Safety in Mines Research Advisory Committee

Quantification of Inherent Respirable Dust Generation Potential (IRDGP) of South African Coals

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Executive Summary

Project SIM020604 was formulated to determine the Inherent Respirable Dust Generation Potential (IRDGP) of various South African coal types from various provinces and its use in dust exposure assessment. The objective was to quantify the amount of inherent respirable dust that becomes airborne from a particular coal type, rather than the respirable crusher product or its size distribution.

The epidemiological findings on the relationship between coal rank and development of Coal Workers' Pneumoconiosis (CWP) led to numerous studies on coal types and generation of respirable dust. Internationally, a number of laboratory studies have been conducted on the relationship between coal characteristics and respirable dust generation. No literature relating rates of CWP in South African mine workers with coal rank has been found. Also, no study has yet been done in South Africa to determine the inherent respirable dust generation potential (IRDGP) of various coal seams or coal types. Therefore, any new information acquired through such a study could be used in future to investigate the relationship between the exposure levels, dust types and the disease rate among South African coal miners from a long-time perspective.

The IRDGP test facility was built at the Kloppersbos research centre. The laboratory test facility comprised a roll crusher located at the intake end of a 0.9 m high by 1.2 m wide wood framed hard board sheet rectangular wind tunnel 8.0 m long. An exhaust fan and a dust collector were located at the discharge end of the tunnel. The roll-crusher used for the study was similar to the specifications used by NIOSH in their dust generation research study. The research study carried out experimental work that resulted in critical information on dust type and IRDGP for the first time for South African coals.

In summary, the following conclusions are made from the IRDGP data of the test coal samples:

- For the first time, a clear delineation of coal types (Bituminous and Anthracite) that possess the most inherent respirable dust generation potential was possible. Apart from a small amount of semi-anthracite found in Kwa Zulu Natal, most of the South African coal is of the semi-bituminous type. Typical range of volatile matter of coal is between 25% and 31%, while ash content is 10% to 24%.
- There is no conclusive relationship between different coal seams (1, 2, 4 and 5) and inherent respirable dust generation potential (IRDGP). The majority of the mine operators are currently exploiting coal from seam 2 and 4.

- Average coal crushing time of coal samples for the study indicated that the crushing time decreases in the order of seams 1 to 5. Kwa Zulu Natal coals took the highest crushing time during the tests when compared to the other coal seams and coal types. The reasons can be attributed due to inherent coal properties of high rank anthracite coals.
- Measured IRDGP of Limpopo coal was less than commonly occurring seam 2 and seam 4 coals in Mpumalanga province.
- Inherent silica content of South African coal seams indicated that average inherent silica for the test coals was 3.54%. Similarly, historically analysed airborne coal dust samples for quartz has indicated that they were below the limit of detection of X-ray spectrometer. However, caution must be exercised when assessing exposure specifically in the presence of sandstone bands and roof-bolt operators.
- Statistical Analysis of Variance (ANOVA) results of the study indicated that coal rank influences the IRDGP of coals ($p = 0.000$). There is no conclusive relationship between different coal seams (1, 2, 4 and 5) and IRDGP ($p = 0.373$) as they are all of semi-bituminous type.
- Based on the measured respirable dust data of the South African coals, it can be concluded that majority of the coal mining operation provinces such as Mpumalanga, Free State, Limpopo have on average similar IRDGP, while Kwa Zulu Natal coal samples which are semi-anthracite type coal have greater IRDGP.

Recommendations

The IRDGP information will be helpful as the effectiveness of a dust-control system is dependent on coal dust type in both surface and underground operations. To date there has been no clear delineation for South African workers who are exposed to different dust types. Therefore, it is recommended that a research study be conducted to investigate prevalence of CWP among workers in Kwa Zulu Natal coal mines and other provinces to assist in determining historic dose and developing a relevant dose-response curve.

Glossary of abbreviations, symbols and terms

Abbreviations

ARD	Airborne Respirable Dust
BMRC	British Medical Research Council
DME	Department of Minerals and Energy
MRE	Mine Research Establishment
SA	South Africa
SIMRAC	Safety in Mines Research Advisory Committee
TWA	Time-Weighted Average

Symbols

%	percentage
µm	micrometres/microns
L/min	litres per minute
m	metre
m/s	metres per second
m^2	square metre
m^3/s	cubic metres per second
mg/m^3	milligrams per cubic metre
mm	millimetre

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1 Introduction

Coals are classified into ranks, which are roughly associated with the relative geological age of the coal and the degree to which the coalification process has progressed (Larson, 1981; Page and Organiscak, 2001). Coal rank is defined by the percentage of fixed carbon (the proportion of carbon that remains when coal is heated and the volatile material is removed), by the percentage of volatile material, and by the heat content of the coal (Mutmansky, 1984). The general classifications of coal include anthracite, semi-anthracite, bituminous, semi-bituminous, and lignite. Anthracite, or “hard coal,” contains between 91 and 95% fixed carbon; and lignite, or “brown coal,” between 65 and 70% fixed carbon (Parkes, 1982). High rank coals are of the greatest geological age and consequently have a high percentage of carbon but a low proportion of volatile matter (VM). Conversely, low rank coals have lower carbon content but higher levels of volatile matter (VM). High rank coal dust is characterized by coarse dust particles enriched with high mineral content with average density greater than low rank coal and explains the apparently greater hazard of breathing high rank coals.

Workers exposed to coal mine dust are at risk of developing simple CWP, PMF, silicosis, and chronic obstructive pulmonary disease (Parks, 1982). A British study by Hart and Aslett (1942) related coal rank and CWP and noted that the descending order of prevalence of radiological abnormalities are viz., anthracite coal mines, steam coal mines and bituminous coal mines. Hicks et al., (1961) studied 20 collieries in Britain and concluded that the average period of work at the coal face required to produce a 20% prevalence of CWP in high, medium and low rank coals are 8 years, 16 years and 36 years respectively. A positive association of the incidence of CWP with the rank of coal has been reported by Nagelschmidt (1965). Efforts to study the prevalence of pneumoconiosis in the United States were initiated in the 1960s. In

1969, the U.S. Public Health Service and the U.S. Bureau of Mines initiated a special study of 31 mines widely scattered throughout the USA. This study, referred to as the National Study of Coal Workers' Pneumoconiosis (NSCWP), included medical examinations and exposure measurements. In 1972, Morgan et al., using data from that study, reported on the prevalence of CWP and PMF found in the bituminous and anthracite coal miners of Pennsylvania. For anthracite miners, the data showed that the prevalence was 60% as a whole for pneumoconiosis and 14% for PMF; for bituminous miners, it was 47 and 2.4%, respectively. In addition, the prevalence of bronchitis was found to be higher in the anthracite miners.

Mines operating in high rank coal have been generally found to produce a coal dust with a lower ash, including higher quartz content (Casswell et al., 1971; Douglas, 1986). Toxicity studies have confirmed that there are pronounced differences in specific risk from different fine coal dusts. Reisner's (1971) study to investigate the cytotoxic effect of different fine coal dusts showed increased cytotoxicity related to higher rank coals. Reisner (1971) and Jacobsen's (1980) observations in coal miner's data showed that very strong variations existed in the prevalence and progression of CWP between different regions and individual mines, despite similar cumulative exposures and quartz contents of the coal dusts. However, these studies were unable to identify specific factors causing the variation, suggesting that some mines produce coal dust that is more pathogenic than others.

A radiographical study (Jacobsen, et al., 1980) indicated that South Wales (UK) mines producing high rank coals are more hazardous than others. It was found that in high rank coal mines, the mean exposure period for the development of Pulmonary Massive Fibrosis (PMF) was 34 years, while in low rank coal mines the mean was between 41 and 44 years (Douglas, 1986). This differential mean age for developing PMF indicated that high rank coals might cause more rapid and severe pathogenic effects for a given degree of exposure than low rank coals. Serological testing on a series of healthy miners and miners suffering from CWP revealed the possibility that certain ranks of coal produce a more inflammogenic dust (Lippman, et al., 1973). However, the study concluded that more research in the area was necessary to elucidate the results and examine other types of immunological activity associated with CWP.

Attfield and Morring (1992) investigated the relationship between pneumoconiosis and respirable dust in U.S. coal miners. Their results showed that the exposure-response relationship was a function of coal rank and age. Relationship between decrease in lung function and type coal has been studied by Morgan et al., (1972) and Attfield and Hodous (1992). The later study showed a greater decline in FEV1 (amount of air exhaled in one second) among miners exposed to high rank coal. The results of Attfield and Hodous (1992) were similar to those found in the British Pneumoconiosis Field Research (PFR) studies (McLintock, 1972; Jacobsen et al., 1970; Hurley and Maclaren, 1984; Maclaren et al., 1989) which estimated prevalence of CWP was approximately two times higher. The authors (Attfield and Morring, 1992) noted that the results from the British research should be interpreted with caution because of the lack of knowledge of occupational exposures prior to 1969, the lack of being able to reliably adjust the data for mine-specific factors, and uncertainties associated with the model at dust levels below 2 mg/m^3. Finally, epidemiological studies both in the USA and in Great Britain have demonstrated that the prevalence of category 1 and greater CWP and PMF are dependent on the rank of the coal dust to which miners are exposed.

2 Coal Characteristics and Dust Generation

The epidemiological findings on the relationship between coal rank and development of CWP led to numerous studies on coal types and generation of respirable dust.

Internationally, a number of laboratory studies have been conducted on the relationship between coal characteristics and respirable dust generation. Some of the findings of the past research on coal types and dust generation potential are summarized as follows:

- A laboratory study (Thakur, 1973) involving 20 coals from lignite to anthracite in the USA indicated that the yield of respirable dust varies with coal properties and coal seams.
- Higher rank coals produce larger masses of dust in the finer size range (Thakur, 1974).
- Laboratory studies indicated a consistent positive correlation between coal rank and the amount of respirable-sized particles found in the product (Srikanth et al. 1995; Moore and Bise 1984; Baafi and Ramani 1979). However, these results were based on measurement of dust in the *product* and not measurements of airborne respirable dust. In the mining and roll crushing of coal there is much less regrinding compared to jaw crushing (Organiscak and Page 1998; Ramani et al. 1987).
- The Airborne Dust Release Capacity (ADRC) defined as the ratio of the mass of dust that actually becomes airborne to the total mass of the airborne size fraction increases with coal rank (Polat, 1990).
- Work by Organiscak et al. (1992) indicated that high volatile, low ash coal seams (lower rank coals) tended to produce more airborne respirable dust.
- Airborne respirable dust (ARD) concentrations increased with volatile matter (VM) content, and decreased with increase in fixed carbon content of the bituminous coal samples tested (Page et al., 1993).
- A USBM longwall dust generation study (Organiscak et al., 1990) found that seam type was related to the amount of ARD found at the operation. Low ash, high-volatile bituminous coal seams tend to generate more dust.

- In the research study by Organiscak and Page (1998), coal rank and CWP relationship was reported to be in part related to the increase in dust cloud charging properties of higher rank bituminous coals and the increase in lung deposition observed by Melandri et al. 1983.

The search for the cause(s) of CWP continues despite the vast amount of research that has been undertaken over the past forty to fifty years. Good correlation between the mass of dust inhaled over workers' lifetimes and the incidence of the disease has led to the development of effective standards and implementation of proper dust control procedures in the workplace. Results of investigations in the field of pneumoconiosis in the past 30 years indicate that the mine dusts in the various deposits of the European and American hard coal mines have a different fibrogenicity. With their medical surveillance program, NIOSH has recently determined that coal miners continue to have an elevated risk for CWP under the current dust standard and NIOSH has recommended reducing dust levels. In order to achieve this goal, dust exposure of the workers must be reduced significantly. Recently, ACGIH recommended a TLV-TWA of 0.9 mg/m^3, for miners exposed to bituminous dust or lignite coal dust and a TLV-TWA of 0.4 mg/m^3 for miners exposed to anthracite coal dust (ACGIH 2001). Therefore, inherent respirable dust generation rates of different coal types may give administrative direction to control dust in South Africa and could probably assist in evaluating the medical surveillance data of coal mine workers.

3 Use of Dust type as Exposure Parameter

As discussed earlier, the historic research studies indicate the influence of coal dust type on propensity of developing CWP. Although the coal dust type is more fundamental to dust generation, it can also be viewed as an administrative (better management) parameter in controlling the worker exposure to specific dust type of dust in an operation as well as an indicator of exposure.

No literature relating South African mine workers with various CWP levels to coal rank has been found. A research study by single breakage of nine American and four South African coals indicated that the primary respirable dust generation rates of South African coals were higher than those of six out of the nine American High volatile bituminous coals tested (Ramani and Srikanth, 1996). However, no study has yet been done in South Africa, to determine the inherent respirable dust generation potential (IRDGP) of various coal seams. Therefore, any new information acquired through such a study could be used in future to investigate the relationship between the exposure levels, dust types and the disease rate among South African coal miners from a long-time perspective.

Determination of IRDGP in actual underground conditions would give discrepancies as coal-cutting involves primary, secondary and multiple breakage of coal and respective dust measurement is affected by a number of coal-specific and environment-related factors. Therefore, laboratory crushing studies would better reflect the IRDGP or dustiness of different coal types.

4 Experimental Procedure

The present study focussed on investigating the inherent respirable dust generation potential (IRDGP) of different coal types. The aim of this part of the research study was to contribute to the understanding of the IRDGP or dustiness of South African coal types. The objective was to quantify the amount of inherent respirable dust that becomes airborne from a particular coal type, rather than the respirable crusher product or its size distribution.

4.1 Test Facility

The IRDGP test facility was built at the Kloppersbos research centre. The line diagram of the laboratory crushing set-up is shown in Figure 4.1a. The laboratory test facility comprised a roll crusher located at the intake end of a 0.9 m high by 1.2 m wide wood framed hard board sheet rectangular wind tunnel 8.0 m long (Figure 4.1b). An exhaust fan and a dust collector were located at the discharge end of the tunnel. The roll-crusher used for the study was similar to the specifications used by NIOSH in their dust generation research study (Organiscak, 1999).

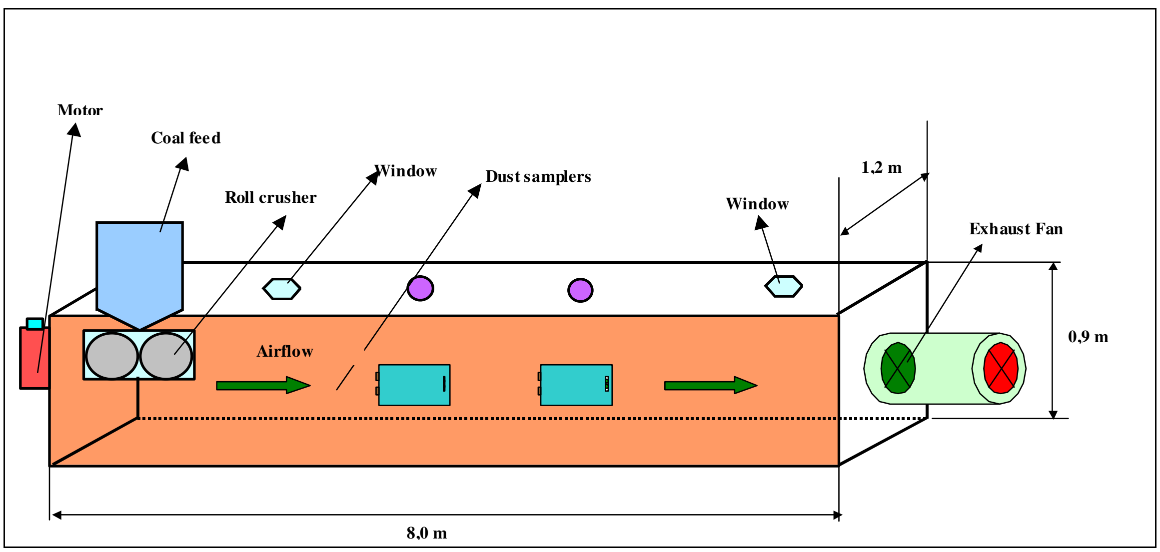

Figure 4.1a: Line diagram of the test facility

Figure 4.1b: Photographic view of the test facility

The crusher was a 1.1 kW compact double roll-crusher (79.4 mm diameter rolls) operating at 70 rpm consistently with twenty-four 12.7 mm high staggered teeth on each roll. The roll crusher had a fixed gap of 28.57 mm (1.125 inches) between the rolls. The crusher was designed to produce a product size less than or equal to 15.88 mm or 0.625 inches. Airborne gravimetric respirable dust samples were collected downstream of the crusher at an approximate distance of 2.0 m from the crusher.

4.2 Coal Sample Collection and Properties of SA coals

The majority of South African coal seams are classified into five different seams, viz., Seam 1, Seam 2, Seam 3, Seam 4 and Seam 5. Coal seams were numbered according to geological formation (bottom-up). In South Africa, coal mines are found in Mpumalanga, Kwa Zulu Natal, Free State and Limpopo (Northern) provinces (Figure 4.2).

Figure 4.2: South African provinces

Table 4.2 below shows the summary of Run Of Mine (ROM) coal samples used for the roll-crusher experiments.

Table 4.2: Summary of Run Of Mine (ROM) coal samples for the tests

Province	Operato r	Mine	Coal seam	Coal type	Coal Rank
Limpopo	A	Elisras	Bench 2	Bituminous	Medium-Rank C
		Elisras	Bench 3	Bituminous	Medium-Rank C
		Elisras	Bench 4	Bituminous	Medium-Rank C
		Elisras	Bench 5	Bituminous	Medium-Rank C
		Elisras	Bench 6	Bituminous	Medium-Rank C
		Elisras	Bench 7B	Bituminous	Medium-Rank C
		Elisras	Bench 9A	Bituminous	Medium-Rank C
		Elisras	Bench 9B	Bituminous	Medium-Rank C
		Elisras	Bench 11	Bituminous	Medium-Rank C
Mpumalanga	B	Bosspruit	4	Bituminous	Medium-Rank C
		Twistdraai West	4	Bituminous	Medium-Rank C
		Syferfontein	4	Bituminous	Medium-Rank C
		Middlebult	4	Bituminous	Medium-Rank C
		Boosjespruit	4	Bituminous	Medium-Rank C
		Twistdraai East	4	Bituminous	Medium-Rank C

		Sigma colliery	2	Bituminous	Medium-Rank C
		Sigma colliery	2	Bituminous	Medium-Rank C
		Brandspruit	4	Bituminous	Medium-Rank C
		Twistdraai Central	4	Bituminous	Medium-Rank C
Mpumalanga	C	NDC	4	Bituminous	Medium-Rank C
		Goedhoep	2	Bituminous	Medium-Rank C
		Goedhoep	4	Bituminous	Medium-Rank C
		Bank	2	Bituminous	Medium-Rank C
		Bank	5	Bituminous	Medium-Rank C
Mpumalanga	D	Khutala	4	Bituminous	Medium-Rank C
		Rietspruit	1	Bituminous	Medium-Rank C
		Rietspruit	4	Bituminous	Medium-Rank C
		Rietspruit	5	Bituminous	Medium-Rank C
		Middleburg	1	Bituminous	Medium-Rank C
		Middleburg	2	Bituminous	Medium-Rank C
		Middleburg	4	Bituminous	Medium-Rank C
		Middleburg	5	Bituminous	Medium-Rank C
		Koornfontein	2	Bituminous	Medium-Rank C
		Douglas	2	Bituminous	Medium-Rank C
		Douglas	4	Bituminous	Medium-Rank C
		Douglas	5	Bituminous	Medium-Rank C
		Optimum	2	Bituminous	Medium-Rank C
		ATC	5	Bituminous	Medium-Rank C
Kwa Zulu Natal		Zululand Anthracite	Main	Anthracite	Medium-Rank B

For the laboratory tests, the bulk ROM coal samples were collected from four different operators representing different coal seams, coal types and geographical regions. The ROM coal samples with an approximate size of 120 mm in thickness representing various coal types were collected from face area. Of note, there were no operating coal mines with coal seam number 3. The majority of the coal samples collected were from coal seam 2 and 4.

Based on the rank designation parameter (Vitrinite Random Reflectance-VRT), all South African bituminous coals fall under the Medium–Rank C (Ortho-Bituminous) category except Kwa Zulu-Natal Anthracite coals which fall in to category Medium-Rank B (Meta-Bituminous) in accordance with the International Classification of Coal

Seams Using Rank Parameter (Energy/WP.1/R.50; Bulletin 112, 1998). Overall, it can be concluded that there are only two coal types in South Africa, i.e., bituminous coals and Kwa Zulu Natal higher rank anthracite coals. An ash content of between 15 and 20 percent is fairly common in most of the South African coals, except anthracite coal which has an ash content of less than 10%.

4.3 Dust Instrumentation

Dust sampling was carried out using a Hund real-time dust monitor and three gravimetric samplers operated at 2.2 L/min according to the new ISO/CEN/ACGIH respirable size-selective curve. The Hund real-time monitor continuously monitored the respirable fraction of the dust and was positioned in the middle of the chamber facing the air stream for the duration of the test. All the gravimetric dust sampler inlets were positioned facing towards the airflow. Preliminary crushing trials indicated that the dust chamber air velocity to maximize dust concentrations and mass collection was 0.8 m/sec; therefore, chamber air velocity was maintained at 0.8 m/sec for all the experiments.

4.4 Laboratory Experimental Procedure

The following procedure was followed during the laboratory studies:

1. Before commencement of the experiment, the intake end of the dust chamber and intake feeder of the crusher were cleaned. Clean air was passed using exhaust fan for over five minutes to create a continuous fresh airflow prior to the introduction of the coal sample.

2. Prior to the tests, all the dust pumps were calibrated. A Gilibrator primary standard flow meter was used to establish the required air flow rate using an equivalent pressure restriction of the cyclone and filter assembly.
3. The dust monitors were placed inside the chamber at identified position and the crusher was then switched on.
4. After approximately five minutes, a fixed mass of different coal sample mix was fed manually into the crusher hopper in order to obtain enough dust on the filters.
5. The coal samples were randomly run in the roll crusher test facility. The airborne respirable dust generated per unit of coal crushed in the air-stream was determined by gravimetric sampling along the length of the test chamber[3].
6. After sampling ceased, the air pumps and real-time monitors were turned off and the time noted. Throughout the experiment, the air pumps and the condition and operation of the sampling train were monitored.
7. The dust samples were removed from the samplers for determination of mass.
8. At the conclusion of the test, a PC was used to download data from the Hund real-time monitor. This data was then translated into an ASCII text file that may be read with a spreadsheet program to calculate average dust concentrations during the test periods.

After each test, dust monitors were then cleaned, new filters installed, and prepared for the next test. After completion of each test, the roll-crusher was switched off and the dust chamber was cleaned.

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[3] In each experiment, data on gravimetric dust samples, instantaneous concentrations recorded by real-time monitor, amount of batch feed coal sample, crushing times were recorded.

4.5 Data Analysis

The gravimetric dust samples collected during the experiments were analysed to determine the airborne respirable dust levels. Using the real-time data, individual respirable dust levels were determined for each coal sample crushed. The specific inherent respirable dust generation potential (IRDGP) for each crushed coal sample was calculated as follows:

$$\text{SRDM (mg)} = \frac{\text{SC (mg/m}^3) \times 2.2 \times \text{Sampling Time (min.)}}{1000} \qquad (11.1)$$

where:

SRDM is the sample respirable dust mass for the crushed coal sample

SC is the sample concentration for the crushed coal sample

2.2 is the sampling flow rate (L/min) of cyclone

$$\text{TMIRD} = \text{SRDM} \times 0.864 \times \text{Crushing Time (min)} \qquad (11.2)$$

Where:

TMIRD is the total mass of inherent respirable dust for the air volume (mg)

0.864 is the volume of air through the chamber (m^3/min)[4]

Therefore, inherent respirable dust generation potential (IRDGP) is equal to:

$$\text{IRDGP} = \frac{\text{TMIRD}}{\text{CSW} \times 0.001} \qquad (11.3)$$

where,

IRDGP	is the inherent respirable dust generation potential (mg/ton)
TMIRD	is the total mass of inherent respirable dust mass (mg)
CSW	is the crushed coal sample mass (kg)

Essentially the IRDGP data will be in the form of $IRDGP_{ijk}$ (mg/ton). The subscripts have the following definitions:

i = coal seam type, i = 1 is seam #1; i = 2 is seam #2; i = 3 is seam #3; i = 4 is seam #4; i = 5 is seam #5; i = 6 is Elisras coal; and i = 7 is Kwa Zulu Natal coal
j = coal rank type, j = 1 is Bituminous coal; j = 2 is Anthracite coal
k = mine operator, k = 1 is operator A; k = 2 is operator B; k = 3 is operator C; k =4 is operator D.

Associations between the experimental variables on the IRDGP were analysed by scatter plot examination and statistical analysis of significance of individual parameters. Statistical package MINITAB 13.0 was used for analysis purposes. The IRDGP information on different coal samples was used as a tool for classification of the coal type in dust control mechanisms and, indirectly, in assessing the worker exposure.

5 Results and Discussions

This section covers the IRDGP results of various ROM coal samples crushed during the tests. The real-time data of the experiments were shown in Appendix A.

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[4] $0.9\ m \times 1.2\ m \times 60\ sec \times 0.8\ m/sec$

5.1 IRDGP of ROM Coal Samples-Operator A

Table 5.1 summarizes the relevant measured and calculated parameters for the ROM coal samples from operator A. The coal samples represent Bituminous medium rank C and were from an opencast operation in Limpopo province. There were a total of 29 coal samples crushed with an average feed mass of 14.56 kg and average crushing time of 149 seconds. The analysis of the crushing data indicated that there was no clear relationship between crushing time and feed mass.

Table 5.1: Summary of ROM coal samples from operator A

Sample #	Sample weight	Crushing time	Respirable dust level	IRDGP
	Kg	Sec.	mg/m^3	mg/ton
E-3	14.40	106	50.48	1247.71
E-3	12.70	110	39.61	1195.46
E-7b	15.00	95	12.71	242.23
E-7b	15.30	99	10.04	203.70
E-7b	16.60	137	10.62	380.28
E-7b	15.50	171	11.77	703.26
E-5	13.30	176	7.25	534.94
E-5	14.70	179	9.92	684.81
E-5	13.40	127	8.50	324.11
E-5	13.20	116	10.76	347.54
E-2	13.50	205	11.51	1134.66
E-2	14.70	183	15.96	1151.74
E-2	15.50	145	9.66	415.33
E-2	17.50	140	13.65	484.23
E-11	14.90	270	12.04	1866.30
E-11	12.40	222	19.15	2411.21

E-11	15.80	224	13.87	1395.50
E-11	15.00	96	12.91	251.20
E-4	15.10	156	11.87	785.97
E-4	12.60	192	12.95	1028.04
E-4	14.60	144	16.16	1106.88
E-9B	16.10	166	21.42	1161.32
E-9B	13.50	172	21.25	1475.57
E-9A	14.70	197	21.47	1795.39
E-9A	10.90	104	19.13	601.51
E-9A	13.10	140	25.22	1195.41
E-6	14.20	89	15.70	277.36
E-6	15.00	79	17.84	235.15
E-6	19.00	85	26.78	322.57

Figure 5.1 shows the IRDGP of operator A coal samples from different operating benches.

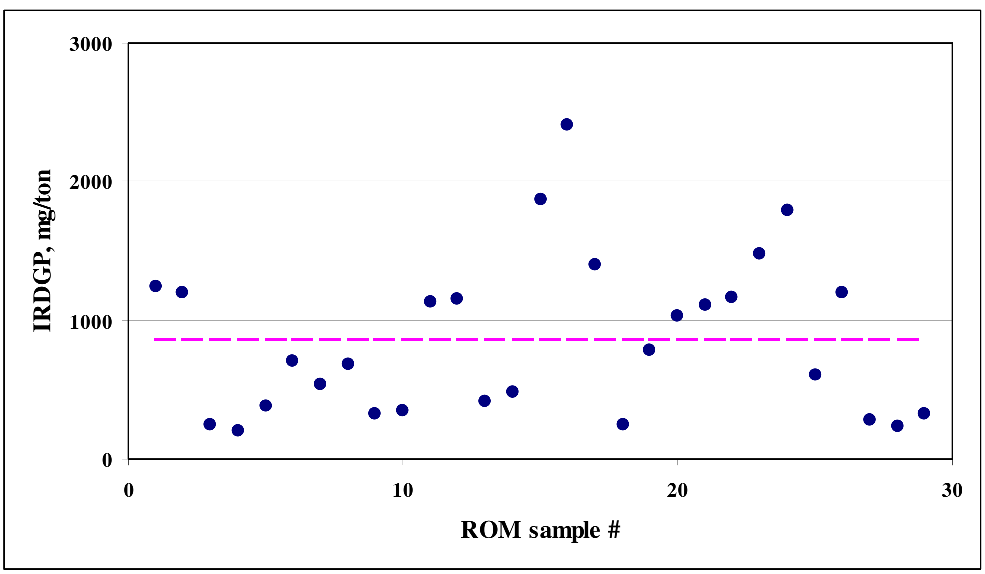

Figure 5.1: IRDGP of ROM coal samples from operator A

The mean or average IRDGP of operator A coal samples was 860 mg/ton with minimum and maximum IRDGP values of 204 mg/ton and 2411 mg/ton respectively for the test conditions. From the plot, it can be seen that scatter is wide and approximately 45% of the samples were above average IRDGP of the ROM coal samples crushed. The reasons can be attributed to the coal samples which contained host rock materials such as sandstone and shale bands and it took a longer time to crush the coal samples.

5.2 IRDGP of ROM Coal Samples-Operator B

Table 5.2 summarizes the pertinent measured and calculated parameters for the coal mine operator B ROM samples. The coal samples crushed represent Bituminous medium rank C and were from underground operations from seam 1, 2 and 4 in Mpumalanga province. There were a total of 28 coal samples with an average feed mass of 14.00 kg of coal and average crushing time of 145 seconds for individual tests.

Table 5.2: Summary of ROM coal samples from operator B

Sample #	Sample weight	Crushing time	Respirable dust level	IRDGP
	Kg	Secs.	mg/m^3	mg/ton
Bosjesspruit-1	13.00	171	9.42	724.26
Bosjesspruit-2	12.20	63	1.03	84.73
Bosjesspruit-3	9.50	54	0.76	79.83
Bosjesspruit-4	14.50	253	58.71	4048.97
Syferfontein-1	14.50	75	3.88	267.87
Syferfontein-2	14.80	107	6.07	409.97
Syferfontein-3	11.60	73	2.18	188.32

Syferfontein-4	12.30	138	9.94	807.92
Middelbult	7.00	31	0.39	56.01
Sigma-S1	12.20	162	5.90	483.28
Sigma-S2	14.40	116	3.13	217.46
Sigma-S3	16.50	136	4.39	266.29
Sigma-S4	13.20	72	2.13	161.47
Twistdraai W1	11.90	117	4.37	367.59
Twistdraai-E1	18.00	180	11.21	622.81
Twistdraai-E2	14.20	116	5.09	358.48
Twistdraai-E3	13.40	142	8.51	635.09
Twistdrai-E4	16.00	284	16.56	1034.98
Twistdrai-E5	14.00	101	2.97	212.18
Twistdraai-C1	14.80	242	49.53	3346.79
Twistdraai-C2	14.00	206	38.60	2757.04
Twistdraai-C3	12.00	238	43.08	3589.82
Twistdraai-C4	14.50	154	15.55	1072.30
Twistdraai-C5	17.40	106	11.96	687.64
Twistdraai-C6	16.00	176	19.15	1197.10
Brandspruit-1	12.70	224	21.18	1667.64
Brandspruit-2	13.20	106	5.73	434.29
Brandspruit-3	23.00	245	31.41	1365.72

Figure 5.2 shows the Inherent Respirable Dust Generation Potential (IRDGP) of operator B coal samples.

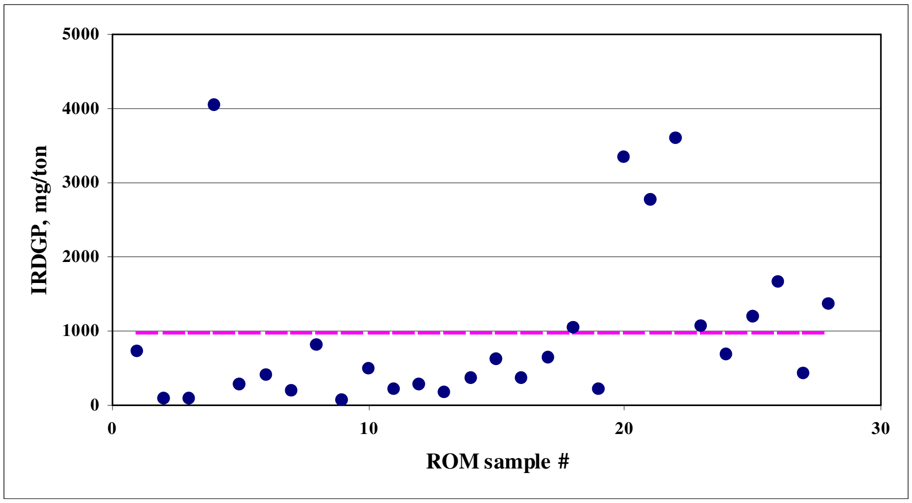

Figure 5.2: IRDGP of ROM coal samples from operator B

The mean or average IRDGP of operator B coal samples was 970 mg/ton with minimum and maximum IRDGP values of 56 mg/ton and 4048 mg/ton respectively. The outliers in the plot were due to the long crushing time of coal samples and not necessarily due to the differences in type of coal seam. This can be attributed to the presence of host rock material. From the plot we notice that approximately 32% of the samples were above average IRDGP for the coal samples crushed.

5.3 IRDGP of ROM coal samples-Operator C

Table 5.3 summarizes the pertinent measured and calculated parameters for operator C ROM coal mine samples. The coal samples crushed represent Bituminous medium rank C and were from underground operations from seam 2, 4 and 5 in Mpumalanga province. There were a total of 40 coal samples with an average feed mass of 14.56 kg and average crushing time of 149 seconds. The analysis of the crushing data indicated that there was no clear relationship between crushing time and feed mass.

Table 5.3: Summary of Run Of-Mine (ROM) coal samples from operator C

Sample #	Sample weight	Crushing time	Respirable dust level	IRDGP
	Kg	Sec.	mg/m^3	mg/ton
Bank Coal-2	11.80	218	24.67	3147.27
Bank Coal-2	11.90	143	20.56	1119.32
Bank Coal-2	11.80	215	19.95	2475.59
Bank Coal-2	12.00	180	21.32	1823.92
Bank Coal-2	11.90	95	26.32	632.39
Bank Coal-2	12.10	237	13.56	1993.82
Bank Coal-2	11.90	144	19.23	1061.68
Bank Coal-2	16.40	192	27.16	1934.14
Bank Coal-2	14.10	108	17.85	467.68
Bank Coal-2	14.60	142	18.74	819.83
Bank Coal-2	12.70	254	14.17	2279.82
Bank Coal-2	12.90	246	12.93	1920.91
Bank Coal-2	12.90	86	18.52	336.38
Bank Coal-2	14.80	236	11.49	1369.91
Bank Coal-5	12.90	112	15.93	490.86
Bank Coal-5	12.90	130	9.95	413.01
Bank Coal-5	12.90	178	6.72	523.06
Bank Coal-5	12.00	179	6.08	513.90
Bank Coal-5	13.00	93	13.52	285.01
Bank Coal-5	13.00	117	12.60	420.27
Bank Coal-5	13.00	103	14.00	361.82
Bank Coal-5	12.50	76	15.48	226.63
Goedhope-2	12.90	196	22.44	2116.74
Goedhope-2	12.70	146	19.68	1046.26
Goedhope-2	13.00	196	15.23	1425.86
Goedhope-2	12.70	150	25.49	1430.41

Goedhope-4	13.50	174	21.14	1501.83
Goedhope-4	13.70	150	22.14	1151.74
Goedhope-4	15.20	248	13.69	1754.84
Goedhope-4	14.60	121	11.89	377.71
Goedhope-4	15.20	115	12.09	333.34
Goedhope-4	14.50	173	11.76	769.07
Goedhope-4	16.00	211	10.13	892.75
Goedhope-4	19.70	181	13.33	702.12
NDC-4	15.00	97	13.77	273.66
NDC-4	14.10	90	12.79	232.79
NDC-4	15.10	111	10.17	262.91
NDC-4	15.10	82	18.69	263.61
NDC-4	15.90	144	11.92	492.29
NDC-4	15.60	94	17.70	317.56
NDC-4	15.50	111	15.86	399.52

Figure 5.3 shows the Inherent Respirable Dust Generation Potential (IRDGP) of operator C ROM coal samples. The coal samples crushed represent Bituminous medium rank C and were from underground operations in Mpumalanga province. The average IRDGP of operator C samples was 984 mg/ton, with minimum and maximum IRDGP values of 227 mg/ton and 3147 mg/ton respectively. From the plot, it can be seen that approximately 42% of the samples were above average IRDGP for the coal samples crushed.

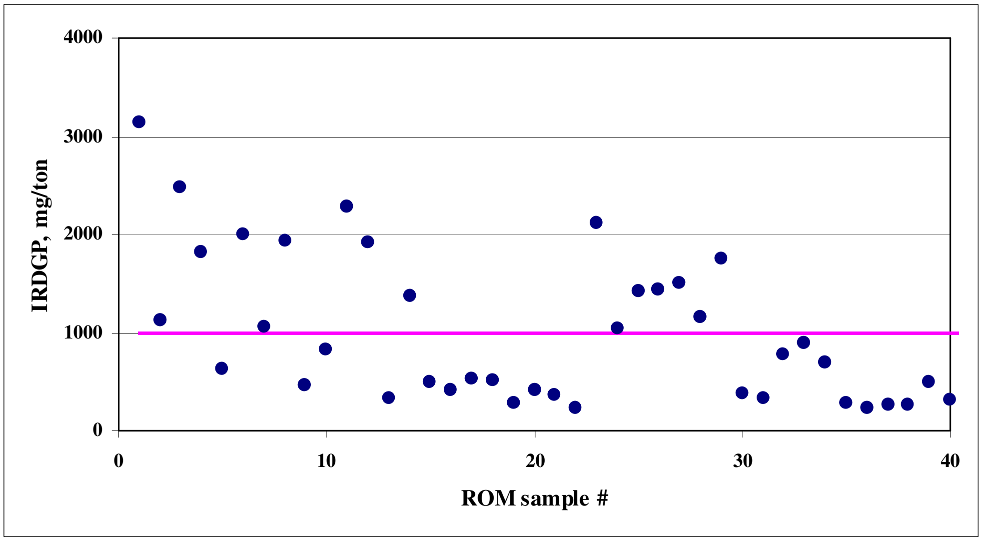

Figure 5.3: IRDGP of ROM coal samples from operator C

5.4 IRDGP of Coal Samples-Operator D

Table 5.4a summarizes the pertinent measured and calculated parameters for the operator D ROM coal mine samples. The coal samples crushed represent Bituminous medium rank C and were from underground operations from seam 1, 2, 4 and 5 in Mpumalanga province. Also, anthracite coal samples of medium rank B were from underground operations from main seam in Kwa Zulu Natal province were crushed. There were a total of 77 coal samples with an average feed mass of 12 kg and average crushing time of 186 seconds.

Table 5.4a: Summary of ROM coal samples from operator D

Sample #	Sample weight	Crushing time	Respirable dust level	IRDGP
	Kg	Sec.	mg/m^3	Mg/ton
Middleburg-4	12.00	120	0.83	68.83

Middleburg-4	15.00	178	1.90	126.63
Middleburg-5	10.30	108	1.44	139.98
Middleburg-5	10.00	128	2.31	230.56
Middleburg-4	10.30	110	1.21	117.91
Middleburg-4	10.90	168	4.63	424.77
Middleburg-4	7.70	128	3.48	451.69
Middleburg-4	11.40	294	10.39	911.67
Middleburg-2	11.20	98	2.55	227.95
Middleburg-2	12.20	120	5.10	418.35
Middleburg-2	9.60	102	3.69	384.76
Middleburg-2	11.20	212	9.65	861.47
Middleburg-2	11.10	156	9.15	824.61
Middleburg-2	11.50	104	4.93	429.09
Middleburg-2	11.90	112	1.55	130.30
Middleburg-2	11.30	148	6.77	599.48
Middleburg-2	11.30	210	10.45	924.67
Middleburg-4	12.80	141	6.51	508.58
Middleburg-4	12.80	107	5.64	440.93
Middleburg-4	12.80	207	13.47	1052.50
Middleburg-4	12.80	194	18.13	1416.24
Middleburg-4	11.60	168	9.20	793.38
Middleburg-2	12.80	295	14.68	1146.78
Middleburg-2	12.80	117	5.76	449.82
Middleburg-2	12.70	145	7.83	616.16
Middleburg-2	12.90	77	2.86	221.56
Middleburg-2	12.80	126	8.26	645.38
Middleburg-2	12.80	92	3.64	284.57
Middleburg-1	12.90	204	16.07	1245.82
Middleburg-1	12.80	121	6.29	491.72
Middleburg-1	12.80	130	6.87	536.41

Middleburg-1	13.40	186	11.73	875.65
Middleburg-5	12.90	278	17.52	1358.12
Middleburg-5	13.00	166	12.16	935.32
Middleburg-4	12.80	136	9.32	728.37
Middleburg-4	12.70	233	12.87	1013.00
Middleburg-4	13.50	254	15.67	1160.64

Table 5.4a: Contd. Summary of ROM coal samples from operator D

Sample #	Sample weight	Crushing time	Respirable dust level	IRDGP
	Kg	Sec.	mg/m^3	mg/ton
Koornfontein-2	11.00	116	1.41	127.85
Koornfontein-2	10.00	168	2.51	251.27
Koornfontein-2	11.60	149	3.25	279.99
Koornfontein-2	10.00	136	2.05	205.09
Koornfontein-2	11.60	91	1.77	152.42
Koornfontein-2	11.00	164	3.19	289.86
Douglas-1	10.20	162	3.42	334.92
Douglas-2	13.20	388	7.23	547.59
Douglas-2	11.90	430	5.60	470.56
Douglas-4	12.00	212	5.22	435.33
Douglas-5	11.00	324	5.11	464.44
KZN-E	13.00	174	18.32	1408.99
KZN-E	12.70	145	20.94	1648.52
KZN-E	12.40	631	206.30	16637.07
KZN-Main	12.90	226	53.29	4130.63
KZN-Main	18.00	469	391.53	21751.69
KZN-Main	11.90	303	32.77	2753.44

KZN-Main	18.70	727	256.69	13726.76
KZN-Main	12.80	243	69.46	5426.81
KZN-Main	12.20	184	34.28	2810.00
Optimum-2	6.40	56	1.18	184.45
Optimum-2	12.50	128	7.25	580.36
Optimum-4	10.00	165	9.96	996.49
Rietspruit-5	12.90	162	8.33	645.76
Rietspruit-5	12.90	98	4.43	343.67
Rietspruit-5	13.00	80	3.62	278.58
Rietspruit-5	12.90	273	8.16	632.70
Rietspruit-5	14.00	177	9.71	693.80
Rietspruit-4	13.00	134	8.04	618.76
Rietspruit-4	13.00	170	15.56	1196.66
Rietspruit-4	12.90	184	6.32	490.11
Rietspruit-4	13.00	138	5.88	452.32
Rietspruit-4	13.00	190	19.24	1479.88
Rietspruit-4	13.10	244	14.79	1128.78
Rietspruit-4	14.60	148	7.79	533.90
Rietspruit-1	13.10	208	12.98	990.65
Rietspruit-1	12.80	188	12.43	971.20
Duiker-5	4.00	52	2.11	527.58
Duiker-5	8.20	126	8.05	981.45
Khutala-4	10.00	55	2.29	228.65

Figure 5.4a shows the Inherent Respirable Dust Generation Potential (IRDGP) of operator D coal samples.

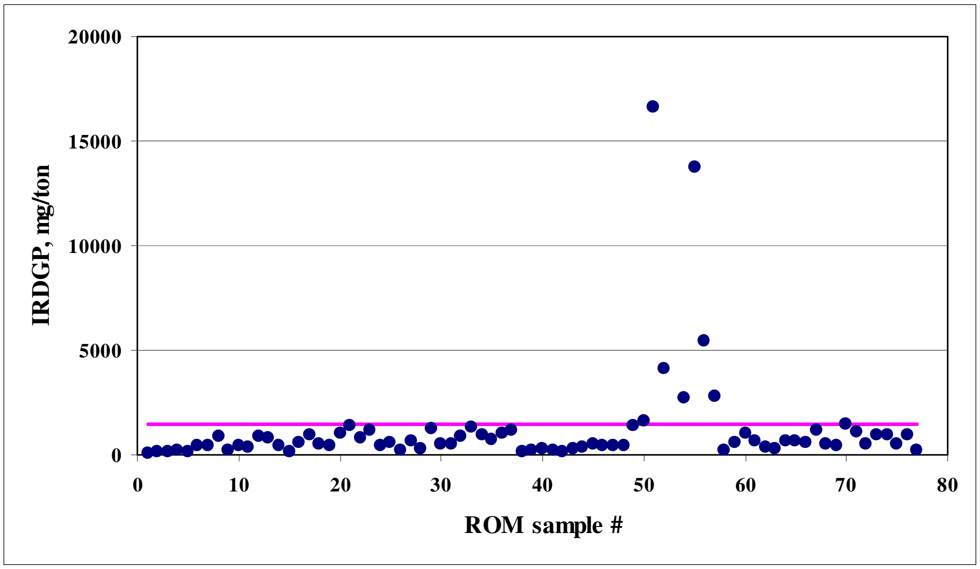

Figure 5.4a: IRDGP of ROM coal samples from operator D

The average IRDGP of operator D coal sample was 1442 mg/ton with minimum and maximum IRDGP values of 69 mg/ton and 21 751 mg/ton respectively. Excluding the Kwa Zulu Natal coal samples, the IRDGP for the operator D samples was 590 mg/ton. The average IRDGP for the Kwa Zulu Natal anthracite coal was 7810 mg/ton. From the plot, a clear distinction between the coal types was noticeable. Kwa Zulu Natal coals were anthracite (medium rank B) and other coals are bituminous coals (medium rank C).

Table 5.4.b summarizes the IRDGP of different coal types, coal operators and coal seams for all the test samples.

Figure 5.4b shows the average IRDGP for different coal types, coal seams and mine operators during the study.

Table 5.4b: Summary of average IRDGP data for the ROM coal samples

Description	IRDGP Data, mg/ton				
	Minimum	Maximum	Average	No. of Samples	Avg. crushing time, sec.
Coal Seam-1	335	1246	778	7	171
Coal Seam-2	128	3147	847	47	162
Coal Seam-4	56	4049	833	63	155
Coal Seam-5	140	1358	523	20	148
Elisras Coal	204	2411	860	29	149
Natal Coal	1409	21752	7810	9	345

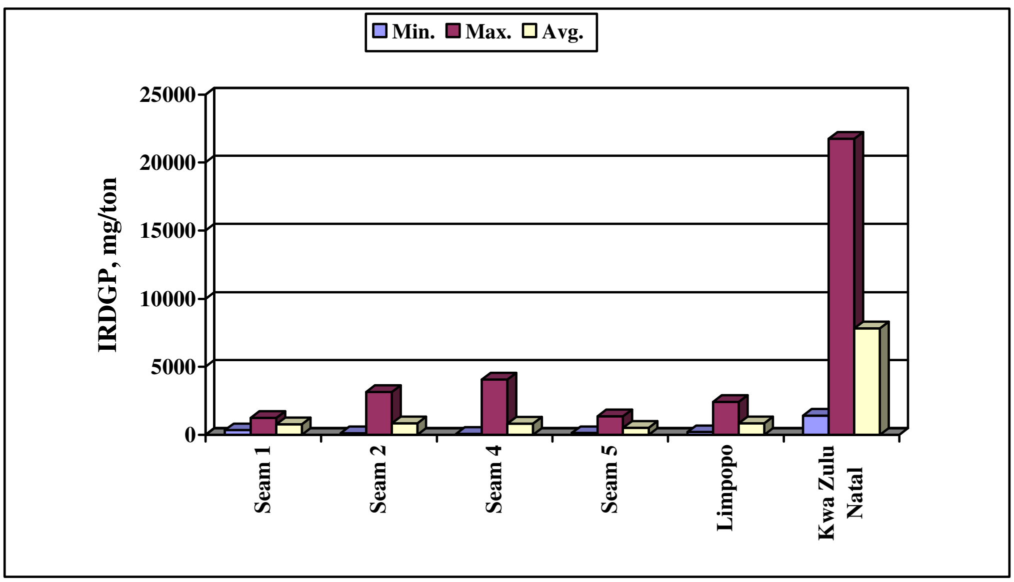

Figure 5.4b: Summary of IRDGP of ROM coal samples

Statistical analyses was carried out on the IRDGP data obtained from this laboratory study. Analysis of Variance (ANOVA) was used to test the effect of coal rank on

IRDGP. The value of the F-ratio obtained from the study was 67.84; and the p-value was 0.000 at the 5% level of significance indicating that coal rank influences the IRDGP of coals. Similarly, there was no significant effect of coal seam type ($p = 0.373$) on IRDGP for this study.

6 Inherent respirable airborne silica content in coal mines

Efforts have been made in the past to quantify the inherent silica content in the South African coal seams. It is apparent that scant published research data are available for the coal mining industry. A SIMRAC handbook of occupational health practice in the South African mining industry reports that Mpumalanga, Gauteng and Free State coal have a quartz content of about 2%, whereas that of Kwa Zulu Natal coal contains 3% quartz. Fundamental studies on the relationship between quartz levels in the host material and the respirable dust generated during coal mining have indicated that the quartz contents in the airborne dust are generally higher than those in the host material (Ramani et al., 1987).

As a part of this study, investigations were extended to quantify the inherent respirable silica content of different coal seams and coal types, representing various coal mines operating in different provinces. From these tests, 25 different airborne respirable coal dust samples representing SA coal seams were analysed for inherent silica content. Figure 6 shows the silica content of the inherent respirable coal samples representing various coal types in South Africa.

From the results, it is seen that 54% of the analysed coal dust samples did not have any detectable silica content. The maximum measured silica content of the South African coal seam was from a surface mine coal sample with 6.6% silica content. This is probably due to the presence of shale or other host rock containing silica. The average measured silica content of all the coal seams containing silica dust was 3.5%. Overall, it can be concluded that the inherent silica content is less than 5% in the test samples of South African coal mines. Based on the inherent silica content of the South African coal, worker exposure to silica dust is relatively low compared to metalliferous mines.

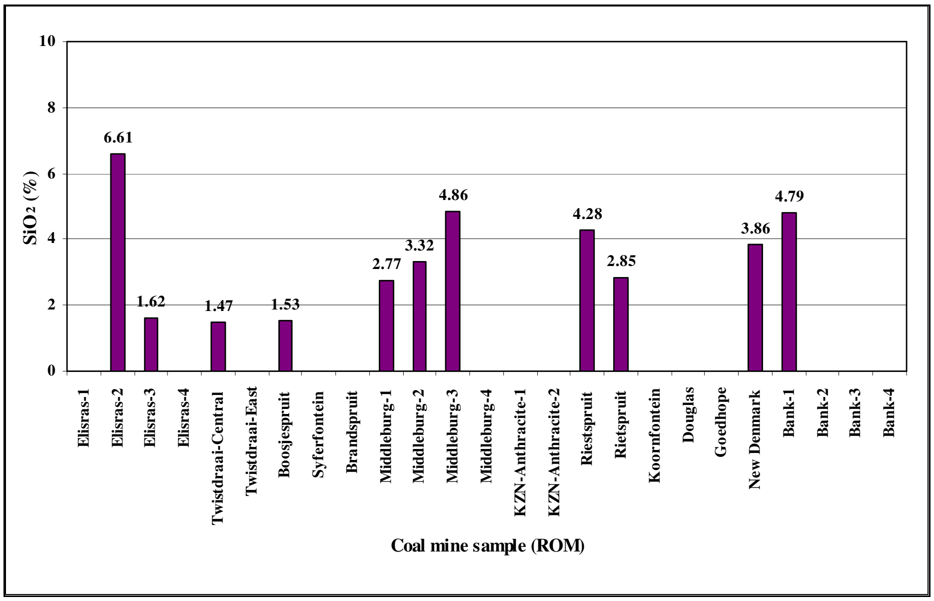

Figure 6: Inherent respirable silica content of the South African coals

7 Conclusions

In summary, the following observations can be made from the IRDGP data of the test coal samples:

- For the first time, a clear delineation of coal types (Bituminous and Anthracite) that possess the most inherent respirable dust generation potential was possible.
- There is no conclusive relationship between different coal seams (1, 2, 4 and 5) and inherent respirable dust generation potential (IRDGP). The majority of the mine operators are currently exploiting coal from seam 2 and 4.
- Average coal crushing time of coal samples for this study indicated that the crushing time decreases in the order of seams 1 to 5. Kwa Zulu Natal coals took highest crushing time during the tests when compared to the other coal seams and coal types. The reasons can be attributed due to inherent coal properties of high rank anthracite coals.
- Measured IRDGP of Limpopo coal was less than commonly occurring seam 2 and seam 4 coals in Mpumalanga province.
- Inherent silica content of South African coal seams indicate that average inherent silica for the test coals was 3.54%.
- Statistical analyses have indicated that the coal rank has a significant influence ($p = 0.000$) on inherent respirable dust generation potential (IRDGP) and inconclusive relationship between SA coal seams and IRDGP ($p = 0.373$).

8 Coal Dust Type as Dust Exposure Parameter

The intention of determining the IRDGP of South African coals is to transmit the new information and model to the mine risk assessors and risk managers. The information will assist the coal mining industry to protect the workers from exposure to specific dust as well as to encourage effective control of face area dust. Mass distributions of respirable dust from various coal samples from US mines have indicated that anthracite coal produces larger masses of dust in the finer size range. Consequently, the mass of dust permanently deposited in the lungs per unit time, which determines the degree of hazard, is higher for anthracite than high volatile bituminous coal (Thakur, 1974).

Mine dust standards are applied uniformly to every coal mine type in South Africa. However, ACGIH recommends a TLV-TWA of 0.9 mg/m^3, for miners exposed to bituminous dust or lignite coal dust; a TLV-TWA of 0.4 mg/m^3 for miners exposed to anthracite coal dust (ACGIH 2001). Therefore, based on past health studies and inherent respirable dust generation studies, effective use of coal dust type is therefore proposed and a matrix has been developed (Table 8). The contents are based on the IRDGP data, dust level for an 8-hr period and health risk on exposure is marked for the respective concentration zones as shown in Figure 8. Based on the dust levels and coal type, the plot (Figure 8) is divided into A, B, C and D categories in order for its use as an Dust Exposure Level Index (DELI).

Table 8: Coal dust type indicator model for dust exposure levels

Concentration	Coal Type	Concentration zone	Colour	Health Risk	Description
< 1 mg/m^3	Bituminous	A	Green	I	Good
< 1 mg/m^3	Anthracite	D	Green	II	Below Par
1 to 2.0 mg/m^3	Bituminous	B	Yellow	II	Average
1 to 2.0 mg/m^3	Anthracite	E	Orange	III	Poor
> 2 mg/m^3	Bituminous	C	Red	III	Worse
> 2 mg/m^3	Anthracite	F	Red	IV	Unacceptable

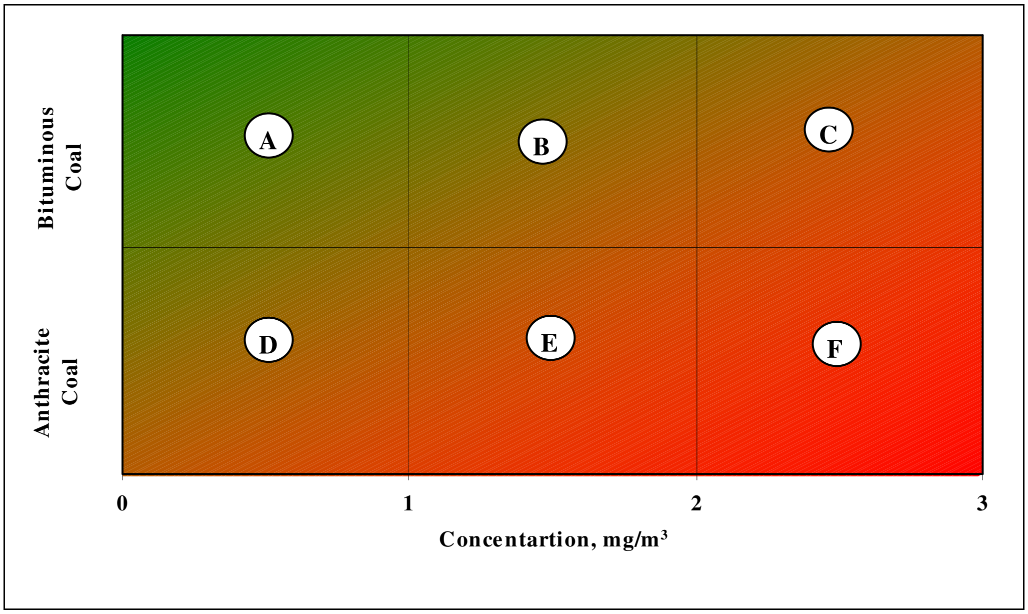

Figure 8: Use of the coal type parameter in dust exposure level index

9 Summary

This chapter summarizes the inherent respirable dust generation potential (IRDGP) of South African coals. The resulting information and its use as an index of worker exposure to dust is discussed. This study carried out experimental work that resulted in critical information on dust type and inherent respirable dust generation potential for the first time for South African coals. Based on the measured respirable dust data of the South African coals, it can be concluded that majority of the coal mining operation provinces such as Mpumalanga, Free State, Limpopo have on average has similar IRDGP, while Kwa Zulu Natal coal samples which are anthracite type coal have greater IRDGP.

This information will be helpful for dust control in both surface and underground operations. The intention to use the coal dust type is that it is a clear parameter that will assist in assessing dust exposure risk of workers to coal dust. Also, the effectiveness of a dust-control system is also dependent on coal dust type. Although coal dust type is fundamental in dust generation, it can be used as an administrative type of exposure control parameter and as an exposure index for health risk where the management can effectively rotate the worker to different operations so as to reduce the increased risk of CWP. The coal dust type parameter in an overall exposure assessment tool is recommended for use in exposure surveillance by the occupational hygiene professionals for developing dose-response relationships for South African coal miners working in different coal types. To date there has been no clear delineation for South African workers who are exposed to different dust types. Therefore, it is recommended that a research study be conducted to investigate prevalence of CWP among workers in Kwa Zulu Natal mines and other provinces to assist in determining historic dose and developing a relevant dose-response curve.

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APPENDIX-A

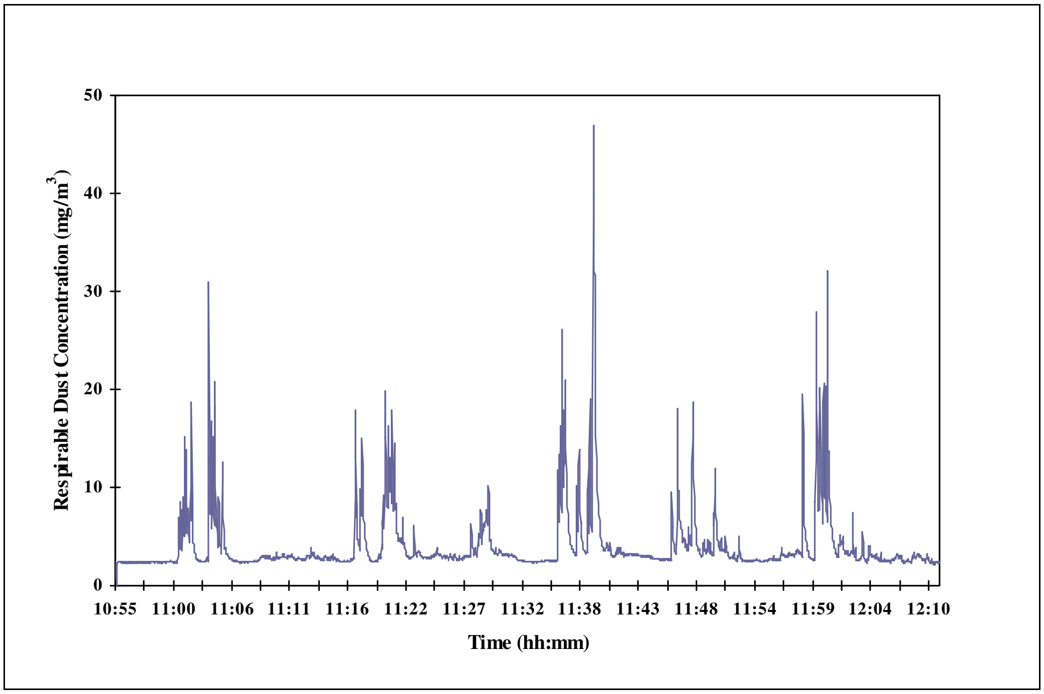

Figure A1: ARD profile recorded by the real-time monitor for Middleburg coal

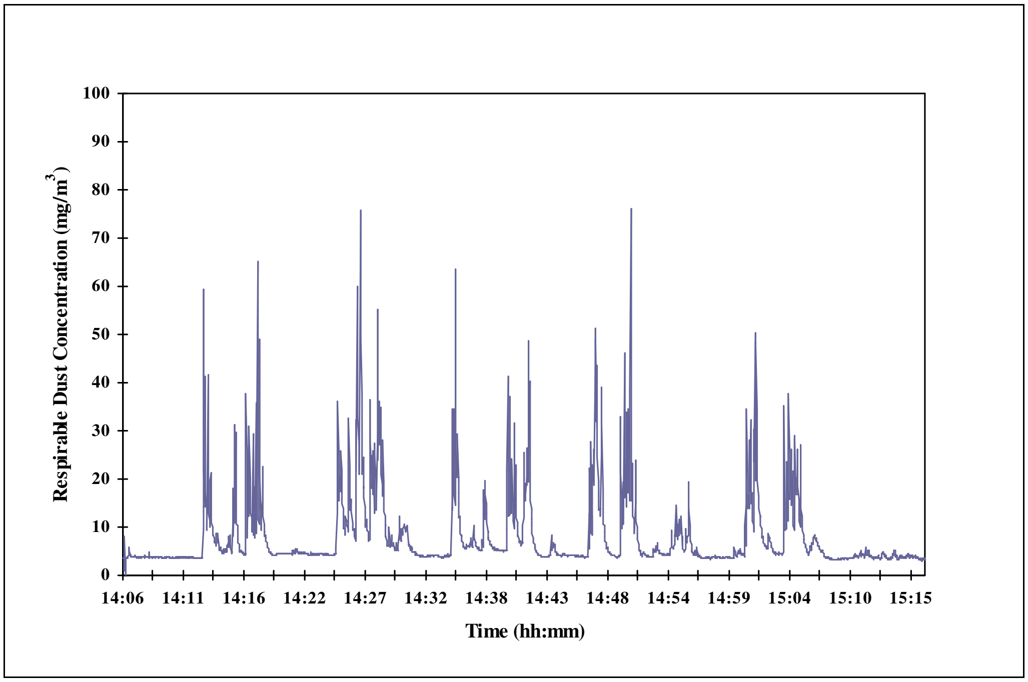

Figure A2: ARD profile recorded by the real-time monitor for Middleburg coal

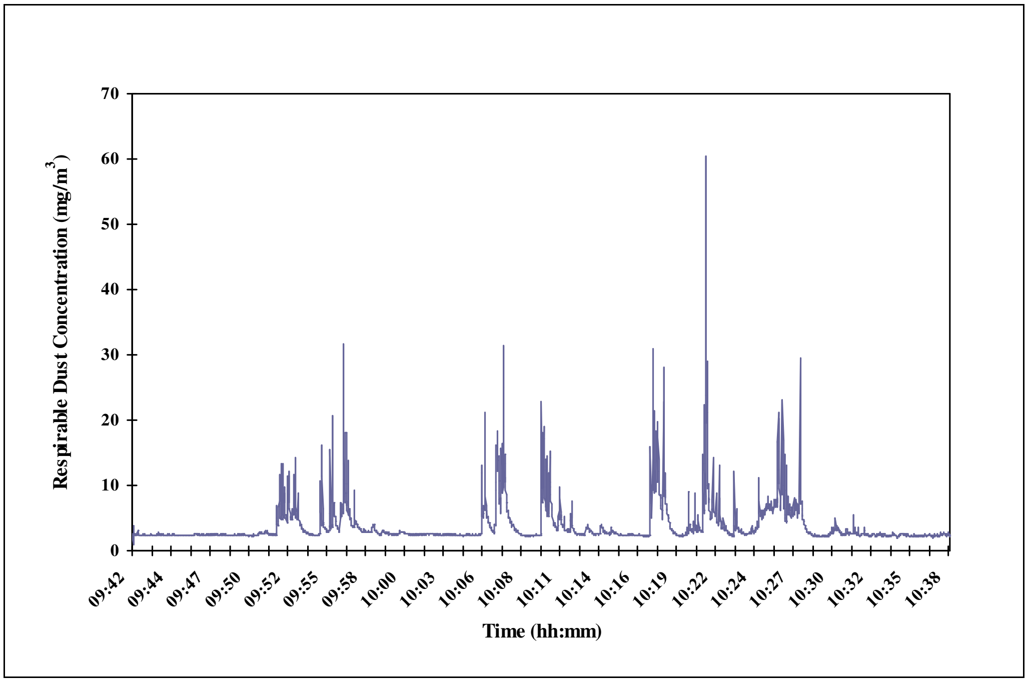

Figure A3: ARD profile recorded by the real-time monitor for Koornfontein coal

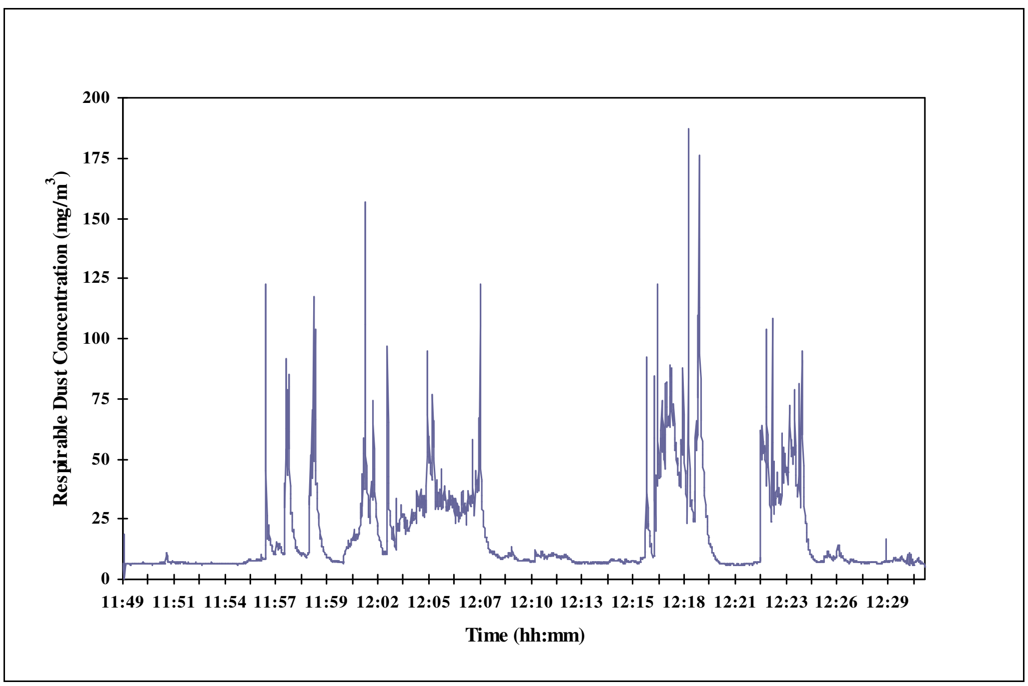

Figure A4: ARD profile recorded by the real-time monitor for Kwa Zulu Natal coal

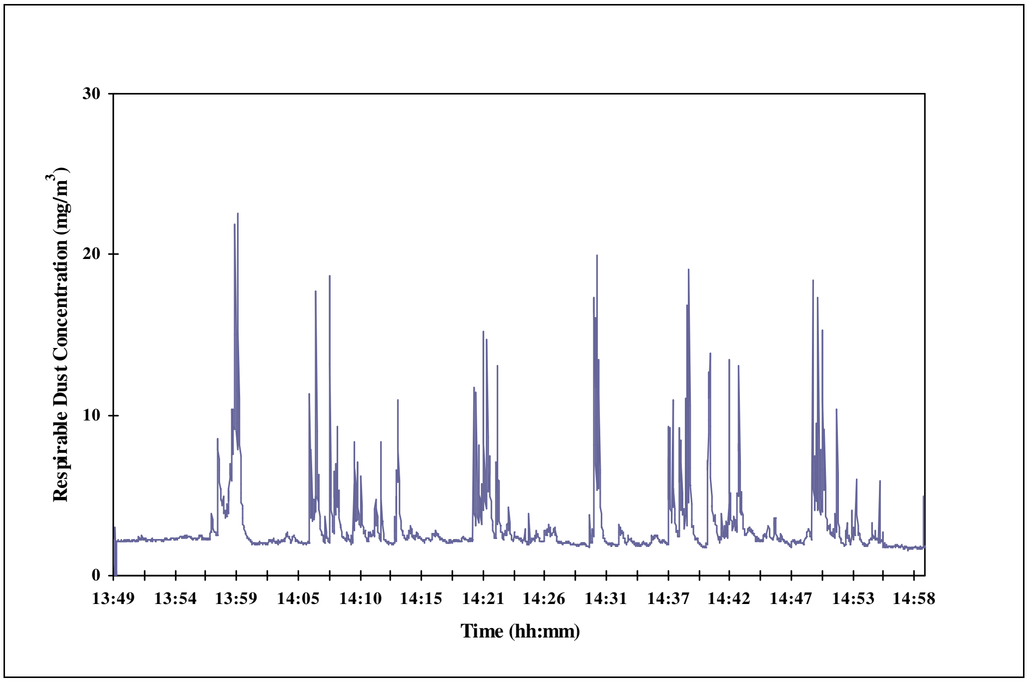

Figure A5: ARD profile recorded by the real-time monitor for Douglas coal

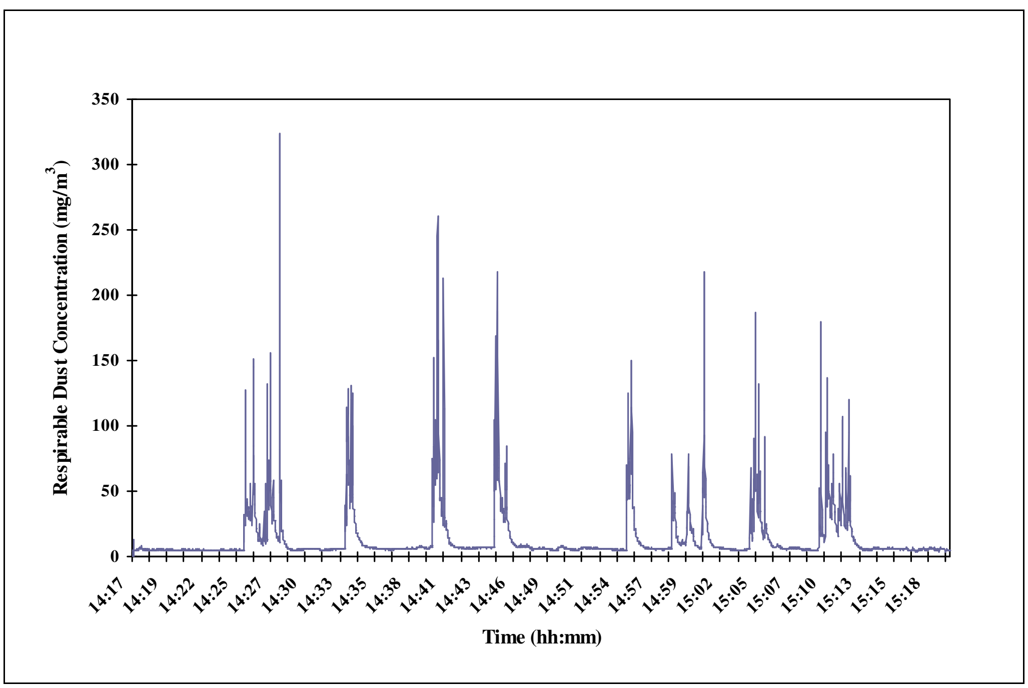

Figure A6: ARD profile recorded by the real-time monitor for Bank coal

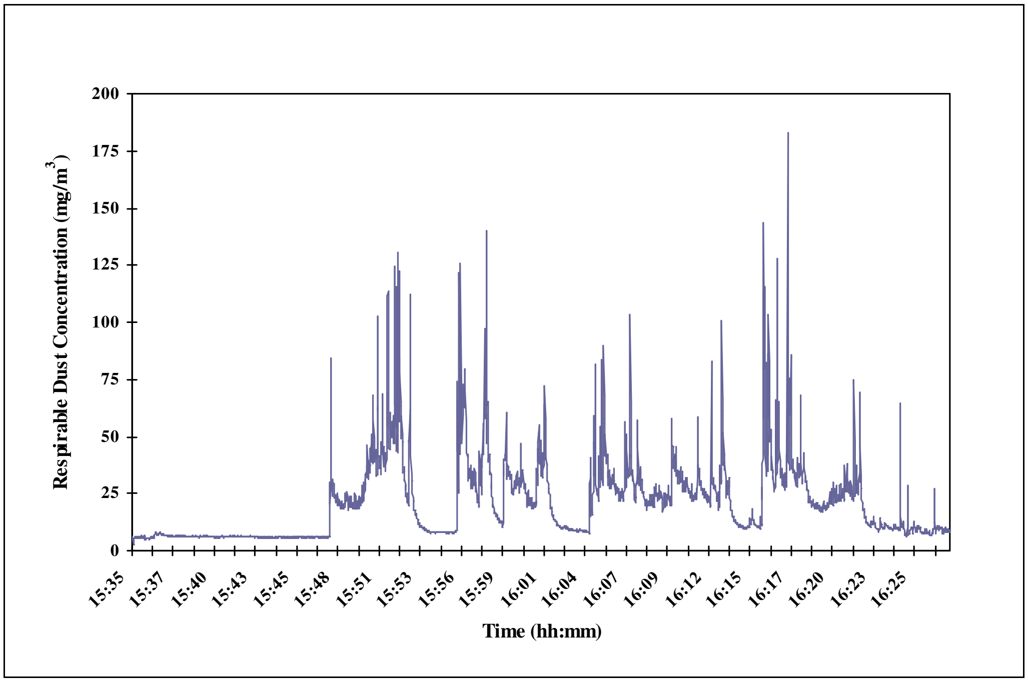

Figure A7: ARD profile recorded by the real-time monitor for Bank coal

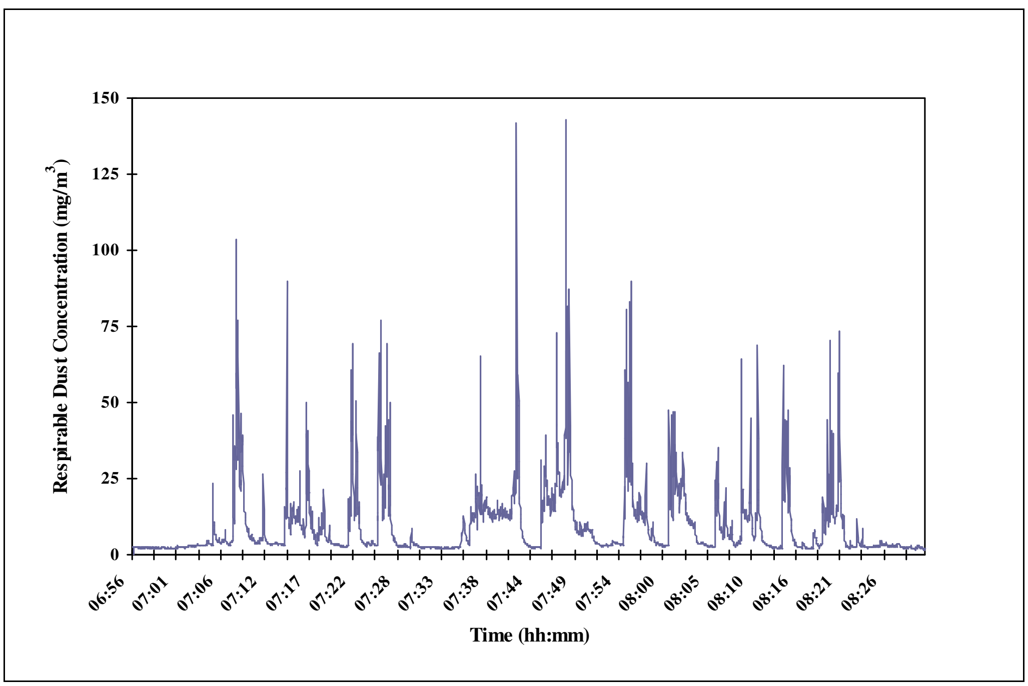

Figure A8: ARD profile recorded by the real-time monitor for Bank coal

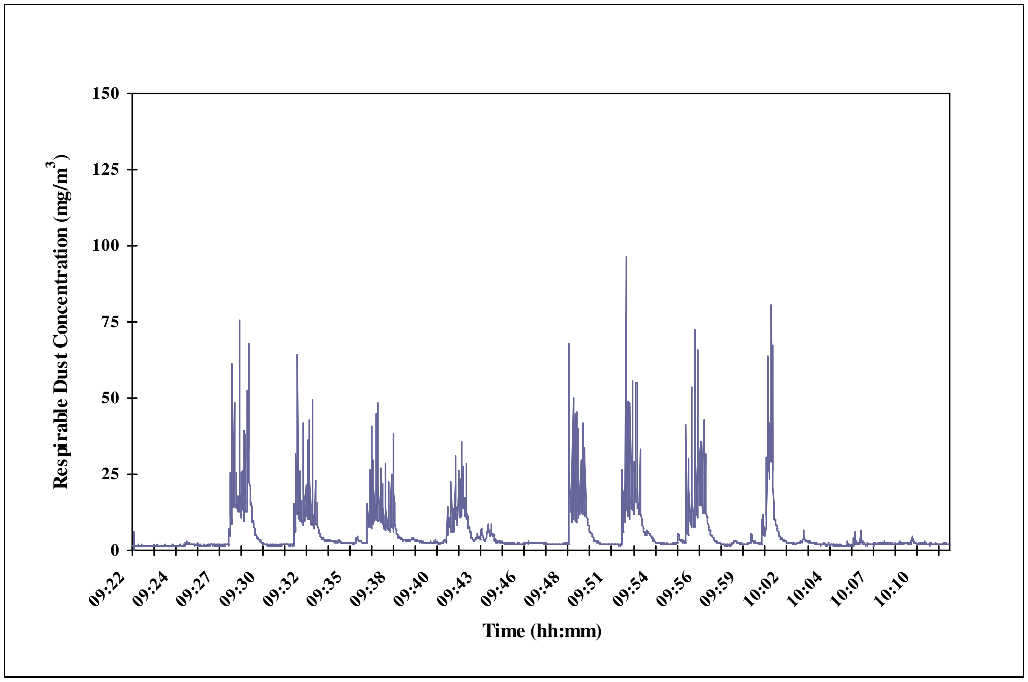

Figure A9: ARD profile recorded by the real-time monitor for Bank coal

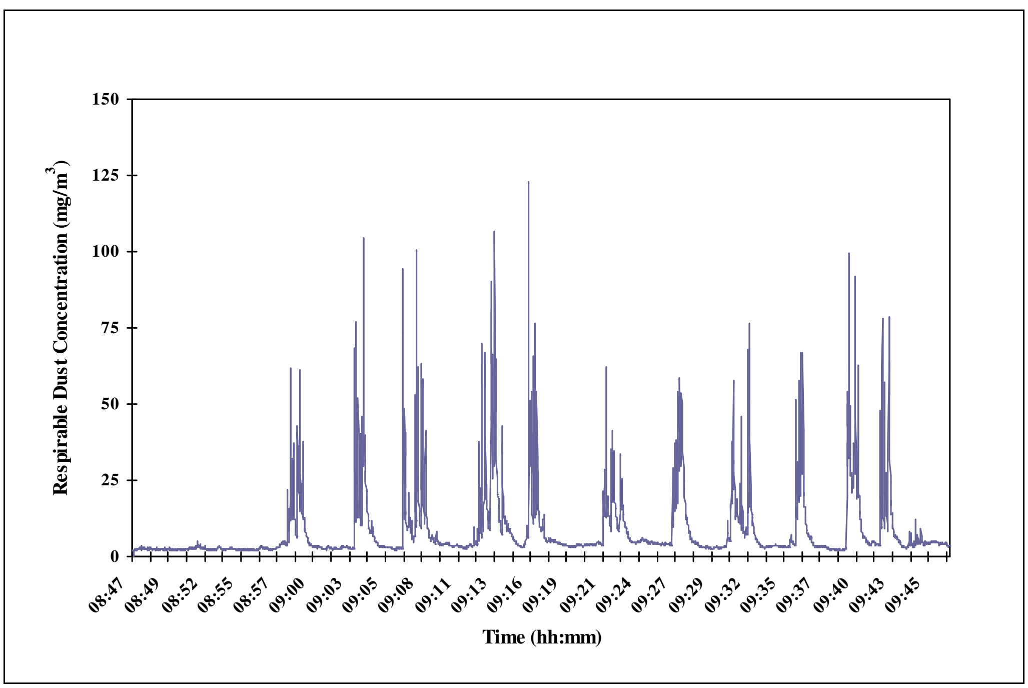

Figure A10: ARD profile recorded by the real-time monitor for Middleburg coal

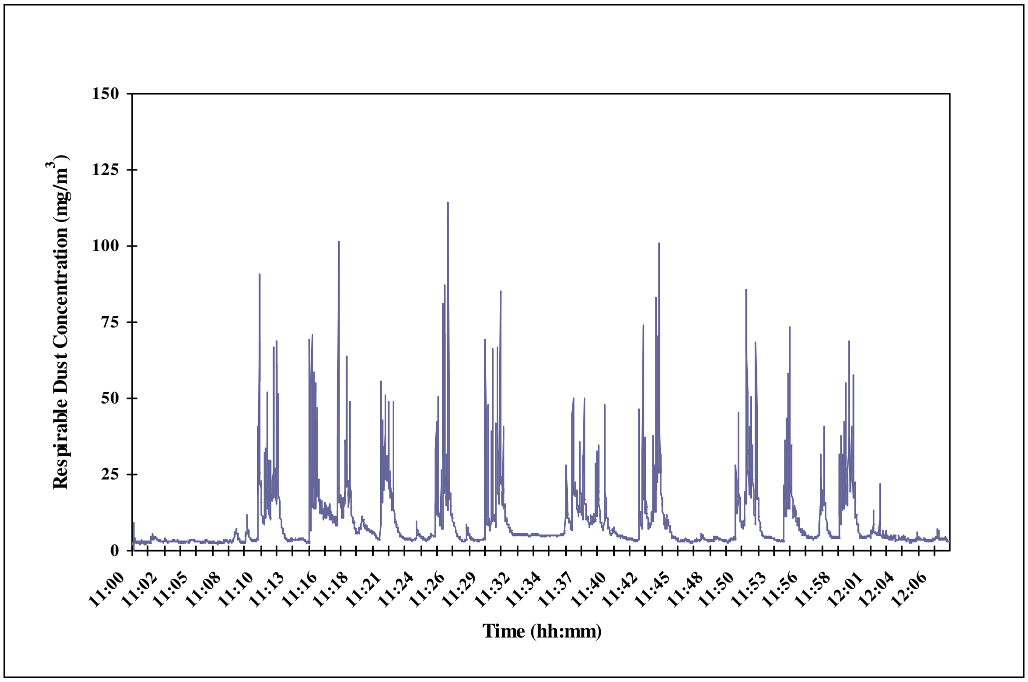

Figure A11: ARD profile recorded by the real-time monitor for Middleburg coal

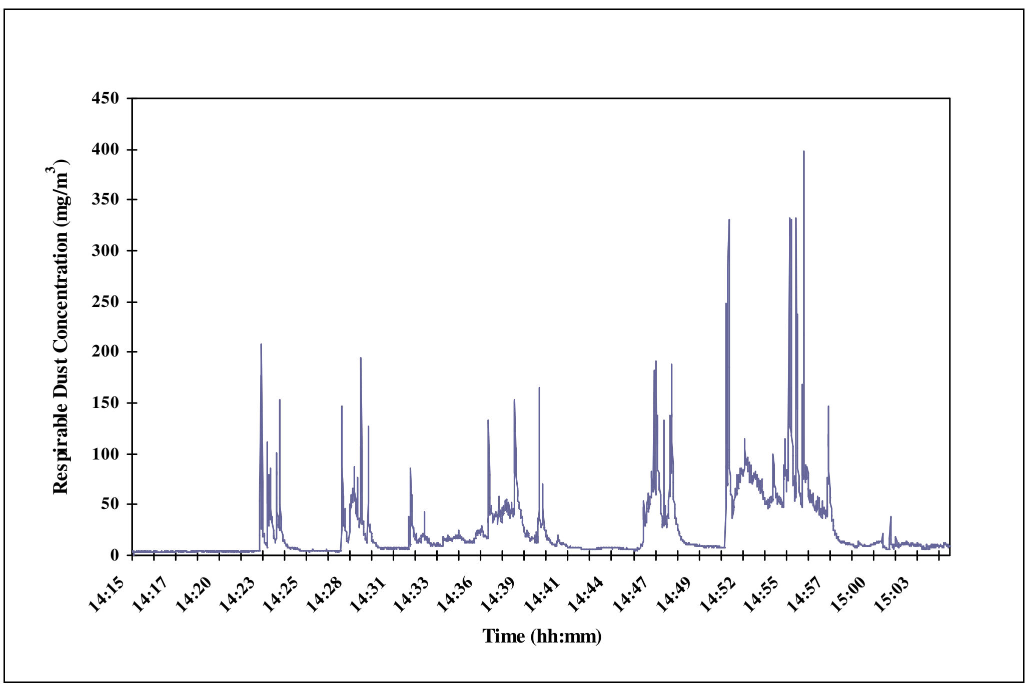

Figure A12: ARD profile recorded by the real-time monitor for Kwa Zulu Natal coal

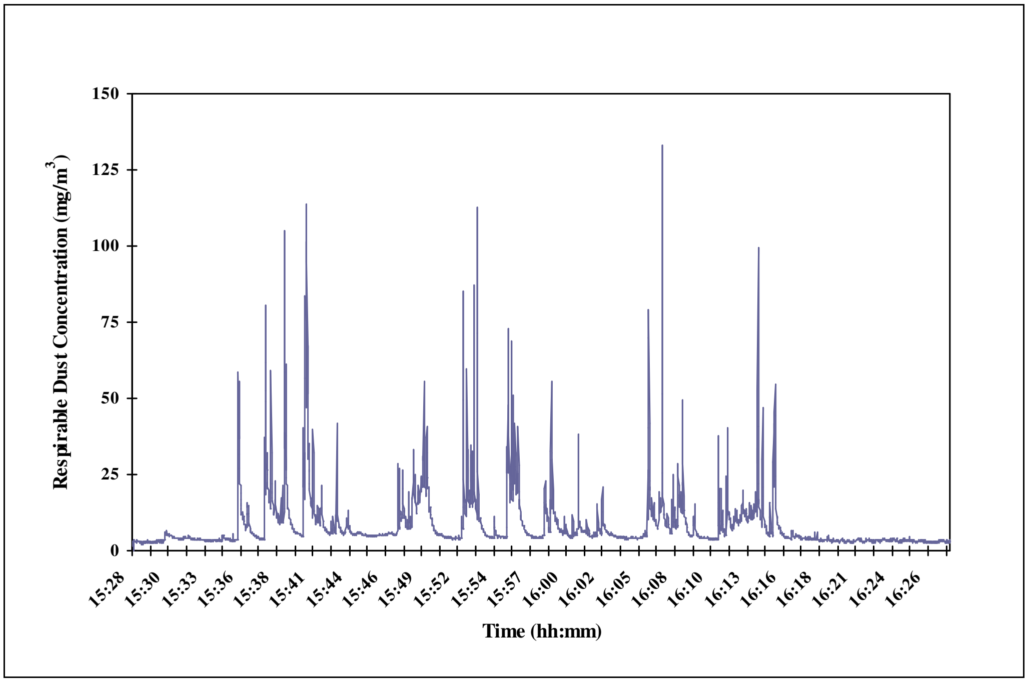

Figure A13: ARD profile recorded by the real-time monitor for Optimum and Rietspruit coal

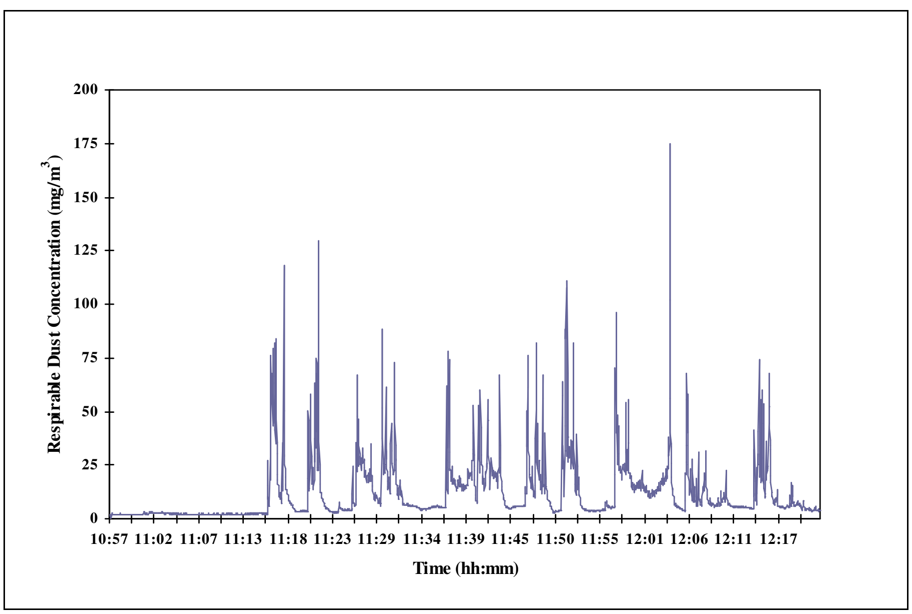

Figure A14: ARD profile recorded by the real-time monitor for Goedhoep coal

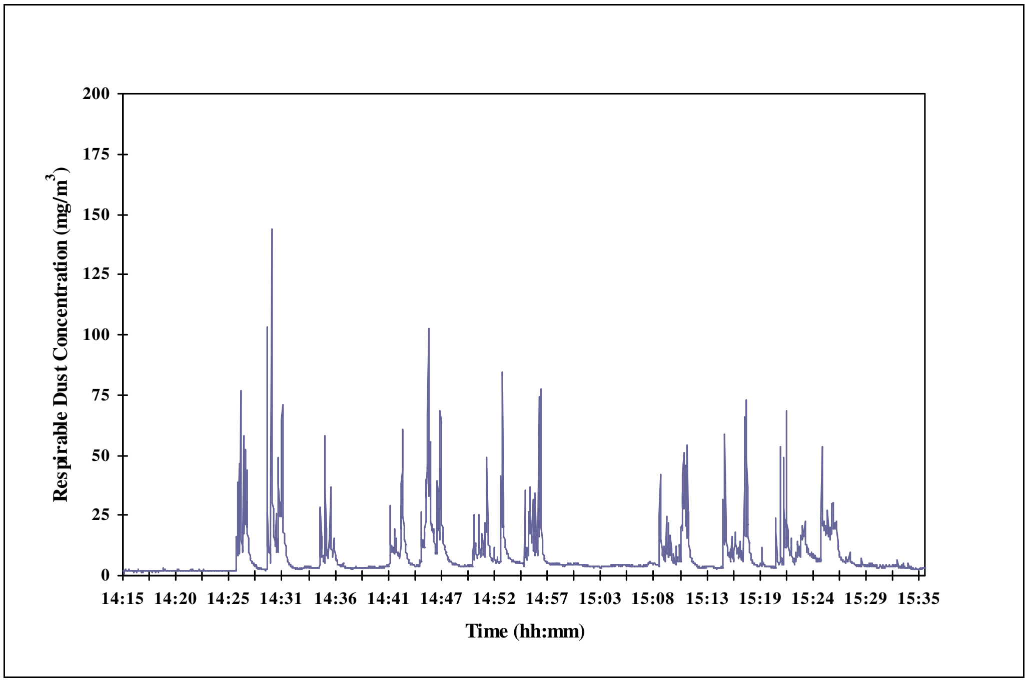

Figure A15: ARD profile recorded by the real-time monitor for Rietspruit coal

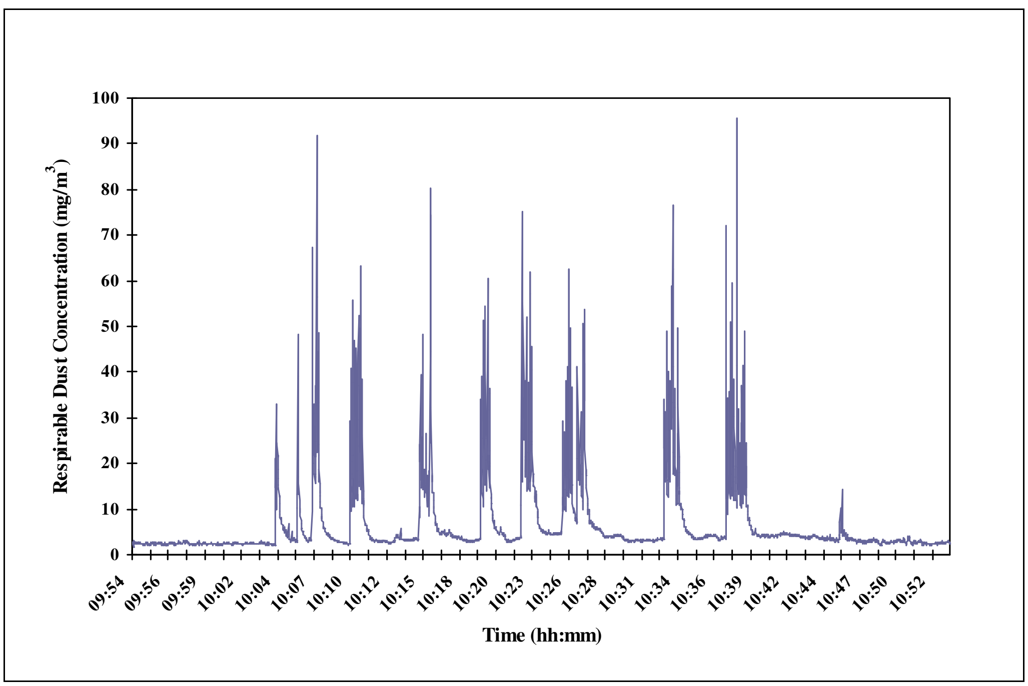

Figure A16: ARD profile recorded by the real-time monitor for NDC coal

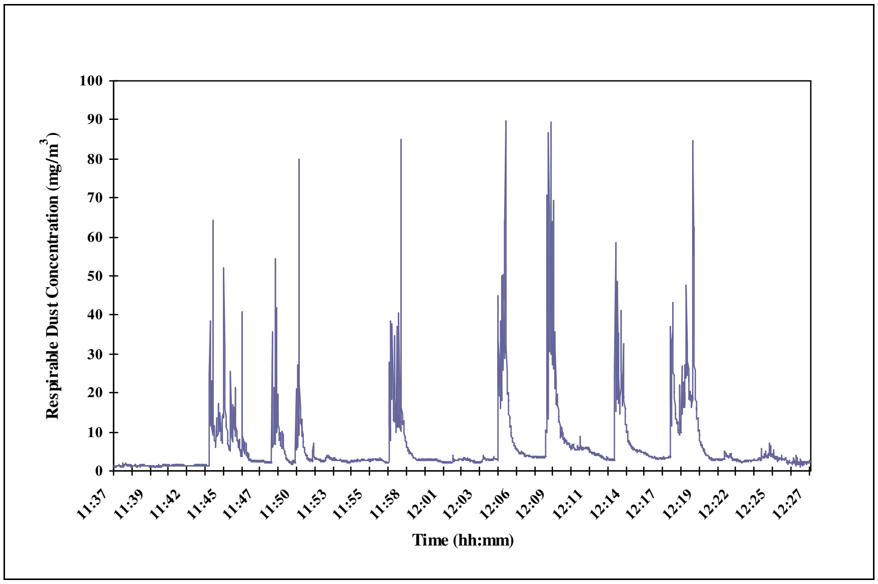

Figure A17: ARD profile recorded by the real-time monitor for Bosspruit, Twistdraai West, Syferfontein coal

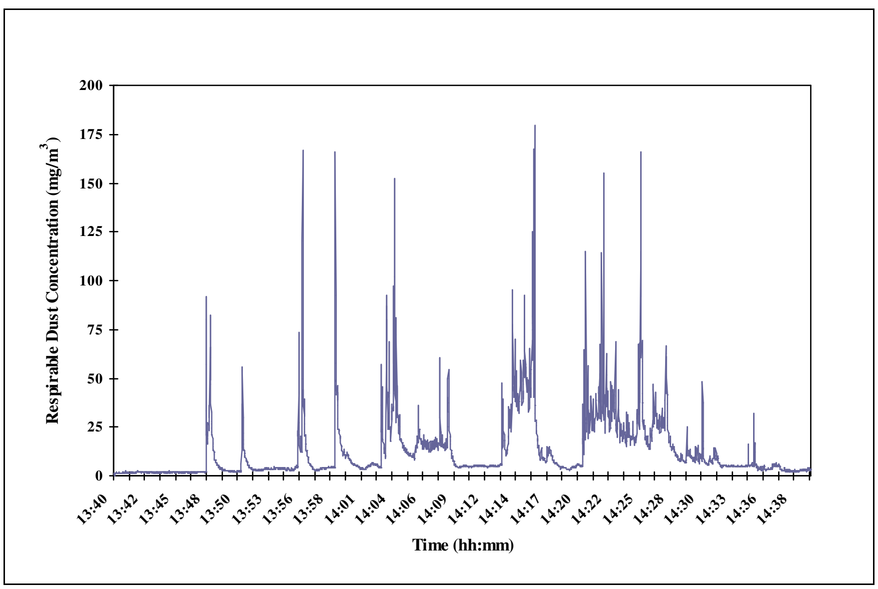

Figure A18: ARD profile recorded by the real-time monitor for Duiker, Middlebult, Boosjespruit coal

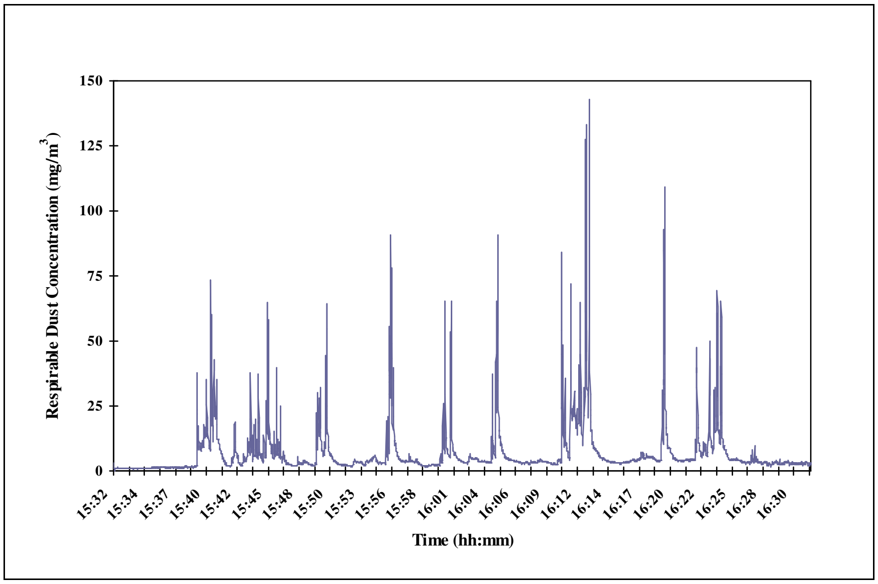

Figure A19: ARD profile recorded by the real-time monitor for Twistdraai East, Sigma and Brandspruit coal

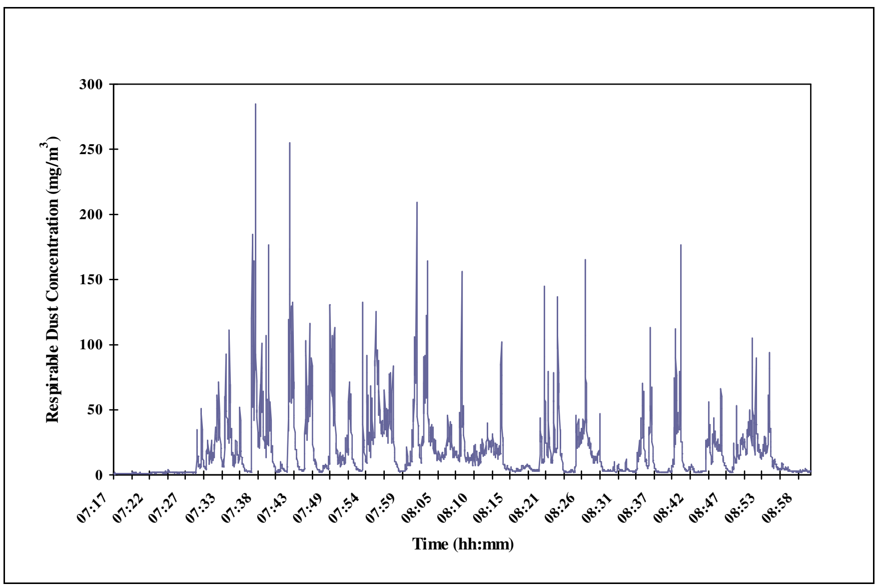

Figure A20: ARD profile recorded by the real-time monitor for Elisras and Twistdraai Central coal

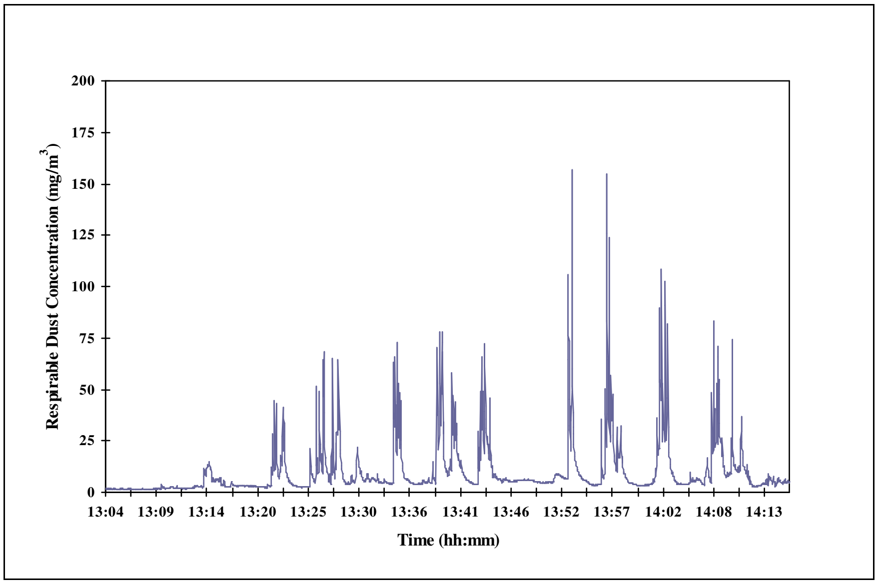

Figure A21: ARD profile recorded by the real-time monitor for Twistdraai East, Brandspruit, and Goedhoep coal

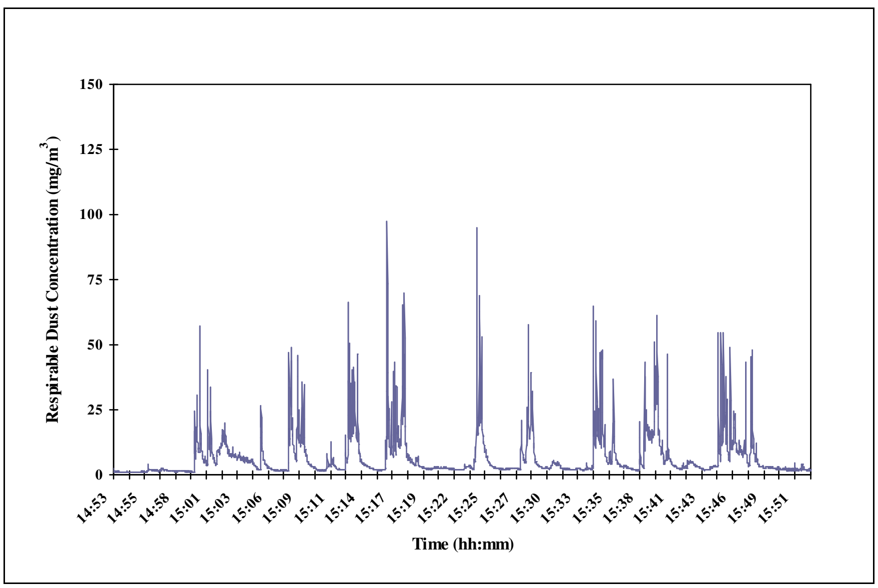

Figure A22: ARD profile recorded by the real-time monitor for Goedhoep and Elisras coal

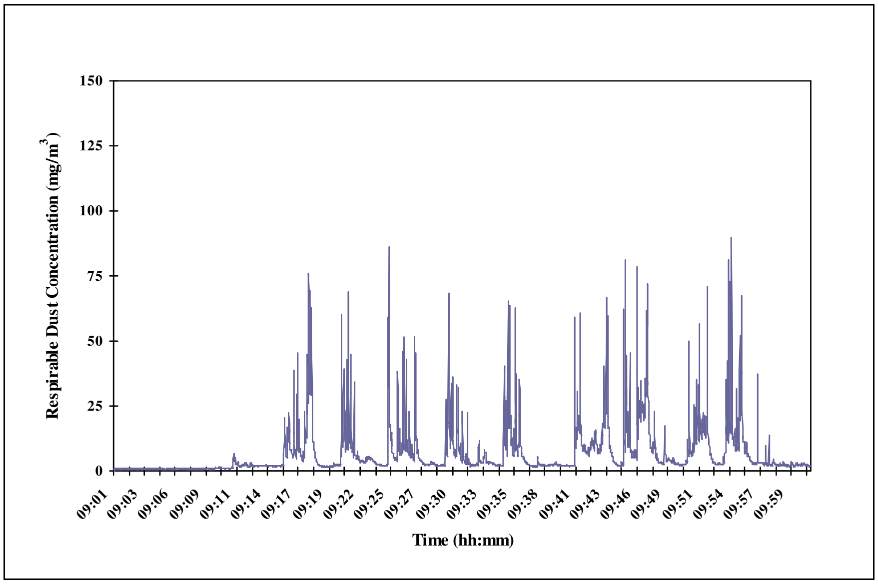

Figure A23: ARD profile recorded by the real-time monitor for Goedhoep and Elisras coal

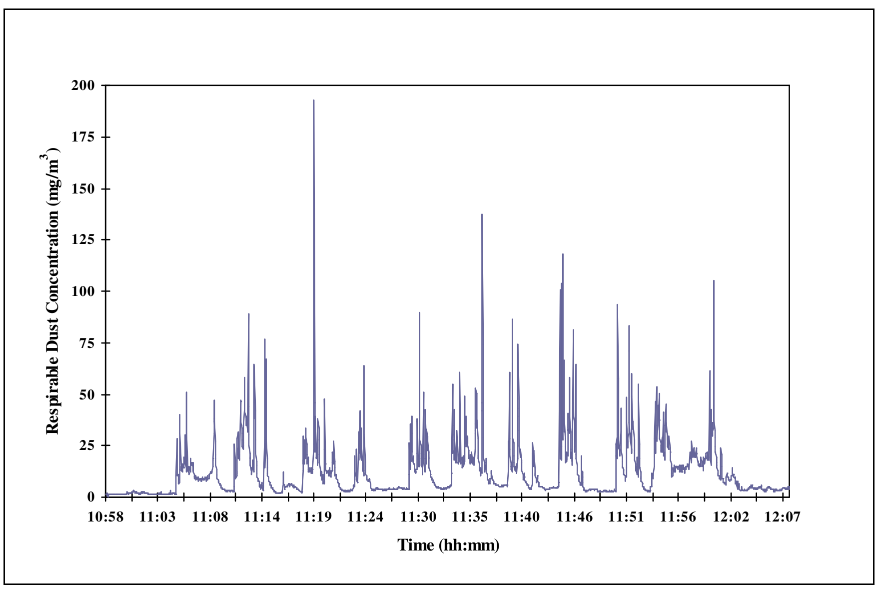

Figure A24: ARD profile recorded by the real-time monitor for Elisras coal

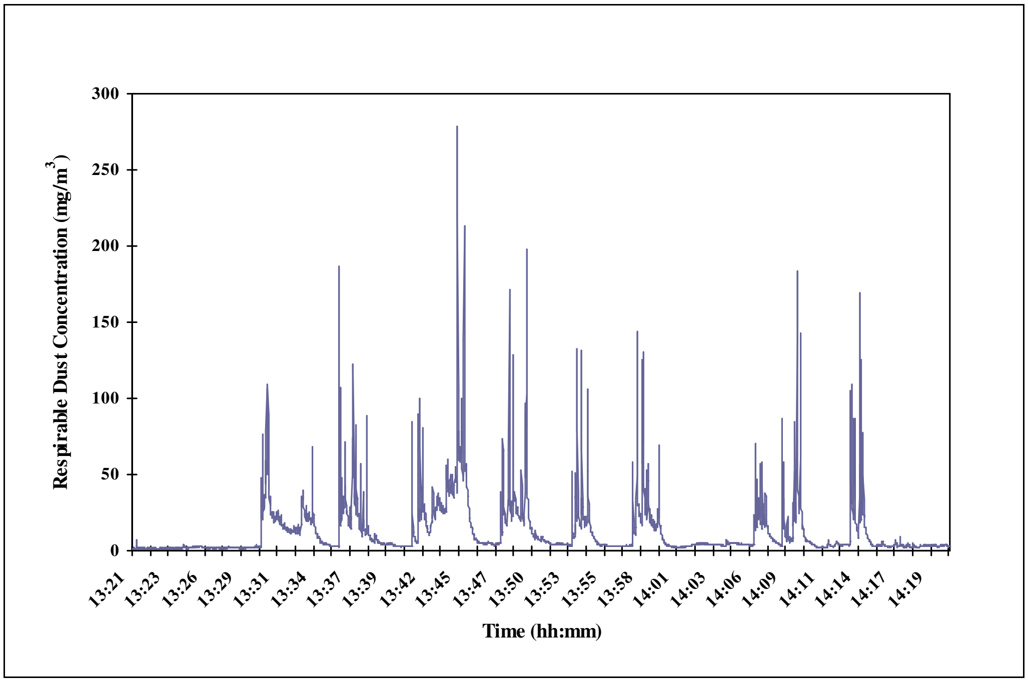

Figure A25: ARD profile recorded by the real-time monitor for Elisras coal