P Golledge

SPONTANEOUS COMBUSTION IN UNDERGROUND COAL MINES

Compiled by:

HOWARD JONES, B.Sc., C.Eng., F.G.S., F.I.M.E., M.(Aust.) I.M.M.

Consulting Mining Engineer

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For Coal Mine Management

SPONTANEOUS COMBUSTION IN UNDERGROUND COAL MINES

(Notes for Mine Management)

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THE DEPARTMENT OF MINES, QUEENSLAND

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FOREWORD

The phenomenon of spontaneous combustion in underground coal mines is not a new one. Its associated problems have been of great concern wherever and whenever coal mining has been practised.

Two unfortunate accidents, at Box Flat in 1972 and at Kianga in 1975, which together claimed thirty-one lives, have focused attention on the need for all associated with the industry in Queensland to gain a full appreciation of the nature of the problems and how they can best be handled.

Among the recommendations made by the Board of Inquiry into the Kianga Disaster were—

(a) There is a basic need for all members of the coal mining industry in Queensland to improve their knowledge with regard to the fundamentals of spontaneous combustion and the underground mining problems associated therewith. A lack of appreciation of these fundamentals obviously contributed to the disaster at Kianga.

(b) A publication be assembled urgently and distributed to all members of the industry by the Mines Department explaining the hazards and giving guide-lines for handling of underground fires and heatings. The Queensland Coal Owners' Association and the Queensland Combined Mining Unions should assist in this task.

This publication, under the authorship of Mr. Howard Jones, who as a coal mining engineer has had experience in the problems of spontaneous combustion in Great Britain and Australia, has been produced in a co-operative venture by the three organisations concerned, as a step in the implementation of these recommendations.

It is aimed at producing a better understanding of the processes of spontaneous combustion and the nature and interaction of mine gases. Detection methods, including continuous monitoring of mine air, together with precautionary and corrective measures, are discussed.

Treatment of this comprehensive subject in this publication is not claimed to be exhaustive, and references to some additional literature have been listed by the author.

The distribution of this publication is to be followed up by a series of discussions in coal mining centres throughout Queensland, again on the same co-operative basis, as a further step in the education of all associated with the industry in this most important field.

J. T. Woods
Under Secretary,
Department of Mines

INTRODUCTION

The self heating or spontaneous combustion of coal has been the subject of systematic scientific research since Dr. Plot, the Professor of Chemistry at Oxford in 1686 described the occurrence of fires in coal heaps in Staffordshire, and after experimental work attributed this to the oxidation of pyrites. His theory was accepted for some 200 years until several papers during the latter half of the 19th century, demonstrated that coal free from pyrites absorbed oxygen with the evolution of heat, and work by subsequent researchers demonstrated that the presence of pyrites is not a key but simply one of many possible contributing factors.

Tremendous research has been accomplished during the past 100 years and more than 500 papers have been produced on the subject.

Almost invariably disasters in coal mines have drawn renewed attention to the problem. In 1905 six men were killed erecting stoppings following an incipient heating at Stanford Merthyr Colliery in New South Wales, and during that year of sixteen fatalities, eleven occurred in the Greta Seam in the South Maitland coalfield which is well known for its spontaneous combustion potential. Following the Greta seam incidents, Professor David warned of the great dangers of fire from spontaneous combustion and emphasised the need for taking extra precautions in the coal mines where spontaneous combustion constitutes a hazard.

Similar disastrous incidents drew attention to the problem elsewhere. In 1912 a gas explosion occurred at Cadeby Main Colliery in Yorkshire. It was the result of spontaneous fires of some years standing which was never completely eradicated and some 88 men were killed, either by the explosion or by the inhalation of poisonous gases caused by the explosion and possible subsequent fires.

Without doubt this disaster prompted the most important advance in research because in that year the Doncaster Coal Owners established the Coal Owners' Research Laboratories under the direction of that eminent Scientist, Dr. J. S. Haldane. Haldane and Scientists like Wheeler, Stopes and Graham established, in precise terms, the physiological factors associated with the gases evolved during a spontaneous heating. They established methods of determining the rate of evolution, the timetables associated with the formation of gases, and together with recent researchers, established techniques for the precise analyses of the products of the oxidation process which now permit the early detection of incidents below ground.

All of this information has been documented in scientific papers as are the developments in method of work which can minimise the risk and these are well known to Mining Engineers. Unfortunately much of this information is set aside in the course of time and general operating expertise can be diminished.

In Queensland during the past five years, thirty-one men have been killed in two mining disasters, both caused by violent explosions initiated by spontaneous heatings underground and in both cases the official inquiries drew attention to the need for the updating of management's knowledge in this field.

This booklet has been compiled in an attempt to fill part of this need. It is not a comprehensive text book, but it is hoped that it may stimulate further reading of the many papers which have been produced on the subject and so develop greater operating expertise in this important problem.

THE DEVELOPMENT OF A SPONTANEOUS HEATING

The surface of all coal absorbs oxygen to some degree; the process starts with a minimal evolution of the oxides of carbon and water vapour and if the heat which is generated in this exothermic reaction is dissipated to the atmosphere, a slow oxidation continues under safe controlled conditions.

Conditions in some parts of underground workings—such as unventilated goafs, leakage airway and old pillar areas—do not necessarily enjoy controlled ventilation circumstances. The heat generated by the exothermic reaction cannot be dissipated, the general temperature of the coal mass increases and spontaneous heating conditions are initiated.

Researchers have established that the heat generated raises the mass temperature and the rate of oxidation is accelerated until self ignition temperatures are achieved. Work undertaken by J. Graham in 1920 demonstrated this trend and Table I shows the results of some of his experiments.

Similar work undertaken elsewhere in the world indicates the same order of events in most other coals and these experiments emphasise the importance of coal rank and ambient temperatures in assessing the potential heating hazard in coal mines.

Basic research has tended to demonstrate that in all coals the oxidation process can be divided into distinct stages. The early effects of oxidation are an initial rise in the temperature followed by a slow but increasing evolution of the oxides of carbon. The temperature increases up to about 100°C and traces of hydrocarbons normally exist in the gaseous products. Almost immediately the dehydration of inherent and combined moisture occurs, the rate of

TABLE I

Coal	Seyler Classification	Oxygen absorbed in C.C. at N.T.P. (Per 100 grms. of Coal)					
		30°C	50°C	60°C	70°C	100°C	120°C
Lignite		1800		4650			
Barnsley Seam Yorkshire Top Softs	Meta Lignitious	520	880		1690	4550	8030
Cockshead Seam N. Stafford-shire	Para Bitumin-ous	40		336	363	1875	4460
Bullhurst Seam N. Stafford-shire	Para Bitumin-ous	33		227		1606	4230
Main Seam Cumberland	Ortho-Bitumin-ous	60	153		450	1686	4335
Anthracite S. Wales	Ortho-Anthra-cite	200				448	814

oxidation accelerates to a rapid state and at temperatures of about 200°C combustion takes place in the accepted sense of the word.

These identifiable phases are clearly important to the operating Mining Engineer because they provide the key to early detection and events which exist before open fire conditions occur. The precise timings of these critical changes vary in almost all coal seams but the sequence is generally similar.

Some thirty years ago, the Wigan Coal Corporation issued notes on the subject and Figure I illustrates the stages which tend to occur in the development of spontaneous combustion in some Lancashire coals.

These coals can be classified as para-bituminous or meta lignitious and are similar in type to coal seams found in Central and Southern Queensland and in the New South Wales coalfields.

Research work up to 1930 indicated that carbon dioxide and carbon monoxide were evolved during the early stages of all incipient heatings and clearly the early detection of these gases provides a key to an early warning system.

Figure I draws attention to the general stage in the development of an incipient heating and much research work has been undertaken since Graham, in order to establish more precise events in a spontaneous heating. Work by Chamberlain, Hall and Thirlaway led to an understanding on the development of gaseous products which become significant after the accelerated production of carbon monoxide and carbon dioxide. Figure II indicates the order of development of other "tracer" gases as the mass temperature rises.

This shows that the generation of carbon monoxide is much the same as in Figure I and clearly demonstrates similar trends in the evolution of hydrogen, ethylene and propylene at temperatures around 100°C, 140°C and 150°C respectively. The formation of these gases occurs after the accelerated production of carbon monoxide and can indicate the serious development of a heating towards normal combustion conditions.

The evolution of these gases can reach serious proportions as indicated by samples obtained from

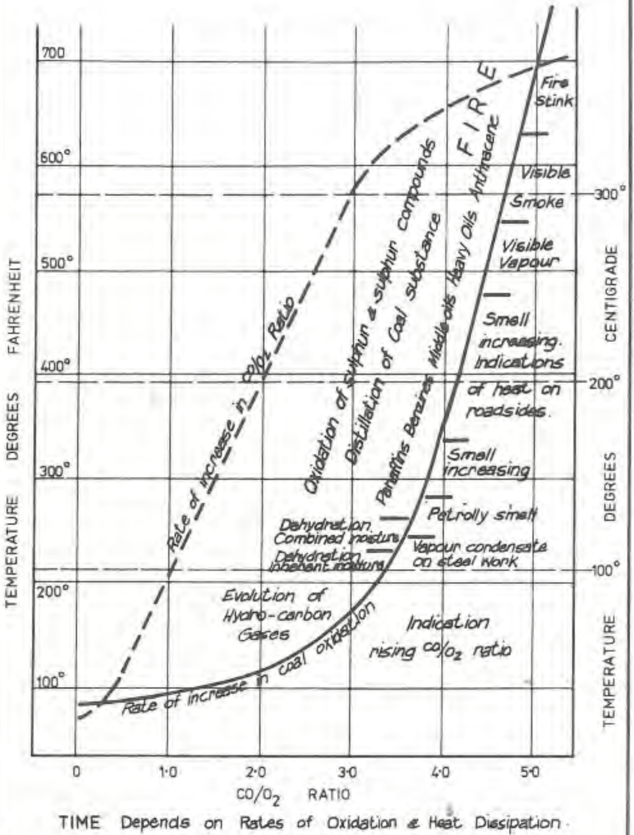

TEMPERATURE DEGREES FAHRENHEIT
700
600°
500°
400°
300°
200°
100°
TEMPERATURE DEGREES CENTIGRADE
300°
200°
100°
0
1·0
2·0
3·0
4·0
5·0
CO/O2 RATIO
TIME Depends on Rates of Oxidation & Heat Dissipation.
FIRE
Fire Stink
Visible Smoke
Visible Vapour
Small increasing. Indications of heat on roadsides.
Small increasing
Petrolly smell
Vapour condensate on steel work
Indication rising co/o2 ratio
Rate of increase in co/o2 Ratio
Oxidation of sulphur & sulphur compounds
Distillation of Coal substance
Paraffins Benzines Middle oils Heavy Oils Anthracene
Dehydration Combined moisture
Dehydration Inherent moisture
Evolution of Hydro-carbon Gases
Rate of increase in coal oxidation

FIGURE 1

behind stoppings in Lynemouth Colliery in Northumberland in January 1965 which gave the following results:—

Firedamp	4.4	per cent
Oxygen	1.6	,, ,,
Carbon Dioxide	19.50	,, ,,
Carbon Monoxide . . .	3.60	,, ,,
Hydrogen	6.06	,, ,,
CO/O_2 def. ratio . . .	19.60	,, ,,

The detection of these gases is clearly of paramount importance to the Mining Engineer if he is to make a proper assessment of the progress of an underground heating.

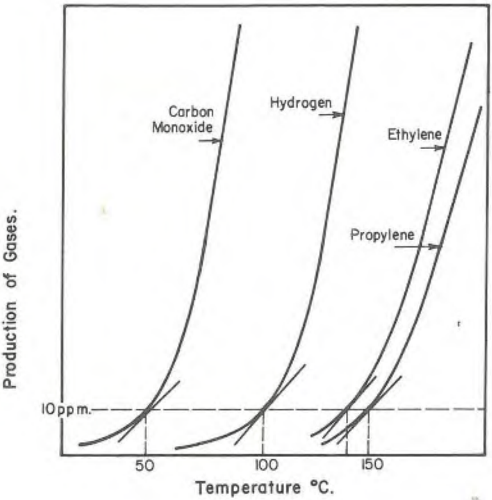

Carbon Monoxide
Hydrogen
Ethylene
Propylene
Production of Gases.
10ppm.
50
100
150
Temperature °C.

FIGURE 11

DETECTION OF A SPONTANEOUS HEATING

The processes involved in the generation of a spontaneous heating are now well known, and clearly an early method of detection is essential if Mining Engineers are to have time to deal with the problems involved.

The value of personal inspections by Deputies and other underground officials cannot be overstressed but they cannot be expected to detect physical and qualitative changes until after the process of acceleration has commenced.

Haldane and Graham emphasised the significance of carbon monoxide and together with later researchers, they established that movements in the production of carbon monoxide give the best indication of the onset of spontaneous combustion. The positive determination of the precise volume of carbon monoxide can clearly indicate the progress of a heating but such a determination requires a precise analysis for the carbon monoxide content and an equally precise determination of the ventilation quantity simultaneously.

Graham recognised the difficulties associated with such simultaneous determinations and this led to the formation of the carbon monoxide/oxygen deficiency ratio (CO/O_2) and carbon dioxide/oxygen deficiency ratio (CO_2/O_2).

An increase in temperature of the oxidising coal mass gives an increase in the CO/O_2 ratio under all circumstances but the CO_2/O_2 ratio in the early stages at lower temperatures is sometimes higher than in later stages when the temperature is greater. Some of the carbon dioxide evolved in these cases is not the result of oxidation but has been shown to be due to the gradual evolution of the small amount of carbon dioxide absorbed by the coal in its natural state. This relative solubility of carbon dioxide is very high compared with other common gases and again this was demonstrated experimentally by Graham as shown in Table II.

TABLE II

Gas	30°C	100°C
Methane	—	48
Carbon Monoxide	71	16
Carbon Dioxide	800	148
Nitrogen	58	11
Hydrogen	7	4

The CO/O_2 ratio, on the other hand, always shows an increase in time and temperature when coal is oxidised providing the oxidation is allowed to proceed continually. Carbon monoxide, unlike carbon dioxide, is not found in appreciable proportions in the gases which are evolved from freshly exposed coal, and when a mine air analysis shows the presence of carbon monoxide it invariably demonstrates that coal is undergoing oxidation.

For these reasons carbon monoxide is universally accepted as a better base than carbon dioxide as an indicator of spontaneous heatings in its early stages, and the CO/O_2 ratio, which is independent of ventilation circumstances, is universally accepted.

If, however, the heating progresses to a combustion condition the important gas is carbon dioxide and the CO/O_2 ratio can actually decrease. This condition only exists when open fire circumstances are imminent and clearly are not associated with an "early warning" system.

Carbon Monoxide/Oxygen Deficiency Ratio

This ratio increases with the spread and intensity of a heating and its determination for every section of a mine, under normal circumstances, is of great importance. It is the ratio between the percentage of carbon monoxide in the air and the percentage of oxygen absorbed at a given sampling point and it is usually expressed as a percentage in order to give a convenient number. As previously indicated, this ratio is independent of the ventilation providing the air in the intake has no oxygen deficiency.

It should be remembered that fresh air contains:—

20.93 per cent oxygen
79.03 ,, ,, nitrogen

and the method of calculation is as follows.

Consider a sample containing 19.10 % O_2, 78.90 % N_2 and 0.0091 % CO.

Fresh air contains 79.03 % nitrogen and 20.93 parts of oxygen.

It therefore follows that in fresh air

$$\frac{78.9}{79.03} \times 20.93 = 20.89\%$$

The oxygen deficiency is therefore—

$$20.89 - 19.10 = 1.79\%$$

To give a CO/O_2 ratio of $\frac{0.0091}{1.79} = 0.00508$

Which is generally expressed as 0.51 %

This, like any calculation, is subject to limits of analytical errors and it is generally considered that oxygen deficiency of 0.2 % or less would introduce gross errors.

This point is made so that caution can be exercised in interpreting results when such low oxygen deficiencies occur.

Every mine and every district in a mine will have its own individual CO/O_2 ratio and any analysis showing an abnormally high ratio should be immediately resampled. If the initial result is confirmed a CO/O_2 ratio survey should be undertaken so that the precise location of the heating can be determined.

Clearly the carbon monoxide content can be affected by fumes from diesel engines and shotfiring, so control samples should be organised when interference from such sources can be avoided.

Figure I showed the progress of a CO/O_2 ratio graph as heating progressed and the results obtained during an incident should be graphed on a time basis so the trends can be easily observed.

ANALYTICAL DETERMINATION OF CARBON MONOXIDE

General information on carbon monoxide is given later but simple methods of determination are not available to workmen and special training is necessary if accurate determinations are needed.

Portable instruments are available for use below ground—but they have some degree of inaccuracy and are incapable in themselves of predicting the progress of a heating. They are, however, necessary to establish that safe environmental conditions exist at working places, particularly if remedial work is being undertaken, and can give warning to underground supervisors who can relate a rapid increase in carbon monoxide to possible ventilation changes.

Portable equipment of this type is manufactured by Draeger, M.S.A. and Siebe Gorman and consists of a granulated bed of silica gel impregnated with a chemical compound contained in a sealed glass tube. Such tubes have sealed ends which are broken off and placed into a suitable aspirator which draws a fixed volume of air at a controlled rate through the tube.

The percentage of carbon monoxide is indicated by the length of the stained section of the tube which can be read to an associated scale or by comparing the colour of the stain with a standard tube chart. The tubes can read concentrations from 5 to 3000 p.p.m. (High or low reading tubes being available).

Such apparatus is in general use in Australia and in all cases the manufacturers' instructions should be followed carefully if "false" readings are to be avoided.

A portable carbon monoxide alarm and recorder (known in Great Britain as the Electronic Canary) were developed some years ago and are commonly used at return stopping sites. This instrument is about the same size as a standard underground canary cage and air is sampled on a continuous basis. The sample stream is catalytically oxidised by a small bed of hopcalite to carbon dioxide and this process causes a temperature rise which is related to the carbon monoxide concentration. The instrument measures the temperature and indicates carbon monoxide concentrations on a suitable dial scale.

The instrument scrubs out water vapour and carbon dioxide before the sample passes over the hopcalite bed. Some time is necessary before the whole process is completed and normally a complete change occurs within 3 minutes. The instrument can determine concentrations of between 0-300 p.p.m. with an accuracy of ± 10 p.p.m., 0-1000 p.p.m. with an accuracy of ± 30 p.p.m. and 0-3000 p.p.m. with an accuracy of ± 100 p.p.m.

The variation in accuracy is related to the inevitable "poisoning" of the hopcalite bed and the instrument is not generally regarded as reliable after 8 hours operation, when the apparatus is cleaned and fresh reagent bed installed.

Determinations of carbon monoxide obtained by such instruments can, if used with precise quantity determinations, lead to an interpretation of progress when a heating is developing. The instruments are not, however, designed to give precise readings. They tend to need frequent recalibration and they should not be regarded as suitable if accurate results are required.

Their prime purpose is to ensure that the official in charge is immediately aware of the build-up of noxious gases at a working site, and any changes should be communicated to a surface controller who will be in a better position to make overall judgments.

Constituent gases in mine air samples must be analysed accurately if Mine Managers are to make correct assessments on the progress of a spontaneous heating. Work by Haldane led to the development of his well known gas analysis apparatus which was the main method of analysis for mine air until the middle of the 20th century when more sophisticated methods were developed. At the present time laboratory and semi-portable instruments are available which can give the high degree of accuracy which is needed.

Gas-Solid Chromatography units can accurately determine concentration of hydrogen to 1 p.p.m. Infra-red analysers can determine carbon monoxide concentration to 1 p.p.m. Flame Ionization Chromatographs can determine methane concentration to 0.5 p.p.m., ethane to 0.5 p.p.m., ethylene to 0.5 p.p.m., propylene to 1.5 p.p.m. and such instruments are being developed to give greater precision year by year.

These analytical instruments are capable of giving fast, or in some cases continuous, results to mine management. Following work by Dr. Chamberlain, the Director of Scientific Control for the National Coal Board, and other researchers in 1970, it became obvious that provided systematic analysis is organised at an underground coal mine, it is now possible with present analytical techniques for carbon monoxide, to detect with certainty any increase in coal temperature 10°C above the ambient temperature conditions of the strata.

This clearly is capable of indicating gaseous changes which occur at about 40°C to 50°C and demonstrates that very early detection of a spontaneous heating is completely practical.

MINE GASES ASSOCIATED WITH SPONTANEOUS COMBUSTION

Research work has shown that the process of spontaneous heatings can lead to the formation of gases and open fire conditions, and many fatalities have occurred because of the explosion which has followed such developments. Clearly a knowledge of these gases is important to the operating Mining Engineer who will be called upon to deal with the associated dangerous occurrences. Such information is given below.

Carbon Monoxide

Some oxidation takes place in all coal mines and small percentages of carbon monoxide, generally less than twenty parts per million, can be considered harmless. Threshold limits in general industry are given as about 0.01 % or 100 parts per million but in the presence of such concentration in the general body underground should be more than sufficient to indicate the need for a general investigation.

The gas is highly poisonous and initial experiments by Haldane, Wheeler and Stokes indicated that the haemoglobin of the blood has an affinity for carbon monoxide 250 to 300 times greater than for oxygen and that continued exposure to the gas will eventually cause the blood to be saturated with carbon monoxide to the almost complete exclusion of oxygen.

Figure III is based on observation by Haldane and when half of the haemoglobin is united with carbon monoxide a person will lose consciousness.

The table shows clearly that concentration of 0.1 % can bring this about and the general physiological effects at various percentages are approximately as follows:

0.01 per cent—Threshold limit value
0.02 per cent—Headaches after 7 hours of resting or 2 hours if working
0.04 per cent—Headaches and discomfort with possibility of collapse after 2 hours of rest or 45 minutes exertion.
0.12 per cent—Palpitations after 30 minutes at rest or 10 minutes exertion.
0.20 per cent—Unconsciousness after 30 minutes at rest or 10 minutes exertion.

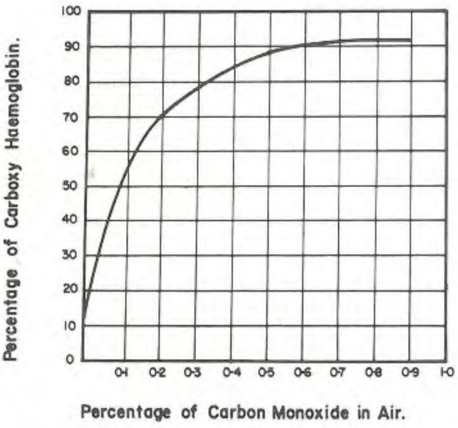
The possibility of such accumulations does exist if a spontaneous heating is occurring in a coal mine, particularly in the main return serving an affected district when final sealing is being undertaken.

Protection can be given by using a canary which is affected 15 to 20 times quicker than a human being and the continual use of some automatic instrument with an audible alarm such as the N.C.B. "Electronic Canary" is to be recommended.

Sealing districts when the ignition hazard is minimal generally proceeds in spite of abnormal carbon monoxide contents, but authorities all tend to suggest that all such work should be undertaken by trained rescue teams in self-contained breathing apparatus whenever the general carbon monoxide content persists at a level of more than 0.02 per cent or 200 p.p.m.

A suitable fresh air base should always be set up as close as possible to the return stoppings and oxygen rescusitators should be available to give treatment to affected persons.

Carbon monoxide in the blood is eliminated when fresh air or oxygen is inhaled. If, however, the affected person has been exposed to dangerous concentrations, some cells in the brain may sustain irreparable damage and the person so affected should be given medical advice immediately.



100
90
80
70
60
50
40
30
20
10
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
Percentage of Carboxy Haemoglobin.
Percentage of Carbon Monoxide in Air.

FIGURE III

Carbon monoxide is capable of forming an explosive mixture with the limits of explosibility being 12.5% to 74%. It should be remembered that it is a component of water gas and considerable thought should be given to a fire problem underground before the direct application of water is considered.

The important relationship between the carbon monoxide produced and oxygen absorbed has already been explained and even though the ratios at various stages vary with the coal type and the mine circumstances, some general guidance is possible.

Even small sustained increases in the value of the ratio should be regarded as a warning of an early stage of heating. (Normal ratios can be between 0.1 and 1.0 per cent). Increases of the order of 0.5 to 1.0 per cent should develop grave concern; indeed such persistent progressive increases will almost certainly indicate the presence of a serious heating which is approaching active fire circumstances.

Depending on the extent of the heating, ratios may rise to 10 per cent or more and are generally indicative of the presence of producer gas. The temperature of the heating mass will be such that hydrogen, ethylene and propylene can be found; indeed at such ratios the possible formation of carbon monoxide and hydrogen by explosion should be borne in mind.

Methane and Firedamp

This is a colourless, tasteless and odourless gas and has a vapour density of 8 compared with 14.4 for normal air. Its presence underground is well known, as are its buoyancy effects and its ability to form layers of explosive concentrations where ventilating currents are minimal and airways are driven on gradients.

Almost invariably it is present in underground coal mines particularly when spontaneous combustion problems exist. To some degree the risk of a major explosion with a spontaneous heating as an initiating source is not great. Statistical investigations of 168 colliery explosions in which some 6896 lives were lost between 1849 and 1964 in the United Kingdom, showed that only 244 deaths (or 3.5 per cent) were caused by 9 incidents (or 5.4 per cent) where spontaneous heat was established as the main cause.

These statistical trends tend to be similar to those produced by other major coal producing countries. They show that the general consequences of explosions involving spontaneous heatings are more serious than average, and experience in Australia supports such an observation. Clearly an understanding of the make of firedamp in a mine is of utmost importance when trends are being assessed relative to a spontaneous heating and regular determinations of mine, district and section methane emission are of great importance.

These should be subject to systematic analysis at all times so that the probable make of firedamp can be determined with some precision and it is important that the potential make of firedamp can be estimated from every section of a mine when no coal is produced as well as during periods of normal production.

Fortunately the accurate determination of methane below ground is relatively simple. Methods of determination of general body concentrations up to 5 per cent can be made with an approved flame safety lamp, but it should be remembered that a normal lamp is not capable of detecting layers of gas with any degree of certainty. This defect can, of course, be remedied by using a modified flame safety lamp such as the Garforth lamp which is capable of detecting layers containing well in excess of 5 per cent of methane.

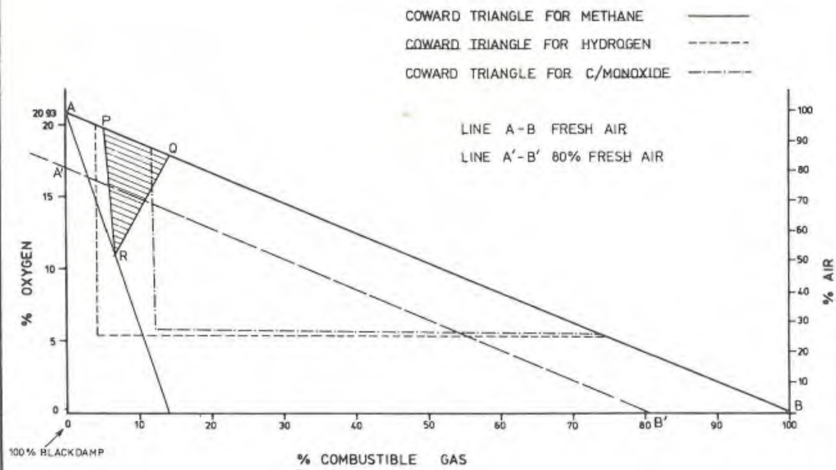
By far the most convenient portable instruments are standard methanometers which are produced by a variety of manufacturers. These instruments contain a heated filament coated with a catalyst which causes any methane (and other combustible gases) to oxidise. The reaction provides an increase in temperature and a change in the electrical resistance of the filament. This resistance variation gives an out of balance current in a Wheatstone bridge network proportional to the methane concentration present in the combustion chamber and methane concentrations are automatically indicated on the instrument display dial.

They are generally capable of accuracies of ± 12 per cent when reading to a maximum of 5 per cent methane or ± 10 per cent if a high reading instrument beyond 5 per cent methane is employed.

As pointed out the filament oxidises methane and other combustible gases and even though it satisfies safety requirements at underground working sites, a need exists to establish the trends of other constituent gases such as hydrogen, ethylene and propylene. More sophisticated methods of analysis are essential when spontaneous heatings occur and this requires frequent systematic sampling which can be analysed on chromatography units in a convenient surface laboratory.

The Coward Triangle

Some 50 years ago, Coward and Jones investigated the inflammability of methane and other gases in some detail and they developed a graphical method of determining the explosibility circum-



COWARD TRIANGLES

FIGURE IV

stances associated with inflammable gases. Such triangles for methane, hydrogen and carbon monoxide are shown in Figure IV and are worthy of detailed attention when a spontaneous heating occurs in a coal mine.

The ordinate is set out from 0-20.93 per cent oxygen and because fresh air is constant in composition the same ordinate is calibrated 0 to 100 per cent of air. The base is set out 0-100 per cent methane and by difference point 0 represents 100 per cent Blackdamp. (See Page 39.)

The diagram can therefore be used for any mixture of air, methane and blackdamp and any such mixture can be represented by a point on the diagram. This will naturally be inside the diagram if all three components are present, on one of the sides, if there are only two present, and at one of the apices if only one is present. In view of the importance of reliability in explosibility calculations, a special desk top computer has been developed for the purpose of making such quick calculations.

Graphical methods were, however, developed by Hughes and Raybould in 1960 and these are able to permit quick determinations of adequate accuracy. This is accomplished by adopting the permissible expedient of counting any carbon dioxide present as equivalent to nitrogen. The graphs they produced will enable an inflammability triangle to be read off for any mixture of the three principal inflammable gases, methane, carbon monoxide and hydrogen, which are likely to be found in a fire area when associated with air or atmospheres deficient in oxygen.

Four such graphs were produced and these are given in Figures V, VI, VII and VIII.

This method was applied to determine the position where the analysis gave the following results.

Oxygen	13.2%	
Nitrogen	76.1%	82.6
Carbon Dioxide	6.50%	
Carbon Monoxide	2.73%	
Methane	0.38%	5.71
Hydrogen	2.60%	

The explosibility triangle which was developed by using Hughes and Raybold's graphs was as shown in Figure IX and clearly the inflammable content was outside the explosive conditions.

The method of use when employing the graphs is as follows:

i. From the sample analyses, calculate the proportion of methane in the combustibles and also the proportion of hydrogen in the combustibles.

ii. Use Figure V to determine the lower limit of the gas mixture with air.

iii. Use Figure VI to determine the oxygen content of the nose limit.

iv. Use Figure VII to determine the combustible gas content of the nose limit.

v. Use Figure VIII to determine the upper explosive limit of the mixture with air.

Mark these four points on the standard graph to construct the explosive triangle.

Coward's initial triangle was related to a condition when methane is the sole explosive gas present in a sample. This figure is well known and is shown in Figure X.

This is considered to be adequate when methane makes up more than 98% of the combustible gases, and in general terms the following can be regarded as basic guides if other gases are present.

i. Hydrogen reduces the lower limit but until it reaches 15% of the mixture the limit is reduced by less than 0.2%.

ii. If carbon monoxide, hydrogen and methane are present, the lower limit will not exceed that of methane unless the hydrogen concentration is more than five times that of carbon dioxide.

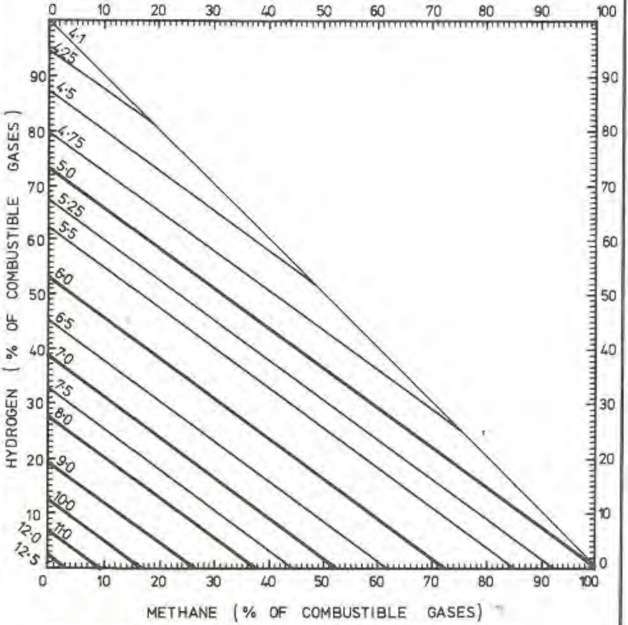
iii. When the proportion of hydrogen and/or carbon monoxide in the total combustibles reaches 2.0%, then the upper explosive limit and the nose limit can be changed by about 0.2%.

Hanging Flames

The explosive circumstances of methane have been outlined and clearly if there is a volume of air with concentrations of more than 15 per cent, the rich mixture cannot be ignited directly. Burning can, however, proceed at the fringe where some mixing with air will take place and such circumstances are referred to as "hanging flames".

Gas, in association with a heating, may be involved in a minor explosion and such circumstances could exist at waste edges. Convection currents from such burning will encourage further mixing and appreciable volumes of mixtures within the explosive range can be reformed.

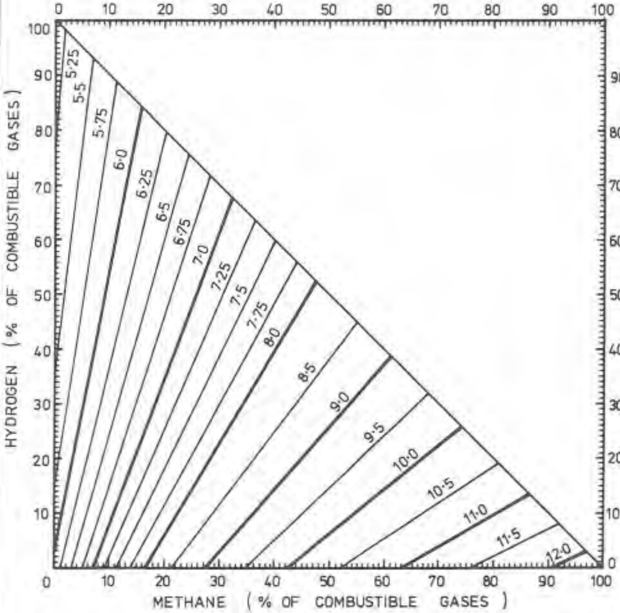
Clearly it would be unwise to fight such a fire at the waste edge because of the likelihood of an explosive mixture in the vicinity of the flame in the waste and men should be withdrawn to effect remedial measures by some other means at a safe distance.



COMBUSTIBLE CONTENT AT THE LOWER EXPLOSIVE LIMIT OF MIXTURES OF METHANE, HYDROGEN AND CARBON MONOXIDE IN AIR

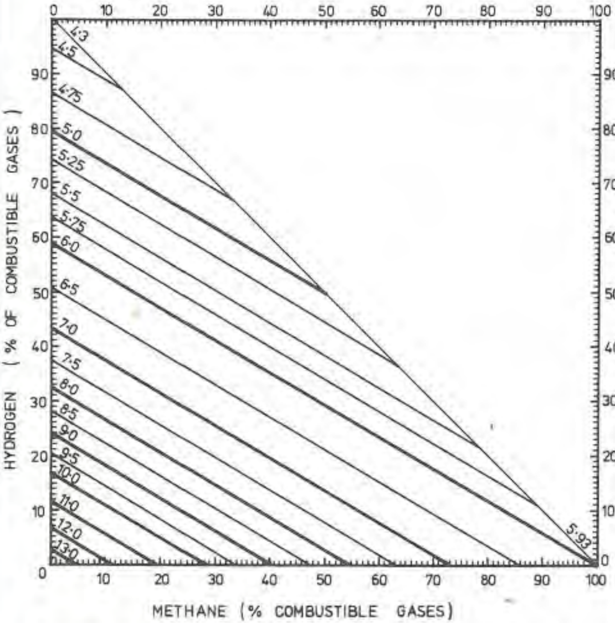
[AFTER HUGHES & RAYBOULD (30)]

FIGURE V



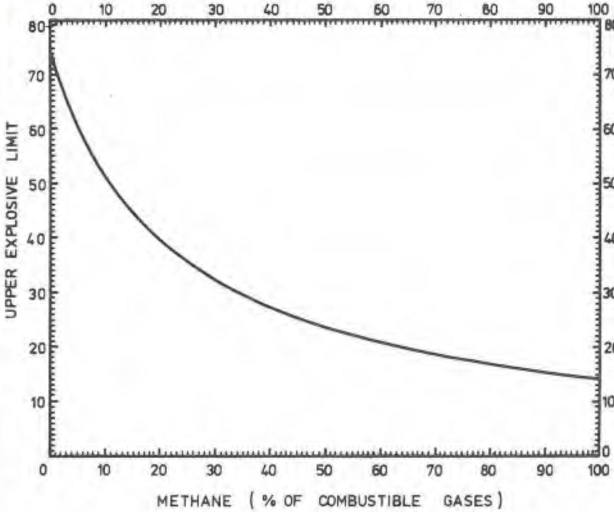
OXYGEN CONTENT AT THE NOSE LIMIT OF MIXTURES OF METHANE, HYDROGEN AND CARBON MONOXIDE IN AIR AND EXCESS NITROGEN [AFTER HUGHES & RAYBOULD (30)]

FIGURE VI



COMBUSTIBLE CONTENT AT THE NOSE LIMIT OF MIXTURES OF METHANE, HYDROGEN AND CARBON MONOXIDE IN AIR AND EXCESS NITROGEN. [AFTER HUGHES & RAYBOULD (30)]

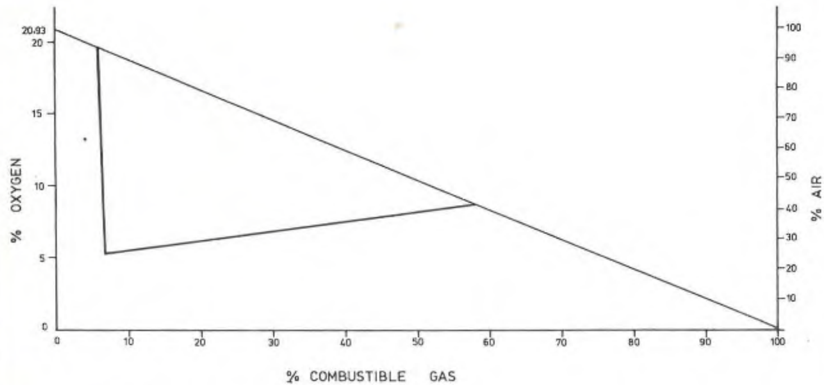
FIGURE VII



COMBUSTIBLE CONTENT AT THE UPPER EXPLOSIVE LIMIT OF MIXTURES OF METHANE HYDROGEN AND CARBON MONOXIDE IN AIR

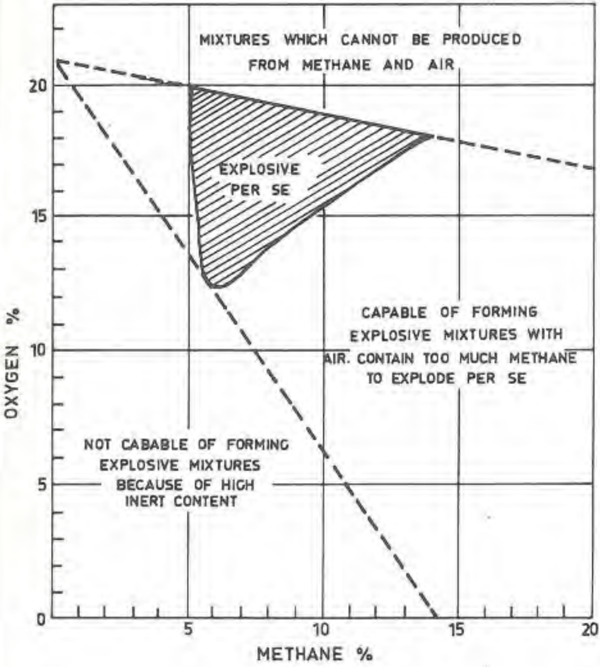
[AFTER HUGHES & RAYBOULD (30)]

FIGURE VIII



% OXYGEN
20.93
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
% COMBUSTIBLE GAS
% AIR
100
90
80
70
60
50
40
30
20
10

FIGURE IX



Relationship between the quantitative composition and the explosibility of mixtures of methane, oxygen & nitrogen.

(The inflammability triangle - after Coward [27])

FIGURE X

Firedamp Layering

Firedamp issuing from large cavities or roof breaks will tend to form a layer at roof levels unless it is continuously swept away by the air current and often ventilation velocities tend to be low when spontaneous heatings are being treated. When such "bleeding" is occurring at the roof of a roadway, ventilated descensionally, the firedamp will "back" along the roof against the downward air current unless the velocity of the air is sufficient. This phenomena must always be remembered because explosive mixtures could accumulate considerable distances upstream from the initial cavity or roof break, and the presence of layers in association with a spontaneous heating should be the subject of considerable investigation because the layer may originate from an accumulation which is close to the heating centre.

Carbon Dioxide

Spontaneous heatings generate small quantities of carbon dioxide and when open fire conditions exist with free access of air it is produced in considerable quantities at the same time reducing the amount of oxygen.

It is a colourless, odourless gas having a slightly acid taste. Its presence can be detected by its action on a flame safety lamp which burns feebly until the oxygen level is reduced to about 16 per cent when the flame is extinguished.

It has a vapour density of 22 compared with 14.4 for normal air. It forms layers at floor level and can give rise to dangerous circumstances in unventilated dip workings.

It is not in itself poisonous. The lower threshold value in general industry is sometimes quoted at

0.5% and at concentrations of about 9% the normal breathing action becomes depressed.

Physiological symptoms are similar to those experienced by oxygen deficiency which are as follows:

Per cent Oxygen

20.93 per cent	—normal fresh air
17.0-14.0	—extinction of a flame safety lamp
13.0	—work is difficult, breathing becomes rapid, lips become blue, nausea and headaches are experienced.
11.0-8.0	—exertion leads to unconsciousness
below 6.0	—rapid unconsciousness and death results.

The symptoms of anoxia or oxygen starvation are insidious and sufferers are often unaware of their condition. Because of this no person should work in isolation in atmosphere likely to be affected by gases evolved by a spontaneous heating or open fire and fresh air bases must be established suitably equipped with oxygen resuscitators, so that affected workmen can be treated promptly.

Blackdamp is the name originally used to describe air vitiated either by the consumption of oxygen or by dilution with carbon dioxide (or possibly nitrogen). Such circumstances exist in old districts which have been sealed off as part of the normal ventilation control circumstances.

It is, however, useful to express an analysis of a sample of mine air in terms of inert gases, and the term blackdamp is used under such circumstances.

In this circumstance, blackdamp is defined as nitrogen and the carbon dioxide proportions of a sample over and above the sum of the proportion of these gases which with the total oxygen would make fresh air.

The following method of calculation is normally adopted.

If in a sample the nitrogen content is $a\%$, the oxygen content is $b\%$ and the carbon dioxide $c\%$, the total blackdamp can be determined as being

$$= (c + a) - \frac{79.07}{20.93} \times b\%$$

(79.07 and 20.93 being the respective percentages of nitrogen and oxygen in fresh air.)

Other Gases

Other gases generally associated with spontaneous heating are hydrogen and other higher hydrocarbons.

Only hydrogen is of dangerous significance because of its possible presence in explosive quantities and this has been previously referred to when the Coward triangles were described.

Its presence in coal mines tends to be isolated to spontaneous heatings, in the thermal decomposition of wood, rubber etc. and it can be produced in quantity by the action of water on a red hot fire.

It is, of course, given off during both the charging and discharging of electric storage batteries, but the use of equipment such as battery locomotives is strictly controlled below ground and generally pollution from that source is negligible.

The explosibility limits of hydrogen in fresh air are 4%-74% and the explosive triangle is referred to elsewhere.

The gas concentration can be very accurately determined by conventional chromatography units and its presence in samples obtained in the return from a suspected heating will always indicate a stage of development well past the accelerated carbon monoxide production phase.

Its effects on the explosibility of gases emphasises the need for precise analytical analyses and laboratory equipment should always be capable of its precise determination together with other important higher hydrocarbons, when spontaneous heatings are being investigated.

PRECAUTIONARY MEASURES

Generally, the risks associated with incipient heatings can be minimised by reasonable planning when operational districts are being designed, by the exercise of care and attention to details during the operational phase and by setting up an effective organisation to deal with a heating which develops to an accelerated condition.

These basic facts are normally well known but some are worthy of repetition.

Estimating the Initial Liability

Work by many investigators has established that there is a broad relationship between coal rank and the liability to spontaneous combustion, although there are exceptions such as physical structure, petrographic composition and porosity which can affect the oxidation characteristics of a particular coal.

Figure XI tends to show the trend in ignition temperatures with general rank and Figure XII shows the same general trend with some of the particular types or layers which exist in coal seams.

These only show a basic situation but recent work by Chamberlain, Hall and Thirlaway involved dynamic oxidation tests on coals whose ranks varied from anthracites to lignites. These indicated the temperatures at which the rate of evolution of carbon monoxide and hydrogen showed significant rates of increase and the general trend is shown on Figure XIII. Again it confirms the tendency for a general increase in risk as the rank deteriorates, and shows that even though oxidation can proceed with any coal, higher temperature conditions are necessary and the overall risk is less with high rank coals.

FIGURE XI

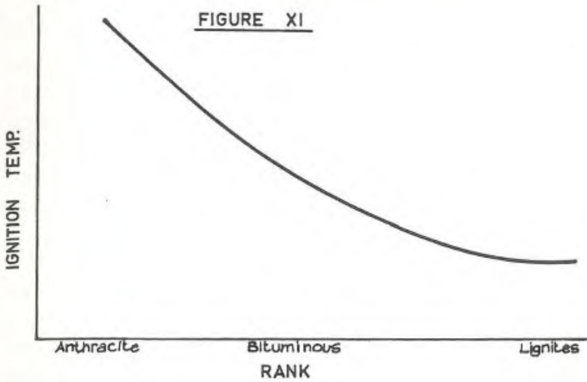
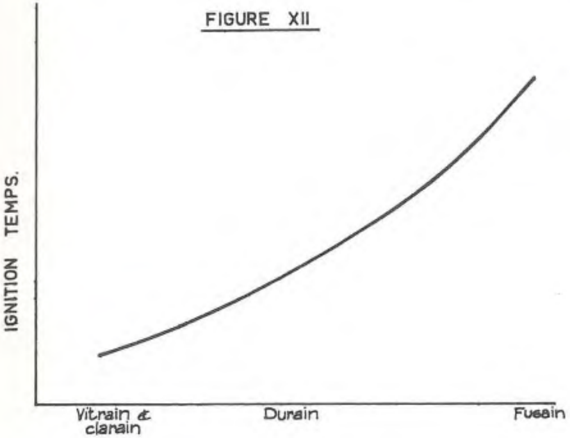


FIGURE XII



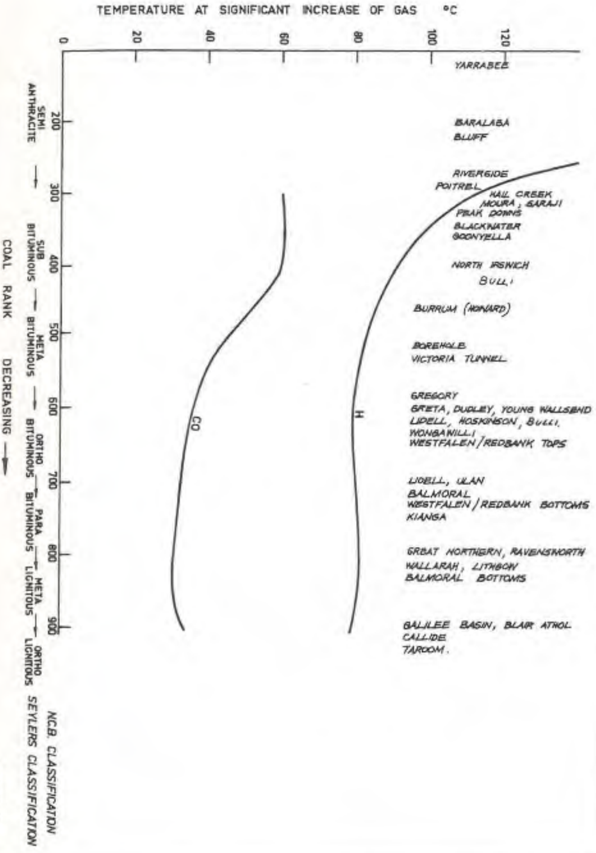
In the United Kingdom the majority of serious heatings have occurred in the lower rank 700's, 800's and 900's coals but over the last twenty years there has been a tendency for the incidence rate to increase in the 500's and 600's coals. Heatings have occurred in 200's coals or semi-anthracites where inferior coal sections were left up to form part of the roof, and the characteristics of all roof coal need careful study when the potential hazard is being assessed.

Figure XIII sets out the approximate rank positions of some coal seams in Queensland and New South Wales and they invariably confirm that rank is significant when an assessment is made of the spontaneous combustion risks.

The potential for heating in 900 coal seams, such as the Callide seam, are well known. The liability of the 600's Greta Seam in the Maitland District, has prompted special investigations of the hazard and incidents at Kianga and heatings in the Blackwater seams (classified as 801 and 302 respectively) confirm that the hazard exists over a fairly wide range of coal.

It is, however, significant that major heatings can occur in fairly high ranking coals when inferior coal is left up as a roof and if this is planned on a major scale the incipient heating risk is increased enormously.

Pre-planning for incipient heating potential, requires a scientific examination of a total coal seam, and each major ply, particularly those which may be left up at roof level. These examinations should establish the petrology and the analysis of volatile matter, calorific value, carbon and hydrogen to establish rank, and the coal physical strength in-



TEMPERATURE AT SIGNIFICANT INCREASE OF GAS °C
0
20
40
60
80
100
120
200
300
400
500
600
700
800
900
SEMI ANTHRACITE
SUB BITUMINOUS
META BITUMINOUS
ORTHO BITUMINOUS
PARA BITUMINOUS
META LIGNITOUS
ORTHO LIGNITOUS
COAL RANK DECREASING
NCB. CLASSIFICATION
SEYLERS CLASSIFICATION
CO
H
YARRABEE
BARALABA
BLUFF
RIVERSIDE
POITREL
HAIL CREEK
MOURA, SARAJI
PEAK DOWNS
BLACKWATER
GOONYELLA
NORTH IPSWICH
BULLI
BURRUM (HOWARD)
BOREHOLE
VICTORIA TUNNEL
GREGORY
GRETA, DUDLEY, YOUNG WALLSEND
LIDELL, HOSKINSON, BULLI.
WONGAWILLI
WESTFALEN/REDBANK TOPS
LIDELL, ULAN
BALMORAL
WESTFALEN / REDBANK BOTTOMS
KIANGA
GREAT NORTHERN, RAVENSWORTH
WALLARAH, LITHGOW
BALMORAL BOTTOMS
GALILEE BASIN, BLAIR ATHOL
CALLIDE
TAROOM.

FIGURE XIII

cluding grindability should be determined in order to assist pillar strength assessments.

Methods of Work

If the spontaneous heating risk warrants special attention, the objectives must be associated with:

i. The attainment of complete extraction of a section at maximum speed.

ii. The positive ventilation of a goaf containing roof coal or coal fenders to guarantee heat dissipation or

iii. The practical exclusion of ventilation from a goaf area containing coal to ensure that oxidation cannot take place.

iv. The design of working section which will permit the erection of suitable seals at the minimum number of points at maximum speed with a balanced ventilation condition across them.

v. The setting up of systematic air sampling points to ensure quantitative control during the production process.

vi. The setting up of suitable laboratory services to ensure accurate analytical results.

vii. The education of all involved personnel relative to the basic problems of spontaneous combustion.

viii. The setting up of good emergency procedures.

ix. The design of pillars and direction of working in order to minimise risk.

x. The setting of high standards for all work involved in the installation of ventilation aids including the design and installation of seals, separation doors, air crossings etc.

Four basic methods of work are available for the high productivity requirements within Australian mines and these are:

1. Bord and Pillar formation,
2. Mechanised pillar extraction,
3. Shortwall extraction, and
4. Longwall retreat.

Bord and Pillar

Without doubt the lowest frequency of heatings occurs during pillar formation and almost inevitably heatings develop in pillars which are incorrectly designed to give broken conditions at pillar edges or in pillars which have been subject to ventilation leakage through pillar edges and coal roofs following the poor installation of seals, air doors and air crossings etc.

The remedies for such failures are obvious.

All such ventilation aids should be well constructed, set well back into solid roof, floor and sides and ventilating pressure differences should be maintained at the lowest possible levels consistent with the provision of adequate ventilation.

Generally, the development of a pillar heating can be detected by a systematic air sampling system. The value of physical inspection on a weekly basis cannot be overstressed for all airways formed in pillar work because of the detrimental effects of localised falls which can contain poor quality coal under rock piles and which can cause localised pressure variations.

Conventional pillar extraction appears to pose the main problem at the present time and recent incidents highlight the dangers inherent in the system when roof coal and isolated ribs are left in the waste areas. It is unrealistic to assume that coal will not be left in wastes in spite of all efforts to minimise the problems and unless history confirms that the spontaneous risks are non-existent, the extraction areas should be designed so that they retreat at maximum speed towards a minimum number of entries which can be stopped off quickly.

The size of such districts can only be decided by consideration of local factors.

Ideally, a period of about 4 to 6 months is required to justify the setting out of a conventional panel, but the precise period will depend on the type of coal, the competence of roof and floors, the gradients, the make of firedamp, the equipment in use and the overall ventilation circumstances of the mine.

The risks can be minimised by employing special techniques such as the injection of inert gas, the formation of intermediate waste barriers, but generally these have not been universally successful and should not be considered as prime measures.

Trials with bleeder entries have been undertaken with some success with pillared areas, especially in the bituminous coal-fields of Pennsylvania. The prime purpose, however, was to effect a reduction in methane emissions. The use of such a system is fraught with dangers when applied to seams which have a high spontaneous combustion risk and such bleeder systems simply serve to enlarge the total waste frontal areas.

Normally, reasonably high ventilating pressures are required if adequate ventilation is to be provided in the bleeder roads themselves and trials in the U.S.A. have shown that in tight goaf conditions very little of the ventilation is coursed through the interior of the waste. However, up to 40 per cent of the intake air can flow into and along the waste fringes where a spontaneous heating can easily develop.

Shortwall Retreat

This system is well known and a reasonably extensive pillar needs to be developed if the high installation costs are to be justified.

Hydraulic supports tend to be limited to about 3.5 metre seam extraction conditions but provided the equipment is properly engineered the advantages become clear as far as the incipient heating risk is concerned.

The waste areas cave more systematically over a well designed straight line front. No inflammable timber is left in the waste and it is possible to extract all the seam except roof coal. In general the extraction process is clean and the section being extracted can be designed with as few as two main entries and with twin development roadways at the wings.

Without doubt the system has much to commend it providing the initial cost can be justified and there can be little doubt that the risk factor is much less than with the more conventional methods.

Longwall Retreating

Generally, the walls are about 80 metres long and long pillars capable of providing about 250,000 tonnes of coal are needed to justify the large capital expenditure involved plus the high installation and transfer costs.

The system permits the complete extraction of seams up to four metres and roof control problems tend to be less than shortwall because of the narrow webs taken by shearer type machines.

Conservative production rates of 1000 tonnes per operating shift will provide systematic retreat rates of four metres per shift in a three metre coal section. Supports capable of operating in such seam sections tend to be of the "shield" or six leg box type and their designs permit only the minimum of leakage into the waste behind the goaf canopies or anti-flushing shields.

Great attention is necessary to ensure that these supports are removed quickly after the section is extracted to eliminate the possible formation of a heating at the final waste edge and special equipment must be provided if this is to be done at maximum speed.

The system has not enjoyed great success in Australia but fast moving, high production units are being installed in the U.S.A. Clearly it has much to commend it as a method of minimising an incipient heating risk.

Systematic Air Sampling

The organisation of systematic air sampling from strategic ventilation points in an underground coal mine is essential if the overall risk is to be minimised. Irrespective of minimum legal requirements it is essential that air quantity measurements and qualitative samples be obtained from all intakes and returns which serve all sections of an underground mine.

The samples should be obtained from fixed stations and the analysis should give precise determination of oxygen, nitrogen, methane, carbon dioxide, carbon monoxide and in an emergency apparatus should be capable of giving precise determinations of hydrogen, ethylene, and propylene.

Suitable sampling points should be at shaft bottoms, main returns and intake splits, at the outbye end of district intakes and returns and in the case of longwall and shortwall retreat installations, approximately 10 metres outbye from the working face in the intake and return. These stations should be the minimum and additional ones may be required at regular intervals if bleeder roadways or lengthy goaf sections are in existence.

Samples should be taken at least every 30 days where methane levels are insignificant or if the incipient heating hazards are considered negligible.

If, however, a spontaneous combustion hazard is anticipated, qualitative samples should be made weekly but the analytical and sampling equipment should be capable of dealing with daily samples from about 25 per cent of the locations and up to hourly from up to twelve detailed stations which may have to be set up to deal with an incipient heating emergency.

Such analytical procedure will require the probable acquisition of two chromatography units, two infra red analysers and suitable portable apparatus together with an adequate supply of sample tubes, aspirator pumps and sample bags.

All results should be logged in a special book district by district so that an adequate history of information can be available on which to base trends in an emergency.

Emergency Procedures

In spite of adequate planning and analytical control, an incipient heat may still develop to accelerated conditions and an emergency procedure must be pre-planned for such an eventuality.

It is clearly impossible to set out a standard procedure but it must positively identify areas of responsibility for individuals and these must be set out in specific terms and frequent practices should be organised to ensure a smooth operation when emergencies occur.

A dangerous occurrence involving an incipient heating will require decisions that can ultimately only be taken by the Mine Manager and it is of utmost importance that any procedure be oriented to give him the maximum systematic information and advice.

STOPPINGS

If correct air analysis procedures have been adopted, it will be possible to anticipate the probable development of a heating and a decision could be made to seal off the affected area. Such a decision should be made fairly early and depending on the information available, it may be possible to install stoppings for the sole purpose of preventing a heating developing to high temperatures and open fire conditions. Under such circumstances, the use of non-explosion proof stoppings can be considered but any such decision to stop the normal ventilation flow can only be taken when all the facts demonstrate that explosive circumstances will be impossible while the stoppings are being constructed.

The construction of such seals is varied but they must be sited in positions which can guarantee sound foundations in roof side and floor, be capable of containing sampling facilities, and be sufficiently far from the site to ensure that the completed faces of the stoppings are leakproof and have balanced ventilation conditions.

Such seals would clearly be placed long before dangerous conditions exist and their prime purpose would be to prevent the oxidation process developing into dangerous proportions.

In spite of all precautions, however, circumstances can develop which indicate that a heating is out of control and the only remedial method available is to seal the entire area.

The method of sealing off must clearly be adapted to the nature and urgency of the circumstances and particular regard must be paid to the possibility that an inflammable atmosphere may be formed within the area to be sealed, and perhaps at the site of the fire once the ventilation is interrupted or seriously reduced.

In such cases the location of the stopping sites should be decided after the following factors are considered.

i. The normal make of firedamp in the area and the probable main points of emission relative to the heating site.
ii. The quantity and distribution of the ventilation under normal circumstances and the probable variation which may occur as the stoppings are being erected.
iii. The gradients in the area.
iv. The effects of the make of methane, the gradients and probable ventilation circumstances on the possible large accumulations of firedamp which could be capable of ignition.
v. The effect of the fire source on ventilation within the area and
vi. The coal dust hazard which could exist particularly if a gas explosion occurred.

The distance will obviously vary with circumstances but in extreme cases, it is necessary to site stoppings outbye at the shafts. Each case must, however, be judged on its own merit but a wise precaution may be to site stoppings several hundreds of metres back from the heating site, liberally stonedust access roadways inbye of the stoppings and erect light and heavy stonedust barriers which will be capable of arresting the spread of an explosion well before it reaches the stopping positions.

Design and Construction of Seals

Detailed experiments at the explosion gallery at Buxton in England and in the U.S.A. have shown that the most violent explosions occur when firedamp and airborne coal dust are involved and flame speeds of between 1000 and 2000 metres per second have been measured together with peak pulse pressures of up to 690 kPa (100 lbs/sq. inch).

It is not possible to assess the intensity of pressure which may occur at a particular location, but most authorities consider pressures in excess of 345 kPa (50 lbs. per square inch) most unlikely in underground conditions and explosion-proof stoppings should probably be capable of dealing with such loads.

In the past explosion-proof stoppings were constructed of sandbags filled with either sand or fine rubble with the retaining walls set well into the sides of the roadway with old girder-rails or pipes set at an angle between roof and floor providing interior reinforcing.

A well built compact structure of that kind was considered satisfactory if it filled a large roadway over a length of 9 metres, but shorter lengths were obviously employed if the stoppings were erected in a smaller roadway.

Such stoppings were built with a one metre diameter steel tube set at about 0.3 metre above floor level with fast closing armoured doors at either end to ensure the simultaneous sealing of all stoppings, and to permit easy re-entry to trained rescue men if the sealed area was subsequently re-opened.

Even though such stoppings were effective, they took considerable time to complete and quicker methods of construction are necessary particularly in Australian conditions where access roads are generally large.

Monolithic stoppings clearly satisfy such a need. They are inherently stronger and consequently they are relatively short.

Hardstop, which is partially dehydrated gypsum (hydrated calcium sulphate) has been used with considerable success in British mines, and such structures could well satisfy Australian needs. The hardstop is mixed with mine water by passing it through a dry feed hopper to a mixing chamber containing a spiral, and water inlets and the mixture is then pumped via a flexible hose between two retaining walls set into the roof sides and floor at the stopping site. Such a basic arrangement can deal with up to 30 tonnes per hour; the mixture stiffens after about 10 minutes and then hardens rapidly.

The bulk density of the mixture after setting is about 0.88 g/cm^3 (55 lbs. per cubic foot) and the compressive load to crushing is between 4,140 to 5,520 kPa (600 to 800 lbs. per sq. inch) after about three hours and between 10,350 to 15,870 kPa (1500 to 2300 lbs. per sq. inch) after final hardening. Again a steel tube is employed through the structure at floor level and normally the approved length of such a stopping is half the sum of the height and width of a containing roadway or about 3 metres whichever is the longer.

Such monolithic stoppings have been tested in experimental galleries under adverse explosion conditions. They were successful and without doubt they provide a practical method of sealing off in modern mechanised mines.

Similar monolithic stoppings have been constructed, by using a mixture of cement, bentonite and pit shale, and the ability of bentonite to hold relatively fine grains of shale in suspension during placing, tends to produce a good homogeneous plug.

Bentonite mixtures do, however, decrease in strength when the setting process occurs and this requires a good design to ensure competent foundations and a great deal of care and attention when the upper and final levels of stoppings are being completed.

Such explosion-proof stoppings should have provision for speedy final sealing and future access, and it is important that sampling proceeds during construction and after the seals are completed.

Initially the seal locations will have minimal air velocities and the possibility of stratification should be guarded against by taking 3 samples, one at floor level, one at roof level and one at a mid-section.

The velocity will, however, change progressively and as soon as convenient, the samples should be obtained from a permanent sample station, which should be at least 5 metres inbye from the stopping if no re-entry is anticipated and at least 20 metres inbye from the stopping if re-entry is to take place.

This will involve the use of sample tubes, normally of copper with about 6 mm bore, suitably protected within the stopping mass and from falling stones etc. by placing it inside a standard 50 mm pipe sealed around the 6 mm tube at each end. The sampling end should be sited at about mid-height position although its precise level will obviously be dictated by gradients and water seepage rates.

Such sample pipes will require a suction pump to obtain inbye samples under balanced conditions and can be used to determine pressure drop across the structure if pressure chambers need to be anticipated.

FINAL SEALING

In order to minimise the risk of explosion, great care must be exercised in general planning to ensure that all seals are completed simultaneously and all men must be withdrawn from all sections likely to be affected by an explosion. Generally, all men are withdrawn from the mine.

As soon as the ventilation is stopped, an immediate adjustment occurs to the atmosphere inside the seals. This is obviously due to the sudden pressure changes and to local heat convection, followed by further changes as natural ventilation circumstances are set up by the fire itself.

The possibility of explosive mixture at previously remote points backing to the fire is obvious and the possibility of an immediate explosion hazard must be considered seriously. Following such a possible occurrence, there is a further build up of hazard due to continual increases in firedamp and possibly fire gases until the oxygen is consumed to a point of extinction as far as gaseous combustion is concerned, generally between 10 to 12 per cent oxygen.

Unless the rate of firedamp production is very small and the fire is large with a high consumption of oxygen, the atmosphere behind the seals almost inevitably passes through a period where it is explosive. It is impossible to know how frequently ignitions occur, but the dangers of being present at stopping sites during such a period are well known and have been harshly demonstrated by incidents such as the Bickershaw explosion of 1959. At this mine the stoppings had been sealed but the intake stopping had not been completed to its explosion length of about 11 yards. This work was in progress when an explosion within the sealed off area blew out the top of the seal and killed 5 workmen.

An estimate can be made of the duration of the danger period from the known make of firedamp coupled with knowledge of the sealed area and details of complete air samples. If such calculations are made it is wise to employ a large safety factor.

Generally, however, experience in a variety of circumstances has shown that all men should be withdrawn for a minimum period of 24 hours. After such a period an inspection of the sites should be made by rescue team members who should obtain samples from each stopping.

If the analysis of such samples shows extinctive conditions, it is an obvious precaution to organise check samples.

If, however, the samples do not give extinctive conditions, systematic sampling, possibly up to two hour frequency, should be instituted until safe trends become obvious. Clearly, remote sampling arrangements should be employed and the use of tube bundle techniques to automatic sampling stations should always be used if the equipment is available.

Preparatory Stoppings

The need to preplan districts with an incipient heating hazard has been previously mentioned and under general Australian conditions, sites can be prepared, roof, sides and floor can be excavated at the stopping wall positions and the outer perimeter of the final walls should be constructed as soon as entries are made.

It is important that detailed final construction plans be made available when such preparatory work is undertaken and all the necessary materials are stored at the sites at the start. In an emergency, supply problems are the main reasons for slow progress and it should be remembered that even if a relatively quick hardstop stopping is constructed, a roadway 4.8 m by 3 m will require a stopping 3 m long and need some 40 tonnes of hardstop or nearly 8,000—22 kg. bags.

Relatively thick seams with fairly good ground pressure characteristics exist in many Australian mines, and it should be possible to design easily erected steel prefabricated structures to withstand explosive impact pressures of 345 kPa (50 lbs./square inch).

Such structures should consist of substantial steel frames set well back in reinforced concrete into roof sides and floor, with provision to slot suitable steel sections into steel frame members to form inner and outer retaining sections with about a metre between them. Explosion-proof doors on a short access tunnel should be provided and the void between could be filled very quickly with hardstem or some other suitable material if explosion-proof seals are required.

If no incipient heating occurs, it is possible to remove the outer steel form for use elsewhere and use the inner section on a frame for a non-explosion-proof seal.

The possibility of such stoppings was suggested in a memorandum prepared in 1962 by the Institution of Mining Engineers, but the difficult ground conditions in the United Kingdom have prevented the development of such a method.

Conditions are, however, suitable in some Australian mines and the provision of such structures should be encouraged.

Extinctive Conditions

Flaming combustion normally ceases when the oxygen content of the surrounding atmosphere is less than 12 per cent but such levels of oxygen should not be considered to indicate a completely safe condition.

Work by Mason and Tideswell in 1933 showed that at oxygen contents of about 5 per cent, a dying fire can be maintained in an incandescent state, and if the heat insulating properties below ground are good, the continued presence of 2 per cent of oxygen may be capable of maintaining a heating indefinitely.

Clearly areas which were sealed off by explosion-proof stoppings because of a spontaneous combustion fire will not generally present a hazard to the remainder of the mine when samples show oxygen contents of less than 10 per cent, but often machinery representing a large capital commitment and reserves of coal can be sterilized within the area.

Consideration will inevitably be given to the possibility of re-opening an area and this should normally be undertaken only when the analytical facts indicate that a fire is "out".

Obviously the greatest care must be taken before deciding to re-open an area and in many cases a high probability of extinction can be concluded from analytical trends. Such trends need to be observed over fairly lengthy periods because experience has shown that if a fire has involved a large mass of material such as a large pillared area, the period of observation associated with satisfactory cooling may take years, although fairly small sections could well take periods measured in months.

Re-opening involves considerable detailed planning and the available methods are generally classified as follows:—

1. *The direct method.*

   This involves the breaching of the stoppings and the circulation of air round the entire mine or district without inspection by trained rescue brigades.

2. *The inspection method.*

   This requires inspections of the affected areas inbye the permanent seals by rescue teams followed by the circulation of air through the area.

3. *The stage method.*

   This again requires a satisfactory pre-inspection by trained rescue brigades followed by the circulation of air in stages.

4. *The partial re-opening method*

   This requires the building of further explosion-proof stoppings inbye side of the existing stoppings—generally as close as possible to the site of the incident then recirculating air through the rest of the district or mine.

Methods 1, 2 & 3 are not generally recommended when sealing off has been undertaken following an advanced heating with dangers associated with explosive gas mixture.

Almost invariably the partial re-opening method is employed and considerable planning and analysis interpretation is required. Indeed, it is unwise to commence such a task unless expert advice is available and generally, sealed off areas should not be subject to interference unless expert opinions are considered in detail.

Barometric Variations

The effects of sudden barometric variations on large waste areas are well known to mine management, but particular attention to such variations is essential if accurate trends are to be made when a spontaneous heating is being treated.

Incipient heatings within a waste produces carbon monoxide and other gases and if there is a serious heating any sudden decrease in barometric pressure will result in a sudden increase in carbon monoxide content of the ventilating air, but the converse is not necessarily true to the same degree. When an increase in atmospheric pressure occurs, air is forced into the waste but the effect on the composition of the air from the district can often be only marginal.

Complete continuous records of barometric pressure and temperature should be maintained throughout a heating and in addition to considering the carbon monoxide implications, thought should be given to the possible migration of explosive gases towards the fire from local emission points.

Barometric variations should also be taken into consideration when interpretations are being made relative to samples obtained from behind stoppings installed to deal with spontaneous heatings. Obviously if the pressure on the outer face of a stopping exceeds that inbye, fresh air will tend to leak into the area. Samples obtained during such periods will be contaminated with fresh air, sometimes in spite of a 20 metre sampling pipe. Special care must therefore be taken in interpreting results so obtained and it should be remembered that even after the atmospheric pressure stabilises, air that has leaked inbye can remain there for some time before uniform qualitative conditions exist around the sample point.

The effects are often obvious when results are observed and clearly some "rogue" results will have to be disregarded.

CONTINUOUS MONITORING OF MINE AIR

The incidence of spontaneous heatings in underground coal mines has tended to increase in recent years and this can probably be attributed to changes in extraction techniques and the intensive mining methods which have been developed over the past twenty years. The deterioration has led to investigation into the possibility of developing continuous information on mine air quality, and even though it is accepted that the use of the CO/O_2 ratio still constitutes the best method of determining the heating trends, most engineers accept the need for back up protection in the form of a continuous monitoring system.

Two basic methods of continuous monitoring have been developed. One employs infra-red analysers below ground to determine constituent concentrations and the determinations are then telemetered to a recorder conveniently situated below ground or on the surface. The other employs a tube technique which transports continuous samples of mine air to a surface analytical centre where results are continuously recorded.

The tube bundle technique has now become the standard method in the U.K. and successful comprehensive field tests undertaken by the United States Department of the Interior have confirmed the practical advantage of the tube bundle technique and an expansion of its use is occurring in United States underground coal mines.

The advantage of the system is its inherent simplicity and the fact that all the controls and analytical equipment are on the surface where they can be conveniently serviced in an area not restricted by the legal requirements normally associated with F.L.P. and intrinsically safe regulations.

General Layout

The technique used by the National Coal Board is the tube bundle technique which satisfies the basic requirement in that it is capable of providing information on the composition of mine air at intervals which are short enough to discriminate between transient peaks of gas concentrations due to shotfiring etc., and a steady rise which can indicate serious difficulties.

The tubes employed are similar in appearance to multicore electric cables, they are taken down the shaft and along selected underground roadways and by using normal junction boxes individual tubes (about 6 mm I.D. of P.V.C.) can be taken to strategic sampling stations.

Dust filters, water and flame traps are installed into the system as required and a diaphragm pump situated at a surface station draws air continuously from all the sampling points.

A delay factor exists which is related to the length of the tubes and this can be established by timing the period between the introduction of a known gas "slug" at the sampling point and its arrival at the analytical equipment.

The delay depends on the pressure drop, the tube diameter and its resistance but generally periods of up to 2 to 3 hours will not seriously affect the efficiency of the system.

The surface equipment includes a timing relay which works in conjunction with solenoid valves in each sample line, and each line provides samples in a fixed sequence. The air samples are drawn into the system by a small vacuum pump and are analysed for carbon monoxide by a standard infrared analyser and for methane by using pellister type units. The results are recorded automatically on rotating graph paper on a commercial unit and generally two stations are printed on each recorder—separate units being employed for each constituent gas.

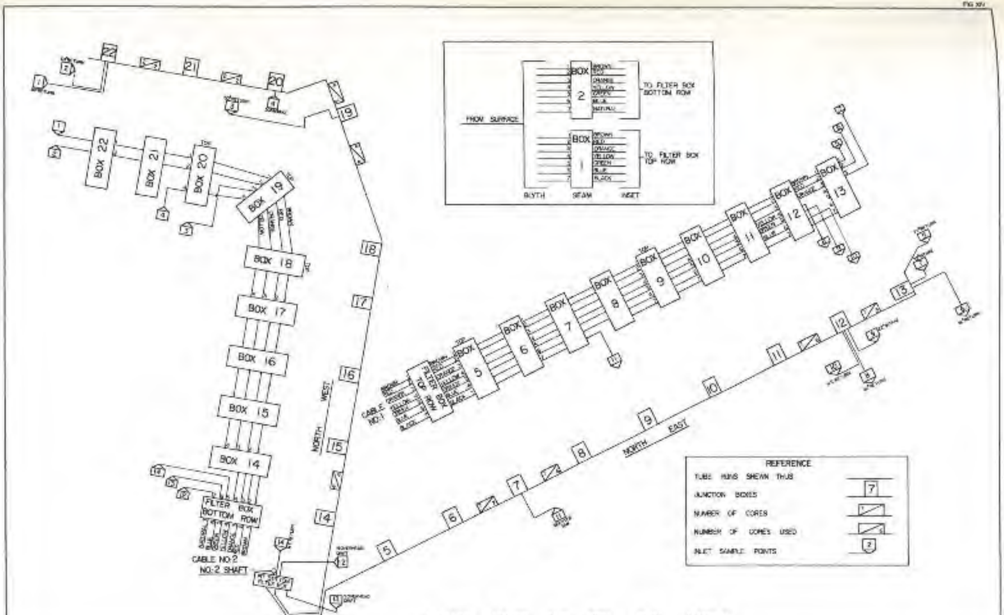
Figure XIV shows the tube run layout for a typical British installation and Figure XV shows part of the trace for carbon monoxide from two sample stations some 3 miles inbye from the shafts.

One installation similar to that shown in Figure XIV involved the fixing of armoured tube bundles down a 3,000 ft. vertical shaft and the systematic placing of tubes to twelve sampling points—some 4 miles from the shafts.

Such installation involved capital expenditure of £18,050 and revenue expenditure of £15,785, which was justified by the very early detections of an incipient heating, by a saving in wages of underground samples, and by removing the costly inconveniences associated with the treatment of a well established heating.

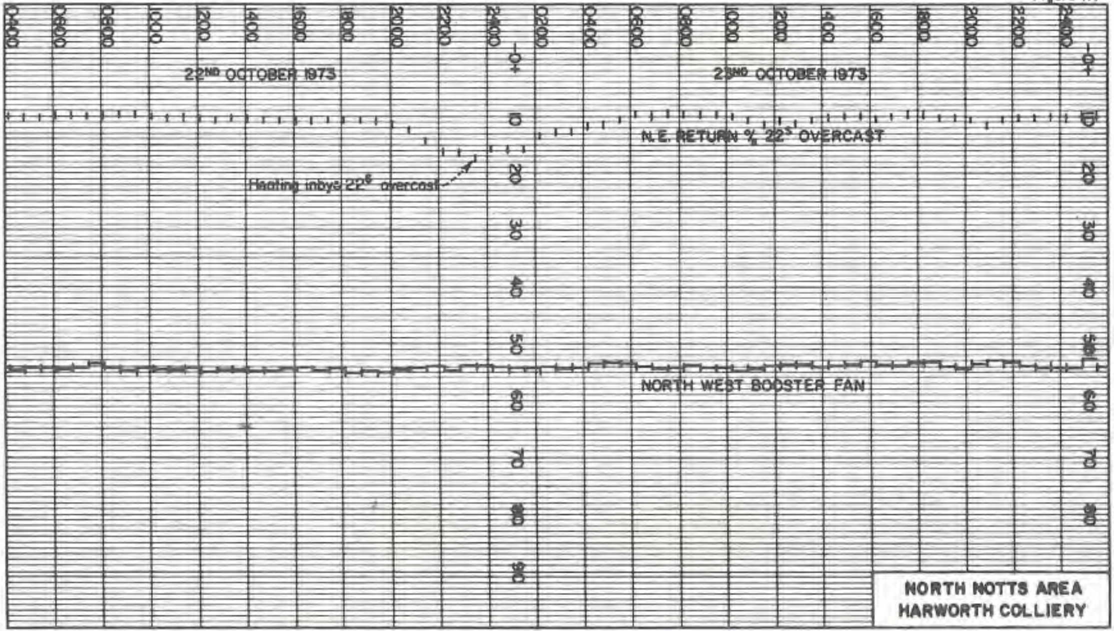
Figure XV shows results being recorded on a 40 minutes interval and a heating developing in the side of a roadway near an overcast. Early remedial work was possible because of early detection and in this case normal conditions were restored within 6 hours.

The total surface installation for up to 16 carbon monoxide and 8 methane stations can be mounted in a relatively small cabinet. One such installation is shown on Plates 1 and 2.



JUNCTION BOXES AND PIPE RUN LAYOUT

Figure XV



22ND OCTOBER 1973
23RD OCTOBER 1973
N.E. RETURN % 22S OVERCAST
Heating inbye 22S overcast
NORTH WEST BOOSTER FAN
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
0200
0
10
20
30
40
50
60
70
80
90
NORTH NOTTS AREA
HARWORTH COLLIERY

CONCLUSIONS

This booklet has been compiled to remind Management of the basic facts associated with the spontaneous combustion hazard in underground coal mines.

Hundreds of papers have been prepared and a brief reference list of some is included, hopefully for further detailed reading and reference particularly by Mine Management who will always be responsible for dealing with this hazardous problem.

The booklet cannot be complete and expert advice should always be sought so that any decisions taken will be the best available relative to the known facts.

The object of the exercise must always be to solve the spontaneous heating problem under the safest possible circumstances and it is hoped that the booklet will promote further discussion so that the risk can be further minimised.

H.J.

March 1976

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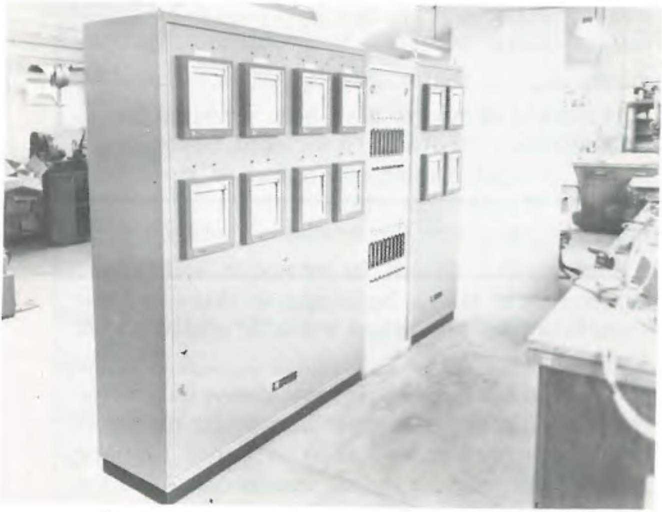

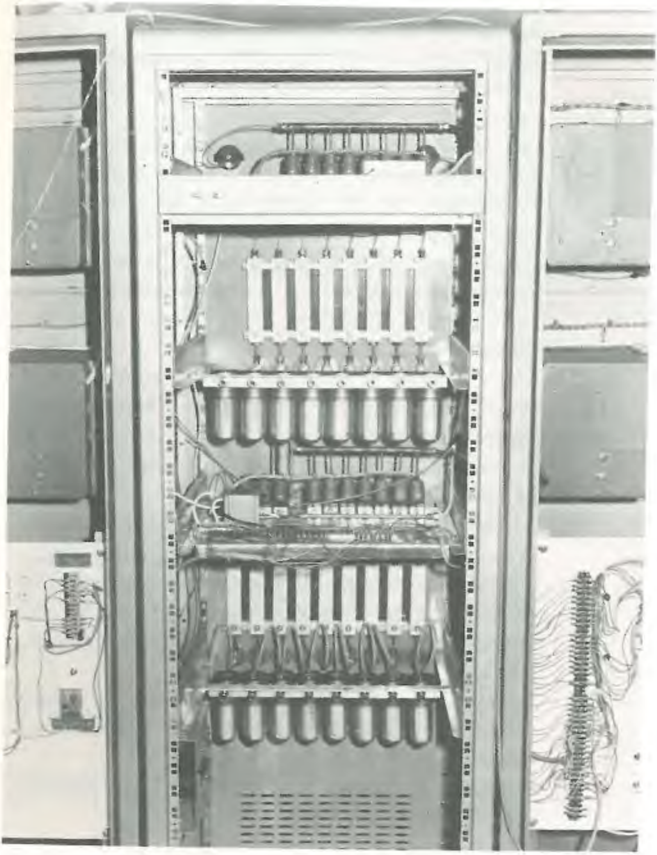

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