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Design and development of a multi-scrubber dust control system for longwall faces: experimental and modelling studies

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University of Wollongong

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DESIGN AND DEVELOPMENT OF A MULTI-SCRUBBER
DUST CONTROL SYSTEM FOR LONGWALL FACES:
EXPERIMENTAL AND MODELLING STUDIES

A Thesis Submitted
in Fulfilment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

from

UNIVERSITY OF WOLLONGONG

by

SRINIVASA RAO BALUSU

Department of Civil and Mining Engineering
November 1993
AFFIRMATION

The work presented in this thesis is my own and has not been previously submitted for a degree to any other University or Institution. The following publications have been based on this research work.


SRINIVASA RAO BALUSU
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis supervisor A/Prof. Naj I. Azi from Department of Civil and Mining Engineering, University of Wollongong for providing me with the opportunity and excellent facilities to work on this challenging project. His support, guidance, encouragement, tolerance and hospitality have been invaluable during the entire course of this research work. I would also like to thank my thesis co-supervisor, Dr. E.Y. Baafi for his advice, encouragement and critical review of several aspects of this study.

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ABSTRACT

The control of respirable dust continues to present a challenge as the longwall mining industry strives for increased productivity and miner safety. Despite extensive research into the development of dust control techniques, it is still difficult to achieve the Australian statutory standard of 3.0 mg/m³ at the face without loss of production. This is because of the complex nature of longwall mining, its environment and the introduction of high capacity machines. The objective of this thesis' research has been to address this problem and advance respirable dust control in longwall mining through the development of a new dust control technique. Major aspect of the research has been to provide a better understanding of the air velocities and respirable dust behaviour, through field studies and mathematical modelling, to assist in the development of new control techniques.

This research has co-ordinated several elements in developing a dust control technique and in understanding respirable dust behaviour. They are: (i) A literature review of dust control on longwall faces (ii) Field investigations in longwall faces to develop a fundamental data set on respirable dust distribution (iii) A new 'multi-scrubber' concept to control dust levels along the walkway of the face; the design and development of a compact prototype scrubber and field tests of the scrubber system in operating longwall faces, and (iv) Mathematical modelling of a longwall face, using finite element techniques to simulate air flow patterns, dust distribution and to assist in the evaluation of dust control methods; field investigations to validate the modelling results.

The first series of field investigations in four longwall faces were conducted to obtain data on respirable dust levels, the spatial and temporal behaviour of dust in the face, and to provide input data for mathematical modelling. The dust concentration data were
related to shearer location, face operations and time, and showed that large dust
gradients occur, not only around the shearer, but also across the whole cross-section of
the longwall face. The surveys helped in gaining a better understanding of the
respirable dust problem at the longwall face, and along with the literature review,
formed the basis of the development of the new dust control technique.

A new 'multi-scrubber' concept was proposed to reduce the longwall face operator's
exposure to dust. This system envisages a number of moderate capacity scrubbers,
which deliver cleaned air at high velocity, to create a relatively clean air zone along the
walkway in the longwall face. A prototype air-powered venturi scrubber was
developed for use in longwall faces which, when tested in the laboratory, yielded an
average efficiency of 92%. A second series of underground investigations in three
longwall faces ascertained that the scrubber system achieved protection efficiencies
ranging between 26 and 55%, at 3m from the scrubber, with face air velocities from
4.5 to 2.0 m/s.

As a supplement to the field studies, a three-dimensional finite element longwall face
model was developed to simulate the airflow patterns and respirable dust behaviour. It
facilitated the analysis of the effect of the shearer body and cutting direction on
longwall airflow characteristics and respirable dust behaviour. The model was also
used to predict the effectiveness of the scrubber system and other dust control
techniques. A third series of field experiments were conducted to validate the model's
predictions under similar operating conditions. A comparative analysis of the airflow
patterns, respirable dust distribution and effectiveness of control techniques shows
close agreement between the mathematical modelling results and field measured values.
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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

\( c \) concentration of particles in air
  \((c_{\text{in}} \text{ inlet; } c_{\text{out}} \text{ outlet})\)

\( C' \) Cunningham correction factor

\( c_i \) concentration of species

\( c_p \) specific heat at constant volume

\( D \) diameter of air-containing device

\( d_d \) water drop diameter

\( d_p \) particle diameter

\( d_{mo} \) molecular diameter

\( d_n \) diameter of water nozzle (internal diameter)

\( d_o \) distance from the axis of the limiting streamline for impaction

\( e \) emissivity

\( f \) velocity ratio \( = \frac{V_r}{V_a} \)

\( f_a \) empirical factor defined as the factor "f" at atomization velocity

\( f_i \) body force vector

\( g_i \) gravitational force vector

\( H \) heat generation

\( j_i \) diffusive mass flux of species

\( K \) inertial impaction parameter

\( k \) Boltzmann constant \( = 1.38062 \times 10^{-23} \)

\( k, \varepsilon \) turbulent kinetic energy and dissipation

\( L \) ratio of liquid to air flow rates

\( P \) air pressure
\( p \)  fluid pressure
\( Q \)  volumetric flow rate \( (Q_w \text{ water; } Q_a \text{ air}) \)
\( q_i \)  heat flux
\( q_m \)  mass flux
\( q_s \)  heat source
\( R \)  radius \( (R_d \text{ drop; } R_p \text{ particle}) \)
\( Re_a \)  flow Reynolds number
\( Re_p \)  particle Reynolds number
\( Re_r \)  Reynolds number of air with respect to water drop
\( R_i \)  source/chemical reaction rate/sink
\( T \)  absolute air temperature
\( t \)  time
\( u_i \)  Eulerian fluid velocity components
\( V_a (\text{crit}) \)  critical minimum velocity of air through venturi
\( V_a \)  air velocity \( (V_p \text{ particle velocity; } V_d \text{ water drop velocity}) \)
\( V_r \)  undisturbed upstream air velocity relative to the drop/collector \( (= V_a - V_d) \)
\( x \)  drag coefficient
\( x_i \)  cartesian coordinates

\( \alpha_c \)  mass diffusivity
\( \alpha_T \)  thermal diffusivity
\( \beta_c \)  volume expansion co-efficient associated with species concentration
\( \beta_T \)  volume expansion co-efficient associated with temperature
\( \delta_{ij} \)  Kronecker delta
\( \epsilon_{ij} \)  shear rate tensor
\( \eta \)  collection efficiency of a single drop
\( \eta_a \)  efficiency "\( \eta \)" at atomization velocity
\( \lambda \)  thermal conductivity
\[ \lambda_a \quad \text{mean free path of air molecules} \]
\[ \mu \quad \text{dynamic viscosity} \]
\[ \mu_a \quad \text{dynamic viscosity of air} \]
\[ \rho \quad \text{density} \]
\[ (\rho_a \quad \text{air}; \quad \rho_w \quad \text{water}; \quad \rho_p \quad \text{particle}) \]

\[ \sigma_{ij} \quad \text{stress tensor} \]
\[ \tau_{ij} \quad \text{deviatoric part of the stress tensor} \]
\[ \varphi_i \quad \text{impingement factor} \]
\[ = 6.65 \times 10^{-2} \mu m \text{ (at normal conditions)} \]
\[ \Phi = 2\varepsilon_{ij}\varepsilon_{ij}, \text{ viscous dissipation is } \mu\Phi \]

**ABBREVIATIONS**

AFC  Armoured Face Conveyor
CEC  Commission of the European Communities
CWP  Coal Workers Pneumoconiosis
EEC  European Economic Communities
IAHR International Association for Hydraulic Research
JCB  Joint Coal Board (of NSW, Australia)
MRDE Mining Research and Development Establishment
MSHA Mining Safety and Health Administration
NCB  National Coal Board (now British Coal, UK)
NERDDC National Energy Research, Development and Demonstration Council
NSW  New South Wales (of Australia)
SME  Society for Mining, Metallurgy and Exploration, Inc. (USA)
USBM United States Bureau of Mines
Chapter 1

INTRODUCTION

1.1 GENERAL

Respirable dust is a continuing problem in the mine environment where it adversely affects the safety and productivity of a miner. Dust is an inevitable product of mining, given the nature of mining operations such as cutting, loading, transference and transportation of coal. It is dispersed into the mine atmosphere by the ventilating airflow, and travels downwind. Once airborne, the respirable dust particles are difficult to capture and remove as they fall very slowly because of associated aerodynamic properties. As a result, miners are exposed to high respirable dust concentration levels.

Prolonged exposure to, and inhalation of, airborne respirable dust particles of between 0 and 7 μm, leads to the accumulation of dust in the lung and to the development of a respiratory disease known as 'pneumoconiosis' or 'black lung disease' (Sinha and Fadiya, 1985). It is the most serious occupational health hazard in underground coal mines, with 40,000 new cases estimated as occurring each year (Taylor, 1988). In an attempt to control the respirable dust problem, coal producing countries around the world have imposed mandatory respirable dust standards. Australian New South Wales (NSW) Coal Mines Regulation Act (NSW Govt., 1946) set down that "each mine operator shall maintain the average concentration of respirable dust in the mine atmosphere during each shift to which each miner in the active workings of such a mine is exposed at or below 175 particles per cubic centimetre of air". This standard was converted in 1984 to 3 mg/m³.
The mines, facing continuous changes, have great difficulty in conforming to these standards. In Australia, three major underground mining methods are employed to extract coal: conventional, continuous and longwall mining. Longwall mining, the most recent and most highly mechanised method of mining, is becoming the most prevalent method used. Whilst it has achieved increased production, improved productivity, better safety for miner's, greater recovery of resources and the general economics of mining coal, the fact remains that, as coal is mined at a faster rate, more dust is generated. Longwalls have been found as having the highest mean concentrations of respirable coal dust (Watts and Parker, 1986) and the greatest number of samples exceeding the statutory dust limits.

Only a small fraction of the total respirable dust does become airborne, (Cheng and Zukovich, 1973), yet it is still too much to be sufficiently diluted by the ventilation airflow so as to maintain respirable dust levels below 3 mg/m$^3$. Studies have shown that for every 1,000 tonnes of coal produced, 0.5 to 1.5 mg/m$^3$ dust is added to the longwall face atmosphere (Sinha, 1982; Wang et al, 1991; Bell et al, 1993a). Current methods can effectively control longwall respirable dust for production levels of 2,000 - 3,000 tonnes/shift, but beyond this it becomes very difficult to control dust. Thus, despite the developments in dust control technology over the past 30 years, many longwall faces are still having difficulty in complying with statutory dust levels.

Longwall face dust is created mainly by the shearer, support movement, spalling of coal, crusher/stage loader and roof falls in the goaf. Bi-directional cutting i.e. cutting in both directions, results in shield setters being exposed to the shearer generated dust in the first half of the mining cycle and the shearer operators being exposed to the shield dust during the second half. This is hazardous, and longwall operators are therefore employing uni-directional cutting methods, rather than bi-directional cutting.
simply to reduce the operators' dust exposure, resulting in an estimated production loss of 10 to 15% per working face (Gillette, Jankowski and Kissell, 1988). In Australia, this represents a potential revenue loss of approximately $120 million.

In addition, the compensation cost of dust induced illness in coal mines is immense. For example, in the USA alone, black lung disease compensation payments in 1987 was nearly $1.8 billion with the cumulative cost of the program well above $22 billion. There are also hidden costs associated with dust which include equipment wear and decreased worker productivity due to the poor work environment. These high costs may be prevented or reduced through long term research directed at understanding the dust generation, entrainment, and control of respirable dust.

In view of the industry trend towards longwall mining, advancement of dust control technology is imperative if production is to increase with safety. The work in this thesis is directed at developing new control techniques for respirable dust, evaluating them in the field, and understanding dust behaviour more clearly through field and mathematical investigations.

1.2 STATEMENT OF THE PROBLEM

The problem of respirable dust control in coal mines is continuing even after many years of research. Dust concentration levels in longwall mining are higher and dust control is inherently more difficult by virtue of the mode of operations employed. Longwall operations quickly disperse dust, unlike continuous miner sections where dust can be boxed in or controlled with scrubbing techniques. Unfortunately, the dust control techniques, such as machine mounted scrubbers, that are highly successful for continuous miners have not yet proved to be successful for longwall faces.

A critical review of these techniques shows that although substantial progress has been made, because of the complex and interactive factors involved not all these techniques are applicable in every longwall face. The physical characteristics of each face directly impact on the dust control requirements to be implemented. As a result, 8 out of 20 longwall faces in New South Wales, Australia, are still facing a difficult task in consistently complying with mandatory dust standards, according to a Joint Coal Board study involving more than 1000 gravimetric respirable dust samples collected between 1984 and 1992.

Much research has been directed at suppressing dust at the shearer, but very little has focussed on reducing dust production from other principal sources, such as from support advance, coal spalling from the face and goaf falls (NCB, 1982; Jankowski, Organiscak and Jayaraman, 1991; Hewitt, 1990a). The increasing use of powered supports has presented a new and difficult problem in dust control, providing a new
challenge for further research. Recent field investigations, carried out by the author of
this thesis in three coal mines of New South Wales to understand the behaviour of dust
clouds in a longwall face, showed that even though the shearer is the major source of
dust, often much is produced during support movement and face spalling, and
specifically, during falls of crushed roof rock when the supports yield and advance.
Most of this dust becomes airborne, quickly disperses into the walkway and increases
the concentration to unacceptably high levels. Methods developed so far to deal with
this problem are the use of filters and mats over the supports canopy; however, they
are labour and capital intensive and are not practicable. There is therefore a need to
develop a new control technique to combat the respirable dust once it becomes
airborne.

The movement and distribution of respirable dust in a longwall face is complex because
of the nature of longwall mining operations. The generation and transport of airborne
dust is governed mainly by the velocity and the movement pattern of the ventilating air.
In order to develop an effective dust control technique it is necessary to thoroughly
understand the airflow characteristics and respirable dust behaviour in the longwall
face. A few experimental studies on airflow characteristics and dust concentration
levels in the longwall face have been reported (Hall, 1960; Skubonov, 1973; Peng and
Chiang, 1986; Chiang, Luo and Peng, 1987; Ramani, Qin and Jankowski, 1991). A
critical review indicates that there are large variations in dust concentration profiles at
different longwall faces world wide. Such data are inappropriate for Australian
longwall faces which differ in their physical characteristics, ventilation plans and
operating procedures. The Australian gravimetric data that has been collected over the
last 8 years (JCB, 1984-92) on longwall miners' dust exposure was not sufficiently
detailed to permit analysis with respect to mining activities to establish the spatial and
temporal behaviour of dust in longwalls. Very little information is available on the
aerodynamic and dust concentration gradients around the shearer. To develop a dust
control technique it is considered necessary by the author to conduct detailed and extensive instantaneous sampling at longwall faces together with face activity surveys to understand the transient, ambient dust levels in relation to the face activities.

To understand thoroughly the dust behaviour in a complex longwall mining environment and to evaluate any dust control technique, mathematical modelling is necessary to supplement field studies. Most of the early published studies by modelling (Grayson and Peng, 1984; Chiang, Peng and Luo, 1986) focussed on development of empirical models based on dust data collected from longwall faces. These models were input data intensive and ignored the physics of the airflow and respirable dust behaviour in a face, with the result that they are only applicable to the few faces which have similar characteristics. Many expert systems were also developed based on similar studies (Roepke, Hanson and Schmidt, 1985; Hanson and Roepke, 1988; Wirch, Kelly and Jankowski, 1988; Kissell and King, 1988). Some of the recent studies (Partyka, 1989; 1990; Bhaskar, 1987; Qin, 1992) consider the physics of the airflow and dust, but are one dimensional models. These models cannot be used either to understand the three dimensional behaviour of airflow fields and dust particles around the shearer nor to determine the effectiveness of dust control techniques, which depends on their spatial location. Very little research has been conducted on three-dimensional modelling (Nichols and Gregory, 1987; Meyer, Grange and Meyer, 1991) and the use of three dimensional modelling of the behaviour of dust at a longwall face, with mathematical model validation through detailed field investigations in underground coal mines was considered necessary by the author.

In summary, it became evident from early research that there was a need for the development of a dust extraction system once dust became airborne. This would require detailed and extensive sampling at longwall faces to understand the airflow characteristics and behaviour of respirable dust in the longwall face. In addition,
mathematical modelling of air velocities, dust behaviour and dust control techniques was considered necessary to supplement field investigations in the development of effective dust control techniques.

1.3 SCOPE OF WORK

The objective of this research was to advance the technology for respirable dust control in longwall mining through the development of a new technique. To achieve the set objective, the research described here has co-ordinated several elements and the scope of work is discussed under three distinct areas:

(i) The first part of the research concerned with conducting underground experiments in operating longwall faces to obtain data on respirable dust levels, on the spatial and temporal behaviour of such dust along the longwall faces, and on airflow patterns to provide input data for mathematical modelling.

(ii) A major part of the research was the design, development and evaluation of a new dust control technique. A new multi-scrubber concept was proposed to reduce miners' exposure to dust in a longwall face. A prototype compact scrubber was developed for that purpose, and comprehensive laboratory experiments and large scale underground investigations were conducted to evaluate the effectiveness of the scrubber technique in the field.

(iii) Another important aspect of the research was the development of a three dimensional model of a longwall face to simulate the airflow patterns, the respirable dust behaviour and the dust concentration distribution to supplement the field evaluation of dust control techniques. Field studies conducted to validate the modelling results, are also included in this study.
1.4 THESIS OUTLINE

The thesis contains eight chapters as follows:

Chapter 1 briefly examines the longwall dust problem and outlines the scope of the research work. A review of fundamental studies on longwall dust behaviour, dust control methods and modelling studies, is given in chapter 2.

Chapter 3 describes studies carried out in four longwall faces of the Southern coalfields of NSW to understand the respirable dust behaviour with respect to face operations. The design of the underground experiments, sampling procedures, the experimental results, and an analysis of the data to determine the spatial dust concentration and its temporal behaviour to assist in better understanding the dust problem are discussed. The instantaneous dust data were correlated with shearer location, face operations and time.

Chapter 4 details the design and development of a compact prototype venturi scrubber for use in longwalls. Laboratory experiments, examining the effect of parameters such as compressed air consumption, water flow rates and air quantity through the venturi on the scrubber's efficiency are discussed. Its efficiency over various respirable dust size ranges was also investigated.

Chapter 5 details extensive field investigations conducted to determine the influence of face air velocity, scrubber exhaust velocity and the location of the scrubber on its efficiency. The results supported the concept of a multi-scrubber system as a dust control technique in a longwall face, providing 40 to 50% protection from respirable dust in faces with less than 3.5 m/s air velocity.
Chapter 6 discusses the development of a three dimensional finite element longwall face model to simulate airflow patterns and respirable dust behaviour and to evaluate the effectiveness of various dust control techniques, including the scrubber system. Prior to modelling, an extensive literature review was made on turbulent airflow and dust dispersion modelling. Path traces of particles introduced near the cutting drums, with different dust control techniques installed, were computed to show the behaviour of respirable dust around the shearer.

Chapter 7 deals with the validation of the mathematical modelling results. It presents the results of the field investigations and comparisons with modelling results, which shows that the model is a reliable predictor of air velocity profiles and dust concentration along a longwall face. The results also show that finite element techniques can be used successfully to predict the effectiveness of different dust control techniques and, when used in conjunction with field investigations, are invaluable in developing new dust control technology.

The conclusions and recommendations for future research are presented in chapter 8.
Chapter 2

REVIEW OF DUST CONTROL AT LONGWALL FACES

2.1 INTRODUCTION

Ever since dust has been identified as principal agent in the development of a disease known as 'pneumoconiosis' there has been a growing interest in the development of dust control techniques in coal mines. Allowable dust concentration standards continued this trend, with many dust control methods and operating practices being developed over the past 30 years to reduce miners' dust exposure on longwall faces. Although significant progress has been achieved, respirable dust exposures on longwall faces are significantly higher than in other mining environments, and the problem of containing dust concentration to acceptable levels continues to impede progress towards realizing the full potential of the longwall mining method. Recent longwall mining trends, including higher production levels and longer face lengths, are placing even more stringent demands on dust control.

Although there is extensive scientific and technical literature which addresses dust control measures, few studies have sought to define the spatial and temporal variability of the respirable dust concentration gradients in longwall faces. A U.S. National Academy of Sciences study (Cook et al, 1980) concluded that "improvement in dust control research was obtained principally through the adoption of existing technology, but continuation along these lines is likely to yield diminishing returns. Research should be directed more toward obtaining fundamental understanding of the origin, transport and characteristics of respirable coal mine dust".
In addition, very few attempts have been made either to supplement the field investigations of dust control techniques with numerical simulations or to use mathematical modelling techniques for a better understanding of the airflow characteristics or respirable dust behaviour around the shearer in a longwall face. In view of the enormous progress over the last two decades in other fields, in computer hardware and software technology and in the understanding of airflow and aerosol dispersion systems, it would appear that there is an opportunity for the introduction of new and innovative ideas into dust control technology.

2.2 RESPIRABLE DUST STANDARDS

Respirable dust is defined as the dust which penetrates to the alveolar regions of the lungs. Due to the size-selective nature of the particle removal mechanisms in the nasal passages and lung airways, the criteria defining respirable particles must be a function of the particle size. At present, two criteria are accepted for defining the respirable dust, both approximating the dust deposition in the nonciliated portions of the lung. The first, resulting from work performed by the U.S. Atomic Energy Commission (AEC), is defined by the curve labelled AEC in Figure 2.1. The other criterion for the respirable fraction of dust, recommended by the British Medical Research Council, is defined by the sampling efficiency curve labeled BMRC in Figure 2.1. The pulmonary deposition curve is also shown in Figure 2.1. Particle sizes refer to equivalent diameter, which is defined as the diameter of a spherical particle of unit density having the same falling velocity as the particle in question.

Lung diseases have held the attention of scientists for well over 400 years. Agricola discussed the consequences of dust trades in his 1556 publication De Re Metallica. He understood that the lethal lung diseases resulted from working in mines. The term
'pneumoconiosis' was introduced by Zenker in 1867 for the first time (Ulmer, 1988). Bedford and Warner's report (1944) was a major turning point in our understanding of the impact of inhaled coal dust and of dust control in mines. This report stipulated the adoption of airborne dust concentration standards in coal mines. The Particle Number Standards, introduced in Britain in 1949, remained basically the same until 1970, when gravimetric standards were introduced. The International Pneumoconiosis Conference held in Johannesburg in 1959 (Orenstein, 1960) was a milestone in that it recommended that dust measurements should be made by gravimetric methods. As a result, in the late 1960's, many major coal producing countries adopted gravimetric respirable dust standards in their coal mines in an effort to control the disease.

Prior to establishing the coal mine dust standards, extensive epidemiological investigations were conducted to ascertain the exact mechanism of pneumoconiosis and to estimate the disease risk levels associated with different levels of dustiness. In England, 25 pits were studied over a period of 10 years to provide the data base for
epidemiological studies (Jacobson et al, 1970; 1971; 1972; Jacobson, 1988). The German studies took place in ten coal mines over a 10 year period (Reisner, 1976). The studies suggested a close correlation between the degree of disease contracted and the mass of coal dust accumulated in the lungs. Based on these studies, a U.S. Committee on Education and Labor (1970) has reported that at 7.0 mg/m³, the rate of development of simple pneumoconiosis per 1,000 miners, after 35 years' exposure, would be 360 (36%); at 4.5 mg/m³ the expected rate would be 150 (15%); at 3.0 mg/m³ the expected rate would be 50 (5%); and at 2.0 mg/m³ the expected rate would be 20 (2%). This shows that the probability of developing simple pneumoconiosis decreases with decreasing dust concentration. The respirable dust standards in different countries are shown in Table 2.1.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Country</th>
<th>Tolerable limit (mg/m³)</th>
<th>Measuring strategy /Location</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Germany</td>
<td>8.0</td>
<td>fixed point on the face - near the return end</td>
</tr>
<tr>
<td>2</td>
<td>USA</td>
<td>2.0</td>
<td>personal sampling</td>
</tr>
<tr>
<td>3</td>
<td>UK</td>
<td>8.0</td>
<td>fixed point in the return - 70 m away from face</td>
</tr>
<tr>
<td>4</td>
<td>Russia</td>
<td>2.0</td>
<td>fixed point sampling 10 m behind the shearer</td>
</tr>
<tr>
<td>5</td>
<td>Australia</td>
<td>3.0</td>
<td>personal sampling</td>
</tr>
<tr>
<td>6</td>
<td>France</td>
<td>( I = 3.22 \log C_t - 10.6 )</td>
<td>( C ) = dust conc. in ppcc ( t ) = percentage of quartz 10.6 = correction for soluble filters</td>
</tr>
<tr>
<td>7</td>
<td>Poland</td>
<td>1500 ppcc 500 ppcc</td>
<td>- without incombustibles - incombustible &gt; 70%</td>
</tr>
<tr>
<td>8</td>
<td>India</td>
<td>3.0</td>
<td>fixed point near the return end of the face</td>
</tr>
</tbody>
</table>
Because of an increased health risk associated with exposure to quartz, the dust standard in all the above cases decreases if the quartz content of the sample is more than 5%.

Absolute values of respirable dust concentrations obtained from different countries or from different locations are not suitable for a comparison unless the sampling strategy is also included. For example, in Germany, the respirable dust concentration has to be measured where the maximum concentration is expected, i.e. at the return end of the face. In the U.K., the values at a fixed measuring point, located in the return airway approximately 70 m behind the face, are used to assess the dust conditions at the face. The reasoning for this location is that it is only there that the measuring results are no longer influenced by the coarse dust or the unequal distribution of the respirable dust. Corrections are used to account for deposition of dust before the measuring point. The measuring strategy in Russia focuses on monitoring dust suppression at the face. When cutting coal with the shearer, the airborne dust concentration, with particles up to 74 μm, is measured directly behind the shearer. The measuring strategy in the USA and Australia provides for a measurement of the respirable dust concentration by means of personal dust samplers directly within the employee's breathing zone. This is normally achieved by placing the samplers on the left upper side of the chest, and over the left-pocket.

The dust control measures applied in the different countries depends on their measuring strategies. The measuring strategies of Germany, U.K, and Russia call for control techniques which reduce the dust concentration in the entire return air section. In the U.S.A. and Australia, dust control measures focus on reducing miners' dust exposure. This becomes particularly clear in the shearer clearer (section 2.5.5) control technique in which dust produced by the shearer is kept away from the operators.
2.3 LONGWALL AND DUST CONDITIONS IN AUSTRALIA

2.3.1 Longwall method

The longwall mining method was introduced in Australia in the 1960's and it is now the predominant trend in underground mining. In 1992, 162 million tonnes of coal was produced in Australia from 124 mines, of which 73 were underground mines and 51 open-cuts. Longwall faces produced 27 million tonnes of raw coal which represented 45% of the total underground coal production (JCB, 1991-92a). The share of longwall in underground coal production in New South Wales, Australia, is shown in Figure 2.2. At present, there are 24 longwall faces in operation in 23 mines, 20 of which are in New South Wales and the remainder in Queensland. Thus, longwall faces are producing an increasing percentage of the output from underground mines, with several longwall faces consistently producing over 6,000 tonnes per day. However, this increase in production has also increased the dust problem.

Figure 2.2 Increase in share of longwall face production during the past 10 years in New South Wales, Australia (after JCB, 1991-92b).
2.3.2 Respirable dust regulations

Dust sampling was introduced in NSW in the mid 1930's. Early dust measurement results varied widely between different collieries and different activities in the same mine, reflecting largely differences in ventilation, watering and stone dusting practices. In 1939, a Royal commission conducted by Mr. Justice Davidson enquired into the safety and health of workers in coal mines. As a result, regulations to control dust levels were developed, but were not proclaimed until 1943 (Hewitt, 1990b).

Early dust measurements were based on a particle count and were expressed as particles per cubic centimetre (ppcc), with Owens' dust pump as the designated measuring instrument. The maximum allowable limit was 175 ppcc with less than 10% free silica in the 0-5 micron size. A study by Philips (1983; 1984) found that 175 ppcc is equivalent to approximately 3.15 mg/m$^3$. In 1984, the mandatory dust standard was changed from 175 ppcc to 3.0 mg/m$^3$ of respirable dust other than dust containing quartz. Quartz containing dust is that which contains more than 5% quartz, in which case the maximum mandatory limit reduces, depending on the total amount of quartz present.

2.3.3 Respirable dust conditions

Respirable dust samples are regularly taken by the JCB and the results are shown in Table 2.2 - 2.3. These results show that some coal mines are more prone to high levels of dust generation than others. Analysis of the results shows that 40% of the samples collected from mines working the Bulli seam of the Southern district of NSW exceeded the statutory level of 3 mg/m$^3$ (see Table 2.3) compared to 5% in the Northern / Western district mines. This is because the inherent moisture in the Bulli
Table 2.2  Typical shift average dust exposures of longwall operators in Australia, over the past 4 years (samples collected by JCB, 1984 - 92).

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Moisture</th>
<th>Hardgrove Grindability Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mg/m³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Southern district</td>
<td>Northern district</td>
</tr>
<tr>
<td></td>
<td>Face 1</td>
<td>Face 2</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>4.80</td>
<td>2.70</td>
</tr>
<tr>
<td>3</td>
<td>3.63</td>
<td>1.81</td>
</tr>
<tr>
<td>4</td>
<td>7.05</td>
<td>4.21</td>
</tr>
<tr>
<td>5</td>
<td>4.06</td>
<td>3.46</td>
</tr>
<tr>
<td>6</td>
<td>3.42</td>
<td>5.08</td>
</tr>
<tr>
<td>7</td>
<td>2.74</td>
<td>3.04</td>
</tr>
<tr>
<td>8</td>
<td>6.10</td>
<td>5.77</td>
</tr>
<tr>
<td>9</td>
<td>5.80</td>
<td>2.10</td>
</tr>
<tr>
<td>10</td>
<td>5.40</td>
<td>3.36</td>
</tr>
<tr>
<td>11</td>
<td>3.30</td>
<td>4.34</td>
</tr>
<tr>
<td>12</td>
<td>2.39</td>
<td>2.80</td>
</tr>
<tr>
<td>13</td>
<td>4.05</td>
<td>3.77</td>
</tr>
<tr>
<td>14</td>
<td>2.21</td>
<td>4.51</td>
</tr>
<tr>
<td>15</td>
<td>6.65</td>
<td>2.15</td>
</tr>
<tr>
<td>16</td>
<td>4.81</td>
<td>2.97</td>
</tr>
</tbody>
</table>

Table 2.3  Dust compliance record of longwall faces in Australia (Hewitt, 1990a).

<table>
<thead>
<tr>
<th>Face</th>
<th>First sample</th>
<th>Last sample</th>
<th>No. of samples</th>
<th>% Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12-04-84</td>
<td>02-02-90</td>
<td>20</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>17-05-84</td>
<td>31-01-90</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>10-02-86</td>
<td>17-10-89</td>
<td>16</td>
<td>88</td>
</tr>
<tr>
<td>4</td>
<td>04-02-86</td>
<td>29-11-89</td>
<td>18</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>14-11-84</td>
<td>09-02-89</td>
<td>17</td>
<td>94</td>
</tr>
<tr>
<td>6</td>
<td>26-02-87</td>
<td>23-11-89</td>
<td>8</td>
<td>62</td>
</tr>
<tr>
<td>7</td>
<td>06-09-84</td>
<td>14-03-89</td>
<td>26</td>
<td>88</td>
</tr>
<tr>
<td>8</td>
<td>08-05-84</td>
<td>28-09-89</td>
<td>62</td>
<td>34</td>
</tr>
<tr>
<td>9</td>
<td>20-03-87</td>
<td>06-02-90</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>24-08-84</td>
<td>20-03-89</td>
<td>27</td>
<td>52</td>
</tr>
<tr>
<td>11</td>
<td>10-04-84</td>
<td>22-02-90</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>27-06-89</td>
<td>13-02-90</td>
<td>8</td>
<td>25</td>
</tr>
</tbody>
</table>
seam is about 1%, compared with Newcastle at approximately 2.1%, and Lithgow 2.4% (Hewitt, 1984-92). The methane drainage operations in the Bulli seam also extract moisture from the seam, reducing it to about 0.4%. Another important contributing factor for high dust levels in the Bulli seam is its high Hardgrove Grindability Index. Figure 2.3 shows the results of an extensive dust survey carried out by JCB at three Queensland longwall faces, which shows that the dust levels exceed the statutory limit when coal production is over 7,000 tonnes/day.

![Graph](Image)

**Figure 2.3** Increase in dust level with production in longwall faces (after Bell et al 1993a).
2.4 FUNDAMENTAL STUDIES

2.4.1 Dust sources

Potential dust sources in a typical longwall face are shown in Table 2.4 and Figure 2.4. As can be seen, there are a variety of dust sources on longwall faces (Kost, Yingling and Mondics, 1981). The relative contribution of each source to the overall airborne dust concentration may vary from one face to another. To develop any dust control technique, it is necessary to know the dust generation from each source. Many studies (Mundell et al, 1980; Bradley, Hadden and Dodgson, 1983; Olson, 1984; Jankowski and Organiscak, 1983a; Page, Jankowski and Kissell, 1982; Jankowski, Organiscak and Jayaraman, 1991) have been conducted to identify and quantify dust sources in a longwall face using short term gravimetric sampling. Five primary dust sources were identified: intake dust, dust generated by coal transport and the stage loader, dust generated by the shearer during the cutting pass, dust generated by the shearer during the clean-up pass and dust generated during the movement of supports. Table 2.4 and Figure 2.5 show the percentage contribution of each source to the total respirable dust exposure of the shearer operators.

Table 2.4 Dust sources analysis (after Jankowski and Organiscak, 1983a)

<table>
<thead>
<tr>
<th>s.n.</th>
<th>Source</th>
<th>Mine A</th>
<th>Mine B</th>
<th>Mine C</th>
<th>Mine D</th>
<th>Mine E</th>
<th>Mine F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Intake</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>stage loader</td>
<td>25</td>
<td>57</td>
<td>19</td>
<td>20.5</td>
<td>64</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>supports</td>
<td>10</td>
<td>31</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>shearer - cutting</td>
<td>60</td>
<td>10</td>
<td>28</td>
<td>53</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>shearer - cleaning</td>
<td>4</td>
<td>7</td>
<td>47</td>
<td>20.5</td>
<td>12</td>
<td>0</td>
</tr>
</tbody>
</table>
Dust sources:
1. shearer, cutting & cleaning
2. support movement
3. stage loader/crusher
4. intake dust contamination
5. coal falling onto AFC
6. goaf falls

Figure 2.4 Dust sources on a typical longwall face

Figure 2.5 Average percentage contribution of the three major sources of dust in a longwall face (after Foster Miller Associates Inc., 1982).
Although, in most instances, the shearer is the major primary dust source, secondary sources in particular the stage loader and support movement also contribute a significant proportion of the total respirable dust. Additional dust sources in some longwall faces include face spalling and caving material falling behind the chock shields. In estimating the effectiveness of machine mounted dust control devices, such as water sprays or scrubbers, it is useful to have an estimate of the total quantity of respirable dust produced during the face operations. Studies by Mundell and Taylor (1977) showed that the respirable dust make from a longwall face varied from 1000 mg to 5000 mg per tonne of coal production. Therefore, in a longwall face producing 10,000 t/day, the total quantity of respirable dust produced amounts to between 10 and 50 kg/day.

2.4.2 Coal characteristics and dust generation

It has been determined that inherent rock properties do influence dust formation (Das, 1973). Panov (1967) similarly concluded dust formation to be a function of the composition, hardness and moisture content of the rock. Another study by Baafi and Ramani (1979) investigated the effect of rank of coal on the generation of dust and concluded that the respirable dust content of coal samples increases as the rank of coal decreases. According to Skochinsky and Kamarov (1969), drilling in hard rock results in the production of large quantities of fine dust.

Moore and Bise (1984) concluded that the Hardgrove Grindability Index of a rock affects dust formation and more recently, Guyaguler (1991; 1993) concluded that the hardness and the brittleness:toughness ratio of a rock are the properties that most significantly influence dust generation (Figure 2.6). Khair and Xu (1991) also concluded that coal with a higher grindability index has high dust concentration coefficients. Evaluation of Pennsylvania and West Virginia data confirmed that there is a very good correlation between the Hardgrove Grindability Indices of coals and the
prevalence of coal workers pneumoconiosis (Mutmansky and Lee, 1984; Ting, 1988). These studies showed that the Hardgrove Grindability Index is a good indicator of the prevalence of CWP because it encompasses many dust generating factors such as rank, ash content, petrographic composition and other factors yet to be isolated.

Large quantities of respirable size dust particles are formed and liberated by the fracture process. A study by Cheng and Zukovich (1973) found that a surprisingly large amount of respirable particles adhere to the broken coal. Their studies revealed that between $10^{11}$ and $10^{12}$ respirable dust particles cling to the surface of each pound (0.45 kg) of coal; approximately $3.6 \times 10^7$ respirable dust particles adhere to each square centimetre of the surface of broken coal. At this rate, 0.45 kg of broken coal would be sufficient to contaminate 30 m³/s of air at a level of 3 mg/m³. Fortunately much less than 1% of these respirable size particles ever become airborne.
Most of the earlier research on dust generation focused on developing empirical correlations between machine operating parameters such as depth of cut, rotational speed, tool geometry and airborne respirable dust concentrations near a cutting tool. Evans and Pomeroy (1966) and Pomeroy (1968) presented their extensive work on the mechanical properties of coal and on the analysis of the design of coal mining machines. The empirical relationship established led to design recommendations for cutting machines and wedge type bits.

The effect of different types of shearer bits on coal cutting forces and dust generation has been well researched (Roepke and Voltz, 1983; Bartholomae and Becker 1983). Strebig and Zeller (1975) found that bit type did not significantly effect dust production, whereas cutting depth was very significant. Zipf and Bieniawski (1989) have applied fracture mechanics principles in their study and proposed that a mechanism for fine fragment formation involves four steps: (i) development of a crushed zone under the tool tip, (ii) macrocrack propagation, (iii) shear movement along macrocracks, and (iv) additional fragmentation from shearing. The dust generation mechanism involves two sources of fine fragments, namely crushing under the tool tip and shearing along the macrocrack surfaces. A review by the U.S. National Academy of Sciences (Cook, et al, 1980) concluded that our present knowledge of the fundamental mechanisms of coal dust generation and entrainment is very meagre and not sufficient to clarify, let alone control, the processes involved.

2.4.3 Air velocity and dust distribution profiles

Studies conducted in four U.S. longwall faces indicated that a significant amount of air leaks into the goaf (Figure 2.7), and that air velocity distribution at the face varies from mine to mine (Peng and Chiang, 1984a; 1986; Ramani, Qin and Jankowski, 1991).
Air velocity distribution along and across the longwall face were presented and visual observations were made on the influence of shearer movement on air velocity distribution. The study found that leakage into the goaf resulted in less dilution of airborne dust and affected the spatial distribution of dust. Air measurements made in Australia by Liu (1991) showed that in some cases, air leakage into the goaf was insignificant, particularly when a 'U' type ventilation system was used.

In addition to understanding air velocities, it is necessary to know airborne dust concentration distribution at the longwall face in order to effectively prevent or reduce the miners' respirable dust exposure. Many gravimetric and instantaneous sampling surveys have been conducted to pin-point dust sources and to evaluate the effectiveness of various dust control measures (USBM, 1982a; 1982b; Organiscak, Listak and Jankowski, 1985; Scott, 1984). These studies showed dust concentration profiles
along the face and around the shearer with, and without, the dust control measures. However, all these studies only presented dust concentration profiles along the face. They were constructed from dust data measured either over the AFC or over the Bretby cable handler along the face. Dust concentration distribution across the face, i.e. at right angles to the face line, an important factor in the development of dust control techniques, was not presented.

The dispersion, transportation of the entrained dust and the variation of respirable dust concentration along and across a longwall face has also been studied by Chiang et al (1984; Chiang, Luo and Peng, 1987), using instantaneous sampling instruments. The dust distribution profiles were found to be somewhat similar to those of the air velocity distribution profiles along the longwall face. The high dust concentration zone was located above the armoured face conveyor, and the dust concentration in the walkway area was usually lower except during support advance. An example of respirable dust concentration distribution around the shearer is shown in Figures 2.8 and 2.9.

Figure 2.8  Dust distribution map in a longwall face on horizontal plan at 0.9 m above the floor (after Chiang, Luo and Peng, 1987).
2.4.4 Size distribution and dust deposition

Studies on size distribution of respirable dust in coal mines (Dumm and Hogg, 1987; Bhaskar, Ramani and Jankowski, 1988; Mutmansky and Xu, 1989; Rubow, Cantrell and Marple, 1988) suggest that airborne respirable dust does follow some size distribution relationship. When the log of the fraction smaller than a certain size is plotted against the log of that size, the result is a straight line. These studies also indicate that size distributions vary considerably from one source of dust to another.

Laboratory and field investigations showed that the dust deposition rate decreases exponentially with distance from the source (Bradshaw, Godbert and Leach, 1954; Ontin, 1965). Courtney, Kost and Colinet (1982) conducted extensive studies in eight...
U.S. mines and found that the rate of dust deposition in the roadways depends upon the concentration of airborne dust and decreases exponentially with distance from the dust source. The study also found that the rate was seemingly independent of the size of the airborne dust particles. Dust deposition studies in mine airways have also been performed by Bhaskar (1987), with the results showing that dust concentration declines sharply within the first 100 m of the source and the deposition rate depends on dust particle size, concentration and air velocity.

2.5 DUST CONTROL METHODS

Many types of dust control measures have been developed to reduce dust generation during cutting, minimise its entrainment, extract and collect airborne dust, and prevent its dispersion to work locations. Different methods of operation to keep workers away from dust have also been adopted. Some methods are more effective than others, but there is no single control technique that can adequately control the dust at all times in all mining operations. The industry must therefore continue to use several controls simultaneously and to continuously refine and advance them to lower dust levels, so as to comply with regulation standards.

2.5.1 Ventilation

Ventilation is one of the principal methods used to control dust on longwall faces. Increasing the air quantity through the face reduces the respirable dust concentration at a longwall face by diluting it. Extensive research has been done over the years to determine the relation between air velocity and dust concentration in coal mines (Hall, 1960; Hodkinson, 1960). Their experiments found that 300 fpm (1.5 m/s) was the optimum air velocity in coal mine roadways.
Studies in the U.S. show that face air velocities of 350 to 450 fpm (1.8 to 2.5 m/s) appear to be the most appropriate for longwall dust control (Mundell et al, 1980; Jankowski and Kissell, 1983; Kelly et al, 1990). The effect of air velocity on the shearer operator respirable dust exposure is shown in Figure 2.10. This figure shows that an increase in the face velocity up to 450 fpm (2.5 m/s) decreases the shearer operators' dust exposure, but beyond that the dust concentration increases due to higher entrainment of dust on the face. Above 4 m/s the problem is not so much a health hazard as it is the physical discomfort of large particles striking the skin. According to German studies (Breuer, 1972; 1983) the optimum velocity may be increased to 700 to 900 fpm (3.5 to 4.5 m/s) when the moisture content of the dust particles is more than 6% (Figure 2.11).

However, an analysis of a large amount of respirable data from U.S. longwall faces does not confirm this conclusion, and does not show any correlation between operators' dust exposures and face air velocity (Foster-Miller Associates, Inc., 1982). Underground observations by the present author in two faces, working the same coal seam under similar conditions, with different velocities (1.9 m/s and 4 m/s), showed that the dust concentration in the face with the high face air velocity was less than that at other face. Recent studies (Tomb, 1992) have also confirmed that as face air velocity increases beyond 5.1 m/s, dust levels along the face decrease.

It should be noted that all of these air velocity vs dust concentration studies were carried out without a shearer clearer. These results show an increase in dust concentration at the shearer operators' position with an increase in air velocity. However, with the shearer clearer, the optimum face velocity may be increased beyond 2.5 m/s, and with modern slow speed drums which allow high water flows through them, air velocity may be increased up to 5 m/s.
Figure 2.10  Relationship between face air velocity and dust levels at the face (after Mundell et al. 1980).

Figure 2.11  Effect of moisture content on optimum air velocity for minimal dust levels (after Breuer, 1972).
Goaf curtain

Studies have shown that a significant amount of air leaks into the goaf near the main entry (Shirey, Colinet and Kost, 1985; Peng and Chiang, 1986) and this results in less dilution of dust at the face. A 'goaf curtain' (Figure 2.12), installed from roof to floor between the first support and the adjacent rib on the gallery, forces the airflow to stay on the face side, rather than leaking into the goaf. During underground trials, the average face air velocity was 35% greater with the curtain than without it (Jayaraman, 1981b; Niewiadomski, Jankowski and Kissell, 1982; Jankowski, Kissell and Daniel, 1986).

Wing curtain

An effective way to minimise the shearer operators' dust exposure during maingate sumping/ cut-out is to install a 'wing curtain' (Figure 2.13) between the rib and the stage loader. This shields the maingate drum from the air stream as it cuts into the maingate entry, and can reduce shearer operators' dust exposure by 50 to 60% during maingate cut-out (USBM, 1982c; Babbitt et al, 1984).

Homotropal ventilation

The simplicity and reproducibility of the longwall face ventilation system makes antitropal ventilation the preferred system (Stevenson, 1985). In this system coal is transported against the airflow, and intake dust from the maingate stage loader and crusher creates a significant proportion of total dust which is often overlooked on many longwall faces (Organiscak, Jankowski and Kelly, 1986). Homotropal ventilation, in which air travels in the direction of the coal transport, places the out-by dust sources downstream of the face workers, eliminating dust exposure from these sources. Tests have shown that homotropal ventilation can lower instantaneous intake dust concentrations along the face by about 90% (Jayaraman, 1982; Kelly and Jankowski, 1984).
A portion of the ventilation air from the headgate entry will leak into the gob, lowering the airflow along the longwall face.

Gob curtain closes gap between shield #1 and the adjacent rib, forcing more air along the longwall face.

Figure 2.12  Goaf curtain to lower air leakage into the gob and raise the airflow along the face (after Jayaraman, 1981b).

Figure 2.13  Wing curtain to reduce dust exposure of shearer operator's when cutting out at the main gate (after USBM, 1982c).
2.5.2 Drum water sprays

Water sprays on the shearer cutting picks on the drum is the second most important airborne dust control method. Studies in the U.S. (Taylor and Jankowski, 1982; Scott, 1982; Jankowski, 1982) have found that the longwalls which were consistently maintaining compliance with dust standards were using large volumes of water, more than 65 gpm. Figure 2.14 shows the effects of high water flow to the cutting drums. Many investigations were conducted to determine the optimum water quantity to the shearer drums, and they showed that increasing water flow from 45 gpm to 65 gpm (245 l/min) reduces shearer operators dust exposure by 40% (Shirey, Colinet and Kost, 1985; Ruggieri and Babbitt, 1983; Chiang et al, 1984). Where this is not possible, directing a large proportion of the water to the upwind drum results in lower respirable dust exposure for the shearer operators (Jankowski, 1982; Pimental, Adam and Jankowski, 1984). Recent studies have found that increasing the water flow beyond 70 gpm no longer proportionally decreases dust levels, and should be maintained around 65-70 gpm for optimum results (McClelland, Babbitt and Jankowski, 1987).

U.S. Bureau of Mines studies have shown that poorly designed water sprays, especially high water pressure, however, can increase shearer operators' dust exposure (Jankowski, Kissell and Daniel, 1986). Many studies have been conducted on the optimal flowrate and pressure, size and velocity of droplets in the spray, nozzle type and the arrangement of spray nozzles (Courtney and Chang, 1977; Mundell et al, 1980; Jayaraman et al 1981; Mukherjee and Singh, 1984; Whitehead, Erchard and saltsman, 1976). Their studies indicate that the maximum drum spray pressure should be between 480 and 700 kPa (70 and 100 psi), and that the water flow rates should be increased by increasing the orifice size, rather than by increasing the spray pressure.
The three commonly used drum water spray systems, namely pick point flushing (Jankowski and Hetrick, 1982), cavity filling system and water through bit system, were compared in two longwall mining conditions (Jankowski, 1986; Shirey, Colinet and Kost, 1985). The studies indicated that the pick point flushing with jet nozzles was the most effective in reducing dust exposure of the shearer operators. The pick point system with cone type sprays was only 70% as effective as the pick point jet spray system, the water through the bit system was 60% as effective and the cavity filling system was 47% as effective.
2.5.3 Deep cutting with reduced drum speed

Deep cutting with reduced drum speed is another important dust control technique to reduce respirable dust levels in a longwall face. Many studies have endeavoured to determine the relationship between coal cutting and the generation of respirable dust (Hamilton, 1972; Roepke, Lindroth and Myren, 1976; Hanson and Roepke, 1979; Niewiadomski, Jankowski and Kissell, 1982). Deep cutting, in the sense of increased bit penetration rather than a wider web, is a function of drum speed, pick spacing and gauge length and machine advance rate. Several field tests (Ludlow, 1981; Wilson, 1981; Ludlow and Wilson, 1982; Ludlow and Jankowski, 1984) established that deep cutting with reduced drum speed achieved a 60% reduction in dust generation when drum speed reduced from 70 to 35 rpm (Figure 2.15), with bit penetration increased from 43 to 86 mm.

Studies with a single pick show that under constant drum speed, the average dust generation decreases as the cutting depth increases (Figure 2.16). Studies to determine the effect of deep cutting with fewer bits per line show that dust levels were reduced by 20% when the bit penetration was doubled by removing alternate vane bits (Brooker, 1979a; 1979b; Babbitt et al, 1984; Peng and Chiang, 1984b; Ludlow and Wilson, 1982). These studies show however, that increased bit penetration by reducing the number of bits is not as effective as lower drum speeds.

Several other studies confirm that different bit geometries do not influence airborne respirable dust generation as much as cutting depth (Roepke and Hanson, 1983a; 1983b; Roepke and Voltz, 1983; Strebig and Zeller, 1975; Black and Schmidt, 1977). Recent field trials (Olson and Roepke, 1984) have shown that the clearance, or backface bits, are the single greatest dust source on the longwall face and should therefore be minimised wherever possible. Roepke (1984) has recommended that in
order to minimise airborne respirable dust operators should "cut at maximum depth at all times, at minimum RPM with the lowest possible bits, that have the lowest possible included tip angle".

However, deep cutting at slower drum speeds does present some potential pitfalls that the operator must be aware of. Increasing the vane angle is a viable means of counteracting the effect of reduced drum speed on loading efficiency. Increased loads on the bits, bit blocks, gear boxes and ranging arms must also be taken into account. Finally, when fewer bits are used, the drive train components will experience greater torque variation and require equipment that will withstand the increased vibration.

Figure 2.15 Effect of drum speed on dust production (after Niewiadomski, Jankowski, and Kissell, 1982).

Figure 2.16 Effect of depth of cut on dust level (after Hamilton, 1972).
2.5.4 Modified cutting sequences

A bi-directional cutting sequence, cutting full face height in both directions, results in the support setters being exposed to shearer dust for one pass of the mining cycle, and the shearer operators being exposed to the dust from the support for the other pass. For this reason, longwall faces operators are employing uni-directional cutting sequences, cutting coal only in one direction, to reduce the operator's exposure to dust (USBM, 1981b; Peng and Chiang, 1984b).

In a conventional uni-directional cutting sequence, during a typical maingate-to-tailgate cut, the lead drum takes a full cut while the trailing drum cuts the remaining bottom coal. The shearer only cleans up the coal on the return phase. This cutting sequence reduces dust exposure of support personnel by locating the majority of the support and conveyor movement upwind of the shearer. However, the shearer operator's dust exposure still exceeds statutory levels due to the dust generated by the cutting drum upwind of the operator position, and this problem is the impetus for much research.

To this end, a modified uni-directional cutting sequence has been developed (Niewiadomski, Jankowski and Kissell, 1982; Ruggieri and Jankowski, 1983; Scott, 1982), whereby the lead drum continues to take a full cut during the maingate-to-tailgate pass while the trailing drum is free wheeling or cutting a minimal amount of coal, and during the return clean up pass the trailing drum cuts the remaining coal (Figure 2.17). This enables both operators to remain on the intake side of the primary dust generating source thereby significantly reducing their exposure to dust. This modified cutting sequence has been acclaimed by the USBM (1981b) as an effective and simple method of reducing the shearer operators' respirable dust exposure, especially when cutting rock in the bottom.
Figure 2.17  Modified uni-directional cutting sequence to reduce longwall shearer operator's dust exposure (after USBM, 1981b).

Field studies show that the operators' dust exposure was 40-50% higher when cutting against ventilation as opposed to cutting with ventilation (Jankowski, 1984a; Aziz et al, 1993a; Jankowski and Hetrick, 1982). Therefore, cutting in the direction of ventilation is another way of reducing operators' exposure to dust. In addition, when cutting with ventilation, any dust generation caused by spalling of coal ahead of the lead cutting drum occurs downwind of the shearer operators.
2.5.5 Shearer clearer

A major advancement in the prevention of shearer generated dust into the operator's position is the development of a novel shearer spray system, called the 'shearer clearer' by the U.S. Bureau of Mines and Foster-Miller Assoc., Inc., (USBM, 1981a; Kissell et al, 1981; Jayaraman and Kissell, 1981; Taylor and Jankowski, 1982; Ruggieri and Babbitt, 1983; Ruggieri et al, 1983). This system takes advantage of the air moving capabilities of water sprays, and consists of several shearer mounted water sprays oriented downwards, that split the air flow around the shearer into clean and contaminated air (Figure 2.18(a)). The dust generated by the cutting drum is confined to the coal face, while the clean air passes over the shearer operator. Underground evaluation showed that the shearer operator's exposure to dust was reduced by 30 to 50% (Figure 2.18(b)).

In the original shearer clearer system, some water sprays were mounted on top of the shearer, which caused some practical difficulties. Thus an 'improved shearer clearer system' was developed, which eliminates all sprays mounted on the top of the shearer body and uses fewer sprays than the original system (Jayaraman, Jankowski and Kissell, 1985; Jayaraman, 1986; Jankowski, Kissell and Daniel, 1986). Field tests showed that this reduced the dust exposure of both the operators significantly.

However, this shearer clearer technique does not reduce the overall dust concentration in the face nor does it affect the tailgate workers' exposure to dust. It also needs about 90 l/min (20 gpm) of water at 1000 kPa (150 psi) to be effective. Improper design of the system, such as using more than 1000 kPa water pressure will, in fact, increase the shearer operator's dust exposure. In general, shearer clearer type water sprays are not compatible with extraction drums that rely on capture of dust from a highly concentrated, relatively undisturbed region.
Figure 2.18(a) Characteristic dust transport profile with conventional and shearer clearer external water spray systems (after Jankowski, Kissell and Daniel, 1986).

Figure 2.18(b) Effectiveness of shearer clearer system on reducing dust levels in a longwall face (after Organiscak, Listak and Jankowski, 1985).
2.5.6 Extraction drum

Research work on small, water powered dust capture tubes in the 1970's (McQuaid, 1975; Jones, 1978; Jones and James, 1987; Clarke and Wilkes, 1989) led to the development, in the UK, of effective dust extraction systems for use on longwall shearers (Hamilton, French and James, 1980). In these systems, open ended tubes were integrated with coal loading doors or cowls around the cutting zone. But these resulted in low capturing efficiency (French, 1983; Ford, Brierley and Brooks, 1987; Divers, Jankowski and Kelly, 1987). Later, the extraction drum was devised in 1981 for use with shearer cutting drums (James, 1983; Ford et al 1986; James and Browning, 1988).

This extraction drum utilises water sprays, in tubes mounted through the drum, to collect dust laden air, to scrub the dust and discharge the clean air and dirty water on the goaf side of the drum (Figure 2.19). Each tube houses one water spray which

![Figure 2.19](image-url) Cut-away view components and airflow paths of the extraction drum (after Divers, 1987).
operates at very high pressure to induce air through them. A water pressure of 11 MPa (1600 psi) is required to produce an air flow of approximately 1.9 m$^3$/s for each drum, and a booster pump mounted on the shearer is necessary to generate such pressure. The spray tubes acts as scrubbers removing 90% to 95% of respirable dust from the air drawn through them.

Tests carried out on single-ended ranging drum shearers in U.K. showed reductions in respirable dust of 60% to 80% compared with conventional wet cutting (Hamilton and French, 1984; Ford and Hole, 1988; Ford, Brierley and Brooks, 1987; Ford et al, 1987). However, tests carried out in U.S.A. on double-ended ranging drum shearers were not so promising; the 40% to 50% reduction in respirable dust concentration in some faces was marred by frequent blockage of tubes (Divers, 1987; Kelly and Muldoon, 1987). During trials with extraction drums in Australia, mines have experienced difficulties with blocked sprays (Hewitt, 1989). In summary, this method is not being used on many faces due to drum diameter restrictions, high cost, and limited hub space available on some shearers.

2.5.7 Water infusion

Longwall water infusion techniques have been recognised and widely practised for many years in European mines as an effective means of dust control. Belgium has used this technique for over 20 years, and in the northern coalfields of France it is the main dust control technique for 89% of the coal produced (Neels and Dequildre, 1973; Ducrocq, 1973). Field tests in Belgium show that water infusion at the rate of 10 litres/tonne of coal suppressed 95% of the respirable dust produced at the face. Mining regulations in Germany require water infusion where possible and over 50% of their
longwalls are infused (Schlick, 1970). There, experience has shown that a minimum of 1.9 gal of water per ton of coal is necessary to suppress dust (Becker, 1973; Heising and Becker, 1980).

The water infusion technique involves drilling holes and injecting water into the coal seam at low flow rates and at low pressure prior to coal extraction. This increases both the moisture content of the coal seam and the wettability of the coal, and therefore reduces the dust generated during mining. The success of water infusion depends on the natural or induced permeability of the coal seam. Figure 2.20 shows the relationship between cleat systems and infusion zones. In Europe, the coal seams tend to increase in permeability towards the east which explains why the technique is successful in Germany and other Eastern European countries, but has limited success in the UK.

Water infusion investigations conducted in the U.S.A. showed a 38% to 50% reduction in dust concentration levels in the infused zones (Cervick, 1977; Occidental Research Corp, 1983; Cervick, Sainato and Baker, 1983; Shirey, Colinet and Kost, 1985; McClelland et al, 1987). Trials in the Bulli coal seam of Australia indicated that infusion did not significantly reduce dust levels and the researchers attributed this to the heavy fractures and to the seams' high permeability (Hewitt and Lama, 1988).

In summary, water infusion is a viable longwall dust control technique, but its success and cost effectiveness depends primarily on coal seam conditions. Relevant characteristics are fracture porosity, moisture content in fracture pores prior to infusion, the cleat system and its orientation relative to the axis of the longwall panels.
and depth of cover. Infusion has the disadvantage of being a slow process if it is to be effective, and it should not be used in weak roof or floor strata areas or close to faults. It is important to investigate the in situ permeability of the coal before using water infusion.

Figure 2.20  Relationship between cleat systems and water infusion zones (after McClelland, et al, 1987).
2.5.8 Support generated dust control

According to Australian and U.S. Bureau of Mines studies significant amount of respirable dust is produced during support movement and goaf fall (Hewitt, 1990b; Jankowski and Organiscak, 1983a) (Figure 2.21). The severity of this problem will depend on the amount of fallen debris that has accumulated on the canopy and can range from negligible to very severe. U.S. Bureau of Mines investigations found that as much as 30 - 40% of the respirable dust that shearer operators are exposed to is generated by the movement of longwall roof supports.

Figure 2.21 Dust level profile around shearer showing intake contamination due to dust generated by support movement (after Jankowski and Organiscak, 1983a).
So far most research effort has been directed towards controlling dust from the shearer and very little research has been carried out on the control of support generated dust (Hewitt, 1990a; Jankowski and Organiscak, 1983b; Organiscak, Listak and Jankowski, 1985). Some of the methods suggested for controlling dust from support movement are minimising debris on top of canopies, advancing supports during the clean-up pass cycle against the airflow, maintaining a distance of at least 15 m between support movement and shearer, washing down supports, wetting the immediate roof with shearer water, mounting water sprays on supports and increasing the airflow to promote dilution and diffusion (Organiscak, 1984). However, most of the above methods have some limitations and are not practicable in many cases. For example, water application in some seams can cause deterioration and ground control problems, and delaying the advance of supports can cause roof control problems.

Work by European researchers has resulted in limited practicable dust control technology for support generated dust (Becker, Goretz and Kemper, 1981). The research concentrated on redesigning the shields to minimize gaps on the goaf side, and included water sprays on shields, contact advance of supports, plastic mesh to bridge the gap between the canopies and the use of dust collecting troughs. Dust measurements in longwall faces equipped with water sprays on shields showed dust suppression efficiencies of between 42% and 68%. However, it was reported by Goretz (NCB, 1982) that the water sprays proved unsuitable in practice, as it resulted in roof deterioration and the face crew were wetted by the sprays. Becker et al (1988) found that dust collecting troughs and plastic mesh are not practicable either.
2.5.9 Scrubbers, Air curtains and Air sprays

A mechanical dust collector or scrubber typically consists of an air mover to direct the dust laden air into the scrubber, a dust removal system to separate the dust particles from the air stream and a demister to remove the water from the air stream. Scrubbers are being used successfully in continuous miner development sections to control the dust levels at the face (Hill, 1974; Divers, 1976; 1977; Divers, Lascola and Hundman, 1981; Niewiadomski, 1983; Sartaine, 1985; Rawicki, 1983; Gillies, 1983; James, 1983; Jayaraman, Volkwein and Kissell, 1990; O'Green, 1983; 1990). The USBM has tested and reported the results of evaluation of many scrubbers in an attempt to increase the use of scrubbers in the coal mines (Divers and Janosik, 1978; 1980). However, to date, dust collectors have only been installed on longwall shearers (Figure 2.22) for research purposes. Several USBM attempts to retrofit existing shearers with scrubber systems have ended in failure (Grigal, 1980).

Fan-powered Scrubbers

Many of these scrubbers have been tested on longwall shearers with little success (Jayaraman and Grigal, 1977; Kelly, Muldoon and Schroeder, 1982; Kelly and Muldoon, 1987). Various problems encountered include: inadequate vertical clearance, a tendency for the intake and discharge ducts to clog and a low collection efficiency caused by inadequate fan capacity which is a result of space limitations and therefore undersized fans. Other problems included maintenance, replacement of filter panel in a flooded bed scrubber etc. These problems led to rejection of the high capacity machine mounted scrubber as a viable dust control technique for U.S. longwall faces.

Water-powered Scrubbers

These scrubbers are simply water powered dust capture tubes mounted on the shearer body. Studies conducted in the U.K. and U.S.A. have shown that these devices can
achieve high dust capture efficiencies and result in dust reductions of over 50% (Ford, Brierley and Brooks, 1987; French, 1983; USBM, 1981c; Organiscak, Volkwein and Jankowski, 1983; O'Green, 1983). However, the requirement of high pressure water (more than 10,000 kPa) has restricted their use in the longwall faces. Therefore, there is a need for the development of a reliable scrubber with low water usage, high capture efficiency and effective mist elimination, which also must be very compact to fit into the limited space available in the face.

Figure 2.22 A double-ended ranging drum shearer equipped with a set of dust collectors (after Jayaraman, 1977).
Air curtains

Air curtains are being used in development headings successfully over the years. Two types of curtains are in use; 'canopy air curtains' to provide a zone of clean air around the operator and 'air curtain tubes' to confine the dust cloud in front of the operator (Krisko, 1975; Ford and Hole, 1984; Volkwein, Page and Thimons, 1981). Studies have been conducted in Australia to evaluate the effectiveness of compressed air curtains in a longwall face (Hewitt, 1986a; Lama et al, 1990; Liu, 1991). Twenty seven air curtains were used in every second chock from the 5th chock to the 51st chock. This method has reduced dust levels near the curtains, but it did not effectively provide a curtain between the high dust concentration zone and the walkway. It was concluded that, to be effective, air curtains have to be installed along the full face in every second chock.

Air sprays

The effectiveness of air sprays mounted on roof supports for dust control was simulated using a physical longwall face model by Engineers International, Inc., (1983; Mukherjee et al, 1985; Laurito and Singh, 1987). A total of 2,100 cfm (1.0 m³/s) of compressed air was used for 33 m length of face, and the air spray system reduced dust by between 30% and 75%. In another document (Shirey, Colinet and Kost, 1985) the improvement in dust levels was attributed to the increased total amount of air present in the face. It was not clearly explained in their analysis how 2100 cfm (1.0 m³/s) added to the intake flow of 40,000 cfm (20.0 m³/s) effected reductions of between 30-75%. However, as both air curtain and air spray techniques use only large amounts of compressed air, the systems are not economical.
2.5.10 Other Methods:

Water jet assisted cutting

The use of a high-pressure water jet to assist a mechanical drag bit is known as water-jet assisted cutting. It evolved from a need to overcome the thermal deterioration of the tool, which occurred when cutting strong abrasive rocks (Hood, 1976). It was discovered that suitably directed jets, at pressures of around 70 MPa, would substantially reduce both the forces acting on the bits and the generation of respirable dust (Hood, 1985a; 1985b; Tomlin, 1982; Taylor and Evans, 1985). Other studies (Thimons, 1987; 1988; Taylor, Kovscak and Thimons, 1986; Kovscak et al, 1986) have shown that an increase in the water pressure from 1 to 7 MPa did not significantly change dust levels, but that an increase from 7 to 20 MPa reduced dust levels by 78%. Further increasing the water pressure from 20 to 40 MPa resulted in only a very small additional reduction in dust levels (Figure 2.23).

![Figure 2.23 Effect of water jet pressure and fluid horsepower on dust levels (after Taylor, Kovscak and Thimons, 1986).]
Intake/ stage loader dust control

Dust sources at the intake of a longwall face can contribute significantly to face workers' dust exposure. Field surveys have shown that in many longwall faces, 20-40% of face workers dust exposure was generated at the in-bye side of the face or at the crusher (Jankowski and Organiscak, 1983b; Aziz et al, 1993b). The most effective method of controlling intake dust is homotropal ventilation, in which the stage loader/crusher is placed on the downstream side of the face, thereby reducing intake dust levels by as much as 50 - 90% (USBM, 1982d; Scott, 1984). Other control techniques, such as the water powered scrubber and water sprays located strategically on the stage loader, were developed for use in faces where the homotropal ventilation was too difficult or expensive to implement. These techniques can reduce intake dust levels at support 10 by 45 - 80% (USBM, 1981c; 1982d; 1985; Grigal et al, 1982; Jayaraman, Jankowski and Organiscak, 1992).

Reversed drum rotation

Recent studies have shown that the shearer operators' dust exposure is reduced by 40 to 85% when the direction of the drum rotation is reversed, i.e. the leading drum cutting from the floor to roof rather than from roof to floor (Jankowski and Kelly, 1988; Niewiadomski and Jankowski, 1993). However, there was no evidence that dust levels downwind of the shearer were different in either mode, nor did it significantly affect dust levels during tramming from main to tail gate.

Wetting agent

Although the use of wetting agents has been effective in reducing dust levels in some mining operations, their application in longwall faces has not resulted in significant dust reductions. Tests conducted in U.K. show that wetting agents can be beneficial with coals containing 20 to 30% volatiles (NCB, 1981), but there is no advantage with high volatile low rank coals or anthracite coals. Studies by USBM (Kost, Shirey and
Ford, 1980; Scott, 1983; Wang et al, 1991) have also shown that the addition of a wetting agent to the sprays had no apparent effect on the dust concentration. In Australia, recent studies (Bell, et al 1993b; Hewitt, 1990b) show that the suppressant has a minimal impact on shift average dust levels, but is useful near the stage loader.

External foam application

A number of studies have been conducted to assess the usefulness of foam in suppressing dust (Hiltz and Friel, 1973; Hiltz, 1975; Mukherjee and Singh, 1984; Singh and Laurito, 1984; Laurito and Singh 1987; McClelland, 1989). In most cases the dust reductions were about 20% with some cases showing a 50-70% reduction. Numerous operational difficulties such as special equipment requirements, high cost, possibility of refoaming in the washing plant etc. for a modest dust reduction precludes this method as a practical longwall dust control technique.

Face /walkway curtains and curtains over shearer

Face curtains are intermittently spaced along the face and over the shearer in an attempt to keep the shearer generated dust near the face. Experiments have been conducted with varied curtain lengths, orientation and spacing (USBM, 1981d; Shirey, Colinet and Kost, 1985; Jankowski and Babbitt, 1986), and all curtain configurations caused eddying of the airflow into the walkway, and consequent increases in walkway dust levels.

Remote control

Remote control of shearer reduces the shearer operators' exposure to dust by enabling them to be upwind of the cutting drum most of the time. Two types of remote controls, umbilical and radio controls, are generally used (Jankowski, 1984b). The problem of dust exposure of support personnel has resulted in the introduction of electro-hydraulic shields, a set of which can be electronically controlled by computer.
This allowed shield setters to achieve the upwind position from this dust source (Haney et al, 1988). Where dust exposure cannot be controlled, personal protection equipment such as face mask respirators, and air helmets are used on longwall faces to reduce the respirable dust exposure. However, personnel protection should only be used as a last resort and should not take the place of dust prevention or dust control techniques.

2.6 MODELLING STUDIES

2.6.1 Expert systems

Expert systems on longwall dust control have been developed by the U.S. Bureau of Mines to provide information and advice on primary dust control techniques (Roepke, Hanson and Schmidt, 1985; Hanson and Roepke, 1988; Wirch, Kelly and Jankowski, 1988; Kissell and King, 1988). These programs have been developed from data obtained from the Bureau's past research on reduction of primary dust generation. The programs use both stored and interactively entered data to evaluate the dust reduction potential of various mining practices. However, the expert systems are not useful in the development of a mathematical model of the dust distribution at a longwall face.

2.6.1 Dust generation, transport and deposition

Fine dust generation depends on the interaction between the cutting tool and the coal. Many mathematical models have been developed to simulate the action of cutting bits and crack growths (Pariseau and Fairhurst, 1967; Nishimatsu, 1972; Zipf and Bieniawski, 1989), but there are very few published mathematical modelling studies of dust transport from basic engineering and scientific data. Examination of the current literature on dust transport shows that most of the early models were focussed on deriving empirical formulae from research in some operating longwall faces.
Courtney, Kost and Colinet (1982) proposed an exponential decay model for calculating dust concentration as a function of time. This represents the results of a physical phenomenon without regard for the mechanisms of deposition. A mathematical model to predict the size distribution and concentration of dust as it travels along the longwall face was proposed by Chiang, Peng and Luo (1986), which assumes an exponential drop in dust concentration with distance. Grayson and Peng (1984) devised a simple model to predict the respirable dust concentration at specific locations along the longwall face. This empirical equation was derived by performing a linear regression analysis on sampling data collected from two mines. A simple algebraic mathematical model has been developed by Liu (1991) to evaluate a multi-scrubber system. The models described are input-data-intensive and ignore the physics of the airflow and respirable dust behaviour in a face. As a result, they are only applicable to those few faces which have similar characteristics.

Partyka (1989; 1990; 1991) developed a dust distribution model for one-dimensional flows which took into account convection-diffusion mechanics. Bhaskar (1984; 1987; Ramani and Bhaskar, 1988) developed a convective-diffusion mathematical model for transport and deposition of dust in mine airways which considered source strength, dust cloud characteristics and basic mechanisms affecting particle behaviour in mines. Results showed that the deposition rate per unit of concentration increases with an increase in airborne concentration (Figure 2.24). A mathematical model for predicting dust concentration along the longwall face (Figure 2.25) has been developed by Qin (1992). However, all the above models are one dimensional and cannot be used either to understand the three dimensional behaviour of airflow fields and dust particles around the shearer or to determine the effectiveness of the dust control techniques.
Figure 2.24  Comparison of model output with mine experimental data of ambient dust concentration in a roadway (after Bhaskar, 1987).

Figure 2.25  Comparison between experimental results and model predictions of respirable dust concentration along longwall face (after Qin, 1992).
2.6.3 Airflow patterns and dust control methods

Understanding of the entrainment of dust particles is fundamental to the development of a dust control technique. Studies showed that respirable dust particles follow the turbulent motion of the ventilating air more closely (Hodkinson, 1960), and therefore the study of airflow patterns in a face, particularly around the shearer, is also very important to advance dust control technology. Skobunov (1973) has carried out extensive field investigations and developed equations to determine the coefficients of transverse and longitudinal turbulent diffusion and the coefficients of heat and mass transfer for mine workings. The resistance of a longwall face significantly affects dust deposition along the face, and a theoretical method for determining such resistance has been suggested by Bruner and McPherson (1987). These studies are helpful in deriving the input parameters for the longwall dust model.

Very little research work has been done in the area of three dimensional modelling of airflow patterns and respirable dust behaviour. Nichols and Gregory (1987) developed a computer program that simulates the airflow and particle transport around sampling devices and predicts the particle sampling rate. Airflow fields and air improvement methods in a developing heading were modelled by Meyer, Grange and Meyer (1991). Therefore, there remains a need for the development of a three dimensional model of dust distribution at a longwall face, and validation of the mathematical model through detailed field investigations in underground coal mines.

2.7 SUMMARY

A critical review of studies on airflow characteristics and dust concentration levels in the longwall face indicates that there are large variations in dust concentration profiles at different longwall faces. Very little information is available on the aerodynamic and
dust concentration gradients around the shearer. The variations in the physical characteristics of the longwall face, ventilation plan and operating procedures make the data inappropriate for Australian longwall faces. The full shift average gravimetric data available in Australia is not sufficient to characterise longwall dust behaviour. There is a need for detailed and extensive dust sampling at longwall faces to understand the transient and ambient dust concentrations, the knowledge of which is essential for the development of new dust control techniques.

Many of the dust control methods developed so far have been aimed at reducing the shearer operators' dust exposure. Dust suppression around powered supports is, in general, not yet satisfactory. As some techniques are not suitable for all longwall faces, local conditions should be considered to determine the appropriate control measures, and several techniques must be used in combination to reduce the dust concentration. In many longwall faces, the control measures described above would not achieve an acceptable degree of dust suppression. In such cases, installing separating elements, such as local airflow systems between the AFC and walkway area, would be useful in reducing the face operators' exposure to dust. Further research and development is needed to overcome the limitations of the existing techniques and to advance dust control technology at longwall face supports.

The flow of air in a longwall face is highly turbulent and very complex in the presence of machinery and various dust control techniques. Mathematical modelling is therefore necessary for a thorough understanding of the behaviour of dust and for the development and evaluation of dust control techniques. So far, only very simple, input-data-rich and some one dimensional mathematical models have been developed. No known published literature exists on three dimensional modelling of airflows, dust
concentration or dust control techniques in a longwall face, and there is a need for the development of such a model. The mathematical model would require validation through detailed field investigations in underground coal mines.

In summary, there is a need for the development of a longwall dust extraction system once the dust sources becomes airborne. There is an additional need for the mathematical modelling of air velocities and dust concentrations in the face for the development of new effective dust control techniques. Detailed and extensive dust sampling at longwall faces, in order to understand the airflow characteristics and behaviour of respirable dust in the longwall face, is described in chapter 3.
Chapter 3
PARAMETRIC STUDIES OF DUST DISTRIBUTION

3.1 INTRODUCTION

In order to develop an effective dust control technique it was necessary to have a thorough understanding of the airflow characteristics and respirable dust behaviour in a longwall face. A review of the literature showed that only very limited data existed on dust cloud characterisation at a longwall face. Furthermore, the large variations in the dust concentration profiles at different longwall faces and the physical differences in the longwall faces, ventilation plan and operating procedures made the data inapplicable at Australian longwall faces. Thus a need existed for detailed and extensive dust sampling at longwall faces in Australia, both to develop a fundamental data set on spatial and temporal variations in dust levels and to understand respirable dust behaviour in order to develop effective dust control techniques. In addition, information on the size distribution of mine respirable dust was required as the effectiveness of many dust control techniques is particle size dependent.

The generation and transportation of airborne dust is governed mainly by the velocity and the movement pattern of the ventilating air in longwall faces. Thus, it is important to know the air velocity distribution in the face to design a dust control technique. The air velocity profiles may vary from mine to mine due to variations in face geometry, dimensions, type of ventilation system used, height of seam and type of supports used. Experimental studies can however, provide a qualitative understanding of the average air flow conditions in a longwall face.
Hence, extensive field investigations were conducted in four operating longwall faces in the Southern district of New South Wales, Australia. The experiments were designed to determine the influence of various parameters on respirable dust concentration levels and behaviour of dust. Average and instantaneous respirable dust concentration profiles along and across the longwall face were determined, as were air velocity profiles. Data on the face layout, time study of the activities at the face, and size distribution of respirable dust were collected for analysis of the relevant dust behaviour with respect to various face conditions.

3.2 OBJECTIVES OF FIELD INVESTIGATIONS

Experiments were designed to obtain basic data on the concentration levels and behaviour of respirable dust in a longwall face. The primary objectives of these preliminary investigations were to:

(i) identify major dust sources along the longwall face;
(ii) identify the major factors affecting dust distribution profiles along the face;
(iii) determine instantaneous dust concentration profiles along and across the longwall face for better understanding of the real-time behaviour of dust;
(iv) determine the air velocity profiles in the longwall face;
(v) determine the size distribution of respirable dust;
(vi) obtain the basic data for mathematical modelling of the dust behaviour in a longwall face and control techniques, and
(vii) plan new approaches for dust control in the longwall face.
3.3 DESIGN OF UNDERGROUND EXPERIMENTS

The determination of the transient dust profiles at a longwall face required comprehensive planning and execution of underground experiments. Specific aspects which were considered included the types of samples to be collected, selection of proper instruments and detailed sampling and time study plans to correlate the dust concentration with the different activities at the face. Interpretation of the respirable dust survey data required face details from all the longwall faces because the parameters and geometry of the longwall faces differed from one mine to another. To achieve the objectives mentioned in previous section, two types of surveys were conducted, namely time averaged gravimetric sampling surveys and instantaneous respirable dust concentration surveys.

Gravimetric samplers are routinely used by mine operators to determine compliance with dust standards. The gravimetric dust samples provide information on the average airborne dust levels along the face over the entire sampling period. They were also necessary for studying the size distribution of airborne dust in the face. The dust samplers are normally worn by mine personnel, but during these surveys discussed here, they were fixed at predetermined locations along the longwall face.

The instantaneous respirable airborne dust concentration profiles on a continuous basis at a predetermined point can be used to determine the relationship between the dust level, the location of the shearer and shearer activities under given airflow conditions. The information is useful in characterising the temporal behaviour of the respirable dust in relation to mining activities at the face.
3.3.1 Field instrumentation

(a) Gravimetric dust survey instrumentation

The 'Du Pont P-2500' sampling instrument, commonly referred to as personal sampler, was used for measuring the average respirable dust concentration along the longwall face (Hewitt, 1986b; Breslin, Page and Jankowski, 1983). The instrument is shown in Figure 3.1. The sampler consists of an air pump, a 25 mm cassella cyclone and a filter cassette. The air flow range of the instrument is from 1 to 2.5 l/min. The pump used to draw the air into the sampling system was battery powered, weighed less than one kilogram, and had overall dimensions of approximately 18cm x 10cm x 5cm. The cyclone and filter assembly, commonly referred to as the 'sampling head' was connected to the sampling pump by a 3 mm diameter tube.

Figure 3.1  Du Pont personal dust sampler, Model P-2500.
The instrument is designed to be capable of sampling the dust environment a miner is exposed to during his working shift by mounting it on the miner, but has the flexibility of being used as a stationary instrument to obtain measurements of the general dust environment where it is located.

The following set of auxiliary instruments were also used during the surveys:

(i) Charging unit;
(ii) Flowmeter to calibrate the instrument;
(iii) Precision weighing balance;
(iv) Dessicator - to remove moisture.

(b) Instantaneous dust survey instrumentation

A 'Hund' (TM-digital μP, 1991; Hewitt and Aziz, 1993) instantaneous sampler was used to monitor the instantaneous respirable dust concentration on a continuous basis in the longwall face. It uses a wide angle light scattering system to measure the respirable dust concentration in the airflow passing through its light beam. It has the capability of measuring respirable dust concentration without the preliminary separation of coarse particles. A light emitting display shows the respirable dust concentration as the current value for the preceding seconds or as the specified time weighted average. The measuring range of the instrument is from 0 to 100 mg/m$^3$. It is portable, battery powered, weighs 980 gm and has overall dimensions of 193mm x 102mm x 46mm (Figure 3.2). The battery of the instrument, if used continuously, lasts for about 5 to 6 hours.

The Hund continuously records fluctuations in dust levels and calculates a running average that is updated every second. It can be used to measure single and average values for random measuring periods. During these field surveys, average concentration measurements were taken every 15 seconds. The instrument was
Figure 3.2(a)  Hund instantaneous dust sampling instrument.

Figure 3.2(b)  A schematic figure showing measuring chamber with infrared beam opening (after TM-digital μP, 1991).
calibrated regularly to ensure the accuracy of the collected data. The performance of the instrument has been evaluated both in the laboratory (Thompson et al, 1981; Williams, 1983) and in the field (Hwang et al, 1988).

(c) Other instrumentation

A vane anemometer was used to measure the air velocity in the longwall face. A Malvern micron size particle analyser (Malvern Instruments, 1990) was also used to determine the dust size distribution. Cascade impactors are commonly used to obtain the in-situ size distribution of airborne dust, but because of their susceptibility to overloading, they are inconvenient for large scale data collection in mines. Instruments commonly used in the laboratory for size distribution measurement of respirable particles are Coulter Counter, Microtrac Small Particle Analyzer and Scanning Electron Microscope. These instruments use electrical sensing, light scattering and microscopic principles respectively for measuring size distribution (Dumm and Hogg, 1987; Grayson and Peng, 1986).

3.3.2 Sampling procedure

(a) Average gravimetric dust survey

Sampling stations were located along the face to obtain data on time-averaged gravimetric dust concentration levels (Figure 3.3). The first sampling station was positioned in the intake roadway at the crib room. This was to obtain information on intake air dust contamination in a longwall section due to dust generated at out-bye transport roadways. Another sampling station was set up in the return airway. The other six sampling stations were placed at an equal distance from each other between the intake and return sampling stations.
Gravimetric and instantaneous sampling station locations

1. station in intake
2. station at 25 m
3. station at 42 m
4. station at 60 m
5. station at 75 m
6. station at return end
7. station on shearer
8. station at crusher

Figure 3.3 Respirable dust sampling locations along the longwall face A.

The sampling instruments at the face were hung from the shield's canopy over the spill plate/walkway in the miners' breathing zone. The cyclone was attached to the sampling pump to eliminate errors associated with high face velocities. The pumps were calibrated every alternate day in the laboratory using a calibration flowmeter to ensure the accuracy of the data. Sampling was performed over a period of 15 continuous working shifts to eliminate the effects of shift practices. As mentioned earlier, the air velocities along the face were also measured using vane anemometers.
In the laboratory, new filters, preweighed to a precision of 0.001 mg, were mounted in the cyclones. The Du Pont pump flow was adjusted to 1.9 l/min before commencing the experiments. On the site, the cyclones were connected to the sampling pumps by 3 mm diameter tubing. After sampling, the filters were precision weighed again on an electronic microbalance to within 0.001 mg in the laboratory. The samples were desiccated before being weighed to remove any moisture that might have been absorbed. An ionising unit, called a static master, was also used to eliminate static charges on all filters before weighing. The samples were reweighed after drying for 24 hours and the net weight of the respirable dust concentration determined.

Although the sampling time required depends strongly on the dust concentration being measured, it should include at least 30 minutes of cutting time to obtain a sufficient sample (Foster-Miller Associates, Inc., 1982). During these investigations, the samplers were operated for a full shift and the weight of dust collected was determined after the shift. The time-averaged gravimetric dust concentrations over the entire sampling period were calculated on the basis of the mass collected on the filters, the sampling time and the pump flow rate.

The concentration of respirable dust was calculated using the following formula:

\[
x = \frac{m_2 - m_1}{r \cdot t} \times 1000
\]

where,

\[
x = \text{concentration of respirable dust (mg/m}^3)\\
m_1 = \text{mass of filter before use (mg)}\\
m_2 = \text{mass of loaded filter after use (mg)}\\
r = \text{air flow rate through sampling pump (l/min)}\\
t = \text{sampling time (min.)}
\]
(b) Instantaneous dust surveys

(i) Dust profiles along the face: In the longwall mining system, the major dust generating source, the shearer, not only moves as it cuts the coal but its movement can be either with, or against, the direction of airflow in the face. The dust concentration at any given point is a function of the shearer activities at that time, the position of the sampling point, the direction of shearer movement, the air velocity and quantity passing through the face, and other face activities. In order to correlate the instantaneous dust concentration along the longwall face with respect to the shearer position and face activities, two types of instantaneous dust survey methods were used, a moving and a stationary instrument method.

In the moving instrument method, the Hund sampler was moved at a fixed distance from the shearer as it travelled along the face. In different experiments, the position of the moving Hund was changed to obtain dust concentration profiles at different positions relative to the shearer. These positions included the rear operator's location, the mid-point of the shearer, and 5 m, 10 m, and 20 m downwind of the shearer. During the surveys, the Hund was kept on the walkway side of the face and readings were taken at a height of 1.3 - 1.7 m, which was considered to be the most likely inhalation position of the face crew. Averaged instantaneous dust concentration values were read approximately every 15 seconds.

In the stationary instrument sampling method, the Hund monitor was positioned at a fixed location at the face. Dust profiles were obtained at several fixed locations along the face while the shearer was operating. Typically, in one experiment, the sampling station was located near the return end of the face to determine the instantaneous dust concentration levels at the tailgate operator's position during a complete cutting, cleaning and sumping cycle.
(ii) Dust profiles around the shearer: To determine the dust concentration profiles around the shearer the following procedure was followed. The Hund instrument was fixed at a location and, as the shearer approached the sampling point, both the dust levels and distances from the shearer were recorded. Recordings were based on the time and the shearer's trammimg speed. The tram rate was calculated from taking the shearer's passage time at 5-shield intervals, i.e. at shields 10, 15, 20, 25, etc. For example, as the shearer approached the sampling station, dust concentration readings were taken every 5 seconds, beginning 10 minutes prior to the shearer's arrival. At an average trammimg speed of 5 m/min, this would put the shearer approximately 50 m upwind or downwind of the sampling station. After the shearer had passed the sampling location, dust levels were recorded for an additional 5 minutes. Respirable dust profiles were thus obtained for about 70 m reflecting concentrations on the intake and return side of the shearer.

In the case of cutting with ventilation, sampling commenced when the shearer was about 50 m upwind of the sampling station and continued until the shearer had passed and was 20 m downwind of the sampler. In case of cutting against ventilation, readings commenced when the shearer was 20 m downwind of the sampling position and continued until it had passed and was 50 m upwind side of the sampler.

(iii) Miscellaneous data: Instantaneous sampling was carried out for the entire cycle which consisted of one cutting, one sumping and one flitting operation, over about 30 to 60 minutes depending on the face conditions. Production of coal during this period was between 300 and 800 tonnes. During all surveys, dust concentration measurements were taken in the walkway adjacent to the shearer. To correlate the instantaneous respirable dust concentration values with the activities of the shearer and its location, a time study of shearer activities was conducted at the same time. These included tailgate cutting, sumping, cutting time, travelling rate, shearer cutting
direction, face stoppages, support movement and shearer location relative to each sampling station. The information on the shearer activities during every cutting cycle was necessary as cutting cycle times are different for different cuts/faces. Other face details such as coal seam thickness, type of supports, air velocity, etc. were also noted.

(iv) Support generated dust: To measure the support generated dust, one Hund instrument was carried at a constant distance of 3 m on the upwind side of the moving supports and another Hund instrument was carried at a constant distance on the downwind side of the moving supports. The distance between the moving supports and downwind sampling instrument was kept at 1 m, 5 m, and 10 m during different experiments. Dust concentrations were read approximately every 4 seconds. The difference between the readings of the two instruments gives the level of dust generated by support movement.

(iv) Dust profiles across the section of the face: The ideal procedure to obtain dust gradients across the face is to position 10-15 instantaneous sampling instruments across the face and to collect the readings simultaneously for 20 - 30 minutes. Owing to resources limitation, two instruments were used and the following procedure was adopted to obtain this data. First, the whole cross section of the face was divided into 9 - 15 arbitrary sections. The two instantaneous samplers were located approximately 1.0 to 1.5 m distant apart in one section of the face. The location of the instruments was changed to different sections of the face in different experiments to obtain dust gradients in parts. For example, during experiment 1, one sampler was located over the panline while the second one was positioned in the front walkway, i.e. between the spill plate and front legs. During the second experiment, the first sampler was located over the spill plate while the second one was positioned in the back walkway, i.e. in between the two rows of legs. Similarly several other experiments were conducted to
collect dust gradients across all sections of the face. Data from all sections was used to
determine the dust gradient across the full section of the face.

Four longwall faces each with a poor dust compliance record were selected for the field
investigations. They are referred to as longwall faces 'A', 'B', 'C' and 'D'. The main
characteristics of the faces are listed in Table 3.1 and brief description of the faces and
the results of the field studies are provided in the following sections.

Table 3.1. Main characteristics of the longwall faces - parametric studies

<table>
<thead>
<tr>
<th>Face</th>
<th>Seam thickness (m)</th>
<th>Face length (m)</th>
<th>Cutting direction</th>
<th>Ventilation</th>
<th>Air velocity (m/s)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>2.1 - 2.5</td>
<td>100</td>
<td>with ventilation</td>
<td>homotropal</td>
<td>2.0 - 2.2</td>
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<tr>
<td>B</td>
<td>2.2 - 2.7</td>
<td>200</td>
<td>against ventilation</td>
<td>antitropal</td>
<td>3.3 - 3.8</td>
</tr>
<tr>
<td>C</td>
<td>2.1 - 2.5</td>
<td>150</td>
<td>with ventilation</td>
<td>homotropal</td>
<td>1.8 - 2.1</td>
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<tr>
<td>D</td>
<td>1.9 - 2.2</td>
<td>200</td>
<td>against ventilation</td>
<td>antitropal</td>
<td>2.6 - 2.8</td>
</tr>
</tbody>
</table>

3.4 RESULTS OF INVESTIGATIONS IN LONGWALL FACE 'A'

Longwall face A was operating in the Bulli Seam in the Southern district of NSW,
Australia. The working height was between 2.1 and 2.5 m and the main properties of
the seam were as follows: thickness 2.1 - 3.2 m, moisture 1.0 - 1.1%, volatile matter
26%, Hardgrove Grindability Index 69 - 80. The longwall face length was 100 m and
the length of the panel was 1250 m. A EDW-300-L Eichoff double ended ranging
drum shearer and 2 x 460 tonnes split base two legged shields were used in this face.
The diameter and width of the cutting drums were 1.2 m and 0.9 m respectively. The
average tram speed of the shearer while cutting was approximately 7 m/min.
The cutting sequence was uni-directional with cutting from tailgate to maingate in the direction of ventilation. The roof supports were advanced on the intake side of the shearer immediately after cutting. A homotropal ventilation system was used and the face air velocity varied between 2.0 and 2.2 m/s. The average daily production from the face was about 5400 tonnes and the annual production was approximately 1.6 million tonnes.

3.4.1 Average dust concentration profiles

Average dust concentration survey results from some experiments are given in Table 3.2 showing dust levels at different stations along the longwall face. During each of the experiments the shearer completed between 3 and 6 full cuts in each shift, producing between 900 and 2000 tonnes. From these, typical average dust concentration profiles along longwall face A were determined and are shown in Figures 3.4 and 3.5. The data shows that the concentration varies with the location of the sampling point. The dust concentration at the beginning of the face is low because of the homotropal ventilation system and there is a general increase in dust concentration from intake to return. The dust level at the return end station is highest because all the dust generated has to pass through this station, as opposed to other sampling stations which are downwind for only some part of the cutting process. These profiles differ from those in U.S. mines, because of the bleeder ventilation system used.

As this face is homotropally ventilated, the dust generated at the stage loader goes directly into the return airway. Thus, the stage loader dust did not add to longwall face dust levels, but did overload the rock dusting requirements in the return airway. To measure this dust generation, one sampling station was located in the return airway on the return side of the stage loader. Therefore the results presented in the last column of
Table 3.2. Average dust concentration levels along the face (in mg/m³)

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Face intake</th>
<th>17th Chock</th>
<th>42nd Chock</th>
<th>65th Chock</th>
<th>Production (tonnes)</th>
<th>Shearer (crusher)</th>
<th>Boot End (crusher)</th>
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<td>2.93</td>
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<td>0.99</td>
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<td>3.33</td>
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<tr>
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<td>2000</td>
<td>-</td>
<td>14.30</td>
</tr>
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<td>4.94</td>
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<td>2.99</td>
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</table>
Figure 3.4 Average gravimetric airborne respirable dust concentration profiles along the longwall face A for experiments 1, 2 and 3.

Figure 3.5 Average gravimetric airborne respirable dust concentration profiles along the longwall face A for experiments 4, 5 and 6.
Table 3.2 relate to the return side of the stage loader and represents only the dust generated at the stage loader and do not indicate the total longwall face dust levels. Figures 3.6 and 3.7 show the relationship between production and dust level along the longwall face. The figures indicate that the dust levels exceeded the statutory limit of 3 mg/m³ when the production per shift was more than 2000 tonnes.

Measurement of airborne dust by personal samplers is a commonly accepted means of monitoring worker's exposure to hazardous dust in the workplace. While such routine measurements provide a direct measurement of the average exposure over a complete shift, they do not provide information on variations of concentration in time and space as the worker proceeds with his duties. Full shift gravimetric samplers are usually not adequate to determine specific dust sources, and therefore, these results cannot be used to determine the effect of different operating practices on spatial variations in dust levels at different locations.
3.4.2 Instantaneous dust concentration profiles

(i) Dust profiles near the return end of the face: The instantaneous sampling survey results of the first series of experiments in longwall face A at the return end sampling station are shown in Table 3.3 and Figures 3.8 - 3.9, along with the activities of the shearer indicated on the X axis. The instantaneous dust concentration levels during different cutting cycles show that the profiles are somewhat similar, but not identical. Once the shearer was on the downwind side of the Hund, dust levels at the sampling station decreased rapidly. It took between 3 and 5 minutes before most of the dust generated by the shearer upwind of the sampling station was carried past the sampling station. The figures shows that during most of the cutting cycle, the dust concentration was more than 3 mg/m³. Further analysis of figures indicates that even during the sumping operation at the tailgate entry, the dust concentration was higher than the allowable limit.
Table 3.3. Instantaneous dust concentration levels during a cutting cycle

<table>
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<tr>
<th>Time (min.)</th>
<th>Dust level (Exp. 1) (mg/m$^3$)</th>
<th>Dust level (Exp. 2) (mg/m$^3$)</th>
<th>Dust level (Exp. 3) (mg/m$^3$)</th>
<th>Dust level (Exp. 4) (mg/m$^3$)</th>
<th>Dust level (Exp. 5) (mg/m$^3$)</th>
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Figure 3.8  Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face A for experiment 1.

Figure 3.9  Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face A for experiment 2.
A plot of instantaneous respirable dust levels at the stage loader is shown in Figure 3.10. As a homotropal ventilation system was used in this face, the dust generated at this location did not contribute to the longwall face dust concentration, but overloaded the rock dusting requirements in the return airway. However, results show that a large amount of respirable dust was generated at the stage loader. Therefore, it is very important to control the dust generation at the stage loader and at other intake dust sources in antitropally ventilated faces.

Figure 3.10 Instantaneous respirable dust concentration at crusher /stage loader during a cutting cycle in longwall face A.

(ii) Dust profiles around the shearer: Respirable dust concentration profiles around the shearer, a major dust source, are given in Figures 3.11 and 3.12. These figures show clearly the pattern in which the dust emanates from the shearer which is the major dust source. A very high dust concentration zone was observed near the cutting drums but was beyond the surveyor’s reach. As the distance from the shearer increased, the
Figure 3.11  Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face A for experiment 1.

Figure 3.12  Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face A for experiment 2.
airborne dust in the high concentration zone gradually dispersed into the whole ventilation space. Analysis shows that the dust concentration decreased continuously from the midpoint of the shearer to the downstream side and reached the lowest level at 5 to 10 m downstream of the lead drum. After this point, the dust concentration increased gradually until it reached its highest level, which was generally 3 to 4 times higher than that around the leading drum operator.

Figures 3.11 and 3.12 show very high dust concentration levels at the rear/upwind drum operator's position. To check these unusual high dust levels when cutting in the direction of ventilation, a sampling survey with a moving instrument was conducted. During this survey, the instrument was positioned at the upwind drum operator's position throughout the cutting cycle. The results of this survey for one complete cycle are given in Figure 3.13. The very high dust concentration levels obtained at the shearer's rear drum were due primarily to the effect of the 'boiling' over of dust caused by misdirected water sprays at the rear of the shearer. Support movement upwind of the rear operators was also found to be one of the contributing factors. As indicated in Figure 3.13, the dust concentration levels around chocks 18 and 31 were very high. An analysis of time data showed that, at these locations, the shearer was cutting a small rock band which produced large amounts of dust.

Figures 3.14 and 3.15 show the dust concentration at the lead/main drum operator's position, and at a distance 5 m downwind of the shearer during the entire cutting cycle. Most of the time the dust levels were within the statutory limit of 3 mg/m³. These figures suggest that the best location for the downwind drum operator would be 4 m ahead of the shearer to reduce his dust exposure levels.
Figure 3.13  Instantaneous respirable dust concentration at upwind cutting drum operator's position during a cutting cycle in longwall face A.

Figure 3.14  Instantaneous respirable dust concentration at downwind drum operator's position during a cutting cycle in longwall face A.
Figure 3.15  Instantaneous respirable dust concentration at 5 m downstream of shearer during a cutting cycle in longwall face A.

(iii) Support generated dust profiles: Typical support generated dust concentration profiles along the face at 1 m, 5 m and 10 m downwind of the support movement are shown in Table 3.4 and Figure 3.16. The difference between the upwind and downwind concentration levels during support movement gives the dust generated by supports, which is shown as the shaded area in the plots. The dust generation varies significantly along the face. For example, in figure 3.16(a), the dust concentration downwind of the supports ranged between 38.5 and 7.5 mg/m$^3$. The average upwind dust concentration was 0.9 mg/m$^3$ and the downwind dust concentration was 17.10 mg/m$^3$, with the overall average support generated dust concentration being 16.20 mg/m$^3$.

The dust level in walkway decreased as the distance to the moving supports increased. The average dust concentration at 1 m downwind of the moving supports was 17.1 mg/m$^3$, at 5 m it was 8.8 mg/m$^3$ and at 10 m downwind the dust level was only 3.7 mg/m$^3$. This is because the primary ventilating airflow dilutes and diffuses the
Table 3.4. Dust generation during support movement

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Figure 3.16(a) Instantaneous respirable dust concentration at 1 m downwind of support movement in longwall face A.

Figure 3.16(b) Instantaneous respirable dust concentration at 5 m downwind of support movement in longwall face A.
dust generated by supports towards the face side. It can be inferred from these results that the contribution of support generated dust to the shearer operator's dust exposure varied depending on the distance between the shearer and support movement.

### 3.4.3 Respirable dust size distribution

The size distribution of respirable dust samples from longwall face 'A' was measured using a laser particle analyser. The results are shown in Figures 3.17 and 3.18 as histograms of weight percentage frequency against particle size. In these graphs the total percentage represents 100% and integration of the data results in the cumulative percentage curves. A plot of the cumulative percent of undersize by weight versus particle diameter in microns produced a typical S-type curve as shown in Figure 3.19. The median is readily observed from figure 3.19 as occurring at approximately 3.8 microns diameter. The size data for experiment 1, plotted on a log-normal scale, is shown in Figure 3.20. The size distribution of respirable dust found in this study are in general agreement with other studies (Ramani, Qin and Jankowski, 1992).
Figure 3.17  Particle size distribution of airborne respirable dust samples collected from longwall face A for experiment 1.

Figure 3.18  Particle size distribution of airborne respirable dust samples collected from longwall face A for experiment 2.
Figure 3.19  Typical cumulative particle size distribution of respirable dust samples collected from longwall face A.

Figure 3.20  Typical cumulative particle size distribution of respirable dust samples collected from longwall face A on log-probability scale.
3.5 RESULTS OF INVESTIGATIONS IN LONGWALL FACE 'B'

Longwall face B was operating in the Bulli seam in the Southern district of NSW, Australia. The working height was between 2.2 and 2.7 m, the longwall face length 200 m and the length of the panel 1900 m. Anderson AM-500 double ended ranging drum shearer and Gullick 4 x 1000 tonnes four legged chock shields were used in this face. The diameter and width of the cutting drums were 1.8 m and 0.8 m respectively. The average tram speed of the shearer while cutting was approximately 7 m/min.

The cutting sequence was uni-directional with cutting from tailgate to maingate against the direction of ventilation. The roof supports were advanced on the return side of the shearer immediately after cutting. The ventilation system was antitropical and the face air velocity varied between 3.5 and 4.3 m/s. The daily production from the face was about 6 800 tonnes and the annual production was approximately 1.9 million tonnes.

3.5.1 Instantaneous dust concentration profiles

(i) Dust profiles near the return end of the face: The instantaneous sampling survey results of the experiments in longwall face B for one complete cutting cycle are shown in Figures 3.21 - 3.23. The activities of the shearer are indicated on the X axis. In figure 3.23 dust concentration profiles at two cutting speeds are presented. The average dust concentration was 9.7 mg/m³ at 14 m/min cutting speed and 4.3 mg/m³ at 7 m/min cutting speed. Results show that at high cutting speed dust levels are 2 to 2.5 times higher during both the cutting and cleaning phases of the cut cycle.
Figure 3.21 Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face B for experiment 1.

Figure 3.22 Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face B for experiment 2.
Figure 3.23 Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face B with two cutting speeds.

(ii) Dust profiles at other sampling stations along the face: Dust concentration data at different locations along the face are shown in Figure 3.24. The dust peaks sampled near the maingate have short widths because these stations were upwind of the shearer most of the time. Towards the return end sampling station, however, the peaks of dust levels become wider. The average dust concentration levels at the 30th, 60th, 90th and 120th chock positions were 1.8, 3.2, 4.2 and 5.6 mg/m³ respectively.
Figure 3.24(a) Instantaneous respirable dust concentration at 30th chock sampling station during a cut cycle in longwall face B (when cutting against ventilation).

Figure 3.24(b) Instantaneous respirable dust concentration at 60th chock sampling station during a cut cycle in longwall face B (when cutting against ventilation).
Figure 3.24(c) Instantaneous respirable dust concentration at 90th chock sampling station during a cut cycle in longwall face B (when cutting against ventilation).

Figure 3.24(d) Instantaneous respirable dust concentration at 120th chock sampling station during a cut cycle in longwall face B (when cutting against ventilation).
(iii) **Dust profiles around the shearer:** Typical respirable dust concentration profiles around the shearer are given in Figures 3.25 and 3.26. It can be seen that the pattern of dust profiles differ from those of in longwall face A, particularly in the vicinity of the shearer. Dust produced by the upstream lead drum quickly dispersed into the walkway over the shearer. The dust levels around the shearer increased rapidly from about 1.0 m on the return side of the shearer upstream/lead drum exposing both the operators to high dust concentration. This can be attributed to the cutting sequence which, in this case, was against the ventilation.

![Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face B for experiment 1.](image)

Figure 3.25 Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face B for experiment 1.
(iv) Dust profiles across the section of the face: Table 3.5 and Figure 3.27 shows a comparison of instantaneous dust concentration profiles at four different locations across the section of the face. The average concentrations were 5.9 mg/m$^3$ over the panline, 3.7 mg/m$^3$ in the front walkway, 5.4 mg/m$^3$ over the spill plate and 2.8 mg/m$^3$ in the back walkway. Perhaps the most surprising aspect is that these differences exist even after 50 m downwind of the shearer. A typical average dust concentration gradient across the section of the longwall face at the miner's breathing height (0.4 m below roof) is given in Figure 3.28. These figures demonstrate that large dust gradients exist, not only around the shearer, but also across the section of the longwall face. The dust profiles show that correct siting of sampling stations is crucial to the successful evaluation of dust control techniques.
Table 3.5. Dust levels at different locations across the longwall face

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Figure 3.27(a)  Instantaneous respirable dust concentration at two different locations across the longwall face B (0.4 m below roof).

Figure 3.27(b)  Instantaneous respirable dust concentration at two different locations across the longwall face B (0.4 m below roof).
3.5.2 Respirable dust size distribution

The particle size distribution of respirable dust samples from longwall face B is shown in Figures 3.29 - 3.30. A comparison of particle size distribution between dust samples from faces B and A is shown in Tables 3.6 - 3.7. It can be seen that the size distribution of dust from face B is quite different from that of face A. There are more fines in the dust sample from face B than that of face A. The cutting sequence, which is against the ventilation in this face, is one of the contributing factors to the high percentage of fines in the respirable dust. The median dust particle diameter of the respirable dust was approximately 3.45 microns. Figure 3.31 is a plot of the particle size against the cumulative weight percentage of particles smaller than that size on a log-normal scale.
Figure 3.29 Particle size distribution of airborne respirable dust samples collected from longwall face B for experiment 1.

Figure 3.30 Particle size distribution of airborne respirable dust samples collected from longwall face B for experiment 2.
### Table 3.6. Respirable dust size distribution

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3.6 RESULTS OF INVESTIGATIONS IN LONGWALL FACE 'C'

Longwall face C was operating in the Bulli seam in the Southern district of NSW, Australia. The working height was between 2.1 and 2.5 m, the longwall face length 150 m and the length of the panel 1300 m. Anderson AM 500 double ended ranging drum shearer and 4 x 600 tonnes Meco four legged chocks were used in this face. The diameter and width of the cutting drums were 1.6 m and 0.9 m respectively. The average tram speed of the shearer, while cutting, was approximately 6.5 m/min. The cutting sequence was uni-directional with cutting from tailgate to maingate in the direction of ventilation. The roof supports were advanced on the intake side of the shearer immediately after cutting. A homotropal ventilation system was used and the face air velocity varied between 1.9 and 2.1 m/s. The daily production from the face was about 4,500 tonnes and the annual production was approximately 1.6 million tonnes.
3.6.1 Instantaneous dust concentration profiles

(i) Dust profiles near the return end of the face: Instantaneous dust concentration profiles at the return end sampling station at the face over one complete cutting cycle are shown in Figures 3.32 and 3.33. The results show that the rate of dust generation by the shearer was variable, reflected in the varying heights of the peaks. A large number of smaller peaks represents secondary dust sources such as support advance, face spalling, rock cutting and roof collapse in the goaf. More specifically, in figure 3.32 there is a peak at the 23rd minute, which a time study attributes to the shearer cutting a fallen rock boulder and generating large amounts of dust. This figure also reinforces the fact that dust generated during the sumping phase contributes significantly to the miners' dust exposure.

![Figure 3.32 Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face C for experiment 1.](image-url)
(ii) Dust profiles at other sampling stations along the face: Dust concentration data at different sampled locations along the face are shown in Figure 3.34. The dust peaks near the maingate are narrow, indicating that they are of short duration, because the sampling stations were upwind of the shearer most of the time. Towards the tailgate, however, the peaks become progressively wider. In the last sampling station, which is near the tailgate and is downwind of the shearer for most of the time, the observed dust peaks are the widest, indicating longer dust exposure.
Figure 3.34(a) Instantaneous respirable dust concentration at 25th chock sampling station during a cut cycle in longwall face C (when cutting with ventilation).

Figure 3.34(b) Instantaneous respirable dust concentration at 50th chock sampling station during a cut cycle in longwall face C (when cutting with ventilation).
Figure 3.34(c) Instantaneous respirable dust concentration at 75th chock sampling station during a cut cycle in longwall face C (when cutting with ventilation).

Figure 3.34(d) Instantaneous respirable dust concentration at 100th chock sampling station during a cut cycle in longwall face C (when cutting with ventilation).
(iii) Dust profiles around the shearer: Respirable dust concentration profiles around the shearer are given in Figures 3.35 and 3.36. Analysis of the figures show that they differ from those of in longwall faces A and B, especially in the vicinity of the shearer. The dust concentration level was lowest between 5 and 8 m downwind of the shearer's lead drum position and increased from there onwards towards the return end of the face. However, the dust concentration around the trailing upwind drum operator's position was higher than expected. This can be attributed to poor installation of water sprays on the shearer and the upwind support movement.

![Dust concentration profile graph](image)

Figure 3.35 Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face C for experiment 1.
Figure 3.36 Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face C for experiment 2.

(iv) Support generated dust profiles: Dust generated by support movement along the face is profiled in Figure 3.37. The average dust concentration at 1 m downwind of the moving supports was 7.6 mg/m³ and at 5 m it was 3.5 mg/m³. These figures show that although support generated dust was less as a component of overall shearer operator's dust exposure than in face A, it still represented a significant proportion of total dust exposure.
Figure 3.37(a) Instantaneous respirable dust concentration at 1 m downwind of support movement in longwall face C.

Figure 3.37(b) Instantaneous respirable dust concentration at 5 m downwind of support movement in longwall face C.
(v) *Dust profiles across the section of the face*: Two typical instantaneous dust concentration profiles at two different locations across the face are shown in Figure 3.38(a). The average concentration, over approximately 15 min, were 10.5 mg/m³ over the panline and 6.1 mg/m³ in the walkway. Overall, the two profiles appear to be different; for example, at the 8th minute on the x-axis, when the panline concentrations were 24.4 mg/m³, no measurement exceeded 8 mg/m³ in the walkway. Dust profiles at different locations across the section of the face, given in Figure 3.38(b), show that the average dust level over the spill plate was 9.3 mg/m³ and 4.3 mg/m³ in the back walkway. Figure 3.39 shows the average dust gradient, across the section of the face, at a height of 1.5 m and demonstrates that there are high dust gradients across the section of the longwall face.

![Graph showing dust concentration over time](image)

*Figure 3.38(a)* Instantaneous respirable dust concentration at two different locations across the longwall face C (0.4 m below roof).
Chapter 3: Dust Distribution

Figure 3.38(b) Instantaneous respirable dust concentration at two different locations across the longwall face C (0.4 m below roof).

Figure 3.39 Typical respirable concentration profile across the longwall face C at miner's breathing height (0.4 m below the roof).
3.6.2 Air velocity patterns

Air velocities measured with an anemometer along the face are presented in Figure 3.40. The decreased air velocity at the second station is the result of air from the tailgate entry being pushed into the back of the supports and settling down after some distance. Overall, there was not much variation along the face. There was no bleeder entry in this face, and therefore air leakage into the goaf was negligible. It is the air leakage component which made these air velocity profiles different from those of the Qin (1992) for U.S. longwall faces using a bleeder entry ventilation system. Air velocity measurements across the face, at different heights, are shown in Figure 3.41, which shows that air velocity was not uniform across the face. It was highest over the AFC area and lowest in the walkway, where it is half of that in the AFC area. This variation must be taken into account during the development of a dust control technique, as it affects the respirable dust behaviour and dispersion.

![Figure 3.40 Air velocity over AFC along the longwall face C.](image-url)
3.7 RESULTS OF INVESTIGATIONS IN LONGWALL FACE 'D'

Longwall face D was operating in the Bulli seam in the Southern district of NSW, Australia. The working height was between 2.2 and 2.5 m, the longwall face length was 200 m and the length of the panel was 1650 m. A 500 KW Mitsui Miike double ended ranging drum shearer and Dowty 4 x 680 tonnes four legged chock shields were used in this face. The diameter and width of the cutting drums were 1.6 m and 1.0 m respectively. The average tram speed of the shearer while cutting was approximately 7 m/min. The cutting sequence was uni-directional with cutting from tailgate to maingate against the direction of ventilation. The roof supports were advanced on the return side of the shearer immediately after cutting. Antitropical ventilation system was used and the face air velocity varied between 2.6 and 2.8 m/s. The daily production from the face was about 7200 tonnes and the annual production was approximately 2.1 million tonnes.
3.7.1 Instantaneous dust concentration profiles

(i) Dust profiles near the return end of the face: The results of the instantaneous sampling surveys for one complete cutting cycle are shown in Figures 3.42 and 3.43. The shearer activities are indicated on the X axis. Each point shown is the average of four readings. These figures show the dust exposure during each phase of the mining cycle and indicate that the dust level during the cutting phase was always above the statutory limit of 3 mg/m$^3$. It is also evident that the return end operators were only exposed to dust during the cutting and cleaning phases of the cycle. Dust produced during the sumping phase went directly into the return airway because the ventilation system is antitropal and cutting was against the airflow.

![Diagram](image)

Figure 3.42 Instantaneous respirable dust concentration at return end sampling station during a cutting cycle in longwall face D for experiment 1.
(ii) Dust profiles around the shearer: Respirable dust concentration profiles around the shearer are given in Figures 3.44 to 3.45. It can be seen that in face 'D', where cutting was against the ventilation, dust produced by the upstream lead drum quickly dispersed into the walkway over the shearer, thereby exposing both operators to high dust concentration levels. The pattern of these dust profiles is different from those of in longwall faces A and C.
Figure 3.44 Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face D for experiment 1.

Figure 3.45 Instantaneous respirable dust concentration profile around shearer during cutting cycle in longwall face D for experiment 2.
3.7.2 Respirable dust size distribution

The size distribution of respirable dust samples in longwall face 'D' is shown in Figures 3.46 and 3.47. It can be seen that the size distribution of respirable dust from face D was similar to that in face B. The median diameters for experiments 1 & 2 in face D are 3.6 and 3.45 respectively. Figure 3.48 is a plot of the log of the particle size against the cumulative weight/mass percent of particles smaller than that size.

3.7.3 Air velocity patterns

Air velocities along the face, measured with an anemometer, are presented in Figure 3.49. Although in this face the air velocity was slightly high, the general pattern of air velocity along the face was the same as that in face 'C'. Analysis of results shows that air velocity did not vary much along the face and indicates that there was negligible air leakage into the goaf. Air velocity measurements across the face, at different heights, are shown in Figure 3.50. These results also confirm the fact that the velocity was not uniform across the section of the face.
Figure 3.47  Particle size distribution of airborne respirable dust samples collected from longwall face D for experiment 2.

Figure 3.48  Typical cumulative particle size distribution of respirable dust samples collected from longwall face D on log-probability scale.
Figure 3.49  Air velocity over AFC along the longwall face D.

Figure 3.50  Air velocity profiles across the longwall face D at three heights.
3.8 COMPARISON AND SUMMARY

High respirable airborne dust levels at the working face is a difficult problem associated with longwall mining. There is only very limited fundamental data available to characterise the respirable dust behaviour at longwall faces. To augment this data, and to obtain data from Australian longwall faces in this research, field experiments were performed in four longwall faces in the Southern district of New South Wales. The shift average gravimetric dust data shows that respirable dust concentration increased with distance to the return end of the longwall face. However, the large variations in the dust gradients, measured over a period of 14 consecutive shifts in the same longwall face, indicates that the relationship between the dust level and the distance from the intake end was complex and not easily generalised owing to the large number of factors involved. In addition, as the average dust concentration levels could not be correlated with face activities, it was decided to conduct instantaneous dust sampling surveys in subsequent experiments to give a clearer picture of respirable dust conditions at the face.

The instantaneous dust concentration profiles show that the dust distribution patterns were different during different cutting operations in a cycle e.g. the cutting, cleaning and sumping. Badly positioned water sprays on the shearer were found to increase dust concentration at the rear drum operator's position. A comparison of dust data showed that respirable dust concentration levels and patterns were variable from one face to another. For example in face 'A', the dust level was around 11 mg/m³ and in longwall face 'B' it was around 5 mg/m³. Studies in face 'B' confirmed that higher cutting speed resulted in higher dust levels all along the longwall face. Respirable dust profiles around the shearer showed that cutting against the ventilation system dispersed more dust into the shearer operator's position than when cutting with ventilation.
However, when cutting at the maingate with the ventilation during which the drum makes a number of partial sumping cuts, produced a significant proportion of the total respirable dust.

It should be noted that the instantaneous dust concentration plots did not indicate the average shift dust concentration as they were set up to operate only during the cutting process. Therefore the high, but short, peaks of concentration should not be interpreted as the worst dust conditions, but their duration should be included in the interpretation of results. An increase in the width, hence duration, of the peaks signifies an increase in average dust concentration. Studies in faces 'A' and 'C' showed support movement significantly contributed to miners' dust exposure at the longwall faces.

Air velocity and quantity data showed that there was no significant air leakage into the goaf. A comparison of air velocity, quantity and respirable dust levels in the faces showed that low air velocity/quantity was associated with high dust concentration levels in faces A & C. Air velocity profiles across the face showed that air velocity was not uniform across the face; it was highest over the AFC area and lowest in the walkway. A comparison of air velocity with dust levels across the face indicated that the dispersion and distribution of respirable dust depended largely on the airflow patterns. Therefore, the variation in air velocity across the face should be taken into account during the development of a dust control technique, as it affects the respirable dust behaviour and dispersion. The size distribution of airborne respirable dust samples was found to be quite different from mine to mine.

These studies also showed that there are high dust level gradients around the shearer and across the section of the longwall face and indicated that the correct siting of sampling stations is crucial in successful evaluation of dust control techniques. These
experimental studies have been useful in identifying some of the important parameters affecting dust transport and in characterizing dust cloud behaviour at longwall faces. The studies have also provided a data base for the development of dust control techniques to minimise the miners' exposure to dust. The knowledge of dust behaviour under numerous conditions, obtained during this study, formed the basis of the development of the multi-scrubber dust control system discussed in chapter 4.
Chapter 4

DEVELOPMENT OF A NEW PROTOTYPE SCRUBBER

4.1 INTRODUCTION

Field investigations carried out in four longwall faces showed that dust sources other than the shearer also contribute significantly to the total respirable dust concentration in the longwall face (details are presented in chapter 3) and these findings support earlier work by the U.S. Bureau of Mines (Jankowski, Organiscak and Jayaraman, 1991; Jankowski and Organiscak, 1983b). Most of the dust produced from other sources, such as support movement and face spalling, becomes airborne and quickly disperses into the walkway, thereby increasing the respirable dust concentration to unacceptable levels. A critical review of dust control research over the last three decades shows that whilst enormous effort has been directed at suppressing dust at the shearer, very little work has been done to reduce dust make from these other important dust sources (NCB, 1982; Jankowski and Organiscak, 1983a; Hewitt, 1990a; 1990b). The methods developed so far, to deal with this problem, such as use of filters and mats over the supports canopy, were labour-intensive, capital-intensive, and were found to be impracticable (Becker et al, 1988).

Therefore the control of these dust clouds is very important in order to reduce the dust exposure of longwall miners, which calls for the development of control techniques aimed at controlling the dust already airborne. In such cases, the installation of separating elements between the AFC and walkway area, such as local airflow systems, can be useful in reducing the face operators’ dust exposure (McPherson, 1988; Hewitt, 1986a). Compressed air nozzles and air curtains have been tried in the
past to provide the local airflow systems and separate the AFC from the walkway. These techniques reduced the walkway dust levels by between 25% and 70%. However, as both the techniques use only compressed air, the requirement of large quantities to compete with the primary face airflow made them uneconomical. In view of the above, the use of a multi-scrubber system along the walkway of the longwall face has been proposed.

Longwall dust control presents some unique problems. Some of the standard dust control techniques that are very effective in other mining situations may not work on longwalls. For example, machine mounted scrubbers have been highly successful in controlling dust from continuous miners. However, tests conducted on shearer's with the available scrubbers were unsuccessful, as they were too large to be practicable. A detailed review of scrubbers, compressed air nozzles and air curtains has been given in section 2.5.9. The design and development of very compact and reliable scrubbers with low water usage, high capture efficiency and an effective mist eliminator is important for their successful application in a longwall face. Limited space in a longwall face dictates that the scrubbers also be compact.

The varied uses of scrubbers in longwall faces places different requirements on the manufacturers with respect to design and operation as well as performance. The manufacturers are not prepared, however, in the light of the high development costs, to offer a specialized manufacturing programme to the longwall mining industry, especially since the number of scrubbers required would inevitably be small and they would find little application in other sectors of the industry. Therefore, there is a need for the design and development of a prototype scrubber for use in longwall faces.
4.2 MULTI-SCRUBBER SYSTEM

4.2.1 Proposed concept

Since test results with a single scrubber proved unsuccessful to reduce dust levels in the longwall face, it was therefore decided to investigate the application of a multi-scrubber system in a longwall face, i.e. using a number of scrubbers along a face, to reduce miners' dust exposure (Aziz et al, 1993b). There are two ways in which scrubbers can be deployed in the multi-scrubber system. The first approach aims to reduce the total respirable dust concentration levels at the face, whereas the objective of the second approach is to provide a clean air zone along the walkway to reduce face operators' dust exposure.

The first approach involves using a number of high capacity (2 to 3 m³/s) scrubbers to extract a large proportion of the respirable dust produced at the face. Modelling studies by Liu (1991) concluded that the minimum quantity of air through each scrubber should be between 2 and 3 m³/s and that between 50 and 60 scrubbers are necessary to achieve a significant dust reduction in a longwall face. In addition, all the scrubbers would need to be operated throughout the shift to achieve the objective. However, this approach does not appear to be practicable for the following reasons: (i) the large space requirements of high capacity scrubbers which is a major constraint in a longwall face, and (ii) even if more scrubbers were installed in the face, only the scrubbers downstream of the shearer would be effective at any one time. Therefore, given that the longwall shearer moves from one end to the other, it is unlikely that all of the dust cloud would be captured by, and pulled through, one scrubber or even a series of scrubbers. It was therefore decided to investigate the second concept for reducing miners' dust exposure.
Chapter 4: Scrubber Development

The second approach involves using a number of small capacity scrubbers to deliver cleaned air at high velocity into the front walkway area, to create a relatively clean air zone. The technique was aimed at reducing the dust in the operators' working area rather than reducing the dust levels in the entire face. It therefore requires between 12 and 18 scrubbers to be installed in the return part of the face and only a set of 4 to 8 scrubbers would need to be operated at any one time.

Another feature which favours the second concept of a multi-scrubber system is that the velocity contours at right angles to the longwall face show that the velocity is not uniform, being highest over the AFC area and lowest in the walkway. Therefore, if a high velocity split of air is produced by a multi-scrubber system in the low velocity walkway zone, the air will flow into the high velocity AFC zone, preventing dust diffusion into the low velocity walkway area. The air will also carry any support generated dust more quickly towards the face side, thus reducing the dust concentration in the walkway area.

As there was no scrubber available for use in a longwall face to begin research on the concept of a longwall multi-scrubber system, it was first necessary to design and develop a prototype scrubber in the laboratory. In a longwall face, the parameters of a multi-scrubber system which will determine the overall effectiveness of a scrubber are the size, capacity, location, dust removal efficiency, and exit velocity of clean air. They must be optimised to maximise the benefit from the system.

4.2.2 Design requirements of the scrubber

The design requirement of the scrubber system was to produce a relatively simple, efficient, small and practical unit suitable for operating in a longwall face. The other important features of the design were size, capacity, water consumption, maintenance
and safety. The length of the scrubber had to be less than 1.3 m long, so that it could fit into one chock. To provide a clean split of air, the scrubber capacity had to be reasonably high, with a minimum of 0.5 m³/s to compete with the face airflow of 15 to 20 m³/s in moderately gassy longwall faces. As the scrubber was to be used in a multi-scrubber system, it was important to minimise the water consumption and design scrubbers without filters, so as to avoid the heavy maintenance involved in scrubbers with filters.

Originally, the proposed scrubber design consisted of a fan, an hydraulic motor and a dust capturing unit. As the design progressed it was found that it was not practicable to use fan powered scrubbers in a multi-scrubber system in longwall faces because of the following reasons:

(i) the size of the fan needed would be larger than 0.5 m φ x 1.0 m to provide the required quantity of air, and therefore would not fit in the chock shields.

(ii) the pressure developed by the small fans is in the range of 50 - 150 mm of water gauge, which is not sufficient for the efficient operation of compact scrubbers such as venturi scrubbers.

(iii) fans, if used in confined and continuously moving longwall chocks, are subject to fouling of the blades which may lead to methane gas explosions.

In view of the above, it was decided to develop an air powered venturi scrubber designed for use at longwalls, which used a small quantity of compressed air in conjunction with small amount of water. Air powered scrubbers are very sensitive to air pressure or restrictions on the suction and exhaust side, as they work on the principle of inducing secondary air. Therefore, effort was also directed towards the development of a very small, high velocity and minimum pressure drop water drop eliminator.
4.3 THEORETICAL CONSIDERATIONS

4.3.1 Particle characteristics

Dust particles formed by the grinding action of mining machines are dispersed into the air and remain suspended through the action of air currents. The particles range in size between $10^{-3}$ and $10^3$ μm, which represents a variation of $10^6$ in size and $10^8$ in mass. The size distribution of respirable dust at longwall faces have been discussed in sections 3.4.3, 3.5.2 and 3.7.2. Physical properties of dust particles differ over this wide size range, as does particle behaviour in relation to these properties, e.g. resistance of the medium to particle movement, rate of evaporation and cooling, light scattering, and dominant mechanism of particle removal from the medium.

Particle concentrations are expressed either as a number or as a mass concentration. The number concentration of particles is the ratio of the number of particles in a given volume to the air volume. In the mine atmosphere, respirable particles concentration will be in the order of 100 to 1000/cm³, with instantaneous/source concentrations being greater by several orders of magnitude. The particle mass concentration is defined as the ratio of mass of particles in a given volume to the air volume. The particle mass concentration can be determined by filtering a known volume of air and weighting the collected particles. Particles mass concentration in coal mines ranges from 0.2 to 50 mg/m³.

Some of the non dimensional parameters that characterise the aerosol system (Patterson, 1984) are given below. These parameters are relevant to particle behaviour and collection mechanisms.
(a) Flow Reynolds Number \((Re_a)\)

The flow Reynolds number is the ratio of inertial to viscous forces of a flowing fluid. When the \(Re_a < 2100\), viscous forces dominate and the flow is laminar. For \(Re_a > 4000\), the flow becomes turbulent.

The flow Reynolds number is

\[
Re_a = \frac{V_a \rho_a D}{\mu_a} \quad \ldots \ldots \quad 4.1
\]

(b) Particle Reynolds Number \((Re_p)\)

Particle motion in the air stream is characterised by the particle Reynolds number which is defined by

\[
Re_p = \frac{d_p (V_p - V_a) \rho_a}{\mu_a} \quad \ldots \ldots \quad 4.2
\]

It is to be noted that the particle Reynolds number is dependent on the particle velocity relative to the air stream and the fluid properties. Typically, the particle Reynolds number will be in the order of \(10^{-4}\) to \(10^2\).

(c) Knudsen Number \((Kn)\):

Knudsen number is the ratio of the mean free path of gas molecules to the particle diameter and is given as

\[
Kn = \frac{2 \lambda_a}{d_p} \quad \ldots \ldots \quad 4.3
\]

From the kinetic theory of gases the mean free path, \(\lambda_a\) is

\[
\lambda_a = \frac{kT}{2 \pi \rho D_{mo}^2} \quad \ldots \ldots \quad 4.4
\]
The value of the mean free path of air molecules at 20°C and 760 mm of Hg pressure is approximately 6.53 \times 10^{-2} \, \mu m. For very small particles the gas appears discontinuous and the particles tend to slip between the gas molecules. This occurs when Kn > 0.1.

(d) **Cunningham slip correction factor (C')**

When the Knudsen number, Kn, is greater than about 0.1, particles slip between gas molecules and the resistance of the air is considered as discontinuous. In the Cunningham slip flow regime a correction factor is applied to account for the slippage. The correction factor includes thermal and momentum accommodation factors and is empirically fit to a wide range of Kn values.

The Cunningham slip correction factor can be calculated from

\[ C' = 1 + \left[ 1.257 + 0.4 \exp(-1.1 \frac{d_p}{2\lambda_a}) \right] \frac{2\lambda_a}{d_p} \]  \tag{4.5}

A simplified equation given by Calvert et al (1972) for use in air at normal pressure is

\[ C' = 1 + \frac{6.21 \times 10^{-4}}{d_p} T \]  \tag{4.6}

The Cunningham slip correction factor becomes negligible for particles larger than approximately 1 \, \mu m under normal conditions.

**4.3.2 Principles of venturi scrubbing**

Wet dust scrubbing is a process in which dust particles are transferred from an air stream to a liquid. This transfer process depends strongly on the size of the interfacial area between air and liquid and on the relative motion between the two fluid phases and between the dust particle and liquid.
a) **Principles of dust particle collection**

The collision of dust particles with water drops is discussed for the case given in Figure 4.1. The following assumptions are made:

- (a) air and dust particles have the same velocity;
- (b) air and water drops have the same flow direction;
- (c) there is a relative velocity between air and water drop;
- (d) the water drop has a spherical shape.

Fig 4.1a shows the movement of the air and the dust particles by streamlines and trajectories. Due to inertia forces, the dust particles approaching the water drop will not follow but cross the streamlines of the air and impinge on the drop. The possibility for dust particles to cross the streamlines of the air will increase with

- increasing inertia force of the dust particles, and
- decreasing radius of curvature of the air streamline

![Diagram of dust particle collection](image)

*Figure 4.1* Dust particle collection by a liquid drop in a simple airflow field (after Brauer and Varma, 1981).
All those particles approaching the drop inside an area with diameter $d_o$ will impinge on the drop as indicated in Fig 4.1c. The dust particles will either accumulate on the surface of the drop, in the case of poor wettability of the dust (Fig 4.1d), or penetrate the drop in the case of good wettability (Fig 4.1e). The dust particles impinged on the drop surface will move forward and accumulate at the rear stagnation point. Those dust particles that hit the drop close to the forward stagnation point will, however, remain there because the tangential velocity at the interface of the drop tends toward zero when the forward stagnation point is approached.

The collection efficiency of wet scrubbers has, for some time, been considered to greatly depend on the wettability of dust particles. However, experimental evidence proves that all dust particles that hit the surface of the drop will either penetrate the drop or adhere to the surface (Brauer and Varma, 1981). This process is independent of interfacial tension.

The diameter ratio $d_o/d_d$ is called impingement factor:

$$\varphi_i = \frac{d_o}{d_d}$$  \hspace{1cm} (4.8)

This factor can vary between 0 and 1 and has been shown to be a function of the inertia parameter/number $K$, which is defined by

$$K = \frac{2C \rho_p R_p^2 V_r}{9 \mu_a R_d}$$ \hspace{1cm} (4.9)

Sometimes, this dimensionless group is also called Stokes' number.

Figure 4.2 describes the dependence of the impingement factor on the inertia number and indicates that the probability for impingement will increase with increasing relative
velocity \( V_r \), dust particle density \( \rho_p \) and diameter \( d_p \) due to the inertia of the particles. The chances of impingement will, however, diminish when air viscosity \( \eta_a \) and drop diameter \( d_d \) increase, because in this case the frictional forces will dominate and the gas carries the dust particles away.

The parameter \( \text{Re}_r \) is the Reynolds number of the air with respect to the collector and is defined as (Calvert, 1984)

\[
\text{Re}_r = \frac{V_r \rho_a d_d}{\mu_a}
\]

At high values of \( \text{Re}_r \), the parting of the air streamlines occurs close to the collector. The sudden spreading of the streamlines at a high Reynolds number enhances the influence of particle inertia and therefore causes a higher collection efficiency.

![Impingement factor plotted against the inertia number with Reynolds number as a parameter (after Brauer and Varma, 1981).](image)
The impingement factor given in Fig 4.2 is of qualitative value only. Real conditions for the movement of air, dust particles and drops will be quite different from the assumed ones. For potential flow and for values of $K$ greater than 0.2, the experimental values of inertial collection efficiency for spheres can be approximated by the correlation

$$\eta = \left(\frac{K}{K + 0.7}\right)^2 \quad \cdots \cdots \quad 4.11$$

(b) Atomization of water spray

Two types of atomization are likely to occur in the throat section of the venturi scrubber (Hesketh, 1973; 1974). The first, called drop type atomization, occurs when the liquid is introduced into the high velocity air stream from small diameter (< 1 mm internal diameter) nozzles, or when the liquid is introduced into the air stream in drop form. Cloud type atomization is the second type and results when the water is introduced as a stream (usually from nozzles that are more than 1 mm internal diameter). Cloud type results in the formation of much smaller droplets. However, the very small droplets formed by cloud type atomization join together by hydrostatic force without coalescing to form clouds which would move as a single system and have a much larger effective diameter. Using atomized droplet size, velocity and acceleration observations, Hesketh (1973) found that <10 $\mu$m droplets form clouds with an effective diameter of 170 $\mu$m to 500 $\mu$m, depending on the velocity.

Cloud atomization is desirable to produce sufficient inertial impaction targets for particulate matter collection and to produce a high surface area for absorption. It also keeps the droplet acceleration rate as low as possible which provides the greatest velocity difference between the particles being collected and the droplet target. Pneumatic atomization cannot be effective if the liquid introduced is not projected into
the air stream, and then it will be atomized only when the air velocities are above critical.

A high airflow velocity is required in order to atomize the injected liquid by pneumatic Atomization. The minimum critical velocities required for the atomization of water by airflow can be found using the formula:

$$V_a (\text{crit}) = 1.7 \left[ \left( \frac{8550}{d_n} \right)^{1/2} + 15.3 \right]$$

... 4.12

The clouds, moving as a whole because of the cohesive force between droplets, provide large effective impaction targets for the particulate matter and stop most of the particulate matter within 0.5 cm of the throat scrubbing liquid inlets.

(c) Particle collection by high velocity air

The interaction of dust particles with drops, described in this section, is typical of the situation occurring in the throat of a venturi scrubber. Figure 4.3 shows the situation where drops, dust particles and air move cocurrently at widely different velocities. The final section of the large size drop movement is sketched in figure 4.3 (a). The action of frictional forces, due to the high velocity gas stream, will enforce disintegration of the big drop into several smaller ones that assume and retain spherical shape. Intermediate steps of the disintegration process are illustrated in figures 4.3b and 4.3c.

This process involves the following steps:

a) deformation of spherical drops into ellipsoidal ones;

b) further deformation into the parachute lamella;

c) disintegration of the lamella into liquid filaments and drops;

d) disintegration of liquid filaments into drops.
Figure 4.3  Dust particle collection by water drops moving with very low velocity cocurrently with a high velocity air/dust particle stream (after Brauer and Varma, 1981).

The energy required for the deformation and disintegration process is provided by the high velocity air stream. Air flow and particle movement around an ellipsoidal drop is illustrated in figure 4.3 (b). Because of the small radius of curvature of the streamlines close to the rear of the ellipsoidal drop, the collection efficiency is quite high. This stresses the point that the directions of the drop and air/dust particle movement, as well as the shape of the drops, are of fundamental importance to particle collection.
The ellipsoidal drop is just an intermediate state of the disintegration process. With progressing drop deformation, another important intermediate state is reached in which the liquid is spread out in a parachute-like lamella. In this state, the surface of the drop available for particle collection has attained its maximum. The active particle collection surface is the inner surface of the parachute-like lamella. Close to this area, the air streamlines are reversed while the dust particles remain almost unaffected by this movement and impinge on the surface of the lamellae.

The parachute is characterized by the thin liquid lamella and also by the liquid torus at the rim of the lamella and, at the breaking points of the torus, by small drops. On account of inertial forces, the liquid torus will break away from the lamella and disintegrate into small drops. At the rim of the remaining lamella, a new torus will build up, break away and disintegrate into secondary drops. This process repeats itself until the originally large drop is split up into small drops containing the dust particles. Dust particle collection is most effective in the intermediate states of ellipsoidal drops and parachute-like lamellae.

4.3.3 Particle collection mechanism in the venturi scrubber

In a venturi scrubber, liquid is atomized by high velocity air at the entrance to the throat section. Particles from air are collected by water drops.

Calvert (1972; 1984) described particle collection in a venturi as follows:

$$\frac{dc}{c} = \frac{Q_w}{Q_a} \frac{4R_d}{55\mu_a} \rho_w V_a \eta df$$  \hspace{1cm} 4.13
Equation 4.13 is modified for particle collection by water drops, based on the following assumptions:

1. Particles are collected only by atomized liquid.

2. The collection of particles by single drops is inertial and based on the relative velocity between the drop and the air. The inertial collection efficiency of the drop is approximated by

\[
\eta = \left[ \frac{K}{K + 0.7} \right]^2 
\]

where \( K \) is the inertial impaction parameter

\[
K = \frac{2C' \rho_p R_p^2 V_r}{9\mu_a R_d} 
\]

\[
C' = 1 + \frac{6.21 \times 10^{-4}}{d_p} T
\]

The Cunningham slip correlation factor becomes negligible for particles larger than approximately 1 \( \mu \)m under normal conditions.

3. The acceleration of liquid drops is approximated by

\[
x = \frac{55}{Re_r}
\]

where

\[
Re_r = \frac{V_r \rho_a d_d}{\mu_a}
\]

Assuming efficiency varies linearly with \( f \),

\[
\frac{\eta_a}{\eta} = f_a / f
\]
The use of equation 4.16 in 4.13 resulted in the following equation

\[-\ln \frac{C_{\text{out}}}{C_{\text{in}}} = \left[13,500 \text{ L} + 1.2 \text{ L}^2 V_a\right] \times \left(\frac{\eta_{a,f}}{2}\right) \times 10^{-4}\]  

4.17

Rather than using the assumption of equation 4.16, equation 4.17 has been modified to account for the point-by-point variation of collection efficiency with relative velocity.

Utilizing the definition

\[V_r = fV_a\]  

4.18

We obtain

\[K = \left[\frac{2C \rho \rho_p^2 V_a}{9 \mu_a R_d}\right] f = K_2 f\]  

4.19

and

\[\eta = \left[\frac{K_2 f}{K_2 f + 0.7}\right]^2\]  

4.20

Substituting equation 4.20 in 4.13 gives

\[
\int_{C_{\text{in}}}^{C_{\text{out}}} \frac{dc}{c} = \frac{4Q_w R_d \rho_w V_a K_2^2}{55Q_a \mu_a} \times \int_0^f \left[\frac{K_2 f}{K_2 f + 0.7}\right]^2 df
\]  

4.21

Integration of equation 4.21 yields

\[\ln \frac{C_{\text{out}}}{C_{\text{in}}} = \left(\frac{4Q_w R_d \rho_w V_a}{55Q_a \mu_a}\right) f(K_2, f)\]  

4.22

where

\[f(K_2, f) = \frac{1}{K_2} \left[-0.7 - K_2 f + 1.4 \ln \frac{K_2 f + 0.7}{0.7} + \frac{0.49}{0.7 + K_2 f}\right]\]  

4.23

Equation 4.22 and 4.23 were used for calculating the theoretical efficiency of the scrubber.
4.4 GENERAL DESCRIPTION OF THE PROTOTYPE SCRUBBER

4.4.1 General description

The basic scrubber unit consists of an air powered venturi (Senior Australia Pty Ltd, 1991) water spray arrangement and a wavy blade type water droplet eliminator. Compressed air is used instead of a fan to move the air and to help atomise the water. Primary compressed air enters the manifold of the venturi through a radial connection and is released through the annular gap to accelerate over the aerofoil section as shown in Figure 4.4. Secondary air is induced into the throat of the venturi scrubber because of the vacuum created by the injected compressed air. The ratio of induced air to primary compressed air used varies between 10 and 25 depending on the load conditions.

A non-wetted approach was used with water introduced at the throat rather than on the walls of the converging inlet section of the scrubber. A full cone wide angled spray nozzle with 1.6 mm diameter orifice was used in the scrubber. The nozzle was located 150 mm above the throat and was directed towards it. This arrangement ensured that the water spray covered the full pipe before the venturi throat and properly distributed the water. The water pressure was 1000 kPa (150 psi).

An impingement vane type water droplet eliminator (Figure 4.5), positioned approximately 0.6 m downstream of the venturi scrubber, removed the water droplets along with the dust particles. Two stages were used in the demister to remove the water from the cleaned discharge air stream. The demister vanes were made from galvanised zinc sheets. The demister box could be removed from the scrubber.
Figure 4.4  A schematic diagram of the prototype air powered venturi scrubber.

Figure 4.5  Photograph of the demister used in the prototype scrubber.
very easily for repairs, if necessary. The slurry of dust particles was drained, by gravity, into a sump and was piped away from the scrubber.

The size of the scrubber unit is 0.17 m $\phi$ x 1.0 m long with a venturi throat of 100 mm diameter. The demister unit dimensions are 0.2 m x 0.2 m x 0.3 m. The total length of the unit was 1.2 m which easily fits in one chock shield. Figure 4.6 shows a photograph of the prototype scrubber unit.

4.4.2 Principle

The mechanism affecting collection of particles in the venturi scrubber are numerous. The physical phenomena involved are inertia, diffusion, electrostatics, brownian motion, nucleation growth and condensation. All of these affect particulate collection in a venturi scrubber, but it is generally agreed that the predominant phenomenon is inertia. The detailed mechanism of dust particle collection in the venturi scrubber is given in section 4.3.3.

The throat is the narrowest section of the venturi scrubber. The dust laden induced air is accelerated to high velocity (70 m/s) in the venturi throat section. This high velocity converts the static pressure head to kinetic energy. Water introduced to the throat is atomised by the high velocity air into very fine droplets and the high differential velocity between the air and atomised water droplets causes the airborne particles and fine water droplets to impact. In the expander section, the air slows down as the cross sectional area increases and some of the kinetic energy from the water droplets transfers back to the air stream pressure energy.
Chapter 4: Scrubber Development

Figure 4.6 Photograph of the prototype scrubber developed in the laboratory.
A venturi scrubber removes dust from air more efficiently when the scrubbing fluid is effectively atomized. Cloud type Atomization has been used in this prototype scrubber to produce sufficient inertial impaction targets for particle collection and to produce a high surface area for absorption. It also keeps the droplet acceleration rate as low as possible and provides the greatest velocity difference between the particles being collected and the droplet target.

In the demister unit, curved profile blades are arranged to create separate parallel flow channels. The operation involves three stages: (i) the mist flow is divided at the bends because while the air flows through the bends, centrifugal forces prevent the water drops from following the air flow (ii) the inertial force created by the deflecting mist stream causes water drops to impinge on the blades and form a liquid film, and (iii) the film is forced towards phase separating downwind bends by the air stream and drops to the sump by gravity. Mist collection pockets at the bends were tried but it was found that more water drops were dispersed into the air stream due to the high air velocity and short demister length. Therefore, to channel the water film into the sump, some air quantity was allowed to leak towards the sump. This compact unit has a low pressure drop and a low clogging potential.

4.4.3 Advantages

Along with a high dust collection efficiency, the venturi scrubber also possesses most of the other characteristics desirable for a good underground scrubber. Some of the advantages of this prototype air powered scrubber are:

1. simple and very compact;
2. no fan or electric / hydraulic motor to maintain;
3. virtually maintenance free - no clogging, self cleaning;
4. high pressure water pumps are not required;
5. no electricity needed
   - very safe in high gas areas - no inherent permissibility problems;
6. can be easily installed in a longwall face;
7. uses very little water compared with a water powered scrubber;
8. does not split the air stream - no purge or bleed air;
9. uses facilities that are normally available in the face and does not need any special equipment for its operation.

4.5 LABORATORY STUDIES

A special wind tunnel facility was constructed in the laboratory so that a quantitative evaluation of the air powered venturi scrubber could be carried out. The facility is shown schematically in Figure 4.7. The test facility consisted of the following major elements. (1) ducting (2) measuring probes (3) dust feeding arrangement, (4) blower for dust dispersion (5) pitot static tubes and (6) Du Pont personal samplers. The test assembly is approximately 8 m long and the scrubber being tested was placed in the centre of a horizontal section of duct. Ducts of 300 mm diameter were used to keep frictional losses to a minimum yet maintain adequate transport velocity for dust tests. Ducts were fitted with a plexiglass side panel to allow observation of dust flow, samplers position etc. through the unit. Duct sections were made from 4 mm thick plastic with glued joints. This kept air leakage between sampling points to a minimum. The duct is designed for air velocity in the order of 5 to 10 m/s. These medium velocities helped to avoid sampling problems associated with high air velocities.
A vibrator type dust feeder was located at the inlet, to provide a constant respirable dust flow between 1 and 100 mg/m³ during dust collection efficiency tests. Dust from the vibrator was dispersed into the wind tunnel by a blower. The coal dust feed rate was controlled by a high turn-down ratio of the vibrator feeder thus providing a good control on dust flow. A blower was used to discharge dust in front of the ducting. With this dust feeding arrangement, a wide range of respirable dust concentrations and size distributions, typical of coal mine face operations, could be set up and maintained for long periods, thus enabling systematic evaluation of prototype scrubbers.
For the laboratory results to be more meaningful, it was decided to use coal dust which is similar to mine dust in size distribution. To prepare the coal dust for tests, coal pieces were ground in a ring pulveriser and then sieved through a 100 μm mesh. The fine pulverised dust has a size distribution similar to that of airborne coal mine dust, as indicated in Figures 4.8 and 4.9. Most tests were conducted with respirable dust concentration of between 8 and 30 mg/m³. Various dust concentrations were achieved by changing the feed rate on the vibrator feeder.

Dust sampling cyclones and pitot static tubes were positioned in the ducts before, and after, the scrubber to measure dust concentration, pressure drop and air velocity upstream and downstream of the scrubber. The dust sampling cyclones were positioned 1 m upstream and 3 m downstream of the scrubber. A series of tests were conducted to determine the dust capturing efficiency of the prototype scrubber, and involved the measuring of airborne dust concentration with gravimetric samplers, before and after passing through the scrubber. The dust capturing efficiency was thus measured as a reduction of respirable dust concentration at the outlet.

During these investigations the samplers were operated for a period of 30 to 50 minutes and the weight of dust collected was determined after the experiment. Time averaged gravimetric dust concentrations over the entire sampling period were calculated based on the mass collected on the filters, sampling time and the pump flow rate.

The concentration of respirable dust was calculated using the following formula:

\[
x = \frac{m_2 - m_1}{r \cdot t} \times 1000
\]

where,
- \( x \) = concentration of respirable dust (in mg/m³)
- \( m_1 \) = mass of filter before use (mg)
- \( m_2 \) = mass of loaded filter after use (mg)
Figure 4.8  Typical size distribution of airborne respirable coal dust used in the laboratory experiments.

Figure 4.9  Typical cumulative size distribution of airborne respirable coal dust used in the laboratory experiments on log-probability scale.
The air flow rate through the sampling pump is given by \( r \) (1/min) and the duration of sampling is given by \( t \) (minutes).

The efficiency of the scrubber is calculated by

\[
\eta = \left( \frac{x_1 - x_2}{x_1} \right) \times 100 \% 
\]

where, \( x_1 \) = respirable dust concentration at inlet to the scrubber (mg/m\(^3\))
\( x_2 \) = respirable dust concentration at outlet of the scrubber (mg/m\(^3\))

Airflow through the scrubber was measured with an anemometer and confirmed with pitot tube measurements in the ducting, and the pressure drop was measured using pitot static tubes and a manometer. Compressed air consumption and water consumption were also measured with flow meters connected to the lines. The rate of water flow through the nozzle was varied by changing the pressure to the nozzle and the nozzle orifice diameter. The air flow was varied between 0.3 and 0.7 m\(^3\)/s and water flow rate varied between 2.0 and 6.0 l/min.

### 4.6 RESULTS AND ANALYSIS

Results of the laboratory investigations carried out to determine the efficiency of the scrubber are given in Tables 4.1 to 4.2. It can be seen that at a water flow rate of 2.5 l/min for 0.55 m\(^3\)/s the scrubber efficiency is only 85%. By maintaining approximately the same air flow and increasing the water flow to 4 l/min, the efficiency increased to 90%. A further increase in the spray water rate to 6 l/min increased the scrubber efficiency to 92%. In summary, these experiments demonstrated 92% dust collection efficiency at a maximum air pressure differential and maximum water flow rate, i.e. 240 mm of wg and 6 l/min per 0.5 m\(^3\)/s respectively. The relatively low efficiency of 92% for this prototype scrubber is mainly due to the low water usage and very short length.
Table 4.1  Efficiency of the scrubber - Results of laboratory experiments  
(at 2.0 - 2.5 l/min water flow rate).

<table>
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<tr>
<th>Sl. No.</th>
<th>Airflow (m³/s)</th>
<th>Pressure drop (mm wg)</th>
<th>Water flow at 700 kPa (l/min.)</th>
<th>Upstream res.dust conc. (mg/m³)</th>
<th>Downstream res.dust (mg/m³)</th>
<th>Scrubbing efficiency (%)</th>
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Table 4.2 Efficiency of the scrubber - Results of laboratory experiments (at 4.0 - 6.0 l/min water flow rate).

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<th>Airflow (m³/s)</th>
<th>Pressure drop (mm wg)</th>
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Analysis of the results shows that the dust collection efficiency is a function of the water/air ratio for various throat velocities. Table 4.3 and Figure 4.10 shows that the efficiency of the scrubber increases with an increase in water quantity, and that a minimum of 5.0 to 6.0 l/min of water is required to achieve greater than 90% efficiency. A further increase in water pressure and quantity would increase efficiency, but it would not be practicable in some longwall faces owing to soft floor conditions.

The mist eliminator on the scrubber acts as a trap for water droplets carried with the air stream and was very efficient at less than 12 m/s air velocity. It also knocks down some dust particles, making it a second scrubber. When the air velocity was between 12 m/s and 17 m/s, some re-entrainment of water out of the primary drain sump was observed. This flow was stopped by adding a horizontal metal strip inside the demister frame which, in effect, extended the sump plate beyond the back edges of the demister vanes.

Table 4.3  Comparison of scrubber efficiency at different water flow rates

<table>
<thead>
<tr>
<th>S.No.</th>
<th>water flow (l/min)</th>
<th>scrubber efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>79.15</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>85.30</td>
</tr>
<tr>
<td>3</td>
<td>4.0</td>
<td>89.80</td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
<td>92.45</td>
</tr>
</tbody>
</table>
Figure 4.10 Efficiency of the prototype scrubber at different water flow rates.

Table 4.1 also show the effect of varying the air quantity and pressure drop on the scrubber's efficiency. When the air quantity was less than 0.3 m$^3$/s (600 cfm) the efficiency was very low, because at such low airflow quantity, the velocity of air through the venturi throat is very low and cannot atomise the water droplets. Tests shows that a minimum of 0.4 m$^3$/s (800 cfm) air is required for effective Atomization of the water.

When the airflow was increased to 0.65 m$^3$/s (1300 cfm), under the same conditions, the efficiency dropped to 89% due to a low water/air ratio. More importantly, it was found that when airflow was greater than 0.65 m$^3$/s, or exit velocities were more than 20 m/s, the scrubber discharge still had some water drops. A larger demister was therefore needed which would not meet the design requirements. Thus in meeting the design criteria, the quantity of air flowing through the scrubber should be between 0.4 and 0.65 m$^3$/s (800 cfm and 1300 cfm). At this level of airflow, it was observed that the demister was effective and the effluent air stream was free of visible water drops.
As the overall efficiency of the scrubbers is dependent on the particle size distribution of the airborne dust, it was important to ascertain the size dependent efficiency of the scrubber. In addition, size fraction efficiency is most valuable for scrubbers intended for mining applications. Size distribution of the upstream and downstream dust samples from the scrubber are shown in Figures 4.11 - 4.13, and the efficiency of the scrubber over various sizes is shown in Table 4.4 and Figures 4.14 - 4.16. These results show that the removal efficiency of the scrubber is 63%, 88% and 97% respectively for 0.5 to 1.5, 1.5 to 3.0 and 3.0 to 7.0 micron size ranges. As the median size of the respirable particles in longwall faces is well above 3 microns, this scrubber can be successfully used to remove the dust in the longwall face.

Figure 4.11  Size distribution of scrubber's inlet and outlet respirable dust when the water flow through the scrubber is 2.5 l/min.
Figure 4.12  Size distribution of scrubber's inlet and outlet respirable dust when the water flow through the scrubber is 4.0 l/min.

Figure 4.13  Size distribution of scrubber's inlet and outlet respirable dust when the water flow through the scrubber is 6.0 l/min.
Table 4.4  Scrubber efficiency over various particle size ranges

<table>
<thead>
<tr>
<th>particle size (μm)</th>
<th>collection efficiency at water flow of (2.5 l/min)</th>
<th>(4.0 l/min)</th>
<th>(6.0 l/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.8</td>
<td>58.3</td>
<td>63.5</td>
</tr>
<tr>
<td>2</td>
<td>76.6</td>
<td>82.8</td>
<td>86.6</td>
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<tr>
<td>3</td>
<td>85.1</td>
<td>90.2</td>
<td>93.9</td>
</tr>
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<td>4</td>
<td>88.9</td>
<td>93.1</td>
<td>96.2</td>
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<tr>
<td>5</td>
<td>93.1</td>
<td>95.3</td>
<td>97.0</td>
</tr>
</tbody>
</table>

Figure 4.14  The size dependent efficiency curve of the prototype scrubber at a water flow of 2.5 l/min.
Figure 4.15 The size dependent efficiency curve of the prototype scrubber at a water flow of 4.0 l/min.

Figure 4.16 The size dependent efficiency curve of the prototype scrubber at a water flow of 6.0 l/min.
When the simplified theoretical collection efficiency equations (4.22 and 4.23), presented in section 4.3, were applied to the prototype scrubber, efficiency values between 75% and 99% were obtained for particles in the range of 1 to 5 μm as illustrated in Table 4.5 and Fig 4.17. The efficiency values shown were determined by using a mean water mist cloud size of 300 μm. The relative velocity value used was a rough approximation, obtained from the difference between the calculated air velocity in the throat and the water drop inlet velocity. The efficiency values shown in Figure 4.17 indicate that satisfactory results are theoretically possible for particle sizes down to 1 μm in diameter. The relationships between efficiency, water flow and particle size indicates that only a marginal change in the theoretical efficiency occurs with changes in the water flow for particles sized 8 μm and above. Conversely, for particles of approximately 1 μm the Equation 4.22 indicates that changes in water flow can cause major changes in the collection efficiency.

<table>
<thead>
<tr>
<th>particle size (μm)</th>
<th>collection efficiency at water flow of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(2.5 l/min)</td>
</tr>
<tr>
<td>1</td>
<td>63.2</td>
</tr>
<tr>
<td>2</td>
<td>81.5</td>
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<tr>
<td>3</td>
<td>87.6</td>
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<td>4</td>
<td>91.3</td>
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<tr>
<td>5</td>
<td>94.5</td>
</tr>
</tbody>
</table>
Figure 4.17  Theoretical efficiency curve of the prototype scrubber for various particle sizes at different water flow rates.

A comparison of theoretical and experimental efficiency values is given in Figures 4.18 and 4.19. It can be seen that the theoretical values were higher than the experimental values. The major reasons for this discrepancy are: (i) the majority of water drop clouds are far from uniform in size and are in the range of 100 to 500 μm (ii) the relative velocity between the water drops and dust particles is not constant throughout the length of the scrubber and is also extremely difficult to determine.
Figure 4.18  Comparison between theoretical predictions and experimental results of scrubber's efficiency at 2.5 l/min water flow.

Figure 4.19  Comparison between theoretical predictions and experimental results of scrubber's efficiency at 6.0 l/min water flow.
4.7 SUMMARY

A critical review of dust control research showed that very little research had been conducted into reducing dust make from principal sources of dust other than the shearer, such as from support advance, coal spalling from the face and goaf falls etc. During the field investigations carried out in two longwall faces (described in sections 3.4.2 & 3.6.1) it was observed that even though the shearer is the major source of dust, in many cases a considerable portion of the dust was produced during support movement and face spalling. Therefore there was a need to develop a new technique which could be used to reduce the respirable dust once it became airborne. With this objective in mind, the use of a multi-scrubber system along the walkway of the longwall face was proposed.

The aim of the multi-scrubber system proposed was to reduce miners' dust exposure along the walkway rather than concentrating on reducing total face respirable dust levels. The multi-scrubber system uses a number of moderate capacity scrubbers to deliver cleaned air at high velocity into the front walkway area, and thus create a relatively clean air zone in the face. As there was no scrubber suitable for use in longwall faces, it was first necessary to design and develop a prototype scrubber in the laboratory to investigate this concept.

The design requirement of the scrubber system was to produce a relatively simple, efficient, small and practical unit suitable for operating in the longwall face. The basic scrubber unit consists of an air powered venturi, a water spray arrangement and a wavy blade type water droplet eliminator. Compressed air was used, instead of a fan, to move the air and and to help atomise the water. A prototype air-powered venturi scrubber was developed for use in longwall faces. The total length of the unit was
1.2 m and can be fitted into one chock shield very easily. An impingement vane type demister was used in the scrubber.

A special wind tunnel facility was constructed in the laboratory to carry out a quantitative evaluation of the air powered venturi scrubber. Coal dust, which is similar to mine dust in size distribution, was used during the laboratory studies. During these experiments the maximum respirable dust collection efficiency of 92% was obtained at an air pressure differential of 240 mm of water gauge and a water flow rate of 6 l/min per 0.5 m³/s of air. The relatively low efficiency (92%) of this prototype scrubber is mainly due to the low water usage and very short length. When air pressure and the nozzle water flow rate were not adjusted properly the scrubber performed very poorly. Results of the laboratory tests showed that air pressure, airflow and water flow are predominant factors in the scrubber's performance. The evaluation of prototype scrubber's performance in the field is discussed in chapter 5.
Chapter 5

FIELD TESTING OF THE PROTOTYPE SCRUBBER

Extensive field investigations were conducted in three longwall faces to evaluate the effectiveness of the prototype scrubber and the multi-scrubber system in providing a clean air zone along the walkway. These longwalls, 'A', 'B' and 'C', described in chapter 3, were located in the southern district of New South Wales and had the worst dust compliance record, and different working conditions. The main characteristics of the longwall faces are listed in Table 5.1. Only one scrubber was tested in 'A' and 'B', whereas in face 'C' two scrubbers were operated simultaneously to determine the effect of the upwind scrubber on the downwind scrubber. Tests were also conducted to investigate the effectiveness of change in the scrubber capacity and their location.

Respirable dust data obtained from field surveys and described in chapter 3 showed that there were large dust gradients across the face. Therefore, the selection of sampling locations was extremely important during evaluation of dust control techniques. A change in sampling location during a survey could have a greater effect on the measured dust concentration than the control technique being evaluated. The studies also showed that whilst the dust profile patterns were similar during different cuts, the average dust concentration levels varied greatly. It was therefore considered that the evaluation of the scrubbers should include simultaneous dust sampling upwind and downwind of the scrubber.

Gravimetric personnel samplers in fixed positions were used to evaluate the system's effectiveness. The results of the field study are reported as dust reductions at the
operator's position rather than reductions in the return airway which, due to Australian Coal Mines' compliance requirements, is a reasonable approach.

Table 5.1. Main characteristics of the longwall faces - scrubber evaluation

<table>
<thead>
<tr>
<th>Face</th>
<th>Seam thickness (m)</th>
<th>Face length (m)</th>
<th>Cutting direction</th>
<th>Ventilation</th>
<th>Air velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.1 - 2.5</td>
<td>100</td>
<td>with ventilation</td>
<td>homotropal</td>
<td>2.0 - 2.2</td>
</tr>
<tr>
<td>B</td>
<td>2.2 - 2.7</td>
<td>200</td>
<td>against ventilation</td>
<td>antitropal</td>
<td>3.8 - 4.5</td>
</tr>
<tr>
<td>C</td>
<td>2.1 - 2.5</td>
<td>150</td>
<td>with ventilation</td>
<td>homotropal</td>
<td>1.8 - 2.1</td>
</tr>
</tbody>
</table>

5.1 FIELD INVESTIGATIONS

Testing was conducted with the simplest and most practical arrangement. The scrubber was chained to the canopy in an horizontal position. It was installed near the front legs, 0.3 m below the roof canopy, in the front walkway, which all face personnel habitually use rather than the walkway between the front and back legs (Figure 5.1). If installation at this position were to obstruct the workers, it could be installed in the back walkway and clean air could be ducted to the front walkway. An adequate supply of compressed air and water was available at the longwall faces, hence it was not necessary to install any new compressors or high pressure pumps underground.

The compressed air and water supply to the scrubber consisted of 38 to 50 mm hose lines running along the face. All hoses were heavy duty material and suitable for mines. The 38 mm air supply had a filter and water trap mounted in the line near the intake airway which, in turn, was connected to main supply line. Each scrubber was
Figure 5.1(a) Position of scrubber and sampling arrangement during field investigations in a longwall face.

Figure 5.1(b) Position of the scrubber across the section of the longwall face during field investigations.
connected to the compressed air and water lines through ball valves, which allowed each scrubber to turn on and off. Snap couplings were used for easy installation. The scrubber system used the mine’s water supply, connections to which were also of the snap coupling type for easy installation. The scrubber sump discharge was piped to the floor of the chocks and then to the goaf to prevent water spilling on to the miners.

5.1.1 Sampling procedure

To determine the effectiveness of the scrubber system in providing a clean air zone along the walkway dust was sampled simultaneously upwind and downwind of the scrubber using gravimetric samplers. The sampling instruments used during these studies are described in chapter 3. Both upwind and downwind sampling instruments were located in the walkway and were positioned 0.3 to 0.5 m below the roof to read the dust concentration in the miners’ normal breathing zone. The position of sampling stations is shown in Figure 5.1(a). Downstream samplers were located at distances of 1.5 m, 3.0 m and at 4.5 m from the scrubber. At each station, two samplers were used to ensure accuracy and to obtain valid average dust readings.

Du Pont model P-2500 samplers, set at 1.9 l/min, and cassella cyclones with pre-weighed filters were used throughout the investigations. The sampling cyclones were positioned next to the instrument, to shield them from the effects of high velocity. Dust samples were collected for about 40 to 60 minutes. The samplers were turned on when the shearer cutting out at the maingate and turned off when the shearer was at the same point later in the shift. If production stopped for any length of time, all gravimetric samplers were turned off and the time was recorded and when production resumed the samplers were re-started and the time recorded. Production during the sampling period was about 400 to 800 tonnes.
5.1.2 Protection efficiency

In the laboratory, samplers at the downstream sampling position were only exposed to the scrubber clean air. No contaminated air infiltrated into the downstream sampling position, and therefore the scrubber's efficiency in the laboratory refers to the dust reduction in the air that actually passed through the scrubber. In the field, however, the downstream samples were exposed to mixture of clean air from the scrubber exhaust and some contaminated air which did not pass through the scrubber. The resulting average respirable dust readings were used to determine the percentage reduction of dust in the walkway in front of scrubber, referred to as the 'protection efficiency of the system'. The degree of turbulence and consequent mixing of clean and contaminated air determines the protection efficiency of the scrubber system. In this case the reduction represents the efficiency of the total system including the effect of the scrubber capacity, air velocity and location of the scrubber as well as, face air velocity.

5.2 RESULTS AND ANALYSIS

5.2.1 Experiments in longwall face A

The field investigations were carried out with a 0.5 m³/s capacity scrubber and the water flow through the nozzle was maintained at 6.0 l/min. Table 5.2 summarises the results obtained during the underground evaluation of the prototype scrubber in longwall face A. Typically, the dust concentration upstream of the scrubber was 3.59 mg/m³ and at 1.5 m, 3 m and 4.5 m downstream of the scrubber the dust levels were 1.19, 1.86, and 2.38 mg/m³, respectively. The protection efficiency declined with increasing distance from the scrubber, as shown in Figure 5.2 A photograph of the field installation of the scrubber in the longwall face is shown in Figure 5.3.
Table 5.2  Scrubber evaluation - Results of experiments in face A

<table>
<thead>
<tr>
<th>s.no.</th>
<th>Respirable dust concentration (mg/m³)</th>
<th></th>
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</thead>
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<td></td>
<td>upstream side</td>
<td>downstream side</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.21</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>downstream samplers at 1.5 m away from scrubber</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.95</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.41</td>
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<td>2.03</td>
</tr>
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<td>2.97</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>3.63</td>
</tr>
<tr>
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<td>1.69</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1.62</td>
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<td>downstream samplers at 3.0 m away from scrubber</td>
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</tr>
<tr>
<td></td>
<td>15</td>
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<td>19</td>
<td>3.21</td>
</tr>
<tr>
<td></td>
<td>downstream samplers at 4.0 m away from scrubber</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.80</td>
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</tbody>
</table>
Figure 5.2  Typical variation in protection efficiency of the system with distance from the scrubber in longwall face A.

Figure 5.3  Field installation of the prototype scrubber in longwall face A.
Overall, the results showed that an average protection efficiency of 50% can be obtained at a distance of 3 m from the scrubber, at a moderate face air velocity of 2.1 m/s. The velocity of the clean air exhausted from the scrubber was 10 m/s, and at 3 m downstream the air velocity was 3 m/s which was about 2.0 - 2.5 times the normal face air velocity at that location.

A comparison of the typical dust concentration profiles along the face with, and without, the scrubber are shown in Figures 5.4 - 5.5. It can be seen that dust concentration levels around the scrubber were 50% lower with the scrubber operating. Typical dust concentration profiles across the section of the face, 3 m downstream of the scrubber, are shown in Figures 5.6 - 5.7. It can be seen that the scrubber system provides a clean air zone near the miners' breathing area. The installation of scrubber also resulted in a 33% reduction in dust level in between the chock legs.

Field tests were carried out to investigate the effect of scrubber capacity and exhaust air velocity on dust concentration levels. When the scrubber capacity was reduced from 0.5 to 0.3 m$^3$/s, the average dust concentration 3 m downstream of the scrubber dropped from 4.6 mg/m$^3$ to 3.36 mg/m$^3$, i.e by 27%. That scrubber capacity was inadequate to achieve any reasonable reduction in dust levels, and a further decrease in scrubber capacity to 0.2 m$^3$/s resulted in only 12% reduction in dust levels.
Figure 5.4 Respirable dust concentration profiles along the longwall face A with, and without, scrubber for experiment 1.

Figure 5.5 Respirable dust concentration profiles along the longwall face A with, and without, scrubber for experiment 2.
Figure 5.6  Respirable dust concentration profiles across the longwall face A with, and without, scrubber (at 3m downstream) for exp. 3.

Figure 5.7  Respirable dust concentration profiles across the longwall face A with, and without, scrubber (at 3m downstream) for exp. 4.
5.2.2 Experiments in longwall face B

The results of the field tests with the scrubber at longwall face B are given in Table 5.3. The scrubber capacity was 0.5 m$^3$/s (1000 cfm) of air, and the water flow through the nozzle was 6.0 l/min. The dust concentration upstream of the scrubber was 5.14 mg/m$^3$ and at 1.5 m, 2.2 m and 4.5 m downstream of the scrubber, the dust levels were respectively 3.03, 3.5, and 3.95 mg/m$^3$. The results showed an average protection efficiency of 26%, with a high face air velocity of 4.5 m/s and this reduced efficiency was caused by the high turbulence generated by the high face air velocity. The protection efficiency varied with distance from the scrubber, and as shown in Figure 5.8, decreased as distance from the scrubber increased.

A comparison of the typical dust concentration profiles along the face with, and without, the scrubber, given in Figures 5.9 - 5.10, shows that with the scrubber the dust levels were 26% lower. Typical dust concentration profiles across the face, 3 m downstream of the scrubber, are shown in Figures 5.11 - 5.12. They show that the scrubber system provides a clean air zone in the miners' breathing zone. The scrubber also reduced the dust level in between the chock legs by 15%. The effect of the scrubber location on dust protection efficiency was also investigated. When the scrubber was located 1.2 m below the roof canopy in the front walkway, the dust concentration only decreased from 5.62 mg/m$^3$ to 5.23 mg/m$^3$, a 7% reduction. This variation in scrubber performance with scrubber location was caused by the primary ventilation airflow patterns in the longwall face.
Table 5.3  Scrubber evaluation - Results of Experiments in Face B

<table>
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<th>Respirable dust concentration (mg/m$^3$)</th>
<th>% reduction</th>
</tr>
</thead>
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<td>downstream side</td>
</tr>
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<td></td>
</tr>
<tr>
<td>1</td>
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<td>3.05</td>
</tr>
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<td>3.11</td>
</tr>
<tr>
<td>4</td>
<td>7.40</td>
<td>4.92</td>
</tr>
<tr>
<td></td>
<td>downstream samplers at 1.5 m away from scrubber</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9.07</td>
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<td>11</td>
<td>9.72</td>
<td>6.47</td>
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<td>downstream samplers at 2.2 m away from scrubber</td>
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</tr>
<tr>
<td>12</td>
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<td>downstream samplers at 3.0 m away from scrubber</td>
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</tr>
<tr>
<td>15</td>
<td>6.81</td>
<td>6.23</td>
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<td></td>
<td>downstream samplers at 4.5 m away from scrubber</td>
<td></td>
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</table>
Figure 5.8  Typical variation in protection efficiency of the system with distance from the scrubber in longwall face B.

Figure 5.9  Respirable dust concentration profiles along the longwall face B with, and without, scrubber for experiment 1.
Figure 5.10  Respirable dust concentration profiles along the longwall face B with, and without, scrubber for experiment 2.

Figure 5.11  Respirable dust concentration profiles across the longwall face B with, and without, scrubber (at 3m downstream) for exp. 3.
Figure 5.12  Respirable dust concentration profiles across the longwall face B with, and without, scrubber (at 3m downstream) for exp. 4.

5.2.3 Experiments in longwall face C

As in longwall faces 'A' and 'B' the scrubber capacity was 0.5 m$^3$/s of air and the water flow was 6.0 l/min at longwall face C. Figure 5.13 shows the scrubber installation in longwall face 'C'. Results of the underground investigations carried out with the prototype scrubber in longwall face 'C' are given in Tables 5.4 - 5.5. The dust concentration upstream of the scrubber was 4.43 mg/m$^3$ and at 1.5 m, 3 m and 4.5 m downstream of the scrubber the dust levels were respectively 1.67, 2.08, and 2.96 mg/m$^3$. The results showed that an average protection efficiency of 57% being obtained at a distance of 3 m from scrubber, at a moderate face air velocity of 1.9 m/s. The scrubber's clean air exhaust velocity at 3 m downstream was 3.2 m/s which was about 2.3 times the normal air velocity at that location.
Figure 5.13 Scrubber installation in longwall face C.

Table 5.4 Scrubber evaluation - Results of Experiments in Face C

<table>
<thead>
<tr>
<th>s.no.</th>
<th>Respirable dust concentration (mg/m³)</th>
<th>% reduction</th>
</tr>
</thead>
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</tr>
<tr>
<td></td>
<td>downstream samplers at 1.5 m away from scrubber</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9.36</td>
<td>4.76</td>
</tr>
<tr>
<td>5</td>
<td>8.54</td>
<td>2.88</td>
</tr>
<tr>
<td>6</td>
<td>7.80</td>
<td>3.30</td>
</tr>
<tr>
<td></td>
<td>downstream samplers at 3.0 m away from scrubber</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4.90</td>
<td>3.09</td>
</tr>
<tr>
<td>8</td>
<td>4.03</td>
<td>2.92</td>
</tr>
</tbody>
</table>
Additional testing was conducted with two scrubbers operating simultaneously at 4.5 m apart to ascertain the effect of the first scrubber on the second. The results of these tests are shown in Table 5.5. The typical dust concentration upstream of the scrubber was 4.79 mg/m³ and at 3 m downstream of the first and second scrubber the dust levels were 2.02 and 2.25 mg/m³ respectively. Analysis shows that there was no big difference in the protection effected by the two scrubbers and the presence of the upwind scrubber did not affect the performance of the downwind scrubber. Figure 5.14 shows that the protection efficiency decreases with increasing distance from the scrubbers. A comparison of the typical dust concentration profiles along the face with, and without, the scrubber are shown in Figures 5.15 - 5.16 and profiles across the face are shown in Figures 5.17 - 5.18. These figures show that the scrubber system provides a clean air zone along the walkway.

Figure 5.14 Typical variation in protection efficiency of the system with distance from the scrubber in longwall face C.
Table 5.5  Scrubber's evaluation - Results of Experiments in Face C (two scrubbers)

<table>
<thead>
<tr>
<th>s.no.</th>
<th>Respirable dust concentration (mg/m³)</th>
<th>% reduction</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>upstream side</td>
<td>downstream side</td>
<td></td>
</tr>
<tr>
<td></td>
<td>s.no.</td>
<td>upstream side</td>
<td>downstream side</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.88</td>
<td>3.23</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>9.52</td>
<td>2.43</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4.43</td>
<td>1.89</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>8.49</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>downstream samplers at 1.5 m away from scrubber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>4.79</td>
<td>2.01</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>8.68</td>
<td>5.01</td>
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<td>3.01</td>
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<td>3.59</td>
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<tr>
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<td></td>
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<td>2.86</td>
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<td>12</td>
<td></td>
<td>4.43</td>
<td>2.21</td>
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<td>7.97</td>
<td>4.23</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>9.52</td>
<td>3.72</td>
</tr>
<tr>
<td></td>
<td>downstream samplers at 3.0 m away from scrubber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>8.68</td>
<td>5.79</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>4.79</td>
<td>2.92</td>
</tr>
<tr>
<td>17</td>
<td></td>
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<td>3.84</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>8.88</td>
<td>5.13</td>
</tr>
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<td></td>
<td>9.52</td>
<td>6.68</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>4.79</td>
<td>3.14</td>
</tr>
</tbody>
</table>
Figure 5.15  Respirable dust concentration profiles along the longwall face C with, and without, scrubber for experiment 1.

Figure 5.16  Respirable dust concentration profiles along the longwall face C with, and without, scrubber for experiment 2.
Figure 5.17  Respirable dust concentration profiles across the longwall face C with, and without, scrubber (at 3m downstream) for exp. 3.

Figure 5.18  Respirable dust concentration profiles across the longwall face C with, and without, scrubber (at 3m downstream) for exp. 4.
The typical dust concentration profiles along and across the face with two scrubbers installed are shown in Figures 5.19 - 5.21. They show that dust levels 3 m downstream of the scrubbers were reduced by about 57%, and whilst two scrubbers do not increase the dust protection levels per se, they do increase the length of the clean air zone from three chocks to six chocks, i.e. from 4.5 m to 9 m. These tests show that scrubbers need to be installed on every third chock, i.e. at 4.5 m intervals, in the return part of the face to provide an effective clean air zone along the walkway. As an example, a 150 m longwall face would require approximately 12 to 18 scrubber units depending on the dust conditions.

Figure 5.19 Respirable dust concentration profiles along the longwall face C with two scrubbers installed for experiment 1.
Figure 5.20  Respirable dust concentration profiles along the longwall face C with two scrubbers installed for experiment 2.

Figure 5.21  Respirable dust concentration profiles across the longwall face C at 3m downstream of the second scrubber in a two scrubber system.
Investigations were made into the effect of scrubber installation on airflow patterns in the face. Table 5.6 and Figure 5.22 show results of air velocity measurements with, and without, scrubber and show that installation of the scrubber modifies the airflow patterns in the longwall face. The air velocity in the walkway between the chock legs reduced from 0.8 m/s to 0.42 m/s when scrubbers were installed in the front walkway.

Table 5.6 Air velocity across the longwall face near the scrubber at a height of 1.6 m from floor

<table>
<thead>
<tr>
<th>distance (m)</th>
<th>Air velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without scrubber</td>
</tr>
<tr>
<td>0.30</td>
<td>1.90</td>
</tr>
<tr>
<td>1.00</td>
<td>2.00</td>
</tr>
<tr>
<td>1.80</td>
<td>1.90</td>
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<tr>
<td>2.40</td>
<td>1.75</td>
</tr>
<tr>
<td>2.70</td>
<td>-</td>
</tr>
<tr>
<td>3.00</td>
<td>1.43</td>
</tr>
<tr>
<td>3.15</td>
<td>-</td>
</tr>
<tr>
<td>3.25</td>
<td>1.28</td>
</tr>
<tr>
<td>3.35</td>
<td>-</td>
</tr>
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</tr>
<tr>
<td>4.05</td>
<td>0.80</td>
</tr>
<tr>
<td>4.25</td>
<td>0.60</td>
</tr>
<tr>
<td>4.35</td>
<td>-</td>
</tr>
</tbody>
</table>

5.2.4 Comparison of results from different faces

A comparison of the results in the three faces shows that the effectiveness of the scrubber system changes with face air velocity. Figure 5.23 shows that the efficiency decreases with increasing face air velocity. An analysis of changes in scrubber
Figure 5.22 Typical air velocity profiles across the longwall face C with, and without, scrubber (at 3m downstream of the scrubber).

Figure 5.23 Typical variation in protection efficiency of the system with face air velocity (at 3m downstream of the scrubber).
capacity and exhaust air velocity in face A, change in scrubber location in face B, and a comparison of results in face A, B and C all indicate that scrubber exhaust air velocity, face air velocity and the difference between the two velocities have a profound effect on the effectiveness of the scrubber system in longwall faces. These results indicate that this dust control technique at the face is more sensitive to air velocity than to air volume.

The results of the measurements at the operator's position showed a higher than expected reduction and led to the conclusion that the scrubber improves the operator's environment in two ways. Firstly, it captures and removes a portion of the dust which affects the operator, and in so doing provides a clean split of air along the walkway. Secondly, the scrubber changes the airflow pattern, particularly in the walkway region, which also reduces the operator's dust exposure levels. This modified airflow prevents dust diffusion into the low velocity area and also carries the dust generated by support movements more quickly into the face side, thus further reducing the dust concentration in the walkway area. There was no recirculation of scrubber discharge air or primary air in the face during field investigations, and there is therefore no danger of build-up of methane gas. In summary, the results confirmed that the dust protection efficiency of the scrubber system depends strongly on the air movements it creates, the scrubber air quantity, the scrubber exhaust air velocity, the face air velocity at the face and the distance from the scrubber.

5.2.5 Cost and other application areas

The approximate cost of each prototype scrubber unit is about $3,000 - $4,000, thus making the cost of fully equipping a 150 m longwall face $50,000 - $80,000 (12 - 18 units x $4,000). The costs of the compressed air and water supply to the units also have to be included. However, the exact cost of the system depends on installation and
operational costs which are very difficult to estimate as they vary from mine to mine and from country to country. The cost benefits from the system are also difficult to determine, as they derive from production increases and reduced miners’ health costs.

The air powered scrubber is highly flexible and can be used in other applications such as:

i) in the shearer extraction drum or as a shearer mounted scrubber

ii) at transfer points

iii) on continuous miners in development headings

iv) to reduce tailgate workers' dust exposure.

5.3 SUMMARY

Extensive field investigations were conducted in three longwall faces, with a bad dust compliance record, to evaluate the protection effected by the prototype scrubber to personnel along the walkway, and to optimise its location to maximise such protection. Dust was sampled simultaneously upwind and downwind of the scrubber, using gravimetric samplers, to determine the effectiveness of the scrubber system in providing a clean air zone along the walkway. At each station two samplers were used to ensure accuracy.

Observed system protection efficiencies, 3 to 4 m downstream of the scrubber, were approximately 50 %, 26% and 57% at face air velocities of 2.1 m/s, 4.5 m/s and 1.9 m/s, respectively. A low 26% protection efficiency in the second face was due to high face air velocity. One of the main conclusions reached in this study is that scrubber capacity, cleaned air exhaust velocity and scrubber location are the three important parameters which determine the protection efficiency of the system. Furthermore, the
velocity of air in a longwall face greatly determines the amount of turbulence, and hence effectiveness of the system in reducing dust exposure.

To be most effective, the scrubber should operate at 0.05 m$^3$/s (100 cfm) compressed airflow at 400 kPa pressure and with a water flow rate of 6 l/min at normal 700 kPa (100 psi) pressure. In addition, the scrubber should be delivering a minimum airflow of 0.5 m$^3$/s (1000 cfm) at 10 m/s exit velocity and the scrubber discharge point should be located near the roof in the front walkway area. Underground evaluations have established that the system was capable of reducing respirable dust in the walkway in longwall faces with low to medium face air velocity.

During the course of this research the complexities of the dust movements and control techniques effectiveness in a longwall face were exposed, and the idea of applying mathematical modelling techniques to simulate the interchange of many variables, as a supplement to practical manoeuvres, was conceived. The research into applying finite element techniques to model longwall face conditions is discussed in the following chapter.
Chapter 6
MATHEMATICAL MODELLING STUDIES

6.1 INTRODUCTION

Air flow fields and the spatial distribution of dust concentration levels are quite complex in a longwall face. An increase in air quantity can dilute dust concentration, but secondary airflow patterns around the machinery may pick up the dust cloud and negate these benefits. The development of any dust control technique therefore requires a thorough understanding of all secondary airflow fields around the cutting drums and the dust behaviour. It is not possible to use standard mine ventilation network analysis programs to analyse these airflow fields at the face or those around mining machinery, and finite element techniques have proved very useful in our understanding of the physics of the airflows and the dust behaviour. They also reduce the development time for a new dust control technique.

Past dust research projects have concentrated on the design and development of dust control techniques and their field evaluation. This has been very expensive and time consuming due to the extensive variations in face conditions and the complexity of coal mining operations. To reduce the number of experimental design variations associated with field tests, mathematical modelling can be used cost effectively to supplement the field evaluation of dust control techniques. It can ascertain optimal features of the control techniques, e.g. the location and direction of control devices, operational procedures, etc. at a fraction of the cost of underground tests. Problems, such as recirculation zones and gas build up, can also be identified during modelling and
suitable design changes can be made. Therefore, mathematical modelling of the airflow patterns and dust distribution at the longwall face was performed to supplement the field investigations to predict the behaviour of respirable dust with other innovative dust control techniques in operation.

6.2 SCOPE OF MODELLING WORK

The major objective of the modelling exercise was to create a three dimensional finite element model of a longwall face to simulate airflow patterns and the respirable dust concentration distribution. The effect of the shearer and cutting drums on the airflow characteristics was analysed for both cutting directions, i.e cutting with, and against, ventilation. Particular emphasis was given to simulating respirable dust particle behaviour around the shearer under different conditions.

The model was also used to evaluate the scrubber system and other dust control techniques such as a curtain over shearer, face curtains, etc. This involved the prediction of new dust concentration levels and computation of path traces of particles being introduced near the cutting drums. As the effectiveness of most of the dust control techniques is dependent on the spatial location of such devices, three dimensional simulations were performed.

6.3 GOVERNING EQUATIONS

In this research work, time averaged Navier-Stokes equations are used to describe the airflow field. This formulation is based on first principles and typically blends the mean value equations for momentum, energy and heat with phenomenological models of turbulence for closure (Rodi, 1980; 1984; Bradshaw, Cebeci and Whitelaw, 1981; Cebeci, 1982; Drummond, Barankiewicz and Cannon, 1991). Finite element method is

The essential characteristic of a fluid is its inability to sustain shear stress when at rest and only hydrostatic stress or pressure is possible. Any analysis must therefore concentrate on the motion, and the essential independent variable is thus the velocity 'u' or 'u_i' with the indicial notation. In this notation, the x, y, z axes are referred to as x_i, i = 1, 2, 3.

6.3.1 Momentum conservation

Application of the principle of conservation of linear momentum to a fluid element leads to the following equation

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j u_{i,j}\right) = \sigma_{ij,j} + \rho f_i$$

where

- $i, j = 1, 2, 3$ for three dimensional flows
- $\rho f_i = \text{force due to gravity}$

Most commonly, $\rho f_i$ is the force due to gravity, in which case $f_i$ is gravitational acceleration. However, the term $\rho f_i$ may also represent a coriolis or centrifugal force in equations that are written relative to a rotating frame of reference.

For a fluid, the stress tensor can be written as:

$$\sigma_{ij} = -\rho \delta_{ij} + \tau_{ij}$$

The relationship between the deviatoric stress and the shear rate tensor is:

$$\tau_{ij} = 2\mu \varepsilon_{ij}$$
where, \( \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \) \hspace{2cm} 6.1.4

By substituting 6.1.2 - 6.1.4 into 6.1.1, that equation becomes:

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j u_{i,j} \right) = -p_{.,i} + \left( [\mu(u_{i,j} + u_{j,i})]_{.,j} + \rho f_i \right) \quad 6.1.5
\]

### 6.3.2 Mass conservation

Application of the principle of mass conservation to the fluid results in the equation:

\[
\frac{\partial \rho}{\partial t} + (\rho u_j)_{,j} = 0 \quad \hspace{2cm} 6.2
\]

In addition, mass conservation applies to the individual components of a fluid. The rate of change of mass concentration of species is due to advection, diffusion and chemical reaction. The equation is

\[
\rho \left( \frac{\partial c_j}{\partial t} + u_j c_{,j} \right) = -j_{j,j} + q_c + R \quad \hspace{2cm} 6.3.1
\]

The species diffusion is due to concentration gradients and obeys Fick's Law:

\[
j_{j} = -\rho \alpha c_{,j} \quad \hspace{2cm} 6.3.2
\]

By substituting 6.3.2 into 6.3.1, that equation becomes

\[
\rho \left( \frac{\partial c_j}{\partial t} + u_j c_{,j} \right) = (\rho \alpha c_{,j})_{,j} + q_c + R \quad \hspace{2cm} 6.3.3
\]

### 6.3.3 Energy conservation

The principle of conservation of thermal energy is expressed by the equation:

\[
\rho c_p \left( \frac{\partial T}{\partial t} + u_j T_{,j} \right) = -q_{j,j} + H \quad \hspace{2cm} 6.4.1
\]
The heat flux is determined by Fourier's law

\[ q_j = -\lambda T_{,j} \quad \ldots \ldots \ldots . \quad 6.4.2 \]

and equation 6.4.1 becomes

\[ \rho c_p \left( \frac{\partial T}{\partial t} + u_j T_{,j} \right) = (\lambda T_{,j})_{,j} + H \quad \ldots \ldots \ldots \quad 6.4.3 \]

### 6.3.4 Equation of state

In the above equations the independent variables are \( u_i \) (velocity), \( p \) (pressure) and \( \rho \) (density). The stresses were defined in terms of velocities and hence are not independent. Obviously, there are too many dependents per variable for this equation system to be capable of solution. However, if density is assumed to be constant (as in incompressible fluids) or if a single relationship linking pressure and density can be established then the system becomes complete and is solvable.

The equation of state typically relates density, temperature and species concentration. Since only incompressible air is considered, pressure is not present in the equation of state. As there is no change in the density in the problem under consideration, the Boussinesq approximation is used.

In the Boussinesq approximation, the equation of state simply takes the form that the density is constant:

\[ \rho = \rho_o \quad \ldots \ldots \ldots \quad 6.5.1 \]

except that, in the presence of a gravitational field a buoyance force exists due to density variations, and is represented by:
The governing equations in the Boussinesq approximation are

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j u_{i,j} \right) = -p_{,i} + [\mu(u_{i,j} + u_{j,i})]_{,j} + \rho g_i \beta \left( T - T_o \right) + \beta_c (c - c_o) \quad \ldots \ldots \quad 6.6
\]

\[
u_{j,j} = 0 \quad \ldots \ldots \quad 6.7
\]

\[
\rho \left( \frac{\partial c}{\partial t} + u_j c_{,j} \right) = (\rho \alpha c_{,j})_{,j} + q_c + R \quad \ldots \ldots \quad 6.8
\]

\[
\rho c_p \left( \frac{\partial T}{\partial t} + u_j T_{,j} \right) = (\lambda T_{,j})_{,j} + H \quad \ldots \ldots \quad 6.9
\]

### 6.3.5 Turbulence modelling

The solution of the time-dependent three dimensional equations 6.6 to 6.9 can also describe turbulent flows completely. However, even today's super computers are neither fast enough nor do they have the storage capacity to solve these equations directly for the required range of length and time scales, even for simple flows (Rodi, 1984). This is because the turbulent motion contains scales which are much smaller than the extent of the flow domain, typically $10^{-3}$ times smaller. To resolve the motion of these scales in a numerical procedure would require a mesh discretization far beyond the capabilities of today's computers. Hence, it is of practical importance to describe turbulent motion in terms of time averaged quantities rather than instantaneous ones.

A statistical approach, first suggested by Osborne Reynolds, was taken and each of field variables (velocity, pressure, etc) was separated into mean and fluctuating quantities (Rodi, 1984; Engelman, 1991). Thus the mean values of the field variables
were used to model the large scale flow characteristics. For example, for field variable \( u \), its mean value can be defined as:

\[
\bar{u} = \frac{1}{\Delta t} \int_t^{t+\Delta t} u \, dt \quad \ldots \ldots \ldots \ldots \quad 6.10.1
\]

where the averaging time \( \Delta t \) is long compared with the time scale of the turbulent motion.

Then the variable \( u \) can be decomposed as follows

\[
u = \bar{u} + \hat{u} \quad \ldots \ldots \ldots \ldots \quad 6.10.2
\]

where \( \hat{u} \) reflects the small scale fluctuations associated with turbulence.

When this decomposition is directly applied to the governing equations and integrated over the time interval \( t, t+\Delta t \) results in the following mean field equations:

\[
\rho \left( \frac{du_i}{dt} + u_j u_{i,j} \right) = -p_{,i} + \left[ \mu (u_{i,j} + u_{j,i}) - \rho \bar{u} \bar{u}_{i,j} \right] + pf_{i} - \rho g_{i} \left[ \beta_T (T - T_0) + \beta_c (c - c_0) \right] \quad \ldots \quad 6.11
\]

\[
u_{j,j} = 0 \quad \ldots \ldots \ldots \ldots \quad 6.12
\]

\[
\rho \left( \frac{dc}{dt} + u_j c_{,j} \right) = \left( \rho \alpha_{,j} - \rho \bar{u} \bar{c}_{,j} \right) + q_c + R \quad \ldots \ldots \ldots \quad 6.13
\]

\[
\rho c_p \left( \frac{dT}{dt} + u_j T_{,j} \right) = \left( \lambda T_{,j} - \rho c_p \bar{u} T_{,j} \right) + H \quad \ldots \ldots \ldots \quad 6.14
\]

These are the equations governing the mean flow quantities \( u, p, T \) and \( c \).

These equations are also exact since no assumption was introduced in deriving them; but they no longer form a closed set. Due to the nonlinearity of governing equations,
the averaging process has introduced unknown correlations between fluctuating velocities \( \overline{u_iu_j} \), between velocity and temperature fluctuations \( \overline{u_iT} \), and between velocity and species concentration fluctuations \( \overline{u_iC} \). Physically, these correlations represent the transport of momentum, heat and mass due to the fluctuating/turbulent motion.

The term

\[
\rho \overline{u_iu_j} = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} \rho \; \dot{u}_i \overline{u}_j \; dt
\]

is the transport of \( x_i \) momentum in the direction of \( x_j \); it acts as a stress on the fluid and is called the turbulent Reynolds stress tensor. It characterises the effect of turbulent eddy behaviour on the mean flow. \( \rho c_p \overline{u_iT} \) is the transport of heat in the direction \( x \) and is known as the turbulent heat flux. Similarly, \( \rho \overline{u_iC} \) represents the transport of species concentration, via the fluctuating velocity field, in the direction of \( x \) and is known as turbulent mass flux.

The mean flow equations 6.11 to 6.14 of velocity, pressure, temperature and species concentration can be solved only when the turbulence correlations can be determined in some way. Thus a turbulence model, which approximates these correlations in some manner, typically by expressing them in terms of mean flow quantities, would be necessary. Such a turbulence model, together with the mean flow equations 6.11 to 6.14, form a closed set of equations for the mean values of velocity, pressure, temperature and species concentration.

The most widely used approach to modelling the Reynolds stresses is the Boussinesq eddy viscosity concept which assumes that, in analogy to the viscous stresses in laminar flow, the components of the Reynolds stress tensor are proportional to the mean velocity gradients, i.e.
\[- \rho u_i u_j = \mu_t (u_{i,j} + u_{j,i}) \quad \ldots \ldots \ldots \quad 6.16\]

The proportionality parameter $\mu_t$ is known as the 'eddy viscosity', and unlike the molecular viscosity $\mu_o$ which is a fluid property, depends on the turbulence of the flow and hence is a function of position. This approximation allows equation 6.11 to be rewritten as equation 6.6 provided the total viscosity is identified with the sum of the laminar and eddy viscosities:

$$\mu = \mu_o + \mu_t \quad \ldots \ldots \ldots \quad 6.17$$

Similarly, equation 6.14 can be rewritten as equation 6.9 with the introduction of a turbulent thermal conductivity $\lambda_t$ such that:

$$\lambda = \lambda_o + \lambda_t \quad \ldots \ldots \ldots \quad 6.18.1$$

$$\lambda_t = \frac{c_p \mu_t}{\sigma_t} \quad \ldots \ldots \ldots \quad 6.18.2$$

where $\sigma_t$ is the turbulent Prandtl number. Finally equation 6.13 can be rewritten as equation 6.8 with the introduction of a turbulent diffusivity $\alpha_t$ such that:

$$\alpha = \alpha_o + \alpha_t \quad \ldots \ldots \ldots \quad 6.19.1$$

$$\alpha_t = \frac{\mu_t}{\rho S_t} \quad \ldots \ldots \ldots \quad 6.19.2$$

where $S_t$ is the turbulent Schmidt number.

Here, the proportionality constant $\mu_t$ is known as the eddy viscosity. This eddy viscosity concept shifts the problem of turbulence modelling to the determination of the distribution of $\mu_t$; the additional unknowns are limited to this single variable $\mu_t$. Two fundamental approaches to modelling the eddy viscosity are in common practice. The first draws on algebraic equations to express the dependence of eddy viscosity in terms
of mean flow properties; this is the so-called 'algebraic or zero-equation' approach. In contrast, the second approach known as the 'two equation k-ε model', involves solving two additional transport equations and the computation of eddy viscosity values. The second approach, the two equation k-ε model, has been used during the simulations in this thesis.

**Two-Equation k-ε model**

In the k-ε turbulence model the turbulence field is characterised in terms of two variables, the turbulent kinetic energy $k$, which is defined as (Rodi, 1984)

$$ k = \frac{1}{2} \bar{u}_i \bar{u}_i $$  \hspace{2cm} 6.20

and the viscous dissipation rate of turbulent kinetic energy $\varepsilon$, which is defined as

$$ \varepsilon = \nu \bar{u}_{i,j} \bar{u}_{i,j} = \nu \frac{1}{\Delta t} \int_t^{t+\Delta t} \bar{u}_{i,j} \bar{u}_{i,j} \, dt $$  \hspace{2cm} 6.21

Typical turbulent eddy velocity and length scales, denoted by $u_l$ and $l_t$, may be characterized as $k^{1/2}$ and $k^{1.5}/\varepsilon$, respectively. An extension of this dimensional reasoning also leads to an expression for $\mu_t$ in terms of the characteristic scales of the turbulent eddies

$$ \mu_t \propto \rho u_l l_t \propto \rho k^{2}/\varepsilon $$  \hspace{2cm} 6.22

Thus the turbulent viscosity $\mu_t$ is directly related to the turbulent quantities $k$ and $\varepsilon$. A transport equation for $k$ can be obtained from the Navier-Stokes equations by a sequence of algebraic manipulations. This transport equation in addition to $\varepsilon$ contains a number of unknown correlations. A second transport equation for $\varepsilon$ can also be derived from the Navier-stokes equations, and then the unknown variables become $u_i$, $c$, $T$, $k$, $\varepsilon$. Thus, the corresponding field equations are
\[ \rho \left( \frac{\partial u_{i}}{\partial t} + u_{j} u_{i,j} \right) = -p_{i,i} + \left[ \mu \left( u_{i,j} + u_{j,i} \right) \right]_{j,i} + \rho f_{i} \]
\[ - \rho g_{i} \left[ \beta_{T}(T-T_{0}) + \beta_{c}(c-c_{0}) \right] \] ............ 6.23

\[ u_{j,j} = 0 \] ......................... 6.24

\[ \rho \left( \frac{\partial e}{\partial t} + u_{j} e_{j} \right) = \left( \rho \alpha_{c}.j \right)_{j} + q_{e} + R \] ......................... 6.25

\[ \rho c_{p} \left( \frac{\partial T}{\partial t} + u_{j} T_{j} \right) = \left( \lambda T_{j} \right)_{j} + \mu \Phi + H \] ......................... 6.26

\[ \rho \left( \frac{\partial k}{\partial t} + u_{j} k_{j} \right) = \left( \frac{\mu_{t} k_{j}}{\sigma_{k} \epsilon} \right)_{j} + \mu_{t} \Phi - \rho e \left( \frac{\beta_{T} T}{\sigma_{t}} \right)_{j} + \frac{\mu_{t} c_{j}}{\sigma_{c}} \] ............ 6.27

\[ \rho \left( \frac{\partial e}{\partial t} + u_{j} e_{j} \right) = \left( \frac{\mu_{t} e_{j}}{\sigma_{t} \epsilon} \right)_{j} + c_{1} \frac{e_{j}}{k} \mu_{t} \Phi - \rho c_{2} \frac{e_{j}^{2}}{k} \]
\[ + c_{3} \left( 1 - c_{3} \right) \frac{e_{j}}{k} \mu_{t} \beta_{T} T_{j} + \frac{\mu_{t}}{S_{t}} \beta_{c} c_{j} \] ............ 6.28

\[ \mu_{t} = \rho c_{\mu} \frac{k^{2}}{\epsilon} \] ......................... 6.29

The above equations contain empirical constants \( \sigma_{t}, S_{t}, \sigma_{k}, \sigma_{e}, c_{\mu}, c_{1}, c_{2}, c_{3} \). The k-\( \epsilon \) model has been tested, optimized and fine tuned against a wide range of flows of actual flow values, over a number of years. For isothermal flows with no mass transfer, this has led to the recommended set of model constants given in Table 6.1 (Launder and Spalding, 1974)

\[ \begin{array}{|c|c|c|c|c|}
\hline
 c_{\mu} & c_{1} & c_{2} & \sigma_{k} & \sigma_{e} \\
0.09 & 1.44 & 1.92 & 1.0 & 1.3 \\
\hline
\end{array} \]
Vector notation

It is sometimes convenient to consider the governing equations in vector, rather than tensor notation. The vector analogs of equations 6.23 - 6.28 are:

\[
\begin{align*}
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) &= - \nabla p + \nabla \left[ \mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \right] + \rho f \\
&\quad - \rho g_i \left[ \beta_T (T-T_0) + \beta_c (c-c_0) \right] \tag{6.30} \\
\nabla \cdot \mathbf{u} &= 0 \tag{6.31} \\
\rho \left( \frac{\partial \mathbf{c}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c} \right) &= \rho \nabla \cdot (\alpha \nabla \mathbf{c}) + \mathbf{q}_c + \mathbf{R} \tag{6.32} \\
\rho c_p \left( \frac{dT}{dt} + \mathbf{u} \cdot \nabla T \right) &= \nabla (\lambda \nabla T) + \mu \Phi + \mathbf{H} \tag{6.33} \\
\rho \left( \frac{\partial \kappa}{\partial t} + \mathbf{u} \cdot \nabla \kappa \right) &= \nabla \left( \frac{\mu_t}{\sigma_k} \nabla \kappa \right) + \mu_t \Phi - \rho \epsilon_k + \mu_t \frac{\beta_T}{\sigma_t} \nabla T + \frac{\beta_c}{\sigma_t} \nabla \mathbf{c} \tag{6.34} \\
\rho \left( \frac{\partial \epsilon}{\partial t} + \mathbf{u} \cdot \nabla \epsilon \right) &= \nabla \left( \frac{\mu_t}{\sigma_\epsilon} \nabla \epsilon \right) + \frac{c_1 \epsilon}{k} \mu_t \Phi - \rho c_2 \frac{\epsilon^2}{k} \Phi \\
&\quad + c_3 (1-c_3) \frac{\epsilon}{k} g_j \left( \frac{\mu_1}{\sigma_t} \beta_T \nabla T + \frac{\mu_1}{\sigma_t} \beta_c \nabla \mathbf{c} \right) \tag{6.35}
\end{align*}
\]

The form of the momentum equation 6.30 is known as the stress-divergence form. In the case that the viscosity is constant, equation 6.30 can be written as:

\[
\begin{align*}
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) &= - \nabla p + \mu \nabla^2 \mathbf{u} + \rho f \\
&\quad - \rho g_i \left[ \beta_T (T-T_0) + \beta_c (c-c_0) \right] \tag{6.36}
\end{align*}
\]

The form of equation 6.36 is known as the Navier-Stokes form of the momentum equation.
6.3.6 Particle path

Particle path plots are used to simulate the behaviour of respirable dust in the longwall face airflow. In a particle path plot, a mass-less particle is introduced at a point (or points) in the flow domain and the particle's path of motion and trajectory is tracked based on the computed flow field.

When all external effects are neglected except drag, gravity and centrifugal force, the equations of the motion of the particles can be written as:

\[ \rho_p \frac{du_p}{dt} = F_D(u_F^F - u_p^F) + (\rho_p^F - \rho_F)g_i + (\rho_p^F - \rho_F)f_i \quad \ldots \quad 6.37 \]

and the equations of trajectory are:

\[ \frac{dx_i}{dt} = u_p^F \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad 6.38 \]

where the superscript F refers to the continuous fluid phase and P to the particle phase.

The first term on the right-hand side of equation 6.37 represents a generalized stokes drag. The second term is the buoyancy induced drag while the final term is the drag due to centrifugal forces.

The coefficient \( F_D \) is given by:

\[ F_D = \frac{18\mu_F}{D_p^2} C_D \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad 6.39 \]

where the drag coefficient, \( C_D \) is a function of the relative Reynold's number

\[ Re_p = \frac{D_p|u_F^F - u_p^F|\rho_F}{\mu_F} \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad 6.40 \]

and is defined by:
\[ C_D = a + b \text{Re}_p + c \text{Re}_p^2 + e/\text{Re}_p \]  

In the above formulas, \( \rho_p \) is the particle density, \( \mu_F \) is the viscosity of the fluid, \( D_p \) is the diameter of the particle and \( g_i \) is the acceleration due to gravity vector.

The coefficients \( a, b, c, \) and \( e \) are constants which apply over several ranges of Reynold's number given by Morsi and Alexander (1972).

For example, for \( \text{Re}_p \leq 100 \)

\[ C_D = 1 + 0.0975 \text{Re}_p - 0.636 \times 10^{-3} \text{Re}_p^2 \]

This formulation is based on the assumption that the second phase is sufficiently dilute so that particle - particle interactions are negligible.

### 6.4 MATHEMATICAL MODELLING

All mathematical modelling studies were performed using FIDAP, a three dimensional finite element computational fluid dynamics analysis program (Engelman, 1991). This program was developed by Fluid Dynamics International, Inc., and consists of a suite of computer programs for the analysis of fluid flow, heat and mass transfer and chemical reaction. The program solves steady or transient flows and heat transfer in two or three dimensions. FIDAP offers several different solution techniques and time integration methods and allows the implementation of user-supplied or position dependent physical properties of the fluid or volumetric forces acting on the fluid. A wide range of boundary conditions can also be specified, including applied pressure gradients.
6.4.1 Simulations with FIDAP

In general, a flow analysis can be divided into three distinct phases:

(i) pre-processing phase - includes model development and mesh generation, specification of boundary conditions and fluid properties;
(ii) simulation phase - equations solving/computations;
(iii) post-processing phase - analysis of results.

The FIDAP program has four different modules to perform all these phases of flow analysis, namely FIMESH, FIPREP, FISOLV and FIPOST.

The FIMESH program module provides a general purpose mesh generator, specifically designed to generate two or three-dimensional meshes for the main analysis program. The program utilizes a meshing procedure between a logical plane and a geometric space. It uses an indexing scheme to number boundaries, surfaces and regions and to control the generation of nodal points, elements, mesh grading and the application of boundary conditions. The FIPREP program module handles the automatic integration of the nodes and elements generated by FIMESH as well as the interactive preparation of the control options and model description. These are then translated into an input file for use by FISOLV.

The FISOLV program includes a number of algorithms for computing the unknown flow variables from the set of equations and boundary conditions. Once the mesh and boundary conditions have been specified, the solution procedure can be set by selecting one of the algorithms available in FISOLV. The FIPOST module includes algorithms to graphically represent the results of mathematical solution. The program allows the
production of mesh, velocity vectors, contours, particle path plots as well as many other types of plots. It has numerous other additional capabilities for analysing results computed by FISOLV.

6.4.2 Finite element method

In the finite element method, the flow region is subdivided into a number of small regions, called finite elements. The partial differential equations of fluid mechanics covering the flow region as a whole are replaced by ordinary differential or algebraic equations in each element. Element equations are derived from minimisation of the residual left after a trial solution is substituted into the governing differential equations. The element equations, along with boundary conditions, are assembled into a global matrix form. The equations are then solved by sophisticated mathematical techniques to determine the unknown parameters such as velocities, pressures, temperatures, species concentration, etc. throughout the flow region.

The great advantage of FEM over other methods is its inherent flexibility in treating arbitrarily complex domains and boundary conditions. Unstructured grids can be designed which allow an area of interest to be studied in greater detail without the need for excessive grid points throughout the flow domain. FEM allows the imposition of natural and correct boundary conditions on curved boundaries. It also has a sophisticated mathematical formulation which allows the derivation of comprehensive error estimates and the determination of accurate solutions to within user prescribed tolerances. At the same time, fluid simulation with FEM allows access to the wealth of powerful graphics, pre- and post-processing packages available.
6.5 MODELLING OF LONGWALL FACE - METHODOLOGY

6.5.1 Problem description

Before developing a model, field investigations were first conducted in a longwall face to obtain basic information on dimensions, airflow characteristics and respirable dust behaviour. The longwall face selected was 5 m wide by 2.5 m high and had four legged chock shields. The average airflow velocity was 2.1 m/s. The shearer was 10 m long, 1 m wide and 1 m high with drums of 1.5 m diameter and 0.8 m width. Figure 6.1 shows a schematic view of the longwall face.

Measurements of airflow in the face showed it to be highly turbulent and isothermal. Air leakage into the goaf was negligible. Most of the airborne respirable dust which was generated by the shearer and by support movement was carried to the end of the face, and therefore, for the return part of the face the dust source is continuous and distributed across the full section of the face. The multi-scrubber system and six other dust control techniques were modelled and included: curtain over shearer, curtain on in-bye side of the shearer downwind drum, curtain on in-bye side of the shearer upwind drum, semi see-through curtain, face curtains and air curtains in walkway.

6.5.2 Model development

Based on the data collected during field studies in longwall faces, the following assumptions were made during modelling:

(a) the airflow in a longwall face is incompressible;
(b) the airflow in a longwall face is turbulent;
(c) the airflow in the longwall face is isothermal;
Figure 6.1  A schematic representation of a part of the longwall face in plan, side and section views.
(d) four legged chock shields were used in the longwall face;
(e) there is no air leakage through the face into the goaf;
(f) support movement is one of the major sources of dust;
(g) dust particles have negligible inertia and follow the airflow closely apart from diffusional effects;
(h) in the 'curtain in front of shearer' dust control technique, there is air leakage near the top and face side of the curtain.

A three dimensional model was necessary to provide useful information on airflow patterns and dust behaviour in a longwall face owing to the complex nature of the geometry and the operations involved. Thus, a three-dimensional full-scale model of a 40 m longwall face was created using field data gained on dimensions, dust sources and airflow characteristics. It was recognised that a detailed three dimensional model of the longwall face with all cables, components and support legs was not practical given the computer resources available. Since the main focus of this study was on system level characteristics, a component level simplification in the geometry was made (Similar simplifications were made by Mansingh and Misegades (1990) during modelling of a Cray computer). In modelling the cables and chock legs, it was assumed that between the spill plate and the back row of legs, a certain percentage of the flow passage was blocked by the front row of legs. The shearer was modelled as one block, with the drums and ranging arms modelled as two separate blocks on each side of the shearer.

The full model was divided into smaller finite elements using 8-node brick elements (Figure 6.2). The Sun Sparc Workstation used for the simulations did not have the capacity to process a three dimensional model of the full longwall face which would have required well over 100,000 elements. Therefore, in this study, only 40 m of the longwall face was modelled. The final mesh consisted of over 7,000 nodes and over
6,000 elements and a sectional view of the mesh is shown in Figure 6.2. It was graded at the walls of the face, so as to accommodate the expected velocity gradients near the walls, and was optimized and adopted to the turbulent variables.

Figure 6.2  Sectional view of the finite element mesh showing part of the longwall face model for airflow simulation.

6.5.3  Boundary conditions

On all the solid surfaces of the physical and blocked regions, a no-slip velocity boundary condition was specified, in which all components of velocity were zero. At the inlet boundary, a constant velocity for developing flow, and values for the turbulent kinetic energy and dissipation, were specified. At the outlet boundary, no boundary condition was specified and was assumed to be stress free to ensure that it did not influence the fluid flow field inside the solution domain.
When the k-ε turbulence model is used, special attention must be directed to boundary conditions at solid wall boundaries. At a boundary wall, the no slip condition leads to predominantly viscous behaviour and is termed 'the viscous sublayer'. For turbulent flows it is often desirable not to compute the flow right up to the wall, as it would require the equations to be integrated through the viscous sublayer present near the wall. This presents a problem in that:

* firstly, very steep gradients prevail in the viscous sublayer so that, for proper resolution, many mesh points would have to be placed in this layer and the computation would be prohibitively expensive;

* secondly, viscous effects are important in this layer so that the high Reynolds number k-ε turbulence model is not applicable in this region.

Thus the finite element mesh was not extended completely to the wall, rather an empirical law of wall (Rodi, 1984; Haroutunian and Engelman, 1991) was employed to connect the finite element mesh to the wall conditions. Basically this approach used the computed velocity at the boundary to derive a shear stress and associated k and ε values which were then applied as boundary conditions.

No leakage of air through the face was specified. As only the return part of the longwall face was modelled for the steady state analysis, the dust source was given at the inlet of the model and was assumed to be constant and uniform across the full section. In simulations with the shearer, the dust source was given at the cutting drums.
6.5.4 Simulations

A finite element approach for the discretization of the equations and the segregated algorithm (Haroutunian, Engelman and Hasbani, 1991; Shaw, 1991; Engelman, 1991) were used to solve the equations. During the simulation of airflows in the face, the energy equation, the species equation and the buoyancy term in the momentum equation were discarded as there was no temperature or species dependence. The time-averaged Navier-Stokes equations were solved in the non-dimensional form to reduce numerical instability. The turbulent flow was modelled using a k-ε equation model with standard values for the constants given in Table 6.1. Since the k-ε turbulence model is not valid in the viscosity affected regions close to the wall, a near-wall modelling approach (Rodi, 1984) was used in close proximity to the solid walls.

For these simulations, 8-node isoparametric linear brick elements, with a mixed function approach using a discontinuous pressure approximation, was employed. A three dimensional, non-linear and steady state analysis was specified. Transient analyses were not performed on the three dimensional models due to CPU limitation of the computer. Four-node isoparametric tetrahedron boundary wall elements were used near the fixed walls.

Two approaches were used to model the respirable dust concentrations in the longwall face. In the first, particles were introduced into the flow as a dispersed second phase and their path was tracked using particle tracking procedure. Since respirable dust contains billions of particles, it is not possible to use this technique to predict the dust concentration in the three dimensional longwall face. The second approach assumed that respirable dust particles have negligible inertia and follow the air flow closely, apart from diffusional effects. This approach was adopted in the simulation of dust concentration along the longwall face.
It was assumed that respirable dust particles have no effect on the flow pattern, and therefore the approach employed to the analysis of the problem was to solve the flow field equations independently of the species/pollutant equation. The pollutant equation was then solved directly using the computed velocity field values. The numerical simulations were carried out in stages. Initially, only the longwall face was modelled. The shearer was then added to the model and the effects of both antitropal and homotropal ventilation systems were investigated. Finally, dust control techniques were introduced into the model one at a time.

All simulations were carried out on a Sun Sparc Workstation running under UNIX environment. In these simulations, convergence was assumed when the relative error was less than 0.02 for all degrees of freedom. In view of the field conditions, the simulation focussed on getting overall trends of the pertinent variables rather than their absolute values. Given that other simplifications in the model had been made, it was felt that this level of convergence and accuracy was adequate. On a Sun Sparc station, it took about 10 hours of CPU time for each computation and needed 40 MB of main memory and 300 MB of scratch disk space.

6.6 LONGWALL FACE MODEL -RESULTS AND ANALYSIS

6.6.1 Airflow patterns in the face

The airflow velocity profiles across the section of the longwall face, i.e. at right angles to the face, are shown in Figures 6.3 and 6.4. An analysis of these simulations shows that the air velocity at right angles to the face is not uniform and varies from a maximum over the Armoured Face Conveyor (AFC) area to a minimum in the walkway. The maximum velocity in the walkway between the chock legs is about 40
maximum velocity = 2.15 m/s

Figure 6.3 Modelling results of air velocity pattern across the longwall face shown as a surface graph.

Figure 6.4 Air velocity profiles across the face at four different heights.
to 50% of the maximum value over the AFC area. Several simulations, with different types of supports, showed that the variation in velocity across the face largely depended on the type of supports, i.e. the cross sectional shape of the longwall face.

6.6.2 Dust concentration distribution

Respirable dust concentration contours and profiles at more than 30 m from the source of dust and at right angles to the longwall face, show that the dust concentration in the walkway is less than that in the AFC area (see Figures 6.5 and 6.6). Nevertheless, it is still often well above the Australian statutory limit of 3 mg/m³. The results also show that dust concentration profiles depend largely on the airflow characteristics.

Figure 6.5 Simulated respirable dust concentration contours across the face.
6.6.3 Airflow and dust behaviour around shearer

Velocity vector plots at the shearer cutting drums with cutting in the direction of airflow and cutting against it are shown in Figures 6.7 and 6.8. In the case of cutting with ventilation, the upwind drum was in the lowered position near the floor, and with cutting against the ventilation, the upwind drum was in the raised position near the roof. The velocity vectors in these plots show the magnitude and direction of air flow at each point. Figure 6.7(a) shows that, in the case of cutting with ventilation, there is a gradual diversion of the primary airflow into the walkway, indicating that dust produced at this upwind drum disperses slowly into the walkway. Figure 6.8(a) shows that in the case of cutting against the ventilation, there is a sharp diversion of the primary airflow into the walkway, indicating that dust produced at the upstream tailgate drum disperses very quickly into the walkway area.
Figure 6.7 Air velocity vectors near the cutting drums on a plane normal to airflow when cutting with ventilation.
(a) near the upwind maingate cutting (leading) drum

(b) near the downwind tailgate cutting (trailing) drum

Figure 6.8 Air velocity vectors near the cutting drums on a plane normal to airflow when cutting against ventilation.
Figures 6.9 show the velocity contours along the face in plan view, near the shearer at three different heights above the floor, when cutting with ventilation. Figure 6.9(a) shows that there is a considerable increase in air velocity in the walkway next to the shearer. But the velocity contours at 0.2 m and 0.4 m above the shearer body (Figures 6.9(b) and 6.9(c)) show that the increase in velocity in these planes is marginal.

\[
\begin{align*}
\text{air velocity (m/s)} & \\
E &= 0.31 \\
F &= 0.86 \\
G &= 1.43 \\
H &= 1.98 \\
I &= 2.54
\end{align*}
\]

(a) at a height of 1.2 m above the floor.

(b) at a height of 0.2 m above the shearer.

Figure 6.9 Air velocity contours in the vicinity of shearer in plan view when cutting with ventilation.
air velocity (m/s)
E = 0.31
F = 0.86
G = 1.43
H = 1.98
I = 2.54

downwind
leading drum

upwind
trailing drum
goaf side

Figure 6.9(c)  Air velocity contours in the vicinity of shearer at a height of 0.4 m above the shearer in plan view when cutting with ventilation.

Figures 6.10 and 6.11 showing the air velocity contours across the face near the shearer cutting drum and Figure 6.12, which presents the simulated air velocity gradients across the face near the shearer, demonstrates that the presence of the shearer only increases the maximum air velocity by about 10%, even though it occupies 30% to 35% of the cross-sectional area. Near the shearer, the air velocity increases only marginally because the back walkway area, which normally has a lower velocity than in the AFC area, is accommodating the displaced air quantity. The maximum velocity zone has shifted from the AFC area to the walkway area.
(a)  at the upwind tailgate cutting (trailing) drum

(b)  2.0 m downstream of upwind cutting drum

Figure 6.10  Velocity contours across the longwall face near the upwind cutting drum.
(a) 2.0 m upstream of the downwind cutting drum

(b) at the downwind maingate cutting (leading) drum

Figure 6.11 Velocity contours across the face near the downwind cutting drum.
Path traces of particles introduced into the flow field at 1.0 m, 2.0 m and 3.3 m from the upwind drum, and at 0.3 m above the shearer in plan view when cutting in the direction of airflow, are shown in Figure 6.13. Figure 6.14 shows similar particle path trace plots when cutting against ventilation. These path traces provide a qualitative feel for the mean flow and respirable dust behaviour close to the shearer. In both cases, the dust particles dispersed into the walkway, but at a greater rate when cutting against the ventilation. More particles were dispersed into the walkway when particles were introduced 2.0 m and more from the cutting drum. The figures show that the shearer operators are exposed to greater amounts of dust when cutting against the ventilation.
(a) particles introduced at the upwind cutting drum

(b) particles introduced 2.0 m away from the upwind cutting drum

(c) particles introduced 3.3 m away from the upwind cutting drum

Figure 6.13 Simulated path traces of respirable dust particles introduced into the airflow near the upwind cutting drum (when cutting with ventilation).
Figure 6.14 Simulated path traces of respirable dust particles introduced into the airflow near the upwind cutting drum (when cutting against ventilation).
6.7 SIMULATION OF DUST CONTROL TECHNIQUES - RESULTS AND ANALYSIS

6.7.1 Curtain over shearer

The curtain-over shearer dust control technique (USBM, 1981d; Shirey, Colinet and Kost, 1985), was aimed at modifying the secondary airflow patterns over the shearer to prevent the trailing drum dust being dispersed onto the shearer operator's work area. In modelling this, a 50 cm high curtain was mounted along the full length of the goaf edge of the shearer body (Figure 6.15).

![Diagram showing the position of curtain over shearer](image)

Figure 6.15 A schematic diagram showing the position of curtain over shearer.
The velocity vector plots at the upwind drum with a passive belt barrier installed over the shearer body, when cutting with and against ventilation, are shown in Figures 6.16 and 6.17 respectively. When cutting with ventilation these vectors are directed towards the face. A comparison of figures 6.16 and 6.7(a), which show velocity vectors with, and without, installation of a curtain over the shearer, shows that, when cutting with ventilation the curtain modified the airflow direction significantly. However, a comparison of figures 6.17 and 6.8(a) shows that, when cutting against ventilation, the curtain had little effect on airflow direction near the upwind drum.

Figure 6.16  Velocity vectors across the face near the upwind cutting drum with curtain installed over the shearer (when cutting with ventilation).
Path traces of particles introduced 1.0 m from the upwind cutting drum, when cutting with ventilation, are shown in Figure 6.18(a). It can seen that the curtain is very effective in that it prevents the dust cloud from passing over the shearer body onto the downwind drum operator's position. Analysis of results when particles were introduced 2.0 m from the upwind trailing drum (Figure 6.18(b)) shows that the effectiveness of this control technique decreases significantly. Figure 6.19 shows the similar particle trace plots when cutting against ventilation, which indicates that, with this cutting direction, the control technique is not effective in reducing miners' dust exposures.
Figure 6.18 Path traces of respirable dust particles introduced near the upwind cutting drum with curtain installed over shearer (when cutting with ventilation).

Figure 6.19 Path traces of respirable dust particles introduced near the upwind cutting drum with curtain installed over shearer (when cutting against ventilation).
6.7.2 **Curtain on in-by e side of the shearer downwind drum**

The 'curtain on in-by e side of the shearer downwind drum' dust control technique was devised to shield the downwind cutting drum from high velocity primary ventilation. In modelling this, a 1.8 m wide by 1.0 m high curtain was installed over the shearer at 3.0 m on the in-by e side of the shearer downwind drum and was positioned at right angles to the primary airflow direction (Figure 6.20). The curtain can be attached to the shearer body, and sprung so that when the supports lowered to advance, they do not damage the curtain. To simulate the practical conditions, a gap of 0.3 m was left on the top and on the face side of the curtain. Figure 2.21 shows the velocity vectors near the downwind cutting drum.

![Figure 6.20](image-url)

(a) plan view

(b) side view

Figure 6.20 A schematic diagram showing the position of curtain on in-by e side of the downwind drum.
When respirable dust particles are introduced near the downwind cutting drum with cutting in the direction of ventilation, the dust particles disperse towards the longwall face, as shown in Figure 6.22, suggesting that this technique is effective in keeping the dust generated at this drum towards the face. When respirable dust particles are introduced at the upwind trailing drum, they are pushed into the walkway near the downwind shearer operators' position, as shown in Figure 6.23, which indicates that this is not an effective control technique for dust generated at this drum. This technique can therefore only be used when cutting with ventilation and when dust generated at the upwind trailing drum is not a major problem.
Figure 6.22 Path traces of respirable dust particles introduced into the airflow near the downwind cutting drum with curtain installed on in-bye side of the shearer downwind drum (when cutting with ventilation).

Figure 6.23 Path traces of respirable dust particles introduced into the airflow near the upwind cutting drum with curtain installed on in-bye side of the shearer downwind drum (when cutting with ventilation).
6.7.3 Curtain on in-byde side of the shearer upwind drum

To control the dust produced at the upwind drum, a curtain was installed on the in-byde side of the shearer upwind drum, instead of at the downwind drum. It was devised to shield the upwind drum from primary ventilation. In modelling this, a 1.5 m wide by 1.0 m high curtain was installed 2.5 m in front of the shearer over the AFC area (Figure 6.24). To simulate the practical conditions, a gap of 0.3 m was left on the top and face sides of the curtains.

Figure 6.24 A schematic diagram showing the position of the proposed 'curtain on in-byde side of the upwind drum' dust control technique.
The velocity vectors near the upwind drum, with belting installed, are towards the face side, as shown in Figures 6.25 and 6.26, which suggests that the dust produced at this cutting drum will not roll over onto the shearer operator's position. Path traces of particles, introduced 1.0 m upwind of the cutting drum, when cutting with, and against airflow, are shown in Figures 6.27 and 6.28. In both cases, the dust is moving towards the face and results in very low dust exposure for the shearer operators. Although this dust control technique requires careful planning, design and installation, it appears to be very effective in reducing the shearer operators' dust exposure.

Figure 6.25  Velocity vectors near the upwind cutting drum with curtain installed on in-byde side of the upwind drum (when cutting with ventilation).
Figure 6.26  Velocity vectors near the upwind cutting drum with curtain installed on in-bye side of the upwind drum (when cutting against ventilation).

Figure 6.27  Path traces of respirable dust particles introduced into the airflow near the upwind cutting drum with curtain installed on in-bye side of the shearer upwind drum (when cutting with ventilation).
Figure 6.28 Path traces of respirable dust particles introduced into the airflow near the upwind cutting drum with curtain installed on in-byre side of the shearer upwind drum (when cutting against ventilation).
6.7.4 Semi-see-through curtain

In the semi-see-through curtain technique (USBM, 1992) the curtains were installed all along the face, once along the spill plate and the second time alongside of the front row of chock legs, to prevent the dispersion of shearer generated dust into the walkway (Figure 6.29).

Figure 6.29 A schematic diagram showing the position of semi-see-through curtain.
Mathematical results of this dust control technique, when used along the spill plate, show that it reduces dust levels by 25 to 30% in the walkway (see Figure 6.30). The effect of installing a curtain along the front legs was also modelled and found that it results in a 30 to 35% reduction in dust concentration in the back walkway i.e. between the two rows of legs. This latter technique could be useful provided that miners use the back walkway rather than the front walkway.

![Respirable dust concentration contours across the longwall face with semi-see-through curtain installed along the spill plate.](image)

**Figure 6.30** Respirable dust concentration contours across the longwall face with semi-see-through curtain installed along the spill plate.

### 6.7.5 Face curtains at 1.5 m intervals

The aim of the face curtain technique (Babbitt, et al, 1984) was to keep the shearer generated dust towards the face side. In modelling this, a number of intermittently spaced curtains were suspended from the roof supports along the face and were oriented parallel to the airflow direction (Figure 6.31).
Figure 6.31 A schematic diagram showing the position of face curtains in the face.

The simulated dust concentration contours, with face curtains installed, show that the dust concentration in the walkway area is high (are shown in Figure 6.32.) and the technique is not effective. A comparison of dust concentration contours in figures 6.32 & 6.5 shows that, with curtains, there is a slight increase in walkway dust concentration. This may be due to the eddying of the airflow caused by the presence of intermittently spaced face curtains.
Chapter 6: Modelling Studies

6.7.6 Air curtains in the walkway

The air curtain technique (Hewitt, 1986a; Lama et al, 1990) aims to create an air curtain between the high dust concentration area and the walkway, by installing air curtains, of 0.05 to 0.1 m$^3$/s capacity, in every or alternate chocks (Figure 6.33). The velocity contours on the downwind side of the air curtain, in Figure 6.34 show that the air curtain modifies the airflow patterns around the walkway. Figure 6.35. shows the respirable dust concentration contours with air curtains installed. A comparison of the dust concentration profile at 0.4 m below the roof level with, and without, the air curtain (Figure 6.36) shows that there is only a 15 to 20% reduction in the dust concentration level close to the air curtain. The results indicate that it is not possible to create an air curtain between the high dust concentration area and the walkway if the quantity of air passing through each air curtain is less than 0.1 m$^3$/s (200 cfm). Higher quantities may not be practicable, nor cost effective.
Figure 6.33  A schematic diagram showing the position of air curtains in the face.

Figure 6.34  Air velocity contours across the longwall face at 2.5 m downstream of the air curtain.
Figure 6.35  Respirable dust concentration contours across the longwall face at 2.5 m downstream of the air curtain.

Figure 6.36  Respirable dust concentration across the face at 2.5m downstream of the air curtain and a comparison with normal dust level, showing the efficiency of the air curtain system.
6.7.7 Scrubber system in the walkway

The scrubber system dust control technique (described in chapters 4 & 5), was aimed at creating a reduced dust concentration zone along the walkway by using a number of air powered venturi scrubbers, spaced at 4.5 m intervals, which deliver cleaned air at high exhaust velocity. In modelling this, 0.5 m$^3$/s capacity scrubbers were mounted in the front walkway (see Figure 5.1, chapter 5). The longwall face velocity was set at 2.1 m/s. An analysis of velocity vectors shows that the scrubber exhaust modifies the air flow pattern in the walkway area (see Figure 6.37).

Figure 6.37 Air velocity vectors at 3.0 m downstream of the scrubber.
The dust concentration contours, ascertained by mathematical modelling of the scrubber system, are shown in Figures 6.38 and - 6.39, and a comparison of simulated dust concentration values in the longwall face with, and without scrubber, is shown in Figure 6.40 and 6.41. This shows that the scrubber system provides clean air near the miners' breathing area. Analysis of figures 6.39, 6.5, 6.40 and 6.41 shows that, on an average, a protection efficiency of 40-50% can be obtained in the miners' breathing zone. The installation of the scrubber also decreased dust levels by 25-30% in between the chock legs.

Figure 6.38  Respirable dust concentration contours across the face at 3.0 m downstream of the scrubber.
Figure 6.39 Respirable dust concentration contours across the face at 5.0 m downstream of the scrubber.

Figure 6.40 Respirable dust concentration across the face at 3m downstream of the scrubber system and a comparison with normal dust level, showing the efficiency of the system.
With the scrubber located 1.2 m below the roof canopy in the front walkway, simulations were conducted to investigate the effect of the scrubber location on dust concentration levels in walkway and findings are given in Figure 6.42. It can be seen that with the scrubber at this location, dust levels decreased by only 20% in the walkway.

The results of mathematical investigations, with two scrubbers installed, are presented in Figure 6.43 showing a typical dust concentration profile along the longwall face. Analysis shows that there is no difference in the protection efficiency effected by either scrubber. The installation of the second scrubber does not increase the overall protection efficiency of the scrubber system, but does increase the length of the clean air zone from 5 m to 10 m.
Figure 6.42 Respirable dust concentration contours across the face at 3.0 m downstream of the scrubber when it was installed 1.0 m below the roof.

Figure 6.43 Respirable dust level profile along the face at miner's breathing height (0.4 m below roof) with two scrubber system and a comparison with normal dust level.
Advantages of mathematical modelling

The advantages of using mathematical modelling techniques to complement experimental testing in dust control technology are:

(1) the capability of providing detailed information on variables, such as air velocity, dust concentration, etc., throughout the flow field;
(2) the ability to investigate the implications of design changes within a relatively short time which gives greater design flexibility;
(3) the reduction in time and cost;
(4) the reduction in the range of conditions over which field testing is required;
(5) the capability of providing greater insight into the flow fields and recirculation patterns that may develop as a result of the presence of dust control techniques.

6.8 SUMMARY

The extensive variations in face ventilation conditions and operations inherent in longwall mining make mathematical modelling an invaluable tool in both the development and evaluation of dust control devices. In this study, a three-dimensional finite element computational fluid dynamics code, FIDAP, was used to model air velocities and the effect of dust control techniques on dust concentration at a typical longwall face. The longwall face was modelled in three dimensions and the finite element techniques were successfully applied to supplement the field investigations.

The longwall face model was subsequently used to simulate the airflow patterns and respirable dust concentration distribution. The general flow characteristics around the shearer, with both antitropical and homotropical ventilation systems, were also computed.
The effect of the shearer body, and the cutting direction with respect to the ventilation on the longwall face airflow patterns, and on respirable dust behaviour, was analysed. The particle path traces provided a qualitative feel for the mean flow and respirable dust behaviour closer to the shearer.

The model was also used to evaluate the scrubber system and other dust control techniques such as curtain over shearer, face curtains, etc. As the effectiveness of most of the dust control techniques depends on the spatial location of such devices, three dimensional simulations were performed. Path traces of particles introduced near the cutting drums, with various dust control techniques installed, were computed. The model has the ability to add or to remove any dust control technique, and to alter the intake air velocities with relative ease so as to study their effect on respirable dust behaviour.

Overall, the analysis of the results show that finite element modelling techniques are advantageous for a thorough understanding of air flow fields in a longwall face and for initial testing of new dust control techniques. The mathematical longwall face model allows new dust control design ideas to be investigated quickly and economically before proceeding with field investigations, and is therefore a valuable supplement to field studies. Validation of the model by comparing with the results presented in chapters 3 and 5 and results of additional field studies is presented in chapter 7.
An important aspect of any modelling exercise is to validate the results of mathematical modelling by comparing with field measurements. Experiments were conducted in four operating longwall faces to collect the data for model validation. A description of the longwall faces and the sampling procedures are given in chapter 3. The major difference between the experiments described here and those presented in chapter 3 is that, this set were designed to collect the data on the variation in air velocities, dust levels across the section of the face and around the shearer. Some of the results presented in chapter 3 and the field evaluation of the scrubber system presented in chapter 5 are also used for comparison with model results.

7.1 COMPARISON OF AIR VELOCITY PATTERNS FROM MODELLING RESULTS AND FIELD MEASUREMENTS

Air velocity profiles measured at different locations across the section of longwall faces B and C are shown in Figures 7.1 and 7.2. It can seen that although the air velocity values differ in each face, the airflow patterns are similar. Figures 7.3 and 7.4 show a comparison between simulated and field measured values of air velocity at different heights across face 'C'. It can be seen that they are practically similar. A comparison of air velocities from field measurements at longwall face B and modelling results, presented in Figure 7.5, show that the field measured values near the front chock legs are marginally lower than the model predictions.
Figure 7.1  Field measured air velocity values across the section of the longwall face B

Figure 7.2  Field measured air velocity values across the section of the longwall face C
Figure 7.3  Comparison between model predictions and field results of air velocity across the longwall face C at two different heights near the floor.

Figure 7.4  Comparison between model predictions and field results of air velocity across the longwall face C at two different heights near the roof.
Figure 7.5(a) Comparison between model predictions and field results of air velocity across the longwall face B at a height of 1.2 m above the floor.

Figure 7.5(b) Comparison between model predictions and field results of air velocity across the longwall face B at a level of 0.4 m below the roof.
These figures show that, in general, the results from modelling are close to the field measured values except near the boundary walls. It should be noted that in the model, it was assumed that the air velocity at the solid boundaries was zero, whereas in underground coal mines it is very difficult to measure the air velocity very close, i.e. within 1 to 3 cm of the wall, to the solid boundaries. This is the reason for the variation in the patterns of the air velocity profiles near the walls, but the velocities in general are comparable.

Air velocity profiles near the shearer cutting drum from the modelling and field measurements are compared given in Table 7.1 and Figures 7.6 - 7.7. These results show that the model predictions for the effect of shearer on air velocity are very close to the actual values. It can be seen that the air velocity near the roof has increased marginally due to the presence of the shearer.

Table 7.1 Comparison of air velocity near the shearer across the longwall face between model predictions and field measurements

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<tr>
<th>S.No</th>
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Figure 7.6(a) Comparison between model predictions and field results of air velocity across the longwall face C (near the shearer and away from the shearer).

Figure 7.6(b) Comparison between model predictions and field results of air velocity across the longwall face C (near the shearer and away from the shearer).
Figure 7.7 Comparison between model predictions and field results of air velocity across the longwall face B (near the shearer and away from the shearer).
7.2 COMPARISON OF DUST CONCENTRATION PROFILES

Figures 7.8 and 7.9 show typical dust concentration values across the longwall faces B and C. The dust concentration distribution in face B is significantly different from that in face C, which can be attributed to the difference in operational procedures such as cutting direction with respect to the airflow and use of the shearer clearer. In figure 7.10 two typical instantaneous dust profiles, at two different locations, across face B show that the dust concentration over 15 minutes averaged 16.90 mg/m³ over the panline, 10.76 mg/m³ in the front walkway and 7.10 mg/m³ in the back walkway. They also show large dust gradients exist around the shearer as well as across the section of the longwall face.

![Diagram of dust concentration values across the section of the longwall face B](image)

Figure 7.8 Field measured dust concentration values across the section of the longwall face B
Figure 7.9  Field measured dust concentration values across the section of the longwall face C

Figure 7.10(a)  Measured respirable dust levels across the face B in two different locations at miner's breathing height (0.4 m below roof).
Figure 7.10(b) Measured respirable dust levels across the face B in two different locations at miner's breathing height (0.4 m below roof).

The simulated dust concentration values were compared with field measured values in face B at the miner's breathing level i.e at a height of 0.4 - 0.5 m the below roof in Table 7.2 and Figures 7.11 - 7.12. The comparison shows close agreement between corresponding values over the spill plate and front walkway areas, whereas near the back chock legs field values are significantly higher than model predictions. Field measurements of respirable dust concentration levels in faces A and C compare well with computer simulations as shown in Figures 7.13 and 7.14. The figures show that the dust concentration distribution predicted by the model is similar to field measurements.
Table 7.2  Comparison of dust levels across the longwall face between model predictions and field measurements

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<tr>
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</table>

Figure 7.11  Comparison of respirable dust levels between model predictions and field results across the longwall face B at miner’s breathing height (0.4 m below roof) for experiment 1.
Figure 7.12  Comparison of respirable dust levels between model predictions and field results across the longwall face B at miner’s breathing height (0.4 m below roof) for experiment 2.

Figure 7.13  Comparison of respirable dust levels between model predictions and field results across the longwall face A at miner’s breathing height (0.4 m below the roof).
Figure 7.14 Comparison of respirable dust levels between model predictions and field results across the longwall face C at miner's breathing height (0.4 m below the roof).

Figure 7.15 compares the respirable dust concentration values from modelling and field measurements when cutting with, and against, the airflow. These profiles are similar to the numerical path trace plots of particle behaviour presented in Figures 6.13 and 6.14. The figures show that, in general, model simulations predict the same patterns of dust levels across the face as observed in the field studies.
Figure 7.15(a) Field measured instantaneous dust level profiles around shearer when cutting with, and against, ventilation for experiment 1.

Figure 7.15(b) Field measured instantaneous dust level profiles around shearer when cutting with, and against, ventilation for experiment 2.
7.3 COMPARISON OF SCRUBBER SYSTEM EFFECTIVENESS

A comparison between dust concentration values from the simulations and field measurements in the miner's breathing zone in face A with, and without, the scrubber is shown in Figures 7.16 and 7.17. It can be seen from that, most of the measurements are within the model prediction region and the trend is for the model predictions to agree with the experimental results. However, the protection efficiency of the system along the centre line of the scrubber tends to be higher slightly in the simulated values than in the field values. This variation may be due to the longwall face supports moving constantly throughout the cycle underground, whereas in the model they are stationary.

![Graph showing comparison of respirable dust levels between model predictions and field results along the longwall face A with, and without scrubber.](image-url)
Figure 7.17 Comparison of respirable dust levels between model predictions and field results across the longwall face A with, and without, scrubber (at 3m downstream of the scrubber).

Figures 7.18 to 7.21 compares modelled predictions of scrubber efficiency with corresponding experimental results in face C. The figures vary marginally around the front legs of the chocks, and much of the difference between experimental data and model results are attributable to simplifications made in the chock section of the face. The variation in protection efficiency relative to distance from the scrubber predicted by modelling is compared with the actual variation in Figures 7.22 - 7.24. A similar comparison for the protection efficiency along the walkway with two scrubbers installed is shown in Figures 7.25 and 7.26. It can be seen that the mathematical simulations predicted the same protection efficiency as was observed in experimental results.
Figure 7.18  Comparison of respirable dust levels between model predictions and field results along the longwall face C with, and without, scrubber for experiment 1.

Figure 7.19  Comparison of respirable dust levels between model predictions and field results along the longwall face C with, and without, scrubber for experiment 2.
Figure 7.20  Comparison of respirable dust levels between model predictions and field results across the longwall face C with, and without, scrubber (at 3m downstream) for experiment 1.

Figure 7.21  Comparison of respirable dust levels between model predictions and field results across the longwall face C with, and without, scrubber (at 3m downstream) for experiment 2.
Figure 7.22  Comparison of protection efficiency of the scrubber system between model predictions and field results in longwall face A.

Figure 7.23  Comparison of protection efficiency of the scrubber system between model predictions and field results in longwall face C for exp. 1.
Figure 7.24 Comparison of protection efficiency of the scrubber system between model predictions and field results in longwall face C for exp. 2.

Figure 7.25 Comparison of respirable dust levels with two scrubber system between model predictions and field results along the longwall face C.
The results from other dust control techniques modelled are compared with results from the U.S. Bureau of Mines and other studies. Investigations with face curtains (Babbitt et al, 1984) were found to cause eddying of the airflow into the walkway with subsequent increases in walkway dust levels, which agrees with the results from the simulations. Field investigations with an air curtain (Liu, 1991) showed that although it reduces dust slightly in close proximity to it, it is not effective in separating the high dust concentration zone and the walkway. This agreed with the modelling results.

Studies show that the 'curtain over shearer' approach (Shirey, Colinet and Kost, 1985; USBM, 1981d) reduces the shearer operators' dust exposure when cutting with ventilation. Similar results were obtained with modelling as can be seen from particle path traces in figure 6.18.
Analysis of the results shows that the results of simulations are, in general, in good agreement with field measured values. However, small variations do exist in some experiments, particularly near the boundaries, which can be attributed to the following:

(i) The activities at an operating longwall face are more complex than those in a modelled longwall face. At an operating longwall face, there are usually multiple and intermittent dust sources, which vary from one cutting cycle to another. Unlike the model, the actual shearer production rate and haulage speed are rarely constant in any cutting cycle. In the model, computer limitations dictated that a uniform and constant dust source across the face be assumed. This equalled the average values obtained during preliminary studies.

(ii) The cross sectional areas at different places of an operating longwall face vary as the face advance. In the computer simulations, the width and height of the face were assumed to be constants, being equal to the average width and height of the face at different sampling stations. Therefore, the model predicts the same airflow dust concentration patterns in every simulation.

(iii) A slightly coarser meshes than desired were used near the wall boundaries due to the limitation of the computer and to keep the computation of variables within a reasonable time frame. To investigate the effect of a fine mesh near the walls, and to ensure that the selected mesh size could realistically accommodate the variations in airflow fields, a series of test simulations were performed on a considerably finer mesh. Each of these computations took more than a week to solve. A comparison of fine mesh simulations and slightly coarser mesh showed that in all cases, the air flow pattern, dust distribution and maximum concentration levels in the face remained the same except in the regions very close to the walls, where the variation was around 4 - 7%.
7.4 SUMMARY

For the purpose of validation of the results from modelling, field experiments were conducted in three operating longwall faces. A comparison of the results from field measurements with simulation results have been presented in this chapter. The mathematical simulations of airflow and dust patterns are in excellent agreement with the results from field measurements in operating longwall faces, except in the regions very close to the boundary walls. The model predictions of the effectiveness of the dust control techniques are also within 10% of the field measured values.

The CPU limitation of the computer placed some restrictions on the three dimensional modelling of the longwall face, including the inability to model the full length of the face, to use very fine mesh near the boundary walls or to model all chock legs and cables individually. Despite these limitations, results from the simulations provided good results extending the understanding of respirable dust behaviour in a longwall face and has helped in optimising the location of dust control systems in the face.

The good agreement between modelling results and field measured values suggests that a finite element longwall face model could predict flowfield characteristics and dust distribution in coal mines. Finite element modelling techniques are therefore invaluable for a thorough understanding of air flow fields and dust behaviour and can be used to facilitate develop effective dust control techniques in underground coal mines.
The conclusions of this research work undertaken to advance the control of respirable dust levels in longwall mining are summarised in the following sections.

8.1.1 Field investigations

The field experimental studies have been very useful in identifying some of the important parameters affecting dust transport and in characterizing dust cloud behaviour at longwall faces. It provided a comprehensive data base for the development of a dust control technique that is effective in minimising the dust exposure of miners working at the face. A brief outline of the observations from the field studies are as follows:

1) The respirable dust concentration increases with distance towards the return end of the longwall face. However, the large variation in the dust gradients along the same longwall face indicated that the relationship between the dust level and distance from the intake end is complex and not easily generalised owing to the numerous factors involved. Furthermore, the average dust concentration levels could not be correlated with face activities, and it was necessary to conduct instantaneous dust sampling surveys to give a clear picture of respirable dust conditions at the face.
2) The dust distribution patterns are different for different phases of the cutting cycle, i.e. the cutting, cleaning and sumping operations. Although the trend of respirable dust concentration profiles was consistent in the different longwall faces investigated, there were significant variations in dust levels. These variations could be attributed to the differences in ventilation plans, operating procedures and dust control techniques.

3) Under the same operating conditions, a higher cutting speed results in higher dust concentration levels. Misdirected water sprays on the shearer increases dust concentration at the rear drum operator’s position.

4) A comparison of air quantity and respirable dust levels in different faces indicates that low air quantity and consequential low air velocity (less than 2.2 m/s), at the face could be one of the main reasons for the high dust concentration levels in the longwall faces A & C.

5) Cutting against the ventilation disperses more dust into the shearer operator’s position than when cutting with the ventilation. However, when cutting with ventilation, the maingate cut-out, during which the drum makes a number of partial sumping cuts, produces a significant proportion of the total respirable dust.

6) There are large dust gradients, not only around the shearer, but also across the section of the longwall face. Dust levels over the AFC area were higher than those in the walkway between the chock legs and these differences exist even 50 m downwind of the shearer. Thus, the assumption that the dust cloud, under turbulent flow, becomes well mixed and uniform in a relatively short distance, is doubtful. Careful selection of a sampling site is therefore critical when evaluating the effectiveness of any dust control technique. A change in sampling location
during a survey can have a greater effect on the measured dust level than the dust control technique being evaluated.

7) Based on the air velocity and quantity data from the measurements, there was no indication of significant air leakage into the goaf. Air velocity profiles across the face showed that velocity is not uniform; it is highest over the AFC area and lowest in the walkway. Air velocity patterns in the walkway also differed from face to face depending on the type of supports used. Also, the spatial distribution of respirable dust depends largely on the airflow patterns. These variations are important considerations in the development of a dust control technique, as they affect the respirable dust behaviour and dispersion.

8) Sources other than the shearer, for example support advance, also contribute significantly to the total respirable dust concentration in a longwall face. Therefore, to reduce the longwall miners' exposure to these dust clouds requires that the development of control techniques focuses on reducing the dust that is already airborne. One such method of control could be the installation of separating elements, such as local airflow systems, between the AFC and walkway area.

8.1.2 Scrubber system for longwall face and field evaluation

1) A prototype air-powered venturi scrubber has been developed for use in longwall faces. The capacity of the scrubber is 0.5 m$^3$/s. The total length of the unit is 1.2 m and can be fitted in one chock shield very easily. The scrubber is self-cleansing, needs very low maintenance and is safe for use in hazardous conditions since it has no moving parts.
2) Laboratory studies showed that the average efficiency of the scrubber was 91% and a maximum efficiency of 92% was obtained at 2400 kPa pressure drop and a water flow rate of 6.0 l/min per 0.5 m³/s of air.

3) A minimum of 0.4 m³/s air quantity, or 50 m/s air velocity in the throat of the venturi, is required for effective atomisation of the water in the unit. The scrubber efficiency increases with an increase in water quantity.

4) To be most effective, the scrubber should operate at 0.05 m³/s compressed air flow, at 400 kPa pressure, and with a water flow rate of 6.0 l/min at a normal 700 kPa pressure. In addition, the scrubber should be delivering a minimum air flow of 0.5 m³/s at 10 m/s exit velocity and the scrubber discharge point should be located near the roof in the front walkway area.

5) Underground evaluation of the scrubber system provided protection efficiencies between 26 and 55%, at 3 m from the scrubber, with face air velocity between 4.5 and 2.0 m/s. The low efficiency (26%) in the faces with high air velocities is attributed to turbulence.

6) Experiments with two scrubbers installed also yields dust reductions of 57% at 3 m downstream of the scrubbers. Whilst two scrubbers do not increase the dust protection levels, they do increase the length of clean air zone from three chocks (4.5 m) to six chocks (9 m). For effective dust reductions in the walkway of the longwall face, a multi-scrubber system could be designed by installing scrubbers on every third chock. Thus, a 150 m longwall face would require approximately 12 to 18 scrubbers, depending on the dust conditions.
7) The installation of scrubbers modifies the airflow patterns in a longwall face, particularly in the walkway. These modified airflow patterns also contribute significantly in reducing the walkway dust concentration.

8) Scrubber capacity, cleaned air exit velocity and scrubber location are the three important parameters of the system determining its protection efficiency. Furthermore, the air velocity in a longwall face determines the amount of turbulence and hence, the effectiveness of the system in reducing dust exposure.

9) Along with a high dust collection efficiency, the venturi scrubber also possesses most of the other characteristics desirable for a good underground scrubber. Some of the advantages of this prototype air powered scrubber are:

   a. simple and very compact;
   b. no fan or electric / hydraulic motor to maintain;
   c. virtually maintenance free - no clogging, self cleaning;
   d. high pressure water pumps are not required;
   e. no electricity needed - very safe and no inherent permissibility problems;
   f. does not need any special facilities;
   g. can be easily installed in a longwall face;
   h. uses very little water compared with water powered scrubber.

10) Owing to its simplicity and flexibility the scrubber has a number of other applications including:

   a. in a shearer extraction drum or as a shearer mounted scrubber;
   b. at transfer points;
   c. at tailgate worker's position.
8.1.3 Modelling studies and validation by field measurements

1) A three dimensional model of a longwall face has been developed and finite element techniques have been successfully applied to supplement the field investigations. The particle path plots provided a qualitative understanding of the airflow characteristics at the longwall face.

2) The results of mathematical simulations of air velocities and dust concentration levels across the longwall face are in agreement with the results from field measurements, except in the regions very close to the boundary walls.

3) The predicted particle flow paths for two cutting directions and comparisons with field observations, confirmed that cutting against the ventilation disperses more dust into the walkway of the longwall face.

4) The predicted protection efficiency of the scrubber system was very close to the field measured values.

5) Simulations of other dust control techniques such as curtain-over-shearer, air curtains, face curtains, etc also closely agreed with the field results obtained by other researchers. In general, the protection efficiency of the dust control techniques predicted by the model was very close to the field values.

6) The results of modelling the 'curtain-on-in-bye-side of the downwind drum' control technique indicates that the technique is effective in controlling dust dispersion at the downwind maingate cutting drum when cutting with ventilation. 'curtain-on-in-bye-side of the shearer upwind drum' dust control technique could
also be very effective in controlling the shearer operators' dust exposure in both cutting directions.

7) The close agreement between the modelling results and field measured values suggests that finite element modelling techniques are useful for a thorough understanding of air flow and dust distribution patterns in a longwall face. It has been shown that the finite element modelling techniques are capable of predicting the effect of different ventilation systems and dust control techniques on the behaviour of dust, and are an invaluable tool in the development of new dust control techniques.

8) The ability of mathematical modelling to manipulate variables such as air velocity and the dust control mechanism and to examine the effect on dust behaviour, makes it a quick and economical method for investigating new dust control designs before proceeding to the field. It is also a useful supplement to studies on viable dust control techniques.

Based on the above findings, it can be concluded that the finite element longwall face model can be confidently used to simulate airflow patterns, dust concentration levels, respirable dust particle behaviour and to ascertain the effectiveness of dust control techniques.
8.2 SUGGESTIONS FOR FURTHER RESEARCH

This research has provided a comprehensive understanding of respirable dust behaviour and has promoted the advance of longwall dust control technology through the development of a new dust control technique, but there is still scope for further research in this area. Such research should be pursued on dust control techniques which separates the AFC and walkway areas. The concept of isolating the cutting zone from the ventilation air stream, with different curtain configurations, should also be pursued further.

Consideration should be given to integrating the scrubbing units into the powered support system. In the future, when high capacity, high pressure, compact, mine approved fans are available, attention may be given to replacing the compressed air power source with electrically powered fans. The use of electrical fans would make the sequencing of scrubber units very easy, as well as being integrated into the powered supports.

Research should be undertaken on the concept of agglomerating the respirable dust particles into larger particles. One approach would be the application of high powered ultrasonic transducers with, or without, water. Ultrasonic agglomerators could also be used as a pre-conditioners, in-front of the scrubbers, to reduce their load which would make it easier for the scrubbers to collect the larger particles.

Field investigations should continue to gather more data on the transient and spatial dust concentration distribution in longwall faces which have different physical and operating characteristics. Future studies should focus on designing appropriate sampling plans for data collection on secondary dust sources, such as dust from support movement, coal spalling and goaf falls.
Mathematical modelling of the longwall face is another important area which merits further work for a better understanding of secondary airflows around the shearer and dust distribution. Comparative analyses of the mathematical modelling predictions and experimental results highlight areas which need additional modelling. In its present form, the model can predict dust behaviour at the face very closely, but can only provide rough estimates of behaviour very close to boundary walls. To solve this problem, fine mesh needs to be used near the walls. The present model, limited to 40 m in length due to computer capacity, can only be used to simulate dust concentration profiles around the shearer and across the face. A full length model should be developed to simulate the dust profiles along the full length of the longwall face.

In addition, a better fit between the simulated and field results near the blocked regions could be achieved if the components of the longwall face were individually modelled and evaluated with experimental data. Further modelling should include the simulation of total dust behaviour, i.e. include particles larger than 10 microns, to determine the interaction between particles. The modelling of large particles, which have inertia and a relative velocity with respect to airflow, requires separate equations for particle transport. All these additional features require greater computer capacity for simulations.

The trend of increased production from longwall faces and the consequent increase in dust generation will necessitate the use of finite element techniques to simulate airflow patterns and pollutant behaviour in underground coal mines. Developments in the computer hardware technology will also facilitate the use of finite element techniques in airflow modelling in underground coal mines. Application of these techniques to the analysis of other environmental problems in underground coal mines is also recommended.
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