

**THE INHIBITION OF COAL-DUST
EXPLOSIONS WITH STONE DUST IN
A LARGE-SCALE EXPLOSION GALLERY**

PATRICK MICHAEL COOK

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**A dissertation submitted to the Faculty of Engineering, University of the
Witwatersrand, Johannesburg, in fulfilment of the requirements for the
degree of Master of Science in Engineering.**

Johannesburg, 1992

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University. This work was completed under the auspices of the CSIR.



June 1992

ABSTRACT

Regulation 10:24 of the Minerals Act (1991) of the Republic of South Africa is applied for the purpose of preventing the development and propagation of coal-dust explosions in underground coal mines. It requires that an inerting agent called stone dust be used. However, because coal dust has participated in underground explosions where the Regulation has been applied, an evaluation of the Regulation was instituted, for which the 200-m-long G P Badenhorst Explosion Gallery was constructed. No existing procedures were found suitable for the evaluation, so an experimental procedure had to be developed. The procedure uses both a weak and a strong propagating coal-dust explosion as the initiator of a test zone in which stone dust has been applied to a coal-dust deposit as stipulated by the Regulation. It was found that the application of Regulation 10:24 did not inhibit, for the coals investigated, the development or suppress the propagation of propagating coal-dust explosions. This finding implies that a review of the Regulation is necessary.

ACKNOWLEDGEMENTS

The author would like to thank the National Energy Council and the Government Mining Engineer of South Africa for funding and promoting this research. The contribution of the members of the Steering Committee towards the research is gratefully acknowledged. In addition, Professor H R Phillips, Messrs M P Brandt, G v R Landman, D Bryden, P du Toit, J Marema, A Moloya and D Mphela are thanked for their assistance and advice.

The CSIR is similarly thanked for the opportunity of allowing the work to be completed.

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1 INTRODUCTION

In South Africa, 983 people have been fatally injured due to underground explosions in coal mines since mining operations began (Landman, 1990). Of these, 142 died in the 1980s. (Two disasters at Ermelo, one at Middelbult and one at Hlobane collieries (Viljoen, 1989).)

Recent investigations of underground coal mine explosions indicate that coal dust participated in the explosions (Reusch, 1983; Joabert et al., 1973, 1974, 1977, 1981, 1982, 1983), even though preventative measures were applied according to Regulation 10:24 of the Minerals Act (1991) of Republic of South Africa. The purpose of the Regulation is to inhibit the development and to suppress the propagation of coal-dust explosions by the introduction of stone dust. Stone dust is an incombustible material which satisfies the specifications defined in the Regulation.

The explosive nature of coals according to the Regulation is classified in terms of the volatile matter content as indicated in Table 1.1. The ranges of volatile matter thus require a specified minimum percentage of incombustible matter.

Table 1.1 Specified quantity of incombustibles to be present in mine-dust samples according to Regulation 10:24 of the Minerals Act (1991)

Percentage by mass of volatile matter content, calculated on a dry ash-free basis, of coal being mined	Minimum percentage by mass of incombustible matter content
$14 < VM \% < 20$	50
$20 < VM \% < 22$	55
$22 < VM \% < 25$	60
$25 < VM \% < 27$	65
$27 < VM \% < 30$	68
$30 < VM \% < 32$	70
$32 < VM \% < 35$	72
$35 < VM \%$	75

The amount of stone dust, when conjoined with the ash and water content of the coal, is called the total incombustible content in dust samples. No additional amounts of incombustible matter are specified to take the influence of methane into account.

The incombustible content required increases with the volatile matter content of the coal, and this value must be adhered to throughout the coal mine. The control measures for ensuring that the quantity of stone dust is sufficient imply that by agitating the sample taken, the coal dust and stone dust are intimately mixed.

The minimum specifications for stone dust are shown in Table 1.2. Additionally, it is required that the stone dust be light in colour (SABS 0137).

Table 1.2 Specifications of stone dust as required by Regulation 10:24 of the Minerals Act (1991)

ITEM	VALUE
Incombustible content	Mln. 95 %
Free silica	Max. 5 %
Size: 100 % pass	600 μ m sieve
50 % pass	75 μ m sieve (min)

The sampling procedure involves taking a sample from the footwall (25 mm maximum depth) and another from the sidewall and hanging wall (6 mm maximum depth) at a fixed position, and mixing the respective samples. This must be done at every 50 m, on a monthly basis (MA 10:24).

In 1987 the Government Mining Engineer, in conjunction with industry and the National Energy Council, instituted a research programme to evaluate the present stone-dusting regulations. This investigation has been carried out at the GP Badenhorst Research Facility in a 200-m-long explosion gallery.

This dissertation reports on the results of the evaluation of Regulation 10:24 of the Minerals Act (1991). An experimental procedure was developed for this purpose. It involves exposing a mixture of coal dust and stone dust (as required by the Regulation) to both a weak and a strong propagating coal-dust explosion. The criterion for validity of the Regulation is that the mixture must not develop into a coal-dust explosion or propagate further.

The following aspects are discussed:

- A review of the sequential steps of a coal-dust explosion establishes the components of the experimental design that require defining. A literature survey of experimental facilities and procedures reveals the methods used at other research facilities for evaluating stone-dusting practices; the applicability of such procedures and of the results obtained in the test facilities is discussed.
- The G P Badenhorst Test Gallery is then described with the intention of defining the influence of its length, cross-sectional area and strength on the accuracy of the results obtained. Comparison of the results was made possible by exercising strict control over the particle size distribution of the coal dust used; this was achieved by the use of a dedicated milling plant.
- The stages of a coal-dust explosion in the explosion gallery are then described. Both weak and strong propagating explosions have been optimized in the gallery. These explosions from the first coal-dust deposit are used as an initiator for the second deposit or test zone. This test zone has been optimized without stone dust, producing a further coal-dust explosion, and this has provided the test region in which to evaluate the Regulation.

The experimental layout with two coal-dust deposits is termed for

this dissertation a double explosion, even though they are two separate events.

- The regulation amount of incombustible matter was applied to the coal dust in the test zone and the results are discussed.
- The practical implications of the results obtained in the gallery and the procedure developed are discussed, and recommendations are made for actions to be taken.

REVIEW OF INHIBITION AND SUPPRESSION OF COAL-DUST EXPLOSIONS.

The literature reviewed covers the distinct stages of coal-dust explosions that need to be described in an experimental evaluation of the inhibition or suppression of such explosions. These stages are discussed in relation to the work done at other research facilities that have investigated similar explosions and the procedures they have used for testing the effectiveness of stone dust in galleries and experimental mines.

2.1 Coal-dust explosion theory

A basic theoretical understanding of the complexity is necessary to show that empirical solutions via experimentation are the most practical way of investigating the termination of such explosions (Palmer, 1973). This section provides an overview of the theories developed and shows the interrelationship of simultaneous processes that take place during an explosion.

Coal-dust explosions are defined as explosions in which coal dust participates in uncontrolled combustion in an underground environment, resulting in human fatalities, injuries or damage causing financial loss. Their self-propagating potential makes such phenomena extremely dangerous (Holding, 1982).

The analytical approach towards solving this problem of understanding coal-dust explosions has been to reduce the complexity to the study of single-dimensional flames (Essenhigh and Misra, 1990). Such an understanding assists in explaining multi-dimensional flame propagation as is present in coal-dust explosions. Thus the combustion of a single coal particle describes the first dimension of the flame. Heat transfer between particles constitutes the second dimension as in vessels (closed), and the third dimension is that of the flame moving spatially away from the source in a turbulent manner, as in an explosion gallery (open).

The components that are necessary for an explosion to occur, are an energy source, oxygen and coal dust. Oxygen is present to sustain life in mines, thus limiting the ignition sources and coal dust participation are the only practical solutions. The number of severe accidents indicates that ignition sources are present, however, this dissertation addresses the post-ignition conditions.

The questions surrounding the extinguishing of gallery coal-dust explosions pertain to the prevention or rapid termination of one of the stages in the course of a coal-dust explosion. These stages are the ignition, initiation, development, propagation and termination (Richmond et al., 1975). Each stage will be discussed sequentially.

2.1.1 Ignition

The igniter is the thermal source of the explosion and is needed to ignite, and thus cause an explosion. This initial impulse constitutes the ignition stage. Certain minimum conditions have been established for such an occurrence. The minimum ignition energy and temperature, which are specific to particular dispersed coal dusts, are greater than 120 mJ and 600 °C, for coals with volatile matter contents higher than 14 % (BIA-Handbuch, 1987). This is equivalent to the static electricity accumulated by an average-sized walking person on a carpeted floor on a dry day (Nagy, 1981; Flint, 1991). The necessary concentrations of coal dust in air must be more than 60 g/m³, with a suitable coal-dust size distribution. These values, especially the very low energy values, decrease for more highly volatile coals, implying more sensitive explosive conditions.

Laboratory-scale experimentation is the most suitable method for these sensitivity investigations as the apparatuses have been specifically designed to describe the conditions for ignition (Essenhugh et al., 1989).

Complete and thorough investigations of accidents are necessary to identify the specific ignition source and to allow preventative measures to be introduced.

The most prevalent ignition sources resulting in explosions from 1980 - 1991 in terms of fatalities, not the number of events, are: electricity, 68; shotfiring, 39; open flames, 30; unknown, 14; and lightning, 14 (Sichel et al., 1984; Trueman, 1985; Viljoen, 1989). A new hazard that has arisen with mechanized mining is hot surfaces. This aspect has been highlighted by Flint (1991).

Measures such as the declaration of fiery mines, a system of permitted explosives, intrinsic safety measures, and flame and explosion-proofing have been adopted in the past in an effort to eliminate or contain ignition sources.

Although it can be stated that the majority of ignitions do not result in coal-dust explosions (Cybulski, 1973), for the purpose of research investigations into explosion inhibition and suppression it is assumed that the minimum conditions of ignition have been satisfied.

2.1.2 Initiation

The initiation stage consists of the lifting of coal dust into the air and the supplying of heat to start combustion of the coal-dust/air mixture. Accident investigations show that methane explosions are the predominant cause of explosion initiations (Flint, 1991). This is attributed to methane's low ignition energy of 0.3 mJ, and thus the higher probability of ignition.

The rate of development of coal-dust explosions has been found to be dependent upon the initiation strength (Nagy and Mitchell, 1963; Lebecki, 1988), which determines the initial flame speed, and thus strength of the ensuing explosion (Lebecki, 1989). Therefore the initiator must be controllable and experimentally repeatable.

In research, the initiator is categorized separately from the igniter to facilitate defining the purpose of preventative measures. The intimate co-existence of the igniter and initiator must be emphasized, but they may combine simultaneously such as with non-permitted explosives. When detonated, they cause an aerodynamic disturbance producing a cloud of coal dust in the vicinity of a high temperature, resulting in a dust explosion. A coal-dust explosion may initiate a further coal-dust explosion.

2.1.3 Development

The development stage is the commencement of coal-dust combustion, where a pressure increase and coal-dust explosion flame are noted which are not attributable to a methane explosion.

Three mechanisms have been proposed to describe the combustion of coal in an explosion environment which is characterized by high thermal gradients, i.e. greater than 40 000 °C/s.

- Firstly, the volatiles within the coal can be driven off and can combust in a pyrolysis reaction, producing a devolatilized residue (Cashdollar and Hertzberg, 1983; Essenhigh, 1977). The rate-determining step for this reaction is the devolatilization process which is a function of the size, shape and nature of the particles (Krazinski et al., 1978).
- Secondly, a pyrolysis reaction may occur, followed by char combustion in a step-wise process. The limiting step in this case is the diffusion rate of oxygen to the surface of the particle to allow for combustion.
- Thirdly, both processes can occur simultaneously where both volatiles and char combust. A high thermal impulse has been found experimentally to result in such a phenomenon (Farzan and Essenhigh, 1982).

Evidence from explosion investigations, however, indicates that with relevant coals coked particles are present in addition to devolatilized particles (Burghammer and Fromme, 1984), which favours the second and third mechanisms. However, due to the short duration of the flame at a specific position during an explosion, the first mechanism is preferred in which the reaction is predominantly a volatile combustion process. The rate-determining step is the devolatilization process. This means that the coal:air ratio and the thermal impulse are related. A low coal:air ratio with a high thermal impulse, when above the minimum conditions, gives the same result as a high coal:air ratio with a low thermal impulse by combusting the same amount of volatile matter. More detailed descriptions are provided by McLean et al. (1981).

2.1.4 Propagation

When a number of particles of coal dust cause another particle to combust, this introduces a further dimension, that of heat transfer. Here the transfer of heat between particles is the rate-determining step (Field, 1982).

The density of coal in the air or the coal:air ratio is therefore an indicator of the possibility of continuance of such a combustion process. The ability to transfer heat and thus propagate describes the tendency of a specific explosion environment to produce a self-sustaining explosion (Slezak, 1985). Radiation between particles is the predominant mechanism of heat transfer, but convection currents and conduction within the fragmenting particles also occur.

The dispersion or aerodynamic factors (Michelis et al., 1990) that lift the dust into the air during an explosion are essential for propagation (McCarthy and Olson, 1968). This occurs ahead of the flame and thus coal-dust explosions are predominantly deflagration-type explosions, where the flame follows a blast wave, although shock-wave-induced explosions have been noted (Sichel et al., 1984). The damage associated with such tests limits the extent of large-scale investigations.

2.1.5 Termination

The termination or cessation of combustion is the final stage of a coal-dust explosion. The conditions may change and become unfavourable for an explosion to propagate. This occurs when either the heat transfer, the combustion (mass transfer) or the aerodynamic effects are eliminated for open or gallery explosions.

Numerous efforts have been made to artificially promote termination economically and practically, of which the most widely accepted method is to use stone dust.

The mechanisms by which stone dust works vary but appear to consist of one or a combination of the following:

- The limestone may act as a heat sink by absorbing heat during heat transfer; the smaller particles are more effective due to their larger surface area and greater heat absorption potential (Dawes and Wynn, 1952).
- Stone dust may also act as a radiation shield by providing a "curtain" through which the thermal energy cannot be transmitted. This would require larger particles to be more effective.
- The breakdown of stone dust into carbon dioxide due to heating may also contribute to inerting the environment by reducing the mass transfer via oxygen limitation (Choi et al., 1988). This process is considered too slow to be significant.
- Aerodynamic resistance to the dispersion of coal dust is the mechanism favoured by Essenhigh (1962), who contends that this limits the dispersion potential of coal dust.

Whatever the mechanism, stone-dusting has been found to be a practical, controllable and effective solution (Rae, 1972; Michelis, 1991) for

inhibiting the development and suppressing the propagation of coal-dust explosions.

2.2 The research facilities

Most coal-producing countries have a research facility for the prevention of coal-dust explosions, whether on a small or large scale. The most advanced research institutes are in the United Kingdom at Buxton, in Poland at the Barbara experimental mine, in the United States of America at the United States Bureau of Mines in Pittsburgh and in Germany at the Deutsche Montan Technologie in Dortmund.

Research is categorized according to the scale of the equipment used to simulate actual conditions.

2.2.1 Laboratory-scale equipment

Laboratory-scale equipment has been extensively used for sensitivity testing. This has been well documented by Dorsett et al. (1959) and Moore (1979) who conclude that larger scale testing gives practically more applicable results. Scaling-up of laboratory equipment has proved complex but, due to the extensive work by Barknecht (1981), extrinsic correlations have been obtained. These relate the explosion severity of closed vessels to the cubic root of the volume of the vessel and to the maximum rate of pressure rise.

The parameters that have been found to be significant in describing the sensitivity and hazard presented by a specific dust are investigated using the apparatuses shown in Table 2.1.

The minimum conditions are specific to the apparatus and the particular coal dust being tested.

Table 2.1 Laboratory-scale coal dust explosibility apparatuses

APPARATUS	PURPOSE
Vertical tube/Hartman device	Damage potential
Horizontal tube/inflamator	Damage potential
Godbert Greenwald tube	Minimum explosible concentration
Vertical tube	Minimum ignition energy
Godbert Greenwald furnace/ Modified Hartman device/ Hartman bomb	Maximum permissible oxygen concentration
40-litre vessel	Hybrid gas-coal mixtures
20-litre vessel	Minimum ignition temperature
1 m ³ vessel	Damage potential

However, certain generalizations can be made for bituminous coals. The minimum explosive concentration of coal dust is generally greater than 60 g/m³ and the minimum ignition energy and temperature greater than 120 mJ (for dispersed mixtures) and 600 °C respectively. The damage potential has been used to classify different sized coal dusts on a relative scale (Reeh, 1981). Researchers have concluded from their results that the volatile matter content of the coal is an indicator of the damage that will ensue should an explosion occur. This provides a convenient measure as volatile content is easily quantified, and as such describes the susceptibility of a coal dust to explode.

A significant contribution to this field of investigation would be to establish a correlation between laboratory-scale and large-scale experimentation. The difference has been attributed to larger thermal zones as well as to reduced heat losses in apparatuses of larger dimensions (Sapko et al., 1987). Cashdollar et al. (1986, 1988) have related small (8-litre vessel) and large-scale (Bruceton and Lake Lynn) experimental mines apparatuses in terms of the efficacy of inhibitors.

This form of experimentation has not proved suitable for the evaluation of stone-dusting because of the geometrical influences of an apparatus,

and thus aerodynamic dust dispersion, on the course of an explosion. Thus galleries and experimental mines that are more representative of the actual conditions have been constructed.

2.2.2 Galleries and experimental mines.

Multiple-entry experimentation, as carried out at the Bruceton Experimental Mine facilities (Sapko, 1987), would appear most suitable for RSA conditions where bord-and-pillar extraction methods account for more than 50 % of coal production (Hardman, 1990). This facility, which was closed in the 1980s, yielded significant information which has been verified in single-entry galleries.

Table 2.2 lists the large-scale facilities in use, where the cross-sectional area and length distinguish the size.

Table 2.2 Large-scale coal-dust-explosion research facilities

COUNTRY	PLACE	TYPE	SHAPE	SECTION AREA (m ²)	LENGTH (m)
RSA	GP Badenhorst	Gallery	Circular	4,90	200
United Kingdom	Buxton	Gallery	Arch	5,6	266
		Gallery	Circular	1,17	68
Germany	Bergbau Versuchsstreke	Gallery	Circular	2,55	180
	Tremontia	Mine	Rectangular Arch	7,5/14 8/20	100
Poland	Barbara	Mine	Arch	5,2	120/400
		Mine	Rectangular	7,5	200
USA	Bruceton	Mine	Rectangular	6,0	1 300
	Lake Lynn	Mine	Rectangular	12,5 av.	1 700

(From Rae and Beardshall, 1970; Michellis et al., 1987; Lebecki, 1967; Weiss et al., 1989)

The cost of an experimental mine prohibits the extensive use of such facilities but cannot detract from the accuracy afforded. Explosions in true cross-sections and mine geometries can be investigated, allowing direct extrapolation of results to the mining environment. The Barbara, Bruceton and Lake Lynn, and more recently the Tremonia, experimental mines have provided environments for the refinement of inhibition and suppression techniques for those countries' particular mining layouts. Such facilities tend to be limited by their structural strength, which restricts the magnitude of explosions. Explosions of larger magnitude, or high flame speeds are therefore neglected (Essenhigh, 1961), and thus the necessary preventative measures are underestimated. Surface facilities of structurally stronger steel have been constructed at Buxton, Barbara and Deutsche Montan Technologie (DMT), which have resulted in significant advances in evaluating stone-dusting. However, a further limitation is that of noise pollution, which again inhibits the maximum extremity of conditions that can be tested.

Surface roughness significantly affects the experimental results (Rae, 1972). Increased roughness is considered to result in greater flame turbulence and thus a longer combustion zone, producing a stronger explosion. Smooth walls result in an underestimation of the preventative measures needed.

Scaling correlations between large facilities have been carried out by Cybulski (1973) and Sapko et al. (1987). The results indicate that more energy is required to initiate a coal-dust explosion in a gallery of larger cross-section, the resulting explosion is faster and more stone dust is required to effectively inert the coal dust.

2.2.3 Instrumentation and data representation

In the Republic of South Africa, the German surface gallery approach has been followed by establishing a 200-m-long explosion gallery, 2.5 m in diameter, named the G P Badenhorst Research Gallery. This was considered appropriate (CMRCC, 1985) because the German results on the changing of geometries could then be applied to the results obtained at this Gallery.

The sensors that are used are flame sensors, static pressure sensors, wind-force sensors and thermocouples. Flame sensors are photovoltaic sensors that are used to measure the infra-red spectrum which is characteristically emitted by coal-dust explosions and indicates the extent of the flame. The static pressure and wind-force measurements indicate the damage that results from an explosion and thermocouples have been used to measure the effectiveness of suppressors in extinguishing explosions. The environment in which explosions have to be measured makes further quantitative and qualitative measurements difficult, as the instruments need to be explosion-proof (in terms of blast and temperature) and to be able to measure in dusty, smokey and turbulent conditions, thus a degree of precision is sacrificed.

Graphical representation of experimental results proves to be the most valuable analytical tool (Cybulski, 1973). However, in attempting to quantify test results, the parameters that have been selected to evaluate stone-dusting are the extent of the flame and the pressure build-up or overpressure.

2.3 Review of experimental procedures

Experimentation on a large scale has been approached by attempting to duplicate the underground situation with regard to geometry, coal-dust deposition and use of the recent ignition sources and initiators gleaned from accident investigations. Tests designed according to accident reports have been used for these investigations (see Table 2.3).

2.3.1 Sample preparation

Milling plants have been specifically constructed for each of the facilities. Small-scale milling is accomplished by using hammer mills, while larger scale plants have used an assortment of mills, from impact mills to attrition mills. Two size distributions of coal dust are generally used, coarse (80 % > 75 μm) or fine (80 % < 75 μm). The modern trend is to use the fine dust as this is closer to the dust produced by mechanized coal mining methods (Courtney et al., 1982).

2.3.2 Experimental layout

A multitude of test procedures have been developed, each suited to a specific purpose or aim. Stone dust has been deposited within the coal-dust deposit and the effects of the specified igniters and initiators have been measured.

Selected experimental procedures used by research facilities are shown in Table 2.3.

Standard experimental procedures are dependent on the apparatus available and the objective of the experiment. This has resulted in the design of many different tests which were initially governed by the necessity to recreate accidents. The trend more recently is to design tests for evaluating inhibitors and suppressors.

Experimenters have considered the igniter, initiator, coal:air ratio and coal-dust size to be the most significant parameters for determining the course of a coal-dust explosion. The initiator determines the coal:air ratio and is a function of all further experimental variables. These effects and other parameter variations must therefore be accounted for in any new experimental procedure.

Table 2.3 Experimental procedures used at other large-scale research facilities

FACILITY	IGNITER	INITIATOR	COAL/AIR (g/m ³)	STONE DUST	PLACEMENT	COAL
1. Lake Lynn EM	Igniter	10.3 % methane in air, with a volume of 144 m ³	200	65 %	Floor and shelves	Size: 80 % < 20 μ m mesh VM: 25 %
2. Lake Lynn EM	Igniter	10 % methane in air, with a volume of 162 m ³	100	65 %	1/2 floor 1/3 shelves	
3. Bruceton EM	Igniter	10 % methane in air, with a volume of 76 m ³	80-100		1/3 roof 1/3 shelves 1/3 floor	
4. Bruceton EM	Igniter	7 % methane in air, with a volume of 46 m ³	80-100		1/3 roof 1/3 shelves 1/3 floor	
5. Buxton Gallery	Captive rockets W-igniters		100-300			Size: 85 % < 63 μ m VM: 35 %
6. Buxton Gallery	Captive rockets W-igniters		100		Floor	
7. Tremonia EM	2.5 kg black powder	10 kg dispersed coal dust	100		Pneumatically dispersed over total area	Size: 18-22 μ m VM: 25 %
8. Tremonia EM	Igniter	8.5 % methane in air, with a volume of 120 m ³	100		Pneumatically dispersed over total area	Size: 18-22 μ m VM: 25 %
9. Bergbau Versuchsstreke	Black powder	9.5 % methane in air, with a volume of 15 m ³	100			

(Facility 1 & 2: Weiss, 1989; 3 & 4: Sapko, 1987; 5 & 6: Fae, 1971a; 7 & 8: Michells et al., 1937; 9: Burghammer and Fromme, 1984)

Lake Lynn Experimental Mine and Tremonia Experimental Mine have two standard tests according to the difference in initiator, while Buxton varies the igniter to obtain a similar contrast of results.

Two types of igniter have been commonly used: a spark, which is used to ignite methane, or an explosive, which may ignite methane or coal dust directly. This has generally been decided on according to the predominant historical ignition source of that time and has remained as the standard igniter up to the present.

Methane or predispersed coal dust is used as the initiator of a coal-dust explosion. The preference is for methane-air mixtures as they are accurately measurable in terms of volume and concentration and thus provide a repeatable event.

Numerous different coal-dust deposits have been selected to suit the galleries, whose geometries define the concentrations of coal dust in air that are applied. The length of deposits, as well as their position and mass, are varied to produce the desired concentrations.

The degree of explosibility of a coal is expressed as dangerous for the specified conditions of a test where the flame extends further than the length of the coal deposit and vice versa for non-dangerous coal dusts.

The content of incombustible matter, including the ash, hygroscopic water and stone dust, is expressed as the total incombustible content and assigned the value n . When the limit value of n is attained, an explosion is incapable of propagating itself; this value represents the degree of explosibility and is assigned the value S . Therefore the degree of explosibility is a measure of the percentage of incombustible matter in the coal that prevents the development or propagation of an explosion. The index of explosibility, Z , defines the mass of incombustible matter needed to prevent the continuance of a pure coal-dust explosion. This is determined from:

$$Z = \frac{S}{100-S} \quad (\text{Cybulski, 1973})$$

The accuracy of this index is determined by the number of repetitions, which means that a considerable number of tests are needed.

Investigations to achieve the rapid termination of a coal-dust explosion are performed by varying the mass of stone dust introduced. The results of a reference test without stone dust are compared with those of a similar test with stone dust added to the coal-dust deposit.

The variable nature of coal-dust explosions has resulted in extensive damage to research facilities and thus the structural strength limits the explosion severity that can be used. A further limiting condition for surface facilities is the environmental noise pollution. Thus, most research has focused on the weaker explosions.

The classification of the explosiveness of coals in galleries has been approached by adopting a standard coal, and using this comparatively against a sample of the coal to be tested. The effectiveness of stone-dusting is measured in terms of its ability to terminate propagation by extinguishing the flame within the length of the fuel zone and producing a static pressure of less than 0.2 bars (Bellman, 1974).

The available procedures measure the effectiveness of stone dust in inhibiting the influence of initiators on coal-dust explosions, specifically where the explosion is developing. No procedure exists for evaluating the effectiveness of stone dust in preventing the propagation of coal-dust explosions, which is the purpose of Regulation 10.24 of the Minerals Act (1991) of the Republic of South Africa.

Thus it is imperative that the initiator of the explosion be a coal-dust explosion that is propagating into the stone-dusted zone. The importance of testing weak as well as strong coal-dust explosions must also be emphasized. The layout of a methane explosion initiating a coal-dust explosion that propagates into a coal-dust/stone-dust zone is considered.

to represent the in-mine hazard. The literature reveals no methods that satisfy the requirements of evaluating the South African stone-dusting regulation (Murphy 1991). Therefore a method had to be developed.

2.4 Discussion

The complex phenomenon of coal-dust explosions has been briefly reviewed. The review indicates that an empirical approach is the most practical solution to optimizing preventative measures. The gallery at the G P Badenhorst Research Facility provides the most advanced apparatus available in southern Africa for this purpose in terms of scale of experimentation.

The uncontrolled combustion of coal dust in air, where the aerodynamic disturbance caused by this combustion process disperses more coal dust into the air, thus fueling the combustion in a self-sustaining process, is termed a coal-dust explosion. The mechanism is believed to be the combustion of the volatile matter that is released from the coal dust (Cagidollar et al., 1988). This means that the rate-determining step is the devolatilization process. A minimum of two differing rates of devolatilization therefore need to be established to evaluate the effectiveness of stone-dusting. The devolatilization rate is indicated by flame speed, where the higher rate determines a higher flame speed.

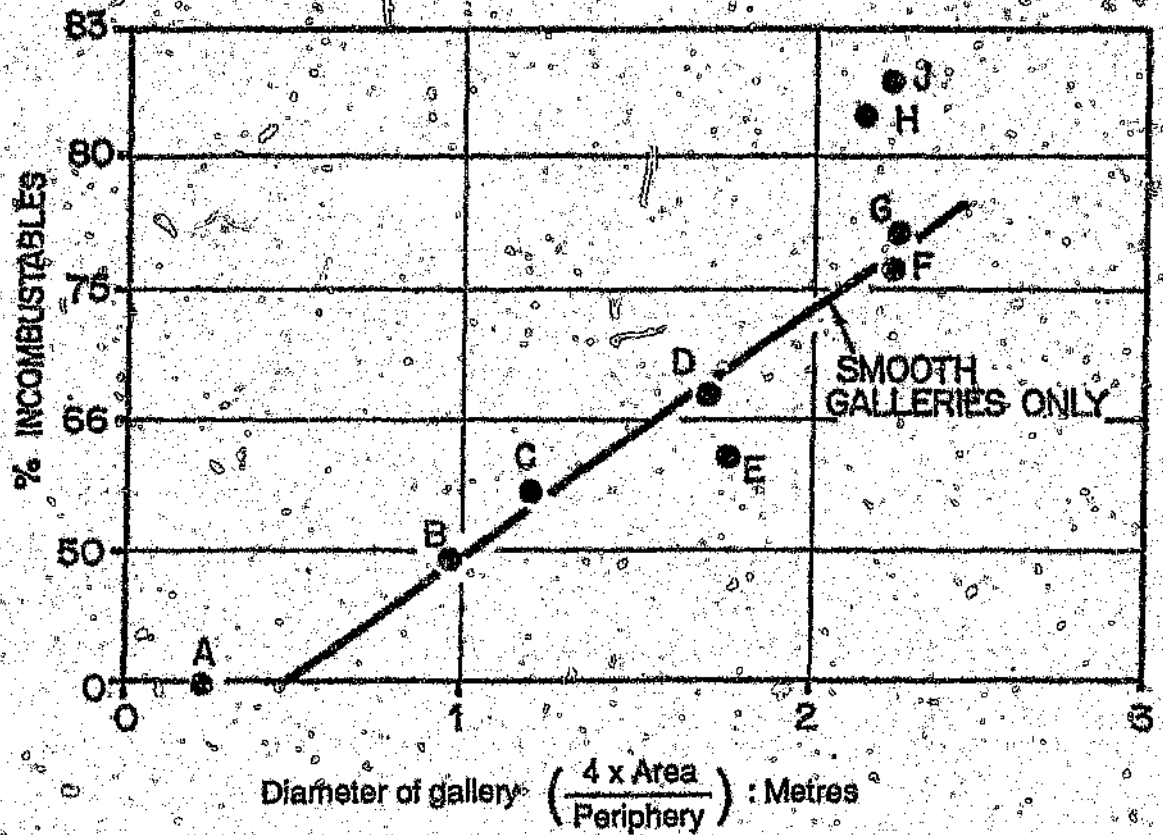
A low-speed flame is termed a "weak" explosion as there is no significant pressure build-up. A high-speed flame produces a significant increase in pressure and is thus called a "strong" explosion. Although a strong explosion does more structural damage, both conditions are dangerous as a weak explosion is capable of burning. The sequential steps of a coal-dust explosion start with the source, which is termed the igniter. This ignites an initiator which is defined as the aerodynamic disturbance and heat source required to start a coal-dust explosion. The coal-dust explosion may develop, according to its initiation energy, into a faster or slower process, which is characterized by an accelerating flame. When

the flame speed is constant, the explosion enters the propagation stage. It may then develop again, or it may terminate due to natural or artificial influences, which extinguish the flame.

To test the applicability of the theory, reactions of differing rates must be obtained for a coal-dust explosion. Regulation 10:24 must be tested against both the slow and fast reaction rates, defined as weak and strong explosions. In addition, for an experimental procedure, the stages of the explosion must be identifiable and be defined.

Galleries and experimental mines have been used to determine effective inerting practices with stone dust. Galleries reduce the expense and time involved for these investigations, but the results need to be verified in an experimental mine. The reason for this is that the dimensions and wall effects significantly affect the incombustible content that is required. The longer galleries afford greater spatial resolution for measurements by allowing longer coal-dust deposits. The smaller cross-sections of galleries result in a higher surface-to-volume ratio and thus wall effects are more significant. The gallery's strength and environmental noise restrictions define the maximum flame speed allowable without causing appreciable damage. The cross-sectional area has a direct influence on the results obtained. Results can be applied to smaller cross-sections, thus the construction of representative cross-sections as in experimental mines has been the tendency. The total incombustible content for experimental mines required to stop an explosion is established as 80 %. A size relationship has been empirically determined for galleries and experimental mines (Willet, 1967), and is verified by recent results (Michelis et al., 1987). (Figure 2.1).

- ✓ The procedures that have been used have been dictated by the predominant cause of explosions, as identified by accident investigations.
- The particle size distributions of the coal dust used have been determined by the mining method that is used, with finer distributions representing mechanized mining methods. The igniters and initiators have been sparks



INDEX:

- A Allison (1926)
- B Mason and Wheeler (1927)
- C Mason and Wheeler (1933)
- D Andilbert and Delmas (1931)
- E Wilke (1937)
- F Explosions in Mines Committee (1913)
- G Rice et al. (1922)
- H Taffanel (1921)
- J Cybulski (1952)
- A to F Smooth steel galleries
- G to J Underground roadways

Figure 2.1 Quantity of inert material needed to suppress coal-dust explosions in various galleries. (Willett, 1967)

and methane explosions, with explosives serving as both igniter and initiator (Holding, 1985).

The need to limit damage and noise has resulted in weak explosions being the experiments in which stone dust has mainly been evaluated. This deficiency has resulted in other inerting methods being introduced, such as barriers which will extinguish an explosion that is weakened by applying stone dust. Stone dust is therefore usually evaluated for its ability to inhibit weakly developing or propagating explosions with slow flame speeds.

The present procedures did not satisfy the requirements for testing the effectiveness of stone-dusting in all environments, and an experimental procedure therefore had to be developed to allow both weak and strong propagating coal-dust explosions to be tested as initiators in a test zone in which the stone-dusting regulation had been applied.

3 THE G P BADENHORST TEST FACILITY

The G P Badenhorst Research Facility is situated 40 km north of Pretoria in a remote area where there is no restriction concerning noise produced during testing. The experimental facilities, including the explosion gallery and the milling plant, were constructed in 1987.

3.1 Gallery description

The design of the gallery was obtained from Deutsche Montan Technologie in Germany. On their recommendation, the gallery was constructed by CONCOR (Pty) Ltd. The gallery is situated at the G P Badenhorst Research Facility which is at an altitude of 1 472 m above sea level. The gallery has two associated systems, namely the methane system and the data-acquisition system. Methane is used as the initiator of the coal-dust explosions and the data-acquisition system incorporates 19 stations spaced along the length of the gallery, recording data from the sensors.

The gallery is 200 m long, 2.5 m in diameter (4.90 m^2) and is closed at one end. It has a paraboloid-shape closed end with an apex of 0.5 m from the 2.5 m internal circumference. The construction is of mild steel and the wall thickness is 19 mm. This has a strength of 16 MPa static pressure and 21 MPa total pressure (Univ. Pret., 1987). The closed end has a reinforced foundation and is rigidly fixed to the ground. The remainder of the gallery is mounted on free-sliding foundations to allow for expansion during testing.

A diagrammatic representation of the explosion gallery is shown in Figure 3.1.

The interior of the gallery is smooth-walled. Circumferential rings near the closed end allow the attachment of a plastic membrane, thus forming

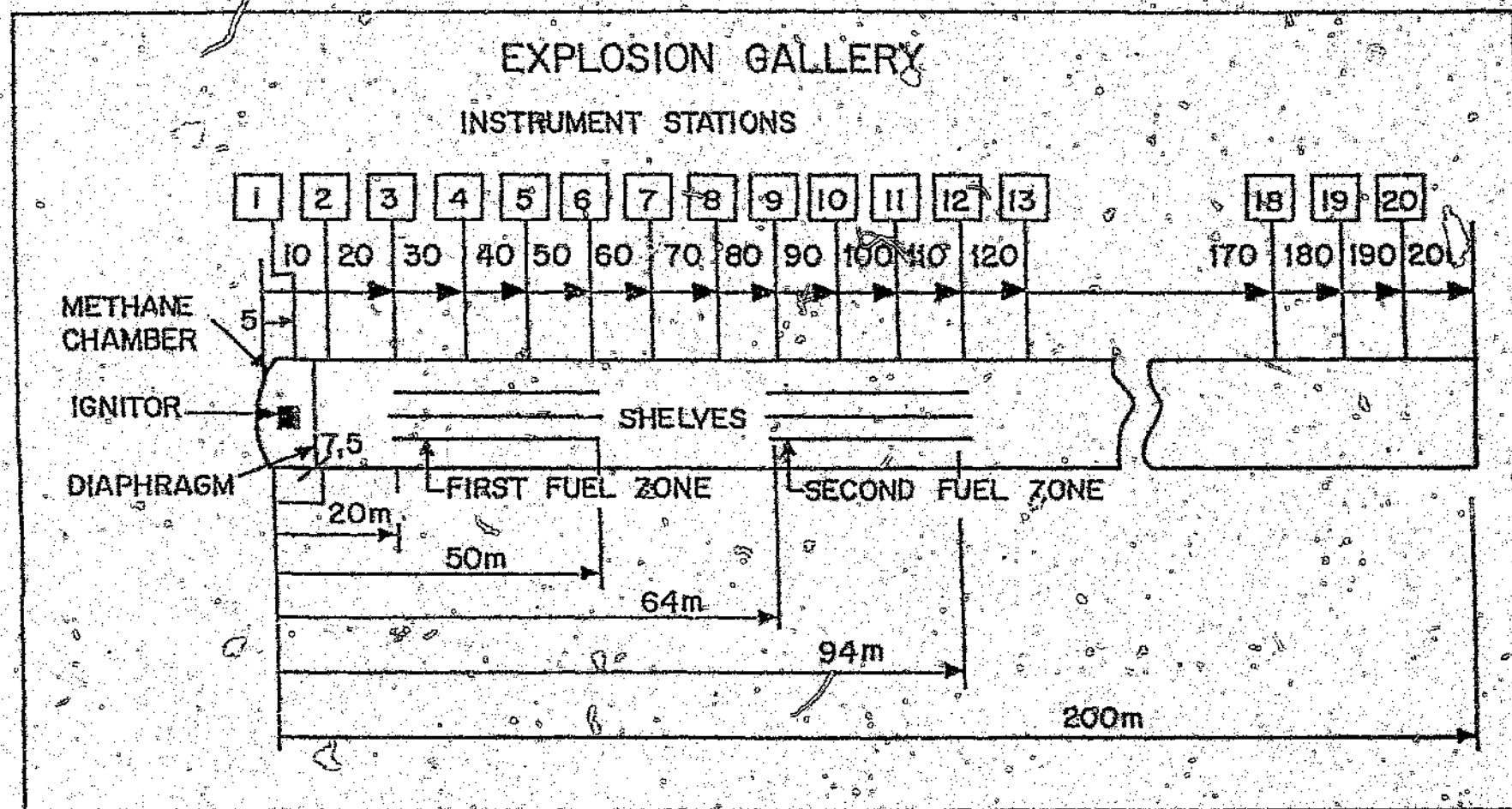


Figure 3.1 Diagrammatic representation of the explosion gallery

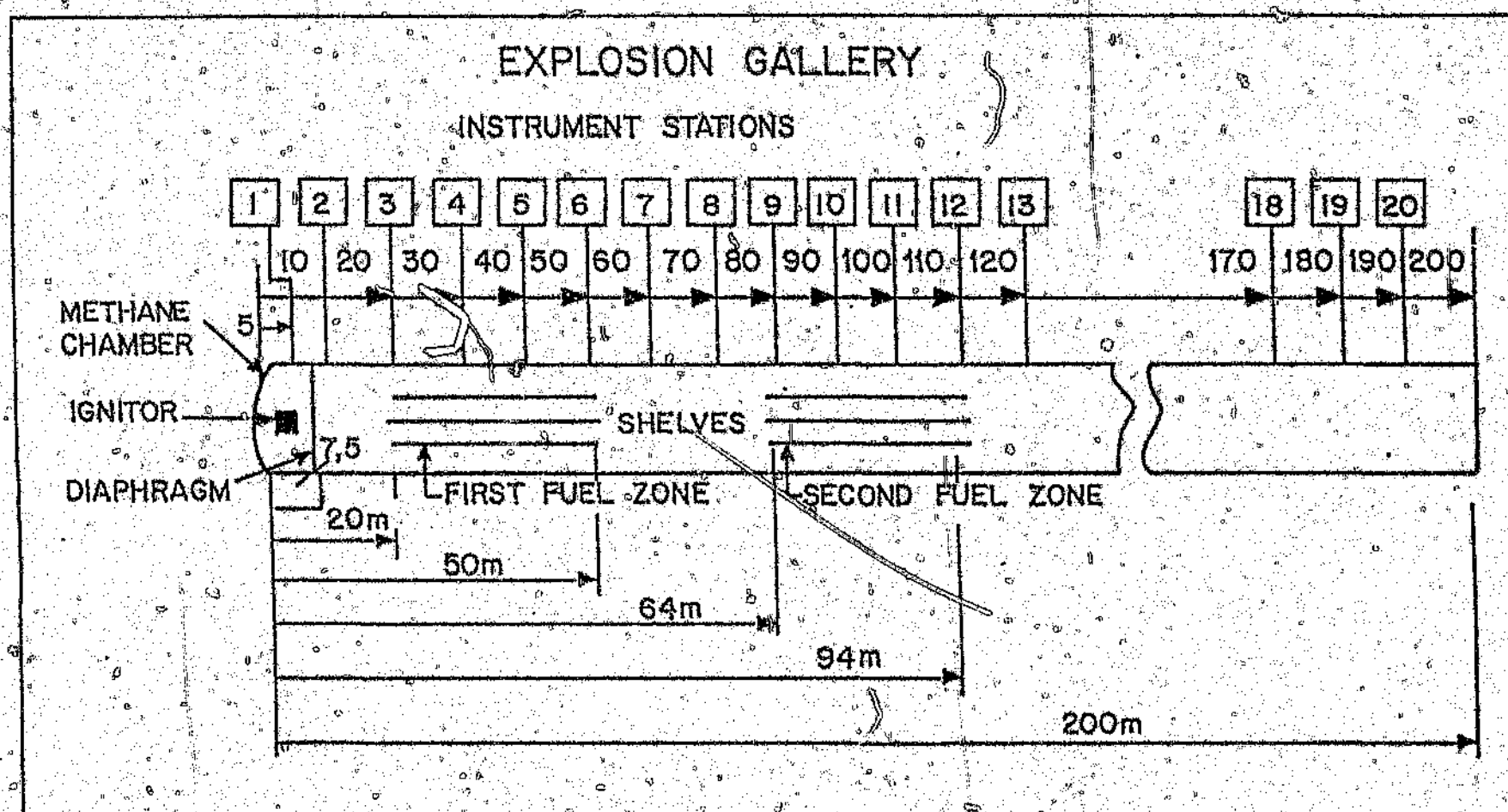


Figure 3.1 Diagrammatic representation of the explosion gallery

a chamber for the methane. The membranes can be positioned at 5 m, 7.5 m and 10 m from the closed end.

The igniter mounting protrudes 0.2 m from the centre of the closed end. A metal rod extension piece was welded in place and the igniter is taped to the mounting.

Shelves were also installed to allow coal dust to be placed in an elevated position. Explosion-proof wall brackets (three per side) were installed every 2 m with wire mesh shelving, 30 m long. They are placed circumferentially at 60, 90, 120, 240, 270 and 300 degrees from the vertical on the gallery.

Holes drilled through the gallery wall are used for mounting the sensors. These holes are situated at the 5 m position and every 10 m thereafter from 10 m to 190 m along the length of the gallery. The holes are placed circumferentially at positions of 10, 30, 60 and 120 degrees from the vertical and are 20 mm in diameter.

Two manholes are used for entry into the gallery. They are 800 mm in diameter and have circular rotating lock mechanisms to ensure that they are explosion-proof.

The main ventilation system has a hole of 1.2 m diameter, 12 m from the closed end, which is connected to the fans and the classifier cleaning circuit. A large extraction fan drawing 16 m³/s is used for cleaning purposes; it draws an exhaust draft down the gallery and through cyclones which extract the explosion-dust residue. The fan motor has a rating of 55 kW. Six cyclones are connected in two parallel circuits and remove dust greater than 10 μ m. A smaller 3 m³/s fan is connected in parallel to the extraction fan to ventilate the gallery when personnel are preparing an experiment. This is connected in series with a single cyclone.

An additional $3 \text{ m}^3/\text{s}$ fan is used as a forced-draught fan 1.5 m from the closed end. Its function is to clear any toxic fume accumulations in the closed end.

The complete ventilation system is sealed during an explosion by gate valves mounted on the ducting leading from the gallery wall.

Cleaning-hose connections to compressed air and water are recessed into the gallery wall. The connectors are positioned at 25, 75, 125 and 175 m from the closed end. The gallery is swept by using compressed air. This is necessary to prevent dust contamination by previous experiments. Such cleaning is a labour- and time-consuming process. This is the limiting factor in the frequency of experimentation. An "eye"-shaped or oval nozzle was developed to allow for a compressed air sweeping action as opposed to the washing action provided by a circular nozzle. This has proved satisfactory for cleaning the gallery walls, using 281 l/min of compressed air at a pressure of 8 bars, supplied by a compressor. The water connections are not used.

When the shelves are used, paper is laid on them first and the coal dust is then deposited on the paper. The coal dust is deposited by hand onto either the floor or the shelves. After an explosion, the paper is observed to be torn apart and burnt around the edges. The contribution of the paper to the explosion is considered negligible as the thermal gradient is too high to burn paper quickly enough for it to contribute to the explosion. The paper does, however, offer greatly enhanced dispersion characteristics over the fixed shelving and its use is preferred.

3.2 Ignition and Initiation systems

3.2.1 Igniter circuit

A $1000 \mu\text{F}$ capacitor is charged and when discharged sends a 10 V signal to trigger both the igniter and the data-acquisition system.

3.2.2 Methane Initiation

A methane-mixing system is used to prepare an explosive methane-air mixture (Figure 3.2). The plastic membrane sealing the closed end of the gallery forms a chamber in which methane is mixed.

External to the gallery is the system shown in Figure 3.2 with inlet and recirculation connections to the gallery chamber.

High-purity methane under pressure passes through the flowmeter (2) and enters the closed-circuit mixing system at the filter (3). The blower (4) then mixes the air drawn from the gallery chamber and the methane in closed circuit. Introduction of the methane raises the pressure, and this is equalized by opening a valve (pressure equalizer) at the base of the gallery to allow bleeding of the system. This introduces a leakage factor that has to be compensated for by mixing for a longer period and is monitored by taking sample measurements.

Further valves are available to allow purging of the methane system before an explosion. A cooler (5) was installed to cool the compressed mixture and ensure that no auto-ignition occurs. For safety purposes, all connections to the gallery have gauze flame-proofing.

The inlet for the methane-air mixture inside the gallery is a perforated pipe which runs the full length of the methane chamber and is bolted onto brackets 12 cm from the floor. This ensures mixing along the full length of the chamber and has given satisfactory mixing results.

The methane-monitoring system (Figure 3.3) is used to control the methane concentration. Three methane-monitoring points (I, II, III) are available to allow measurement of the concentration of the gas mixture in the gallery chamber. Samples are drawn from the chamber through a filter (1) and measured with a UNOR MAIHAK methane analyser (2). The sample is bled to atmosphere with a negligible loss in terms of the total volume of the gallery chamber. Calibration of the

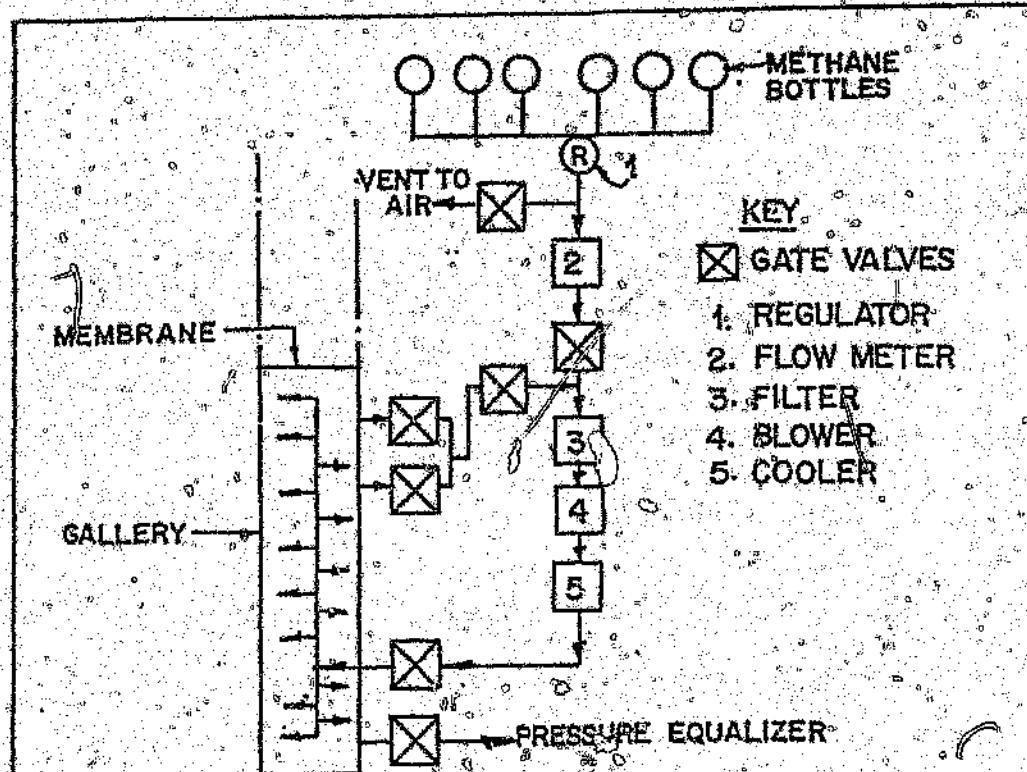


Figure 3.2 Diagrammatic representation of the methane-mixing system

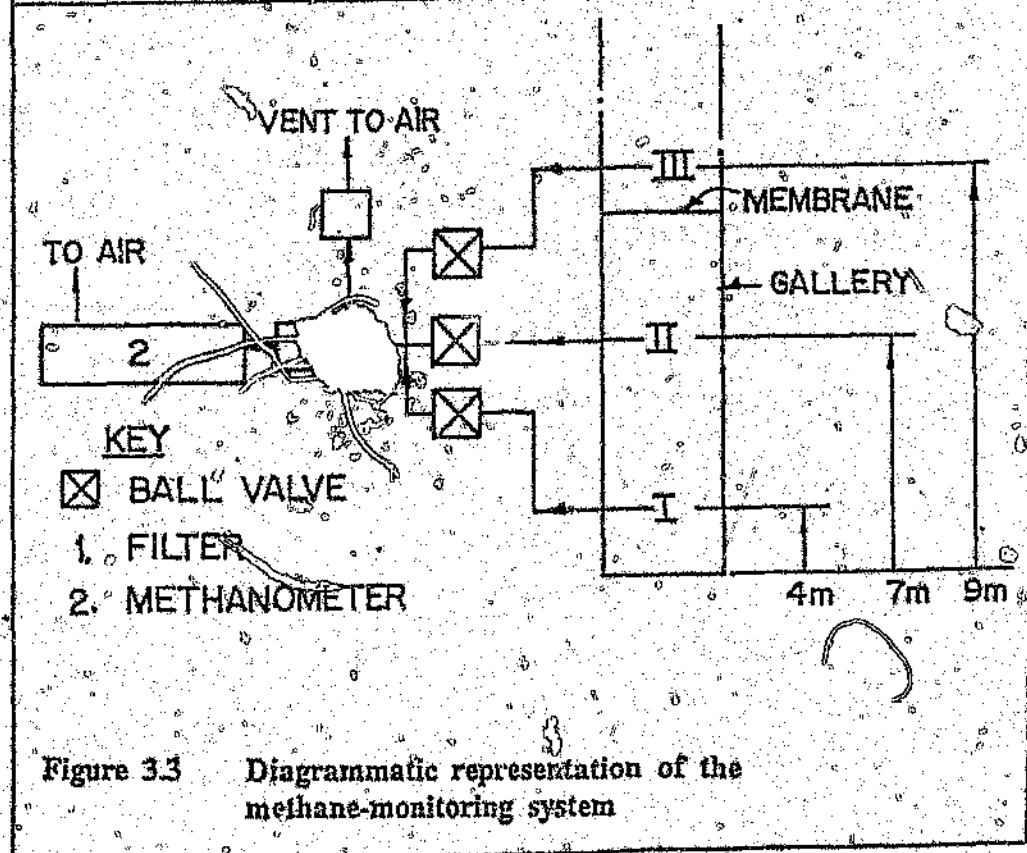


Figure 3.3 Diagrammatic representation of the methane-monitoring system

methanometer is performed at 4 % and 9 % methane-nitrogen mix before mixing commences.

The methane-monitoring system is shown in Figure 3.3. In conjunction with the volumetric measurement of methane, it allows an exact measurement of the mixture to be made. This has been verified by inserting a moveable sampler probe into the chamber, which indicated that the mixture was sufficiently homogeneous. The accuracy is $\pm$ by volume.

3.3 Data-acquisition system

The data-collection process is made up of the sensors, the data-acquisition system and the data-handling process for which customized equipment is required. The sensors have to be explosion-proof to survive in a generally rugged environment. Piezoelectric static pressure sensors and a photovoltaic cell for measuring light intensity are used. The data-acquisition system to which the sensors are coupled also had to be ruggedized, and the data-handling processes had to be developed.

At 5 m and every 10 m thereafter, a data-acquisition station has been constructed. The system was designed for the facility and therefore has specific capabilities suitable for this type of measurement. Nel (1987) has described the specifications of the system. Each station has a motherboard on which is mounted a power supply card and positions for eight data-acquisition channels. The channels have 64 kbytes on-board memory, with a variable sampling rate from 512 bytes/s to 64 kb/s. An independent battery-powered supply ensures that all data captured after trigger are stored for a period of up to 48 hours, at the individual stations.

The software system developed by Nel allows centralized control of all the channels over a length of 200 m. The channels are calibrated electronically using a reference voltage. This software has a diagnostic

function that confirms for each channel that the CTC (clock), CPU, UART, EPROM and Random memory are functional. The communication lines are then tested, after which the microprocessors are activated and calibrated. The system is then armed, awaiting the trigger. The igniter and data-acquisition system are simultaneously triggered.

The data are retrieved sequentially from each channel after an explosion. They are stored in binary form, with each channel being assigned an independent file name. A file server links the stations via daisy chain networking.

At present 36 channels are used. A sampling rate of 12 kHz over a period of 5 seconds has been selected as appropriate.

3.3.1 Sensors

A coal-dust explosion, being dusty, smokey, and having high transient wind velocities and a flame, is an extremely difficult environment within which to take measurements. The time resolution of the sensors also needs to be sufficiently high to measure the passage of the explosion. Static pressure transducers and photovoltaic flame sensors are used to measure the course of the explosion along the length of the gallery. Nineteen pressure transducers and nineteen flame sensors are used. They are calibrated independently using a mobile calibration rig and a five-step static pressure test. The measurement made, although using a static pressure transducer, is actually of quasi-static pressure. This is the transient static pressure as the explosion moves along the length of the gallery. However, the term static pressure has been adopted for gallery research. SENSYM transducers are used (Sensym, 1987). The maximum pressure is 6.9 bars and thus places a limit on the magnitude of explosion that can be quantitatively measured. The response time is 0.1 ms which, when compared with the sampling rate, results in oversampling by the sensor compared with the sampling rate of the data-acquisition system. The sensors are suspended away from the outer wall of the gallery with an extension piece connecting them to the gallery

All conveyance is pneumatic so as to decrease the danger of coal-dust explosions within the plant, by limiting the amount of dust in the general environment.

Figure 3.6 shows a diagrammatic representation of the plant. The specifications of the system have been described by MACSA (1990).

The hoist (21) is used to lift coal samples in batches, with a maximum mass of 125 kg, and tip them into the tipping unit (1). The -25 mm (less than 25 mm) size coal is tipped into the tipping unit (1). The coal passes through a 25 mm screen (2) onto a vibrating feeder (3). It then passes into the hammer mill (4). The product passes through a 5 mm orifice screen at the base of the hammer mill (5) and is pneumatically conveyed to the fan-filter unit (6). This pulsating unit results in the coal dropping into a bin (7). The coal then passes through a rotary valve (8) into a further bin (9) which leads onto a vibrating feeder (10). The coal passes into the pin mill (11), travelling radially in the centre of the stationary pin disc to the outer circumference, being impacted and sheared by the rotating pin disc. The dust is then drawn pneumatically in closed circuit into the classifier (12). The variable-speed classifier mechanically separates the feed into the desired product and the remainder is recycled. The recycle material passes through a rotary valve (13) onto the vibrating feeder (10) to be remilled in the pin mill. The product is drawn into the fan-filter unit (14). After passing through the bin (15), it moves through a rotary valve (16) into a ribbon blender (17), which mixes the dust.

3.4.2 Calibration of the mill

The comminution system required calibration. This is described below: the complexity is needed to obtain specified results for different coals.

Initially, airflow requirements needed attention to ensure proper functioning of all the equipment. Valve (20) required setting to ensure that the hammer mill would be sufficiently air-washed to prevent clogging.

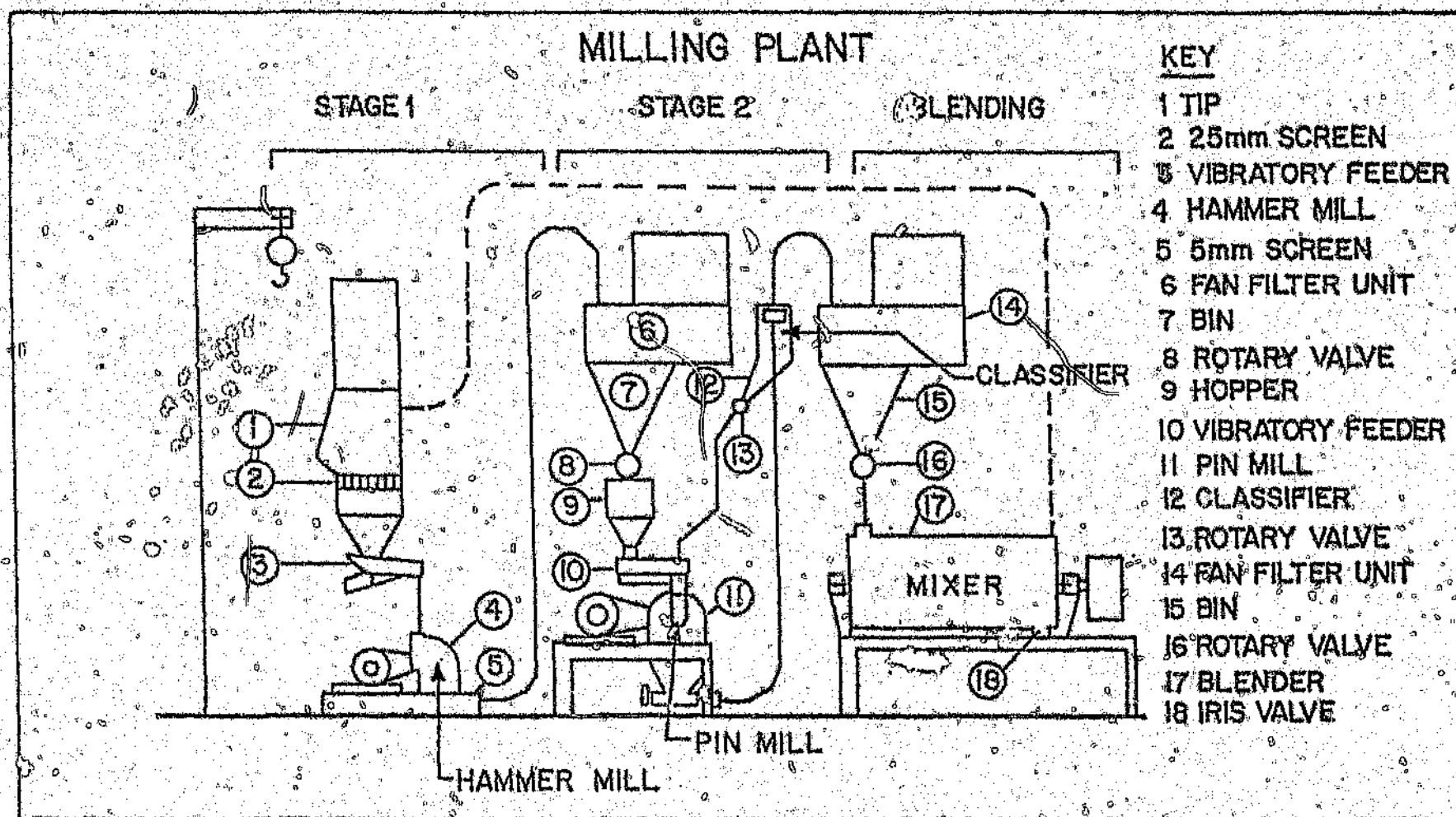


Figure 3.6 Diagrammatic representation of the milling plant

This valve was set at 1/4 closed. A minimum quantity of airflow through the classifier of 15 m³/min was required according to the specifications. In addition, a flow of 9 m³/min was required through the pin mill. A buffer was accordingly set on the fan-filter unit (14). The wash air in the classifier was optimized to 30 %. To allow for an airflow through the pin mill, the buffer valve was set at 85 % open. Valve (19) was set at closed. These settings proved satisfactory for conveying the dust and meeting minimum equipment airflow requirements.

The quantity of coal through the mill required optimizing, where the maximum mass flow criterion was determined by the classifier (12), and was 150 kg/h. A maximum value of 125 kg/h was arbitrarily set as being an acceptable value which would allow for any fluctuations over time due to wear of the mill. Feeder (3) is controlled by a level indicator switch in bin (9), which stops the feeder when the bin is full. Both feeder (3) and the hammer mill (5) can cope with the required mass production and thus do not limit the circuit. Feeder (10) had two variables that required setting, the first being a flap valve controlling the depth of feed across the vibrating feeder base. The feed depth directly affected the quantity. The second variable was the vibrating frequency. Because of the differing cohesiveness of coal dusts, as high a frequency as possible was selected as being suitable to ensure a regular feed and it was found that the frequency directly affected the quantity. The capacity of the feeder was 20 kg/h to 500 kg/h. Allowing for the recycle of the classifier, these two variables were set to produce 80 kg/h, with a minimum allowable feed depth of 15 mm (three times the maximum product size of the primary milling circuit) at a frequency of 400 Hz. The classifier setting directly affected the quantity of product and the recycle needed. According to the classifier's operating manual (Hosokawa, 1991), a maximum of 30 % recycle is acceptable. Thus a value of 37,5 kg/h recycle was established, giving a maximum plant capacity of 117,5 kg/h.

Initial screening (2) was done to ensure that the hammer mill feed was <25 mm. Further screening at the base of the hammer mill (5) was

variable, and a 5 mm screen proved satisfactory. The speed of rotation of the hammer mill was balance limited to 2 000 rpm and a conservative value of 1 700 rpm was selected.

The pin mill has a number of variable parameters. The rotary and stationary discs were selected on the recommendation of the manufacture, Alpine (1991). The speed of the pin mill is variable (2 700 to 9 000 rpm); the higher the speed, the finer the product. The mill can produce a product of tosize 40 μm to 400 μm , with median sizes of 5 μm and 125 μm respectively. The speed was optimized at 5 000 rpm.

The feed rate and the airflow were the final parameters. The higher the feed rate, the coarser the product. The higher the airflow through the mill, the coarser the product as well, due to decreased residence time. These variables were optimized to satisfy the recycle mass flow limitations and to provide a satisfactory size distribution of the product (see Figure 3.7).

The dust then passed from the pin mill to the classifier. The classifier centrifugally separates particles according to particle mass. The parameters for calibration are the speed of rotation and the wash air quantity. Wash air was introduced into the system to enhance the separation of particles. The quantity chosen was 30 %, which controlled the airflow through the pin mill. The speed of the classifier was found to influence the tosize directly and therefore control of the size distribution was exercised through the classifier. The median particle size was controlled by the recycle quantity and the tosize by the airflow speed within the classifier. Since the speed of the classifier controlled both parameters, it was used to control the size distribution.

Control of the impeller (rotation) speed of the classifier was the single parameter that allowed the coal-milling process to be calibrated.

wall. This is to ensure that the heat from the explosion, although transient, does not affect the transducer. A test rig was constructed to check that no interference was being caused by the extension piece and this proved to be true.

A diagnostic program covering all the sensors is run after every test to ensure that the sensors have not deteriorated. If this happens, the sensors are recalibrated or replaced if necessary. In addition, the static pressure transducers are calibrated on a monthly basis.

The flame is measured using a photovoltaic cell (TP 60 1988). The silicon photovoltaic cell measures from 400 nm to 1 100 nm, with a maximum spectral sensitivity at a wavelength of 850 nm. The flame sensors are also placed at the 5 m position and every 10 m thereafter. They are positioned axially along the gallery and are mounted on extension pieces, extending 75 mm from the outer surface of the gallery. This distance has been optimized to limit the viewing angle to 12° (9.5 m resolution along the length of the gallery) but give an adequate signal. A glass cover is placed over each sensor on the gallery wall to protect the sensors.

The glass protection covers of the flame sensors are cleaned and inspected before every test to ensure that the true flame intensity will be recorded. Quartz covers were tried but they did not affect the sensors' output, indicating that the sensors are most sensitive in the infra-red spectrum and thus the ultra-violet absorption by the glass can be disregarded. A flashlight with a magnetic mounting which fits precisely over the sensor and is magnetically attached to the gallery wall allows in situ verification of the sensor outputs. Faulty flame sensors are replaced.

The amplifiers that were built to accommodate the leads from the sensors to the data-acquisition cards only used a 0 to 10 V signal. Thus the 0 to -10 V polarity was not used. This implies that the resolution of the

system was reduced to 128 bytes or 7 bits (as opposed to the 8-bit resolution available).

Increasing the sampling frequency was a possibility but in practice the sampling duration of five seconds was required to yield sufficient resolution.

3.3.2 Data representation

The data-acquisition system produces an array of files on each of the channels during an experiment. Each file has 64 kbytes of data. The data were initially normalized by subtracting the average of the first twenty values from the rest of the data per file. This was required because the gain-setting pods on the hardware system were not of adequate sensitivity. The sensors have linear outputs and thus allowed for such manipulation. Smoothing of the data was accomplished by a three-point moving average process which was done forward and in reverse to ensure no phase shift of the waveform. It was considered essential to produce a three-dimensional representation of the explosion parameters. The time, distance and either static pressure or flame were the domains. The creation of a surface matrix was thus limited by the size of the matrix formed and computing power. Greyben (1990) showed that by reducing the data from 64 kb to 1.2 kb, the results were affected by 0.17 %. For greater precision, the average of 50 points was taken and used to create a 1.2 kb file. This means that the time resolution is reduced to 100 Hz with a precision of 7 over the original data and allows considerably faster computation without appreciable loss of accuracy.

The established matrix includes both the parameters that require quantification. The three-dimensional graphs are obtained using the software package SURFER (1991) which cubic-splines the values. This allows a graphical surface plot as well as a topographical graph. All parameters can be read from these graphs, namely flame length, velocity and duration, as well as static pressure.

Figure 3.4 illustrates the flame plot of data from an experiment. The surface as well as contour plot show the stages of an explosion, and interference of events within the gallery.

The flame data from a coal-dust explosion in the gallery is shown in Figure 3.4. The five stages of the explosion sequence are indicated. The ignition is the zero reference position. After 20 ms the methane explosion is noted which results in the development of the coal-dust explosion. The development is distinguished by an accelerating flame. The constant-velocity flame defines the propagation stage, while the decelerating flame indicates the termination.

The pressure plot is shown in Figure 3.5. The pressure generated by the experiment is shown, and the rarefacted and reflected waves indicated.

For the same coal-dust explosion, the static pressure data are plotted in Figure 3.5. Identifiable stages are again noted, and the pressure increase from the methane explosion is noted. The development stage is characterized by the increase in pressure resulting from the coal-dust explosion. Propagation is indicated. The termination phase is not identifiable.

Reflected waveforms from the open end of the tunnel-air interface can be identified. The complex interference and superposition of waveforms has not been considered, as Bonapace (1990) claims that in the general case, this will be a constant function of the gallery.

It was also noted that at stations 1, 2 and 3 the flame sensors were coated with a tar. The readings from these sensors were thus affected by incident waves while reflected waves resulted in a dust coating adhering to the tar deposit and thus affecting readings.

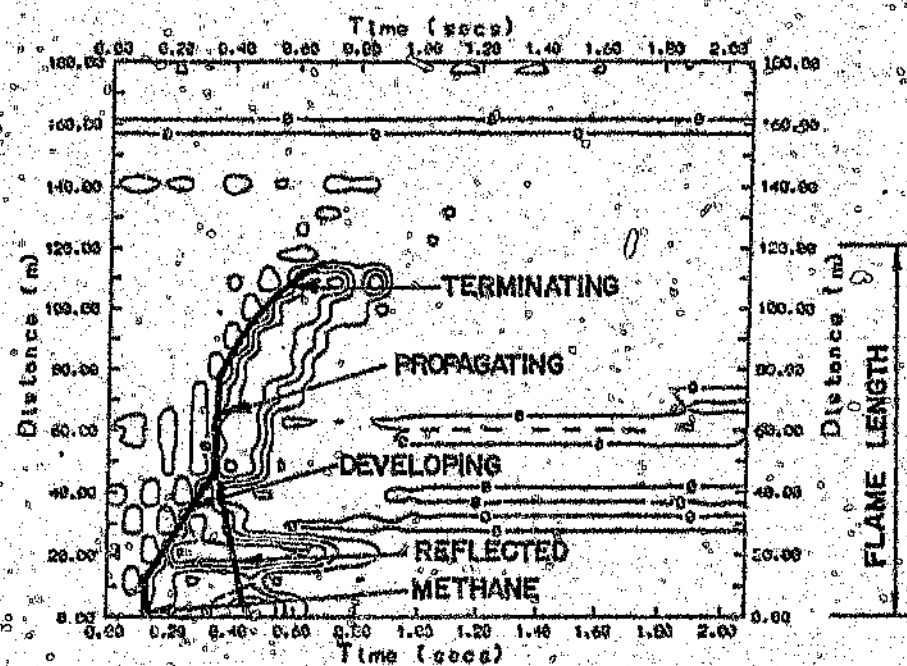
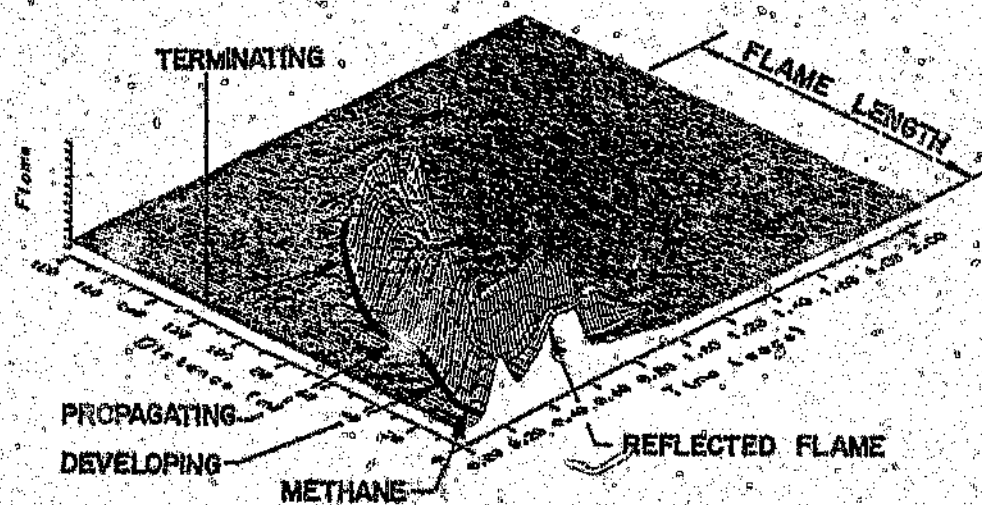


Figure 3.4 Flame for an explosion in the gallery showing the surface and contour plot

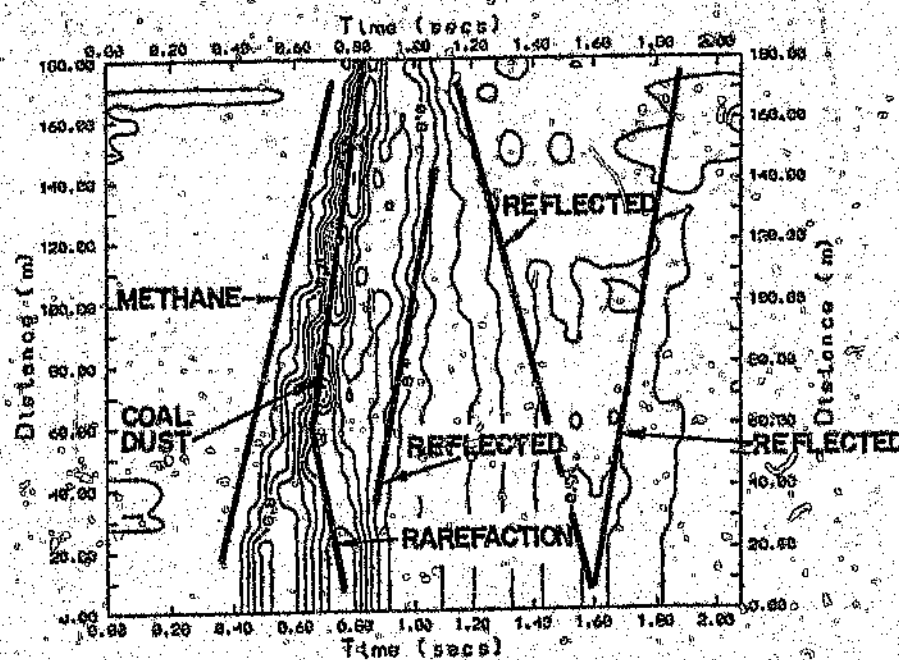
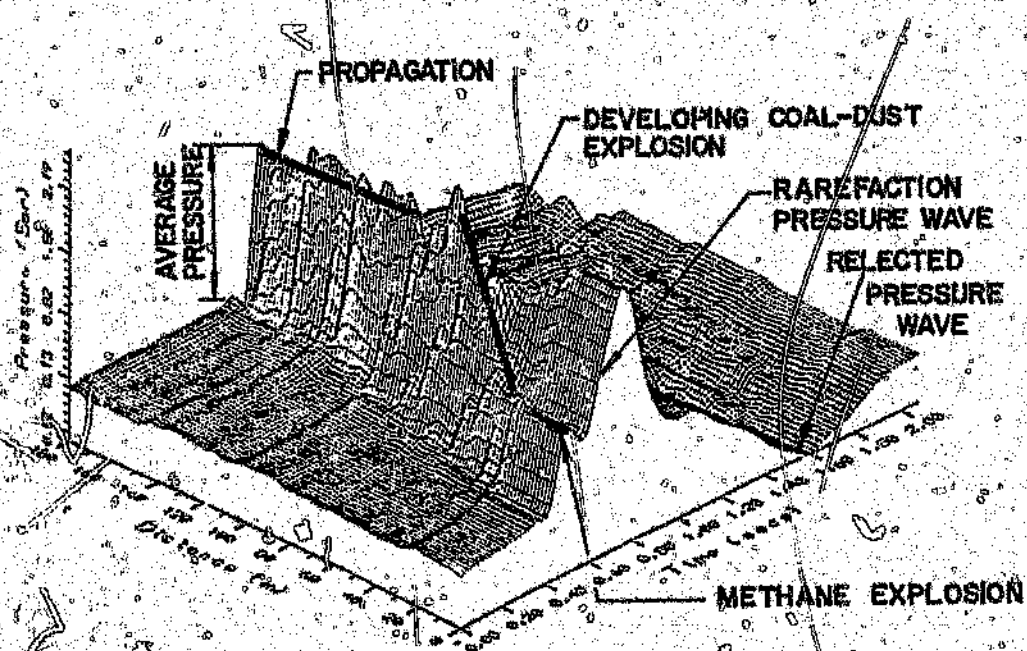


Figure 3.5. Static pressure for an explosion in the gallery

Overall, the three-dimensional plots gave a satisfactory representation of the path of the explosion in the gallery.

3.4 Coal milling

A milling plant was constructed to comminute the coal samples into dust. Precise size distributions are essential in the testing of coal dusts on an experimental basis. This is because the size distribution is directly related to the explosiveness (Reeh and Michelis, 1990). In this case, the size distribution was selected to conform to the finer size distribution tested at the Barbara mine as well as the size distributions used in Germany. This finer size distribution more accurately describes the dust produced by mechanized mining (Cybulski, 1973). Reeh (1981) has described the influence of the coal particle size on the course of an explosion, and finds that the magnitude of the explosion and the quantity of stone dust required both increase with the fineness of the coal dust.

The product specifications required for different goals are:

- (a) The break of the coal must conform to a natural break, producing a natural size distribution.
- (b) The median particle size must be $20 \mu\text{m} \pm 2 \mu\text{m}$, with a topsize of $150 \mu\text{m} \pm 15 \mu\text{m}$ (Michelis et al, 1989).

A natural break is required so as to accurately describe the actual explosive dust that is present in a mine in the collieries. This is considered to be reflected by the Rosin-Rammler-Bennet-Sterling size classification method (Field, 1982; Bennet, 1936).

3.4.1 Description of the mill

The milling plant is a two-stage comminution process. Primary comminution is performed in a hammer mill and secondary comminution by a pin mill in closed circuit with a classifier.

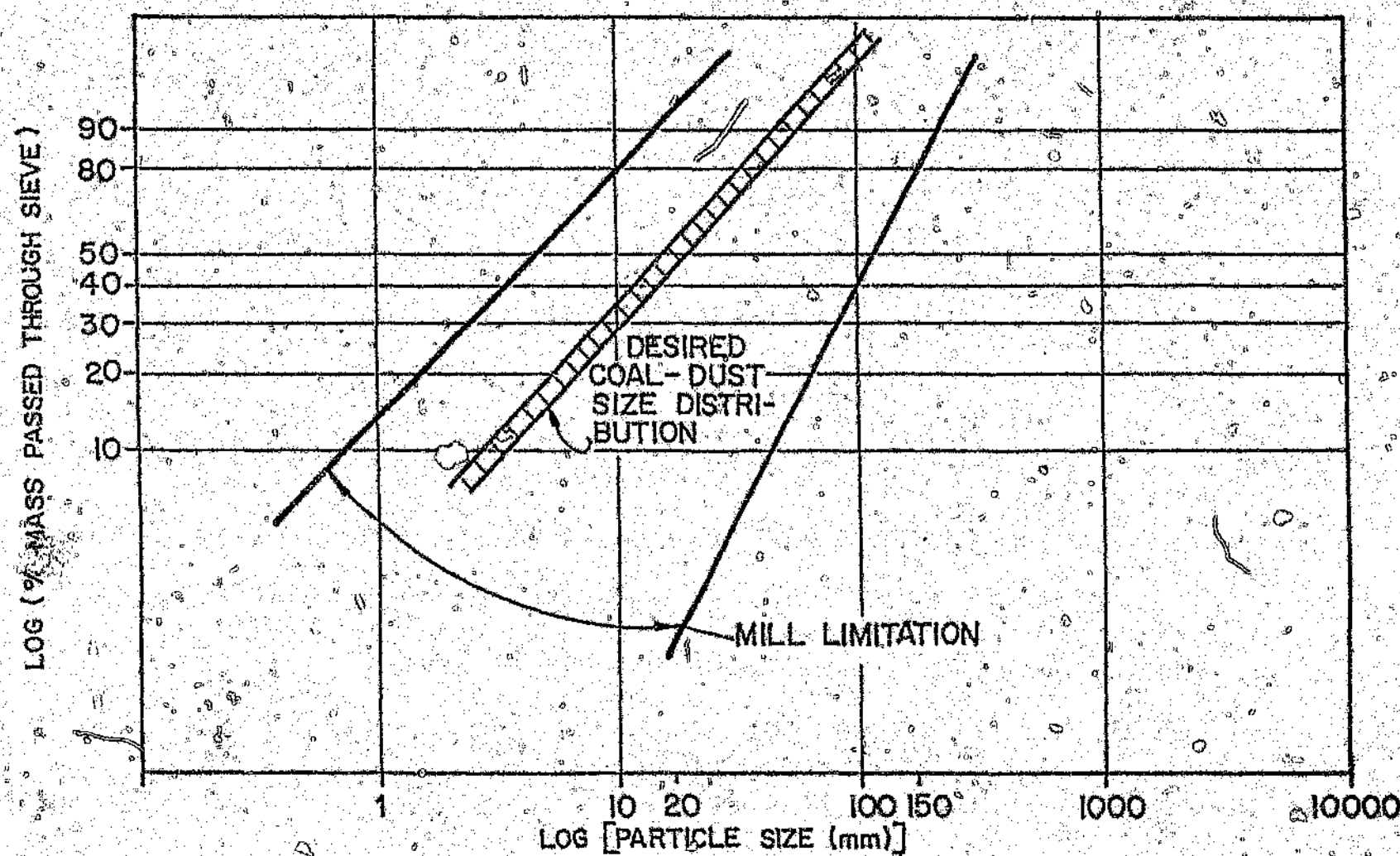


Figure 3.7 Rossin-Rammler-Bennett size distribution of milling plant product

Purging of the system is achieved by closing both the inflow valves, i.e. (19) and (20). Valve (21) is opened. Air dust is then drawn pneumatically through the system and passes into a refuse bin at the outlet of feeder(3).

3.5 Discussion

The equipment at the facility was successfully commissioned and calibrated, and produces the desired results in terms of the experimental specifications.

The gallery itself is a limiting parameter on the requirements of testables for preventing the propagation of explosions. These are the cross-sectional area, the maximum strength and duration determined by the length of the gallery.

The measuring stations along its length. Using a high sampling rate for the data-acquisition system, the space:time resolution can be accommodated by improving the space precision by a factor of 7 and using a cubic spline fit.

The smoothness of the gallery walls reduces the turbulence of the flame and the aerodynamic dispersive conditions, and thus results in slower flame speeds. This and the cross-sectional area are features that are specific to each test gallery. The maximum flame speed in the G P Badenhorst Gallery is determined by the maximum measurable value of 6.9 bars set by the static pressure sensors. The structural strength of the gallery exceeds this value, and it is an advantage that there are no noise restrictions in the vicinity of the gallery.

The inclusion of a mechanical classifier in closed circuit with a pin mill allows a repeatable constant particle size for the coal dust used in the gallery experiments to be produced.

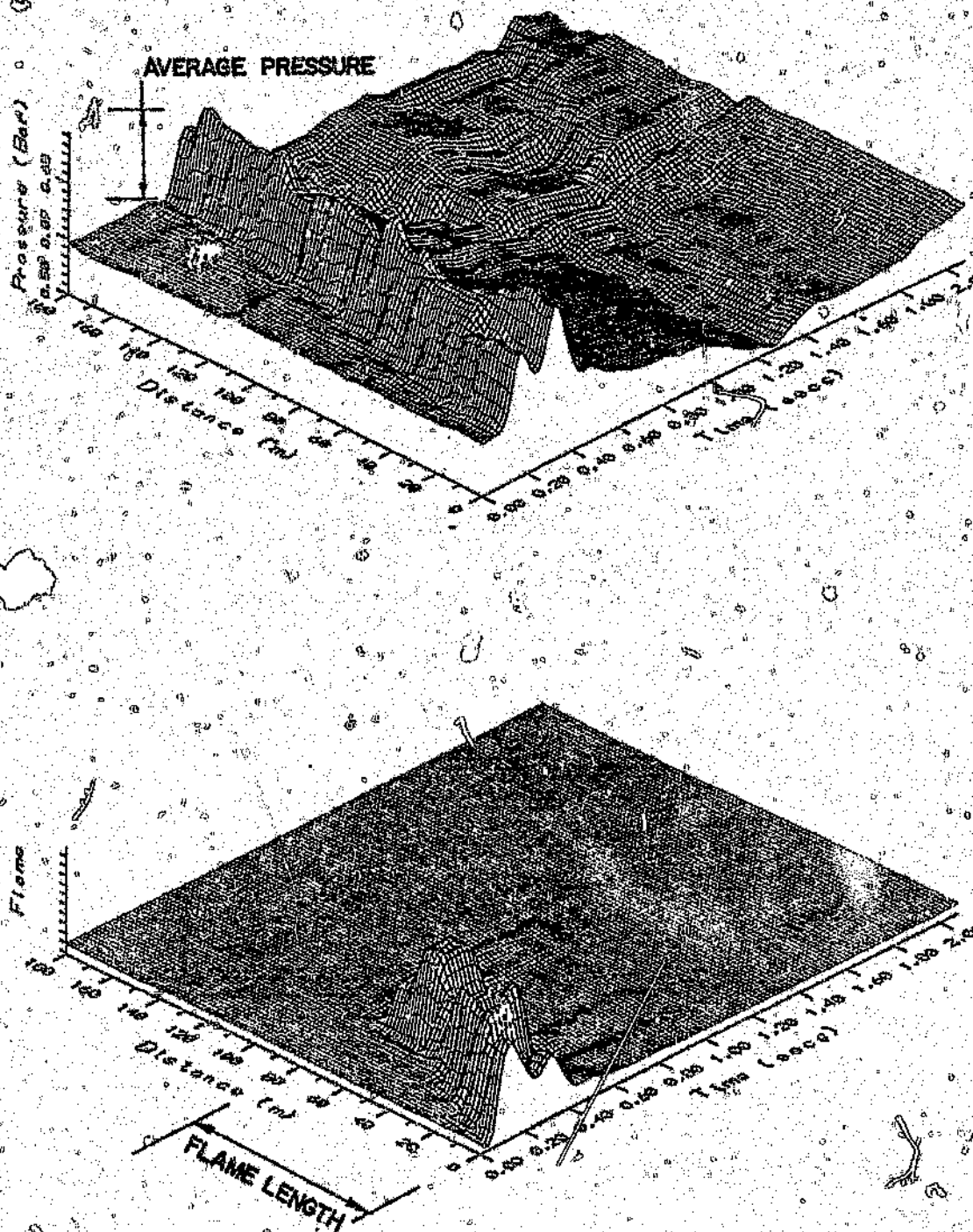


Figure 4.5 Explosion with coal-dust deposit length of 20 m

The equipment and related systems were commissioned and calibrated, which allowed for the development of an experimental procedure.

4 DEVELOPMENT OF EXPERIMENTAL PROCEDURE

The purpose of experimentation was to establish a coal-dust explosion, which would not cause any damage to the gallery, but which would provide a means for a propagating coal-dust explosion to initiate a coal-dust explosion from a second deposit. When stone dust has been applied in the second deposit or test zone, according to Regulation 10.24 of the Minerals Act (1991), comparison with reference experiments with or a second coal-dust zone or without stone dust would provide a measure of the effectiveness of the stone dust. The use of coals with differing volatile matter contents provides a means of evaluating the stone-dusting regulation.

The parameters measured were discussed in Section 3.3.2. This chapter gives a detailed description of the optimization of the transfer parameters for the gallery. The variables investigated in order to design an experimental procedure that would satisfy the objectives are shown in Table 4.1.

Figure 4.1 indicates the variables that were investigated.

The experimental variables are constituted by the experimental layout or arrangement, which determines the transfer of coal dust via an explosion into static pressure and flame during an explosion.

The optimization of the experimental variables was desired to obtain the maximum information from the data-acquisition system and the gallery. The gallery limits the extent or length of the flame to 200 m if it is to be measured. The static pressure must, however, be defined for each explosion that occurs. The methane explosion must not exceed 0,8 bars overpressure, explosion from the first coal-dust deposit, 2 bars and the second coal-dust deposit 4 bars. These values were selected to ensure that, should a more explosive condition be created, a reasonable safety factor would still exist (i.e. safety allowance : 2,9 bars).

GALLERY LAYOUT

Meth. chamb	1st Nonfuel zone	1st Coal dust deposit	2nd Nonfuel zone	2nd Deposit or test zone	
7.5	20	50	64	94	200
7.5	12.5	30	14	30	

METHANE INITIATOR



LENGTH OF DUST DEPOSIT



MASS OF COAL-DUST DEPOSIT



PLACEMENT OF DEPOSIT



1st NONFUEL ZONE



2nd NONFUEL ZONE



Figure 4.1

Zones within the gallery that required investigation and optimization

Table 4.1 Variables investigated for the establishment of a standard experimental procedure

INDEPENDENT VARIABLE		MEASURED PARAMETER
INDEPENDENT VARIABLE	TRANSFER OR EXPERIMENTAL VARIABLE	
Coal dust	Ignition source Initiation: methane	Flame Static pressure
Stone dust	First coal-dust deposit : Length of deposit Mass of dust used Placement of coal dust Non-coal-dust zones Second coal-dust deposit : Length of deposit Mass of dust used Placement of coal dust Non-coal-dust zones	

The parameters that required defining for an experimental procedure were the ignition, the initiation and the coal-dust deposits which develop and propagate as an explosion. Aspects of the coal-dust deposit that needed investigation were the length of the deposits, the nominal concentration, the non-fuel zone and the placement of the deposits.

The transfer or experimental functions are described separately for clarity, but one must not lose sight of the fact that they are sequential, interrelated events in the explosion process.

4.1 Ignition source

A face ignition was best suited to the single-entry gallery arrangement, resulting in the explosion having a uniaxial direction of movement. A central position at the closed end of the gallery was selected for the igniter, ensuring that the flame would develop without obstruction in as uniform a manner as possible. A 0.2 m extension piece was installed

on the closed end for mounting the igniter away from the rear gallery wall.

The purpose of the igniter is to ignite methane in a repeatable manner. An electrochemical igniter was selected. It consists of a metal cylinder containing an electric fuse cap, covered with a mixture of barium nitrate and aluminium powder. A 1,5 g mass of $\text{Ba}(\text{NO}_2)_2 + \text{Al}$ in a ratio of 75:25 % is used. The loading pressure is 1,5 kg/cm². This is then sealed with a 0,5 mm aluminium disc.

A 10 V signal is used to trigger the igniter, which then releases 4 kJ of energy and ignites the methane. The flame front produced has a 3 m radius which gives a single flame front, and more repeatable results. Repeatability tests on the igniter gave a variation in energy release of 5 % (Joubert, 1985), which is negligible when compared with the energy released from the methane or coal-dust explosion.

4.2 Methane initiator for coal-dust explosion

The objective of the methane explosion is to initiate a coal-dust explosion. It was necessary to cause an aerodynamic disturbance which would raise sufficient coal dust into the air to exceed the minimum coal:air ratio required for an explosion, and to generate sufficient heat to initiate coal combustion.

A repeatable explosion was thus imperative. The methane-monitoring system with double measurement capabilities and leakage measurement across the membrane provided the control mechanism. The methane used is given in Table 4.2, which shows that a high-purity methane was employed to ensure that the gaseous mixture was not an uncontrolled variable.

The standard concentration of methane for explosive testing in the Republic of South Africa (Government Gazette, 1987) and the United

Kingdom, from where the legislation was adopted, is a 9 % methane-in-air mixture, although the stoichiometric value is 9,5 %. The 9 % value was selected for conformity.

Table 4.3 Methane mixture for gallery-grade blasting

GAS	gpm (max)
Methane	89,8 %
Nitrogen N ₂	1 000
Oxygen O ₂	20
Argon	150
CO ₂	100
C ₂ H ₆	500
C ₃ H ₈	100
C ₄ H ₁₀	50
C ₂ H ₄	25

The effect of variations in the volume of the chamber (Figure 4.1) was tested with the three available methane chamber sizes. The methane concentration for all tests was fixed at 9 %.

Figure 4.2 with a volume of 24 m³ shows a flame length of 20 m and a static overpressure of 0,56 bars. The 36 m³ chamber results in a 30 m flame and a 0,64 bars overpressure (Figure 4.3), while the 48 m³ chamber give 40 m flame and 0,72 bars overpressure (Figure 4.4).

The larger the volume, the longer the flame extent or length and also, as expected, as indicated by the pressure, the higher the rate of pressure rise and the higher the magnitude of the static pressure.

These results are directly influenced by the quantity of methane available, and the trend indicates that for a fixed concentration the larger the volume, the higher the magnitude of the ensuing explosion.

Detailed reports have been written by Rae (1954, 1971a, 1971b, 1972) on the influence of initiation strength on developing coal-dust explosions. He concludes that the initiation strength determines the minimum initial

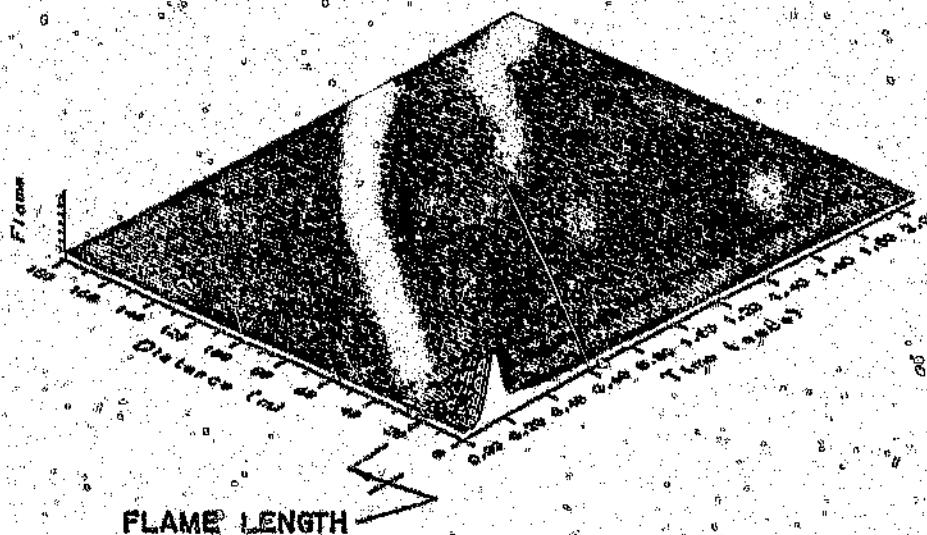
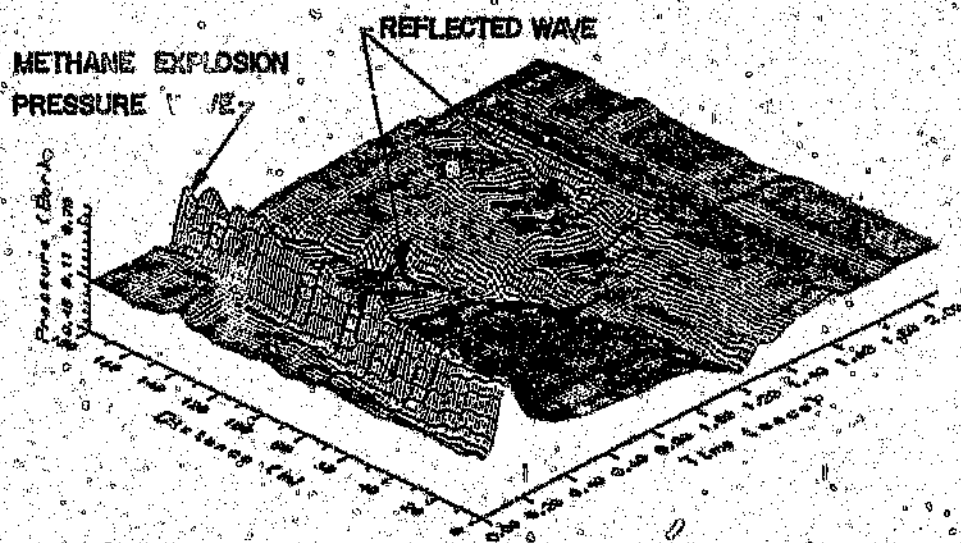


Figure 4.2 Gallery explosion with methane chamber of 24 m³

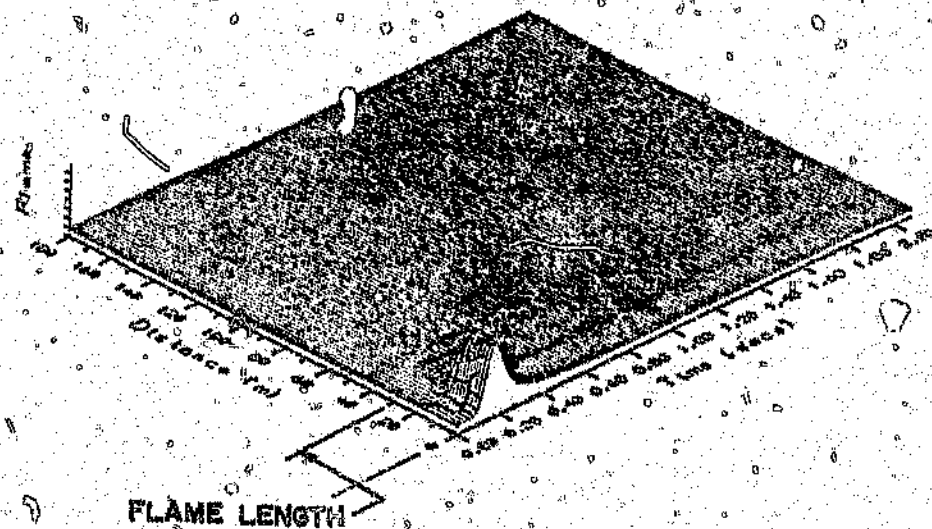
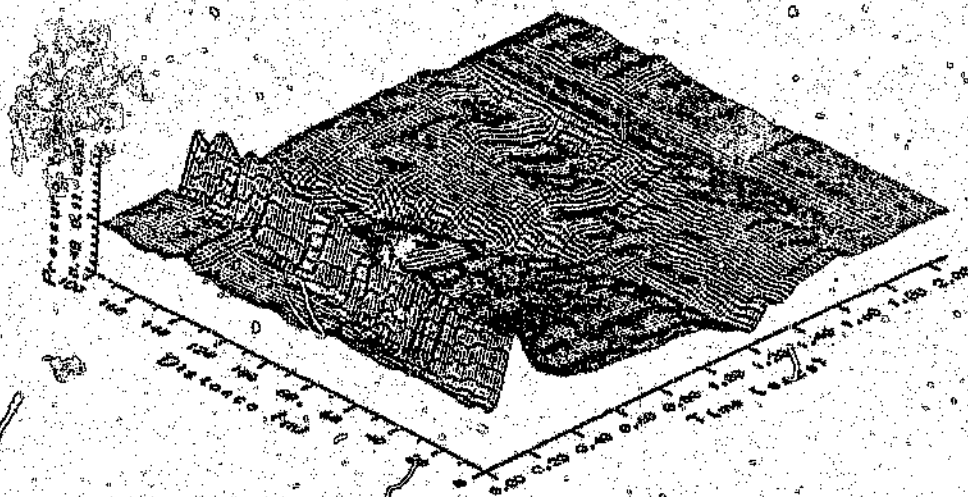


Figure 4.3 Gallery explosion with methane chamber of 36 m^3

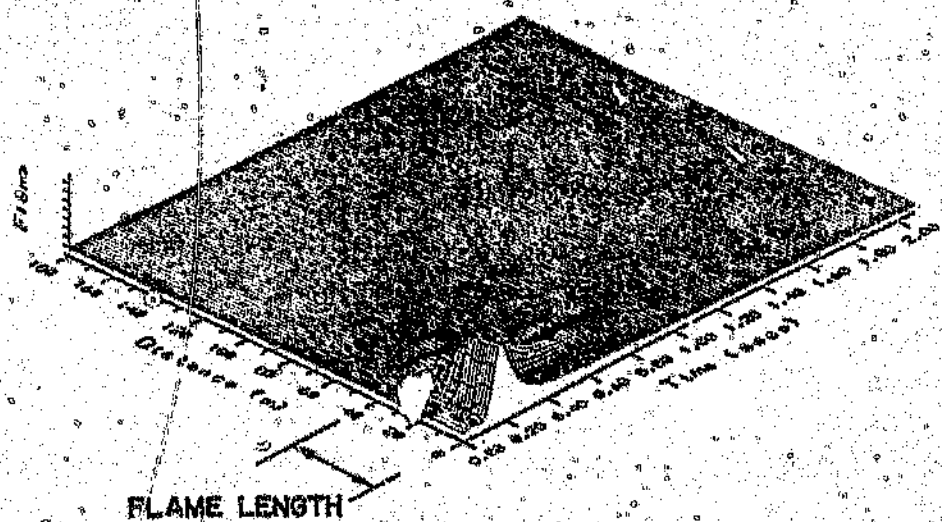
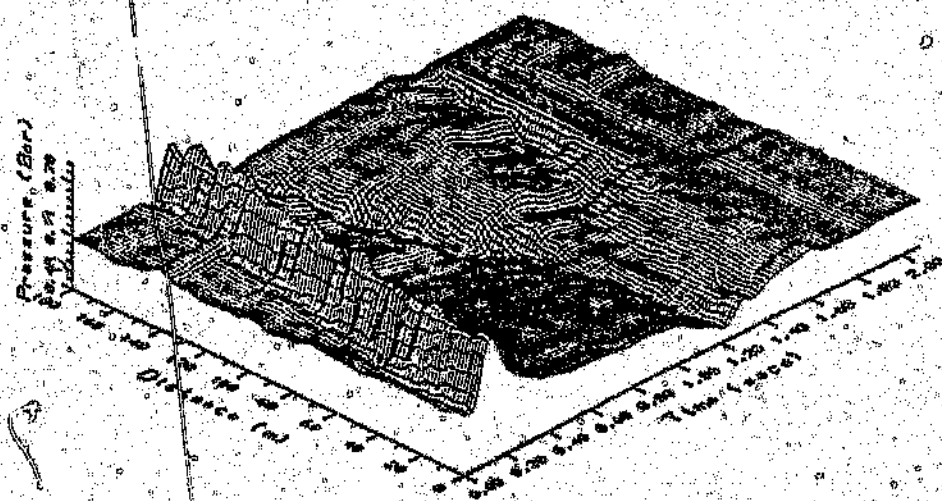


Figure 4.4 Gallery explosion with methane chamber of 48 m³

energy of the coal-dust explosion and directly affects the course of the explosion.

A 9 % methane:air concentration is used, requiring a methane quantity of $4,4 \text{ m}^3$. The excess is required because of leakage from the gallery chamber. This leakage occurs when the chamber is opened to ensure that there is no pressure build-up. The membrane is placed 7,5 m from the closed end of the gallery, resulting in a 36 m^3 chamber.

As the aerodynamic disturbance of all three methane:air volumes proved adequate to raise coal dust into the air stream, the selection of a volume was dependent on the flame length required. The 36 m^3 chamber was selected because a 30 m flame and a 0,64 bars overpressure were obtained which were desirable for initiating a coal-dust explosion for this length of gallery.

Monitoring of the methane concentration in the chamber is done from three independent sampling points. A continuous sample is similarly taken from the methane-free side of the membrane to ensure that there are no leakages across the membrane. Should there be such a leakage, the experimental results are disregarded.

The repeatability of the results is demonstrated in Appendix 1, and appears to be satisfactory.

4.3 Optimization of coal-dust explosion as an initiator

The parameters pertaining to the coal-dust deposit that needed to be optimized for the gallery were the length of the deposit, the nominal concentration and the placement of the coal dust. The length of the deposit is the axial length along the gallery, measured from the closed to the open end. The nominal concentration is the mass of coal dust per unit volume along the length of the deposit, and the placement

refers to the position or location of the deposit, either on the shelves or on the floor of the gallery (refer to Figure 4.1).

In addition, tests were required to ensure that there were no unknown interrelated phenomena which would result in specific peculiarities rather than general occurrences. Thus, combinations of different lengths, nominal concentrations and placements were also tested.

All parameters must be considered as being sequential and interrelated.

4.3.1 Length of coal-dust deposit

The length of the coal-dust deposit had to be limited so as to keep the flame within the gallery for two sequential explosions and allow flame measurements to be made. An arbitrary flame length of 120 m was selected as desirable for this, the first coal-dust deposit. The length could not be excessively limited, however, because the three stages of development, propagation and termination within the gallery were sought.

Several deposit-lengths were tested (Figure 4.1). Deposits longer than 50 m did not reach the propagation stage and continued developing beyond the 120 m mark of the gallery. Thus shorter distances were investigated, from 10 m to 50 m.

Figure 4.5 with a coal-dust deposit length of 20 m shows a flame length of 80 m and static pressure of 1 bar, where the methane explosion is 0,64 bars.

A flame length of 120 m and 1,5 bars overpressure are noted for a deposit length of 30 m as shown in Figure 4.6.

The deposit length of 50 m produces a 140 m flame and 2,1 bars average static overpressure (Figure 4.7).

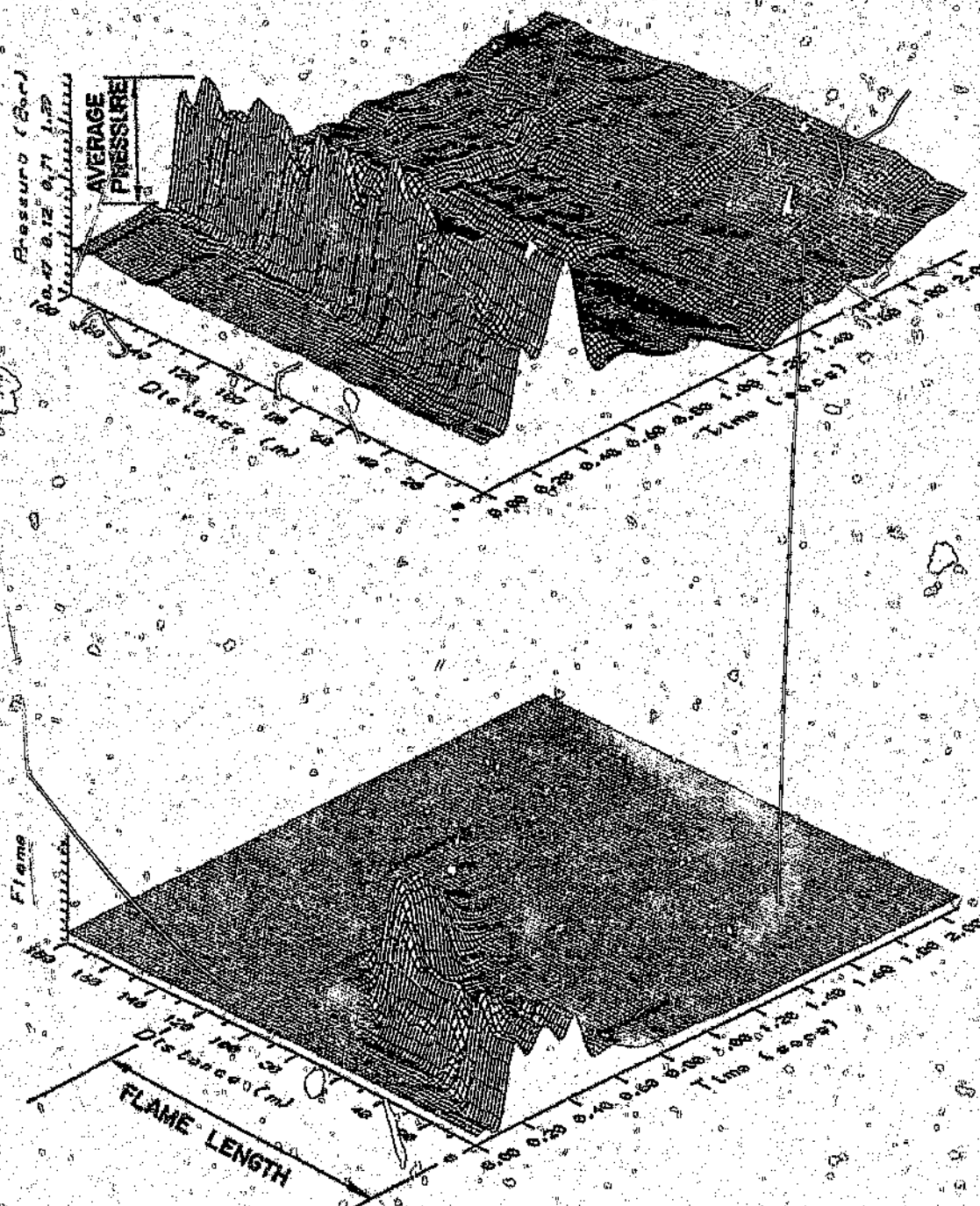


Figure 4.6 Explosion with coal dust deposit length of 30 m

Pressure (Bar)
 0.49 0.11 0.20 1.20 1.87 3.46

AVERAGE
 PRESSURE

MANHOLES

Distance (m)

Flame

Distance (m)

FLAME LENGTH

Figure 4.7. Explosion with coal-dust deposit length of 50 m

It is noted that the longer the deposit, the longer the flame length. This confirms Rae's (1954) results. The static pressure also increases and this is attributed to the longer development stage.

For all the tests, clearly identifiable stages of the explosion were noted. There was a greater fluctuation of the static pressure within the gallery with an increase in deposit length. The two main fluctuations indicated in Figure 4.7 are attributed to the position of the manholes in the gallery wall where there is a pressure loss due to the recessed design of the doors.

An optimum deposit length of 30 m was selected as being suitable for the gallery, as it satisfies the criterion of restricting the experiment to the limits of the gallery. Longer deposits resulted in static overpressures exceeding the range of 2 bars.

4.3.2 Mass of coal dust

A sufficient mass of coal dust must be available to allow the development and propagation of a coal-dust explosion with a static overpressure of less than 2 bars.

For these investigations the length of the coal-dust deposit was fixed at 30 m and the placement was on the shelves (Figure 4.1).

An optimum coal concentration for the gallery was sought. The mass of the coal-dust deposit and the cross-sectional area over the deposit length establish the nominal concentration, in grams per cubic metre. For example, a 35 kg coal dust spread over a length of 30 m, on six shelves, 0.39 mm width, having a surface area of 70 m^2 , gives 1.66 kg/m or 0.50 kg/m^2 . The volume of the gallery over the length of the deposit is 147 m^3 . The nominal concentration is defined as the 35 kg in 147 m^3 or 238 g/m^3 . A nominal coal-dust concentration is used so that a concentration value can be assigned to a specific test. Direct

measurement on a large scale of actual concentration has proved difficult (Cashdollar and Hertzberg, 1982).

Different nominal concentrations were investigated from 136 g/m^3 to 340 g/m^3 (Figures 4.8 to 4.10). Figure 4.8 indicates the static pressure and flame plots with a nominal concentration of 136 g/m^3 or 20 kg/147 m^3 . The static pressure is noted to be 1,05 bars while the flame length is 110 m. A 1,5 bars pressure and 120 m flame are noted for the concentration of 238 g/m^3 , in Figure 4.9. The 340 g/m^3 concentration (50 kg/147 m^3) results in a 2,3 bars pressure and 140 m flame length, as shown in Figure 4.10.

The 238 g/m^3 test was considered most suitable because of the flame length and static pressure.

4.3.3 Non-coal-dust zone

Further optimization of the explosion results was sought to enhance the measurement of the developing explosion and the propagating explosion. It was necessary to vary the position of the total deposit relative to the methane initiation to produce optimized events (Figure 4.1).

The flame front of the methane explosion is ahead of the pressure development and only after 15 m from the source or 7,5 m from the membrane (as used in this discussion) does the dispersion effect or dynamic pressure wave overtake the flame front. Thus it was necessary to introduce a non-fuel zone to allow this condition to occur, as coal-dust explosions are deflagrating explosions, and so the coal dust must be dispersed in the air before the arrival of the flame.

The introduction of a non-fuel zone allowed such optimization. Distances (from the membrane) of 0 m (Figure 4.11), 12,5 m (Figure 4.12) and 22 m (Figure 4.13) were investigated.

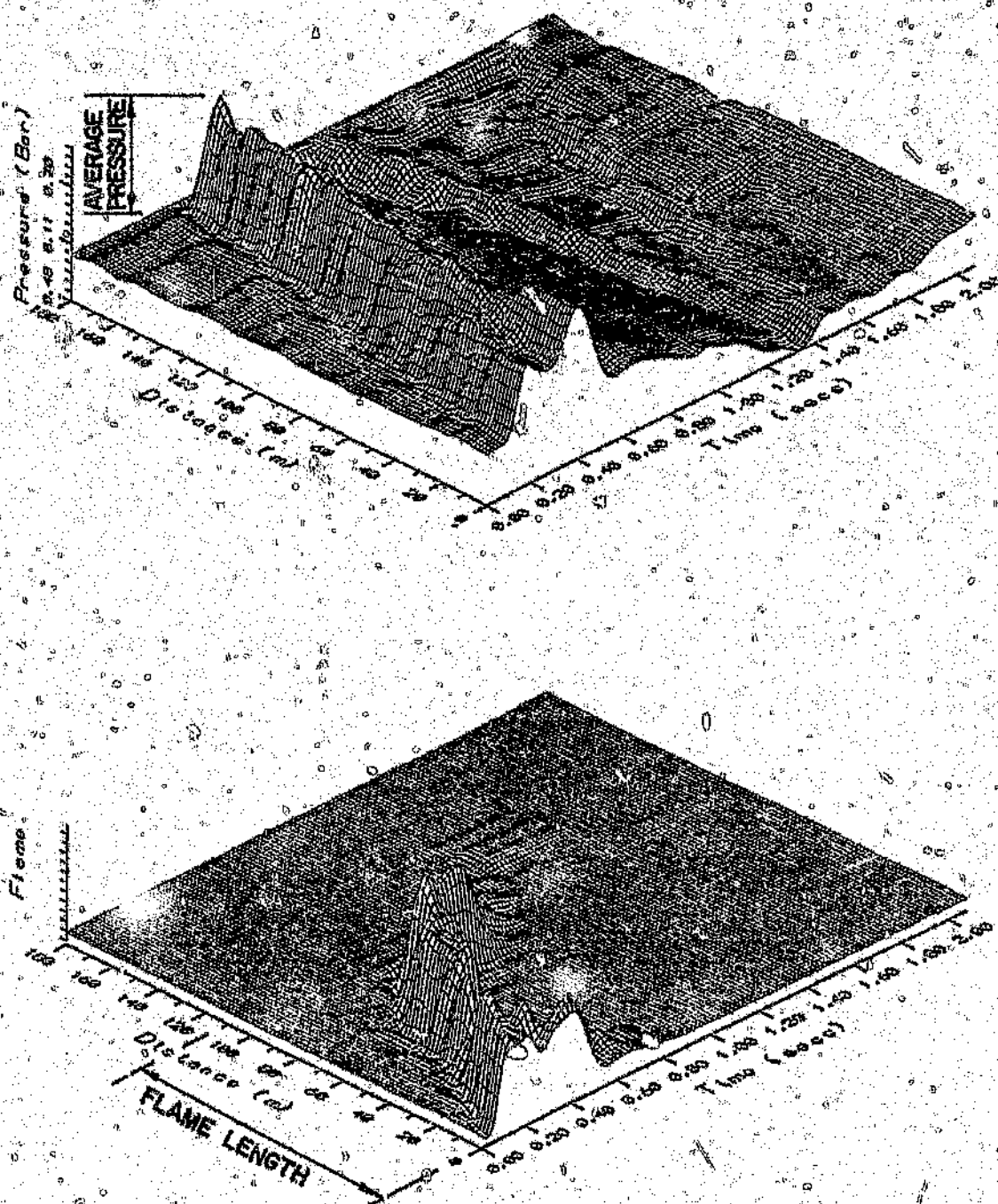


Figure 4.8 Explosion with a nominal coal concentration of 136 g/m^3

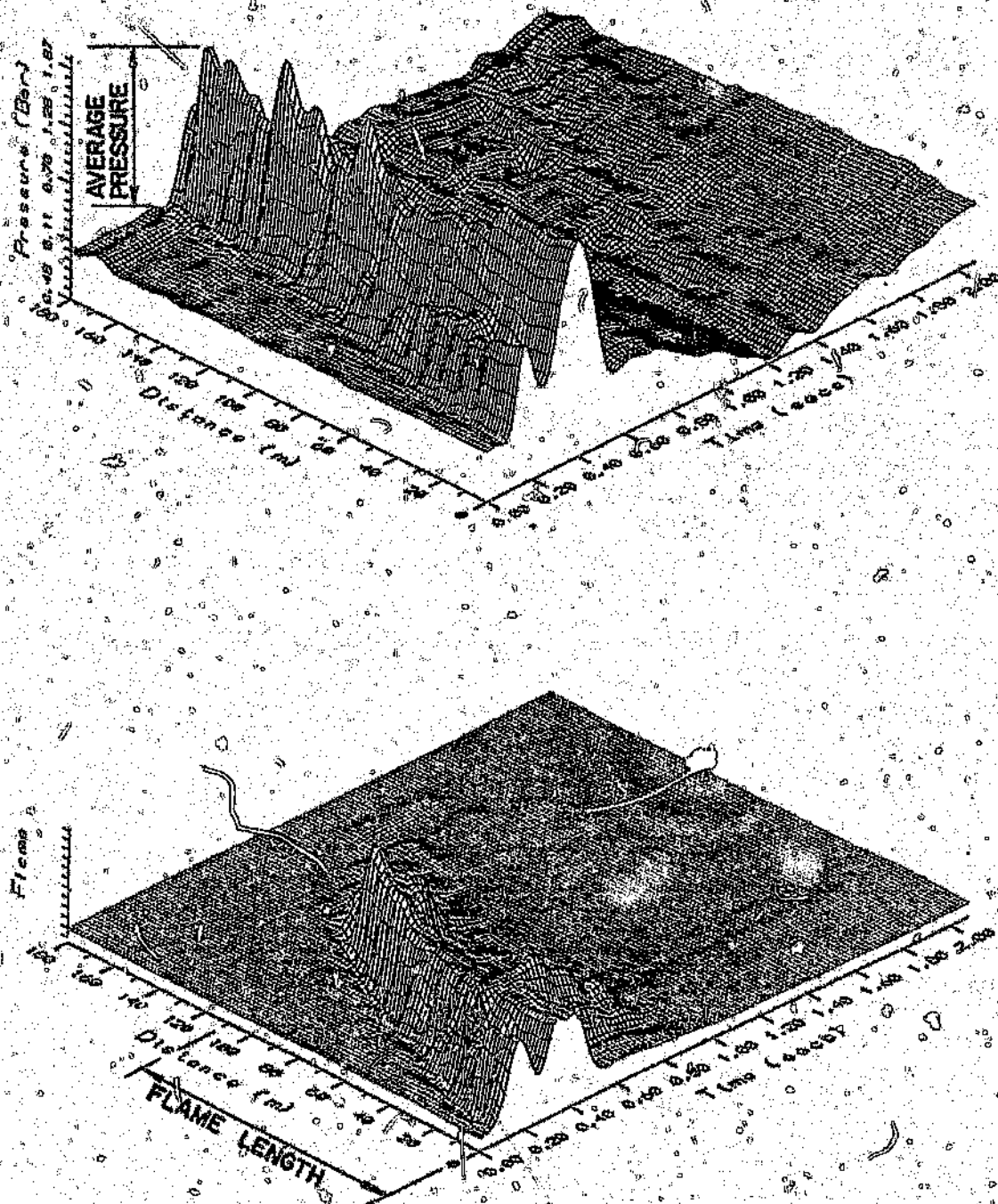


Figure 4.9 Explosion with a nominal coal concentration of 238 g/m^3

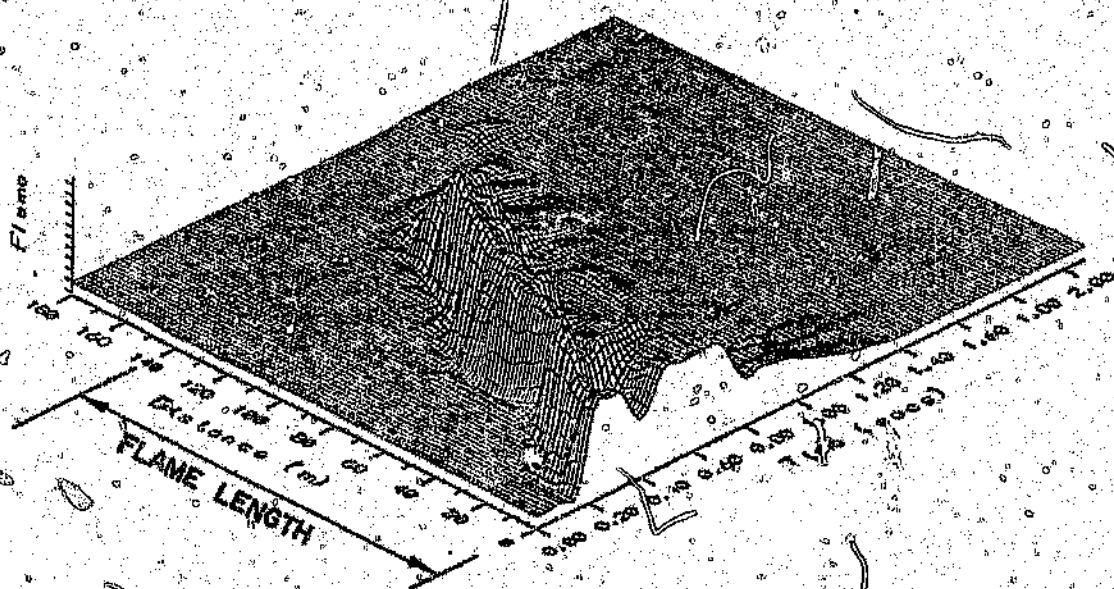
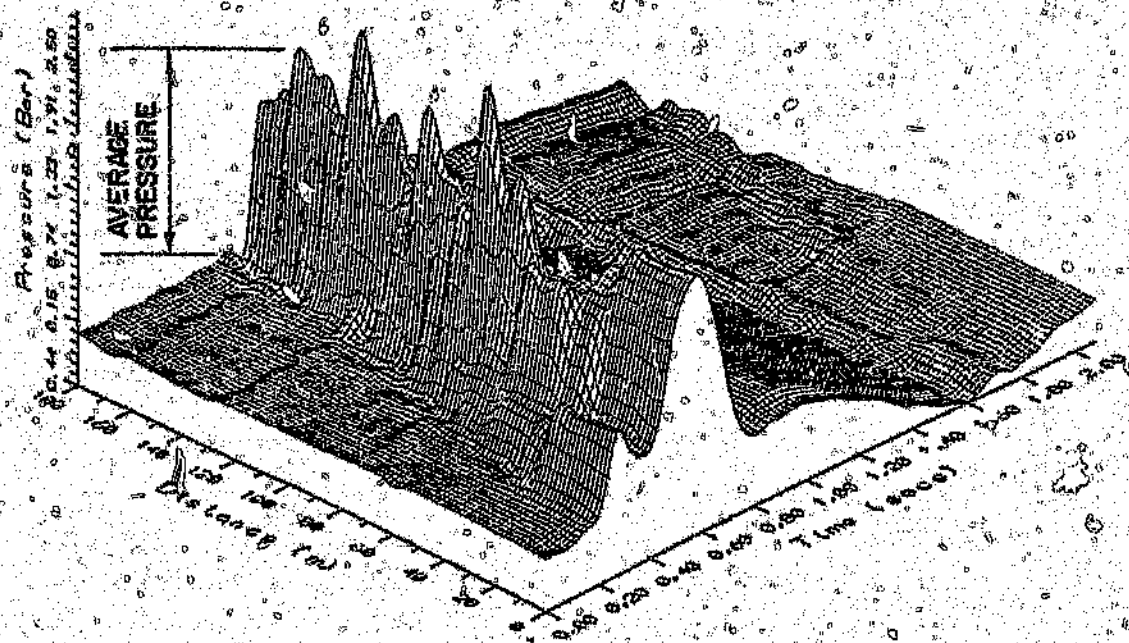


Figure 4.10 Explosion with a nominal coal concentration of 340 g/m^3

The distances of the deposits (0 m, 12,5 m, 22 m) from the membrane position were 7,5 m, 20 m and 29,5 m from the source.

The weak reaction for the 0 m length (Figure 4.11) was attributed to the rapid passing of the flame front and insufficient turbulence, due to the expansion effects of the methane explosion, to disperse the coal dust.

The flame length was 120 m and the static pressure 0,62 bars. The methane pressure wave (0,64 bars) is clearly identifiable, and the coal-dust explosion developed up to 70 m. Further propagation along the gallery (to 180 m) was noted, while the reflected pressure wave re-dispersed coal and resulted in further combustion between the 20 m and 40 m zones in the gallery.

It was found that the optimal static pressure and flame length occurred when this non-fuel zone was 12,5 m in length (Figure 4.12). The fastest flame speed was achieved in comparison with Figures 4.10 and 4.13.

The 22 m length also produced a weak reaction (Figure 4.13). The static pressure was 1,25 bars and the flame length 180 m. This was attributed to a wind-classification process ahead of the flame front, resulting in a lower coal-air concentration, and thus a longer flame but lower static pressure.

The movement of the coal deposit along the length of the gallery is significantly influenced by the initiator (Figure 4.1). Rae (1972) noted that this phenomenon depends on the strength of the initiator, producing similar results to movement of the deposit.

4.3.4 Placement of coal-dust deposit

For these investigations, the nominal coal-dust concentration was set at 238 g/m^3 and the length of the deposit was fixed at 30 m. The coal dust was placed either on the floor or on the shelves, both deposits

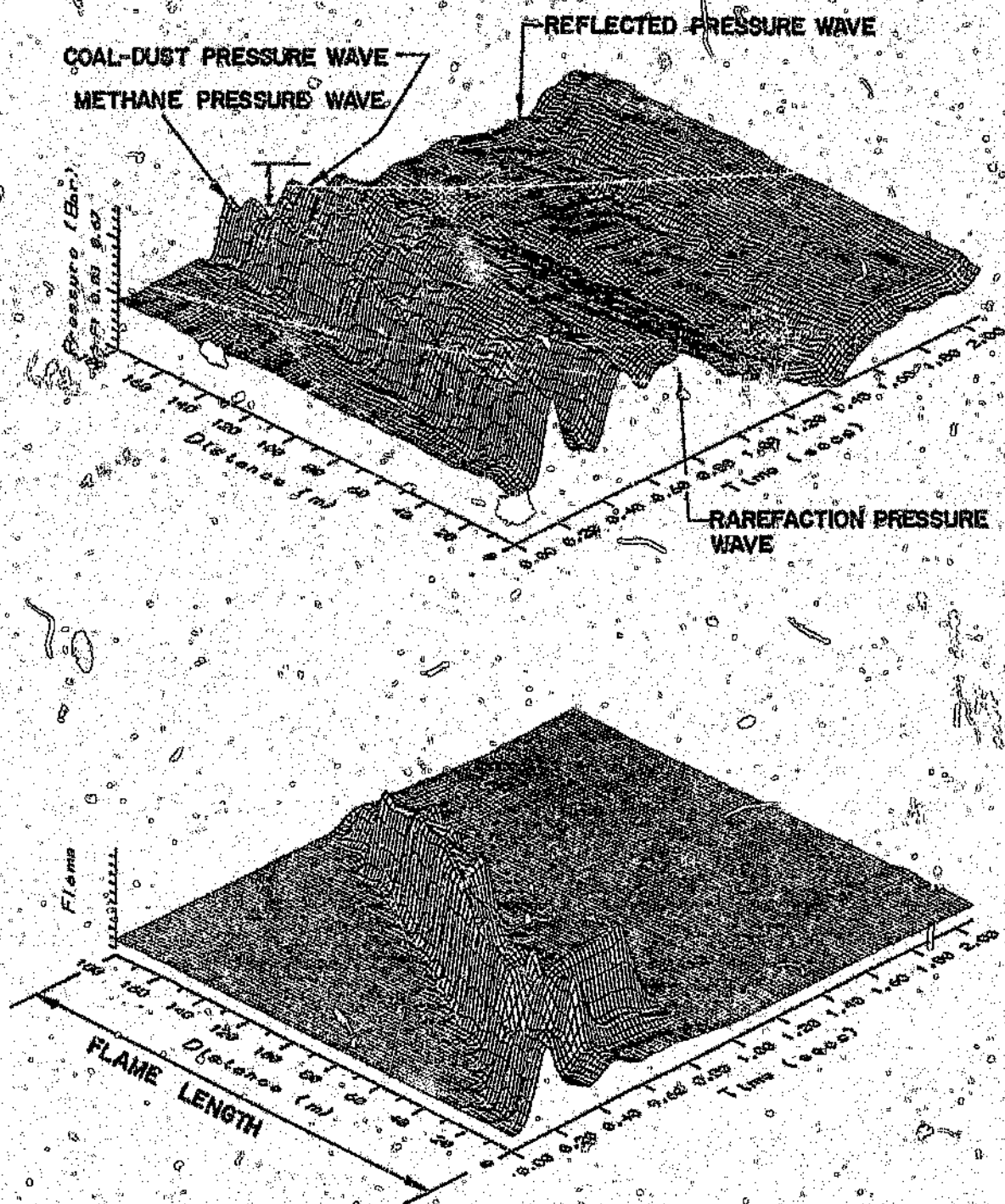


Figure 4.11 Coal-dust deposit 0 m from methane chamber

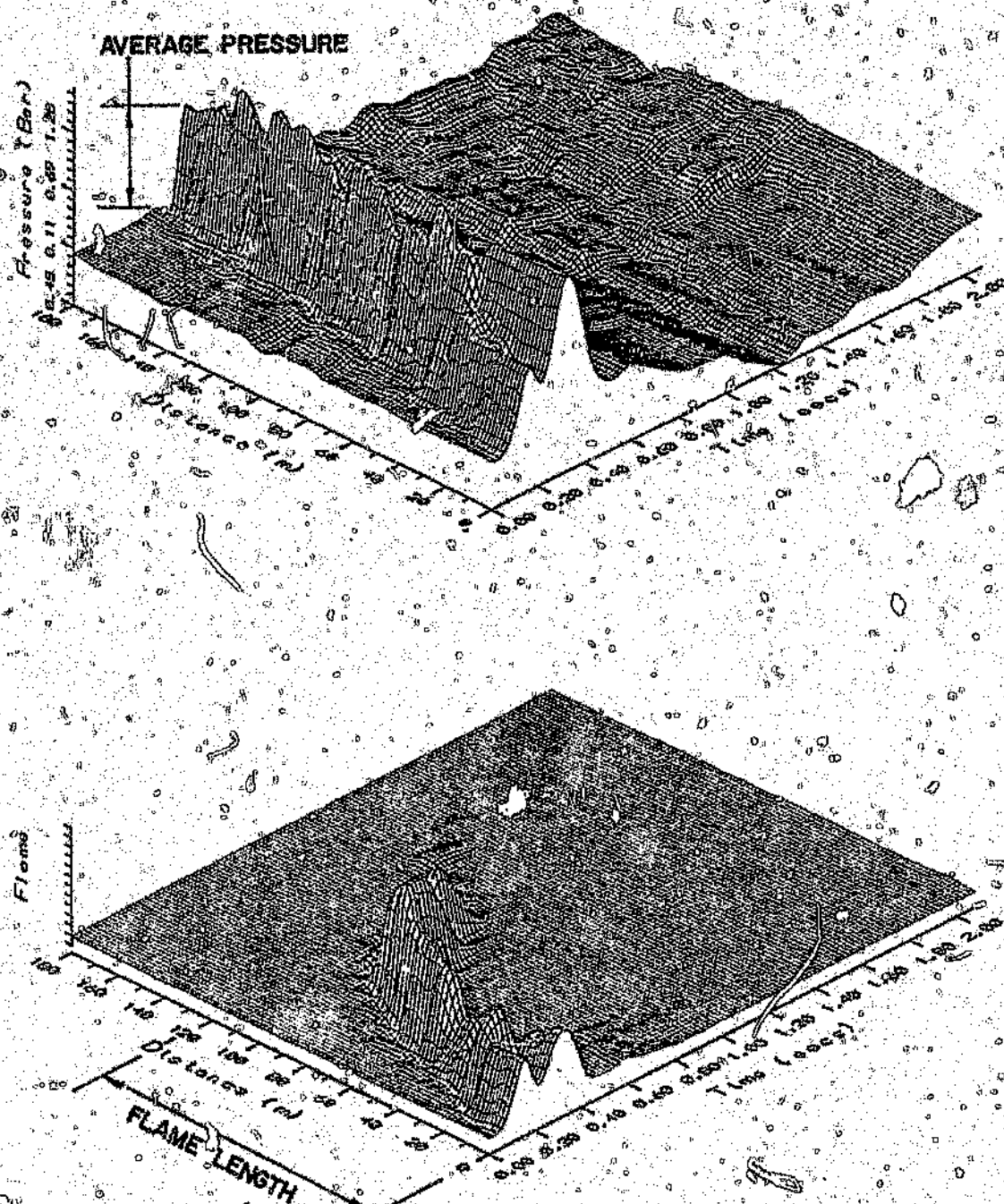


Figure 4.12 Coal-dust deposit 12.5 m from methane chamber

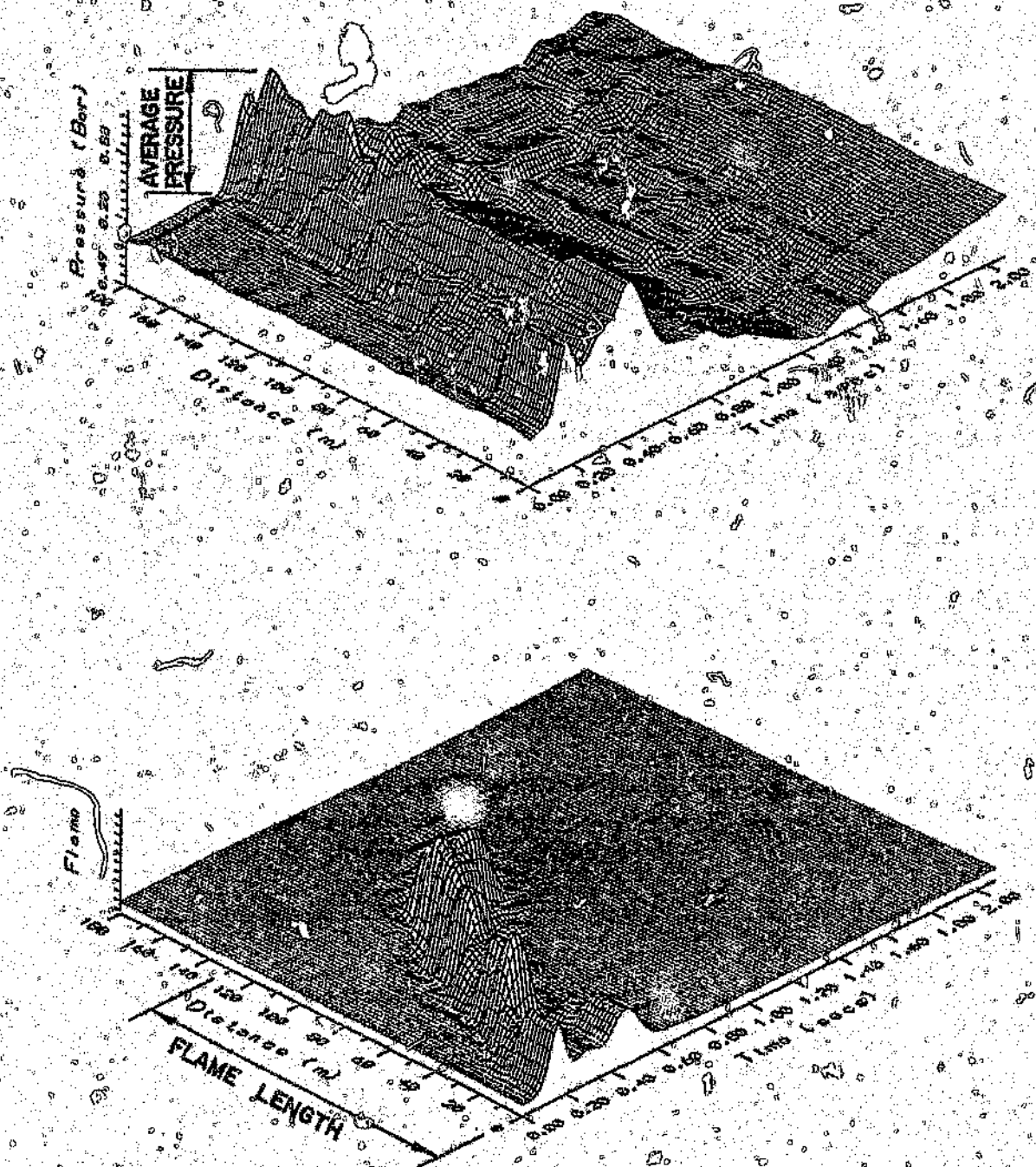


Figure 4.13 Coal-dust deposit 22 m from methane chamber

having a surface area of 70 m^2 ; the shelves were specifically dimensioned to prevent any error from being introduced by the exposed surface area (Figure 4.1).

An optimum coal-dust deposit length and coal-dust mass had already been established, but it was considered necessary to vary the actual coal:air ratio during these investigations by limiting the classifying aerodynamic effect or by increasing the dispersion characteristics of the dust. This was accomplished by placing the coal dust either on the floor or on the shelves. Figures 4.14 and 4.15 show the results of the placement tests.

Significantly different results were obtained, considering that only the placement or elevation was changed. The speed of the flame in the "shelves" explosion is faster, but the duration of the flame is shorter than in the "floor" explosion. The static pressure is similarly significantly higher for the "shelves" explosion.

It was found that by placing the coal dust on the floor only, a slow weakly developed or "weak" coal-dust explosion was established (Figure 4.14). The coal-dust static pressure due to the coal-dust explosion was 0.3 bars and the flame length was 110 m. The weak explosion is attributed to a low dispersion and thus a low coal:air ratio. The increased coal:air ratio obtained by placing the dust on the shelves results in a faster deflagration, as shown in Figure 4.15 where a static pressure of 1.5 bars and a flame length of 120 m were noted.

The dispersion of the coal dust is low for the weak explosion, with the size fractions of the particles being classified in a radial direction. In contrast, there is a predominantly axial classification of dust when it is placed on the shelves.

This increased dispersion of the coal dust resulting from the use of shelves gives a highly developed explosion in the gallery, termed a

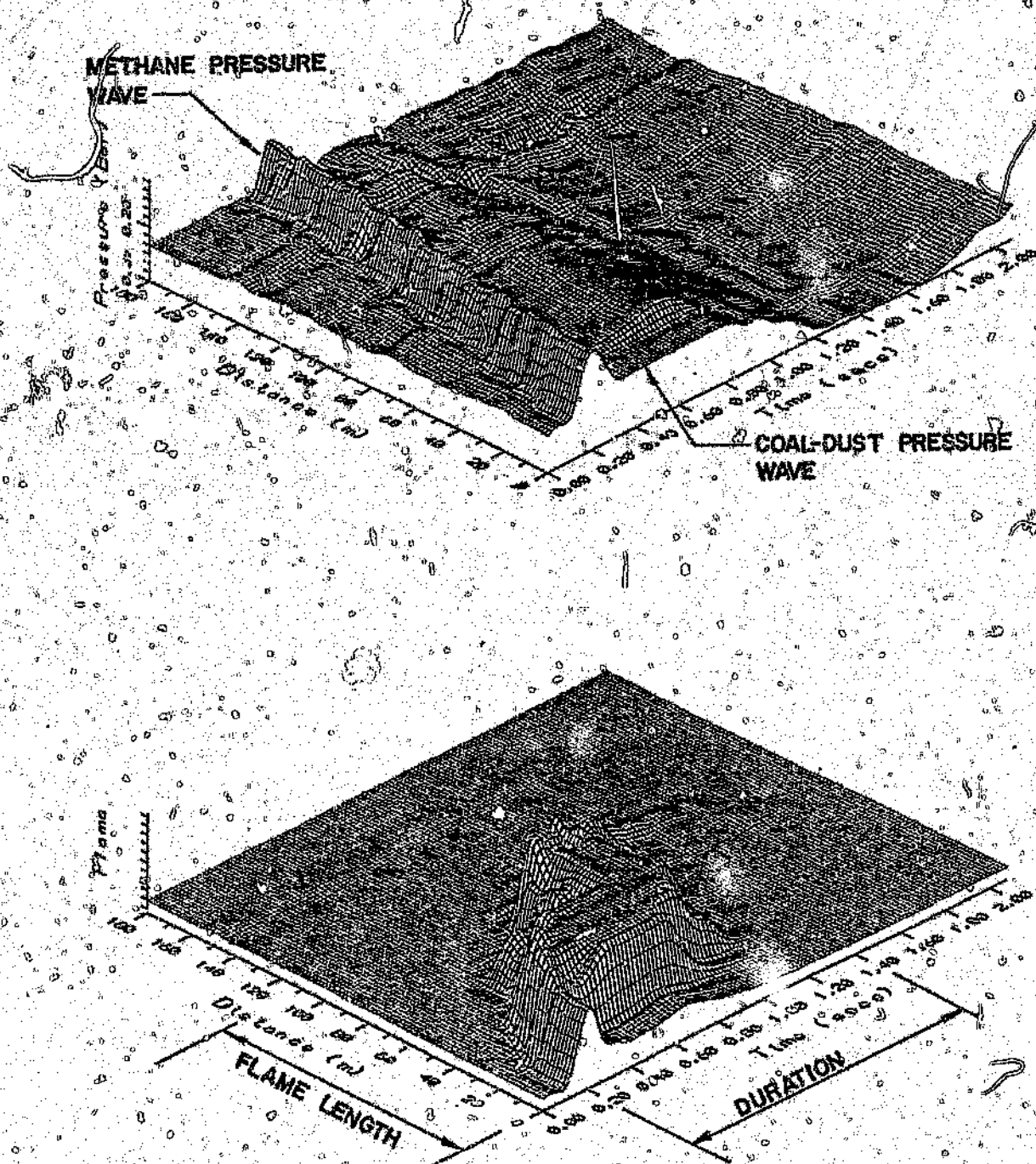


Figure 4.14 Explosion with coal-dust deposit placed on the floor

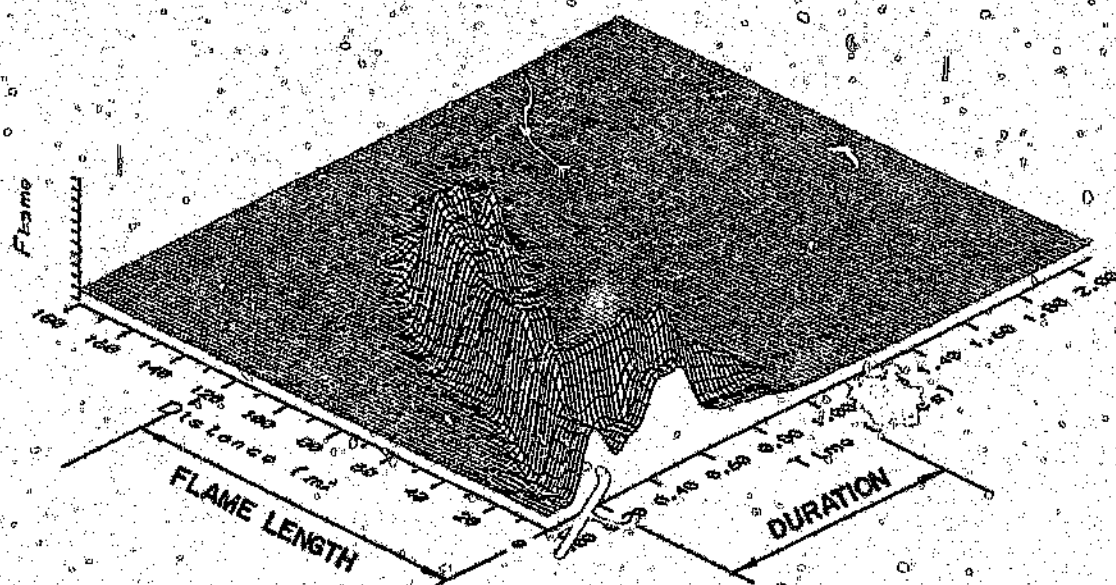
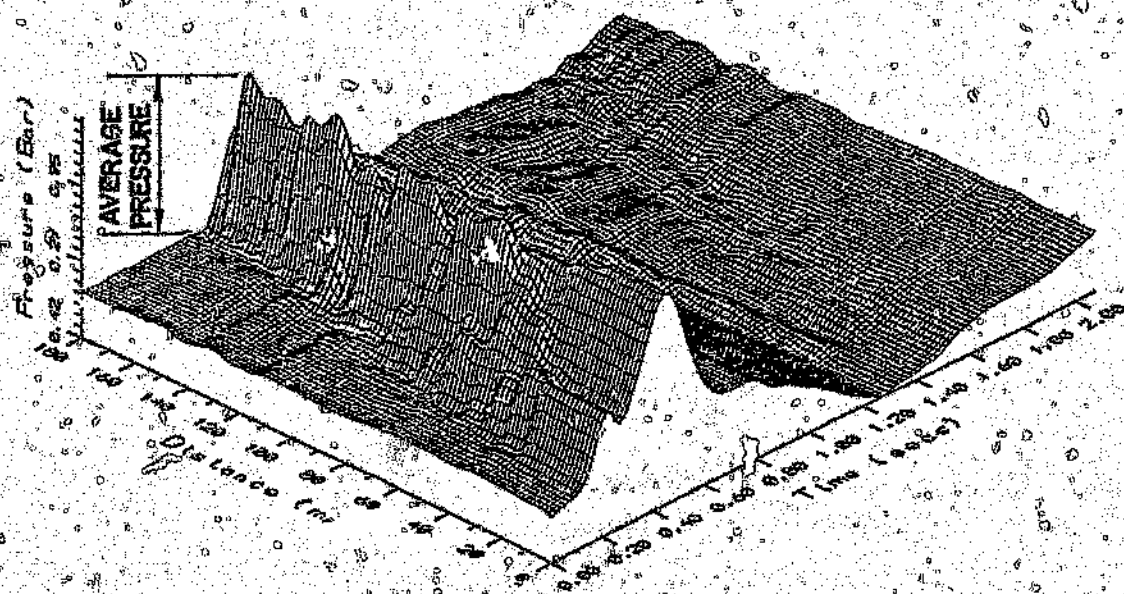


Figure 4.15 Explosion with coal-dust deposit placed on the shelves

"strong" explosion. The effective length of the gallery has in fact been extended by increasing the initial dispersion conditions.

Two different layouts are used. Both have a coal-dust deposit length of 30 m and a nominal concentration of 238 g/m³ or 35 kg of coal dust. In the first layout, the deposits are placed on the floor where a weak explosion occurs. This is defined as the zero reference point for weak explosions for later comparison. In the second layout, the coal dust is placed on the shelves where a strong explosion occurs, and this is the zero reference point for strong explosions.

Six tests of the weak explosion and six of the strong explosion were performed to establish the repeatability. The results are shown in Table 4.3.

Table 4.3 Repeatability of weak and strong, single coal-dust explosions

Coal-dust explosion	Flame length (m)	Average static pressure (bar)
Weak	110	0,64
	110	0,62
	110	0,64
	110	0,64
	110	0,66
	110	0,64
Strong	120	1,48
	120	1,46
	120	1,50
	120	1,46
	120	1,45
	120	1,46

These two layouts confirm that the weak and strong coal-dust explosions can be used as initiators for the second coal-dust explosion.

It is noted that the actual coal:air ratio during an explosion was changed by changing the placement of the coal-dust deposits. Clear development,

propagation and termination stages of the explosions were graphically observed, as is shown in the figures.

4.4 Optimization of coal-dust explosion in the test zone

Suitable weak and strong coal-dust explosions as initiators for the test zone had now been established. The intention of the second coal-dust explosion was to place the deposit in the propagating stage of the initiating coal-dust explosion, but still remain within the limitations of flame length and static pressure presented by the gallery.

It was necessary to optimize the double sequential coal-dust explosion. In this case the flame was to reach the open end of the gallery with the result that, when the stone dust was applied and compared with the reference tests, it should be effective enough to produce a result between the single and double explosions.

4.4.1 Second non-coal-dust zone

In this zone the first explosion must be in a propagating stage (occurring between 70 m and 100 m in the gallery) but must not, when combined with the second explosion, result in damage to the gallery.

There were two conditions that had to be controlled. Firstly, the initial coal-dust explosion had to be in a propagating stage and not developing or terminating. This would allow the magnitude of the first explosion to be ascertained and thus its influence on the second explosion could be described. Secondly, the sequential explosions should not combine and result in an explosion with a magnitude greater than 4 bars, which is the chosen safety limit.

Non-fuel-zone lengths from 40 m to 10 m were tried (Figure 4.1). The optimum was found to be 14 m, where the static pressure was 3.8 bars, and the flame extended visibly 2 m from the open end of the gallery.

4.4.2 Second coal-dust deposit

A flame that reached the open end of the gallery was required. This was obtained with the following second coal-dust deposit: 35 kg of coal dust spread over 30 m, giving a nominal concentration of 238 g/m^3 . The two conditions of placement on the floor and the shelves were again used.

The length, nominal concentration and two positions of the second coal-dust deposit were identical to those of the first deposit (Figure 4.1), however, this deposit was 64 m from the igniter.

Figure 4.16 shows the result of placing the coal dust on the floor; no significant pressure change occurs, indicating a weak explosion. The flame length extends the full length of the gallery, and thus any measured reduction in flame length due to the introduction of stone dust into the seed zone will describe the stone dust's effectiveness under weak conditions. Two propagating stages of the flame are identifiable.

The strong double coal-dust explosion is shown in Figure 4.17. The static pressure plot shows the methane explosion, first coal-dust explosion and second coal-dust explosion. The first coal-dust explosion peaks at 70 m and the second at 140 m. Again, the influence of the second manhole is noted. The flame plot indicates the extent of the flame.

Both weak (Figure 4.16) and strong (Figure 4.17) double explosions were noted.

The double explosions, both weak and strong, determine the maximum control test. The second coal-dust deposit is essentially the same as the first, but it is placed 14 m beyond the first deposit, 64 to 94 m from the closed end of the gallery.

The repeatability of these tests, of which six of each were completed, is shown in Table 4.4. The flame length is consistent while a variation

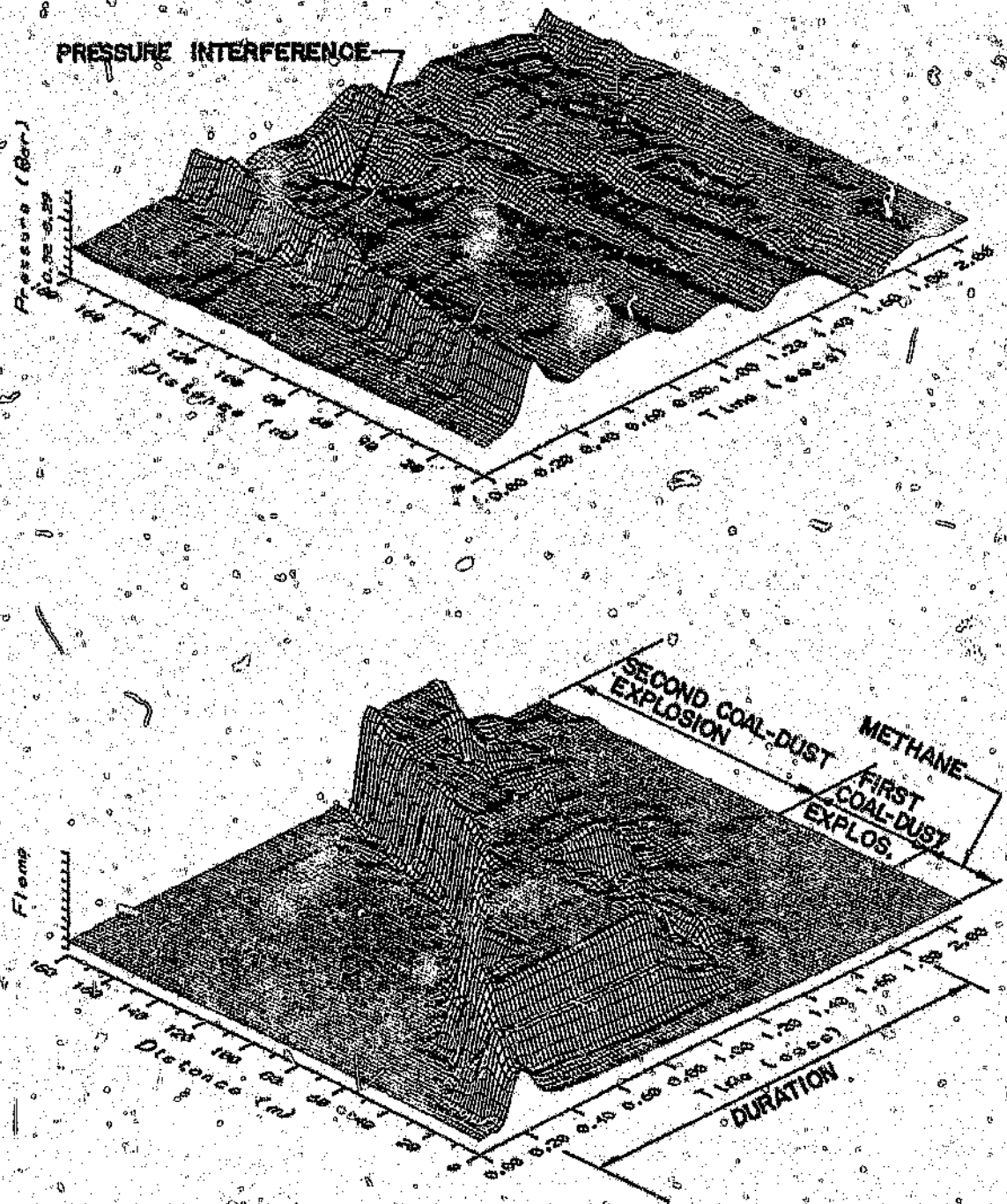


Figure 4.16 Weak double coal-dust explosion with dust placed on the floor

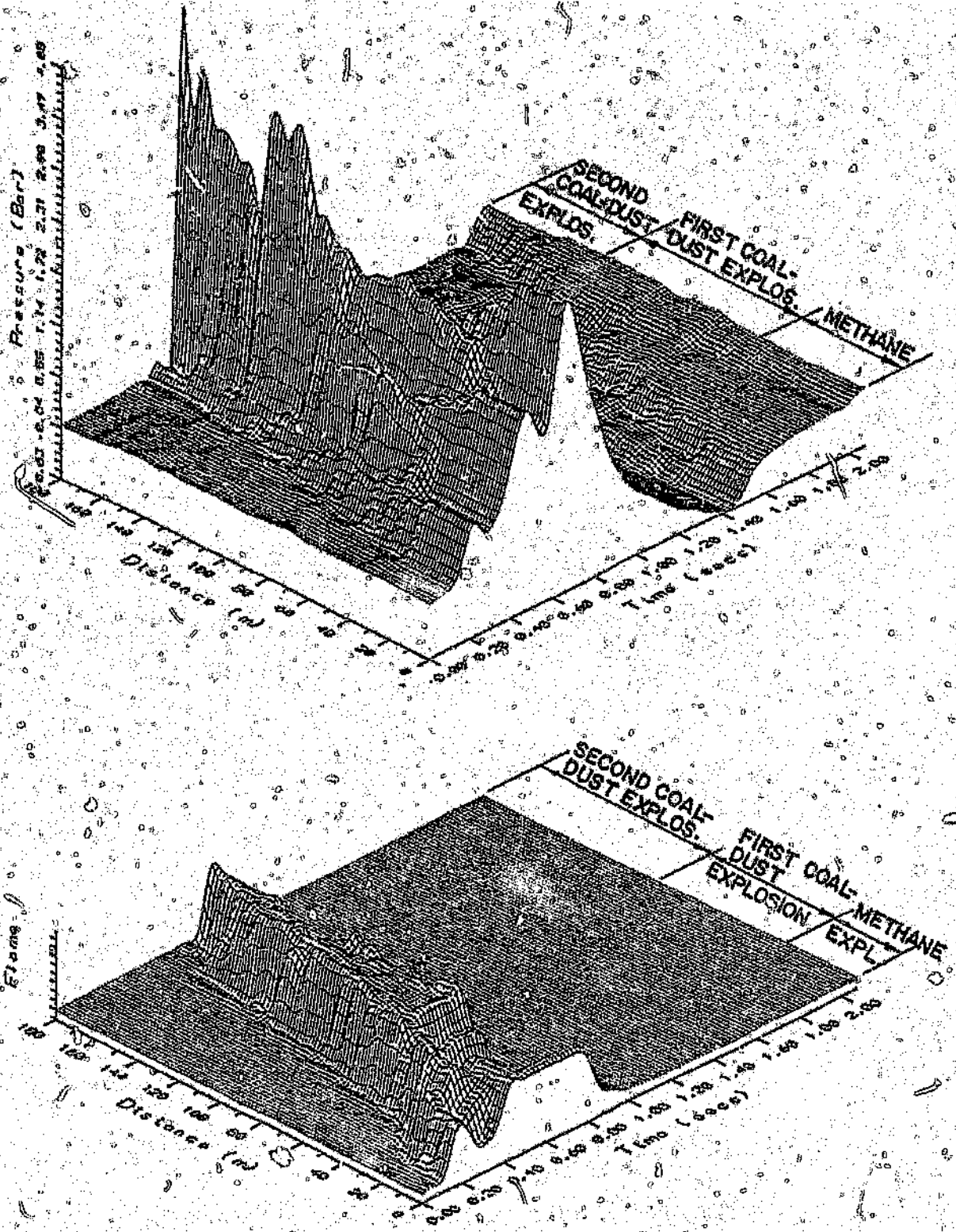


Figure 4.17 Strong double coal-dust explosion with dust placed on the shelves

of 0,1 bar and 0,26 bar is observed for the weak and strong explosions, respectively. Thus, any effect of stone dust must produce a more significant variation in the static pressure.

The precision of the flame length and static pressure for these explosions on a large scale minimizes the need for the repetition of reference or control tests. The accuracy and repeatability of the control tests is essential for assessing the effectiveness of stone dust in preventing and inhibiting the further propagation of coal-dust explosions.

Table 4.4 Repeatability of weak and strong, double coal-dust explosions

Coal dust explosion	Flame length (m)	Average maximum static pressure (bar)
Weak double	200	0,63
	200	0,56
	200	0,58
	200	0,65
	200	0,60
	200	0,55
Strong double	200	3,21
	200	3,39
	200	3,13
	200	3,36
	200	3,31
	200	3,19

4.5 Discussion

An electrochemical igniter was selected to provide a flame that would fill the full cross-section of the gallery. This resulted in the methane initiation having a single flame front. The volume of the methane:air chamber proved suitable for a repeatable initiation of a coal-dust explosion, and adhered to the specific testing procedures prescribed for methane explosions in the Republic of South Africa.

The flame length was controlled by limiting the coal-dust deposit length, and, through optimization, the flame speed was limited. The position of the coal-dust deposits was varied. When the coal dust was placed on the floor, dispersion conditions were poor, and a weak explosion resulted. When the coal dust was placed on the shelves, a higher dispersion and a faster flame were obtained, resulting in a stronger explosion. The explosions were refined by introducing a non-fuel zone. Repeatable weak and strong coal-dust explosions were obtained, with the five explosion stages being graphically identifiable.

The two separately identifiable conditions of explosions with different magnitudes were attained by increasing the initial dispersion characteristics of the coal dust. This was achieved by placing the coal dust on the floor for the weak explosion and on the shelves for the strong explosion. The changing of the position of the coal-dust deposit is the only transfer parameter that is altered in the experimental procedure to obtain characteristically identifiable explosions.

The apparent length of the gallery is effectively increased by enhancing the dispersion of the coal dust and thus promoting the development stage.

The analysis for the effectiveness of the stone dust, however, still required reference values. It was assumed that the single explosions with no second zone present represented explosions where termination was totally effective for the second zone. This approach allowed a relative scale to be determined, which provided the maximum conditions of effectiveness of the stone dust.

By further introducing the test zone, without the use of stone dust, a means was provided of establishing a non-termination condition and thus the minimum effectiveness of the stone dust.

The tests that are used are shown in Figure 4.15. Explosions with the use of stone dust would then provide a means of establishing the actual effectiveness of stone dust.

The test zone was optimized with regard to the coal dust and to the deposit length needed to ensure that a flame terminated at the open end of the gallery. A non-fuel zone was introduced between the test zone and the first coal-dust deposit to limit the flame speed and therefore the maximum static pressure. The five stages of the test-zone explosion were clearly identifiable from the flame and pressure plots.

The implication of this experimental procedure is that control of a propagating explosion in the gallery has been obtained and can be used to initiate an explosion in a second coal-dust deposit, or test zone.

Through the use of a double coal-dust explosion, the stone-dusting regulation can now be appropriately evaluated. The experimental procedures differ from those used elsewhere in that both weak and strong explosions in their propagating stages are used to evaluate the effectiveness of stone dust when applied to inert coal dust. In addition, non-fuel zones have been introduced to allow the establishment of propagating stages within an explosion's course.

In summary, the flame velocity of an explosion has been used to classify so-called weak (slow) and strong (fast) explosions. Testing the stone-dust inhibition of other coal explosions provides a relative measure of the effectiveness. Conventional methods used (Table 2.3) are similar to the weak double coal-dust explosion. The inclusion of the strong explosion allows a more accurate measure, and thus confidence in the explosion-inhibitive safety provided by stone dust.

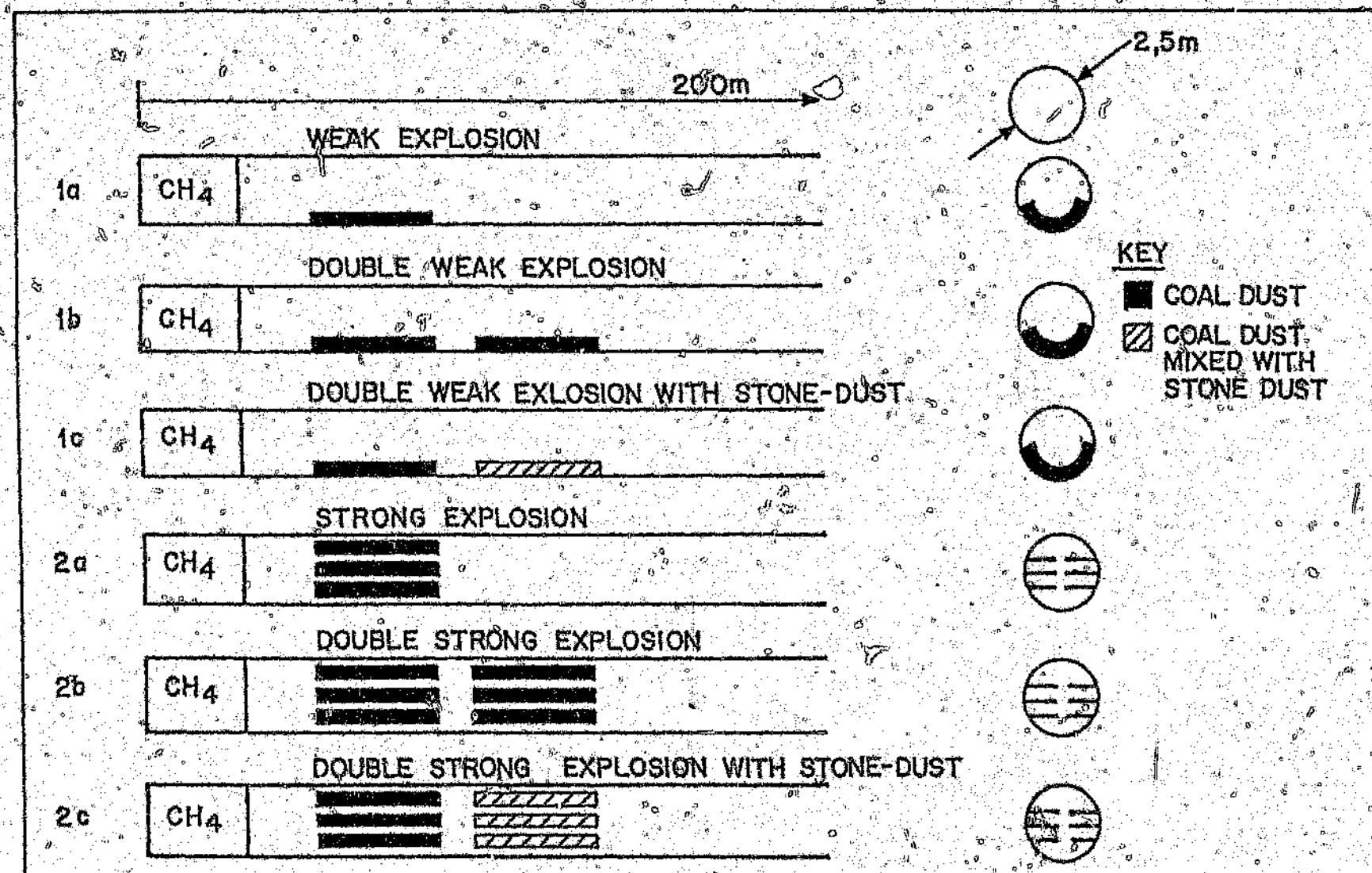


Figure 4.18 Diagrammatic representation of gallery setup for proposed experimental procedure

5 EVALUATION OF REGULATION 10:24 OF THE MINERALS ACT (1991)

This chapter details the experimental procedure followed using chosen coal dusts for the test series and a selected stone dust. The coal dust and stone dust were first characterized and then the stone dust was evaluated in the gallery.

5.1 Sample preparation

Four 3 000 kg samples of low-ash coal were collected from different mines. The samples had to have less than 15 % ash and were not allowed to show signs of oxidation.

The samples were quartered to give a 500 kg sample which was air-dried so as to facilitate milling and prevent clogging.

The mill was thoroughly cleaned and wind-swept before and after use to ensure that no previous sample caused contamination. A 100 kg subsample was then milled to calibrate the mill. Three classifier speeds were selected for the calibration and the resulting particle size distributions determined. Interpolation between the results of the three speeds then allowed the required speed to be chosen; this was verified with a further 50 kg subsample. The remaining 350 kg from the sample was milled for use in the gallery tests.

Once the milling was complete, blending or mixing of the sample was performed for 30 minutes. Samples were then drawn off into 2,33 kg packets. This limited inaccuracies introduced by hand-spreading when distributing the coal dust in the gallery. When 15 bags, constituting 35 kg, have been spread over the 30 m length of the gallery (floor or shelves), the required nominal concentration is achieved for a single coal-dust deposit.

The particle size analysis of the four coals used is shown in Table 5.1.

Table 5.1 Particle size analysis of coal dust samples

% Mass passed	Coal dust			
	1	2	3	4
10	28	20	30	24
30	65	64	65	64
50	84	84	83	83
70	93	96	91	93
90	96	99	96	97
d ₅₀	21	18	19	22
d ₉₀	150	135	165	160

the required specifications were a median particle size of $20 \mu\text{m}$ ($\pm 2 \mu\text{m}$) and a topsize of $150 \mu\text{m}$ ($\pm 15 \mu\text{m}$) for which all samples were within tolerance.

5.2 Characterization of coal

The proximate analysis results of the coals are shown in Table 5.2, where the incombustible content (Total Incombustible Content: % TIC), as required by the Regulation, is also shown (refer to Table 1.1).

Table 5.2 Analysis of the coal selected for experimentation

Analysis	Coal dust			
	1	2	3	4
Proximate				
CV (MJ/kg)	28,8	29,2	30,7	27,6
H ₂ O (%)	2,0	2,7	2,5	2,8
Ash (%)	12,6	11,1	8,1	14,2
VM (%)	26,8	31,3	31,2	22,6
FC (%)	58,6	54,9	58,2	60,6
Total S (%)	0,45	0,73	0,69	0,38
Stone dust (MA Reg. 10:24)				
VM (%) daf	31,4	36,31	34,9	27,1
% TIC required by law	70	75	72	68
K _{ex}	157	187	195	123

Table 5.1 Particle size analysis of coal dust samples

% Mass passed	Coal dust			
	1	2	3	4
10	26	20	30	24
30	65	64	65	64
50	84	84	83	83
70	93	96	91	93
90	96	99	95	97
d ₅₀	21	18	19	22
d ₉₀	150	135	165	160

the required specifications were a median particle size of 20 μm ($\pm 2 \mu\text{m}$) and a topsize of 150 μm ($\pm 15 \mu\text{m}$) for which all samples were within tolerance.

5.2 Characterization of coal

The proximate analysis results of the coals are shown in Table 5.2, where the incombustible content (Total Incombustible Content: % TIC), as required by the Regulation, is also shown (refer to Table 1.1).

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VM (%)	28,8	31,3	31,2	22,5
FC (%)	58,6	54,9	58,2	60,5
Total S (%)	0,45	0,73	0,59	0,38
Stone dust (MA Reg. 10:24)				
VM (%) daf	31,4	36,31	34,9	27,1
% TIC required by law	70	75	72	68
K _{ex}	157	187	195	123

The dry ash-free volatile matter contents of the coals range from 27.1 to 36.31 %. This is representative of the bituminous underground coal mines of South Africa. The required incombustible contents range from 68 to 75 %, with actual values also indicated.

Table 3.2 shows the required amount of incombustibles. The percentage weight of the coal dust was calculated as follows:

$$VM_{daf} = \frac{VM \% \times 100}{(100 - \% Ash - \% Water)}$$

$$\% TIC = \text{read from Regulation 10.24 or Table 1.1}$$

$$\% \text{ Stone dust} = \frac{(\% TIC - \% Ash - \% Water)}{1 - \left(\frac{\% Ash + \% Water}{100} \right)} \quad (\text{Michelis et al. 1989})$$

The K_{ex} values as determined in the 40-litre vessel indicated that all four coals were explosive (Knoetze, 1991) as are all bituminous coals in South Africa.

Petrographic tests on the oxidation of the samples indicated that no weathering of the samples had occurred before gallery experimentation.

5.3 Characterization of stone dust

The chemical analysis of the stone dust used was as follows: the incombustible matter content was 99.85 % and the free silica was 2.17 %. The particle size analysis showed that 100 % passed through a 600 μm sieve and 65.2 % through a 75 μm sieve. The reflectance of the stone dust was 0.7 %. Thus this stone dust satisfied the Minerals Act's minimum specifications (Table 1.2).

5.4 Tests for effectiveness of stone dust

Both weak and strong double coal-dust explosions were used for the tests, with stone dust introduced into the second coal-dust deposit. The coal dust and stone dust were intimately mixed, as required by the Minerals Act. A specific blender was used for this purpose, so as not to contaminate the milling plant blender. The mixture was measured and the total incombustible content was confirmed to be as shown in Table 5.2.

Figure 5.1 shows the weak double explosion with stone dust introduced into the second fuel zone for coal 1. The static pressure of the methane explosion is seen to be 0,64 bars. For the first and second coal-dust explosions, the static pressure was observed to be below 0,3 bars, which was classified as an explosion. However, the flame extended to 150 m in the gallery, 66 m beyond the dust deposit zones.

For the stone dust to be 100 % effective, the same result as is shown in Figure 4.14 (also coal 1) should be observed, where the flame length is 110 m. If, however, the stone dust was completely ineffective, the result would be as in Figure 4.16.

It is seen from Figure 5.1 that the stone dust did not inhibit the development of the explosion, but did reduce the propagation stage and enhance termination.

Figure 5.2 shows the strong double explosion with stone dust introduced into the second fuel zone. The control tests are shown in Figure 4.15 for 100 % effectiveness in explosion inhibition and Figure 4.17 for 0 % effectiveness. From Figure 5.2 the static pressure is seen to be as follows: the methane explosion was at 0,63 bars, the first coal-dust explosion was at 1,57 bars and the second coal-dust explosion at 0,7 bars. Thus the static pressure in the second coal-dust/stone-dust explosion was reduced, but is still classified as an explosion (above 0,2 bars).

The flame extends the full length of the gallery, although between 110 m and 130 m the flame was partially extinguished. However, the explosion is seen to regenerate, develop and propagate beyond the mouth of the gallery. Thus the stone dust itself is considered to be ineffective in inhibiting and suppressing an explosion for the specified conditions and geometrical limitations of the gallery.

The repeatability of the tests for coal 1 was established by repeating both the weak and strong double explosions with stone dust, six times each. The results are shown in Table 5.3. The flame length for the weak double explosion with stone dust was found to be 150 m for all cases. The static pressure from the coal-dust explosion never exceeded 0.3 bars.

Table 5.3 Repeatability of weak and strong double coal-dust explosions with stone dust mixed with the second coal-dust deposit for Coal 1

Test (From Fig. 4.17)	Flame length (m)	Average maximum static pressure (bar)
Weak: 1c	150	0.84
	150	0.57
	150	0.81
	150	0.81
	150	0.60
	150	0.66
Strong: 2c	200	1.56
	200	1.67
	200	1.51
	200	1.69
	200	1.62
	200	1.53

For the strong coal-dust explosion with stone dust, the flame length was always over 200 m, and had a characteristic zone of flame reduction between 110 m and 130 m. The static pressure was as shown in Table 5.3 for the coal-dust explosion.

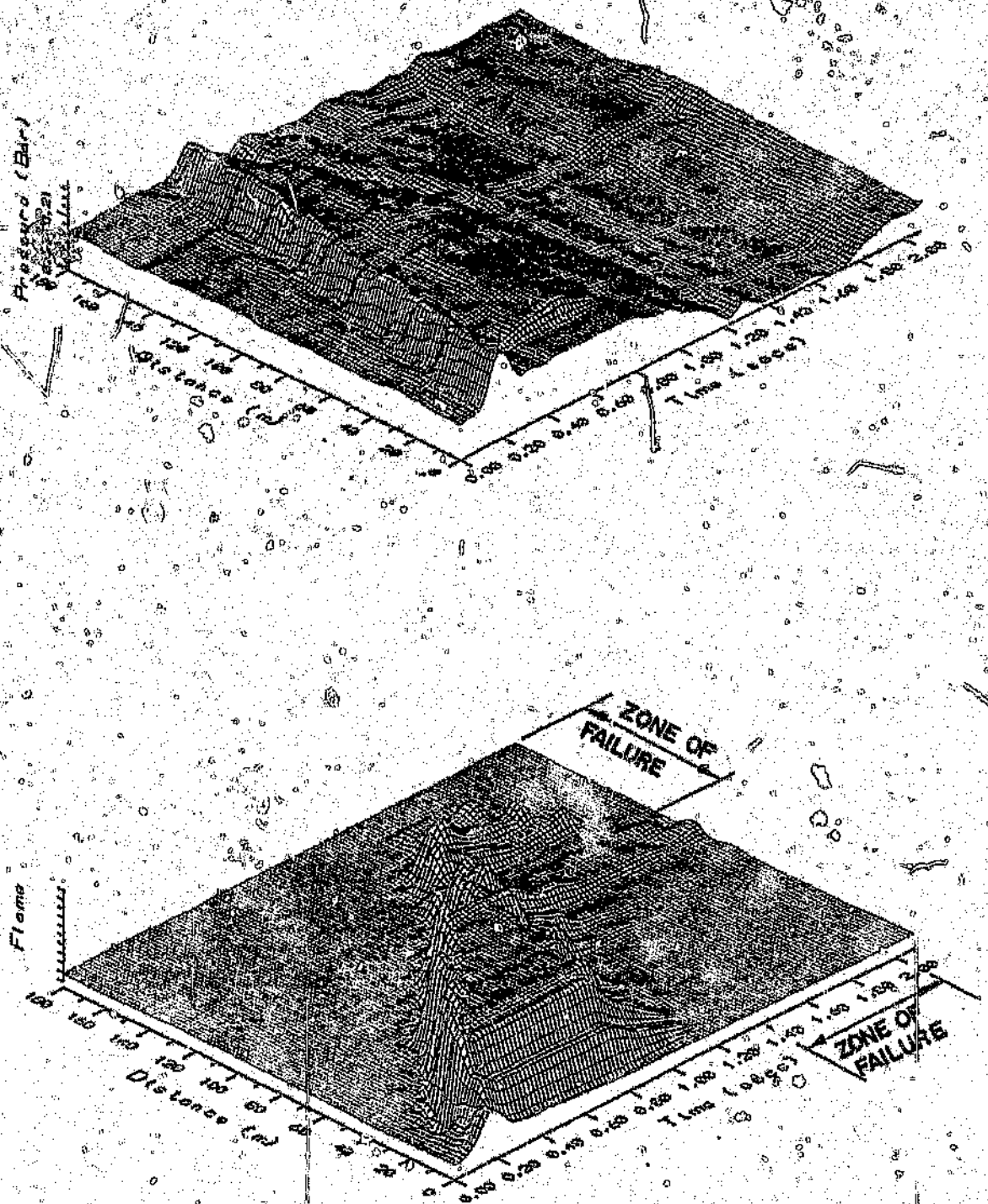


Figure 5.1 Weak double coal-dust explosion with stone dust in the second zone

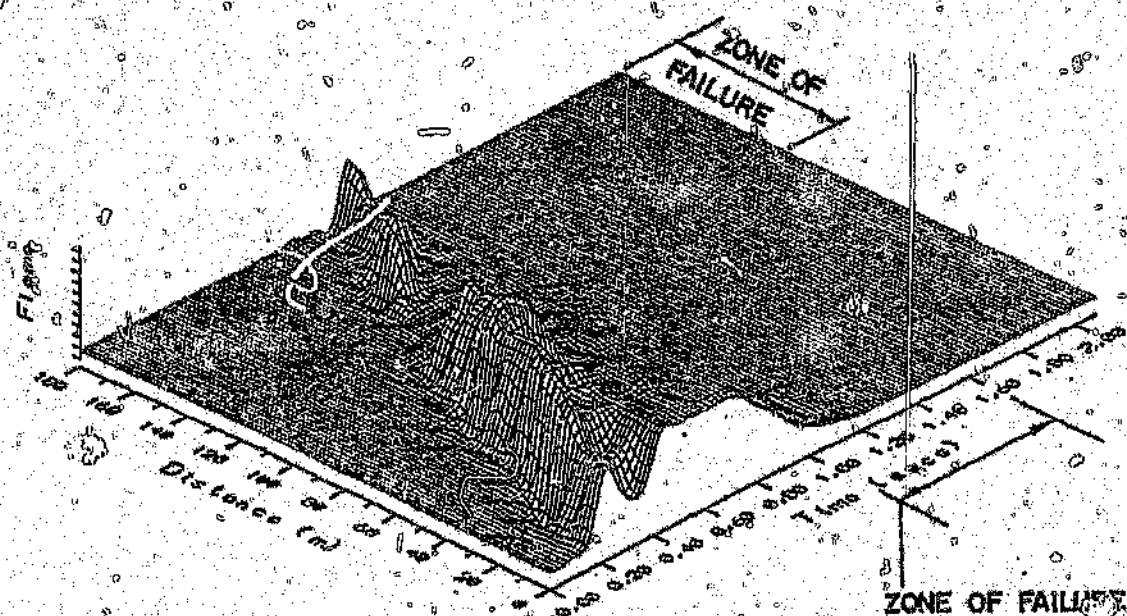
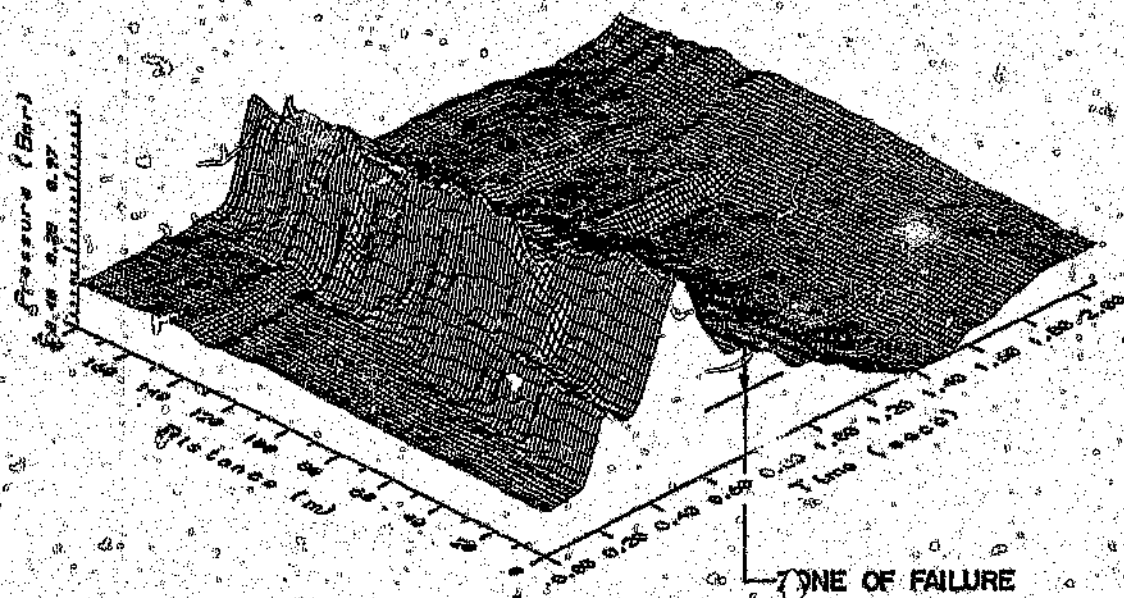


Figure 5.2 Strong double coal-dust explosion with stone dust in the second zone

The other three coals were tested in a similar way, as is shown in Figure 4.18, with no repeatability tests. The results are shown in Table 5.4 for all the coals.

Table 5.4 Overall results using the experimental procedure

Test (from Figure 4.17)	Flame lengths of coal tested (m)			
	1	2	3	4
1a Weak single	110	130	120	110
1b Weak double	200	200	200	200
1c Test + stone dust	150	180	170	140
Difference (1a - 1c)	-40	-50	-50	-30
2a Strong single	120	150	120	120
2b Strong double	200	200	200	200
2c Test + stone dust	200	180	200	200
Difference (2a - 2c)	-80	-30	-80	-80
Difference: Where negative indicates failure				

All the tests where stone dust was used (1c, 2c) show that the flame extended well beyond the respective zero reference values (1a, 2a respectively) indicating failure to inhibit further propagation. However, it is observed that stone dust did inhibit, to some extent, the propagation of explosions (compare 1b with 1c and 2b with 2c).

It is noted that all the test results using this experimental procedure and within confines imposed by the gallery, indicated that the requirements of Regulation 10:24 of the Minerals Act (1991) for preventing the development and propagation of explosions had not been satisfied.

5.5 Discussion

In the weak double explosion with stone dust in the second zone, the effectiveness of the stone dust was measured in terms of its ability to



inhibit the heat transfer conditions that maintain the propagation of an explosion. The strong double explosion with stone dust provides an environment in which a reduction in static pressure is observed. The different placements of the stone dust in the second fuel zone (on the floor or on the shelves) experimentally alter the dust dispersion. This provides a means of establishing the effectiveness of stone dust in terms of its dispersion.

The weak double explosion provides a means of measuring the quality or dispersion potential of stone dust in terms of its ability to inhibit the development of coal-dust explosions under weak conditions. The strong double explosion provides a measure of the quantity of stone dust required to reduce the magnitude of the explosion. Thus the effectiveness of stone dust is described in terms of both quality and quantity.

Stone dust was added to the test zone to evaluate Regulation 10:24 of the Minerals Act (1991). None of the six repetitions of each of the weak and strong coal-dust initiation explosions stopped the development and propagation of the coal-dust explosion that was present in the test zone. These tests were repeated for three other coals and similar failures were noted. This implies that the quality of the stone dust was not suitable for inhibiting the propagation of a weak explosion. The quantity of the stone dust was similarly inadequate to prevent the propagation of a strong coal-dust explosion.

It must be emphasized that this finding is valid in the context of this experimental procedure. The extrapolation to practical underground conditions requires verification in an experimental mine (Cybulski, 1973).

The implications of these results are discussed in the following chapter.

6 IMPLICATIONS AND RECOMMENDATIONS

6.1 General

The Minerals Act (1991) of South Africa adopted the United Kingdom's 1958 regulations concerning the application of stone dust for the inhibition of coal-dust explosion propagation. However, accident investigations indicate that coal dust has participated in the propagation of explosions. The experimental evaluation of the regulations was therefore requested by the Government Mining Engineer. The explosion gallery at the G P Badenhorst Research Facility was specifically constructed and utilized for the evaluation.

The experimental procedures followed at similar research facilities use only weak or developing explosions which were considered unsuitable for this evaluation. A suitable experimental procedure therefore had to be developed.

Control of the five sequential steps of a coal-dust explosion (ignition, initiation, development, propagation and termination) was obtained in the gallery, resulting in both weak and strong propagating coal-dust explosions. These explosions were used to initiate a second coal-dust explosion in the gallery, and it was in this second zone that the total incombustible content, as stipulated in the Regulation, was applied, by adding stone dust.

The experimental procedure developed requires a total of six tests to evaluate stone dust, with an accuracy of 2 %. Weak and strong single coal-dust explosions establish the maximum effectiveness conditions for a stone dust, and weak and strong double coal-dust explosions provide the minimum effectiveness conditions of stone-dusting for a specific coal dust. Introduction of the regulated stone dust into the second fuel zone provides a measure of the effectiveness of the regulated stone dust, in terms of both quality and quantity.

It was found that for the coals (classified as "dangerous") used in this investigation, the regulated stone dust did not inhibit explosion development nor did it suppress explosion propagation, in terms of both the quality (size distribution) and quantity (amount) of the stone dust.

Had the gallery been longer, a longer coal-dust deposit could have been used, which would have allowed a greater spatial resolution. This was compensated for by increasing the dispersion of the dust and producing a stronger explosion earlier in the gallery by using shelves, which allowed the apparent length of the gallery to be experimentally increased.

Due to the inherent limitations of the gallery geometry, viz. the cross-sectional area, single entry and length, verification tests in an experimental mine must be done.

It would be expected that experimental mine investigations would provide sufficient evidence to indicate that Regulation 10:24 requires revision.

6.2 Recommendations

The results obtained under these specific conditions, indicate that Regulation 10:24 of the Minerals Act may need to be revised. To achieve this, the following additional investigations need to be undertaken:

- Confirmation of results with the spectrum of bituminous coals must be undertaken, in a relevant experimental mine.
- The quality and quantity of stone dust that will be sufficient to ensure the effectiveness of this safety measure must be determined.
- Control measures need to be developed to ensure that at the correct quantity and quality of stone dust are used in coal mines. The predominance of bord-and-pillar workings in South Africa, and thus the large open areas for dust deposition, mean that sufficient coal dust

is generally present in mines to allow the development of an initial coal-dust explosion. Mixing of the sample as required by the Regulation implies that no layering of coal-dust on stone dust has occurred. Mixing, however, neglects the layering of the stone dust and although the requirements for total incombustible content may be satisfied, the mixing effect results in a significant error in estimation of the hazard. Thus revision of the control measures is recommended.

- theoretical understanding of the inhibiting and suppressing mechanism of stone dust should be obtained to allow economical optimization of this preventative measure. In this regard, the Facility offers a unique opportunity for studying the mechanism, although it is certain to be a difficult task.

The two explosion strengths can be characterized as follows: The weak condition describes the capacity of the coal dust to maintain the minimum explosive conditions needed to propagate. Where the dispersion environment is unfavourable (i.e. on the floor), the heat transfer process is limited which is explained by the low coal:air ratio. Consequently heat transfer limitations restrict further propagation. The strong condition occurs where the coal:air ratio has been increased by placing the coal dust on shelves. The dominant limiting process under these conditions is the mass transfer during coal devolatilization, the reason being that the rate of mass transfer is limited by a specific environment. These two explosion strengths or conditions therefore provide a means of describing the heat and mass transfer limitations by experimentally changing the dispersion of the coal-dust deposit. An explosion can propagate in either a weakly developed or more highly developed form.

- Tests should be performed to establish the amount of additional stone dust that needs to be applied when methane is present, as it is known (Banhyegi and Egyedi, 1986) that an increase in the requirement for incombustible matter to suppress coal-dust explosions is necessary.
- Other types of stone dust should be evaluated.

This experimental approach affords the opportunity of improving the efficiency and cost-effectiveness of stone-dusting practices which can certainly lower the explosion hazard in South African collieries, this being the matter of immediate concern.

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Table A1 (cont'd)

Test No.	Methane chamber volume (m ³)	Flue non-fuel zone (m)	First coal dust deposit			Second non-fuel zone (m)	Second coal dust deposit			Flame length (m)
			Mass (kg)	Length (m)	Placement		Mass (kg)	Length (m)	Placement	
33	36	12.5	35	30	shelves	-	-	-	-	120
34	36	12.5	35	30	shelves	-	-	-	-	120
35	36	12.5	35	30	shelves	-	-	-	-	120
36	36	12.5	50	30	shelves	-	-	-	-	140
37	36	12.5	50	30	shelves	-	-	-	-	140
38	36	12.5	50	30	shelves	-	-	-	-	140
39	36	0	35	30	shelves	-	-	-	-	180
40	36	0	35	30	shelves	-	-	-	-	180
41	36	0	35	30	shelves	-	-	-	-	180
42	36	12.5	35	30	shelves	-	-	-	-	120
43	36	12.5	35	30	shelves	-	-	-	-	120
44	36	12.5	35	30	shelves	-	-	-	-	120
45	36	22	35	30	shelves	-	-	-	-	130
46	36	22	35	30	shelves	-	-	-	-	130
47	36	22	35	30	shelves	-	-	-	-	130
48	36	12.5	35	30	floor	-	-	-	-	110
49	36	12.5	35	30	floor	-	-	-	-	110
50	36	12.5	35	30	floor	-	-	-	-	110
51	36	12.5	35	30	shelves	40	35	30	shelves	120
52	36	12.5	35	30	shelves	30	35	30	shelves	120
53	36	12.5	35	30	shelves	20	35	30	shelves	150
54	36	12.5	35	30	shelves	10	35	30	shelves	300
56	36	12.5	35	30	shelves	14	35	30	shelves	200
57	36	12.5	35	30	shelves	14	35	30	shelves	200
57	36	12.5	35	30	floor	14	35	30	floor	200
58	36	12.5	35	30	floor	14	35	30	floor	200
59	36	12.5	35	30	floor	-	-	-	-	110
60	36	12.5	35	30	floor	-	-	-	-	110
61	36	12.5	35	30	floor	-	-	-	-	110

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APPENDIX A

Table A1

**Results of the tests performed for the establishing of the
experimental procedure for the evaluation of the
stone-dusting regulations**

Test No.	Methane chamber volume (m ³)	First non-fuel zone (m)	First coal dust deposit			Second non-fuel zone (m)	Second coal dust deposit			Flame length (m)
			Mass (kg)	Length (m)	Placement		Mass (kg)	Length (m)	Placement	
1	24	-	-	-	-	-	-	-	-	20
2	24	-	-	-	-	-	-	-	-	20
3	36	-	-	-	-	-	-	-	-	30
4	36	-	-	-	-	-	-	-	-	20
5	36	-	-	-	-	-	-	-	-	30
6	48	-	-	-	-	-	-	-	-	40
7	48	-	-	-	-	-	-	-	-	40
8	48	-	-	-	-	-	-	-	-	40
9	36	-	-	-	-	-	-	-	-	30
10	36	-	-	-	-	-	-	-	-	30
11	36	-	-	-	-	-	-	-	-	30
12	36	-	-	-	-	-	-	-	-	30
13	36	-	-	-	-	-	-	-	-	30
14	36	-	-	-	-	-	-	-	-	30
15	36	-	-	-	-	-	-	-	-	30
16	36	-	-	-	-	-	-	-	-	30
17	36	-	-	-	-	-	-	-	-	30
18	36	-	-	-	-	-	-	-	-	30
19	36	-	-	-	-	-	-	-	-	30
20	36	-	-	-	-	-	-	-	-	30
21	36	12,5	23	20	shelves	-	-	-	-	90
22	36	12,5	23	20	shelves	-	-	-	-	90
23	36	12,5	23	20	shelves	-	-	-	-	90
24	36	12,5	35	30	shelves	-	-	-	-	120
25	36	12,5	35	30	shelves	-	-	-	-	120
26	36	12,5	35	30	shelves	-	-	-	-	120
27	36	12,5	57	50	shelves	-	-	-	-	140
28	36	12,5	57	50	shelves	-	-	-	-	140
29	36	12,5	57	50	shelves	-	-	-	-	140
30	36	12,5	20	30	shelves	-	-	-	-	110
31	36	12,5	20	30	shelves	-	-	-	-	110
32	36	12,5	20	30	shelves	-	-	-	-	110

Table A1 (cont'd)

Test No.	Methane chamber volume (cc)	First non-fuel zone (m)	First coal dust deposit			Second non-fuel zone (m)	Second coal dust deposit			Flame length (m)
			Mass (kg)	Length (m)	Placement		Mass (kg)	Length (m)	Placement	
62	36	12.5	35	30	shelves	-	-	-	-	120
63	36	12.5	35	30	shelves	-	-	-	-	120
64	36	12.5	35	30	shelves	-	-	-	-	120
65	36	12.5	35	30	floor	14	35	30	floor	200
66	36	12.5	35	30	floor	14	35	30	floor	200
67	36	12.5	35	30	floor	14	35	30	floor	200
68	36	12.5	35	30	shelves	14	35	30	shelves	200
69	36	12.5	35	30	shelves	14	35	30	shelves	200
70	36	12.5	35	30	shelves	14	35	30	shelves	200

Table A2

Different coals tested using the recommended evaluation procedure for measuring the effectiveness of stone dust

Test No.	Methane chamber volume (m ³)	Fuel non-fuel zone (m)	First coal dust deposit			Second non-fuel zone (m)	Test zone Coal dust + stone dust					Flame length (m)
			Mass (kg)	Length (m)	Placement		Mass (kg)	Length (m)	Placement	% IC	% VM	
1	36	12.5	35	30	floor	14	35	30	floor	70	31	150
2	36	12.5	35	30	floor	14	35	30	floor	70	31	150
3	36	12.5	35	30	floor	14	35	30	floor	70	31	150
4	36	12.5	35	30	floor	14	35	30	floor	70	31	150
5	36	12.5	35	30	floor	14	35	30	floor	70	31	150
6	36	12.5	35	30	floor	14	35	30	floor	70	31	150
7	36	12.5	35	30	shelves	14	35	30	shelves	70	31	200
8	36	12.5	35	30	shelves	14	35	30	shelves	70	31	200
9	36	12.5	35	30	shelves	14	35	30	shelves	70	31	200
10	36	12.5	35	30	shelves	14	35	30	shelves	70	31	200
11	36	12.5	35	30	shelves	14	35	30	shelves	70	31	200
12	36	12.5	35	30	shelves	14	35	30	shelves	70	31	200
13	36	12.5	35	30	floor	-	-	-	-	-	36	130
14	36	12.5	35	30	floor	14	35	30	floor	-	36	200
15	36	12.5	35	30	floor	14	35	30	floor	75	36	180
16	36	12.5	35	30	shelves	-	-	-	-	-	36	150
17	36	12.5	35	30	shelves	14	35	30	shelves	-	36	200
18	36	12.5	35	30	shelves	14	35	30	shelves	75	36	180
19	36	12.5	35	30	floor	-	-	-	-	-	28	120
20	36	12.5	35	30	floor	14	35	30	floor	-	28	200
21	36	12.5	35	30	floor	14	35	30	floor	68	28	170
22	36	12.5	35	30	shelves	-	-	-	-	-	28	120
23	36	12.5	35	30	shelves	14	35	30	shelves	-	28	200
24	36	12.5	35	30	shelves	14	35	30	shelves	68	28	200
25	36	12.5	35	30	floor	-	-	-	-	-	30	110
26	36	12.5	35	30	floor	14	35	30	floor	-	30	200
27	36	12.5	35	30	floor	14	35	30	floor	70	30	140
28	36	12.5	35	30	shelves	-	-	-	-	-	30	120
29	36	12.5	35	30	shelves	14	35	30	shelves	-	30	200
30	36	12.5	35	30	shelves	14	35	30	shelves	70	30	200

% IC = Per cent incombustibles.

Author: Cook Patrick Michael.

Name of thesis: The inhibition of coal-dust explosions with stone dust in a large scale explosion gallery.

PUBLISHER:

University of the Witwatersrand, Johannesburg

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