 (6)						200 (6)	180 (449)
19. Other work			190 (54)	370 (23)	200 (12)	200 (9)						210 (100)

TABLE IV CONTD.

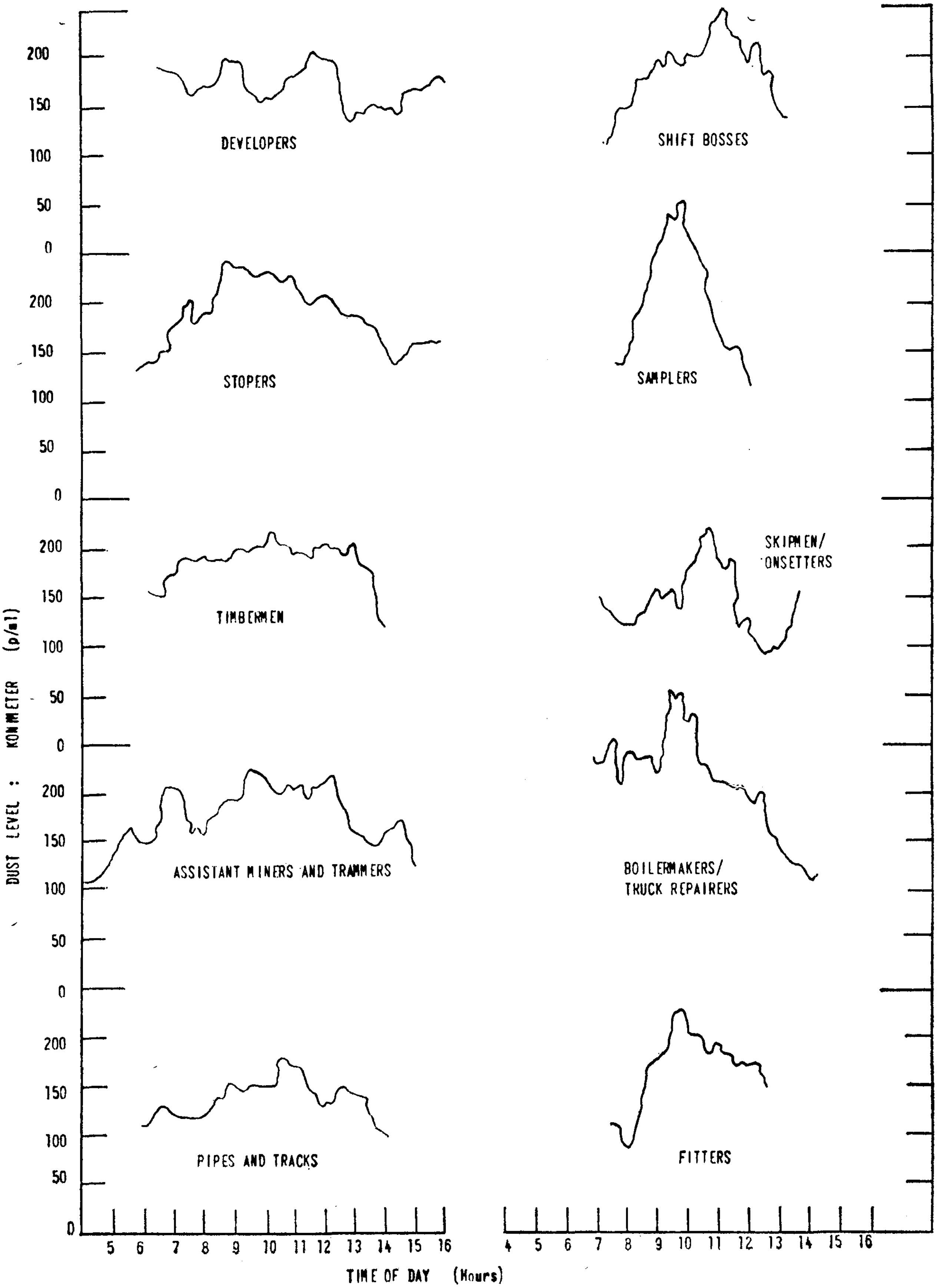
OPERATION IN PROGRESS	OCCUPATIONAL GROUP 1 Shaft-sinkers	2 Developers	3 Stopers	4 Assistant Miners Trammers	5 Shift Bosses	6 Other Officials	7 Banks/ Skips	8 Workers near shafts	9 Boiler-makers	10 Other Artisans	11 Miscell-aneous	Mean Total
IN DEVELOPMENT ENDS AND SINKING SHAFTS 20. Examining/watering down/washing	330 (19)	230 (40)	210 (24)	230 (49)	170 (5)	220 (5)						210 (142)
21. Barring	290 (44)	230 (48)	230 (15)	170 (79)	200 (7)	280 (10)						220 (203)
22. Lashing by hand	350 (51)	230 (135)	200 (113)	170 (393)	190 (29)	200 (74)		120 (13)				180 (810)
23. Mechanical loading	320 (32)	260 (89)	260 (33)	350 (103)	180 (16)	260 (5)						260 (278)
24. Tramming		210 (58)	310 (58)	200 (273)	140 (21)	210 (22)						220 (432)
25. Blowing over; blowing out; etc., of holes	550 (31)	220 (59)	170 (28)	740 (9)		130 (10)						260 (138)
26. Drilling	270 (86)	240 (206)	270 (87)	200 (96)	220 (17)	180 (101)						210 (597)
27. Pipe and track work	130 (24)	250 (36)		230 (18)	190 (5)	120 (5)						170 (91)
28. Charging up/lighting up	280 (26)	270 (120)	190 (71)	90 (10)								180 (236)
29. Other work	140 (71)	240 (57)	150 (36)	170 (122)	200 (8)	180 (16)						190 (310)
SUPERVISORS (U.G. MANAGERS, MINE OVERSEERS, SHIFT BOSSES) 30. In stopes examining/instructing					260 (288)	210 (119)						250 (407)
31. In development ends: examining/ instructing					160 (108)	230 (62)						180 (170)
32. Elsewhere: examining/instructing					180 (159)	190 (67)						180 (226)
SPECIALIST DEPARTMENTS 34. Surveyors—all duties						260 (152)						260 (152)
35. Samplers—all duties						300 (219)						300 (219)
36. Study officials—all duties						240 (204)						240 (204)

TABLE IV CONTD.

OPERATION IN PROGRESS	OCCUPATIONAL GROUP											
	1 Shaft-sinkers	2 Developers	3 Stopers	4 Assistant Miners Trammers	5 Shift Bosses	6 Other Officials	7 Banks/ Skips	8 Workers near shafts	9 Boiler-makers	10 Other Artisans	11 Miscell-aneous	Mean Total
SPECIALIST DEPARTMENTS (contd) 37. Ventilation officials—all duties						210 (45)						210 (45)
38. Native labour control—all duties						200 (293)						200 (293)
ENGINEERING DEPARTMENT 40. Officials: supervising/instructing						170 (37)				230 (5)		220 (42)
41. Boilermakers/fitters/riggers working on 'dirty' materials									400 (210)	210 (48)		260 (258)
42. Boilermakers/fitters/riggers working on 'clean' materials									250 (209)	130 (351)		160 (560)
43. Boilermakers/fitters/riggers in U/G workshops, not working									190 (134)	230 (55)		220 (189)
44. Carpenters all work										120 (43)		120 (43)
45. Carpenters: not working										80 (10)		80
46. Electricians: all work										150 (110)		150 (110)
47. Electricians: not working										50 (26)		50 (26)
48. Masons: all work										120 (27)		120 (27)
49. Masons: not working										210 (9)		210 (9)
OTHER WORKERS 50. Winding engine drivers: In hoist chamber								140 (268)				140 (268)
51. Pumpmen: in pump chamber								70 (161)				70 (161)
52. Timbermen and shaft timbermen transporting material				170 (33)								170 (33)
53. Timbermen and shaft timbermen working with material				220 (461)				50 (37)				100 (498)

TABLE IV CONTD.

OPERATION IN PROGRESS	OCCUPATIONAL GROUP											
	1 Shaft-sinkers	2 Developers	3 Stopers	4 Assistant Miners Trammers	5 Shift Bosses	6 Other Officials	7 Banks/ Skips	8 Workers near shafts	9 Boiler-makers	10 Other Artisans	11 Miscell-aneous	Mean Total
OTHER WORKERS (cont) 54. Shaft timbermen: working in shaft								120 (166)				120 (178)
55. Banksmen and skipmen: at working place, hoisting rock							350 (176)					350 (176)
56. Banksmen and skipmen: at working place, not hoisting rock				120 (11)			90 (661)					110 (672)
57. Banksmen and skipmen: not at working place							70 (2)					70 (2)
58. Locomotive drivers				190 (257)								190 (257)
59. Pipe fitters/Tracklayers: transporting material				140 (26)								140 (26)
60. Pipe fitters/Tracklayers: working with material				150 (368)								150 (368)
61. Sanitation personnel											150 (38)	150 (38)
62. Diamond drillers											110 (83)	110 (83)
63. Lashing/Tramming/Tipping: not in stopes		170 (12)	190 (77)	190 (678)	200 (123)	360 (106)			170 (15)	70 (15)		200 (1 030)
64. Miscellaneous		170 (9)	120 (34)	160 (167)	200 (41)	210 (5)		140 (93)	110 (6)	210 (6)	220 (16)	170 (377)
99. Workers not specified above										210 (75)	130 (18)	170 (93)



TIME TRENDS IN DUST LEVELS

Fig. 1—Time trends in dust levels

table also shows (in parentheses) the number of individual observations on which each mean result is based. As little reliance can be based on means determined from a small number of samples, those results based on less than 5 samples were excluded from individual occupational groups, but were included in the overall mean for a particular operation (i.e. the last column in the table).

In calculating the overall mean dust level for a given operation the individual dust levels were weighted according to the number of men employed in the industry (as given in Table I).

It will be appreciated that it may not always be the mining operation in the neighbourhood of the sampling position which accounts for the dust level. Some — perhaps most — of the dust at a given place may have been carried there from operations conducted some distance away in the intake air. Despite this possibility, it is to be expected that if particular processes are consistently *dusty* they will appreciably influence dust counts taken in the air near to them. Thus where high mean dust levels are regularly found near a specific operation over a large number of samples, this operation is likely to be a major dust producer.

A study of this table reveals much information concerning the most dusty operations and the areas where dust control investigations should be concentrated. The number of samples taken at each operation gives an indication of the proportion of time the operation was in progress, since konimeter samples were taken at intervals of ten minutes throughout the shift.

(a) The major dust-producing operations were scraping, sampling and hoisting rock. [Sampling refers to the chip-sampling method then in use, modern broken-ore sampling would probably give different results.]
(b) If the dust exposure of individual occupational groups is investigated, it is seen that assistant miners and trammers and shaft-sinkers were exposed to very high dust levels while blowing over and blowing out holes in sinking shafts and development ends.
(c) The exposure of boiler-makers was high — possibly due to non-siliceous fumes not removed by the treatment of the samples.
(d) *Other officials*, including mine overseers, were exposed to high scraping-dust levels in stopes, and assistant miners and trammers while charging up/lighting up.

TIME TRENDS IN DUST LEVELS

The time of sampling was recorded for each konimeter sample. Graphs based on this data are given in Fig. 1, showing how mean dust levels experienced by workers in different occupations varied throughout the day. Means were calculated for only those ten-minute intervals for which 20 or more observations had been obtained. These data were plotted for each occupation [N.B. *not* occupational group] and five-point moving averages were calculated. The final graphs were drawn through these averaged points.

Insufficient results were obtained for the occupations not included in the figure.

The information which can be obtained from these figures includes:

(1) Times of day at which control sampling should be carried out, and
(2) Periods during which reasons for high dust counts should be investigated.

CORRELATION BETWEEN MEASUREMENTS OF DIFFERENT PROPERTIES OF THE AIRBORNE DUST

The practice of reporting relationships between measurements of dust based on *means of means* was justifiably criticised at the Johannesburg Pneumoconiosis Conference in 1969. Such information provides only rough conversion factors, and does not give any information as to the scatter found about the mean line, or the confidence with which one may convert from one measure to another.

Table V shows the correlation coefficients obtained for several pairs of the properties of the dust sampled. Fig. 2 shows eye-fit regression lines for those measures where the correlation coefficient was greater than 0,7. If the correlation coefficient is lower than this, conversion from one measure to the other cannot be recommended.

It can be seen that the correlation is high when two properties of the same sample are used, e.g. respirable surface area and 0,5-5 μm particles on a S.T.P. slide, since these are interdependent. Thus the limiting factor is the performance of the instrument used, since it is shown that estimates of surface area, mass, and particle counts within any range can be made from the one sample with a high degree of confidence. Of course, this is only possible when a full sized count is made of the sample and when the size-distribution of the dust is known. A sampling instrument which is unavoidably size-selective cannot yield this information.

CORRELATION OF DUST MEASUREMENTS WITH MEDICAL FINDINGS

The dust measurements reported in the foregoing sections are the real subject matter of this paper. The relationships between these dust exposures and the incidence of silicosis among the exposed miners have been reported in detail on several occasions[1, 2, 3]. However, since many readers of this journal may not have had the opportunity to study these papers, the more pertinent results will be briefly reviewed.

In addition to the dust exposure levels which had been determined, two further sets of data were required:

(1) The occupational histories of cohorts of men who had been employed in the industry for a number of years.
(2) The medical histories (with reference to silicosis) of these men.

Occupational Histories

Two cohorts of men have been considered, one of men who started work underground in, or about, 1936 and a second cohort of men who started in 1946.

TABLE V

CORRELATION COEFFICIENTS OF MEASURED PROPERTIES OF DUST

DUST MEASURE A				DUST MEASURE B				Correlation Coefficient r_{AB}
Instrument	Property Measured	TREATMENT: Ignition	TREATMENT: Acid treatment	Instrument	Property Measured	TREATMENT: Ignition	TREATMENT: Acid treatment	
S.T.P.	Total particles	√		S.T.P.	Total particles	√	√	0,54
M.T.P.	Surface area	√		M.T.P.	Surface area	√	√	0,72
S.T.P.	Total particles	√		M.T.P.	Surface area	√		0,43
S.T.P.	Total particles	√	√	M.T.P.	Surface area	√	√	0,58
S.T.P.	Total particles	√	√	Konimeter	Total particles	√	√	0,45
M.T.P.	Surface area	√	√	Konimeter	Total particles	√	√	0,47
S.T.P.	Respirable surface area	√	√	S.T.P.	Total particles	√	√	0,72
S.T.P.	Respirable surface area	√	√	S.T.P.	0,5-5μm particles	√	√	0,97
S.T.P.	Respirable surface area	√	√	S.T.P.	Respirable mass	√	√	0,98

The first cohort comprised 1 200 men, all of whom had completed at least 3 000 underground shifts in South African gold mines and had no other known dusty occupations. Details of their occupational histories were obtained from mine records. The selected population was not the one that was used for the dust exposure studies.

The second cohort was a group of 500 *Production* men. Because of their shorter service, they were only required to have worked 2 000 shifts.

Medical Histories

Two sets of data were used:

(1) The dates of certification, if any, of the subjects — which were supplied by the Miners' Medical Bureau, and

(2) The years of first evidence of radiological silicosis.

These data were obtained by means of a special reading of the X-ray plates taken during periodic examinations carried out at the Miners' Medical Bureau. The plates were read by Dr G. K. Sluis-Cremer, at that time Director of the Miners' Medical Bureau. Various investigations showed this to be an acceptably precise method of measurement[3].

Survivorship Curves for Production and Non-Production Workers

The methods used to evaluate and present the results of these investigations evolved over a period of time.

The first step was to divide the cohort into *production* and *non-production* categories. The classification of the various occupational groups on this basis is given in Table I. Men were placed in either category only if they had spent 60 per cent of their shifts in appropriate occupations.

Survivorship curves were then drawn which gave the percentage of men who had worked a particular number of shifts and had *survived* i.e. either not been certified or not found to have radiological evidence of silicosis. [Note that these percentages refer only to the men

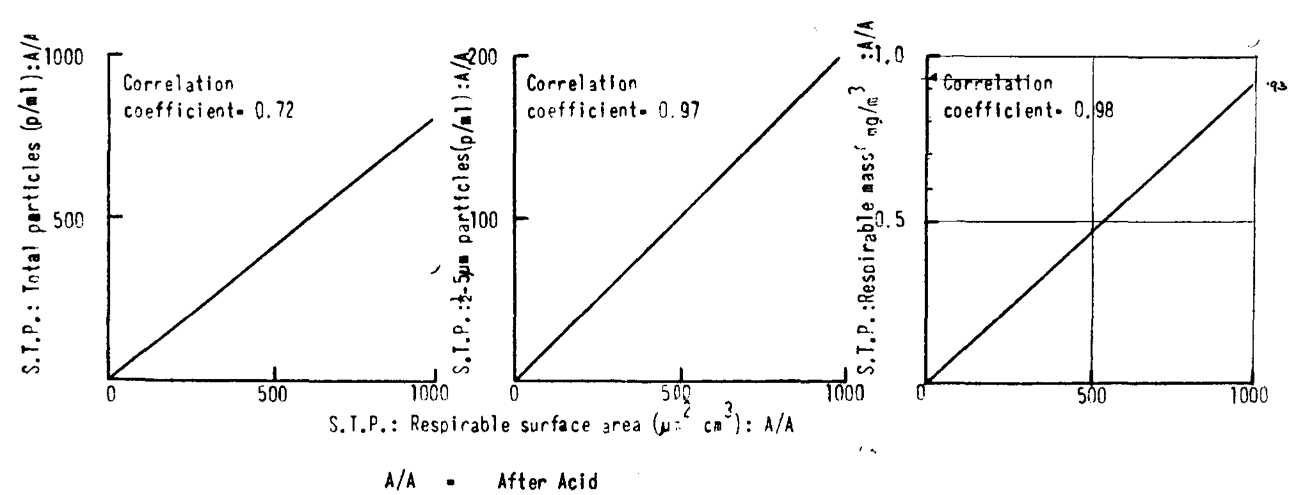


Fig. 2—Conversion between various dust measures

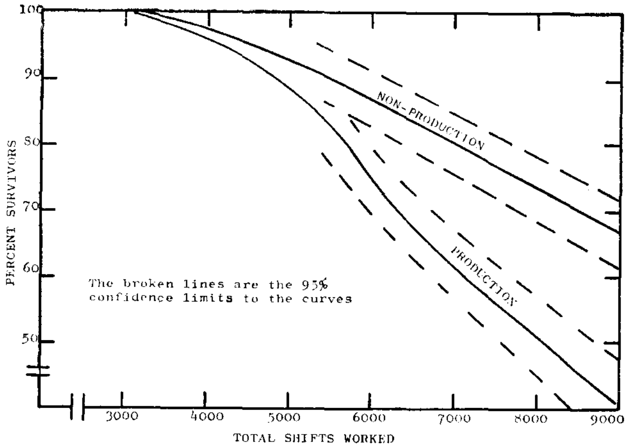


Fig. 3—Survivorship curve based on certification

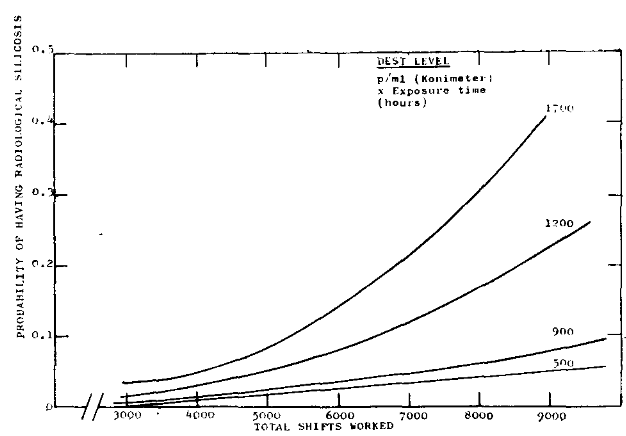


Fig. 5—Probability of having radiological silicosis at the stated number of shifts for dust levels as measured by the Konimeter

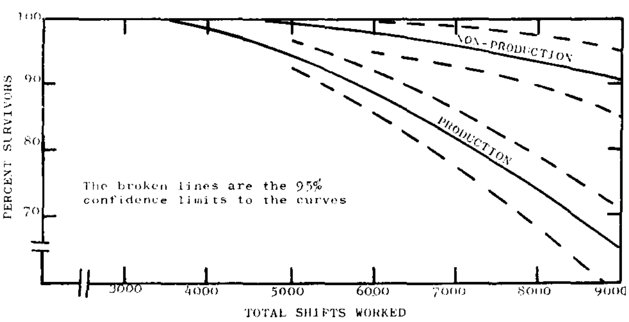


Fig. 4—Survivorship curve based on radiological assessment

remaining in the industry after the specified number of shifts, wastage due to resignations, accidental death, etc. is specifically excluded]. These curves are given in Fig. 3 and Fig. 4.

Two points are immediately obvious:

(1) The rate of certification is much greater than the incidence of radiological evidence of silicosis, at all times.

(2) Survivorship is significantly higher for persons in non-production occupations both with respect to certification and radiological evidence of silicosis. The curves are significantly different at the 95 per cent level beyond about 6 000 shifts in both cases.

These findings were obtained without the use of the dust exposure measurements.

The Probability of Contracting Silicosis at Various Dust Exposures

The occupational histories and medical evidence were then combined with the dust exposure levels and the probability of contracting silicosis at a given dust exposure level after a specified number of shifts was calculated[3].

The probability curves obtained using dust levels as measured by the konimeter are shown in Fig. 5. [The lowest curve was not determined at the same time as the others but on the basis of a supplementary study of a similar type].

DISCUSSION AND CONCLUSIONS

The various sets of data have been briefly discussed as they were presented in the paper. Some interesting points arise from a general consideration of the data:

(1) Despite the obvious disadvantages of a retrospective study such as this, the results form a reasonably coherent body of material from which some useful conclusions can be drawn and which can be analysed with some effect.

(2) There is unquestionably a dose-response relationship between exposure to siliceous dust and the incidence of silicosis. There is no evidence of a lower limit of airborne dust below which the probability of contracting silicosis is zero. This does not necessarily mean that such a level does not exist.

ACKNOWLEDGEMENTS

Although the work which produced the measurements reported was directed throughout by the late Mr Derrick Beadle, expert assistance of various types was provided by a number of persons. Chief among these were Dr G. K. Sluis-Cremer, who evaluated the radiographs, and Dr H. S. Sichel, who was consulted on statistical planning of the sampling and treatment of the results.

The Research Adviser of the South African Chamber of Mines is thanked for permission to publish these results.

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APPENDIX I

MOMENTS OF THE DAILY DUST EXPOSURES EXPRESSED AS DIFFERENT PROPERTIES OF THE STANDARD THERMAL PRECIPITATOR SAMPLES

(MEAN DAILY DUST LEVEL × TIME UNDERGROUND IN HOURS)

Property	Moments of data	OCCUPATIONAL GROUP Shaft-sinkers 1	Developers 2	Stopers 3	Assistant Miners/ Trammers 4	Shift Bosses 5	Other officials 6	Banks/ Skips 7	Workers near shafts 8	Boiler-makers 9	Other Artisans 10	Miscell-aneous 11	Total
Total particles (cm^{-3}) before acid treatment	No. of samples	11	39	112	153	43	109	34	35	40	62	11	649
	Mean	7 120	6 270	5 000	3 960	2 520	2 780	2 790	1 340	7 820	2 140	2 010	3 870
	Std. Deviation	3 540	3 760	4 150	4 280	1 960	3 880	4 310	1 310	9 070	2 550	1 260	4 530
	Range	0 12 500	0 18 500	0 24 500	0 24 500	0 11 500	0 28 500	0 20 500	0 6 500	0 29 500	0 13 500	0 4 500	0 29 500
Total particles (cm^{-3}) after acid treatment	No. of samples	11	38	111	155	43	106	33	33	41	62	11	644
	Mean	3 360	2 020	1 540	1 110	750	730	970	390	1 340	660	840	1 140
	Std. Deviation	2 780	1 450	970	770	330	600	650	330	1 310	670	600	1 050
	Range	0 8 500	0 7 500	0 5 500	0 4 500	0 1 500	0 4 500	0 2 500	0 1 500	0 6 500	0 5 500	0 2 500	0 8 500
Particles 0,5-5μm (cm^{-3}) before acid treatment	No. of samples	11	39	112	153	43	109	34	35	39	62	11	648
	Mean	1 670	840	710	460	380	300	370	200	450	230	310	480
	Std. Deviation	1 330	500	670	420	310	260	300	170	400	200	230	510
	Range	100 5 000	100 2 500	0 5 000	0 4 000	0 1 400	0 1 500	0 1 200	0 800	0 2 000	0 1 100	0 900	0 5 000
Particles 0,5-5μm (cm^{-3}) after acid treatment	No. of samples	11	38	111	155	43	106	33	33	41	62	11	644
	Mean	870	450	340	240	180	160	220	90	200	130	190	250
	Std Deviation	730	320	260	180	120	130	190	80	150	110	150	240
	Range	100 2 200	0 1 700	0 1 800	0 1 100	0 700	0 1 100	0 1 000	0 400	0 900	0 700	0 600	0 2 200
Total surface area ($\mu m^2/cm^3$) before acid treatment	No. of samples	11	39	112	153	43	109	34	35	39	62	11	648
	Mean	31 360	12 030	7 950	6 990	5 430	3 870	8 810	4 020	5 280	3 440	6 870	6 730
	Std. Deviation	26 930	10 910	6 560	5 400	5 110	2 650	9 080	7 360	3 510	2 370	4 930	7 610
	Range	6 000 86 000	0 52 000	0 6 000	0 3 000	0 24 000	0 16 000	0 48 000	0 18 000	0 18 000	0 16 000	0 18 000	0 86 000
Total surface area ($\mu m^2/cm^3$) after acid treatment	No. of samples	11	38	111	155	43	106	33	33	41	62	11	644
	Mean	13 520	5 310	3 750	3 190	2 400	1 880	3 640	1 530	2 280	1 640	2 800	2 999
	Std. Deviation	12 000	4 380	2 250	2 490	2 790	1 280	3 200	1 430	1 440	1 160	1 940	3 180
	Range	2 000 34 000	0 19 000	0 15 000	0 15 000	0 17 000	0 9 000	0 12 000	0 7 000	0 8 000	0 6 000	0 7 000	0 34 000
Respirable surface area ($\mu m^2/cm^3$) before acid treatment	No. of samples	11	39	112	153	43	109	34	35	39	62	11	648
	Mean	9 660	4 500	3 610	2 530	2 070	1 640	2 260	1 210	2 590	1 300	1 700	2 580
	Std. Deviation	7 590	2 820	3 100	1 830	1 550	1 330	1 670	890	2 160	960	890	2 560
	Range	1 000 26 000	0 15 000	0 26 000	0 14 000	0 8 000	0 8 000	0 7 000	0 5 000	0 9 000	0 6 000	0 4 000	0 26 000
Respirable surface area ($\mu m^2/cm^3$) after acid treatment	No. of Samples	11	38	111	155	43	106	33	33	41	62	11	644
	Mean	4 690	2 180	1 660	1 240	910	730	1 290	520	1 020	640	950	1 210
	Std. Deviation	4 020	1 550	1 160	870	730	500	1 380	450	670	500	700	1 210
	Range	500 12 000	0 8 000	0 8 000	0 6 000	0 4 500	0 3 000	0 8 000	0 2 500	0 4 000	0 3 000	0 3 000	0 12 000
Respirable mass (mg/m^3) after acid acid treatment	No. of samples	10	37	113	157	43	106	33	34	41	61	11	646
	Mean	4,44	1,96	1,57	1,20	0,87	0,77	1,31	0,56	1,00	0,64	1,01	1,14
	Std. Deviation	3,94	1,59	1,00	0,93	0,71	0,53	1,38	0,57	0,71	0,51	0,79	1,11
	Range	0,80 12,00	0,30 8,00	0,20 6,00	0 8,00	0,20 4,00	0,10 4,00	0 8,00	0 4,00	0,10 4,00	0,10 4,00	0 4,00	0 12,00

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APPENDIX II

THE ESTIMATION OF RESPIRABLE MASS FROM MICROSCOPE COUNTS

INTRODUCTION

In the original assessment of the dust samples in this survey, particle counts of all standard thermal precipitator slides were made in at least 15 size ranges using the truncated multiple traverse technique. Using these original particle counts, the three constants of the Sichel-distribution of airborne mine dust: α, β and γ, were calculated by computer for each sample. The Sichel-distribution estimate of T.S.A. (total surface area) was also obtained.

In 1959 the Johannesburg Pneumoconiosis Conference concluded that R.S.A. (respirable surface area) was the property most closely related to health hazard for siliceous dusts.

Accordingly, the R.S.A. of each sample in the survey was calculated based on the original, fully-sized counts.

Recently there has been increased world-wide interest in respirable mass as the appropriate property to measure, and thus a method of calculating this from the original counts has been developed.

It must be noted that this conversion to R.M. (respirable mass) is on a theoretical basis, and the accuracy and precision associated with it may not be comparable with results obtained by actually weighing samples, a process subject to its own variations. It should also be noted that the accepted *R.S.A.* is not a direct measure of surface area but is based on a theoretical calculation from the microscopically determined projected surface areas of the samples.

CALCULATION OF THE RESPIRABLE MASS

Joffe[1], developed a method of calculating respirable surface area using the Sichel distribution. This method has been used as a basis for the calculation of respirable mass and similar approximations have been made.

The *respirable* portion of the surface area can be calculated as follows:

$$\text{R.S.A.} = \pi N \int_{\theta}^{6} x^2 p(x) f(x)\, dx$$

where N = total particles (cm^{-3})

θ = assumed smallest particle sized = 0,1 μm

x = equivalent diameter of particles in μm

$f(x)$ = respirable dust sampling curve, the approximation: $y = 1{,}02128 - 0{,}17021\, x$ was used for this work, where y is the sampling efficiency

and $p(x) = Ae^{-\alpha\sqrt{x}}$ which is a reasonable approximation to the Sichel particle size distribution

$$A = \frac{\gamma\alpha^2}{2\,(1+\alpha\sqrt{\theta})e^{-\alpha\sqrt{\theta}}}$$ where α and γ are parameters of the Sichel distribution

The corresponding *respirable* volume is given by

$$\text{R.V.} = 1/6\, \pi N \int_{\theta}^{6} x^3\, p(x) f(x)\, dx$$

A particle density of 2 700 kg/m^3 was assumed for the dust and the respirable mass was then calculated.

The above functions can be reduced to the following terms:

$$\text{R.S.A.} = \gamma\pi N \{f_1(\alpha, \theta) + f_2(\alpha, 6)\}$$

$$\text{R.V.} = 1/6\, \gamma\pi N \{f_3(\alpha, \theta) + f_4(\alpha, 6)\}$$

where f_1, f_2 f_3 and f_4 are functions of α only, since the limits to the size range are constant. Thus the ratio of R.M. to R.S.A. is a function of α only, and is independent of the total particles, particle size, or any other variable. Table VI gives the value of this ratio for various values of α.

TABLE VI

CONVERSION OF RESPIRABLE SURFACE AREA (R.S.A.) TO RESPIRABLE MASS (R.M.)

α	$\frac{\text{R.M.}}{\text{R.S.A.}}$ $\frac{(\text{mg/m}^3)}{(\mu\text{m}^2/\text{cm}^3)}$ $x\ 10^3$
1,6	1,29
2,0	1,18
2,1	1,15
2,5	1,07
3,0	0,96
3,5	0,86
4,0	0,75
4,4	0,67
4,5	0,65
4,8	0,62

LIMITS TO THE CONVERSION FROM RESPIRABLE SURFACE AREA TO RESPIRABLE MASS

Table VI shows that for a wide range of α values (3:1) the R.M./R.S.A. ratio only varies by about 35 per cent around the mean value.

In practice, most α values observed in South African gold mines fall in a much narrower range; Table VII gives a frequency distribution of the individual values of α observed in the occupational dust survey. The 95 per cent confidence limits to α (based on log units) are (2,12:4,37) with mean 3,05.

TABLE VII

FREQUENCY DISTPIBUTIONS OF α IN THE SICHEL SIZE DISTRIBUTION (Shift means as measured by the standard thermal precipitator)

α Value	Before acid treatment	After acid treatment
1,20 — 1,39	1	
1,40 — 1,59	3	
1,60 — 1,79	4	1
1,80 — 1,99	13	3
2,00 — 2,19	28	11
2,20 — 2,39	53	26
2,40 — 2,59	74	66
2,60 — 2,79	91	85
2,80 — 2,99	85	108
3,00 — 3,19	81	98
3,20 — 3,39	57	85
3,40 — 3,59	50	71
3,60 — 3,79	37	46
3,80 — 3,99	28	23
4,00 — 4,19	14	11
4,20 — 4,39	15	3
4,40 — 4,59	1	4
4,60 — 4,79	1	1
4,80 — 4,99	1	2
5,00 — 5,99	5	
Total	642	644

Thus when considering airborne underground dust in South African gold mines the relationship between R.M. and R.S.A. is reasonably constant even if no account is taken of the α value. When deciding on dust sampling strategy it would not matter greatly whether respirable mass or surface area was chosen.

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