Safety In Mines Research Advisory Committee

SIMRAC

Final Project Report

Title: ALTERNATIVE INERTING AGENTS

Author/s: J J L DU PLESSIS

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DRAFT FINAL REPORT

Alternative inerting agents

J J L Du Plessis

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Executive Summary

The inerting of the immediate face area to prevent the ignition of coal dust and an ensuing coal dust explosion is one of the primary measures in the control of underground explosions. However, the problems associated with the application of stone dust during the production cycle are numerous. These include poor visibility and high stone dust concentrations in the air for a period after application.

This project was launched to determine whether other inert material might be suitable to replace or complement the stone dust. The materials investigated were two different types of fly ash, two types of stone dust, water and calcium sulphate.

The test materials were initially evaluated on a small scale in a 40-ℓ explosion vessel to find out if they would be effective alternatives. The increasing order of effectiveness found for the materials was water, calcium sulphate, fly ash 2, the stone dusts and fly ash 1 respectively. When methane was added, the sequence remained essentially unaltered, except that the stone dusts then outperformed fly ash 2.

A number of tests were conducted in the 200-m test gallery for different test scenarios. The materials tested were the same, except that calcium sulphate was not evaluated.

In these tests, water proved to be effective as an inerting material directly in the face area but when tested in the double strong explosion, it failed even at 60 per cent TIC. Stone dust again proved to be effective at 80 per cent TIC. The fly ashes proved effective at 85 per cent TIC in some of the tests, but failed in others.

From all the tests, as well as from the literature study, it became apparent that:

- stone dust is the most widely used and accepted inerting material;
- water will not replace stone dust;
- fly ash requires closer evaluation; and
- calcium sulphate should be evaluated further to prove the small-scale test results.

As the health studies of both fly ash and calcium sulphate proved inconclusive it is also recommended that health studies be conducted to relate the silica contents to the carcinogenic activity.

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Glossary of abbreviations, symbols and terms

Abbreviations

Total Incombustible Content	TIC
total inert content	tic
relative density	RD

Symbols

micron metre	µm

Terminology

Double floor explosions

Coal dust was distributed in two fuel zones on the floor of the 200 m test gallery. In the first fuel zone (20 - 50 m from the closed end of the test gallery), 35 kg of coal dust was distributed and in the second fuel zone (64 - 94 m from the closed end), a further 35 kg of coal dust was distributed. The inert material was mixed into the coal dust in both fuel zones.

Double weak explosion

Coal dust was distributed in two fuel zones on the floor of the 200 m test gallery. In the first fuel zone (20 - 50 m from the closed end of the test gallery), 35 kg of coal dust was distributed and in the second fuel zone (64 - 94 m from the closed end), a further 35 kg of coal dust was distributed. The inert material was only mixed into the coal dust in the second fuel zone.

Double shelves explosion

Coal dust was distributed in two fuel zones on shelves. The shelves were installed from 20 to 50 m and again at 64 to 94 m from the closed end of the gallery. Coal dust (35 kg) was distributed in each of the shelf fuel zones. The inert material was mixed into the coal dust in both fuel zones.

Double strong explosion

Coal dust was distributed in two fuel zones on shelves. The shelves were installed from 20 to 50 m and again at 64 to 94 m from the closed end of the gallery. Coal dust (35 kg) was distributed in each of the fuel zones. The inert material was mixed into the coal dust only in the second fuel zone.

1 Introduction

Stone dust is widely accepted and used to inert coal dust and to prevent underground coal dust explosions. The first investigation into the use of stone dust to inhibit coal dust explosions has been attributed to the French investigator, Taffanel.

Over the years, a large number of studies have been conducted to determine the effectiveness of alternative inerting agents. These tests were conducted at all the major research centres, including Tremonia (Germany), Bruceton (United States of America), the Barbara Experimental Mine (Poland), Buxton (United Kingdom) and the Kloppersbos Research Facility (South Africa).

Most of this work centred on the ability of water, stone dust and clay slate dust to inhibit the propagation of coal dust explosions and on the limits of effective operation. In recent years, various other methods involving the inhibition of coal dust dispersion as an effective means of preventing coal dust explosions have been investigated.

SIMRAC identified the need to re-examine some of the alternative inerting agents, particularly their possible use in the face area.

The main objective of this project was therefore to determine the possible use of alternative inerting agents in the face area.

1.1 Literature review

Material is applied for two distinctly different purposes in preventing coal dust from participating in an underground explosion, namely as an inerting agent and as an agent to prevent the dispersion of dust.

Inerting agents include the well-known stone dust, clay slate dust, gypsum and various chemical dusts. Binding and wetting agents are primarily used to bind coal dust and thus prevent the dispersion of coal dust in the air. Water acts as a combination agent in that it can inertise coal dust and will also inhibit its dispersion.

As this report deals with alternative inerting agents, only limited reference will be made to stone dust in the literature review. Tests conducted worldwide have led to various general conclusions regarding the effectiveness or lack of effectiveness of stone dust and other inerting agents. It is widely held that effectiveness is a function of:

* coal dust particle size (Hertzberg & Cashdollar, 1987 and Hertzberg et al., 1981)
* the strength of the initiator used (Hertzberg & Cashdollar, 1987)
* the experimental procedure used (Hertzberg & Cashdollar, 1987)
* the presence of a coal dust layer,

where effectiveness is measured in terms of the amount of material required to inhibit the propagation of a coal dust explosion.

This is normally measured as the TIC, which is calculated as the total of the inert material combined with the ash and water content of the coal.

One of the most extensive studies conducted on the effectiveness of inhibiting dusts was done by the USBM (Hertzberg, 1982). In this project 37 different inhibitors were investigated. The results of this investigation compared favourably with those of tests done in experimental mines (Gruner, 1975 and Richmond, 1979), as is shown in Table 1.1a.

Table 1.1a

Inerting requirements for Pittsburgh seam coal

Inhibitor	**Weight – percentage required to inert**		
	8-ℓ Chamber	**2-m-Diameter gallery**	**Experimental mine**
$KHCO_3$ (Purple K)	75 – 80	70 – 75	67 - 73
$CaCO_3$ (Rock dust)	~ 60	65 – 70	67 - 70
KCl (Super K)	50 – 55	20 – 30	35 - 40
NaCl (BCD)	45 – 50	18 – 24	35 - 40
$NH_4 H_2 PO_4$ (ABC)	18 – 20	10 – 15	18 - 24

In summary, it was suggested that the effectiveness of the inhibiting salts correlated better with their anion than with their cation components. The approximate order of anion effectiveness is: phosphates > halides > carbonates.

Tests conducted at Lake Lynn Experimental Mine (Greninger et al., 1990) on Pittsburgh coal showed that a coal/stone dust mixture with a TIC between 80 per cent and 82 per cent was required to prevent explosion propagation.

Although clay slate dust was used in the past, this material was subsequently abandoned on account of its high free-silica content. British researchers (Mason & Wheeler, 1933 and 1936) carried out investigations to determine the effectiveness of limestone, clay slate and other stone dusts. It was found that for coal dust with a volatile matter content of 33,3 per cent and tested in a 100-m-long gallery with a diameter of 1,22 m, the following limit percentages (see Table 1.1b) were required to render coal dust incapable of propagating an explosion:

Table 1.1b

Inert limit percentages

Slate	67,5 %
Diatomite	62,5 %
Anhydrite	60,0 %
Limestone	57,5 %
Dolomite	57,5 %
Gypsum	40,0 %

A large number of tests were carried out at the Barbara Experimental Mine (Cybulski, 1954) to verify the above results. In these tests limestone, clay slate and dolomite dusts were evaluated. The final conclusion from this work was that there is no experimental proof that any one of the dusts is better than any other, and that the dusts are equally effective as means of preventing propagating explosions.

In a study (Hartman et al., 1956) conducted during 1955, limestone dust and water were premixed to form a slurry. The experimental results were summarised by Nagy (1981) as follows:

- A premixed slurry of limestone dust and water applied through a nozzle disperses very little dust in the air. About 26,5 to 30,3 ℓ (7 to 8 US gallons) of water per 45,4 kg (100 lbs.) of limestone was required to form a free-flowing slurry.

- Equally effective was limestone dust mixed with water at the nozzle. Six gallons (22,7 ℓ) of water mixed with 100 lbs. (45,4 kg) of limestone dust was found to give a satisfactory mixture for nozzle application.

- At least 1,8 kg (4 lbs.) of wetted rock dust was needed per linear foot of entry to cover the ribs and roof completely.

- About 80 to 85 per cent of the wetted rock dust adhered to the rib and roof surfaces. In comparison, during normal dry rock-dusting by machine, at most only 30 to 35 per cent adheres to the ribs and roof.

- During dry rock-dusting, the airborne dust concentration 25 ft (7,62 m) downstream was as high as 5 000 million particles per cubic foot (± 142 million particles per cubic metre); 100 ft (30,5 m) downstream, the count was about 3 000 million particles per cubic foot (± 85 million particles per cubic metre). When the slurry was applied, the dust count was less than 0,5 per cent of the above values; and when limestone dust and water were mixed by a nozzle, the dust count ranged from 1 to 10 per cent for the above values.

- The time required for wetted rock dust to dry depends on the relative humidity and the airflow. At normal airflow, when the relative humidity of the air was below 80 per cent, the rock dust dried in one to three days; when the humidity was 80 to 90 per cent, the dust dried in about one week; and at still higher humidities, several weeks were required.

- Surface-treated, moisture-resistant limestone was considerably more dispersible after drying than ordinary limestone. In an effort to increase the dispersibility of ordinary limestone, which remained somewhat caked after drying, about 25 different powders were mixed with the limestone before wetting. Several of them appeared to increase the dispersibility after drying, but none was completely effective in preventing caking of the limestone.

- Single-entry explosion tests were done to determine the effectiveness of the wetted limestone dust.

The overall results of the investigation were as follows:

- Dry rock dust distributed by machine was more effective than wetted rock dust.

- Wetted limestone dust was more effective after complete drying than after partial drying.

- Dry rock dust distributed on the floor and wetted rock dust applied to the rib-roof surfaces provided protection against explosion. When the rock-dusted zones started 50 ft (15,24 m) from the face, explosions were arrested readily, except when the rock-dusted surfaces were covered with a heavy layer of float coal dust.

- When the rock-dusted zones started 100 ft (30,5 m) out by the face, difficulty was encountered in stopping explosions by applications of either dry or wetted rock dust.

Ammonium phosphate and salt (NaCl) were tested in an experimental gallery by the USBM (Nagy, 1981). Ammonium phosphate is the main constituent of dry chemical powder extinguishers and is a chemical inhibitor that interacts with the combustion process. As such, it is considerably more effective than stone dust.

A recent study (Jensen & O'Briene, 1997) conducted in Australia suggested the addition of a small quantity of mono ammonium phosphate to stone dust to enhance its effectiveness. It was also suggested that it would be more dispersible than stone dust as its relative density (1,803) is significantly lower than that of stone dust.

Salt was tested by the USBM (Greenwold et al., 1940) as an alternative to stone dust and was found to be two to six times more effective as a flame suppressant than stone dust on a weight basis. The major disadvantage of salt is that it is hygroscopic and highly corrosive.

The effectiveness of water as an inerting agent was studied (Mitchell & Nagy, 1962) in 1962. It was found that water was 2,2 times more effective on a weight basis than limestone dust and that water provided equal protection between 30 and 36 per cent. Nagy (1981) summarised the findings of the report, stating that water is not recommended as the sole safeguard. This statement was based on the following reasons:

- Water evaporates readily from moistened coal. Thus, in a passageway where there is adequate water in the dust, changes in the weather or the ventilation system could dry the dust and make it unsafe within a short period of time. Where adequate rock dust has been applied, drying is not a factor.

- The water content of mine dust along an entry, or in floor, rib or roof deposits may vary appreciably. There may be sufficient moisture at one location but a deficiency a short distance away. With generalised rock-dusting applied systematically, variation in incombustible content is less likely.

- Coal dust, although not wetted by water, adheres better to wet than to dry rib and roof surfaces. Fresh coal deposited from the air current will remain dry even though the undersurface is wet; hence, the explosion hazard in a wet area may be intensified.

- Visual observation is a poor method for estimating the moisture content of mine dusts. The general tendency is to overestimate the moisture content. As an example, an experienced mining engineer was asked to collect wet, wet-to-damp, and damp-to-dry mine dust samples. Analysis showed the respective samples contained 11, 8 and 4,4 per cent moisture, i.e. these dusts were in the dry range.

- Where methane is present in the ventilating current, water as an inert material does not compensate for this additional hazard and generalised rock-dusting must be used.

- Standing pools of water in a passageway do not provide protection against explosion. Water on the floor is rarely dispersed effectively to assist in quenching explosion flames. For example, in the Kinlock Mine explosion of 21 March 1929, explosion flames traversed passageways in which there were 200 ft or more of standing pools of water on the floor.

- Moisture from the ventilating-air current will not make coal dust wet even though the humidity is high. Wetting agents are effective in increasing the rate of absorption of water by dust.

Other results from the study of explosion control (Nagy, 1981) showed the following:

- Excessive deposits of coal dust on the rib and roof surfaces can be washed to the floor by water. During the washing operation, only some of the coal dust becomes wetted.

- The use of rock dust or water barriers should be considered where it is difficult to rock-dust in wet locations.

- When sampling mine dust for adequacy of moisture, separate rib, roof and floor samples should be collected. A moisture deficiency in any of the dust samples indicates that rock dust should be applied.

2 40-ℓ Explosion test results

The explosibility index, also referred to as the K_{ex} value, was developed in Germany in the early 1960s and is still used in South Africa. K_{ex} is defined as the ability of coal dust particles to propagate a coal dust explosion (Knoetze, 1991) and its value is indicative of the damage potential of a particular coal dust. A coal dust explosion will occur when the finely divided combustible matter is dispersed into an atmosphere containing sufficient oxygen, and an ignition source with appropriate energy is introduced (Cashdollar & Hertzberg, 1989).

According to the German standard, a coal dust can be assessed as being either dangerous or safe, depending on whether the average K_{ex} value of the coal sample is more than 95 bar/s or less than 70 bar/s respectively. Further testing in a gallery would be recommended for coal samples with K_{ex} values between 70 bar/s and 95 bar/s. A coal dust with a K_{ex} value above 95 bar/s will participate in the propagation of underground explosions.

The K_{ex} value is determined using the following equation:

$$K_{ex} = \left(\left(\frac{dP}{dt} \right)_{\max} x \left(\frac{dP}{dt} \right)_{av} \right)^{0,5}$$

where: $(dP/dt)_{max}$ is the maximum rate of pressure rise

$(dP/dt)_{av}$ is the average rate of pressure rise

The propagation of a coal mine explosion involving coal dust depends on a conducive environment with respect to the following main factors:

- Sufficient heat radiation must be present to ignite unreacted coal particles.

- The coal dust must be dispersed to form a dust cloud with an explosive concentration.

- The size distribution of the particles must be within the explosive range (Knoetze et al., 1993).

Research conducted by the CSIRO Division of Fossil Fuels in Australia showed that fly ash from coal-fired power stations almost always contains a small proportion of unburnt char and this depends not only on the combustion conditions, but also on certain conditions of the coal, such as the particle size and coalification rank (Shibaoka, 1984). The level of unburnt char in a fly ash has been regarded as one of the indicators of pulverised-fuel combustion performance (Shibaoka, 1986), i.e. if the level of unburnt char is high, the test results are not expected to be the same as for when there is no unburnt char.

2.1 Sample preparation

The coal dust used for the tests in the 40-litre vessel was the standard coal dust used by the Facility for explosion testing. The sample was milled to a standard particle size distribution with the following properties:

d_{50} = 20± 2 μm
topsize of 125 μm.

The following standard formula was used for the calculations relating to the mass of inerting materials required for tests in the explosion vessel and the 200-m test tunnel.

The percentage weight of the inert material was calculated as follows (Michelis et al., 1987):

$$\%\,Inert\ material = \frac{(\%TIC - \%Ash - \%Water)}{1 - \frac{(\%Ash + \%Water)}{100}}$$

where: % TIC = percentage total incombustible content

% Ash = ash inherent in the coal dust

% Water = water content inherent in the coal dust

In these calculations, inherent percentages of ash and water in the coal dust are taken into account when the calculations of the TIC are made.

2.2 Sample properties

2.2.1 Fly ashes

The fly ashes used for the tests were delivered from the power stations to the Facility. A particle size analysis and chemical analyses were conducted on each fly ash. They were found to have a median particle size, M, of 23 µm, a topsize of 500 µm, an RD of 2,09 and 0,5 per cent unburnt char for fly ash 1; and a median particle size, M, of 23 µm, a topsize of 600 µm, an RD of 2,11 and 1,04 per cent unburnt char for fly ash 2. The fly ashes were tested as received.

2.2.2 Stone dusts

The Type 1 stone dust was used as received. A particle size analysis was conducted and Type 1 was found to have a median particle size of 18 µm, a topsize of 180 µm and a RD of 2,86.

The Type 2 stone dust was also used as received. A particle size analysis showed that Type 2 had a median particle size of 28 µm, a topsize of 550 µm and a RD of 2,59. The particle size distribution of the inerting materials used is shown in Appendix 1.

2.2.3 Calcium sulphate

The calcium sulphate ($CaSO_4$) tested for its potential for inerting coal dust was delivered to the Facility in an aqueous form. The properties of the received material are shown in Table 2.2.3. The material was oven-dried overnight at 100 °C. The dried material was then sieved through a 500 µm sieve to remove the iron oxide resin contamination. A chemical analysis conducted on the prepared $CaSO_4$ material showed that it had a pH of 2,06 and a RD of 2,21.

Table 2.2.3

Properties of calcium sulphate

Properties	Cation sludge	Anion sludge
Chemical formula	$CaSO_4\ 2H_2O$ ± 8 % H_2SO_4	$CaSO_4\ 2H_2O$ $Ca\ (OH_2)$
RD	1,3	1,3
Solid mass %	50,0	50,0
PH	0,5	12,0

Both these sludges were combined and thoroughly mixed.

2.3 Average results

The average explosibility results (K_{ex}) of the tests conducted in the 40-litre explosion vessel with the different inerting materials are shown in Table 2.3a. The tests were conducted with six different percentages of the inerting materials, i.e. from 35 to 80 per cent TIC. Three tests were conducted for each concentration and the arithmetic mean was then calculated, as reported in Table 2.3a. Calcium sulphate was used as the basis for determining the K_{ex} variation as shown in Table 2.3a.

The highest K_{ex} value was obtained when fly ash 1, at a concentration of 35 per cent TIC, was tested. This mixture was found to be within the explosive range, i.e. above 95 bar/s. When a 35 per cent concentration of fly ash 2 was tested, lower test results were obtained and these were within the safe range. Fly ash 1 tested above fly ash 2 throughout the test series. For the tests with a TIC level > 45 per cent, the K_{ex} values were within the safe range and no explosion would be expected to propagate under these conditions.

The difference between the two fly ashes, 1 and 2, tested in the 40-litre explosion vessel with no methane introduced is shown in Figure 2.3a. The plot shows the trends in the results for the different percentages of fly ash 1, fly ash 2 and stone dusts Type 1 and Type 2 tested. There is a tendency for the effectiveness of both fly ashes to increase with increasing percentage TIC, with fly ash 2 testing better than fly ash 1 throughout the test series. Equal effectiveness for both fly ash 1 and fly ash 2 was obtained at the 75 and 80 per cent TIC concentrations.

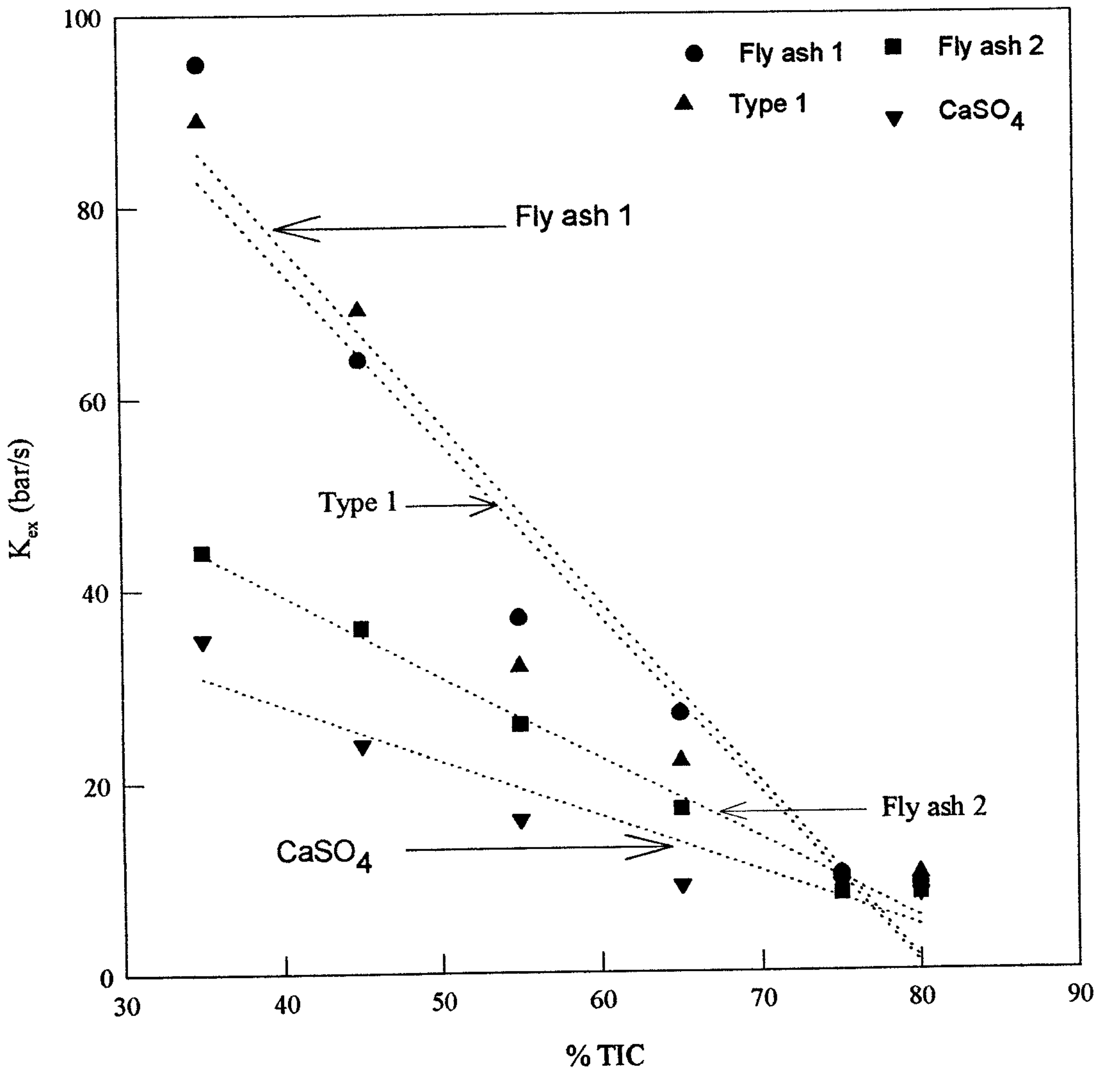


Figure 2.3a: Plot of tests conducted without methane

Table 2.3a

Average results for tests conducted in the 40-ℓ vessel

Inert Concentration % (TIC)	Inert Material	K_{ex} (bar/s)	K_{ex} Variation
35	Fly ash 1	95	+60
	Fly ash 2	44	+09
	Type 1	89	+54
	Type 2	80	+45
	$CaSO_4$	35	0
45	Fly ash 1	64	+40
	Fly ash 2	36	+12
	Type 1	69	+45
	Type 2	64	+40
	$CaSO_4$	24	0
55	Fly ash 1	37	+21
	Fly ash 2	26	+10
	Type 1	32	+16
	Type 2	49	+07
	$CaSO_4$	16	0
65	Fly ash 1	27	+18
	Fly ash 2	17	+08
	Type 1	22	+13
	Type 2	29	+20
	$CaSO_4$	9	0
75	Fly ash 1	10	+ 1
	Fly ash 2	8	- 1
	Type 1	10	+ 1
	Type 2	12	+ 3
	$CaSO_4$	9	0
80	Fly ash 1	9	+ 1
	Fly ash 2	8	0
	Type 1	10	+ 2
	Type 2	9	+ 1
	$CaSO_4$	8	0

When a 35 per cent inert concentration (TIC) of stone dust, for both Types 1 and 2, was tested, lower test results were obtained and these were between the explosive and safe ranges. Similar results were obtained for Type 2 and fly ash 1 when tested, except for the tests at 45 and 55 per cent TIC. For the tests with TIC concentrations ≥ 45 per cent, results show that the mixtures were within the safe range; fly ash 2 produced lower test results than fly ash 1, stone dust Type 1 and Type 2.

The results show that calcium sulphate is more effective than the other inerting materials tested in most of the inert concentration ranges.

Further tests were conducted in the 40-litre explosion vessel with fly ash 1, fly ash 2 and Type 1 stone dust in an environment containing a 1 per cent air/methane mix. The average test results are shown in Table 2.3b. Fly ash 1 produced higher K_{ex} values for all the percentages tested.

However, at 35 per cent TIC, all the inert materials tested are within the explosive range. Also, at 35 per cent TIC, the K_{ex} value for fly ash 2 was below that for fly ash 1 and Type 1 stone dust. The effectiveness of all three inerting materials (fly ash 1, fly ash 2 and Type 1 stone dust) increased with an increasing percentage TIC. The results indicated that stone dust Type 1 is more effective than either fly ash 1 or fly ash 2 in hybrid explosion conditions.

Table 2.3b

Average results for tests conducted with 1 % air/methane mixture

Inert Concentration % (TIC)	**Inert Material**	**K_{ex} (bar/s)**	**K_{ex} Variation**
35	Fly ash 1	102	+58
	Fly ash 2	95	+51
	Type 1	98	+54
	$CaSO_4$	44	0
45	Fly ash 1	77	+36
	Fly ash 2	68	+27
	Type 1	66	+25
	$CaSO_4$	41	0
55	Fly ash 1	77	+48
	Fly ash 2	44	+15
	Type 1	35	+06
	$CaSO_4$	29	0
65	Fly ash 1	35	+21
	Fly ash 2	29	+15
	Type 1	27	+13
	$CaSO_4$	14	0
75	Fly ash 1	19	+11
	Fly ash 2	14	+06
	Type 1	9	+01
	$CaSO_4$	8	0
80	Fly ash 1	8	- 1
	Fly ash 2	8	- 1
	Type 1	8	- 1
	$CaSO_4$	9	0

Figure 2.3b shows the trends drawn from the results for fly ash 1, fly ash 2, Type 1 stone dust, and calcium sulphate when tested within an environment containing a 1 per cent air/methane mix. The plot shows that fly ash 1 was the least effective material for inerting the hybrid explosion created in the vessel.

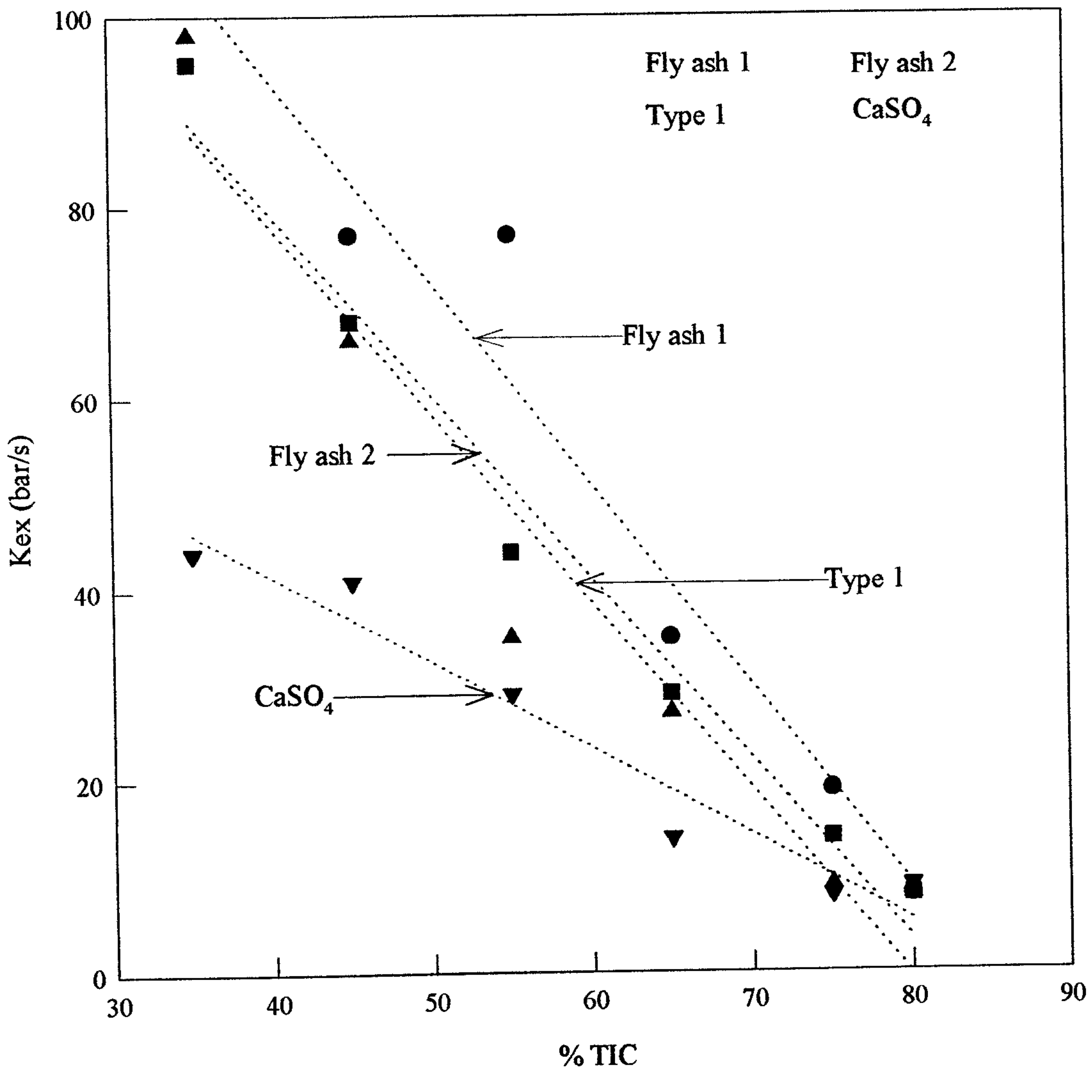


Figure 2.3b: Plot of inerting materials tested with 1 % air/methane mixture

As proved in the previous set of tests, the calcium sulphate again outperformed the other inerting agents. $CaSO_4$ proved to be effective even at the 35 per cent TIC level when compared with the other inert materials.

The average results for the tests conducted with water in the 40-ℓ explosion vessel are shown in Table 2.3c.

Table 2.3c

Average results for tests conducted with water

	No CH_4/Air	**1 % CH_4/Air**
Inert Conc. % (TIC)	**K_{ex} (bar/s)**	**K_{ex} (bar/s)**
15,0	141	127
17,5	62	119
20,0	43	97
22,5	15	36
25,0	6	31

In the tests with water added to the coal dust, difficulty with the effective dispersion of the mixed dust was observed. Figure 2.3c shows the plot for the tests conducted with water as an inerting material.

3 200-m Test gallery results

The test gallery is 200 m long, 2,5 m in diameter and is closed at one end (Cook, 1993). It is constructed of mild steel with walls 19 mm thick. The interior is smooth-walled. The gallery is equipped with flame, temperature, and static (spaced every 10 m along its length) and dynamic sensors with data-collection stations. A diagrammatic presentation of the gallery set-up is shown in Appendix 2.

3.1 Evaluation of the effect of water in the face area

To evaluate the effect of water in inhibiting the propagation of a coal dust explosion, a number of tests were conducted.

In the initial tests, water was added to both fuel zones, on the floor and on the shelves. The purpose was to simulate conditions underground where the immediate face area is

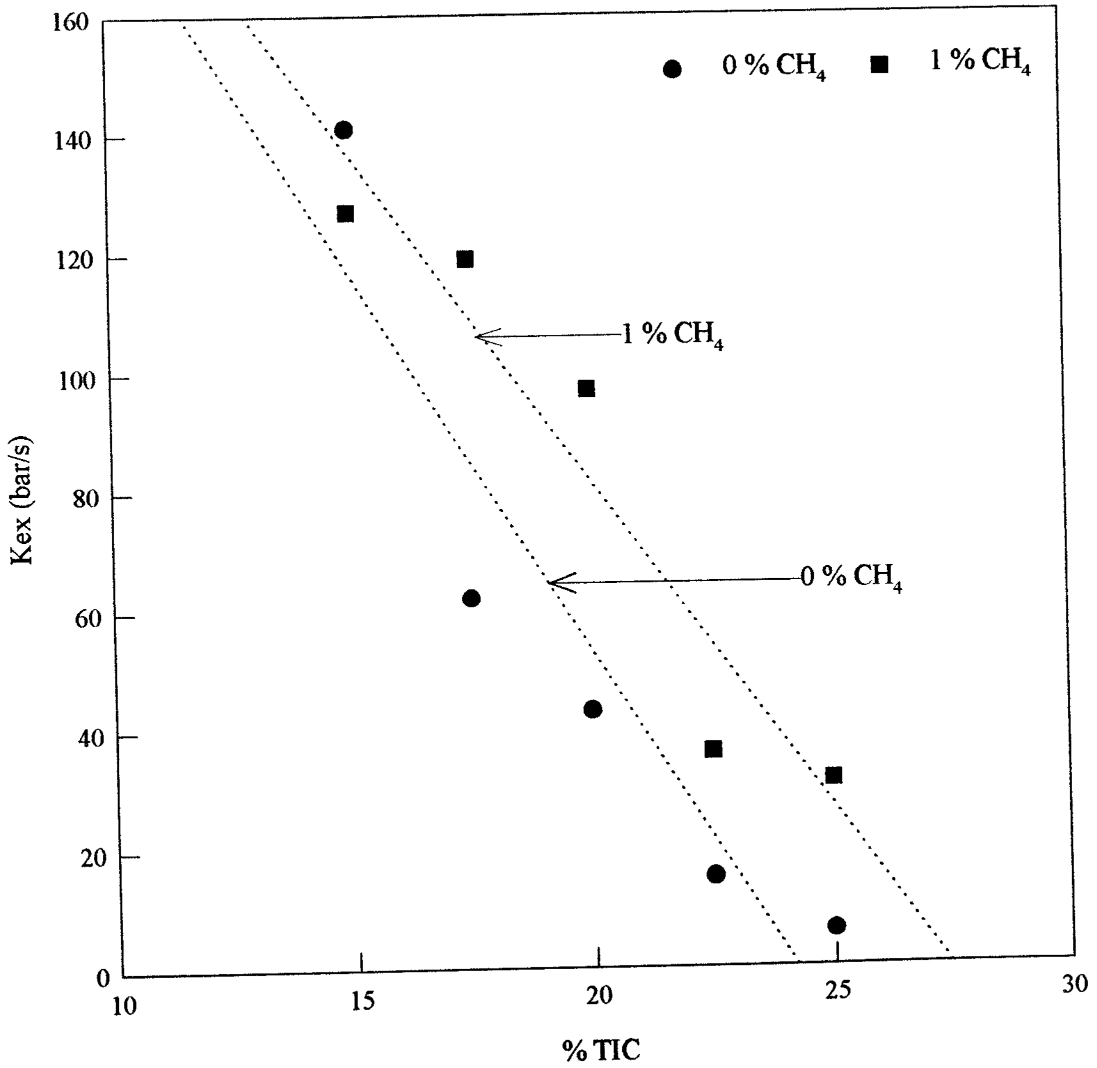


Figure 2.3c: Plot of water as an inerting material

wet. The results of the tests on the two fuel zones on the floor are shown in Table 3.1a.

Table 3.1a

Results of tests with water added to both fuel zones on the floor

Test No.	% TIC	Static pressure (kPa)	Flame distance (m)	Visual flame at gallery mouth
5	20	68	>200	Yes
8	20	59	150	No
9	30	61	70	No
10	30	40	50	No
13	35	40	30	No
14	35	43	30	No

At a 35 per cent TIC, there was no participation of coal dust in the explosion and the flame indicated is only that of the methane explosion.

Further tests were conducted with water added to both fuel zones on the shelves. In these tests, the positioning of the coal dust simulates the usual distribution of coal dust, such as dust on top of the continuous miner and the shuttle car. The results of these tests are shown in Table 3.1b.

Table 3.1b

Results of tests with water added to both fuel zones on the shelves

Test No.	% TIC	Static pressure (kPa)	Flame distance (m)	Visual flame at gallery mouth
6	20	133	>200	Yes
7	20	137	>200	Yes
11	30	114	>200	Yes
12	30	83	>200	Yes
16	35	53	>200	Yes
17	35	179	>200	Yes
19	40	40	20	No
20	40	36	20	No

The results show that there is a decrease in the static pressure as the water and percentage TIC increase (Tables 3.1a and 3.1b). Furthermore, a minimum of 40 per cent TIC was necessary to prevent the ignition of coal dust in the first fuel zone and thus inhibit the propagation of a coal dust explosion in the second fuel zone. The flame lengths shown in tests 19 and 20 are only those of the methane-initiated explosions.

3.2 Double weak explosion test results

In these tests, the double weak coal dust explosion was used to evaluate the effectiveness of the inert material in preventing a coal dust explosion from propagating. The coal dust was distributed on the floor of the 200-m test gallery. Two fuel zones were utilised with 35 kg of coal dust distributed in the first fuel zone (20 - 50 m). In the second fuel zone (64 - 94 m from the closed end of the gallery), the inert material was mixed with a further 35 kg of coal dust.

The results obtained for the tests using fly ash 2 are shown in Table 3.2.

Table 3.2

Results for fly ash 2 in the double weak explosion

Test No.	**% TIC**	**Static pressure (kPa)**	**Flame distance (m)**	**Visual flame at gallery mouth**
36	80	78	100	No
37	80	76	100	No

This type of fly ash proved to be effective at a TIC concentration of 80 per cent.

3.3 Double strong explosion test results

For these tests, shelves were installed in the gallery to allow coal dust to be placed in an elevated position to enhance dust distribution. Wall brackets, three per side, were installed every 2 m to support wire-mesh shelving, 30 m long. The shelves were installed from 20 to 50 m and again at 64 to 94 m from the closed end of the gallery. Paper was laid on the shelves and the coal dust deposited on this paper. A strong double coal dust explosion (Cook, 1993) with 35 kg of coal dust deposited in each fuel zone was used as the baseline explosion. In the evaluation tests, either fly ash, stone dust or water was introduced into the second coal dust deposit. The coal dust and inerting material were thoroughly mixed.

In the first fuel zone, 35 kg of pure coal dust was distributed on the first set of shelves and in the second fuel zone 35 kg of coal dust mixed with inert material. The materials evaluated were water and two types of fly ash. A control test was conducted to show that stone dust (Type 2) is effective at 80 per cent TIC.

The results obtained are shown in Table 3.3.

Table 3.3

Double strong explosion test results

Test No.	**Type of inert material**	**% TIC**	**Static pressure (kPa)**	**Flame distance (m)**	**Visual flame at gallery mouth**
15	None	17	156	>200	yes
21	water	40	94	>200	yes
22	water	45	73	>200	yes
23	water	50	114	>200	yes
24	water	60	103	>200	yes
25	water	60	100	>200	yes
38	fly ash 2	80	117	>200	yes
39	fly ash 2	85	110	>180	no
42*	none	16	212	> 200	yes
45*	fly ash 1	80	151	> 200	yes
46*	fly ash 1	80	160	> 200	yes
55*	Type 2	80	160	100	no
78*	fly ash 2	80	124	> 200	yes
79*	fly ash 2	85	152	80	no
80*	fly ash 2	82	137	> 200	yes

* 1996 Test Results (Mthombeni et al., 1996 and Du Plessis & Vassard, 1996)

In the baseline explosion, a high static pressure was created. In the tests with water, the static pressure was reduced to nearly half of the baseline value. When the tests were stopped at 60 per cent TIC, the flame was still propagating throughout the tunnel.

The tests with fly ash proved that a concentration of 80 per cent TIC is inadequate to prevent further propagation. At a concentration of 85 per cent TIC, fly ash 2 proved to be successful in one test (test no. 79) but failed to ensure total inhibition in a later test (test no. 39): coal dust particles reignited in the tunnel long after the initial propagation had stopped. (See Appendix 3.)

This phenomenon is unexplained but might be attributable to the glowing of smaller ash particles. The flame does not reach the mouth of the tunnel as the vacuum created behind the explosion sucks the explosion back into the tunnel.

4 Health-related implications

The importance of the influence of the individually evaluated inerting agents was investigated in a literature review.

4.1 Health implications of using fly ash

In an article in "Analytical Chemistry" of September 1980 the controversy with regard to the content of crystalline silica in volcano ash was debated. In short, the controversy between independent laboratories relates to the analytical methods used by them to determine the silica (SiO_2) contents. Silica is of primary concern in the formation of silicosis and progressive massive fibrosis (PMF). A major problem in the analysis is the process by which silica and silicates are separated. This article highlights the problems and difficulties encountered with the above and as such the toxicity of ash. Similar problems are encountered with fly ash.

Comprehensive work with regard to the pathogenicity of fly ash was conducted by Eskom in the early 1990s (Simon, et al 1992). The main objective was to investigate the possible involvement of fly ash in causing silicosis.

This investigation involved:

1) a literature survey of medical research

2) information with regard to the chemical and mineral composition and the particle size distribution of fly ash, with specific reference to work conducted by Bosch and Wills in 1990

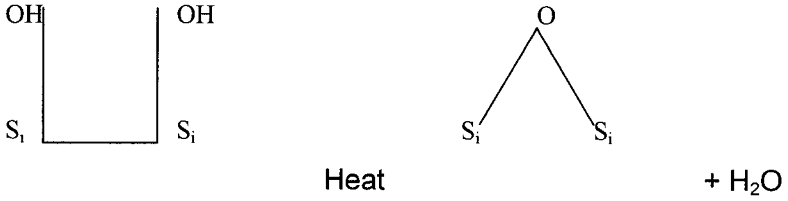
3) chest x-ray screening of all employees from a specific power station.

The main conclusion from this extensive study was that the quartz in fly ash does not cause silicosis. These findings are based upon:

- Human x-ray surveys
- Animal experiments
- Chemical studies.

The main reason for this conclusion lies in the fact that the furnace heating of quartz results in:

a) crystal surface chemical change (loss of silanol groups)



b) Precipitation of iron, aliminium and trace elements on the crystal surface.

This was illustrated in a study by Raask and Schilling, 1980. Both of the above changes neutralize the damaging properties of the quartz crystals.

In Poland, Wozniak et al., 1988 conducted a survey and reported on it in three papers. He found that over an eight-year period, 12 cases of pneumoconiosis were reported. However, no mention was made of whether these patients had been exposed to other dusts.

In these studies the effect on experimental animals was also noted. Fly ash appeared to have caused far less fibrogenic activity than pure silica. Woztozak concluded that the small percentage of occupational respiratory system disease noted within a population occupationally exposed to high concentrations of fly ash confirms the experimentally obtained data, i.e. that fly ash exhibits weak fibrogenic properties.

In another study, Kaw and Khanna (1988) exposed rats initially to fly ash and later to respirable quartz. By way of comparison, another group of rats was exposed to respirable quartz alone. In summary they concluded that:

1) exposure to small amounts of fly ash does not alter pulmonary histopathology

2) lungs pre-exposed to fly ash retarded the fibrotic reaction of quartz exposure.

In a study conducted by the Potchefstroom University for CHO by Dr C.L. Dreyer, (1994) in association with the National Centre for Occupational Health, it was concluded that: "Fly ash is not a fibrogenic dust such as silica".

In 1980 Bonnel et al. published a review about British fuel ash and concluded that fly ash should be treated as nuisance dust and was unlikely to result in pneumoconiosis provided a level of less than 10 mg/m^3 was adhered to.

The presence of crystalline silica in fly ash means that caution should be exercised regarding the desorption and definition of a nuisance dust. If crystalline silica is present at levels below 5 %, treating it similarly to stone dust should be sufficient as studies clearly indicate that it does not lead to an increase in carcinogenic activity when closely associated with fly ash per se.

4.2 Health implications of using calcium sulphate

Calcium sulphate may be considered as a nuisance dust, depending on its silica content. The following exposure limits are recommended by leading health agencies:

Table 4.2

Calcium sulphate exposure levels

Agency	TWA limit (mg/m^3)	Dust concentration	Other requirements
OSHA	5	Respirable	-
OSHA	15	Total	-
ACGIH	10	Total	No asbestos and <1 % crystalline silica
NIOSH	5	Respirable dust	10-hour TWA
NIOSH	10	Total	10-hour TWA

The inhalation of gypsum has been reported to cause irritation of the respiratory tract, chronic rhinitus, laryngitis, phoryngitis, impaired use of smell and taste, epistaxis and reactions of tracheal and bronchial membranes in exposed workers. Experimental animals exposed to gypsum developed pneumonia, interstitial pneumosclerosis and blood and lymph circulation disorders in the lungs, though this has not been scientifically related to gypsum exposure only.

There are as such no data available on its toxicity or the acute toxicity level. Furthermore, it has no carcinogenic status.

The International Chemical Safety cards rate it also as a nuisance dust, with the effects of long-term or repeated exposure being to irritate the eyes and respiratory tract.

5 Conclusions

- The test sequence again demonstrated the importance of the tests used to evaluate a product. The comprehensive set of 200-m test gallery results on the use of water showed that different percentage TICs were required for the different scenarios tested.

- The results from the 40-ℓ explosion vessel and the 200-m test gallery indicated the order of effectiveness of the different inert materials tested. No conclusions are drawn about the comparative effectiveness of the inert materials in the two sets of tests, due to the differing natures of the test conditions.

- The effectiveness of fly ash as an alternative inerting material has not been proved conclusively.

- As proved in the earlier studies, water used as an inerting material can give a false sense of security.

- Small-scale tests on calcium sulphate $CaSO_4$ show that it has promise as an alternative inerting material.

- The health studies of both fly ash and calcium sulphate are inconclusive as in both cases carcinogenic activity is related to their silica content.

6 Recommendations

- Further test work should be done regarding the use of fly ash as an inerting material and to demonstrate the health related implications of different fly ashes.

- Large-scale tests, in the 200-m gallery, should be conducted on calcium sulphate ($CaSO_4$) to evaluate its effectiveness.

- Field tests should be performed on calcium sulphate ($CaSO_4$) as a viable inerting material for industry application in the mines.

- A health study should be performed on calcium sulphate ($CaSO_4$) to determine silica content and related carcinogenic activity.

- A comparative study should be carried out on all the inerting materials tested (small-scale, large-scale and field experiments) in order to evaluate the influence of particle size on the materials' performance.

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APPENDIX 1

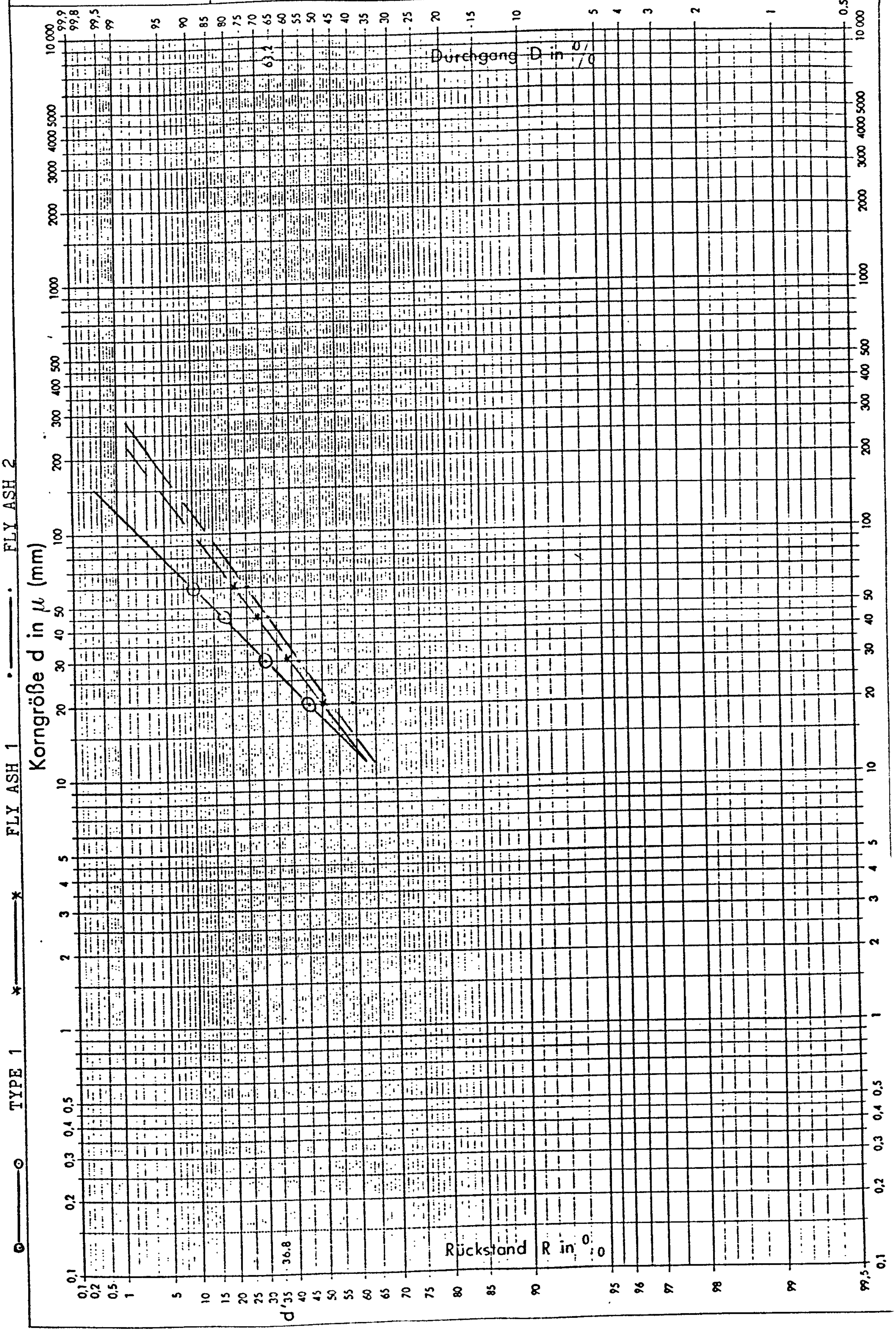
Stoff:

Maschine:

Körnungsnetz

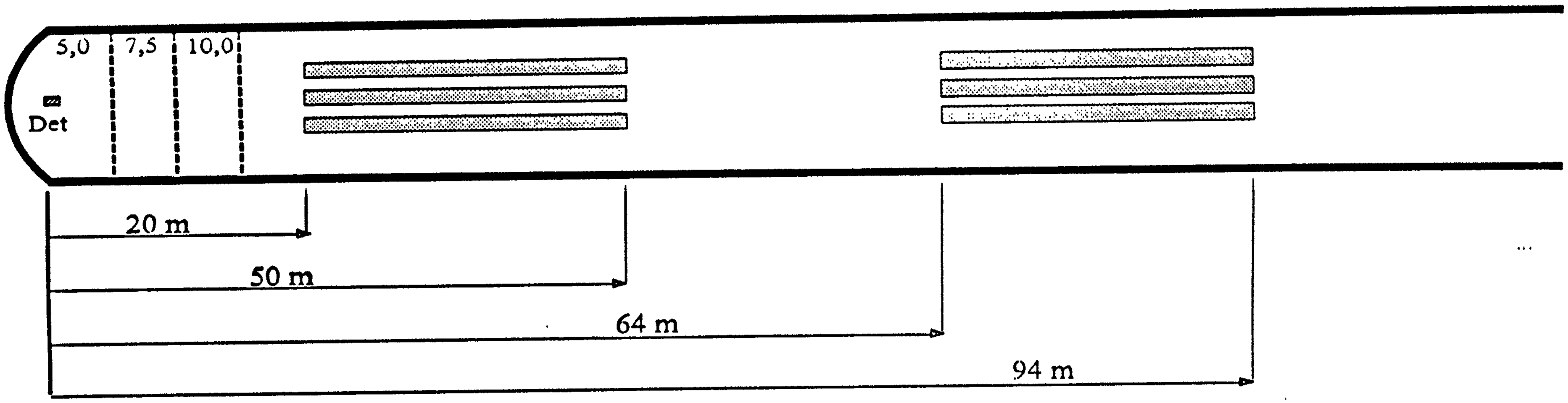
Nr.

Datum:

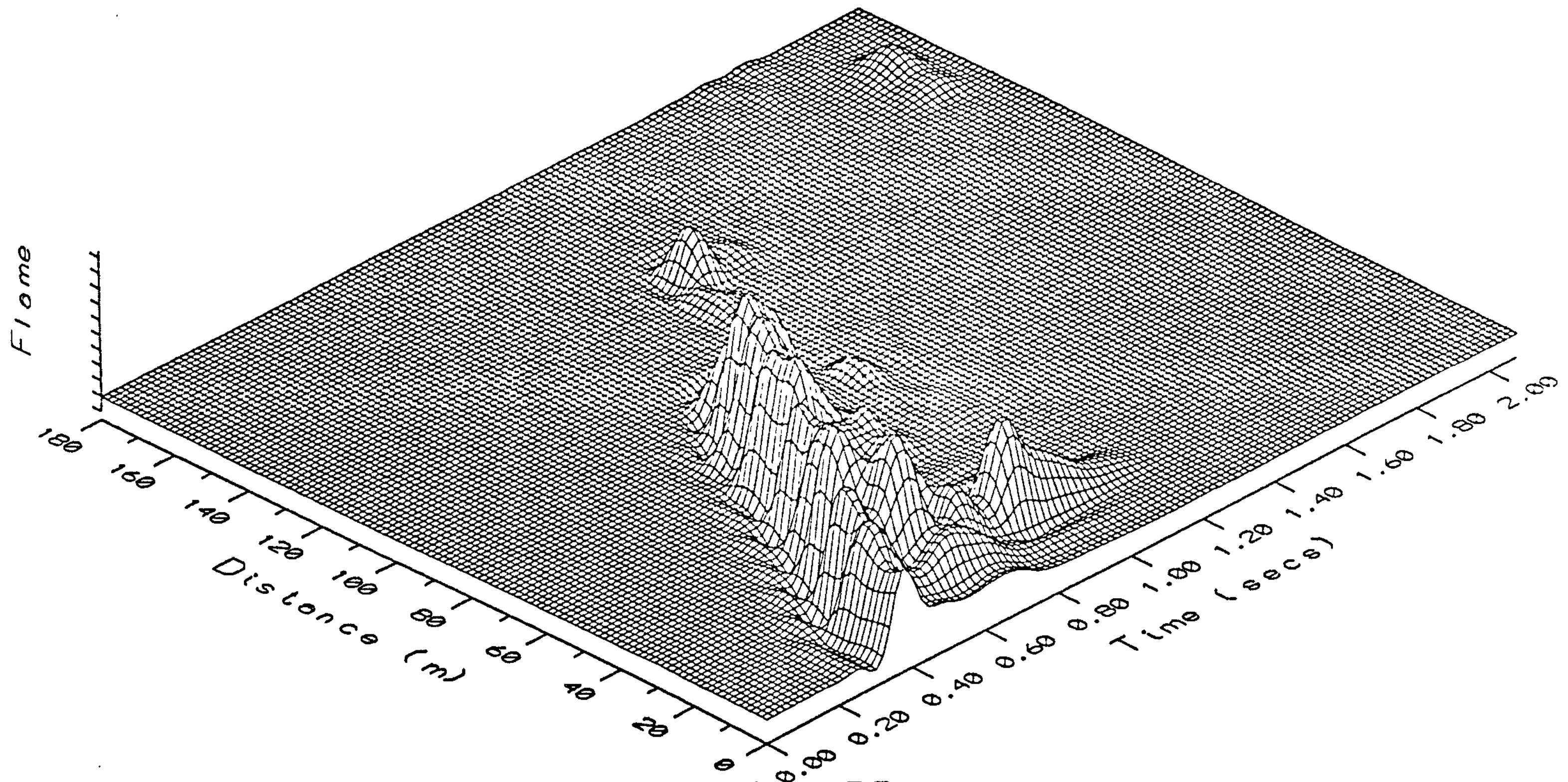


APPENDIX 2

200 - meter gallery



APPENDIX 3



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